1st Quarterly Progress Report

ODOT Research

1st Quarter Ended on March 31
"Quarterly report: State Job #5501.03"

For Quarter Ending:	March 31
Date Submitted:	**April 30**

Project Title:	Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits				
Research Agency:	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, 2019			Spent to Date:	$8,425
% Funds Expended:	2%	% Work Done:	11%	% Time Expired:	12.5%

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. - NCDOT
4. Paul Rowekamp, MnDOT
5. Sheri Little, PennDOT
6. Carlton Spirio, FDOT
7. Jonathan Karam, 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

CUIRE · LEO Consulting, LLC · Structurepoint

Project Schedule Sorted by Start date

2017 | 1th Quarter March 31, 2018 | 2018 | 2019

Task	Responsibility	Description	Dec	Jan	Feb	Mar	Apr	M* Quarterly Progress Report (April 30, 2018)	May	Jun	Jul	M* Quarterly Progress Report (July 31, 2018)	Aug	Sep	Oct	M* Quarterly Progress Report (October 30, 2018)	Nov	Dec	Jan	M* Quarterly Progress Report (January 30, 2019)	Feb	Mar	Apr	M* Quarterly Progress Report (April 31, 2019)	May	Jun	Jul	M* Quarterly Progress Report (July 31, 2019)	Aug	M* Draft Final Report and Draft Fact Sheet (August 20, 2019)	Sep Draft Report Review (Due September 30, 2019)	Oct	Nov	Dec	M* End of Project (December 20, 2019)
2	Dr. Mo Najafi	Literature Search/Participation Material Vendors				57%				Deliver-able																									
11	Dr. Mo Najafi Dr. Xinbao Yu	Lab Testing		Vendor Communication		18.75%																		Deliver-able											
11 - A		Testing Coupons from Vendors **(NTPEP)**																																	
11 - B		Data Acquisition Setup																																	
11 - C		Soil Box Test 1 with Coupons Testing from Samples																																	
11 - D		Soil Box Test 2 with Coupons Testing from Samples																																	
11 - E		Soil Box Test 3 with Coupons Testing from Samples																																	
1	Dr. Mo Najafi	Survey of US DOT's and Canadian Agencies				28.5%							Deliver-able																						
7	Mr. Ed Kampbell	Field Data Collection and Assistance from DOT Partners												Deliver-able																					
3	Mr. Ed Kampbell	Additional Reinforcement									Deliver-able																								
4	Mr. Ed Kampbell	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design									Deliver-able																								
5	Dr. Mo Najafi	Life Cycle Cost Analysis													Deliver-able																				
6	Mr. Ed Kampbell	Review the Cured In Place (CIPP) Design Equations													Deliver-able																				
8	Dr. Firat Sever	Develop a Recommended Structural Design Equations																	Deliver-able																
8 - A		Establish base equations																																	
8 - B		Identify missing parameters																																	
8 - C		Revise equations with field and lab data																																	
8 - D		Verify and finalize equations																																	
10	Dr. Xinabo Yu	Computational Modeling				18.75%																		Deliver-able											
10 - A		Create and Verify Circular Reinforced Concrete Pipe W/O Liner W/O Crack in Granular Soil				42.85%																													
10 - B		Evaluate FEM Models with Design Equations																																	
10 - C		Calibrate FEM Models with LAB Tests																																	
10 - D		Parametric Study of FEM																																	
9	Dr. Firat Sever Mr. Ed Kampbell	Develop Performance Construction Specification																							Deliver-able										
9 - A		Prepare Draft Specs for Polymeric Spray Applied Liners																																	
9 - B		Prepare Draft Specs for Cementitious Spray Applied Liners																																	
9 - C		Prepare Final Specs for Polymeric Spray Applied Liners																																	
9 - D		Prepare Final Specs for Cementitious Spray Applied Liners																																	
13	Dr. Mo Najafi	Draft Final Report and Fact Sheet																											Deliver-able						
14	Dr. Mo Najafi	Final Report and Presentation																														Final Report			
12	Mr. Lynn Osborn	QA/QC				16.7%																												Deliver-able	

* Milestone

First Quarter Progress Completed Percentage (green)

Table 2: Completion Percentage of SAPL Research Project Tasks over the 1st Quarter

		Completion Percentage of Project Tasks over the 1st Quarter			
		2017	2018		
Task	**Description**	**Dec**	**Jan**	**Feb**	**Mar**
1	Survey of US DOT's and Canadian Agencies			**29%**	
2	Literature Search/Participation Material Vendors	**57%**			
10	Computational Modeling		**19%**		
10-A	Create and Verify Circular Reinforced Concrete Pipe W/O Liner W/O Crack in Granular Soil		**43%**		
12	QA/QC	**17%**			

Comparative Status of Actual Versus Estimated Expenditures

Table 3: Quarterly Progress Work of SAPL Research Project

Task Number	Task Description	Total Duration (Months)	Duration Completed (Months)	Budgeted Amount	Percentage of Completed Based on Schedule	Percentage of Total Based on Budget	Percentage Completed This Quarter	Actual Amount Completed This Quarter
Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits								
Quarterly Progress Work								
1	Survey of US DOT's and Canadian Agencies	7	2	$25,751	28.57%	6.44%	60%	$15,451
2	Literature Search/Participation Material Vendors	7	4	$21,875	57.14%	5.47%	70%	$15,312
3	Additional Reinforcement	3	Not Started	$2,100	0.00%	0.52%	0%	$0
4	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design	3	Not Started	$3,900	0.00%	0.97%	0%	$0
5	Life Cycle Cost Analysis	3	Not Started	$29,123	0.00%	7.28%	0%	$0
6	Review the Cured in Place (CIPP) Design Equations	3	Not Started	$13,751	0.00%	3.44%	0%	$0
7	Field Data Collection and Assistance from DOT Partners	5	Not Started	$26,752	0.00%	6.69%	0%	$0
8	Develop a Recommended Structural Design Equations	5	Not Started	$34,081	0.00%	8.52%	0%	$0
9	Develop Performance Construction Specification	7	Not Started	$27,392	0.00%	6.85%	0%	$0
10	Computational Modeling	16	3	$52,039	18.75%	13.01%	5%	$2,602
11	Lab Testing	16	3	$67,001	18.75%	16.75%	15%	$10,050
12	QA/QC	24	4	$8,000	16.67%	2.00%	20%	$1,600
13	Draft Final Report and Fact Sheet	7	Not Started	$88,270	0.00%	22.07%	0%	$0
14	Final Report and Presentation	3	Not Started					
Total				$400,034		100%		$45,015

Table 4: Expenditures Summery of SAPL Research Project

Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits					
Summary of Expenditures					
Description	**Sum Amount**	**Type**	**Name**	**Accounting Date**	**Posted Date**
Student Salaries					
SW Research Assistant	$427.340	Salary	Chimauriya, Hiramani Raj	2/13/2018	3/2/2018
SW Research Assistant	$800.000	Salary	Chimauriya, Hiramani Raj	2/28/2018	3/2/2018
SW Research Assistant	$1,217.360	Salary	Nayak, Anushree	2/28/2018	3/2/2018
SW Student	$1,092.000	Salary	Tabesh, Amir	3/15/2018	4/6/2018
SW Research Assistant	$782.610	Salary	Kohankar Kouchesfehani, Zahra	3/29/2018	4/6/2018
SW Research Assistant	$1,500.000	Salary	Kohankar Kouchesfehani, Zahra	3/29/2018	4/6/2018
SW Research Assistant	$800.000	Salary	Chimauriya, Hiramani Raj	3/31/2018	4/6/2018
SW Research Assistant	$1,500.000	Salary	Kohankar Kouchesfehani, Zahra	3/31/2018	4/6/2018
Fringe Benefits					
Prem Share Active Suppl	$36.340	Fringe	Chimauriya, Hiramani Raj	2/13/2018	3/2/2018
Workers Compensation	$0.860	Fringe	Chimauriya, Hiramani Raj	2/13/2018	3/2/2018
Prem Share Active Suppl	$68.030	Fringe	Chimauriya, Hiramani Raj	2/28/2018	3/2/2018
Workers Compensation	$1.600	Fringe	Chimauriya, Hiramani Raj	2/28/2018	3/2/2018
Workers Compensation	$2.430	Fringe	Nayak, Anushree	2/28/2018	3/2/2018
Unemployment Compensation	$5.280	Fringe	Nayak, Anushree	2/28/2018	3/2/2018
OASI Employer Match	$83.530	Fringe	Tabesh, Amir	3/15/2018	4/6/2018
Prem Share Active Suppl	$36.340	Fringe	Kohankar Kouchesfehani, Zahra	3/29/2018	4/6/2018
Workers Compensation	$1.560	Fringe	Kohankar Kouchesfehani, Zahra	3/29/2018	4/6/2018
Prem Share Active Suppl	$68.030	Fringe	Chimauriya, Hiramani Raj	3/31/2018	4/6/2018
Workers Compensation	$1.600	Fringe	Chimauriya, Hiramani Raj	3/31/2018	4/6/2018
Total	$8,424.91				

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

Principal Investigator: Dr. Mohammad Najafi

General (Appendix A)

- The CUIRE Team created a Google Drive account as an interactive depository of documents for SAPL Research Project.
- An analysis of DOT SAPL Projects are included in this depository and a summary is presented in Appendix A.

Task 1: Survey of U.S. DOTs and Canadian Agencies (Appendix B)

- To supplement the literature search, CUIRE conducted a survey of U.S. DOTs and Canadian Agencies to gather information regarding their experiences and concerns with spray applied pipe liners (SAPL) in gravity storm water conveyance culverts.
- After finalizing and a pilot survey, the survey was sent to U.S. DOTs and Canadian Agencies with a response due date of April 30.
- Appendix B presents the survey form.

Task 2: Literature Search/Participation Material Vendors (Appendix C)

Literature Review (Reference Section provides more details):

- Literature search/review started at the beginning of the project, December 20, 2017, and scheduled completion date is June 30, 2018.
- The following is some of literature sources used for review:

    1. NTPEP Evaluation of Spray Applied Non-Structural and Structural Pipe Liners for Storm Water Conveyance.
    2. Ohio DOT Culvert Management Manual.
    3. Culvert Rehabilitation to Maximize Service Life While Minimizing Direct Costs and Traffic Disruption.
    4. Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe.
    5. Global Review of Spray-on Structural Lining Technologies.
    6. Laboratory Testing and Analysis of Geo-polymer Pipelining Technology for Rehabilitation of Sewer & Stormwater Conduits.
    7. Large Corrugated Metal Pipe Repair Techniques.
    8. Measured Response of Two Deteriorated Metal Culverts Repaired with Sprayed Cementitious Liners.
    9. Numerical Study of Longitudinal Bending in Buried GFRP Pipes Subjected to Lateral Earth Movement.

10. Performance of Deteriorated Corrugated Steel Culverts Rehabilitated with Sprayed-On Cementitious Liners Subjected to Surface Loads.
11. PVA Fiber Reinforced Shotcrete for Rehabilitation and Preventative Maintenance of Aging Culverts.
12. Structural Behavior and Compressive Strength of Concrete Rings Strengthened with a Polyuria Coating System.
13. Structural Capability of No-Dig Manhole Rehabilitation.
14. Structural Classifications of Linings, Suggested Protocol for Product Classification.
15. Trenchless Renewal of Culverts and Storm Sewers.
16. Trenchless Technology: Pipeline and Utility Design, Construction and Renewal.
17. Ultimate Strength Testing of Two Deteriorated Metal Culverts Repaired with Spray-On Cementitious Liners.

- Appendix C presents the literature review conducted in this quarter.

Participation of Material Vendors:

- The CUIRE team has invited 15 vendors for participation.
- The following 7 vendors have replied back, and shown willingness to participate:
  - AP/M Permaform/CentriPipe
  - AWCOOK
  - Epoxytec
  - Milliken
  - Sprayroq
  - The Strong Company
  - Vortex
- The CUIRE Team had several conference calls with SippTech. Since their technology does not coincide with SAPL, they were excluded from current research, and can be scheduled for the next phase of this research. They also stated that they could not line pipes larger than 48 in. diameter.
- The CUIRE Team had a conference call with Dr. Royer from Milliken. He explained some concerns on feasibility of testing liners without the host pipe, specifically for cementitious and geo-polymer materials.
- The vendors first will go through NTPEP laboratory testing process.
- Table D1 in Appendix D presents a complete list of vendors.

<u>Task 11: Laboratory Testing</u>

Testing Coupons from Vendors (NTPEP):

- The CUIRE Team has recommended a laboratory-testing plan according to ASTM Standard Specifications.

- Appendix E presents Laboratory Testing Plan at CUIRE/UTA.

Soil Box Testing:

- The CUIRE Team has prepared a detailed soil box-testing plan using ASTM Standards and AASHTO LRFD Design and Construction Specifications.
- The CUIRE Team prepared a tentative schedule for the Soil Box Testing.
- Appendix F presents the tentative Soil Box Testing Plan and a list of instrumentations and quotes from instrumentation suppliers.

<u>Participation in the Meetings during Conferences, Internal Meetings, Progress Meetings</u>

- Dr. Najafi and CUIRE Team attended the meeting with DOTs and research partners (Ed Kampbell and Lynn Osborn) in Washington, DC, during TRB 2018 Conference last January.
- Dr. Najafi and CUIRE Team had an internal meeting with Mr. Ed Kampbell in conjunction with the UCT Conference in New Orleans on January 30.
- Dr. Najafi held internal weekly meetings with CUIRE Team research partners (Xinabor Yu, Ed Kampbell, Lynn Osborn, and Firat Sever).
- Dr. Najafi and CUIRE Team attended a kickoff and three progress meetings with DOTs.
- During the No-Dig 2018 conference in Palm Springs, Dr. Najafi had meetings with Mr. Ed Kampbell and Dr. Firat Sever regarding Soil Box Testing Plan.
- During the No-Dig 2018 exhibit, Dr. Najafi invited Mr. Asay from Advantagerline Company and Mr. Hallam from Madewell Company to participate as vendors in the SAPL Research Project.

Co-Principal Investigator: Dr. Xinbao Yu

The following are the tasks performed this quarter:

1. Literature review

- Reviewed ASTM standards D4000, D790, D638, D695, D4541, D2240, and D792 to determine testing requirements for polymer liners.
- Reviewed papers on previous work with soil box testing.
- Reviewed AASHTO Standard for Highway Bridges to determine requirements for material types, installation method, compaction requirements, etc. for concrete pipes.
- Reviewed design methods related to pipes buried in soil, including difference in earth pressure distribution for rigid and flexible pipes.

2. Laboratory Tests of Coupon Samples

- **Prepared lists of tests required to obtain material properties for polymer liners**
  - Finalized the testing standards; and determined the test requirements about the testing procedure, loading rates, sample shapes and sizes, number of samples and test setup for each test.
  - Prepared detailed testing plans to perform the selected tests on polymer liners (compressive, flexure, tension).

- **Identified testing capabilities of UTA labs**
  - Checked the MTS machine at the CELB lab.
  - Communicated with the director and lab technician of the Advanced Material and Structures Lab (AMSL) in the Department of Mechanical Engineering to check their testing capabilities and inquired their availability and requirements for future testing.

3. Soil Box Tests

a) Design of Soil Box Tests

- **Prepared and revised design drawings of soil box tests.**
  - Prepared section and plan view for test setup with three circular pipes with 0.5D spacing between them.
  - Prepared section and plan view for six test setups with two pipes with D-spacing between them, including instrumentation number and location, the three test sections and the loading pads.
  - Revised the drawings to show compaction requirements for each level in the soil box.

- Revised the drawings to show section and plan view for four test setups with three pipes with 0.5D-spacing between them, including instrumentation number and location, the three test sections and the loading pads.

b) Testing Soils

- **Sample Collection**
  - Collected two buckets of samples of Pea Gravel from CUIRE soil stockpile.

- **Preliminary lab tests to determine the suitability of fill materials for soil box testing.**
  - Four Sieve Analysis tests were performed on samples from Materials Yard. The samples belonged to category Poorly Graded Gravel (GP).
  - Two Standard Proctor Compaction Tests on samples from CUIRE soil stockpile.

- **Collected one more bucket of sample from CUIRE soil stockpile.**
  - Prepared sample for Hydrometer test but the test was stopped, as material was deemed unsuitable.

- **Agreed using Poorly Graded Sand (SP) as fill and embedment material for the soil box test.**

- **Collected samples of river sand and concrete sand from Holt Excavating Sand & Gravel LLC.**
  - Performed three Standard Proctor Tests and four sieve analysis tests on the samples. Both samples were categorized as Poorly Graded Sand (SP) with River Sanded having higher Optimum Moisture Content (OMC) and lower Maximum Dry Density (MDD) as compared to concrete sand.

c) Instrumentation

- **Collaborated in preparation of a detailed list of instrumentation (including specific models and quotes) required for the soil box testing.**

- **Collaborated in making contacts with different vendors for Strain Gauges, Earth Pressure Cells, String Potentiometers, Sonotubes and Styrofoam, Slings and Slip-sheets**.
  - Contacted four different vendors to inquire about strain gauges. Finalized possible vendors to HBM and TMI after detailed inquiry.
  - Contacted GeoKon for Earth Pressure Cells and inquired about different models and pressure ranges available.

  - Contacted Vishay (Micro Measurements) and TE Connectivity for String Potentiometers. Due to lack of response from TEC, Vishay was the only available vendor.
  - Obtained list of locally available suppliers of Sonotubes.
    - Contacted two suppliers close to Arlington (in Dallas and Fort Worth) and obtained the price of each tube.
  - Checked five vendors for supplying Styrofoam molds.
  - Checked three different vendors for Slings.
  - Checked with three vendors, as well as retail establishments for Slip-sheets.
  - Checked for form release agents when using Styrofoam molds.
  - Revised the number and types of instrumentations to be used and made changes to the drawings accordingly.

- **Obtained prices for the products from respective vendors:**
  - Obtained quotes for Strain Gauges from TMI and HBM and Earth Pressure Cells from GeoKon.
  - Obtained price of Sonotubes from two suppliers located in Dallas and Fort Worth.
  - Obtained price of slings and slip-sheets from different vendors.
  - Obtained price of Styrofoam molds from different vendors, all were found to be in the region of about $1,000 for each pipe.
  - Calculated the total cost for instrumentation purchase for the original testing plan.
  - Recommended using two pipes of same thickness in a single soil box test setup and two different thickness of pipes overall.
  - Obtained updated quotes from vendors for strain gauges, earth pressure cells and price list for convergence meter.
  - Recommended reducing number of instrumentation used in testing by instrumenting whole section below one loading pad and only half the section at other two locations.
  - Calculated total cost of instrumentation for reduced sections.
  - Based on CUIRE past experience, checked alternatives to String Potentiometer, the Convergence Meter from GeoKon.

d) Loading Design

- Recommended using Gravel/Soil load in container as static load instead of concrete blocks to avoid possibility of abrupt failure of pipes.
- Checked the bearing capacity of fill soil.
- It was recommended that the soil pressure at the top of soil box be reduced to account for the effects of pavement.

e) Molds for Fabrication of Liner Pipes/Cementitious Pipes

- Inquired with Machine Shop, Fab Lab, Department of Architecture and Sculptures to check their foam cutting capabilities.
- Checked for alternatives to Styrofoam molds.
- Checked with three vendors for prices of geofoam.
- Recommended using industrial corrugated steel pipe forms, lined with geomembranes/geosynthetic instead of Sonotubes or Styrofoam to cast SAPLs.

4. FEM Modeling (Appendix G)

- Developed the FEM modeling plan. The FEM modeling started with model of intact reinforced concrete pipe. D-Load data of such pipe is available for model development and verification. With the verified FEM model of the pipe, FEM model of pipe in the soil box will be developed to study soil-pipe interactions.
- Developed a modeling approach for concrete circular pipes using Abaqus.
  - Modeling of concrete pipe in D-Load Condition.
  - Modeling of k_o soil pressure.
- Appendix G presents the Summary of the Progress on Numerical Modeling of Circular Pipe Using ABAQUS.

Subcontractor: Mr. Ed Kampbell
Rehabilitation Resource Solutions, LLC

JANUARY 2018

- Attended the project team kick-off meeting in Washington D.C. during TRB as requested.
  - Met for lunch with key members of project team and the various representatives of the DOT sponsors (excepting Florida) to kick off the work.
  - Met with UTA team members in the lobby to discuss and brainstorm what would be required to ensure that we were on track to accomplish the testing needed and promised in the proposal. During this meeting, I produced a rough sketch of the soil box work. I was elected to commit the testing planned to a written document that Dr. Xinbao could work from to add the details that would making it a full-fledged work plan.
- Requested changes/modifications to the project time line
  - Moved Task 3 to the May to July timeframe
  - Moved Task 7 to the May to September timeframe to ensure better weather for accomplishing the site visitations and liner condition assessments
- Met with members of the UTA team at UCT Conference on Jan. 30th
  - Discussed the site visits with Dr. Najafi, Amir Tabesh, and Zahra Kohankar
    - Discussed preparing the list of visits to be made within the various DOT jurisdictions
    - Discussed using DOT personnel to expedite the visit and coordinate the proper safety protocols
    - Zahra may need to become confined space safety trained
  - Discussed further the Lab testing write-up I would be preparing so that the lab could deliver what was intended in the proposal. It was agreed that I would produce a detailed outline that Dr. Xinbao could add to for the completed document.

FEBRUARY 2018

- On 02.13.2018, I transmitted a 3-page write-up of the testing to be accomplished on the various cementitious and polymeric materials keeping said write-up in line with what UTA had submitted in the proposal; and including QC/QA notes to assure the integrity of the testing to be done. Below is a summary of that document…
  - Laboratory testing
    - Cementitious (Portland and geo-polymer) beam samples to be tested using 0.5 in., 1.0 in., and 2.0 in. beams per ASTM C1609
    - Polymeric (epoxy and polyurethane) beam samples to be tested using 0.5 in., 1.0 in., and 2.0 in. beams per ASTM D6272 (this is a deviation from the D790 test shown in the proposal which I recommended to UTA to get approved;

because I felt it better followed the investigation of a structural liner in the size structures we were charged with investigating)

- Testing of circular beam samples prepared from portions of the soil box samples below using a unique fixture to distribute the load across the beam under load and with the ends pinned (able to rotate) to tie the soil box testing to the C1609 and D6272 testing above. This test method could provide the DOT's with a method for more accurate evaluating.

- Soil box samples
  - Cementitious (Portland and/or geo-polymer) pipe samples lined in 60 in. Sonotubes
    - Circular pipe samples in 0.5 in., 1.0 in., and 2.0 in. thicknesses
    - Pipe arch samples in 0.5 in., 1.0 in., and 2.0 in. thicknesses made using a fabricated Styrofoam insert to create a 57 in. x 38 in. pipe arch shape
  - Polymeric (epoxy and/or polyurethane) pipe samples lined in 60 in. Sonotubes
    - Circular pipe samples in 0.5 in., 1.0 in., and 2.0 in. thicknesses
    - Pipe arch samples in 0.5 in., 1.0 in., and 2.0 in. thicknesses made using a fabricated Styrofoam insert to create a 57 in. x 38 in. pipe arch shape
  - Recommended installing the backfill around the pipe samples maintaining a separation of one pipe diameter (5.0 ft.). That the backfill material should be a coarse-grained soil with little or no fines (GW, GP, SW, or SP containing less than 12% fines) at a standard Proctor density of around 80% minimum (ASTM D698). There should be a 4 in. thick bedding for the pipes with the material directly below the invert portion left slightly less dense than the specified 80%. The density of the top 12 in. of cover shall be 95% of the material's standard proctor density (or that which will prevent significant rutting of the wheels as they travel across the buried pipes); which has since been changed to mean won't indent too deeply into the surface.
  - I also recommended loading the pipes at least 5 times so that you could get some statistical look at the data gathered and the performance of the soil surround as it loads and reloads. THIS IS IMPORTANT TO SEE IF YOU REACH A POINT, WHICH MIRRORS A FULLY CONSOLIDATED SOIL SURROUND LIKE IN THE REAL WORLD.
- Participated in several subsequent Friday meetings as the UTA/CUIRE team recommended to further refining my proposal for the lab and soil box testing.

MARCH 2018

- Participated in the Friday conference call on March 9th as requested and fielded questions from the UTA team on proposed changes to the soil box testing plan.
- Participated in an Ohio DOT conference in Columbus on March 19. During this meeting, Mr. Jeff Syar became more comfortable with our proposal to use the 60 in. Sonotubes for forms. We discussed the use of CLSM and sand as pipe embedment materials. My notes show that

at the end we were going to use a sand embedment material and employ jetting to assure consolidation.

- Participated in a conference with Dr. Mo at No-Dig on March 26 that included a brief discussion with Dr. Ian Moore and the approach to the soil box embedment material.

Subcontractor: Dr. Firat Sever
American Structurepoint, Inc.

Subcontractor American Structurepoint, Inc. (ASI) and Dr. Firat Sever are in the contracting phase. Since the inception of the project, Dr. Firat Sever has performed the following:

- Attended five conference calls with the UTA and one conference call with the entire project team.
- Reviewed overall project schedule and task distribution.
- Prepared a schedule and revised fee proposal for ASI and Sever tasks.
- Assigned tasks to graduate students with respect to literature review and design equations development.
- Reviewed draft survey with for owners.
- Reviewed the soil box test plan.

Subcontractor: Mr. Lyn Osborn
LEO Consulting, LLC

Task 12. QA/QC

As a QA/QC reviewer, much of my work depends upon the work and progress of other team members. Following is a summary of progress for the first quarter 2018:

- The customer must be involved in the design & development process. This occurred during an informal meeting with the customer during TRB (January 8) and in a conference call with Ohio DOT to discuss soil cell testing (March 19).
- Reviews must be conducted to evaluate the ability of the results to meet the requirements. This occurred at an internal planning meeting at TRB on January 8 and internal conference calls on February 16 and March 9.
- Reviews were conducted on the DOT Survey Form (two reviews), the CUIRE Test Plan, the NTPEP SAPL Lab Testing Document and the Comparison Document.

Proposed Work for New Quarter

Table 5: SAPL Research Project Tasks for the 2nd Quarter (April 1 through June 30)

CUIRE · LEO Consulting, LLC · R² · American Structurepoint Inc.			Project Tasks for the 2nd Quarter		
			2018		
Task	**Responsibility**	**Description**	**Apr**	**May**	**Jun**
1	Dr. Mo Najafi	Survey of U.S. DOTs and Canadian Agencies			
2	Dr. Mo Najafi	Literature Search/Participation Material Vendors			**Deliverable**
3	Mr. Ed Kampbell	Additional Reinforcement			
4	Mr. Ed Kampbell	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design			
10	Dr. Xinbao Yu	Computational Modeling			
10-A	Dr. Xinbao Yu	Create and Verify Circular Reinforced Concrete Pipe W/O Liner W/O Crack in Granular Soil			
11-B	Dr. Mo Najafi Dr. Xinbao Yu	Data Acquisition Setup			
12	Mr. Lynn Osborn	QA/QC			

Principal Investigator: Dr. Mohammad Najafi

Task 1: Survey of U.S. DOTs and Canadian Agencies

- Survey analysis and results.

Task 2: Literature Search/Participation Material Vendors

Literature Search:

- Complete literature review.

Participation of Material Vendors:

- The CUIRE Team will follow up with material vendors for the Soil Box Testing.

Task 11: Soil Box Testing

Soil Box Testing:

- The CUIRE Team will procure instrumentation for the Soil Box Testing.
- The CUIRE Team will start soil box testing.

Co-Principal Investigator: Dr. Xinbao Yu

Task 10: Computational Modeling

- Verify the modeling approach for circular concrete pipes by comparing the results from numerical simulation with those obtained from laboratory tests.
- Start developing numerical model to simulate pipe buried in soil (soil box test).

Task 11: Testing Coupons from Vendors (NTPEP) and Soil Box Testing

- Collaborate on procuring instruments for the Soil Box test.
- Perform additional soil tests to obtain all the necessary properties of embedment material used in soil box test.
- Begin first set of tests on the soil box.

Subcontractor: Mr. Ed Kampbell
Rehabilitation Resource Solutions, LLC

Work on my assigned tasks 3, 4, and 7 are shown to begin in May and I have begun to plan their execution accordingly.

Task 3. Additional Reinforcement

This task consists of a literature review and an investigation into the incorporation of non-metallic tensile reinforcement systems for the cementitious liner systems. The systems under this study employ the use of non-metallic microfibers, but no macro-fibers. One of the systems has employed a basalt mesh grid system to add additional tensile reinforcement. What other systems are there to use? This task is a relatively quick one and will be completed by the end of July.

Task 4. Evaluation if Corrugations needed to be Completely Filled by the SAPL as Part of the Structural Design

This task is to answer the question regarding lining of corrugated metal pipes and whether the corrugations should be filled, and the lining be placed on that foundation or whether it is fine to let the profile of the liner mimic the profile of the host pipe. This task is also to be completed by the end of July.

Task 7. Field Data Collection and Assistance from DOT Partners

This task is a field survey of what the DOT partners have installed to date, and how they are performing. This task is scheduled to run from May through end of September. My plans are to use May and June to coordinate with each of the DOT partners the sites we will be visiting. Prior to those visits, we expect to gather all the project documentation regarding those installs so that we can work efficiently when on the road with them. Ms. Zahra Kohankar has already begun the process of acquiring the ultrasonic thickness gauge and associated transducers that we will need for this effort. Hopefully, using the tool's display we will be able to capture any anomalies in the liner's layering thereby avoiding the need for any coring. The site visits will hopefully all be conducted in July and August. I picked these months for those visits to give us the best conditions for entering and studying the existing liner installations. I will start with the Ohio DOT's sites to further refine what I need before travelling out to the locations requiring air travel and hotel rooms. I will present you with my detailed work plan in May.

Subcontractor: Dr. Firat Sever
American Structurepoint, Inc.

Task 8. Develop a Recommended Structural Design Equations

The subcontract with ASI is expected to be executed within two weeks, and the following tasks are to be performed by American Structurepoint/Firat Sever in the next quarter:

- Substantially complete literature review on existing liner design equations and specifications.
- Coordinate with Karen Saavedra, PE, and graduate students Ferika Farooghi and Seyed Korky's tasks with respect to design equations and technical specifications development.
- Communicate with manufacturers and other design engineers in the industry on the design equations they use for SAPLs.
- Prepare tables of physical and mechanical properties of cementitious and polymeric SAPLs based on third party data. (Utilize the CUIRE WERF project data acquired by the project team previously.)
- Attend weekly team conference calls (internal).

Subcontractor: Mr. Lyn Osborn
LEO Consulting, LLC

Task 12. QA/QC

QA/QC reviews will continue on design and development planning, inputs and control. 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

Kickoff Meeting Agenda

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

- Introductions
- Lead State Technical Contact: Jeffrey.Syar@dot.ohio.gov
- Lead State Research Contact: cynthia.jones@dot.ohio.gov
- Technical Panel: wes.yang@dot.ny.gov; brian.carmody@dot.ny.gov; jmastin@ncdot.gov; smorgan@ncdot.gov; hheslop@pa.gov; slittle@pa.gov; Andrea.Hendrickson@state.mn.us; deb.fick@state.mn.us; Charles.Smith2@aecom.com; mslauffer@ncdot.gov; paul.rowekamp@state.mn.us; Carlton.Spirio@dot.state.fl.us; Jeffrey.syar@dot.ohio.gov; Cindy.Wang@dot.ohio.gov
- Research Principle Investigator (PI): najafi@uta.edu

- **Expectations**

  - Revised Schedule within two weeks of this meeting (24 months to complete work)
  - Monthly telephone meetings with PI and Technical Team
  - Quarterly Progress Reports

- **Background**

  - Results of this research will be shared with AASHTO NTPEP Technical Committee on Spray Applied Pipe Liners work plan and AASHTO LRFD Bridge Design Committee

- **Assistance from State DOT's**

  - Locations of both cementitious and resin-based product installations will be furnished for evaluation by the research team. These locations may be in Ohio, North Carolina, Florida, New York, Minnesota, or Pennsylvania or at locations specified by the material vendors.
  - A list of known product vendors for cementitious and resin-based materials will be made available to the research team. Ensure other product vendors identified in the US State DOT and Canadian Agency survey results are contacted and included in this research.

- **Goals**

  - The primary objective of this research is to develop design equations for structural renewal of gravity storm water conveyance culverts using spray applied pipe liners for both cementitious and resin-based materials and for circular and non-circular (NC) shapes. Ensure all loading is per AASHTO LRFD Bridge Design Specifications.

- Secondary objectives include:
  - Utilize literature search to minimize amount of laboratory testing and field inspections.
  - Utilize laboratory test methods to develop and validate structural design equations using spray applied pipe liner technology with various shapes and thicknesses.
  - Utilize an accelerated laboratory methodology to determine the spray applied liner material durability.
  - Utilize laboratory testing standards for both cementitious and resin-based spray applied materials.

- **Proposed Tasks Outlined in Proposal**

  - Task 1. Survey of US DOT's and Canadian Agencies
  - Task 2. Literature search/Participation of Material Vendors
  - Task 3. Additional Reinforcement Requirement
  - Task 4. Evaluate if Corrugations need to be completely filled in
  - Task 5. Life Cycle Cost Analysis
  - Task 6. Review of Cured in Place Pipe (CIPP) design methodology
  - Task 7. Field Data Collection and Assistance from DOT Partners
  - Task 8. Develop Structural Design Equations
  - Task 9. Develop Performance Based Construction Specifications
  - Task 10. Computational Modeling – FEM Simulations
  - Task 11. Laboratory Testing
  - Task 12- Installation QA/QC and Monitoring Research Project Progress
  - Task 13- Deliverables and Final Report

- **Project Deliverables Outlined in Proposal**

  - Design equations for structural applications of spray applied pipe liners in gravity storm water conveyance conduits for different cross sections, such as circular, and non-circular (box, egg-shape, etc.) and different existing culvert materials (corrugated metal, concrete, etc.).
  - Result of literature search/participation of material vendors. Existing research will be incorporated to minimize amount of field testing and budget required.
  - Survey of US DOTs and Canadian agencies.
  - Review CIPP design methodologies to evaluate ASTM F1216 and the new ASCE design concept under development.

- Spray applied design equations. Two design procedures, one for polymeric flexible liners, and the other for semi-rigid cementitious spray applied liners including Excel spreadsheet.
- Guidance for performance of structural specifications that allows DOTs to modify based on project objectives.
- A report documenting the mathematical modeling of soil structure system used to validate the proposed design methodologies presented in Task 4.
- A report documenting the qualifications-based type testing to validate the results from the task 6 computational modeling that was used to validate the proposed cementitious liner design equations of Task 4.
- Design spreadsheet to calculate the required thickness for a cementitious and resin-based spray applied liner pipe using the proposed design equations to calculate the required thickness for a cementitious and resin-based spray applied liner pipe using new design equations.
- Recommendations for acceptance and warranty testing
- Quarterly reports
- Final report
- Fact sheet
- Results Presentation

- **Questions/ Concerns**

1st Progress Meeting

- **Delaware DOT added as partner in study**
  - They have appointed two technical experts: Jonathan Karam and Craig Stevens
  - They are working on transferring funds
- **Meeting held in conjunction with TRB**
  - Culvert Material to be lined: CMP and Concrete
  - Culvert Shapes to focus on include: Circular and "Egg Shape"
    - NC and OH - change language to "Pipe arch" in lieu of "Egg Shape"
  - SAPL Materials: Cementitious, Geo-polymer and Polymer (Epoxy, Polyurea and Polyurethane)
    - Structural is the focus of this research. Leave the non-structural and semi-structural for later. Some DOT's are relining with non-structural for INI purposes- mentioned by NY.
- **UTA has employed 2 PhD and 4 Master's students**
- **Survey of DOT's and Canadian Agencies**
  - Mo will send draft to the team by 2/16
  - The 7 partner states should
    - Review, comment, and complete survey
    - Comments to UTA by 3/6
  - Discussion of survey in 3/13 call
  - OH research will distribute the survey in March after it's finalized
    - Can utilize Survey Monkey
- **Discussion on reinforcement requirements**
  - NC – wanted to ensure research was going to evaluate reinforcement needs
  - Reinforcement investigation is a task in the scope
  - FL – uses steel reinforcement cages when using spray applied liners
  - NY indicated that a rotary application would not be feasible when using steel reinforcement cage.
- **Participation of material vendors**
  - Research Team is reaching out to vendors
  - Milliken and SIPP Tech are the two most active vendors to date

- If any other DOT's are aware of other Vendors, send them to the Research Team.

- **Contracts with Partners (Subs) underway**

- **Google Drive**
  - Should that be publicly available
  - UTA will resend instructions on how to access to the DOT team members

- **Discussion on DOT submitted example material**
  - UTA will send a list of DOT's that have & have not submitted materials
  - FL will look into gathering information
  - MN does not have information either
  - Suggested that UTA contact Ed Kampbell for locations

- **Site visit selection criteria**
  - Start in June 2018

- **Core samples**
  - Ok with provided conduit is repaired: NC, OH
  - NC indicated that they have equipment to take cores
  - OH indicated that they do not have equipment to take cores

- **Lab testing of materials**
  - UTA questioned if they should accept material testing results from vendors
  - Preference is for material testing data to come from NTPEP or to be performed by the University.
  - Soil box testing to begin

- **ASCE specification development as part of research**
  - DOT's use ASTM and AASHTO. NC, MN, OH, NY, PA
  - Discussion on funding from ASCE to develop the specification.
  - UTA didn't think ASCE had funding available, but will investigate
  - UTA mentioned ASTM specifications under development for SAPL for pressure pipe applications
  - Pooled Funded Partners are interested in ASTM specifications and would support an effort to include gravity pipe into ASTM specifications. UTA will investigate further

- UTA indicated that an existing ASTM specification for SIPP spray liner exist. They will send to the DOT's.
- Structural design equations are part of the ASTM effort

- **Plan for next month**

  - Change meetings to 1-hr Moving forward

2nd Progress Meeting

- **Laboratory Specimen Testing**
  - Ohio DOT spoke with Milliken, whom was concerned about material testing that the University may perform. Preferred to have a professional lab like TEC to perform material testing.
    - Concerned that Vendors will not participate if material testing is performed by the University
  - Ohio DOT recommended that participating SAPL vendors be required to have material testing performed per AASHTO NTPEP SAPL Work Plan
    - Currently have Three Cementitious and two resin-based vendors enrolled in NTPEP
    - Will not require the structural testing in NTPEP, only the physical material tests
    - Estimated that it will take approx. 3 months for products to go through testing program
    - Will reduce potential complaints from Vendors regarding results of material tests
  - ASTM C 1609 was discussed
    - NTPEP uses specimen size that is smaller than permitted by ASTM
    - NYDOT explained background of C 1609
      - Only 4 AASHTO accredited labs in CONUS
      - Use 2x2x11.25 and 4x4x16 sizes in their testing that is being performed by TEC
      - Test develops Stress-Strain curve where C 78 does not
      - Specimen size may be smaller per ASTM if the reinforcing material is smaller; may be dependent upon SAPL material
  - University will evaluate what material tests should be performed to verify the SAPL material is the same as what was used in the NTPEP testing.
    - Will take coupons when SAPL is applied for Soil box testing
  - Scope of work will not change, but timing of material testing will be pushed back.
  - University to evaluate the NTPEP testing to ensure it will provide enough information for their needs. If additional tests are required, will have to engage NTPEP.

- **Survey**
  - Reviewed revisions to the survey per comments from the DOT members
  - Discussed use of Concrete Pipe Arch; decided to leave in the survey as requested by MNDOT
  - Survey revisions to Cynthia by 3/20. to be sent out to RAC/TranLib by Ohio DOT as an attachment

- **Spreadsheet for Project Summaries and Google Drive**
  - Missing data
  - DOT's commit to assemble missing data by next meeting on 4/10.
  - Ohio DOT will share the Excel file with DOT members due to problems accessing Google drive and Dropbox.

- **Soil Box Testing**
  - Invite sent out to 11 SAPL vendors; unsure how many will be willing to participate
    - Suspect that many will want to participate
  - Vendors must participate in Soil box testing; University requested that Ohio DOT request SAPL vendors to participate
    - Ohio DOT will follow up with Vendors to seek participation
  - Vendors will have to apply SAPL at UTA in a round sonotube or Styrofoam mold for the pipe arch shape.
    - University indicated that the pipe SAPL will be buried after spraying
  - Discussion on the proposed method of loading; University still not set on this method.
    - Ohio DOT and MNDOT expressed concerns for safety and/or application of the load to the wheel contact patch for the proposed loading by use of concrete beams stacked on top of pipe.
    - Ohio DOT referred to previous research performed several years ago that used hydraulic press to apply wheel loads as a possible method of loading
    - University still considering which option to use
  - University directed to look at the AASHTO LRFD Construction Specifications to determine installation method
    - Will review and propose a method of installation.
  - Discussion on pipe deficiencies and impacts to structural capacity
    - Next research project idea: Calculate structural capacity when there are specific deficiencies

- **Plan for next month: Action Items**
  - Dr. Mo & team to look at NTPEP for items that may need to be added.
  - Jeff to confirm to communicate to vendors about soil box testing
  - Survey revisions to Cynthia by 3/20. to be sent out to RAC/TranLib by Zona
  - Spreadsheet - need supplemental info for highlighted records. Send to researcher by 4/10 date of next call. Files are linked within Dropbox/Google Drive. Jeff will share the file with all states
  - Soil Box - AASHTO spec proposal by Dr. Mo

Soil Box Testing Discussion (Skype Call)

- **Testing**
  - Dimensions of Soil Box are 25 X 12 X 10 ft.
  - Drawings for soil box testing and curved beam testing.
  - Position of strain gauges as per ASTM C1609.
  - Sample will be covered by soil before loading for curved beam testing.

- **Samples for Soil Box Testing**
  - Liners of thickness 0.5 in., 1 in. and 2 in. will be tested.
  - Repair of voids in host pipe before spray lining.
  - Sonotube largest diameter is 60 in. Lining them on ground which is uniform so that they will hold their geometry.
  - Sample liners will be sprayed and then transferred to Soil Box for testing with the help of sling which will be placed before spraying. Testing will be carried out after curing the sample liner for 28 days.
  - Distance of one pipe diameter will be maintained between two liner samples.

- **Type of Soil for Embedment**
  - Discussions regarding degree of consolidation of soil around the liner sample.
  - Well-graded sand should be used for embedment as it will provide better consolidation and will help avoid damage to sample. It will also be easier to dig is back up after the test.
  - Fine grained material required near the haunch area so that much energy is not required to compact the material.
  - Measurement of densification of soil to be used for embedment in soil box testing and it was decided to follow AASHTO specification.
  - Standard proctor density of 95% consolidated soil as bedding and on sides and 90% consolidated soil above liner sample. The type of soil SW type soil was discussed as well.

- **Loading for Soil Box Testing**
  - Loading with the help of jacks and static loading with I beams was discussed.
  - It was suggested that 6 data points for each thickness should be used to get loading on liner.
  - Loading with hydraulic jacks was discussed as well.
  - PhD dissertation was discussed.
  - Position of piezometer or strain gauges.

- Measurement of longitudinal and horizontal load on the liner with the help of piezometer placed inside the test liner
- Discussion regarding sending revised package of testing plan to vendors to get their feedback on the plan.
- Research by Ohio DOT was discussed.

- **Pipe Arch Shaped Liners**

  - Spraying of liner for Pipe Arch shaped liner as per the required dimensions was discussed. Placing the Styrofoam in a temporary plywood box for support and then spraying it was suggested. Strings for lifting the pipe should be placed should be further discussed.
  - Machine shopping styrofoam block as per the required shape was discussed.

3rd Progress Meeting

Monthly update call – Spray Applied pipe liners
April 10, 2018

- Phones and internet were not working (Ohio DOT Wide) we were not able to connect to go to meeting for sharing purposes.

- Attendees: Mo, Brian (NY), Jeff & Tom (Ohio DOT), Sherry (Penn DOT), Carl (Fla. DOT), NC DOT

- Corrugated metal conduit used as a form for SAPL soil box testing was proposed. Researchers were to have a meeting with material supplier to discuss.

    - Several DOT's expressed concerned about the feasibility of this working
        - Milliken indicated that they did not think this would work
    - Ohio DOT thought it would work since vendors indicate that the liner does not rely on the host pipe for strength; however, the DOT members need time to review and comment on the proposed plan.
    - Research team will send soil box plan to the DOT members for comments. Comments due back to research team by May 1st.

- Research team discussed survey results to date. Had four DOTs respond.

- Discussion on member states receiving the survey. Ohio DOT will resend the survey to research members as it was sent to the AASHTO RAC members.

- Vendor communications: Several vendors were identified by the research team to be interested in participating

    - Ohio DOT indicated that there were several other vendors that were interested as well
    - Ohio DOT discussed this on the telephone with several of the vendors
    - The question of SIPPTECH, which is a composite system was discussed. DOT members voted that this product should not be considered a SAPL for the purposes of this research project. The Research Team will notify SIPPTECH.
    - Ohio DOT will follow up with vendors regarding NTPEP testing
    - Research team will reach out to the vendors

- Research team indicated that several additional material tests would be required that were missing from the NTPEP testing. They required these tests to perform finite modeling. Research team will send to Ohio DOT.
    - Additional testing may have to be performed by the University
- Next Meeting is May 8, 2018

Appendix A

SAPL Projects from DOT Participants

Table A1: Summary of CMP Projects

Summary of DOT CMP Projects

Circular Pipes

Diameter or Span	No. of Pipes	Liner Material and Thickness					
		Cementitous		Geo-polymer		Polymer	
		No.	Thickness	No.	Thickness	No.	Thickness
30 in. < Dia ≤ 48 in.	27	2	1 in.	1	1 in.	N/A	N/A
		1	1.75 in.	1	2 in.	N/A	N/A
		1	3 in.	N/A	N/A	N/A	N/A
48 in. < Dia ≤ 60 in.	12	1	1 in.	1	1 in.	2	0.5 in.
		3	1.5 in.	N/A	N/A	N/A	N/A
		1	2.25 in.	N/A	N/A	N/A	N/A
60 in. < Dia ≤ 84 in.	15	1	1 in.	2	2.5 in.	1	0.5 in.
		6	1.50 in.	1	3 in.	N/A	N/A
		2	3 in.	N/A	N/A	N/A	N/A
Dia > 84 in.	2	1	1.5 in.	1	4.5 in.	N/A	N/A

Pipe Arch

Diameter or Span	No. of Pipes	Liner Material and Thickness					
		Cementitous		Geo-polymer		Polymer	
		No.	Thickness	No.	Thickness	No.	Thickness
30 in. < Span ≤ 48 in.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
48 in. < Span ≤ 60 in.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60 in. < Span ≤ 84 in.	6	4	1 in.	N/A	N/A	N/A	N/A
		2	1.5 in.	N/A	N/A	N/A	N/A
Span > 84 in.	14	1	1 in.	N/A	N/A	N/A	N/A
		7	1.5 in.	N/A	N/A	N/A	N/A
		2	2 in.	N/A	N/A	N/A	N/A

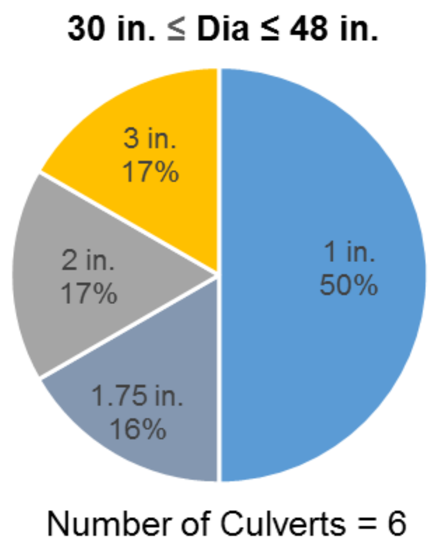
Table A2: Summary of RCP Projects

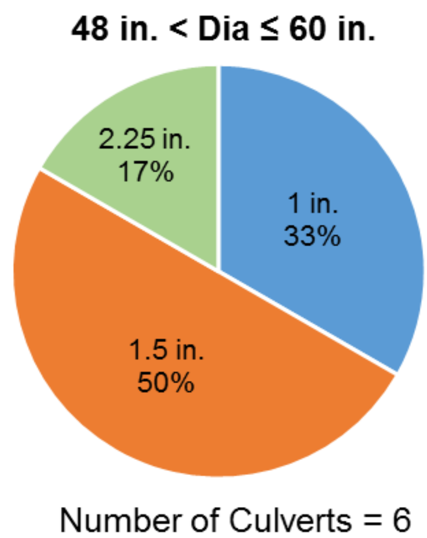
Summary of DOT RCP Projects							
Circular Pipes							
Diameter or Span	No. of Pipes	Liner Material and Thickness					
		Cementitous		Geo-polymer		Polymer	
		No.	Thickness	No.	Thickness	No.	Thickness
30 in. < Dia ≤ 48 in.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
48 in. < Dia ≤ 60 in.	4	1	0.5 in.	N/A	N/A	N/A	N/A
		2	1 in.	N/A	N/A	N/A	N/A
		1	1.5 in.	N/A	N/A	N/A	N/A
60 in. < Dia ≤ 84 in.	3	2	1 in.	1	1 in.	N/A	N/A
Dia > 84 in.	N/A	N/A	N/A	N/A	N/A	N/A	N/A

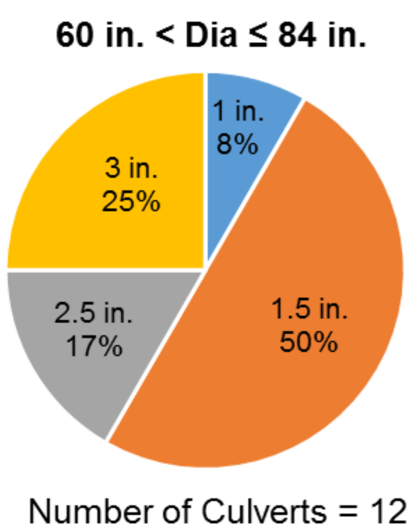
Summary of DOT SAPL Projects

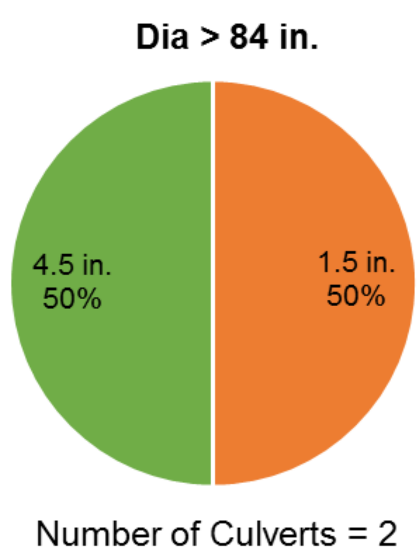
Circular CMP

Liner Thickness for Cementitious/Geo-polymer

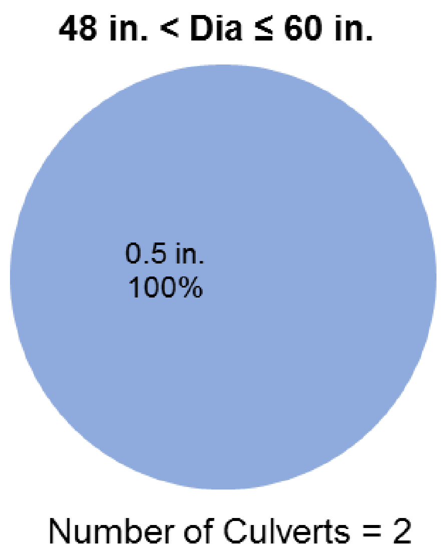


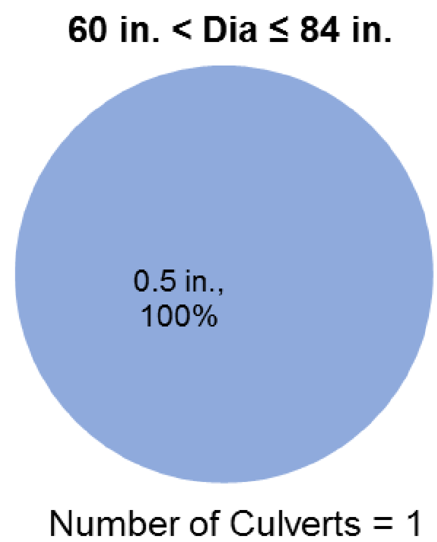




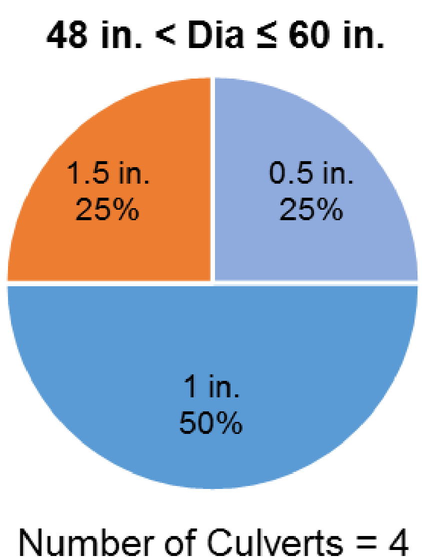


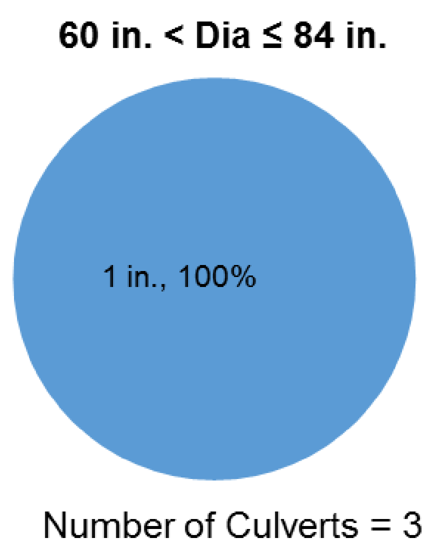
Circular CMP
Liner Thickness for Polymer





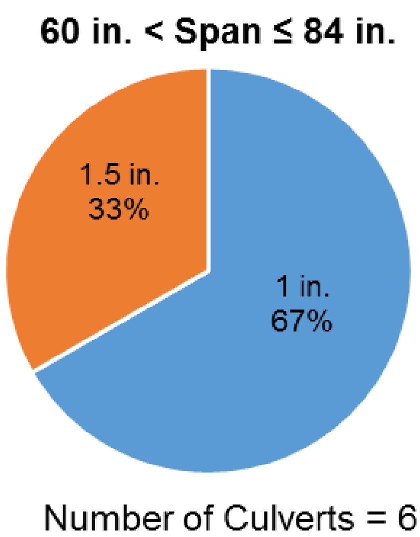
Circular RCP
Liner Thickness for Cementitious/Geo-polymer

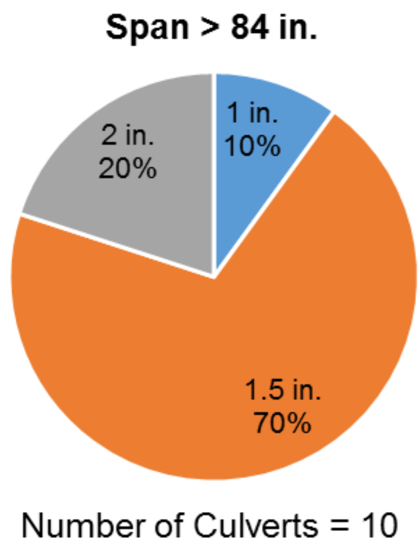




Pipe Arch CMP

Liner Thickness for Cementitious/Geo-polymer





Ohio Department of Transportation

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

Project Description							Host Pipe Information						Spray Applied Liner Information							
District	County	PID	Item	County, Route, and Section	Contractor	Subcontractor	Pipe Diameter	Conduit Shape	Material	Length (ft)	Project Type	Work Type	Spec Year	Letting	Thickness	Material	Type of Issue as Indicated in the Photos by CUIRE	Plan Link
3	ASD	99534	833E10000	ASD CULVERT FY2017 (A)	Kokosing Construction Company Inc.	Inland Water Pollution Control	54"	Round	N/A	158	CULVERT REPLACEMENT	DRNG	2016	2/16/2017	1- thicknesses are lower than minimum allowable with current SS833	IPR/Geopolymer	Failures after Rehabilitation	N/A
3	ASD	99534	833E10000	ASD CULVERT FY2017 (A)	Kokosing Construction Company Inc.	Inland Water Pollution Control	48"	Round	N/A	94	CULVERT REPLACEMENT	DRNG	2016	2/16/2017	1- thicknesses are lower than minimum allowable with current SS833	IPR/Geopolymer	Failure after Rehabilitation	N/A
10	ATH	97381	833E10000	ATH/MRG Var	Allard Excavation LLC	Stanley Miller Construction	78"	Round	CMP	61	CULVERT REPLACEMENT	DRNG	2013	5/5/2016	3"	Concrete	N/A	ODOT\Plans\ATH-97381.pdf
7	AUG	94477	833E12000	AUG-US 33-04.44	Shelly & Sands Inc.	Stanley Miller Construciton	139" x 89"	Pipe-Arch	CMP	266	CULVERT REPLACEMENT	DRNG	2016	10/6/2016	1.5 inches used, calculations indicated far less is required	Concrete	N/A	ODOT\Plans\AUG-94477.pdf
8	BUT	84615	833	BUT-75	R B Jergens Contractors Inc.	Quadex Lining Systems	60"	Round	CMP	N/A	CULVERT REPLACEMENT	N/A	2013	1/9/2014	N/A	GeoKrete/ Geopolymer	N/A	ODOT\Plans\BUT-84615.pdf
8	CLE	91763	N/A	CLE-133-12.43 SFN 1303309- Rebar included at spot	Shelly & Sands Inc.	Quadex Lining Systems	Twin 150" X 95"	Pipe-Arch	CMP	90	BRIDGE REPAIR	N/A	N/A	8/1/2013	N/A	GeoKrete/ Geopolymer	Failure Photos	N/A
8	CLI	94506	833E10000	CLI/WAR-Culverts-FY2016	Shelly & Sands Inc.	Inland Water Pollution Control	78"	Round	CMP	60	CULVERT REPLACEMENT	DRNG	2013	1/14/2016	2.378 - Current Spec would requires 2.5	IPR/Geopolymer	Failure Photos	ODOT\Plans\CLI-94506.pdf
6	FAY	97373	833E10000	D06-Culvert Rehab-FY2016	Shelly & Sands Inc.	Inland Water Pollution Control	84"	Round	CMP	194	CULVERT REPLACEMENT	DRNG	2013	11/5/2015	2.378 - Current Spec would requires 2.5	IPR/Geopolymer	N/A	ODOT\Plans\D06-97373.pdf
5	GUE	93134	833E10000	GUE-IR 77-07.08	Stanley Miller Construction	MCSP	54"	Round	CMP	166	BRIDGE REPAIR	DRNG	2013	5/5/2016	N/A	cement	Failure Photos	ODOT\Plans\GUE-93134.pdf
9	JAC	86588	833E10001	JAC-SR 93-0.15	Shelly & Sands Inc.	Inland Water Pollution Control	180"	Round	CMP	152	BRIDGE REPAIR	DRNG	2013	2/10/2015	Effective thickness = 4.5 in. (S.F. = 5)	IPR/Geopolymer	Failure not found from the photos.	ODOT\Plans\JAC-86588.pdf
5	KNO	13108	833E12000	KNO-US 36-15.90/16.42	Shelly & Sands Inc.	Inland Water Pollution Control	142" X 89"	Pipe-Arch	CMP	95	PREVENTIVE MAINTENANCE	DRNG	2016	2/16/2017	N/A	IPR/Geopolymer	N/A	ODOT\Plans\KNO-13108.pdf
5	KNO	13108	833E12000	KNO-US 36-15.90/16.42	Stanley Miller Construction	MCSP	142" X 89"	Pipe-Arch	CMP	66	PREVENTIVE MAINTENANCE	DRNG	2016	2/16/2017	N/A	cement	N/A	ODOT\Plans\KNO-13108.pdf
2	LUC	77254	833E10000	LUC-75-4.52 Ph 2 (PART 1, PART 2, PART 3)	Kelstin Inc.	Geotech Services Inc.	36"	Round	N/A	208	MAJOR RECONSTRUCTION	GEN	2013	11/20/2014	N/A	N/A	N/A	N/A
2	LUC	77254	833E10000	LUC-75-4.52 Ph 2 (PART 1, PART 2, PART 3)	Proshot Concrete Inc.	N/A	42"	Round	N/A	183	MAJOR RECONSTRUCTION	GEN	2013	11/20/2014	N/A	Shotcrete/Concrete	N/A	N/A
3	MED	88979	833E10000	D03 CULVERT FY2017	Stanley Miller Construction	N/A	42"	Round	CMP	145	CULVERT REPLACEMENT	DRNG	2016	3/2/2017	1.73 - Current Spec would requires 2.0	Cementitious/ Geopolymer	N/A	ODOT\Plans\D03-88979.pdf
3	MED	88979	833E10000	D03 CULVERT FY2017	Stanley Miller Construction	N/A	72"	Round	CMP	154	CULVERT REPLACEMENT	DRNG	2016	3/2/2017		Cementitious/ Geopolymer	N/A	ODOT\Plans\D03-88979.pdf
10	MOE	99390	833E10000	MOE-7-6.59	Proshot Concrete Inc.	N/A	72"	Round	CMP	88			2016	N/A	Minimum thickness = 3 in.	Shotcrete Concrete	N/A	ODOT\Plans\MOE_WAS-99390.pdf
6	MRW	89489	833E10000	MRW-Culvert-FY16	Proshot Concrete Inc.	N/A	72"	Round	CMP	300	CULVERT REPLACEMENT	DRNG	2013	8/11/2016	1.50	Shotcrete/Concrete	N/A	ODOT\Plans\MRW-89489.pdf
5	MUS	97327	833E10000	COS/MUS CUV FY2016	Proshot Concrete Inc.	N/A	42"	Round	CMP	194	CULVERT REPLACEMENT	DRNG	2013	5/19/2016	3.00	Shotcrete/Concrete	Before and After Rehabilitation	ODOT\Plans\MUS-97327.pdf
5	MUS	97327	833E10000	COS/MUS CUV FY2016	Shelly & Sands Inc.	Inland Water Pollution Control	48"	Round	CMP	158	CULVERT REPLACEMENT	DRNG	2013	5/19/2016	N/A	IPR/Geopolymer	Before and After Rehabilitation	ODOT\Plans\MUS-97327.pdf
5	MUS	97327	833E10000	COS/MUS CUV FY2016	Rack & Ballauer Excavation	Inland Water Pollution Control	60"	Round	CMP	314	CULVERT REPLACEMENT	DRNG	2013	5/19/2016	1.5	N/A	Before and After Rehabilitation	ODOT\Plans\MUS-97327.pdf
4	SUM	77269	833E10001	SUM-IR 76-10.00 (Main/Brdway)	N/A	Centripipe	66"	Round	Brick Combined	727	MAJOR RECONSTRUCTION	GEN	2013	5/19/2016	2		N/A	ODOT\Plans\SUM-77269.pdf
4	SUM	77269	833E10001	SUM-IR 76-10.00 (Main/Brdway)	N/A	N/A	54"	Round	Brick Combined	101	MAJOR RECONSTRUCTION	GEN	2013	5/19/2016	3" OVER CORRUGATIONS AS SPECIFIED IN THE PLAN		N/A	ODOT\Plans\SUM-77269.pdf

New York State Department of Transportation

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

Project Description								Host Pipe Information						Liner Information					
District	**County**	**PID**	**Contract ID**	**Item**	**County, Route, and Section**	**Contractor**	**Subcontractor**	**Pipe Diameter**	**Conduit Shape**	**Material**	**Length (ft)**	**Project Type**	**Work Type**	**Spec Year**	**Letting**	**Thickness**	**Material**	**Type of Issue as Indicated in the Photos by CUIRE**	**Plan Link**
3	Onondaga	D262702	D262702	602.2102 XX03 or 602.2102 1063	811 3303 3031	Slate Hill	Arold Construction	98" x 69"	Pipe Arch	CMP	501	Rehab	General	2014	11/6/2014	1"	PL-8,000	N/A	Project Plan
3	Onondaga	D262702	D262702		811 3303 3031	Slate Hill	Arold Construction	N/A	Junction boxes	Conc.	N/A	Rehab	General	2014	11/6/2014	1"	PL-8,000	N/A	
3	Onondaga	D262702	D262702		690 3301 1038	Slate Hill	Arold Construction	72" x 44"	Pipe Arch	CMP	194	Rehab	General	2014	11/6/2014	1"	PL-8,000	N/A	
3	Onondaga	D262702	D262702		690 3303 1802	Slate Hill	Arold Construction	65" x 40"	Pipe Arch	CMP	47	Rehab	General	2014	11/6/2014	1"	PL-8,000	N/A	
3	Onondaga	D262702	D262702		690 3303 1802	Slate Hill	Arold Construction	65" x 40"	Pipe Arch	CMP	47	Rehab	General	2014	11/6/2014	1"	PL-8,000	N/A	
3	Seneca	D262702	D262702		5 3506 1081	Slate Hill	Arold Construction	72" x 44"	Pipe Arch	CMP	167	Rehab	General	2014	11/6/2014	1"	PL-8,000	N/A	N/A
9	Broome	D262549	D262549		52 9601 1299	Suit-Kote	Arold Construction	142" x 91"	Elliptical/Arch	N/A	350	Rehab	General	2014	2/6/2014	2"	PL-8,000	N/A	N/A
9	Broome	D262549	D262549		20 9417 1082	Suit-Kote	Arold Construction	60"	Round	RCP	337	Rehab	General	2014	2/6/2014	1"	PL-8,000	N/A	N/A
9	Delaware	D263037	D263037		10 9301 1503	Suit-Kote	Arold Construction	60"	Round	RCP	96.5	Rehab	General	2015	11/5/2015	1.5"	PL-8,000	N/A	N/A

Pennsylvania Department of Transportation

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

Project Description								Host Pipe Information						Liner Information					
District	County	PID	Contract ID	Item	County, Route, and Section	Contractor	Subcontractor	Pipe Diameter	Conduit Shape	Material	Length (ft)	Project Type	Work Type	Spec Year	Letting	Thickness	Material	Type of Issue as Indicated in the Photos by CUIRE	Plan Link
5	Schuylkill	N/A	BMS# 53-1008-0050-2017	N/A	SR 1008, 0050/ 2107	PIM Corporation, Inc	Vexcon Chemicals , Inc.	74" x 132"	Pipe-arch	metal	61' (72' bottom)	Preventative maintenance	N/A	N/A	2017	2"	Cementitious	After Rehabilitation	N/A
12	Washington	N/A	N/A	N/A	SR 1004, 0010/0000	Centrifugal Lining, Inc	AP/M Permaform	54"	Round	metal	60	Preventative maintenance	N/A	N/A	2015	1"	Cementitious	Before and After Rehabilitation	N/A
12	Washington	N/A	N/A	N/A	SR 1004, 0020/0665	Centrifugal Lining, Inc	AP/M Permaform	48"	Round	metal	55	Preventative maintenance	N/A	N/A	2015	1"	Cementitious		N/A
12	Washington	N/A	N/A	N/A	SR 1004, 0020/2125	Centrifugal Lining, Inc	AP/M Permaform	68"	Round	metal	50	Preventative maintenance	N/A	N/A	2015	1"	Cementitious		N/A
6	Delaware	N/A	N/A	N/A	SR 3012, 0050/1075	Centrifugal Lining, Inc	AP/M Permaform	48"	Round	metal	30	Preventative maintenance	N/A	N/A	2015	1"	Cementitious	N/A	N/A
8	Lancaster	N/A	#82470, SR 0441-023	N/A	SR 441, 0120/1208	Pennsy Supply; Sub-Abel Recon, LLC	SprayRoq	72"	Round	metal	325	Preventative maintenance	N/A	N/A	2012	0.5"	Resin based	N/A	Plan Link
8	Cumberland	N/A	#79747, SR 0011-055	N/A	SR 1027, 0020/2015	H&K; Sub-Albel Recon, LLC	SprayRoq	2-60"	Round	metal	4 Pipes for total 290LF	Preventative maintenance	N/A	N/A	2009	0.5"	Resin based	N/A	N/A
8	Cumberland	N/A		N/A	SR 11, 0860/0710; 0860/0720		SprayRoq	2-54"	Round	metal		Preventative maintenance	N/A	N/A	2009		Resin based	N/A	N/A
4	Pike	N/A	76860	N/A	SR 84, 0360/1077	J.D. Morrissey	Milliken, GeoSpray	48"	Round	metal	440	Preventative maintenance	N/A	N/A	2018	1.75"	Cementitious	N/A	N/A
4	Pike	N/A	76860	N/A	SR 84, 0384/0406	J.D. Morrissey	Milliken, GeoSpray	60"	Round	metal	450	Preventative maintenance	N/A	N/A	2018	2.25"	Cementitious	N/A	N/A

Minnesota Department of Transportation

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

Project Description								Host Pipe Information						Liner Information					
District	County	PID	Contract ID	Item	County, Route, and Section	Contractor	Subcontractor	Pipe Diameter	Conduit Shape	Material	Length (ft)	Project Type	Work Type	Spec Year	Letting	Thickness	Material	Type of Issue as Indicated in the Photos by CUIRE	Plan Link
D2	Beltrami	SP 8822-166	150200	2506603/00 011	Bemidji at TH 197/Pine Ridge Ave NW	Hydro-Klean LLC	None	48"	Catch basin (CB #06)	Bricks	5	District wide manhole and storm sewer structure repair project	Rehabilitation	2016	12/18/2015	1"	QM-1S Restore	Deteriorating and loose mortar	N/A
Metro	Ramsey	SP 6280-380	150189	2507603/ 10084	I35E, Gervais Creek & Little Canada Road	Engineering & Construction Innovation, Inc	AP/Permaform	84"	Concrete pipe culvert	RCP	570	I-35E Gervais Creek culvert rehabilitation	Rehabilitation	2014	12/18/2015	1"	PL 8000	Spalled/derteriorate d concrete surface	N/A
D1	Itasca	SP 8821-181	110070	2501618/ 00010	Itasca, TH 2 in Cohasset	KGM Contractors, Inc	Thul Speciality Contractor, Inc	84"	Concrete pipe culvert	RCP	164	District wide grading, bituminous surfacing and drainage project	Drainage (Culvert Repair)	2005	3/25/2011	1"	SP 15 Spray Mortar		MnDOT\D1 Project Plan.pdf
D6	Wabasha	SP 7903-38	No contract ID	No item #	TH 60 near West Albany	N/A	N/A	36" CMP with 33" CMP Pipe	Corrugated Metal Pipe	CMP	80	Maintenance research pilot project to test CentriPipe. Replacement planned in 2 years due to capacity not condition.	Culvert repair	2005	pilot project No letting date	1.5"	PL 8000 concrete mix provided by AP/Permaform	Large scale rust and holes in both roof and floor and separation in extended metal pipe	N/A
D6	Wabasha	SP 7908-29	110024	2506603/ 00012	TH 63 From County Road 78 to TH 61 in Lake City	Rochester Sand & Gravel Division of Mathy Construction	None	N/A	Collection of 52 CBs and MHs	N/A	225	Bituminous Mill and overlay, signal and ADA Improvement	Drainage	2005	2/25/2011	3/4"	Microsilica Cement Motar	Ring deterioration and loose mortar	N/A
Metro	Washington	SP 8282-116	140200	2503603/ 01354	I 94 & Manning Ave in Saint Paul	New Look Contracting, INC	AP/Permaform	54"	Centrifugally cast storm sewer pipe	RCP	1291	Drainage on TH 94 from Manning Avenue to the St Croix River	Drainage	2014	12/19/2014	1/2"	PL 8000	Spalled/derteriorate d concrete surface	N/A
Metro	Washington	SP 8282-116	140200	2503603/ 01360	I 94 & Manning Ave in Saint Paul	New Look Contracting, INC	AP/Permaform	60"	Centrifugally cast storm sewer pipe	RCP	1029	Drainage on TH 94 from Manning Avenue to the St Croix River	Drainage	2014	12/19/2014	1"	PL 8000	Spalled/derteriorate d concrete surface	N/A
Metro	Washington	SP 8282-116	140200	2503603/ 01372	I 94 & Manning Ave in Saint Paul	New Look Contracting, INC	AP/Permaform	72"	Centrifugally Ccast storm sewer pipe	RCP	1048	Drainage on TH 94 from Manning Avenue to the St Croix River	Drainage	2014	12/19/2014	1"	PL 8000	Spalled/derteriorate d concrete surface	N/A

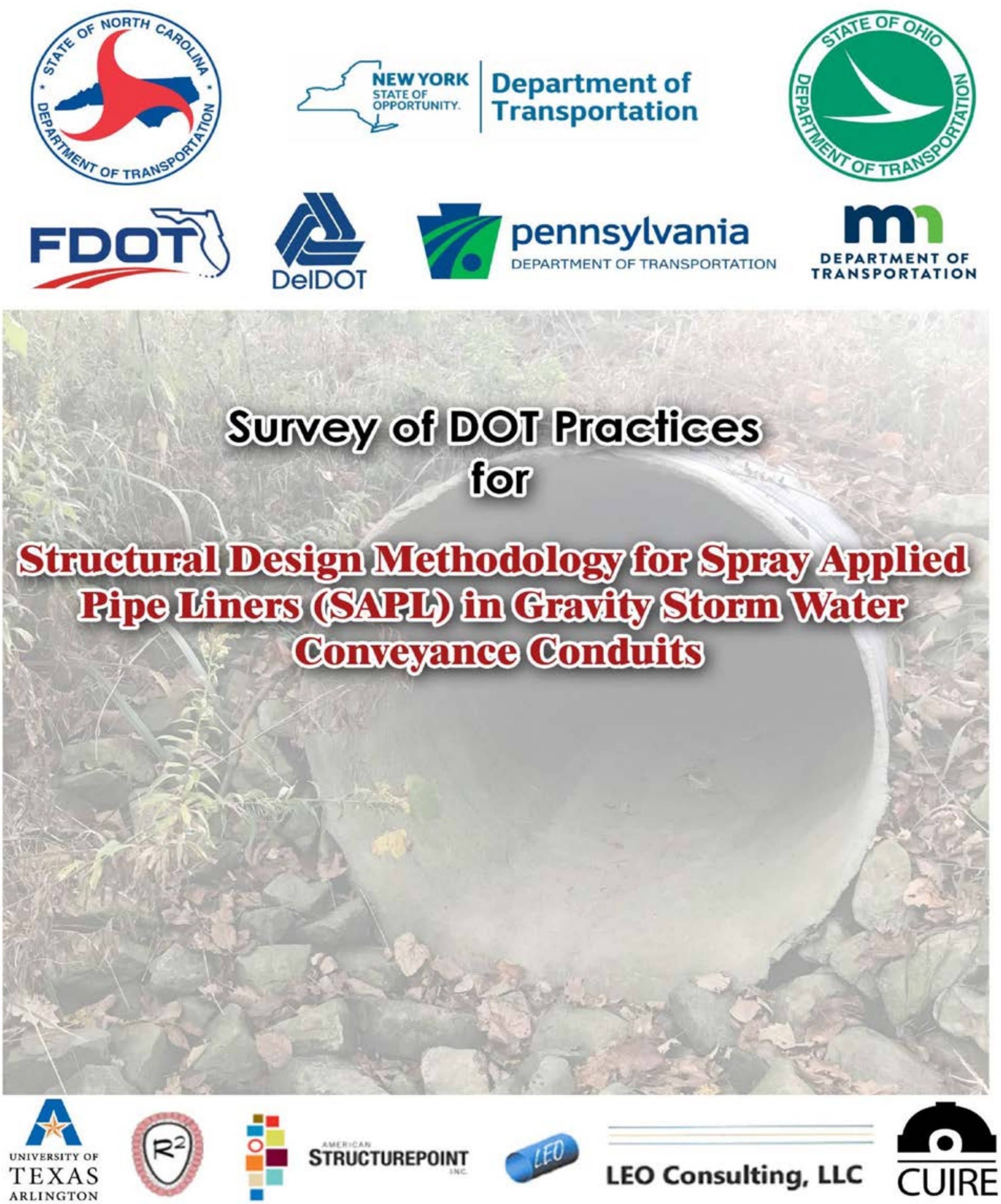
North Carolina Department of Transportation

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

Project Description								Host Pipe Information						Liner Information					
Division	**County**	**PID**	**Contract ID**	**County, Route, and Section**	**Road number**	**Contractor**	**Subcontractor**	**Pipe Diameter**	**Conduit Shape**	**Material**	**Length (ft)**	**Project Type**	**Work Type**	**Spec Year**	**Letting**	**Thickness**	**Material**	**Type of Issue as Indicated in the Photos by CUIRE**	**Plan Link**
3	N/A	N/A	N/A	N/A	I -40	N/A	N/A	54"	Round	N/A	425	Transportation	Drainage	N/A	N/A	1"	Spray cement	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake		15B.13.32	Clif Benson Beltline	I-440	Fred Smith Company Construction	Utility Asset Management	78"	Round	CMP	405	Transportation	Drainage	Special Provision, unique to contract	2017	2.5" to 3" over corrugation	Centrifugally Cast, Fiber-Reinforced Pipe Repair Mortar	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Cliff Benson Beltline	I-40	Granite	N/A	30"	Round	CMP	210	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Cliff Benson Beltline	I-40	Granite	N/A	30"	Round	CMP	280	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Cliff Benson Beltline	I-40	Granite	N/A	48"	Round	CMP	340	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Cliff Benson Beltline	I-40	Granite	N/A	54"	Round	CMP	300	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Cliff Benson Beltline	I-40	Granite	N/A	42"	Round	CMP	300	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Cliff Benson Beltline	I-40	Granite	N/A	48"	Round	CMP	200	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	30"	Round	CMP	400	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	42"	Round	CMP	320	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	Hammond Road	SR 2026	Granite	N/A	36"	Round	CMP	320	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	42"	Round	CMP	300	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	36"	Round	CMP	320	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	36"	Round	CMP	310	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	36"	Round	CMP	1400	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	36"	Round	CMP	1200	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	30"	Round	CMP	200	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	42"	Round	CMP	300	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	42"	Round	CMP	350	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	42"	Round	CMP	400	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	36"	Round	CMP	500	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
5	Wake	I-5338	C203166	N/A	I-40	Granite	N/A	72"	Round	CMP	600	Transportation	Drainage	DB RFP	2017	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Old Leicester Hwy	SR1002	Nu-Pipe	N/A	76" x 112"	Arch	CMP Arch	87.5	Transportation	Drainage	N/A	2016	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Pole Creasman Rd	SR3479	N/A	N/A	72"	Round	N/A	43	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Clayton Road	SR3501	Nu-Pipe	N/A	N/A	Round	N/A		Transportation	Drainage	N/A	2016	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Pole Creasman Road	SR3479	N/A	N/A	54"	Round	N/A	63	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A		NC 213	Nu-Pipe	N/A	N/A	Round	N/A		Transportation	Drainage	N/A	2016	N/A	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Lower Beaverdam Loop	SR3449	N/A	N/A	72" x 108"	Ellip, Arch, or Deformed	N/A	48	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Upper Flat Creek Road	SR2137	N/A	N/A	60"	Round	N/A	42	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Mundy Cove Road	SR2108	N/A	N/A	60" x 84"	Ellip, Arch, or Deformed	N/A	30	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Indian Branch Road	SR1132	N/A	N/A	84"	Round	N/A	71	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Curtis Farm Road	SR1101	N/A	N/A	72" x 96"	Ellip, Arch, or Deformed	N/A	31	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Town Branch Road	SR2165	N/A	N/A	72" x 96"	Ellip, Arch, or Deformed	N/A	40	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Buncombe	N/A	N/A	Monte Vista Road	SR1224	N/A	N/A	72" x 90"	Ellip, Arch, or Deformed	N/A	45	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Burke	N/A	N/A	Tomlinson Loop	SR1613	N/A	N/A	84"	Round	N/A	49	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Burke	N/A	N/A	Butler Hill Road	SR1532	N/A	N/A	64" x 84"	Ellip, Arch, or Deformed	N/A	37	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Burke	N/A	N/A	Powerhouse Road	SR1223	N/A	N/A	78" x 125"	Ellip, Arch, or Deformed	N/A	38	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Burke	N/A	N/A	Milton Road	SR1722	N/A	N/A	72"	Round	N/A	57	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Burke	N/A	N/A	N Drexel Road	SR1531	N/A	N/A	98" x 105"	Ellip, Arch, or Deformed	N/A	43	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	McDowell	N/A	N/A	Mt Hebron Road	SR1100	N/A	N/A	64"	Round	N/A	42	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	McDowell	N/A	N/A	Pine Cove Road	SR1106	N/A	N/A	84"	Round	N/A	50	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	McDowell	N/A	N/A	Silvers Welch Road	SR1128	N/A	N/A	60"	Round	N/A	40	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/
13	Mitchell	N/A	N/A	Stagger Weed Road	SR1206	N/A	N/A	120"	Round	N/A	83	Transportation	Drainage	N/A	2018	1.5"	CCCP	N/A	<a href="https://connect.ncdot.gov/site/

Appendix B

Survey Form for U.S. DOTs and Canadian Agencies


Survey of DOT Practices
for
Structural Design Methodology for Spray Applied
Pipe Liners (SAPL) in Gravity Storm Water
Conveyance Conduits

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Introduction:

Spray Applied Pipe Lining (SAPL) inside a host culvert is used to renew deteriorated gravity storm water conveyance conduits (storm drains and culverts). This project will develop a structural design methodology for SAPL in gravity storm culverts for large diameter (up to 10 ft) Concrete Pipe (CP) and Corrugated Metal Pipe (CMP). The objective of this project is to develop design methodologies and equations for structural application of SAPL for Circular Pipe and Pipe Arch shapes with span larger than 36 inches. The funding commitment was achieved by DelDOT, FDOT, MnDOT, NCDOT, NYSDOT, ODOT, and PennDOT led by Ohio DOT.

This project is conducted by the Center for Underground Infrastructure Research and Education (CUIRE) (www.cuire.org) which is a research, education and outreach organization and is a part of the University of Texas at Arlington's (UTA's) Department of Civil Engineering.

Please submit your completed survey by Monday, April 30th, 2018, to Ms. Cynthia Jones at the Ohio Department of Transportation (Ohio DOT), Phone: 614-466-1975, Email: cynthia.jones@dot.ohio.gov.

If you have any questions or concerns regarding this survey, please contact Mr. Jeffrey Syar, P.E., Administrator, Ohio DOT Office of Hydraulic Engineering, Phone: 614-275-1373, Email: Jeffrey.Syar@dot.ohio.gov; or Dr. Mo Najafi, P.E., Phone: 817-272-9177, Email: najafi@uta.edu, the Principal Investigator for this project.

Your assistance in completing this survey will be kept confidential. We will acknowledge your help in completing this survey in our final report, but we will not refer to your individual responses. Upon completion of this project, expected in December 2019, we will send you a copy of the final report.

We thank you in advance. **Please submit by April 30th**
Email: cynthia.jones@dot.ohio.gov

Contact Information

Respondent's Agency:	
Respondent's Name:	
Title:	
Phone Number:	
Email Address:	

Are you in charge of culvert renewal in your agency?

☐ Yes, *if yes, approximately how many culverts have been renewed by SAPL?*

☐ No, *please forward this to the appropriate subject matter expert within your agency.*

**All terms with "*" are defined in the Glossary section at the end of this survey*

Please save your document as you complete the survey

Part A. SAPL* BEFORE Installation

A.1. What are your decision making priorities when using a SAPL* (1 is high priority through 8 to less priority)?

Rank	Concrete Pipe Culvert	Rank	Corrugated Metal Culvert
--	Contractor experience	--	Contractor experience
--	Project Economics	--	Project Economics
--	Project Schedule	--	Project Schedule
--	Durability*	--	Durability*
--	Hydraulic Capacity due to Liner	--	Hydraulic Capacity due to Liner
--	Minimum Thickness	--	Minimum Thickness
--	Impact to Traveling Public	--	Impact to Traveling Public
--	Others *(please specify)*	--	Others *(please specify)*

Comments:

A.2. Rank the main reasons for selecting fully structural SAPL* with "1" as the highest priority.

Rank	Concrete Pipe Culvert
--	Conservative Design to Avoid Future Failures
--	Longitudinal Cracking*
--	Circumferential (Transverse) cracking*
--	Invert loss/Erosion*
--	Joint Separation*
--	Delamination*
--	Spalling*
--	Access to Culvert
--	Other *(please specify)*

Rank	Corrugated Metal Culvert
--	Conservative Design to Avoid Future Failures
--	Deflection*/Ovality*/Flattening*/Racking*
--	Invert loss*
--	Abrasive Conditions*
--	Access to Culvert
--	Other *(please specify)*

Comments:

**All terms with "*" are defined in the Glossary section at the end of this survey*

A.3. In what conditions do you consider the culvert "fully deteriorated*"? (Check as many as required)

Concrete Pipe Culvert			
Circular		Pipe Arch*	
☐	Longitudinal Cracking*	☐	Longitudinal Cracking*
☐	Circumferential (Transverse) Cracking*	☐	Circumferential (Transverse) Cracking*
☐	Corrosion*	☐	Corrosion*
☐	Joint Separation*	☐	Joint Separation*
☐	Erosion*	☐	Erosion*
☐	Pop-outs*	☐	Pop-outs*
☐	Abrasion*	☐	Abrasion*
☐	Honeycombs*	☐	Honeycombs*
☐	Scaling*	☐	Scaling*
☐	Delamination*	☐	Delamination*
☐	Spalling*	☐	Spalling*
☐	Efflorescence*	☐	Efflorescence*

Corrugated Metal Culvert			
Circular*		Pipe Arch*	
☐	Deflection*/Ovality*	☐	Deflection*/Ovality*
☐	Corrosion at Invert*	☐	Corrosion at Invert*
☐	Abrasion*	☐	Abrasion*
☐	Seam Defects/Cracks*	☐	Seam Defects/Cracks*

Comments:	

A.4. What existing Culvert Conditions and Site Conditions limit application of SAPL*?

	Concrete Pipe Culvert	Corrugated Metal Culvert
Culvert Conditions		
Site Conditions		

Comments:	

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A.5. What factors influence your decision to select a specific SAPL* material for Corrugated Metal Culvert? (Check as many as possible)

	Corrugated Metal Culvert			
	Circular		Pipe Arch	
	Cementitious	Polymer	Cementitious	Polymer
Groundwater	☐	☐	☐	☐
Soil/Embankment Conditions	☐	☐	☐	☐
Depth of Cover	☐	☐	☐	☐
Traffic Load	☐	☐	☐	☐
Long-term Structural Capacity	☐	☐	☐	☐
Durability*	☐	☐	☐	☐
Life-cycle Cost	☐	☐	☐	☐
Impact to Traveling Public	☐	☐	☐	☐
Site Conditions outside of the Culvert	☐	☐	☐	☐
Vendor Recommendation	☐	☐	☐	☐
History of Use	☐	☐	☐	☐
Others *(please specify)*	☐	☐	☐	☐

Comments:

A.6. What factors influence your decision to select a specific SAPL* material for Concrete Pipe Culvert? (Check as many as possible)

	Concrete Pipe Culvert			
	Circular		Pipe Arch	
	Cementitious	Polymer	Cementitious	Polymer
Groundwater	☐	☐	☐	☐
Soil/Embankment Conditions	☐	☐	☐	☐
Depth of Cover	☐	☐	☐	☐
Traffic Load	☐	☐	☐	☐
Long-term Structural Capacity	☐	☐	☐	☐
Durability*	☐	☐	☐	☐

**All terms with "*" are defined in the Glossary section at the end of this survey*

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Life-cycle Cost				
Impact to Traveling Public				
Site Conditions Outside of the Culvert				
Vendor Recommendation				
Establish History of Use				
Others *(please specify)*				

Comments:

A.7. Approximately what percentage of your existing culverts are Circular and Arch Pipe?

Shape of Culvert	Approximate Percentage (%)
Circular	
Arch Pipe	

Comments:

A.8. Which material is more likely to be used for SAPL*? (Rank from one to five with one to be most likely)

1	--
2	--
3	--
4	--
5	--

Comments:

**All terms with "*" are defined in the Glossary section at the end of this survey*

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A.9. Which SAPL* material is prohibited in your jurisdiction, if any? (Please Explain Below)

A.10. Which reinforcement material is permitted? (Check all that applies)

Culvert Type	Carbon Fiber*	Glass Fiber*	Steel Fiber*	Wire-mesh* (Worker Entry)	Reinforcing Steel (Worker Entry)	Other *(please specify)*
Corrugated Metal						
Concrete Pipe Culvert						

Comments:

A.11. Do you consider adhesion of SAPL* with the host culvert necessary for structural application?

1	Cementitious*	--
2	Polymer*	--
3	Other *(please specify)*	

Comments:

A.12. Do you have a minimum thickness requirement for SAPL*? (In SI Unit per mm)
If Yes, please answer the following options
If No, please go to the next question

Type of SAPL	Minimum Thickness
Cementitious*	--
Polymer*	--

Comments:

**All terms with "*" are defined in the Glossary section at the end of this survey*

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Part B. SAPL* DURING Installation

B.1. What type of weather conditions prohibit installation of SAPL*? (Check as many as possible)

	Hot weather	Cold weather	Humidity	Wetness	Freeze/thaw	Others *(please specify)*
Cementitious*						
Geo-polymer*						
Polyurea*						
Polyurethane*						
Epoxy*						

Comments:	

B.2. Does your jurisdiction have a protocol for QA/QC of SAPL* installation, testing and inspection?

	Installation, Testing, Inspection, and Others	If yes, please provide a copy of link or email us the protocol (See note below).
Cementitious*	--	
Geo-polymer*	--	
Polyurea*	--	
Polyurethane*	--	
Epoxy*	--	

Note: Please attach a copy of your QA/QC protocol if no link is available.

Comments:	

B.3. Does your jurisdiction have additional safety protocols in addition to OSHA confined space entry? If yes, please provide a copy or link.

**All terms with "*" are defined in the Glossary section at the end of this survey*

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Part C. SAPL* AFTER Installation

C.1. Do you use any tools or techniques to measure the thickness of SAPL*?

◯	Yes (random)
◯	Yes (continuously)
◯	No
If yes, *(please specify what type of equipment)*	

Comments:	

C.2. What type of problems do you face **AFTER** SAPL* application? If possible, specify the cause, location, and orientation (longitudinal, circumferential, etc.) of the defect such as cracks.

Material	Explanation
Cementitious*	
Geo-polymer*	
Polyurea*	
Polyurethane*	
Epoxy*	

Comments:	

C.3. What is your expected design life for the SAPL*?

Material	Years
Cementitious*	
Geo-polymer*	
Polyurea*	
Polyurethane*	
Epoxy*	

Comments:	

**All terms with "*" are defined in the Glossary section at the end of this survey*

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C.4. Additional information regarding your experiences and concerns with SAPL*:

Please make sure you save the file before submitting

If you have projects using SAPL that you would like to share with us, please email to Jeffrey.Syar@dot.ohio.gov or najafi@uta.edu. We would like to know successful and unsuccessful experiences.

Once again, we greatly appreciate your help in advance for completing this survey. We understand your time and efforts are valuable, however, your input and feedback will provide a comprehensive research that will help the transportation industry.

Please feel free to call or email us if you would like to provide your comments over the phone or email or would like to join this important pooled study (Jeffrey Syar, 614-275-1373, Jeffrey.Syar@dot.ohio.gov ; and Mo Najafi, 817-272-9177, najafi@uta.edu).

Please submit your survey **BY MONDAY, APRIL 30th**.

Thank you again.

Please save your file and submit as an attachment to Ms. Cynthia Jones at Ohio Department of Transportation (Ohio DOT), Phone: 614-466-1975, Email: cynthia.jones@dot.ohio.gov

**All terms with "*" are defined in the Glossary section at the end of this survey*

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GLOSSARY

Abrasion	Abrasion is the gradual wearing away of the culvert wall due to the impingement of bed load and suspended material.
Carbon Fiber	A material consisting of thin, strong crystalline filaments of carbon, used as a strengthening material, especially in resins and ceramics.
Cementitious	Having the properties of a cement
Corrosion	It is a deterioration or dissolution of a material by a chemical or electrochemical reaction with its environment.
Corrugated Pipe	Pipe with ridges (corrugations) going around it to make it stiffer and stronger. The corrugations are usually in the form of a sine wave and are usually made of galvanized steel or aluminum.
Cracking	A fissure in an installed precast concrete culvert. - Circumferential (Transverse) cracking - Longitudinal cracking
Deflection	Change in diameter due to stress, temperature, time and other factors.
Delamination	Splitting apart of material into layers.
Durability	Ability to withstand wear, pressure, or damage.
Efflorescence	Efflorescence is a combination of calcium carbonate leached out of the cement paste and other recrystallized carbonate and chloride compounds. It is a white crystalline or powdery deposit on the surface of the concrete surface and is caused by water seeping through the culvert wall. The water dissolves salts inside the concrete surface, while moving through it, and then evaporates leaving the salts on the surface.
Erosion (Culvert)	Wearing or grinding away of culvert material by water laden with sand, gravel or stones; generally referred to as abrasion.
Fully Deteriorated	A culvert which has insufficient strength to support all soil and live loads.
Flattening	A critical decrease of vertical diameter due to loading that makes the circular shape similar to rectangular shape.
Geo-polymer	Geo-polymers are chains or networks of mineral molecules linked with co-valent bonds.
Glass Fiber	A strong plastic, textile, or other material containing embedded glass filaments for reinforcement.

**All terms with "*" are defined in the Glossary section at the end of this survey*

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Honeycomb	Improper vibration of concrete leads to exposure of aggregate. This exposure of aggregate is called as honeycomb.
Host Culvert	An existing, old, or deteriorated culvert.
Invert-deteriorated	Progressive worsening of part of a culvert below the spring line that represents the lowest point in the internal cross section.
Joints	The means of connecting sectional lengths of culvert system into a continuous line using various types of joining materials.
Joint Failure	Failures which occur in the joints due to uneven bedding, poorly compacted backfilling operations, or unexpected settlements.
Joint Separation	Separation in joint that occurs due to failure in the type of joining material used.
Ovality	The difference between the maximum and mean diameter, divided by the mean diameter, or the difference between the mean and the minimum, divided by the mean. Expressed in percentage.
Partially Deteriorated	A culvert which may have displaced joints, cracks or corrosion, but is structurally able to support all soil and surface loads.
Polymer	A compound of high molecular weight derived either by the addition of many smaller molecules, as polyethylene, or by the condensation of many smaller molecules with the elimination of water, alcohol, or the like, as nylon.
Polyurea	The polymerization of isocyanates with polyamines result in the urea linkage. Generally, polyureas appear to have better elongation properties than polyurethanes; on the other hand polyurethanes provide more stiffness.
Polyurethane	Polyurethane is formed by reaction (or addition) of an isocyanate (-N=C=O) group with a hydroxyl (-OH) group or a polyol. This reaction is triggered by catalysts. Other typical components of the polyurethanes include cross linkers, surfactants, blowing agents, pigments, and fillers.
Popouts	Popouts are conical fragments that break out of the surface of the concrete leaving small holes
Racking	The movement of structural elements out of level or plumb by forces such as stress, material shrinkage or expansion.
Renewal	All aspect of upgrading with a new design life for the performance of existing culvert system. Includes rehabilitation, renovation, and replacement.
Repair	Reconstruction of short culvert lengths, but not the reconstruction of the whole culvert. Therefore a new design life is not provided. In contrast, in culvert renewal, a new design life is provided to existing culvert system.
Replacement	All aspects of upgrading with a new design life for the performance of the existing culvert. Includes rehabilitation and renovation.

**All terms with "*" are defined in the Glossary section at the end of this survey*

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Scaling	Build-up of material on the inside portion of the culvert.
Seam Defects/Cracks	Defects and cracks at the joint of CMP.
Spalling	Breaking of part of culvert into small pieces.
Spring-line	(1) An imaginary horizontal line across the pipe that passes between the points where the pipe has its greatest cross-sectional width. (2) Midpoint of a pipe cross section (equal vertical distance between the crown and the invert of the pipe).
Steel Fiber	A material consisting of thin, strong crystalline filaments of steel, used as a strengthening material, especially in resins and ceramics.
Wire-mesh	A series of horizontal and vertical reinforcement welded together at a specific center-center distance

List of Acronyms

DelDOT	Delaware Department of Transportation
CMP	Corrugated Metal Pipe
CP	Concrete Pipe
CUIRE	Center for Underground Infrastructure Research and Education
FDOT	Florida Department of Transportation
MnDOT	Minnesota Department of Transportation
NCDOT	North Carolina Department of Transportation
NYSDOT	New York State Department of Transportation
ODOT	Ohio Department of Transportation
QA/QC	Quality Assurance / Quality Control
PennDOT	Pennsylvania Department of Transportation
SAPL	Spray Applied Pipe Lining

**All terms with "*" are defined in the Glossary section at the end of this survey*

Appendix C

Literature Review Summary

Drainage infrastructure systems (culvert, storm sewer, outfall and related drainage elements) are buried underground and are in need of special attention in terms of proactive/preventive asset management and rehabilitation/renewal strategies. These drainage infrastructure systems represent an integral portion of roadway assets that routinely require inspection and maintenance. Failure of these systems is costly for departments of transportation (DOTs) both directly due to the replacement of the failed system and indirectly due to the time and money and even in some cases lives lost for the users of the highway. Further challenges are the variety in material types, shapes, backfill materials, types of roads, wide geospatial distribution and environmental exposures that makes every single culvert unique (Najafi et al, 2008).

There has been considerable research conducted on culverts, but mostly looked at the problem from a traditional structural/geotechnical/hydraulic perspective. However, the process for method selection and planning, design, and implementation of specific renewal methods to gain desirable outcomes is complex. Trenchless technologies provides means and methods for renewal and replacement of deteriorated pipes and culverts with minimum disruption of surface and subsurface (Najafi and Gokhale, 2005). These methods have many social and environmental benefits over traditional open-cut or cut-and-cover methods pipeline renewal and replacement and often are most cost-effective. These methods should be used when the project surface and subsurface conditions allow utilizing the trenchless technology environmental and social benefits. Spray applied pipe liners (SAPL) is one of the trenchless technology methods that can potentially be used for structural renewal and replacement of culverts.

Ohio DOT (2017) defines culverts as "a structure that conveys water or forms a passageway through an embankment and is designed to support a super-imposed earth load or other fill material plus live loads. Any structure with a span, diameter or multi-cell structure with total span less than 10 ft when measured parallel to the centerline of the roadway. This is known as the National Bridge Inventory span."

In 2010, American Society of Civil Engineers (ASCE) published a manual of practice (MOP) for trenchless renewal of culverts and storm sewers (ASCE, 2010). After an introduction, such topics as safety consideration, cleaning and inspection, evaluation and condition assessment, a detailed description of all renewal methods are included. SAPLs are separated into coatings and linings. Coatings are considered as barriers for corrosion protection. Linings are used as corrosion protection, as well as structural enhancement. Both coatings and linings can mitigate further degradation of culverts, but only linings can structurally enhance or structurally repair culverts and storm sewers. The most common materials used for renewal of these structures are cementitious, polymers and sheet linings, which include polyvinyl chloride (PVC) and polyethylene (PE) liners.

According to another manual published by ASCE (2016), the proper selection of lining materials, their physical properties, and application methodology provide a way to find suitable solutions for a range of pipe and pipe conditions. This includes consideration for host pipe valves and appurtenances, bends, and service connections. Other factors include pipe material and conditions, operating and surge pressures, number of service connections, installation length, renewal objectives, structural capabilities of the host pipe, and soil and live loadings. If a lining is proposed, determination of the liner thickness is an important design parameter, and the physical properties of the liner material have great bearing on it. Depending on how much deterioration is present in the pipe to be renewed, project designers may choose to utilize liners among the categories described in AWWA M28 (AWWA 2014) as summarized and quoted in the following:

- “Class I linings: These linings are nonstructural systems used primarily to protect the inner surface of the host pipe from corrosion, such as the traditional cement mortar lining (CML) and nonstructural polymers such as epoxy.

- Class II and III linings: These linings are called semi-structural because they interact with the host pipe. According to AWWA M28 (AWWA 2014), Class II and III liners are not expected to survive burst failure of the host pipe, because their long-term (50 year) internal burst strength is less than the maximum allowable operating pressure (MAOP) of the host pipe. Some of these liners are capable of bridging certain holes and gaps. Class II liners have minimal ring stiffness and depend entirely on adhesion to the pipe wall to prevent collapse if the pipe is depressurized. Class III liners are self-supporting with no dependency on the pipe wall adhesion. Use of Class II and III liners is recommended when the host pipe has discernible internal corrosion leading to pinholes and leakage, leakage from faulty joints, and localized external corrosion. Examples of Class II and III liners are close-fit semi-structural linings that can span holes and gaps in the host pipe, but have minimal thickness and require support from the host pipe to prevent collapse during depressurization.

- Class IV linings: These linings are fully structural essentially a pipe within a pipe and they possess a 50-year internal burst strength, when tested independently from the host pipe, equal to or greater than MAOP of the host pipe. They also have the ability to survive any dynamic loading or short term effects associated with sudden failure of the host pipe due to internal pressure loads. Class IV linings are sometimes considered to be equivalent to replacement pipe, although such linings may not be designed to meet the same requirements for external buckling or have the same longitudinal/bending strength as the original pipe. It should be noted that some renewal technologies can offer Class II, III, and IV linings, depending on the type of application, their material characteristics, design thickness, and installation method.”

Spray Applied Pipe Linings (SAPLs) can be used to protect and renew storm sewer conveyance conduits and have many benefits of trenchless technologies (Najafi, 2016). The principal objective of a SAPL is to apply a monolithic layer that inhibits further deterioration and/or provides structural replacement. Type of deterioration is dependent upon existing structure under consideration. According to Najafi (2013), the main objective of a structural renewal is to inhibit further deterioration and can structurally renew severely damaged culverts and drainage structures. The primary materials used for SAPLs generally fall into two broad categories of cementitious materials and polymers such as epoxies, polyurethanes and polyureas. All these different type of SAPLs have advantages and limitations.

Najafi and Osborn (2008) provided a comprehensive decision making procedures for using trenchless technologies in culvert rehabilitation. Different aspect of trenchless technology techniques, such as, safety, cleaning, inspection, evaluation, assessment, quality assurance/quality control and life cycle considerations are discussed. They present a decision making process for method selection that covers specific site and project conditions and capabilities and limitations of each method.

Davidson et al. (2008) studied polyvinyl alcohol (PVA) fiber reinforced concrete. The objective of their paper was to analyze the use of PVA fiber reinforced concrete on corrugated metal pipes (CMPs) to rehabilitate using SAPL. Five topics are included in this study: (1) background review, (2) designing, optimizing, and testing the material formulation, (3) outlining design methodology, (4) demonstrating the application approach and strength, and (5) documenting the technology and results of the project. Finite element analysis was used to evaluate the soil-structure interaction of cementitious liners for CMPs, which was validated by coupon testing and full-scale composite host pipe and liner testing. An analytical approach was used for designing the required liner thickness. Authors stated that PVA offers intriguing and unique characteristics that would minimize the required liner thickness, while providing tension, strength, rigidity and ductility.

Moore and García (2013) compared two deteriorated CMPs with and without cementitious SAPLs. The objectives of this report were: (1) to monitor the vertical and horizontal diameter changes, as well as deflection of the culverts under different loading conditions before and after the lining, (2) to observe and monitor the cracks occurred on liners before failure, and (3) to assess the interaction between the pipe and liner for flexural loadings. Two deteriorated CMPs of 48-in., 23-ft length were embedded with poorly graded sandy gravel (GP-SP). Both culverts were instrumented with strain gauges and string potentiometers (sensors). Simulated single and tandem axle truck loads were applied over these lined CMPs gradually. Geo-polymer material with 2- and 3-in. thicknesses were used as SAPLs and included 48-in. and 83-in. soil covers. Results showed that deteriorated CMPs with SAPLs survived H-20 and HL-93 loads. The loading continued until lined CMPs failed. First crack was at a loading of 146 kips, and then with increasing loads, larger cracks started at 169-180 kips.

Moore and García (2015) analyzed ultimate strength of cementitious SAPLs. The objectives were: (1) to observe the failure of the CMPs with cementitious SAPL and to determine whether their strength was controlled by cracking of SAPL along crowns and inverts, and (2) to obtain measurements to permit quantitative evaluation of SAPL design methodologies. As stated above in the previous report, two deteriorated CMPs of 48-in. diameter, 23-ft length used for these tests. The maximum measured SAPL strain was approximately 10% of the yield strain. Results showed that the difference in liner thickness was 30%, and that extreme fiber tensions during service loading were 7% and 13% of the tensile strength of the liner materials for the 3-in. and 2- in. liner thicknesses that were specified.

Szafran and Matusiak (2017) studied structural behavior of reinforced concrete pipes (RCPs) with polyurea SAPL using experiments. The objective of their study was to evaluate and determine structural behavior and increased compressive strength of RCP lined with polyurea SAPL. Their methodology involved static compressive testing on RCP without, and with internal and external polyurea SAPL application. Results of these tests indicated that using polyurea SAPL on both internal and external surfaces of RCP increased the peak load of failure by about 21.9%. These results concluded that SAPL increases the compressive strength of RCP.

Geo-polymer SAPL is used in trenchless technology rehabilitation of culverts. Royer and Allouche (2016) conducted laboratory testing of RCP and CMP with and without SAPL. The tests were performed in 24-in., 36-in. and 48-in. pipe diameters. For considering the ovality in the CMP host culverts, 24-in. diameter pipes were preloaded to obtain 12% deformation. Compressive strength tests were conducted as per ASTM C39, tensile tests as per ASTM C307 and flexural strength tests as per C78. Authors recommended a minimum thickness of 1-in. for pipes smaller than 54-in. and a minimum of 1.5-in. for larger pipes to compensate for local variations in the installed thickness and material properties.

An ongoing project for NCHRP (Allouche 2017) studies maximizing the service life of culverts by rehabilitation while minimizing direct costs and traffic disruptions. The objectives of rehabilitation are to address stability, bedding deficiencies and hydraulic capacity of culverts. A series of decision-making procedures for rehabilitation of concrete, metal and thermoplastic culverts are prepared. Spray-on coating of metal pipes (SAPL) is part of this study which explains SAPLs used with different thicknesses. For instance, a 60-in. pipe with a length of 1,800 ft, was sprayed with polyurethane at a thickness of 0.3-in. (300 mils.) The authors concluded that the main advantage of polymer SAPL is to protect against corrosion, although it increases structural capacity of host culvert.

Watkins et al. (1982) analyzed the effects of loads on buried corrugated polyethylene pipes. The objective was to determine a relation between pipe deflection and height of soil cover for 32-kip/axle to 54-kip/axle loadings for different densities of soil. The tests included loading of seven pipe samples with varying diameters, which were placed in a sloped trench with height of soil cover from 5- to 40-in. Results showed that side fill material at certain densities restrained the pipe without significant effects from height of soil cover.

Manholes are vertical structures but they share some similarities in concept of rehabilitation with culverts. Najafi and Sever (2015) studied structural capabilities of No-Dig manhole rehabilitation. Their objective was to create a decision support tool to select an appropriate lining material for manhole rehabilitation. Their research consisted case studies, laboratory testing and computational modeling. The flexural tests were conducted as per ASTM C293, compressive strength tests as per ASTM C39, and the D-load tests as per ASTM C497. All of the SAPL materials significantly (or substantially for some) improved the crushing strength of a 24-in. concrete pipe tested according to ASTM C497. The main test results suggested that spray applied epoxies and cementitious linings can substantially enhance the structural properties of a reinforced concrete cylinder if they applied firmly at a certain thickness. On the other hand, some polymer liners survived the crushing test without an apparent failure when the concrete substrate failed by tensile stress cracking at 3:00 and 9:00 o'clock positions. This was essentially due to lower adhesion and/or high flexibility, and did not necessarily translate to higher peak loads at failure.

A CMP arch culvert studied based on the level of corrosion in Muskingum County, Ohio (Sargand et al. 2015). This case study included replacement of invert with concrete, which had soil cover of approximately 4-in. with asphalt pavement. The deflection of culvert was analyzed, before and after rehabilitation. Concrete placement had a variation in thickness from 2- to 5-in. over the invert. Loading on crown was applied in increments of 18 kips, 40 kips and 60 kips. The culvert was also simulated using finite element modeling, both with the 2-dimensional CANDE program and the 3-dimensional ABAQUS program. FEM results were in reasonable agreement with to experimental measurements. Despite the condition, the culvert supported a load considerably larger than the legal limit of 18 kip. The stresses at the interface of the steel culvert and the poured concrete treatment were not very large.

Summary:

The literature review so far concludes that SAPLs have potentials for renewing deteriorated culvert pipes and can be used as a structural application to renew/replace the existing culverts. Many structural and construction issues as well as applicability and host culvert conditions must be investigated. The objective of current research is to highlight these considerations for proper renewal of existing culverts and develop proper design methodologies/equations for structural application of SAPLs. This important task has not been done in the current literature.

Appendix D

Vendor Communication

Table D1: List of Vendors Invited and Responded

Vendor	Invitation Email Sent to	Email Address	Invitation Email Sent on	Vendor's Response
ADVANTAGERLINE	Mr. Asay	dasay@advantagereline.com	3/30/2018	
MADEWELL	Mr. Hallam	steve@madewell.net	3/30/2018	
VORTEX	Mr. Henning	stevehenning@vortexcompanies.com	3/9/2018	would like to participate
SHERWIN-WILLIAMS	Mr. Heywood	murray.c.heywood@sherwin.com	3/9/2018	
EPOXYTEC	Mr. Caputi	mcaputi@epoxytec.com	3/9/2018	would like to participate
HYDRATECH	Mr. Blais	peter.blais@hydratechllc.com	3/9/2018	
IPR	Mr. Collis	cparrish@teamipr.com	3/9/2018	
SPRAYROQ	Mr. Johnson	cjohnson@sprayroq.com	3/8/2018	would like to participate
AP/M PERMAFORM CENTRI PIPE	Mr. Shook	bill@permaform.net	3/8/2018	would like to participate
MILLIKEN	Dr. Royer	joe.royer@milliken.com	3/8/2018	would like to participate
AWCOOK	Mr. Cook	dan@awcookcement.com	3/8/2018	would like to participate
RAVENLINING	Ms. Romans	romansk@ravenlining.com	3/8/2018	
STANDARDCEMENT	Mr. Tamez	mariotamez48@standardcement.com	3/8/2018	
THE STRONG COMPANY	Mr. Kappler	mikekappler@msn.com	4/16/2018	would like to participate

Appendix E

Tentative Laboratory Testing Plan at CUIRE/UTA

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

Testing Plan for

Laboratory Specimen Testing at CUIRE/UTA

Version 1

March 9, 2018

Introduction

The development of practical spray applied structural culvert pipe linings could be of enormous benefit to the Departments of Transportation (DOTs). Such linings could be a key strategy in extending service life and managing the future burden expected from the aging network of culverts and storm sewers. Compared to other culvert rehabilitation systems, spray applied linings promise greater cost effectiveness and less community disruptions.

The funding for this project is provided by 7 DOTs (North Carolina, Florida, Pennsylvania, New York, Minnesota, Delaware and Ohio), leading by Ohio DOT. The University of Texas at Arlington (UTA)'s Center for Underground Infrastructure Research and Education (CUIRE) is selected to conduct this research. The project started in December 2017 and expected to complete in December 2019. The American Association of State Highway Transportation Officials (AASHTO)'s National Transportation Product Evaluation Program (NTPEP) has established a Technical Committee for Spray Applied Pipe Liners (SAPL) in an effort to implement this technology. Data collected via the SAPL NTPEP program will be incorporated into this pooled funded research project in addition to field and laboratory testing via this research project.

The testing and evaluation for this project will be conducted into three stages:

- **Stage I:** Submission of in-house and/or third-party test results and specifications/design calculations and any comments or suggestions (deadline: March 16, 2018).
- **Stage II:** providing laboratory samples for testing at CUIRE/UTA according to attached detailed testing plan (deadline: April 6, 2018). *The following pages will provide details for Stage II of this project.*
- **Stage III:** Soil box testing of large samples on select materials (test details are being developed).

Part 1: ASTM Test Standards for Polymeric Liners

Test A: Tensile Test (ASTM D638)

Standard Test Method for Tensile Properties of Plastics.

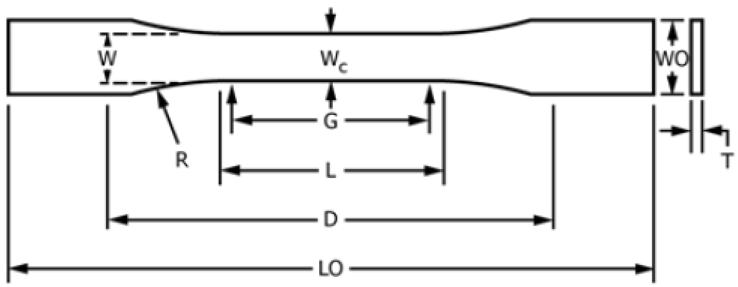

Figure E1: Test Specimen for Tensile Test

Table E1: Specimen Dimensions for Thickness, T, in. (mm)

Specimen Number	A_1	A_2
Thickness	**0.25 in. ± 0.02 in. (6.35 mm ± 0.4 mm)**	**0.55 ± 0.02 in. (14 ± 0.4 mm)**
	ASTM Specimen Type I	ASTM Specimen Type III
W—Width of Narrow Section	0.5 in. (13 mm)	0.75 in. (19 mm)
L—Length of Narrow Section	2.25 in. (57 mm)	2.25 in. (57 mm)
WO—Width Overall, Minimum	0.75 in. (19 mm)	1.13 in. (29 mm)
LO—Length Overall, Minimum	6.5 in. (165 mm)	9.7 in. (246 mm)
G—Gage Length	2 in. (50 mm)	2 in. (50 mm)
D—Distance between Grips	4.5 in. (115 mm)	4.5 in. (115 mm)
R—Radius of Fillet	3 in. (76 mm)	3 in. (76 mm)
No. of Specimens	7	7

Note:

1. The tolerances of the width at the center W_c shall be +0.00 mm, −0.10 mm (+0.000 in., −0.004 in.) compared with width *W* at other parts of the reduced section. Any reduction in *W* at the center shall be gradual, equally on each side so that no abrupt changes in dimension result.

2. **All the particulars of the specimen manufacturing should be documented.**

Test B: Flexural Test (ASTM D6272)

Standard Test Method for Flexural Properties of Plastics by Four-Point Bending.

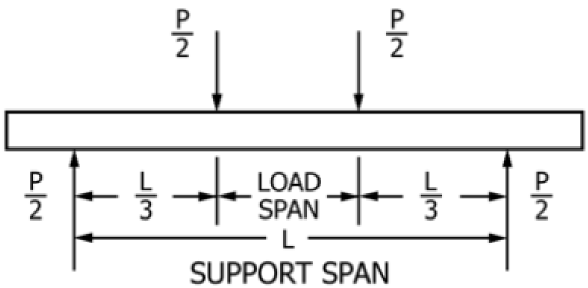

Figure E2: Loading Diagram

Table E2: Specimen (a Bar of Rectangular Cross Section) Dimensions for Thickness, T, in. (mm)

Specimen Number	**B1**	**B2**	**B3**
Thickness	0.5 in. (12.7 mm)	1 in. (25.4 mm)	2 in. (50.8 mm)
Length	9.6 in. (243.84 mm)	19.2 in. (487.68 mm)	38.4 in. (975.36 mm)
Width	2 in. (50.8 mm)	4 in. (101.6 mm)	8 in. (203.2 mm)
Support Span	8 in. (203.2 mm)	16 in. (406.4 mm)	32 in. (812.8 mm)
No. of Specimens	7	7	7

Instructions: The beam specimen shall be built using "lifts," commensurate with those recommended by the manufacturer, according to practice used in actual field installations. For example:

- The 0.5-in. thick epoxy beams should be constructed using two 0.25-in. thick coats applied within the recoat window of that material.
- The 1.0-in. thickness should be applied in 4 lifts.
- The 2.0-in. thickness should be applied in 8 lifts.

Note:

1. **Whatever increments are used should be well documented by the lab who should observe these samples being made.**

2. **All the particulars of the specimen manufacturing should be documented**

Test C: Compression Test (ASTM D695)

Standard Test Method for Compressive Properties of Rigid Plastics

Table E3: Specimen (Cylinder) Dimensions

Specimen Number	**Cylinder C1**	**Cylinder C2**
Diameter	0.50 in. (12.70 mm)	0.50 in. (12.70 mm)
Height	2.00 in. (50.80 mm)	1.00 in. (25.4 mm)
No. of Specimens	7	7

Note:

1. **All the particulars of the specimen manufacturing should be documented.**

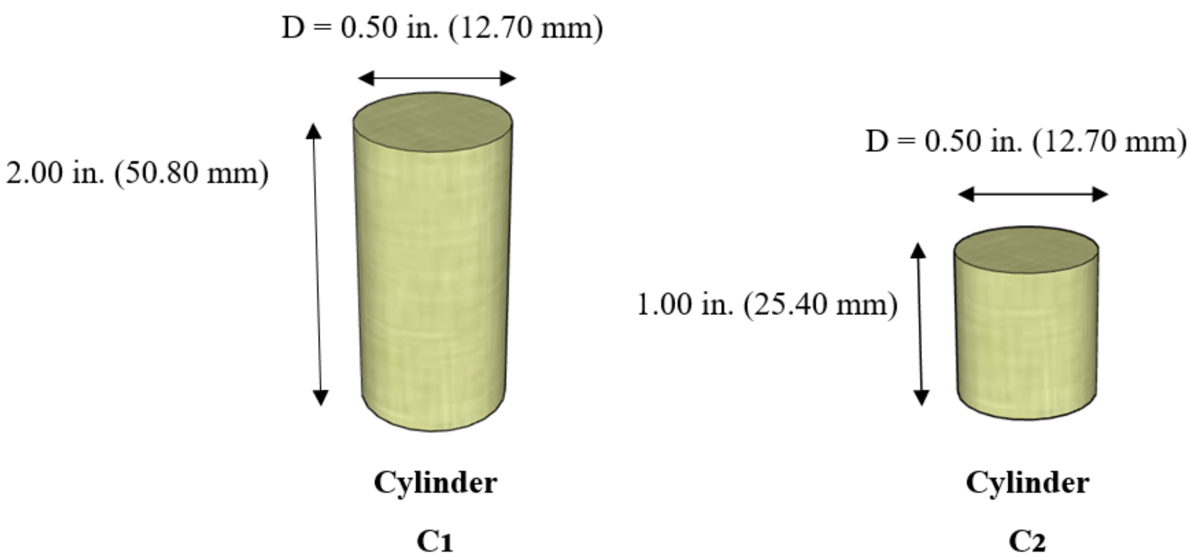

Figure E3: Cylinder Test Specimens

Part 2: ASTM Test Standards for Cementitious and Geo-polymer SAPL

Test D: Flexural Test (ASTM C1609)

Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)

Table E4: Specimen (a bar of square cross section) Dimensions for Thickness, T, in. (mm)

Specimen Number	**D1**	**D2**	**D3**	**D4**	**D5**
Thickness	0.5 in. (12.7 mm)	1 in. (25.4 mm)	2 in. (50.8 mm)	4 in. (100 mm)	6 in. (150 mm)
Length	14 in. (350 mm)	14 in. (350 mm)	14 in. (350 mm)	16 in. (406.4 mm)	20 in. (500 mm)
Depth	0.5 in. (12.7 mm)	1 in. (25.4 mm)	2 in. (50.8 mm)	4 in. (100 mm)	6 in. (150 mm.)
Span Length	12 in. (305 mm)	12 in. (305 mm)	12 in. (305 mm)	12 in. (305 mm)	18 in. (457.2 mm)
Casting	1 Lift	2 Lifts	4 Lifts	According to Instructions* (ASTM C1609)	According to Instructions* (ASTM C1609)
No. of Specimens	5	5	5	5	5

Note:

1. **At least one day of cure time is required between each lift.**
2. **All the particulars of the specimen manufacturing should be documented.**

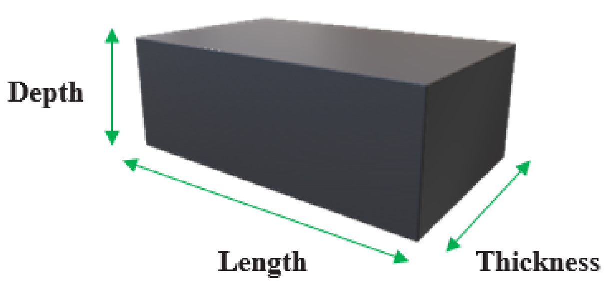

Figure E4: Cementitious Bar Specimen

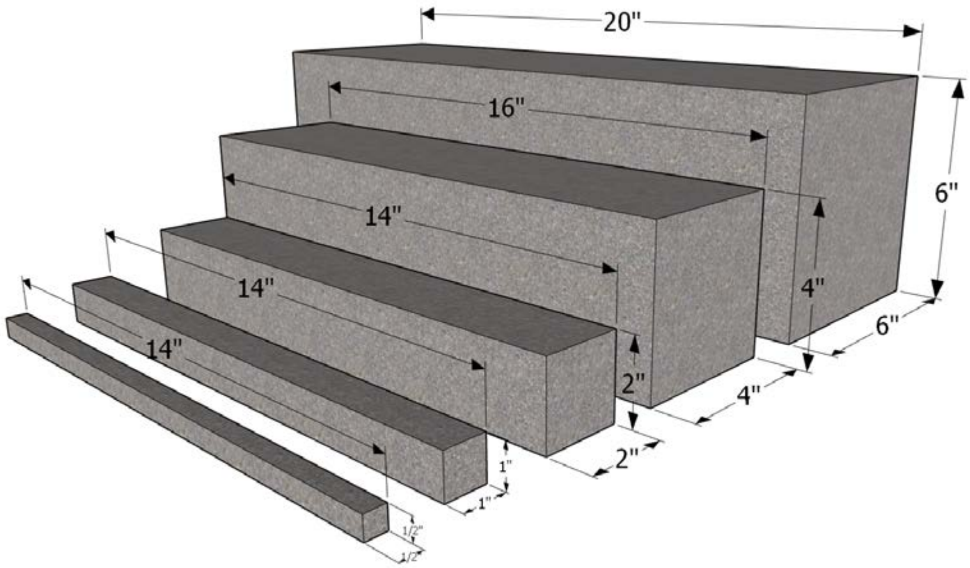

Figure E5: Cementitious Specimens with different dimensions

Instructions:

- The tolerances on the cross-section of the test specimens shall be within ±2%. The test specimens shall have a square cross-section within these tolerances.
- The nominal maximum size of aggregate and cross-sectional dimensions of test specimens shall be in accordance with Practice C31/C31M or Practice C192/C192M when using molded specimens, or in accordance with Test Method C42/C42M when using sawn specimens.
- Freshly Mixed Concrete: Obtain samples of freshly mixed fiber-reinforced concrete for the preparation of test specimens in accordance with Practice C172.
- Mold specimens in accordance with Practice C31/C31M or Practice C192/C192M, except that consolidation shall be by external vibration. Consolidation may be considered to be adequate when entrapped air voids are no longer observed rising to the surface of the specimen.
- Make sure that the time of vibration is sufficient to ensure adequate consolidation, as fiber-reinforced concrete requires a longer vibration time than concrete without fibers, especially when the fiber concentration is relatively high.
- When filling the mold, attempt to add an amount of concrete that will exactly fill the mold after consolidation. When screeding the top surface, continue external vibration to ensure that fibers do not protrude from the finished surface.
- Curing shall be in accordance with Practice C31/C31M or Practice C192/C192M.

- Evaporation Control: When the time between removal of test specimens from a moist curing environment and the start of testing is likely to exceed 15 min, minimize drying by covering with wet burlap, applying a curing compound, or by other appropriate techniques.
- The lab must be careful to ensure that the dry mix cementitious samples which can become segregated during shipping are properly remixed before withdrawing the amount of material needed for the specimen being made at any one time. The fines and the fibers must be present to properly represent the mix applied in the field! Given these concerns, a representative of the cementitious material manufacturer should be present when the beams are being manufactured.

Test E: Compression Test (ASTM C109)

Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)

Table E6: Specimen (Cube) Dimensions

Specimen Number	**Cube** **E1**
Dimensions	2 in. (50 mm)
No. of Specimens	5

Note:

1. **All the particulars of the specimen manufacturing should be documented.**

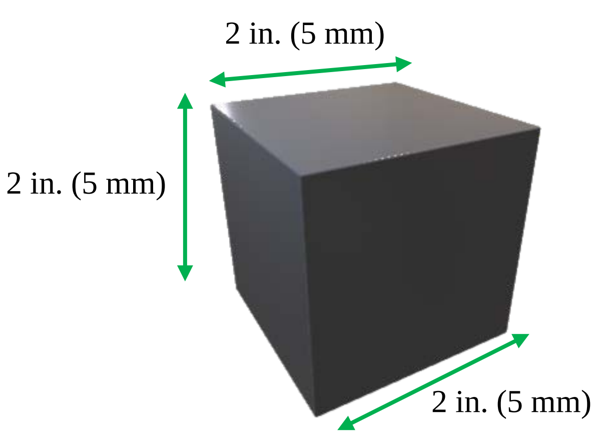

Figure E7: Cube Test Specimens

Table E8: Summary of Laboratory Testing

Test		Test No.	Specimen Number	No. of Specimens	No. of Specimens for Each Test
Polymeric	**Tensile Test ASTM D638**	**A**	A1	7	14
			A2	7	
	Flexural Test ASTM D6272	**B**	B1	7	21
			B2	7	
			B3	7	
	Compression Test ASTM D695	**C**	C1	7	14
			C2	7	
Cementitious	**Flexural Test ASTM C1609**	**D**	D1	5	25
			D2	5	
			D3	5	
			D4	5	
			D5	5	
	Compression Test ASTM C109	**E**	E1	5	5
Total No. of Specimens					79

Appendix F

Tentative Soil Box Testing Plan

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

Work Plan for

Soil Box Testing at CUIRE/UTA

Prepared for:
Ohio Department of Transportation (Ohio DOT)

Prepared by:
Center for Underground Infrastructure Research and Education (CUIRE)
Director: Dr. Mohammad Najafi
The University of Texas at Arlington
Department of Civil Engineering

April 10, 2018

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Test Components

Soil Box

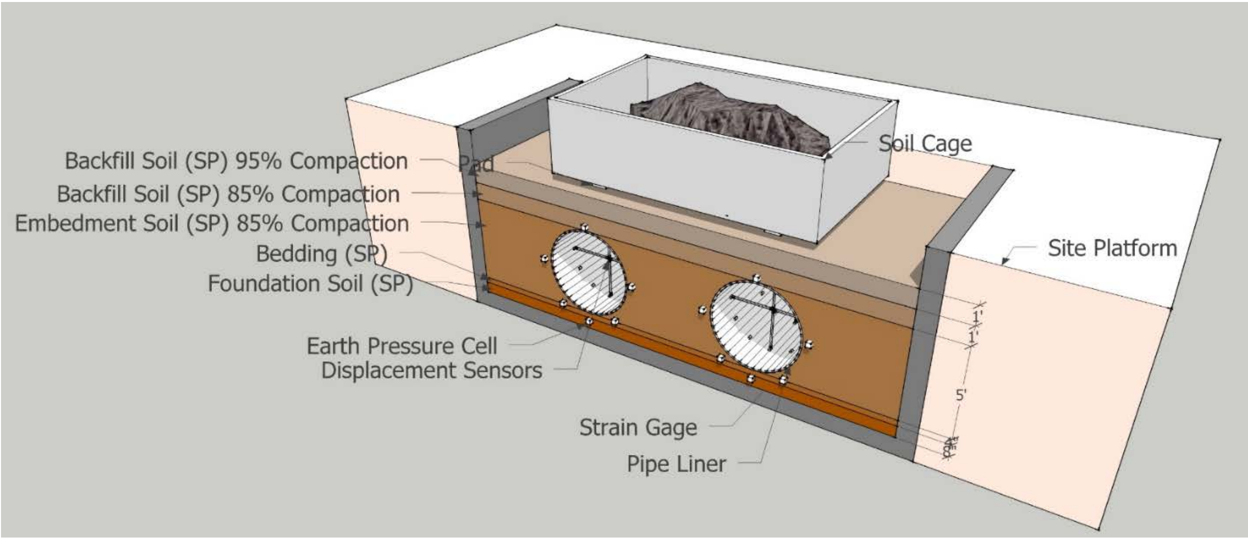


Figure F1: Soil Box Test 3D View (Circular Pipes)

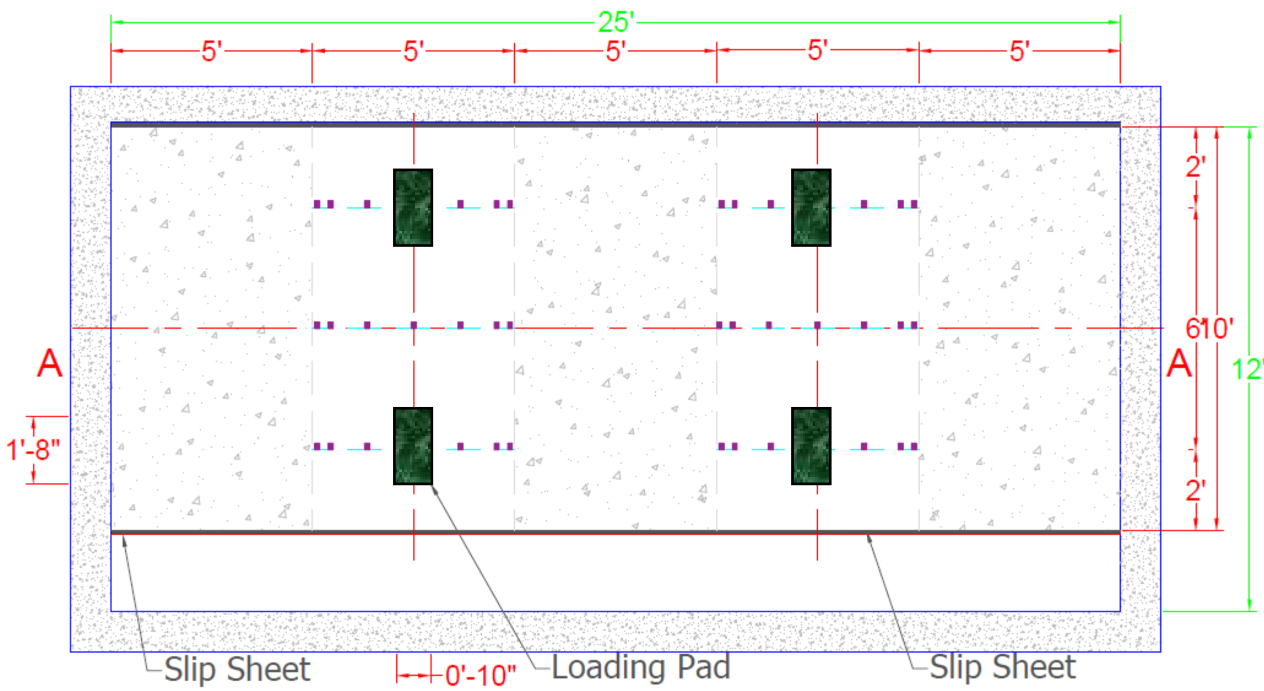


Figure F2: Soil Box Test Plan View (Circular Pipes)

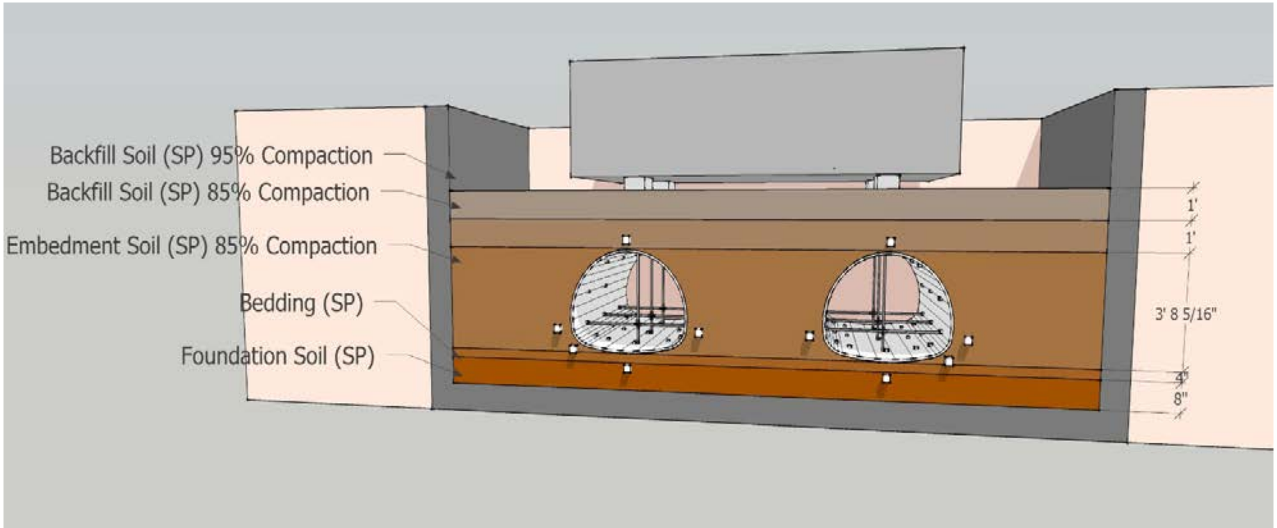


Figure F3: Soil Box Test 3D View (Pipe Arch Shapes)

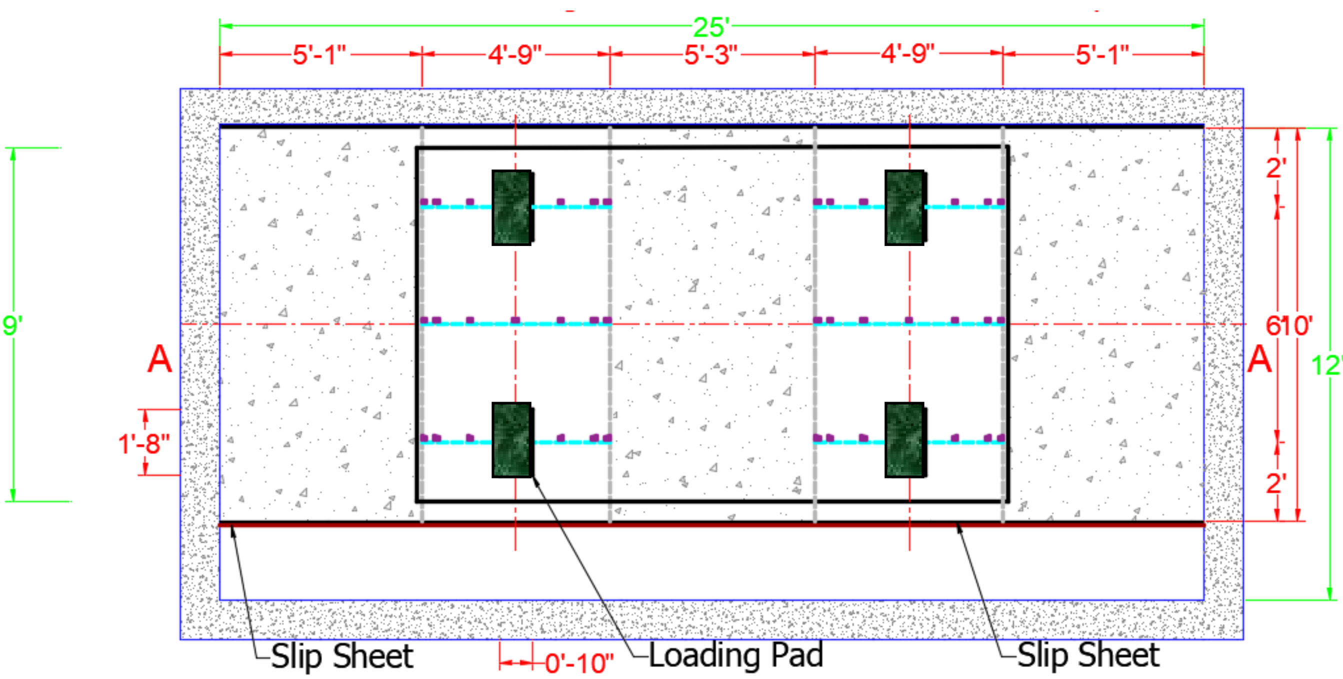


Figure F4: Soil Box Test Plan View (Pipe Arch Shapes)

Spacing between the Pipes

According to AASHTO 12.6.7 and AASHTO C12.6.7, the minimum spacing between pipes should not be less than D/2 for circular pipes and S/3 for pipe arc shape spans.

Table F1: Spacing between the Pipes in the Soil Box

Number of Pipes in the Soil Box	**Spacing Between the Pipes**	
2	Circular Pipes	D (60 in.)
	Pipe Arch Shapes	S (57 in.)

Test Samples

Table F2: Test Samples Details

Shape	**Material**	**Number of Samples**	**Pipe Outside Diameter (in.)**	**Liner Thicknesses (in.)**	**Length of the Pipe (ft.)**
Circular	**Polymeric**	3	60	• Mr Kampbell: 0.5”, 1” and 2” • Dr. Sever: 0.15”, 0.25” and 0.5”	10
	Cementitious	3	60	• Mr Kampbell: 0.5”, 1” and 2” • Dr. Royer: 1”, 1.5” and 2”	
Pipe Arch Shape	**Polymeric**	3	57 × 38	• Mr Kampbell: 0.5”, 1” and 2” • Dr. Sever: 0.15”, 0.25” and 0.5”	10
	Cementitious	3		• Mr Kampbell: 0.5”, 1” and 2” • Dr. Royer: 1”, 1.5” and 2”	

Table F3: Soil Layers Details in the Soil Box

Soil Layers	Material	AASHTO Specification	Thickness (in.)		Compaction
			Circular	Pipe Arch Shape	
Foundation	Poorly Graded Coarse Sand (SP) or Soil Type A1	Construction Specification, Section 27	8”	8”	95%
Bedding	Poorly Graded Coarse Sand (SP) or Soil Type A1	Design Specification, 12.6.2.2.3 Construction Specification, Section 27	4”	4”	95%
Embedment	Poorly Graded Coarse Sand (SP) or Soil Type A1	Construction Specification, Section 27	60”	57	• 85% • 90% around the corner radii
Backfill Soils (Above the Pipe)	Poorly Graded Coarse Sand (SP) or Soil Type A1 (well-compacted of the top 12 in)	Design Specification, 12.4.1.3, 12.6.6.3 and C12.4.1.3	24”	24”	• 85% for 12” over the pipe • 95% for the top 12”

Instrumentation Details

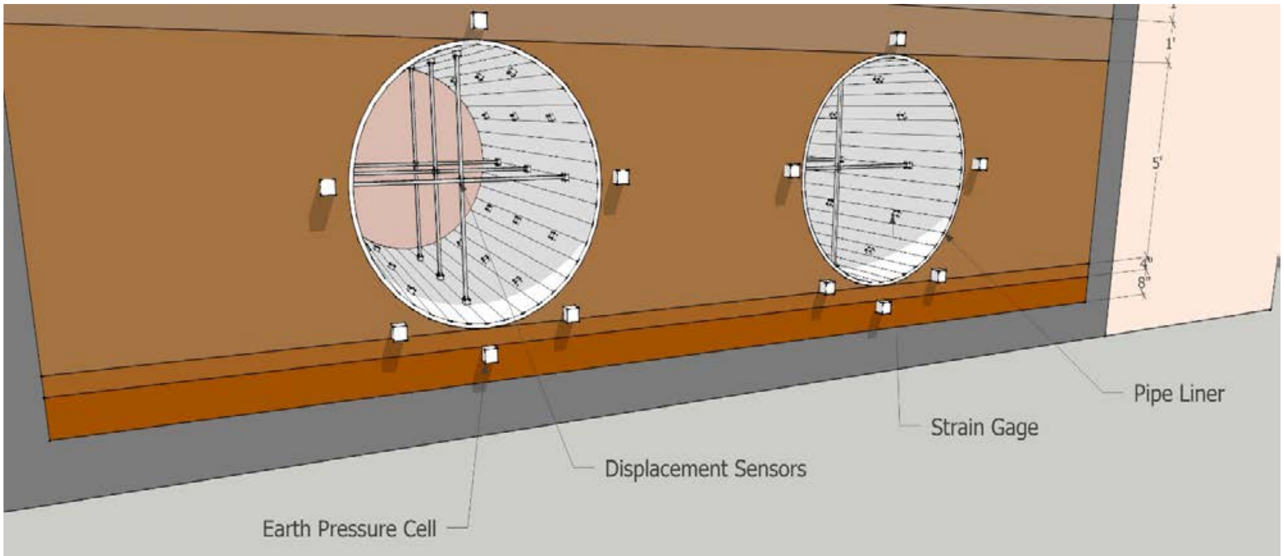


Figure F5: Instrumentations for Circular Pipes

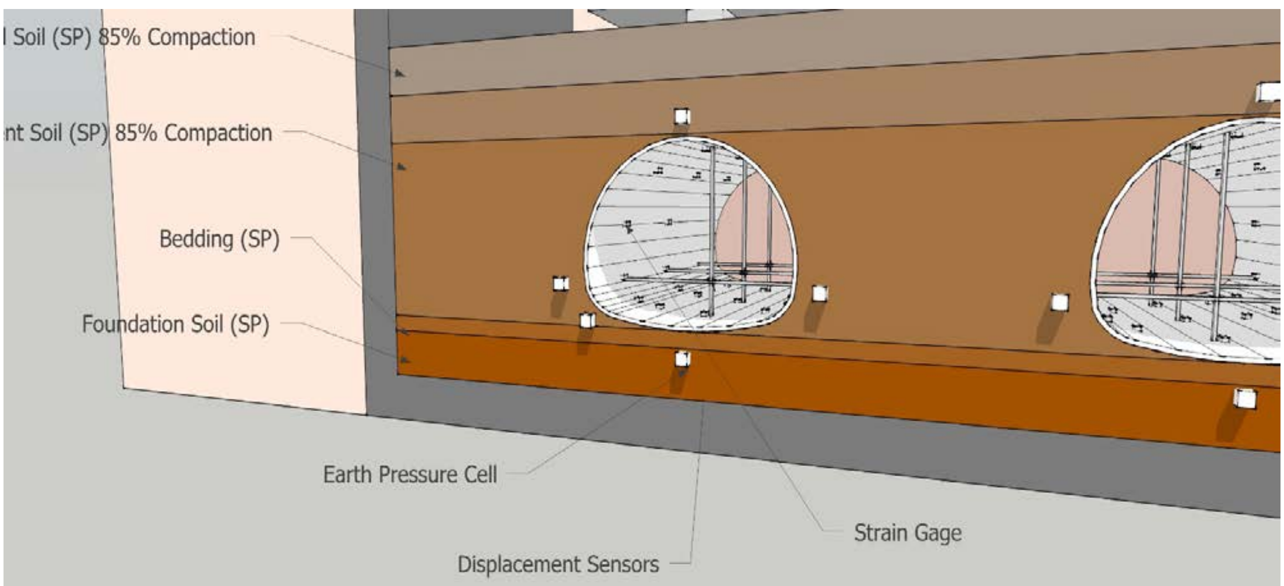


Figure F6: Instrumentations for Pipe Arch Shape

Table F4: Instrumentation Details for Circular Pipes

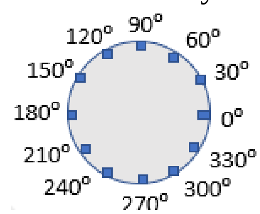
Circular Pipes				
Instruments	**Numbers in Each Cross Section**		**Numbers in Each Pipe**	**Locations**
Strain Gauge	Circumferentially	12	36	• Circumferentially:  • Longitudinally: 1 Center + 2 under 2 pads
Cable Displacement Sensor	Horizontally	1	6	• Longitudinally: 1 Center + 2 under 2 pads
	Vertically	1		
Earth Pressure Cell	Horizontally	2	12	• Longitudinally: 1 Center + 2 under 2 pads
	Vertically	2		

Table F5: Instrumentation Details for Pipe Arch Shapes

Pipe Arch Shape				
Instruments	**Numbers in Each Cross Section**		**Numbers in Each Pipe**	**Locations**
Strain Gauge	Crown	1	30	Longitudinally: 1 Center + 2 under 2 pads
	Invert	1		
	Springlines (Left and Right)	2		
	Between Crown and Springline 30 Degrees Apart (Left and Right)	4		
	Haunch (Left and Right)	2		
Cable Displacement Sensor	Horizontally	1	6	
	Vertically	1		
Earth Pressure Cell	Horizontally	2	12	
	Vertically	2		

Earth Pressure Cells

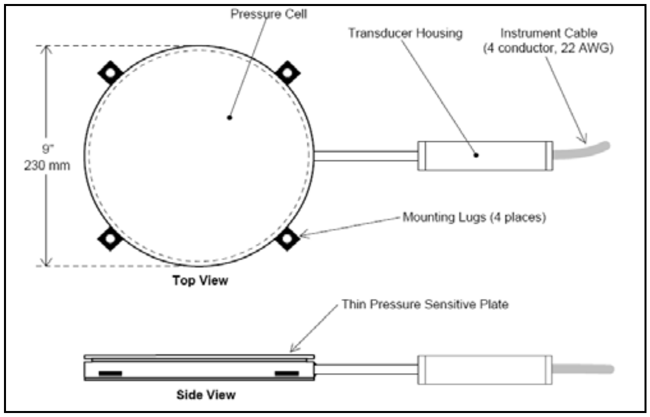


Figure F7: Earth Pressure Cell (Model 4810)

Cable Extension Displacement Sensor

**Figure F8: Cable Displacement Sensor
(Source: Vishay Micro-measurement)**

Strain Gauges

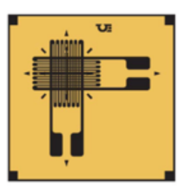


**Figure F9: 2 Axis Strain Gauge
(Source: Vishay)**

Test Setups

Circular Pipes

Table F6: Circular pipes Test Setups

Setup No.	Material	Outside Pipe Diameter (in.)	Thickness (in.)	Length of the Pipe (ft.)
1	Polymeric	60	Needs to be Finalized	10
	Polymeric	60	Needs to be Finalized	10
2	Cementitious	60	Needs to be Finalized	10
	Cementitious	60	Needs to be Finalized	10
3	Polymeric	60	Needs to be Finalized	10
	Cementitious	60	Needs to be Finalized	10

Pipe Arc shapes

Table F7: Pipe Arc Shapes Test Set ups

Setup No.	Material	Outside Pipe Diameters (in.)	Thickness (in.)	Length of the Pipe (ft.)
4	Polymeric	57×38	Needs to be Finalized	10
	Polymeric	57×38	Needs to be Finalized	10
5	Cementitious	57×38	Needs to be Finalized	10
	Cementitious	57×38	Needs to be Finalized	10
6	Polymeric	57×38	Needs to be Finalized	10
	Cementitious	57×38	Needs to be Finalized	10

Live Load

Table F8: Live Load According to AASHTO Specification

Live Load	AASHTO Specification
Soil Cage for Applying 32,000 lb. Load	H20 Axle Truck (Total Weight 32,000 lb.)

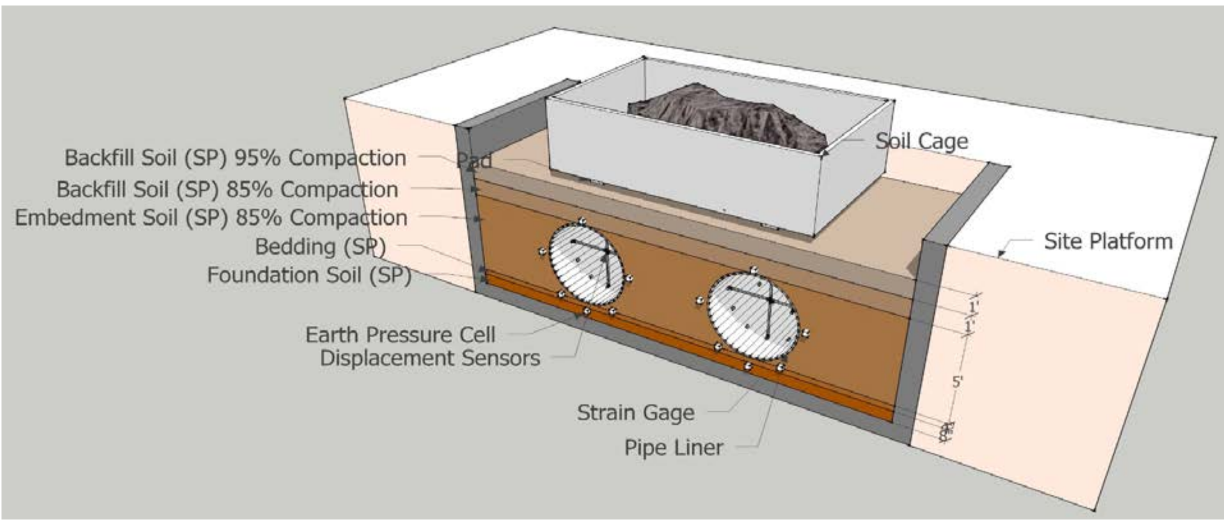


Figure F10: Soil Cage for Applying 32,000 lb. Load (3D View)

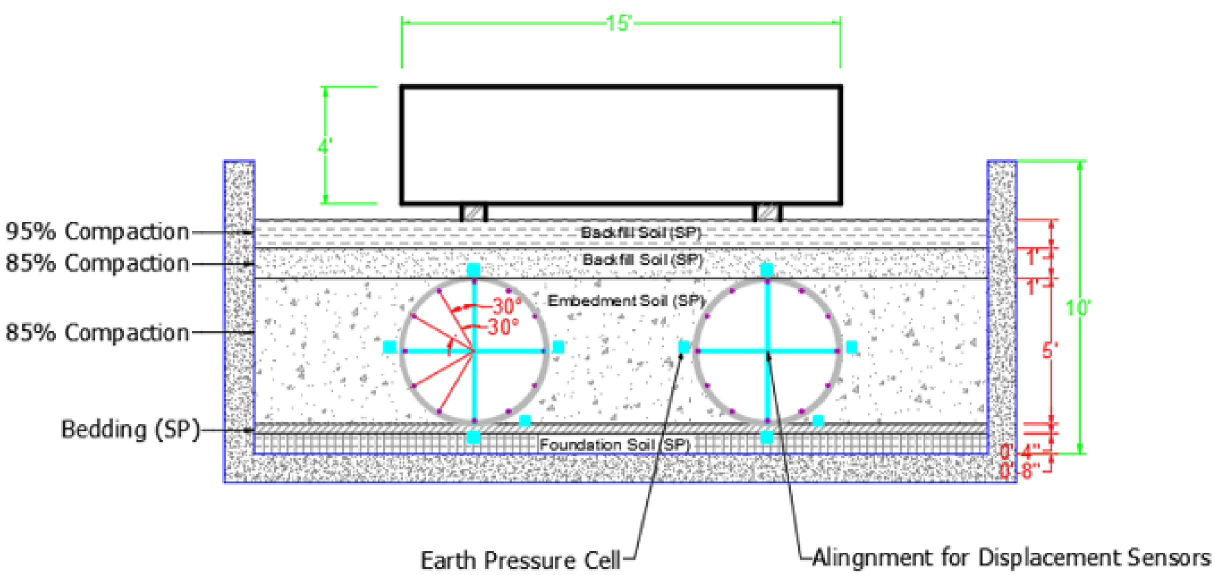


Figure F11: Soil Cage for Applying 32,000 lb. Load (Cross Sectional View)

Vendor Quotes for Instrumentation

Table F9: Instrumentation Quotes for Testing of three (3) Circular Cementitious Linings

Instrument Type	Vendor	Model Number	Unit Price ($)	Number of Packages	Total Cost ($)	Contact Number
Strain Gauge	TMI	PFLC-30-11-5LJB	249	5	1245	Harry Jones (Technical Manager) 979-764-0442 Amy Persyn (Office Manager) 979-764-0442
		PFL-30-11-5LJC	121	6	726	
		Adhesive	49	4	196	
		Total (incl. 5% discount, shipping)			**2167**	
	HBM	XY3	152	10	1520	Bart Morrick 217-607-5735
		LY41-10/120	120	6	720	
		Adhesive	60	1	60	
		Total (not incl. discount, shipping)			**2300**	
Earth Pressure Cells	GeoKon	4815-350kPa	836	6	5016	Matt Sullivan 603-448-1562
		4815-700kPa	836	2	1672	
		02-250V6-E Cable	0.7	TBD	0.7	
		Total (not incl. 5% discount, shipping, wire)			**6688**	

Table F10: Instrumentation Quotes for Testing of four (4) Circular Cementitious Linings

Instrument Type	Vendor	Model Number	Unit Price ($)	Number of Packages	Total Cost ($)	Contact Number
Strain Gauge	TMI	PFLC-30-11-5LJB	249	6	1494	Harry Jones (Technical Manager) 979-764-0442 Amy Persyn (Office Manager) 979-764-0442
		PFL-30-11-5LJC	121	7	847	
		Adhesive	49	5	245	
		Total (incl. 5%discount, shipping)			**2586**	
	HBM	XY3	152	12	1824	Bart Morrick 217-607-5735
		LY41-10/120	120	7	840	
		Adhesive	60	2	120	
		Total (not incl. discount, shipping)			**2784**	
Earth Pressure Cells	GeoKon	4815-350kPa	836	6	5016	Matt Sullivan 603-448-1562
		4815-700kPa	836	2	1672	
		02-250V6-E Cable	0.7	TBD	0.7	
		Total (not incl. 5% discount, shipping, wire)			**6688**	

Table F11: Instrumentation Quotes for Testing of three (3) Circular Polymer Linings

Instrument Type	Vendor	Model Number	Unit Price ($)	Number of Packages	Total Cost ($)	Contact Number
Strain Gauge	TMI	GFLA-3-50-5LJC	145	6	870	Harry Jones (Technical Manager) 979-764-0442 Amy Persyn (Office Manager) 979-764-0442
		GFLA-3-50-5LJC	258	5	1290	
		Adhesive	43	4	172	
		Total (incl. 5%discount, shipping)			**2332**	
	HBM	XY3	152	10	1520	Bart Morrick 217-607-5735
		LY41-10/120	120	6	720	
		Adhesive	60	1	60	
		Total (not incl. discount, shipping)			**2300**	
Earth Pressure Cells	GeoKon	4815-350kPa	836	6	5016	Matt Sullivan 603-448-1562
		4815-700kPa	836	2	1672	
		02-250V6-E Cable	0.7	TBD	0.7	
		Total (not incl. 5% discount, shipping, wire)			**6688**	

Table F12: Instrumentation Quotes for Testing of four (4) Circular Polymer Linings

Instrument Type	Vendor	Model Number	Unit Price ($)	Number of Packages	Total Cost ($)	Contact Number
Strain Gauge	TMI	GFLA-3-50-5LJC	145	7	1015	Harry Jones (Technical Manager) 979-764-0442 Amy Persyn (Office Manager) 979-764-0442
		GFLA-3-50-5LJC	258	6	1548	
		Adhesive	43	5	215	
		Total (incl. 5%discount, shipping)			**2778**	
	HBM	XY3	152	12	1824	Bart Morrick 217-607-5735
		LY41-10/120	120	7	840	
		Adhesive	60	2	120	
		Total (not incl. discount, shipping)			**2784**	
Earth Pressure Cells	GeoKon	4815-350kPa	836	6	5016	Matt Sullivan 603-448-1562
		4815-700kPa	836	2	1672	
		02-250V6-E Cable	0.7	TBD	0.7	
		Total (not incl. 5% discount, shipping, wire)			**6688**	

Table F13: 4425 Vibrating Wire Convergence Meters

Model	Description	Price
4425-1-#	Vibrating Wire Convergence Meter, complete assembly including turnbuckle, VW transducer housing, spring tensioned VW transducer, rod clamp and thermistor. Specify 25 mm or 50 mm range. # corresponds to require range	$620.00/ea
4425-1-#	Vibrating Wire Convergence Meter, complete assembly including turnbuckle, VW transducer housing, spring tensioned VW transducer, rod clamp and thermistor. Specify 100 mm or 150 mm range. # corresponds to require range	$690.00/ea
4425-5	Anchor Points, rockbolt expansion type with eyebolt. For holes 13/8” – 15/8”	$23.00/ea
4425-6	Anchor points, groutable type, 9” rebar with eyebolt.	$26.00/ea
4425-6-1	Spare eyebolts.	$6.50/ea
02-250V6-E	Blue PVC Cable, 0.250” Dia, 2 twisted pairs, for the above	$0.79/ft
02-250V6-M	Blue PVC Cable, 0.250” Dia, 2 twisted pairs, for the above	$2.60/m
ROD-101-E	Flush coupled ¼” stainless steel rod, for the above.	$2.97/ft
ROD-101-M	Flush coupled ¼” stainless steel rod, for the above.	$9.74/m
ROD-103-E	¼” graphite rod. Specify end/coupling type, Swagelok (SWG-235) or threaded M/F (ROD-103-T)	$6.67/ft
ROD-103-M	¼” graphite rod. Specify end/coupling type, Swagelok (SWG-235) or threaded M/F (ROD-103-T)	$21.88/m
ROD-104-E	Continuous ¼” fiberglass rod, for the above	$2.61/ft
ROD-104-M	Continuous ¼” fiberglass rod, for the above	$8.55/m
SWG-235	SS-400-6 ¼” T Union	$17.55/ea
ROD-103-T	Threaded M/F coupling for graphite rod.	$34.90/ea

Table F14: Quotes for Digital Ultrasonic Thickness Gage from OLYMPUS America Inc.,

Item	P/N	Quantity	Description	Tax	Unit Price ($)	Discount	Net Unit Price ($)	Extended Price ($)
U8202413	38DLP-X-U-14E-E-EN	1	Digital Ultrasonic Thickness Gage with waveform verification and internal datalogger. Standard Kit Includes: Carrying Case, User's Manual, GageView interface program, USB cable, Lithium-ion rechargeable battery, B2 Couplant, and a Two-year limited warranty. The selected configuration is supplied with: Power supply rated for 50-60Hz, 100-240 Voltage Charger/AC adaptor, USA Power Cord, 2214E (U8880014) fi e step carbon steel reference block (0.100", 0.200", 0.300", 0.400", 0.500"), and 38DLP/RPC (U8779306) Rubber Protective Case with gage stand and straps. Lead Time : 1 business day(s)	N	3,830.00	7%	3,561.90	3,561.90
U8400019	M1036	1	Contact Transducer, 2.25 MHz, 0.50 in. Element Diameter, Standard Case Style, Straight BNC Connector Lead Time : 1 business day(s)	N	440.00	7%	409.20	409.20
U8400020	M103-SB	1	Contact Transducer, 1 MHz, 0.50 in. element size, Standard Case Style, Straight BNC Connector. Lead Time : 20 business day(s)	N	470.00	7%	437.10	437.10
U8800320	LCB-74-4	2	Cable. Standard LEMO to BNC. 4 ft RG-174 Lead Time : 1 business day(s)	N	56.00	7%	52.08	104.16

Subtotal: $4,512.36
Tax (0%):
Grand Total (USD): $4,512.36

Table F15: Quote for Digital Ultrasonic Thickness Gage from OLYMPUS America Inc.,

Item	P/N	Quantity	Description	Tax	Unit Price ($)	Extended Price ($)
Q0500181	EP6LT-UE	1	EPOCH 6LT Digital Ultrasonic Flaw Detector, Lemo 00 connectors with dual probe auto-recognition pin, USA Power Cord, English Manual. Standard software features include: Full Screen portrait or landscape A-scan mode, Dynamic DAC/TCG, Onboard DGS/AVG, Curved Surface Correction, Manual PRF Control from 10Hz to 2000Hz, Single-Shot Measurement at all PRF Rates, Tunable Square Wave Pulser, Basic Digital Receiver Filters, Auto 80%, 5 User-Customizable Measurement Displays, Soundpath Leg Grid Display Mode, Internal Alphanumeric Datalogger with Expanded File Types, Multiple Report Output formats, and Editable Parameters. Instrument package includes: Color LCD with multiple color schemes and variable brightness control, EPOCH 6LT Calibration Certificate, Lithium Ion rechargeable battery, Wrist Strap, and Transport Case. **Lead Time : 1 business day(s)**	N	6,250.00	6,250.00
U8400019	M1036	1	Contact Transducer, 2.25 MHz, 0.50 in. Element Diameter, Standard Case Style, Straight BNC Connector **Lead Time : 1 business day(s)**	N	440.00	440.00
U8400020	M103-SB	1	Contact Transducer, 1 MHz, 0.50 in. element size, Standard Case Style, Straight BNC Connector. **Lead Time : 20 business day(s)**	N	470.00	470.00
U8800320	LCB-74-4	2	Cable. Standard LEMO to BNC. 4 ft RG-174 **Lead Time : 1 business day(s)**	N	56.00	112.00

Subtotal : $7,727.00
Tax (0%):
Grand Total (USD): $7,727.00

Appendix G

Summary of the Progress on Initial Numerical Modeling of Circular Pipe Using ABAQUS

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Introduction

The works for project “Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits” are underway at CUIRE. This report deals with the numerical modeling of the soil box tests that will be performed over the course of this project. It is imperative that the numerical modeling approach used is capable of simulating the real-life/field conditions appropriately else, the modeling just becomes an exercise and is of no real use. Therefore, the first step in any numerical modeling/simulation approach is to prove the validity of the approach used i.e., model verification. This can be achieved in a number of ways.

The most reliable and widely used method of model verification is to compare the results from the simulation to the results from a real-life experiment or field observation data. For the purposes of this project, the lab test results of different material properties and the data from soil box tests are not yet available and hence cannot be used for the purpose of validating the modeling approach. However, there have been previous studies at The University of Texas at Arlington where tests on concrete circular pipes, which are also the point of interest in this project, were carried out.

The results of these tests are available in the PhD thesis “Evaluation of Structural Capacity of Epoxy-Coated Concrete Pipes and Its Interaction with Soil” by Elmira Riahi, 2016. The test performed was the Three Edge Bearing Test on concrete pipe specimen according to ASTM C497. An Abaqus model was created to perform FEM modeling of this test. The results of this model will be compared to the experimental results presented in the thesis and hence be used to verify the modeling approach for circular pipes. Once the approach is verified, the model will be further developed to simulate the conditions of the soil box test on cementitious and polymeric culverts. Figure G1 shows the flow chart representing work flow for FEM modeling of circular and arch culverts buried in soil.

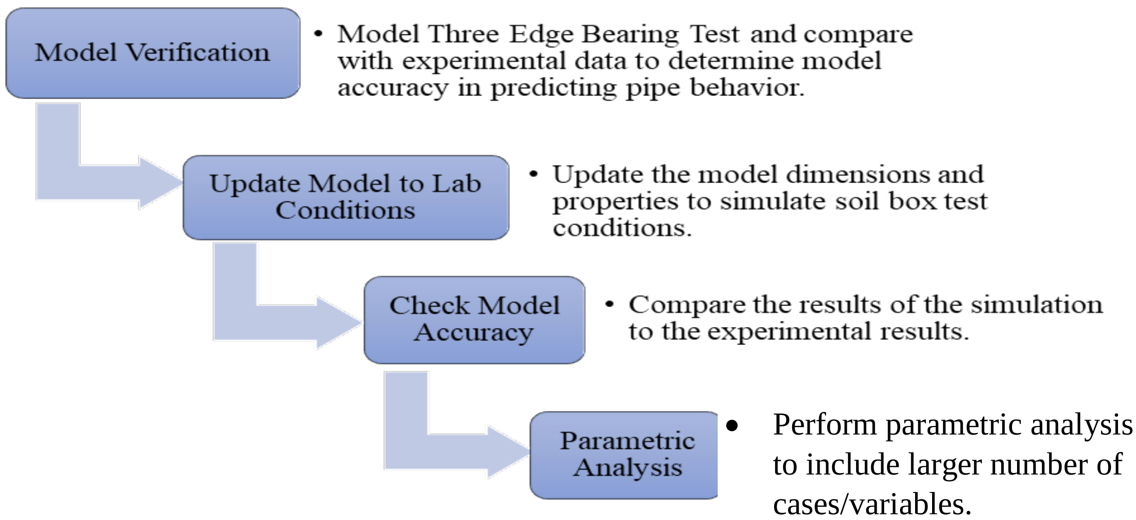

Figure G1: Steps for Finite Element Modeling of SAPL

Therefore, this report details the 2-D finite element modeling of three edge bearing test (D-Load test) of a reinforced concrete pipe using Abaqus 6.14. The properties and materials for the pipe model have been taken from PhD thesis by Elmira Riahi titled “Evaluation of Structural Capacity of Epoxy-Coated Concrete Pipes and Its Interaction with Soil”. The detailed analysis steps and conditions used have been presented in the following sections.

Objective

- To prepare a finite element model simulating D-Load testing of reinforced concrete pipe.
- Verify the modeling approach by preparing a non-reinforced concrete pipe model and comparing with the test results presented in the thesis.

The Three Edge Bearing Test

The Three Edge Bearing test is a standard test, developed for concrete pipe design (indirect design) and evaluation of structural behavior at Iowa State University in 1960s (Tehrani 2016). The D-Load obtained through this test characterizes the load carrying capacity of a buried pipe. The American Concrete Pipe Association defines D-load as “the supporting strength of a pipe loaded under three-edge-bearing test conditions expressed in pounds per linear foot of inside diameter for horizontal span”. For a pipe with inner radius R and span L,

$$D - load\ (lb/ft./ft.) = \frac{P\ (lb)}{R\ ft. \times L\ ft.} \ldots\ldots\ldots\ldots \qquad G1$$

The typical setup for D-load test of a pipe is shown in Figure G2. The pipe is placed between two strips at the top and bottom in the axial direction. The bottom strip has two bearing strips that support the pipe and the load is applied through the top strip.

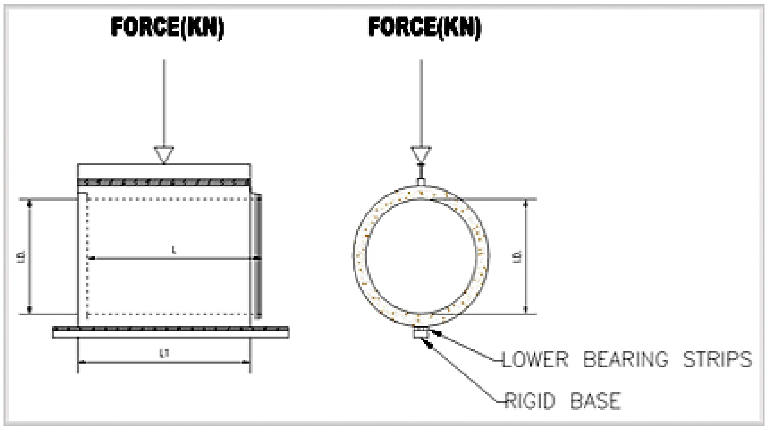

Figure G2: Three edge bearing test setup
Source: http://www.nagadi.com/concrete_pipes

To simulate the D-load test in Abaqus, two approaches are available: load controlled, and displacement controlled. In the load-controlled method, the pipe model is subjected to a certain load and its response to that load is recorded. However, this method has a disadvantage in that for a single value of load or pressure, the pipe may have two different values for displacement (pre- and post-peak condition). Therefore, we cannot be certain the structure has reached peak state while using load-controlled approach. There is also the risk that the load specified is too great for the structure to handle causing it to fail before the specified load is reached and hence disrupting the analysis.

The other approach, and the one that has been adopted in this model, is the displacement control approach. In this approach, the structure (pipe) is subjected to a small value of displacement that is expected in the post-failure state of the structure. Since every displacement/strain in a stress-strain curve is unique as the test progresses, the risk of not reaching the peak state is eliminated using this method.

Laboratory Test

A three-edge bearing test was performed per ASTM C497 to evaluate the behavior of the lined and unlined concrete pipes at The University of Texas at Arlington as part of the thesis (Riahi 2016). The main purpose of this test was to determine the effect of applying epoxy liners on the ultimate strength of lined precast circular pipes. An unlined pipe was also tested to provide a comparison base. The 16 concrete pipes were dry precast pipes manufactured according to ASTM C76 which are typically used for storm sewer and roadway drainage applications. The pipes had an inside diameter of 24” with 3” thickness and 4’ length. A hydraulic jack was used to apply load with the maximum loading rate of 16 kN/min. Two load cells were installed to record applied load during the loading process. After the testing, the process was simulated in ABAQUS model and the load deflection curve from the simulation and the experimental results were compared. Figure G3 shows this comparison.

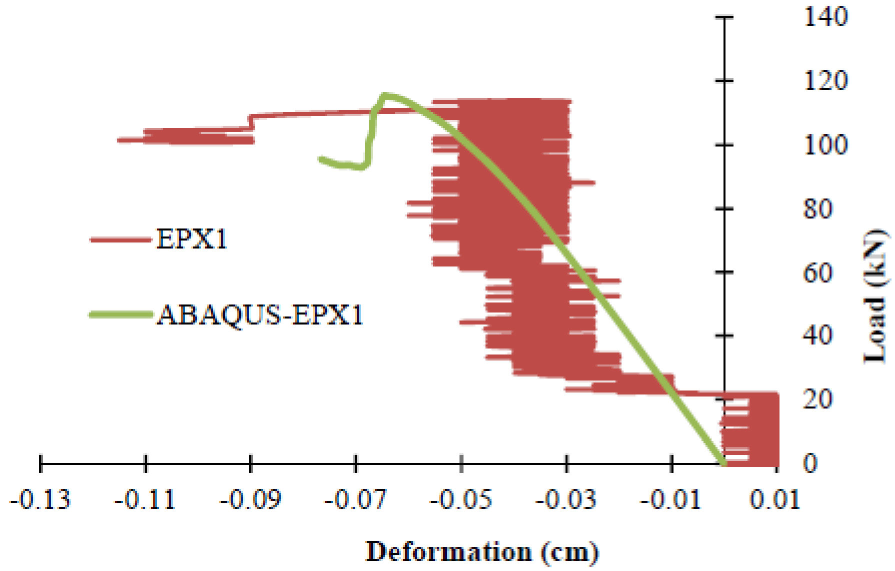

Figure G3: Load deformation curve for lined concrete pipe (Riahi 2016)

FEM Modeling

The FEM modeling of any system can be broadly divided into two general steps: defining a model geometry that represents the real-life scenario and defining properties and material models that can accurately describe the behavior of different parts of the model. The other important aspect is to ascertain that the model and loading systems behave the same way as they would in a real-life situation. This is achieved by defining proper boundary conditions and interaction between different parts of the model. All these required steps are discussed in the following sections.

Model Geometry

The geometry of the Abaqus model is shown in Figure G4. The model geometry consists of three parts:

1. The concrete pipe.
2. The circumferential reinforcement.
3. The top and bottom bearing plates.

Concrete Pipe: The concrete pipe is modelled as a 2-D deformable shell element with 4-node bilinear plane stress quadrilateral CPS4R. Its inner radius is 24" and wall thickness is 3". The pipe is tied to the top and bottom bearing plates at the contact nodes.

Circumferential Reinforcement: ASTM Grade-60 steel bars are used as circumferential reinforcements for the pipe. Two layers of rebars of radius 25" and 36" are used such that they have 1" covers from the walls in both the inner and outer surface. The rebars are modelled as 2-D planar deformable truss element T2D2. They have $0.08in^2$ cross-sectional area. The rebars are modelled as an embedded section within the pipe.

Bearings: Two (1"x0.1") steel strips are used as bearing plates in the top and bottom surfaces. The bearings are modelled using 2-D planar deformable elements with 4-node bilinear plane stress quadrilateral (C3D8R). The top bearing has one restricted degree of freedom and can only move in the vertical direction. The bottom bearing has both degrees of freedom restrained.

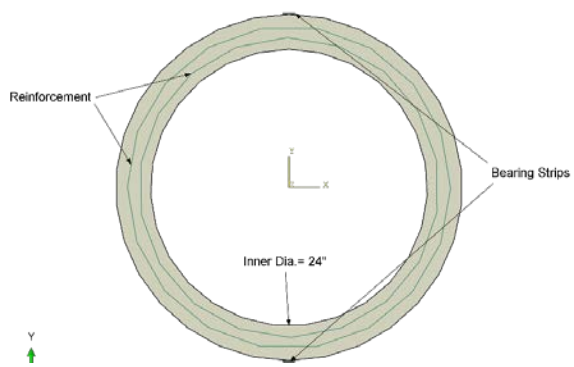

Figure G4: Model geometry

Material Properties

Concrete: Concrete with modulus of elasticity (E) 30GPa and Poisson's ration 0.2 has been used in the analysis. The Concrete Damage Plasticity model which is a widely used model to describe the plastic behavior of concrete is chosen to represent the concrete behavior and degradation under compression and tension. The following values for the parameters were used in the analysis:

Table G1: Parameters for Concrete Damage Plasticity Model (Tehrani 2016)

Parameters	Values
Dilation Angle	38
Eccentricity	0.1
f_{bo}/f_{co}	1.16
K	0.667
Viscosity parameter	0.000001

Steel: A regular ASTM grade 60 steel was used for reinforcement. Following properties were used in the model:

- Density: 7,800 kg/m^3
- Young's Modulus: 200 GPa
- Poisson's Ratio: 0.3
- Yield Strength: 400 Mpa

Boundary Conditions

Defining a proper boundary condition is done by restraining the degrees of freedom of different parts of the model so that they move in the way that is expected in the real-life situation. For the three-edge bearing test, the pipe is held axially between two bearing strips and load is applied perpendicular to the axis of the pipe. Hence, the upper plate is expected to move in downwards direction while the lower bearing strip is supposed to support the entire system. Therefore, the following boundary conditions are applied to the model:

- Upper Bearing: 1 DoF restrained, can move in vertical direction.
- Lower Bearings: 2 DoF restrained.
- Pipe: 0 DoF restrained.

Contact and Interaction Properties

The contact nodes between pipe and bearings are tie constrained so that there is no slip between the bearing strips and the pipe.

Analysis Results

After constructing a model, defining material properties and providing appropriate boundary conditions and interactions, the model is ready to be analysed by the FEM software. In this analysis, general static method of analysis is used to examine the pipe behavior. As previously stated, displacement control has been used to simulate the test and as such, no load is applied to the model. Instead, a displacement of 0.1" was applied to the top bearing.
The vertical reaction forces at the bottom bearing strip have been used to calculate the D-Load and the D-load vs Displacement is shown in Figure G5.

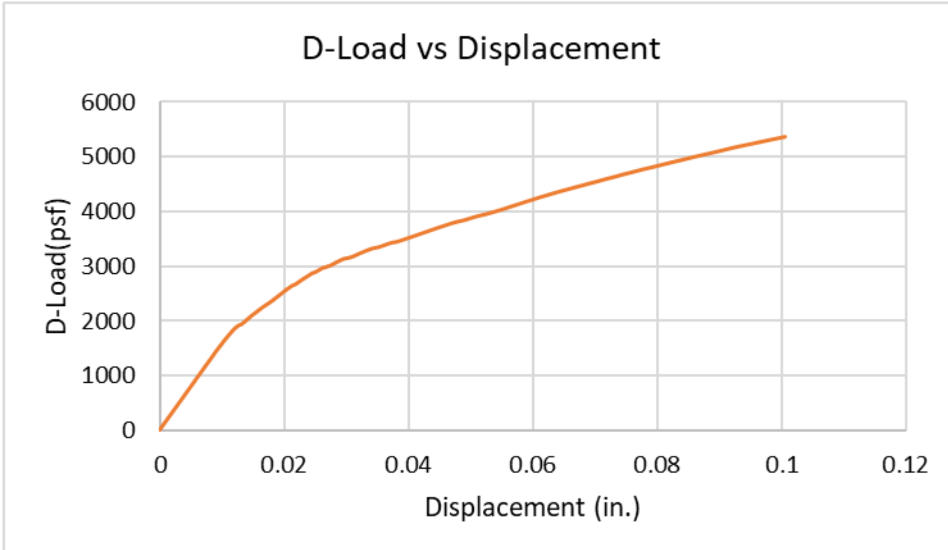

Figure G5: D-Load vs Displacement Plot

The pipe shows linear behavior to a certain point after which, the curve changes slope indicating the pipe has moved on to plastic state. For a non-reinforced pipe, the plastic stage is expected be characterized to with decrease in stress/load and increase in displacement. However, since there are two layers of reinforcement in the current model, the stress decrease in the plastic state is not prominent. Figure G6 shows the plastic strain in the pipe as the load in the pipe went beyond the elastic state. It shows that the pipe first starts to experience damage (cracks) at the crown and invert.

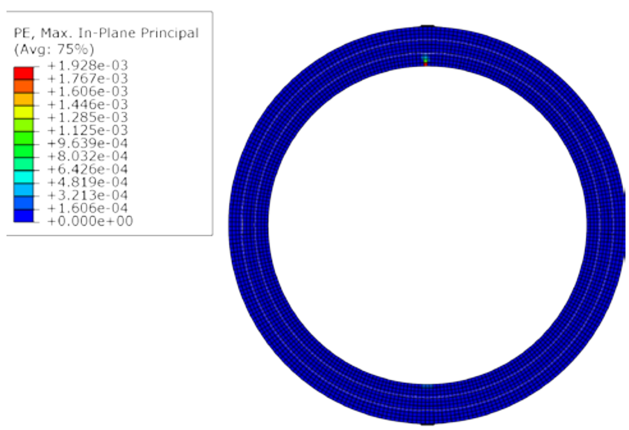

Figure G6: Plastic strain in the pipe just beyond the elastic limit.

Further Steps

The next step in performing the numerical analysis will be to verify the modeling approach by modifying the current model for non-reinforced concrete pipe and comparing the results with the experimental results provided in Riahi 2016.

Finally, upon verifying the modeling procedure, the model will be further modified to study pipes buried in soil.

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