Trenchless Technology Research at UTA

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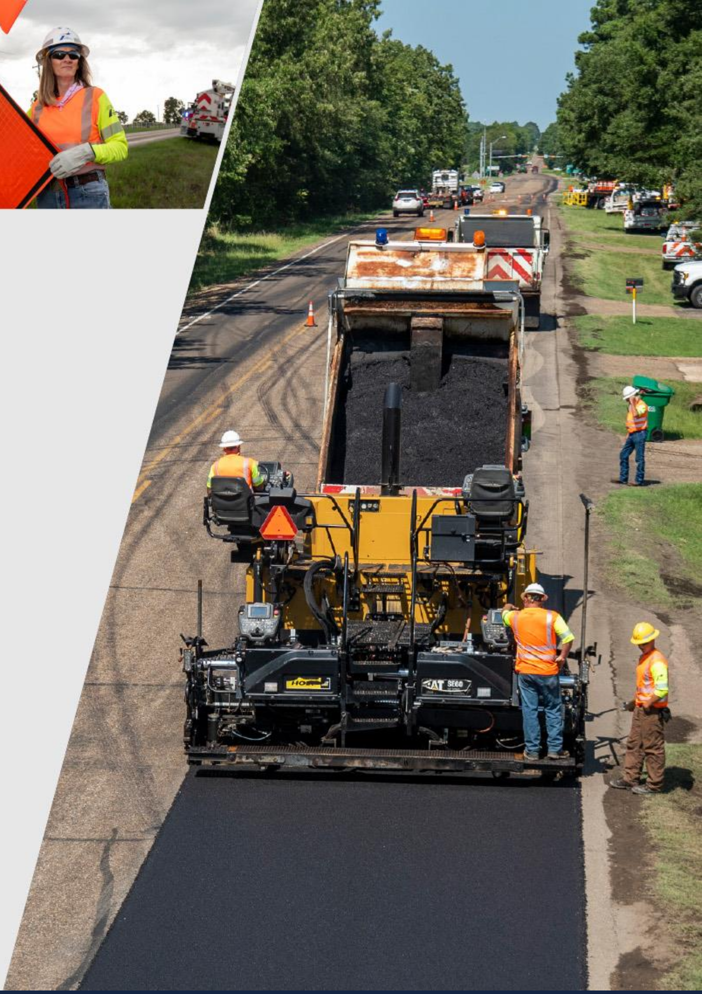
Enhancing Quality of Life for All Texans

December 5, 2022



TxDOT Utility Week Conference

Wednesday, November 2, 2022

Inspecting and Maintaining

Table of Contents

Hot Off The Press!!

Publisher: McGraw-Hill

1. Trenchless Technology: Pipeline and Utility Design, Construction & Renewal, Second Edition (2022).
2. Pipeline Renewal and Asset Management (2016).
3. Trenchless Technology: Planning, Equipment & Methods (2013).
4. Trenchless Technology Piping – Installation and Inspection (2010).
5. Trenchless Technology: Pipeline and Utility Design, Construction & Renewal (2005).

Introduction and Background

- The U.S. road over 4 million miles of network in total length, making it the world's longest and biggest road network with millions of culverts hidden underneath (Najafi, 2008).

- A large proportion of underground infrastructure, including culverts, were installed in the 1950s and 1960s during a period of rapid economic growth (Kaushal, 2019).

Culvert Failure; Overflows

Culvert Failure; Blockages

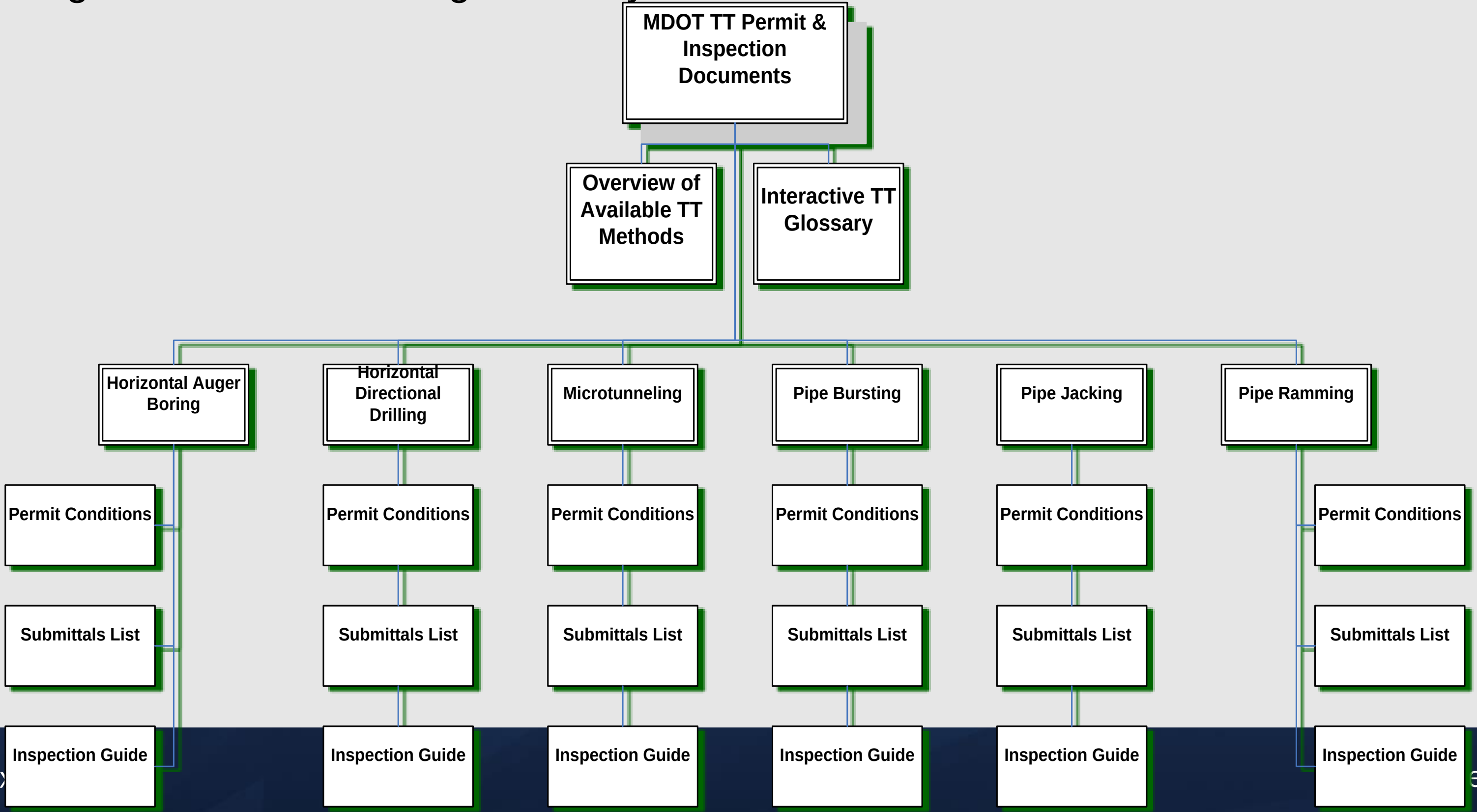
Culvert Failure; Structural Failure

Introduction & Background (Cont'd)

- DOT Concerns for Borehole Stability:
  - Arkansas Field Evaluation – 1993
  - HDD Operator Training and Certification Program – 1998
  - Caltrans HDD Inspector Training and Certification – 1999
  - MoDOT Trenchless Construction Methods and Implementation Support – 2005
    - Preparation of Construction Specifications, Contract Documents, Field Testing, Educational Materials, and Course Offerings for Trenchless Construction

Introduction & Background (Cont'd)

- MDOT Permit Conditions, Submittal Requirements, and Inspection Guides for Trenchless Technologies in the MDOT Right of Way – 2005

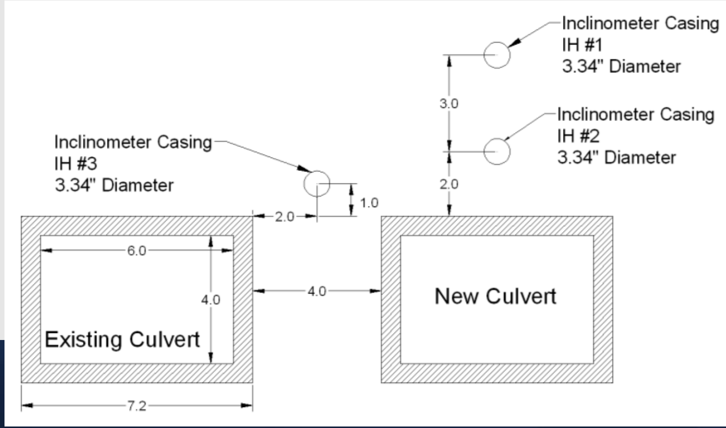


Introduction & Background (Cont'd)

- Hydraulic Analysis of a Corrugated Metal Pipe (CMP) CIPP-Lined Culvert
  - Performed hydraulic analysis to quantify flow capacities for a twin, CIPP lined, 84-inch equivalent diameter corrugated metal plate arch culvert under Interstate I-196 near South Haven, Michigan.
  - The 100-year storm flow was used together with the lined culverts geometries
    - CIPP lining reduced the pipe's roughness coefficient (n)
    - Produced an overall improvement in the total energy loss (H);
    - Total loss for the CMP was 15.75 ft while it was reduced to 7.95 ft for the CIPP lined pipe.

Introduction & Background (Cont'd)

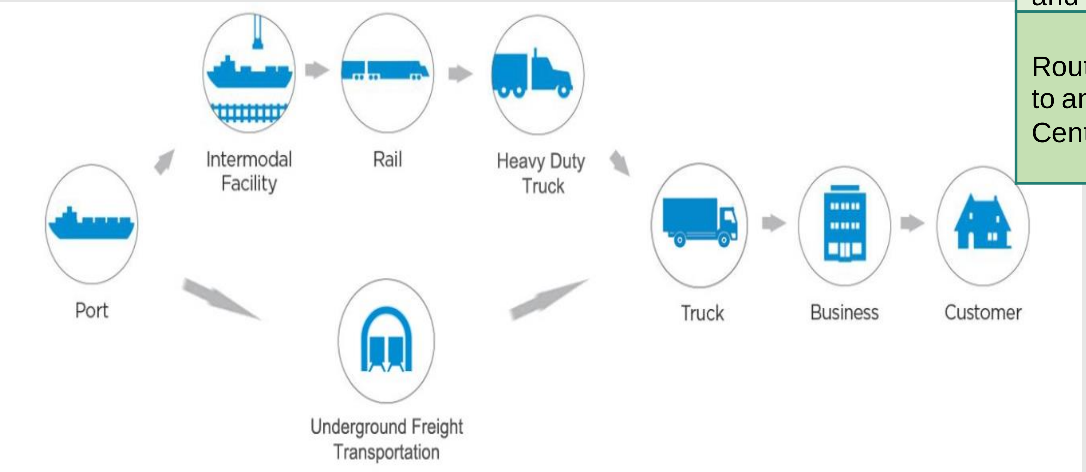
- TxDOT Project 5-9042-01: Validation of Culvert Standards SCP-MD and Jack and Bore Issues – 2013
    - The improper use of boring and tunneling technology to cross highways may results in pavement heave, settlement or other damage to existing utilities causing minor to major user delays.
        - To describe Item 476 in the Box Culverts Precast and Miscellaneous Details (SCP-MD) standard.
        - To provide definitions, references, documentations, forms and inspection required for these permitted operations identified and/or appended to this guide.



Introduction & Background (Cont'd)

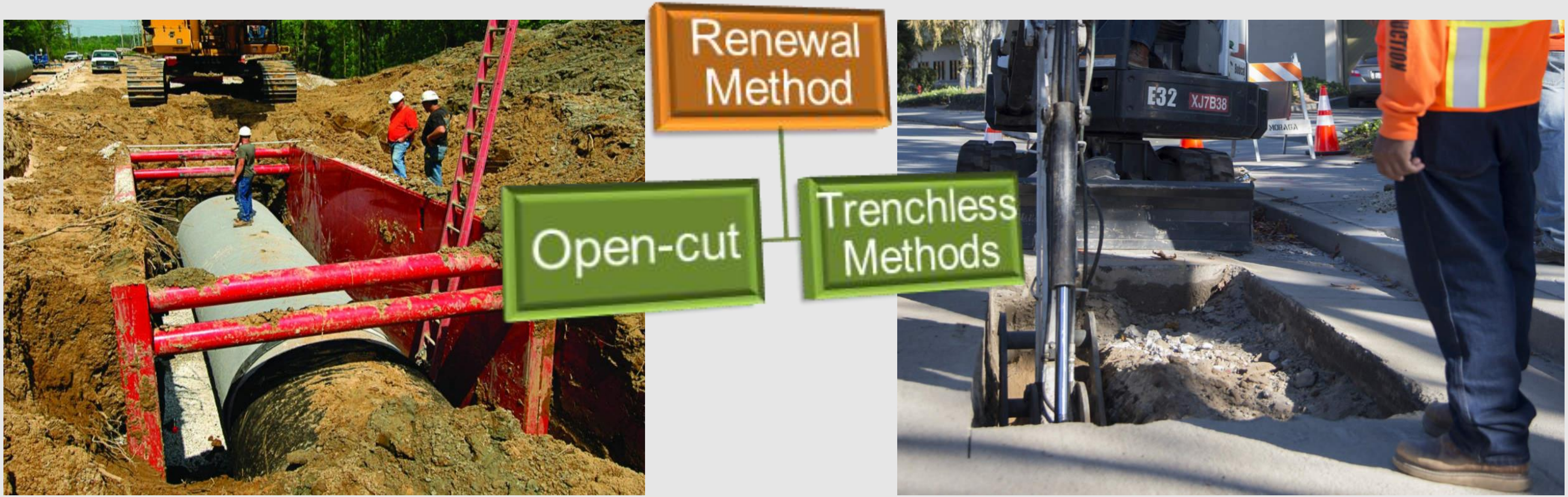
- TxDOT Integrating Underground Freight Transportation into Existing Intermodal Systems – 2016

Route	Length (miles)	Size of Tunnel (Outside Diameter, ft)
Route 1-Port of Houston to Dallas at Lancaster	250	25, 16
Route 2-Border between the U.S. and Mexico in Laredo, TX	4	25
Route 3-Port of Houston to an Inland Satellite Distribution Center in Baytown	15	25, 17.4, 13

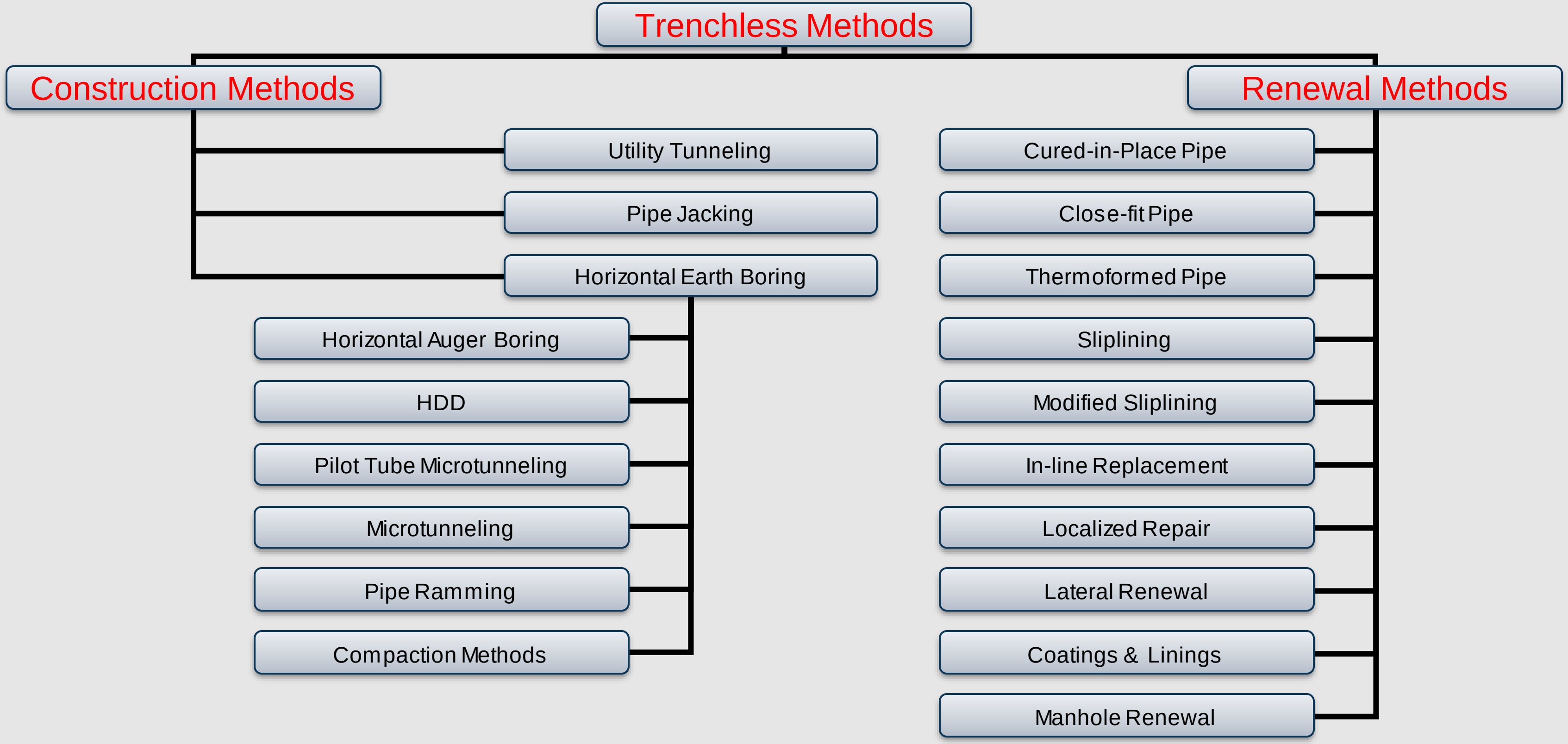


Introduction (Cont'd)

- Culverts are renewed/replaced by two major methods:



Introduction (Cont'd)

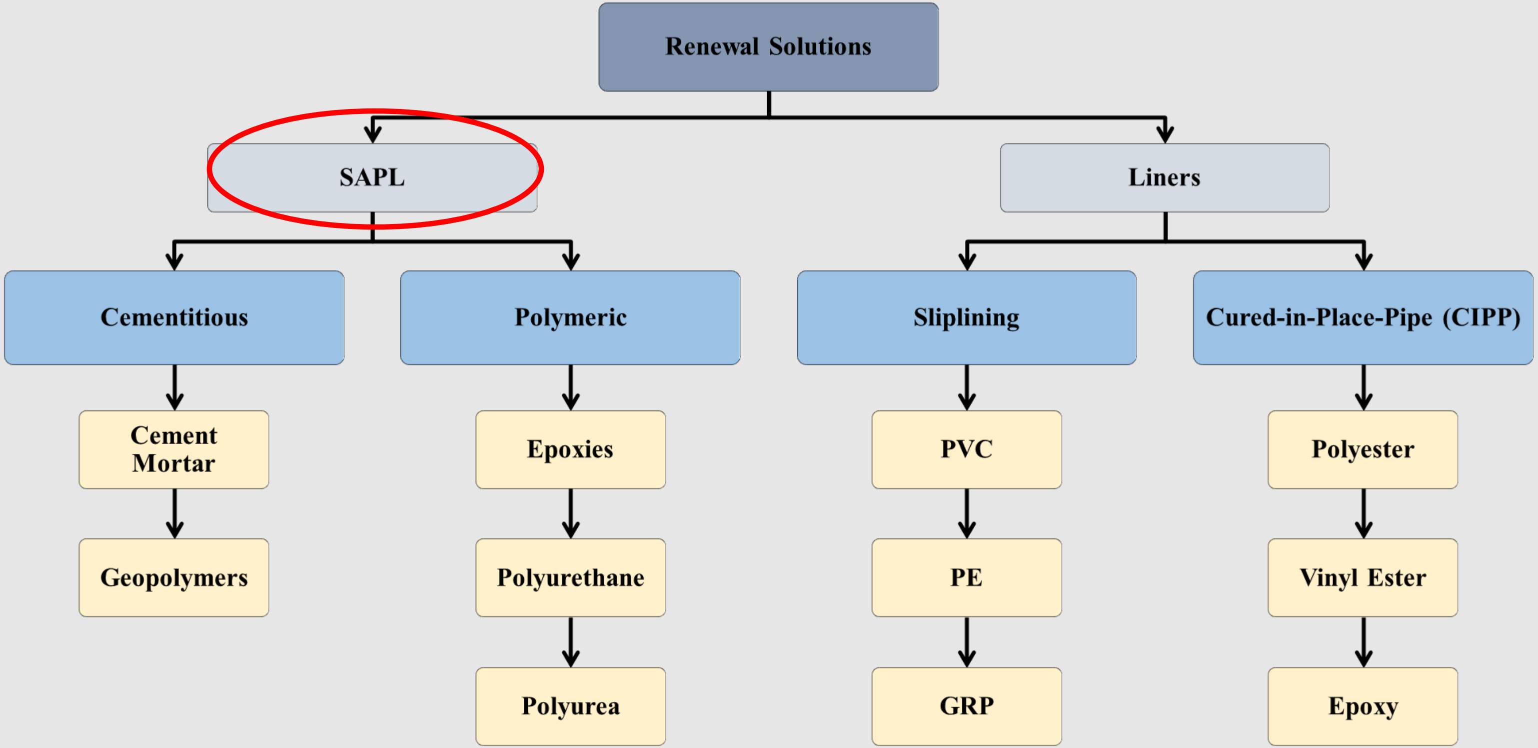


Introduction (Cont'd)

Main Trenchless Renewal Solutions

- **Sliplining**
  - PVC
  - PE
  - GRP
- **Cured-in-Place-Pipe**
  - Polyester
  - Vinyl Ester
  - Epoxy
- **Modified Sliplining**
- **Spiral Wound Lining**
- **Spray Applied Pipe Lining**
  - Cementitious
    - Cement mortar
    - Geopolymers
  - Polymeric
    - Epoxies
    - Polyurethane
    - Polyurea

Introduction (Cont’d)



Introduction to NCHRP Pool - Funded Project on Spray Applied Pipe Liners (SAPL) (2018 – 2021)

Scope

- Large diameter CMP culverts between 36 – 120 in.
- Cementitious and Polymeric SAPLs
- Structural renewal

What is SAPL

- A structurally spray applied pipe lining (SAPL) that inhibits further deterioration and can structurally renew severely damaged culverts and drainage structures.
- Installation: Manual, Spin Caster, Robot

Participating DOTs

ODOT (Project Leader)

- DelDOT
- FDOT
- MnDOT
- NYSDOT
- NCDOT
- PennDOT

SAPL Research Objectives

1. To develop **Design Equations** for structural renewal of gravity storm water conveyance culverts using spray-applied pipe linings (SAPL) for both **cementitious** and **resin-based** materials and for **circular** and **arch** shapes.

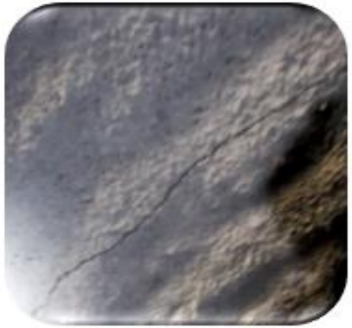
2. To develop **Performance Specifications** allowing contractor innovation and utilization of the most current products and techniques.

SAPL Research Tasks

Task	Description
1	Field Inspection
2	Literature Search
3	Survey of US DOT's and Canadian Agencies
4	Soil Box Testing
5	Finite Element Modeling (FEM)
6	Additional Reinforcement
7	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design
8	Comparison of Construction and Environmental costs for SAPL, Sliplining and CIPP
9	Review the Cured in Place (CIPP) Design Equations
10	Preparation of Structural Design Equations
11	Preparation of Performance Construction Specifications

Task 1 – Field Inspections for Participating DOTs

- Common Cementitious SAPL issues:
  - Circumferential crack
  - Fracture
  - Infiltration weeper
  - Efflorescence
  - Rust staining
  - Non-uniform thickness



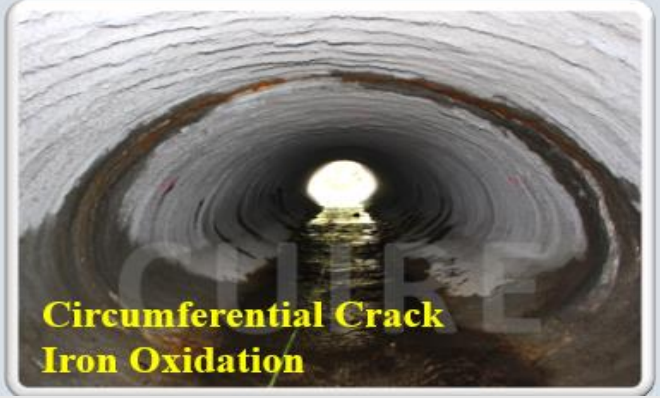
Fracture

Circumferential Crack

Infiltration Weeper

Task 1 – Field Inspection for Participating DOTs (Cont'd)

Task 1 – Field Inspection for Participating DOTs (Cont’d)



Task 2 – Literature Review

- Ward, D.C. (2018): Recommended additional research and synthesis of structural testing and analysis of SAPL
- Moore and García (2013): Deteriorated CMPs with SAPLs survived H-20 and HL-93 loads.
- Royer and Allouche (2016): Recommended a minimum thickness of 1 in. for pipes smaller than 54-in. and a minimum of 1.5-in. for larger pipes
- Mai et al. (2013): Higher deflection occurred at the lower cover with single axle loading configuration
- Sargand et al. (2015): Under service load, there is no difference between paved and original CMP

Task 3 – Survey of US DOTs and Canadian Agencies

Issues Before SAPL installation:

Decision Making Priorities	Rank
Durability	1
Hydraulic Capacity Due to Liner	2
Impact to Travelling Public	3
Project Economics	4
Minimum Thickness	5
Contractor Experience	6
Project Schedule	7
Others: Fish Passage, Host Pipe Condition, Feasibility, and Benefit/Cost Ratio	8

Issues During SAPL Installation:

Protocol for QA/QC

- No official direction
- Testing requirements are included in new contract
- No QA/QC. Standards are under development
- no additional safety protocols for SAPL projects

Issues After SAPL Installation:

Problems faced

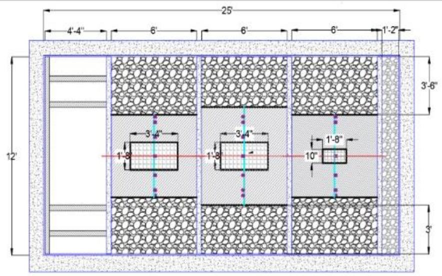
- Longitudinal and circumferential cracking
- Hairline cracking with rust bleeding through cracks
- Cracking at joints
- Spalling
- Delamination
- Rust-through
- Slumping from crown

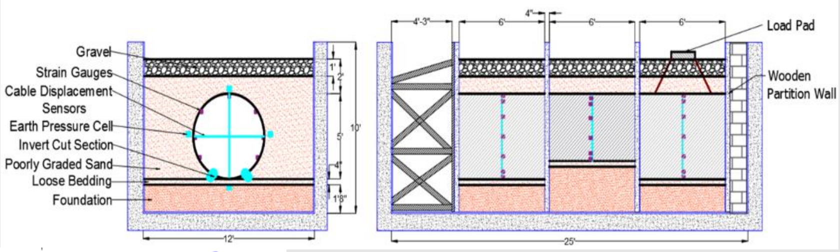
Task 4 – SAPL Soil Box Testing -- Pipe Sample Dimensions

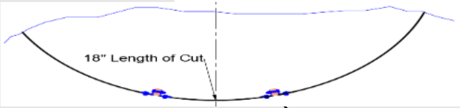
Pipe Samples and SAPL Thicknesses	
60" Circular	Host Pipe
	1.00" Cementitious
	2.00" Cementitious
	3.00" Cementitious
47"*71" Arch	Host Pipe
	1.00" Cementitious
	2.00" Cementitious
	3.00" Cementitious

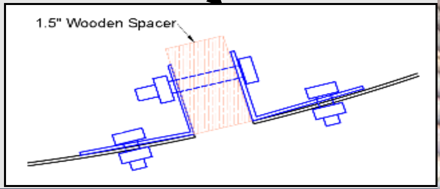
Task 4 – Soil Box Testing (Cont'd)

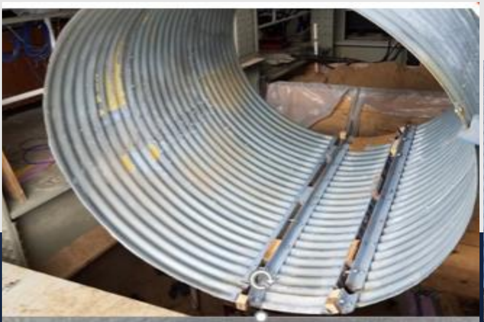
- Control tests
  - Intact CMP
  - Circular invert-cut CMP
  - Arch invert-cut CMP
- Circular & Arch Cementitious, Thicknesses 1, 2 and 3 in.
- Circular & Arch Polymeric, Thicknesses 0.25, 0.5 and 1 in.

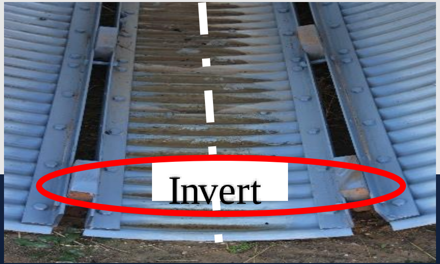












Task 4 – Material Properties & Soil Box Testing Results (Cont'd)

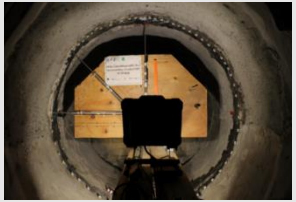
- Polymeric SAPL flexural modulus of **850,000 psi**, the averaged tensile stress of **8,600 psi**, and the elastic modulus of **329,000 psi**
- Average Cementitious SAPL compressive strength was **2,700 psi after 24 hours of curing**, **4,400 psi after 7 days**
- The polymeric circular SAPL renewed CMPs with **thicknesses** of **0.25 in., 0.5 in., and 1 in.** increased the ultimate load bearing capacity by **16.2%, 31.4%, and 80.8%,** respectively.
- The cementitious circular SAPL with thicknesses of **1 in., 2 in., and 3 in.** increased the ultimate load bearing capacity by **79.7%, 113.9%, and 174.7%** respectively.

Task 4 – Soil Box Testing -- Cementitious (Cont'd)

Arch Shape

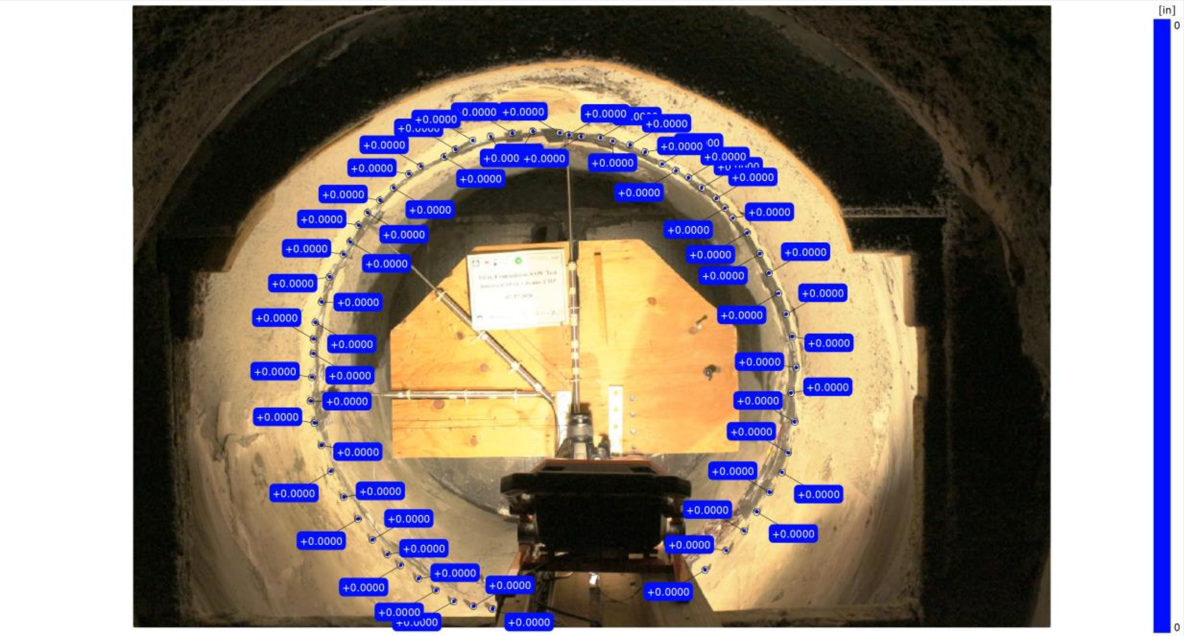
Before Load	After Load	
		3 in • Maximum Load: 67.84 kips
		2 in • Maximum Load: 55.16 kips
		1 in • Maximum Load: 46.5 kips

Circular

Before Load	After Load	
		3 in • Maximum Load: 109.7 kip
		2 in • Maximum Load: 85.42 kips
		1 in • Maximum Load: 71.76 kips

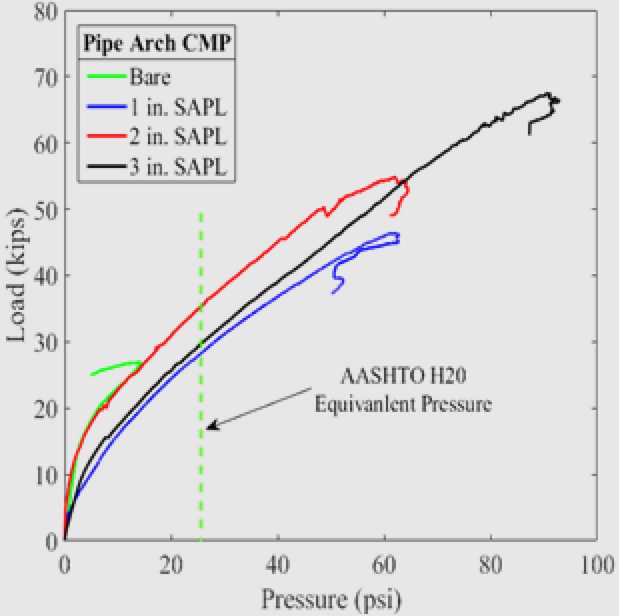
Task 4 – Soil Box Testing (Cont’d)

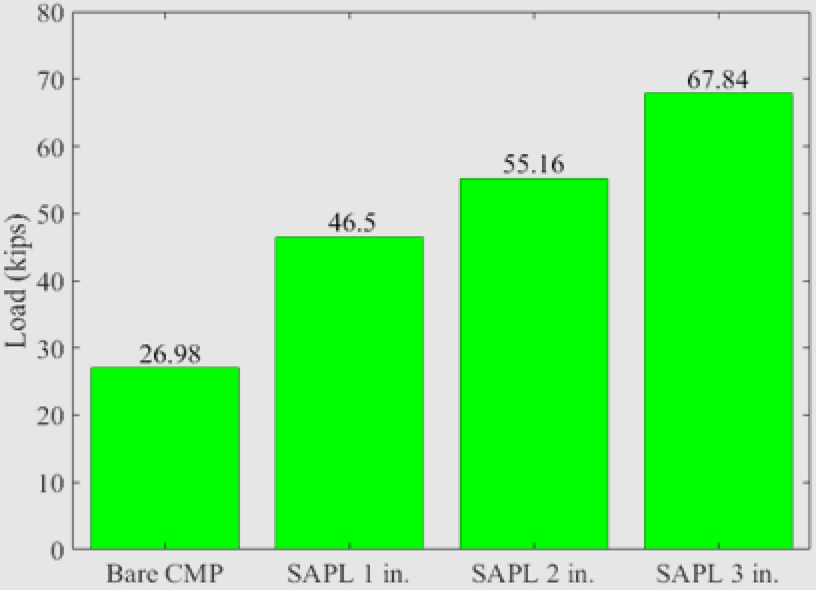
Cementitious - Circular Shape



Circular CMP with 3 in. Cementitious SAPL

Cementitious – Arch Shape

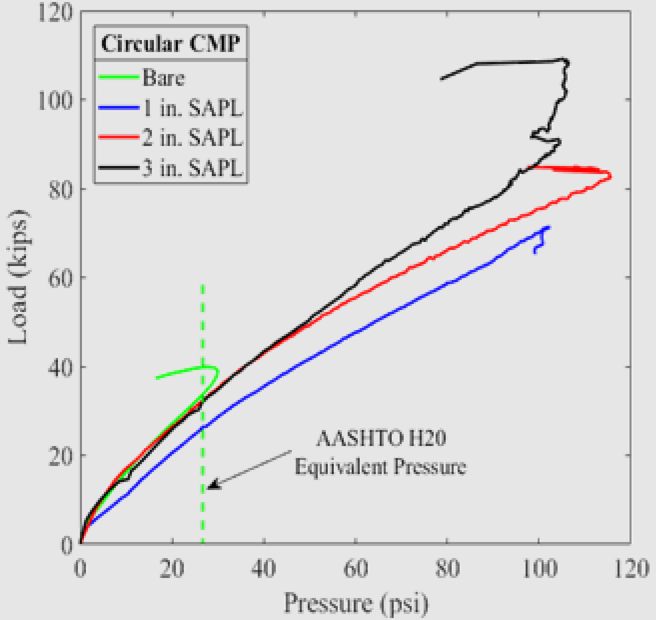


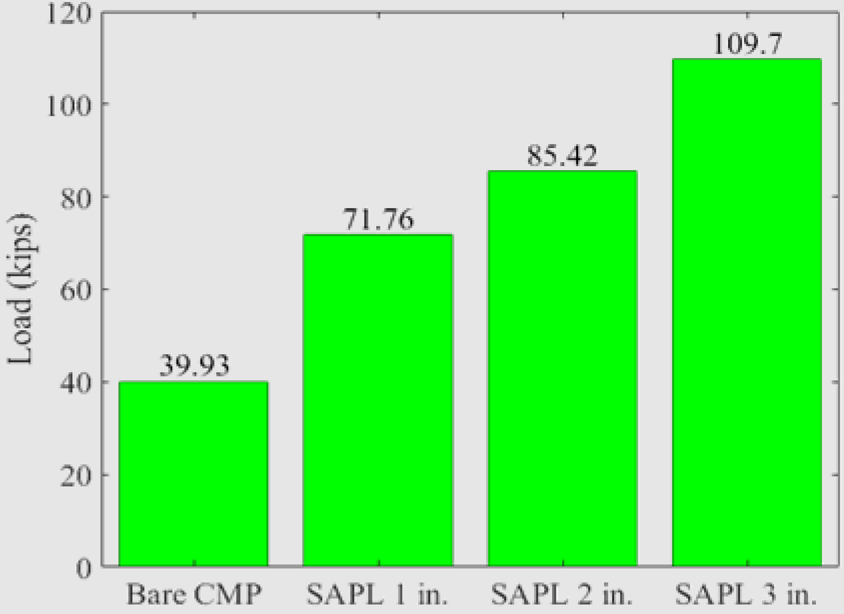


Invert-cut Pipe Arch CMP - Renewed with Cementitious SAPL

Task 4 – Soil Box Testing (Cont'd)

Cementitious - Circular Shape





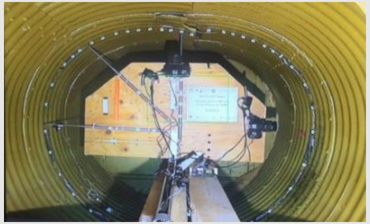
Invert-cut Circular CMP - Renewed with Cementitious SAPL

Task 4 – Soil Box Testing -- Polymeric (Cont'd)

Circular Shape

After Load

- 0.25 in. Polymeric SAPL
- Maximum Load: 38 kips

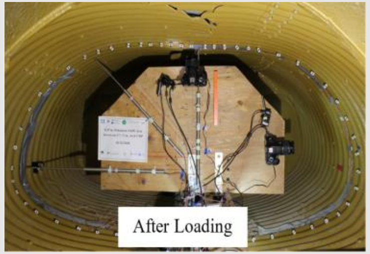


- 0.5 in. Polymeric SAPL
- Maximum Load: 44 kips

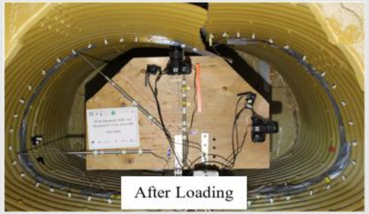
- 1 in. Polymeric SAPL
- Maximum Load: 66 kips

Arch Shape

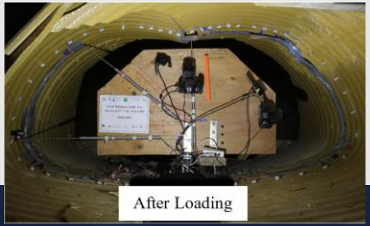
After Load



- 0.25 in. Polymeric SAPL
- Maximum Load: 32.2 kips

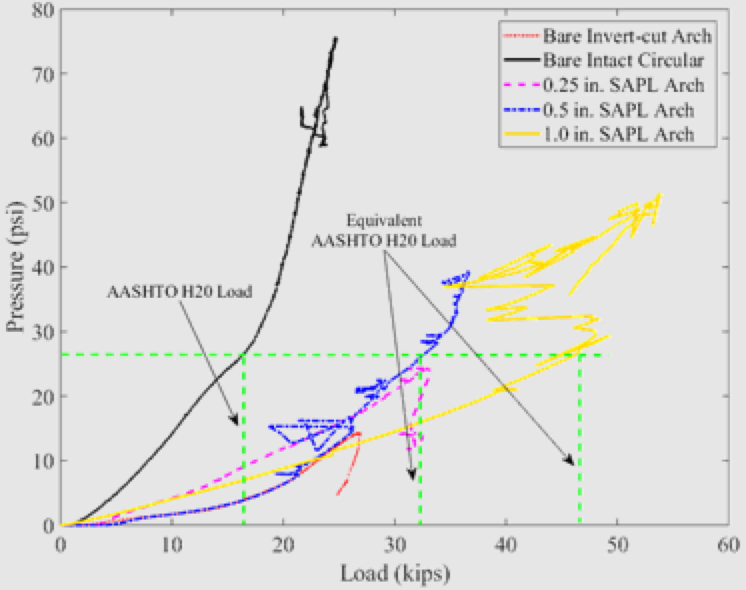


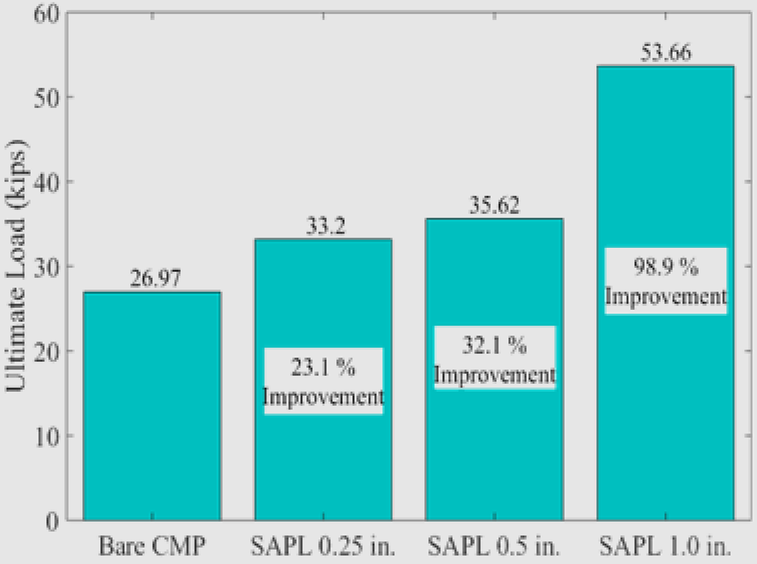
- 0.5 in. Polymeric SAPL
- Maximum Load: 35.5 kips



- 1 in. Polymeric SAPL
- Maximum Load: 54.0 kips

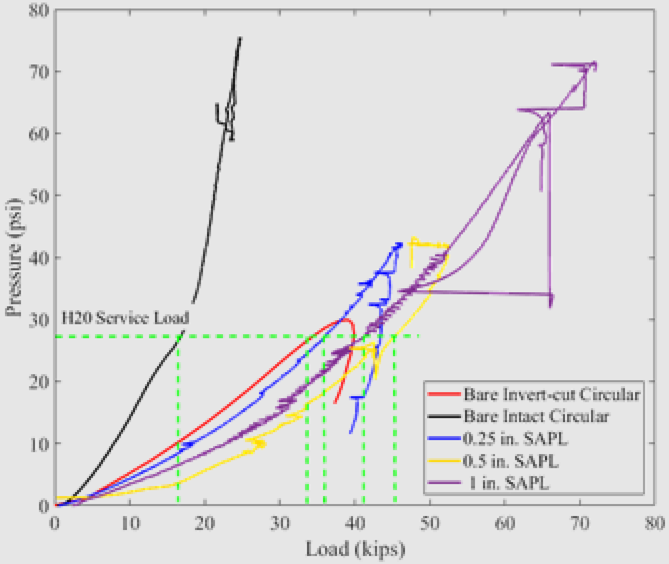
Polymeric – Arch Shape

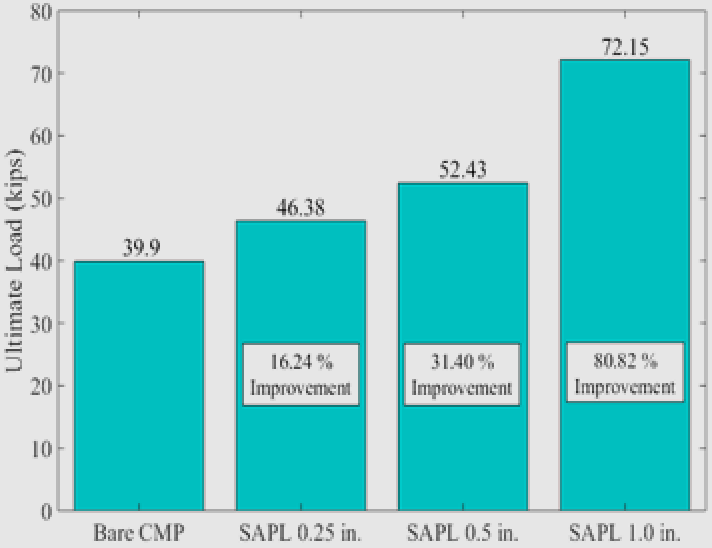




Invert-cut Pipe Arch CMP - Renewed with Polymeric SAPL

Polymeric – Circular Shape

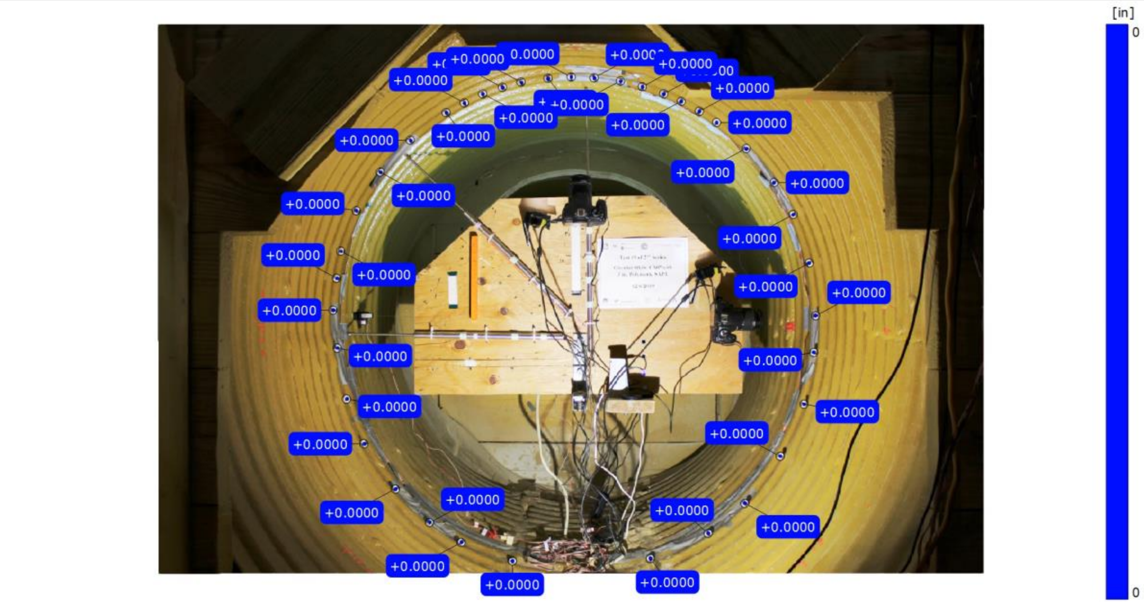




Invert-cut Circular CMP - Renewed with Polymeric SAPL

Task 4 – Soil Box Testing (Cont'd)

Polymeric – Circular Shape



Circular CMP with 1 in. Polymeric SAPL

Task 5 – FEM Modeling

Modelling the Intact CMP → Modeling the invert cut CMP → Update the Model to lined CMP (Polymeric and Cementitious) → Check Model Accuracy → Parametric Analysis

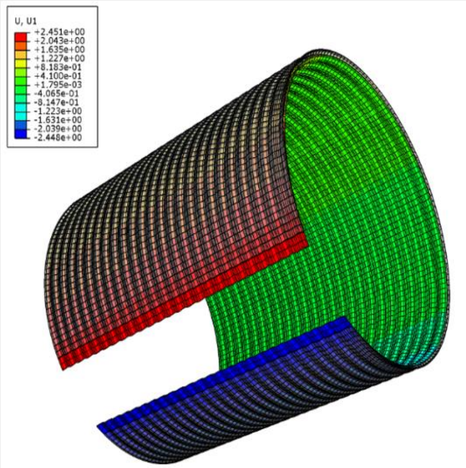
- Model intact CMP under soil box loading conditions

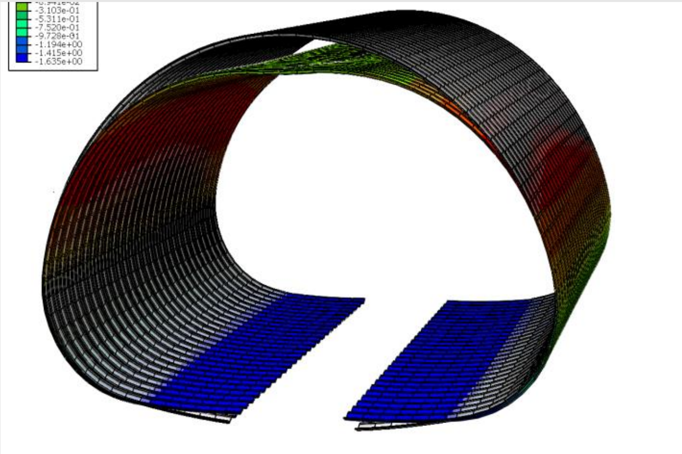
- Model "cut" bare CMP under soil box loading conditions

- Add SAPL to "cut" bare CMP

- Calibrate the model of cut-CMP with SAPLs with soil box testing

Removal of Invert





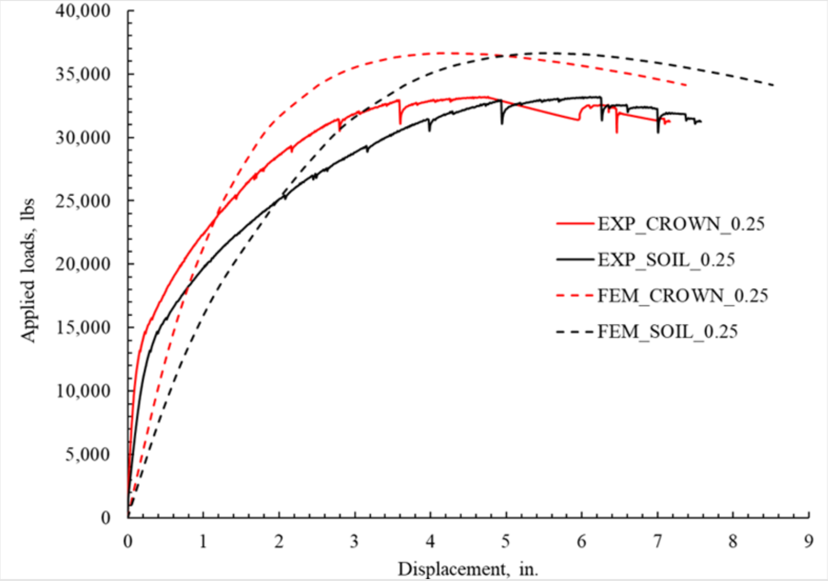
FEM model of circular (left) and arch CMP (right) with removed invert

FEM Results for Circular SAPL (Polymeric)

Comparison between Experiment and FEM results for 0.25-in. thick Circular SAPL

Description	1st plastic strain	1st Crack	Discrepancy Test vs. FEM (%)	Ultimate Load (FEM)	Ultimate Load (Test_	Discrepancy Test vs. FEM (%)
Crown Displacement (in.)	3.13	2.92	6.7	4.98	5.23	5.0
Soil Displacement (in.)	4.79	4.64	3.1	6.48	6.49	0.5
Load (kips)	44.40	41.3	6.9	46.37	45.78	1.2

Arch CMP results: 0.25-in. thick polymeric SAPL



Load Displacement plot at the crown of the liner and load pad

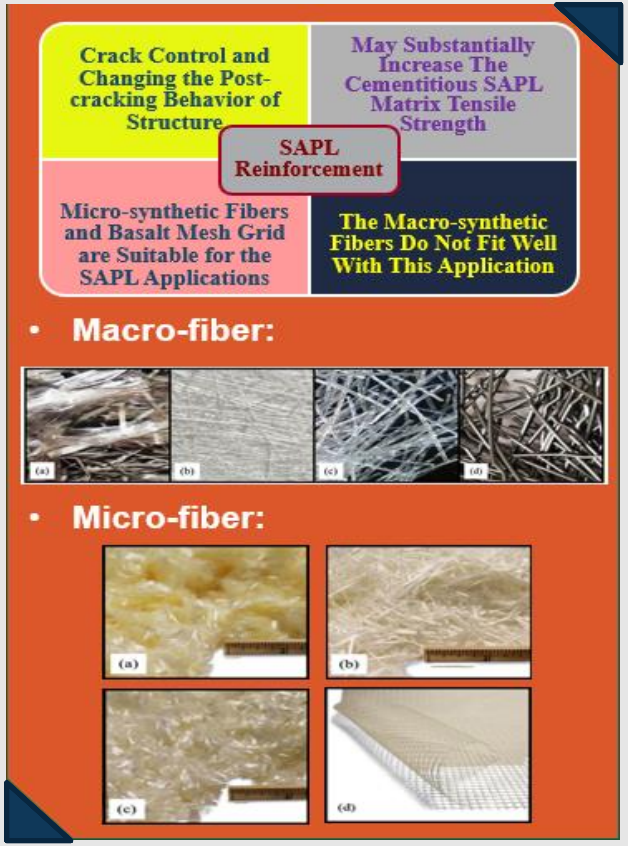
Task 5 – FEM Modeling (Cont'd)

Conclusions for Circular SAPL (Polymeric)

- The experimental and FEM results compared fairly within the discrepancy of less than 10% for the circular SAPL for most of the comparison.
- The rigidity of the CMP increases with the increase in the thickness of the SAPL. This leads to the sudden crack in the SAPL for higher thickness SAPL with small deformation in the CMP.
- The SAPL with more than 0.5-in. thick is successful in re-establishing the lost capacity of CMP due to the complete loss of the invert.

Task 6 – Additional Reinforcement

- The use of fiber reinforcements has many advantages, most importantly crack control and post-cracking behavior
- Fiber reinforcements may substantially increase the cementitious SAPL matrix tensile strength
- Fiber reinforcement can enhance the bond strength between the old substrate (host culvert) and SAPL

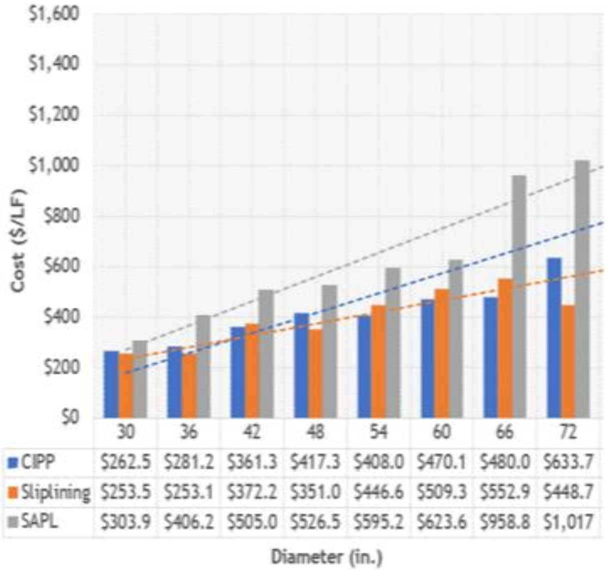


Task 7 – Corrugation

- It is difficult to get the required thickness of the liner
- Crests of the corrugations provide the reference points for thickness
- Production of a smooth interior surface profile liner, is the best long-term design solution for SAPLs
- When filling corrugations, the thrust (compression) in the SAPL becomes the dominant stress at the interior wall surface of the SAPLs

Task 8 – Environmental & Construction Costs

- Compared with CIPP and Sliplining, SAPL has least overall environmental costs
- After 60-in. diameter, the difference between CIPP environmental costs and SAPL will increase by more than 50%.
- For 78 in. to 108 in. diameters, the environmental costs of CIPP and Sliplining are almost the same. For the same range, the environmental costs of both CIPP and Sliplining are twice than SAPL application
- SAPL, CIPP, and Sliplining have the highest to lowest construction costs in culvert with diameter range of 30 in. to 108 in., respectively



Task 8 – Sample Construction Costs (Cont'd)

Sample Construction Costs:

Cementitious (Geopolymer)

Item Description	Pay Unit	Unit Qty	Unit Price	Total Price
66'' CMP, 0.5'' Interior Cement Liner, Includes Labor, Equipment for the installation of an interior cementitious liner	LF	1,046	$245.00 LF	$256,270.00

Polymeric (Polyurethane)

	250 mil	500 mil	1,000 mil
48 ''	$275/ft	$440/ft	$880/ft
54''	300	520	1,040
60''	360	600	1,200
66''	400	660	1,320
72''	450	740	1,480
84''	500	840	1,680
96''	550	950	1,800

Task 9 – CIPP Design Equations

- ASTM F1216 design procedure has been found as being unrealistic for designing flexible conduits and it is over-conservative
- Knowledge of the current performance properties of the surrounding soil are critical to the performance of the rehabilitated soil-structure interaction system
- Any design procedure used for CIPP must recognize the differences in how rigid pipe structures versus flexible pipe structures will transfer loads to consider the stresses and strains created in the CIPP liner itself

Partially Deteriorated

$$P_w = \frac{2KE_L}{(1-\upsilon^2)} \times \frac{1}{(DR-1)^3} \times \frac{C}{N}$$

Fully Deteriorated

$$q_t = \frac{1}{N}[32R_w B' E_s' \,.\, C(E_L I/D^3)]^{1/2}$$

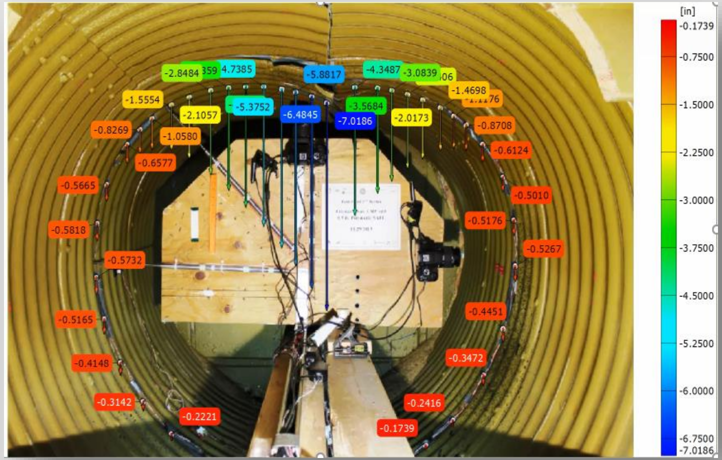
Task 10 – SAPL Design Equations

Cementitious SAPLs:

- Diameter or Span less than 120 inches
- Bonding between the host pipe and the SAPL required
- Semi-rigid design approach is taken
- Circular Pipes: Use of modified Iowa equation
- Arch Pipes: Use of mechanical analysis of a thin-walled ring structure
- Design loading as per AASHTO's Load and Resistance Factor Design (LRFD) Bridge Design Specifications was used

Polymeric SAPLs:

- Diameter or Span less than 120 inches
- No bonding between the host pipe and the SAPL considered
- Need to evaluate the effects of creep under long-term loading conditions
- Modified AASHTO Bride Design Specifications was used which included AWWA M45 design method for thermoset flexible materials.
- Analytical calculations were verified with experimental results
- Design loading as per AASHTO's Load and Resistance Factor Design (LRFD) Bridge Design Specifications was used



Task 11 - Performance Construction Specifications

Cementitious Based Structural SAPL Properties

Property	Test Method	Duration	Minimum Requirements
Compressive Strength	ASTM C109 (2.0-inch cubes)	28 day (min)	Declared Value, but not less than 8,000 psi
Flexural Strength (Modulus of Rupture)	ASTM C 1609	28 days (min)	Declared Value, but not less than 1,000 psi
Compressive Modulus of Elasticity	ASTM C 469	28 days (min)	Declared Value, but not less than 3,500,000 psi

Task 11 - Performance Construction Specifications (Cont’d)

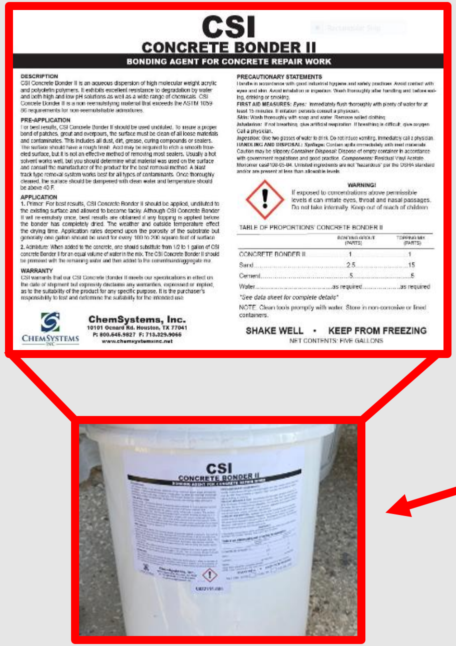
Polymeric Based Structural SAPL Properties

Property	Test Method	Minimum Requirements
Flexural Strength **Flexural Modulus** **Flexural Creep**	ASTM D790-17 ASTM D790-17 ASTM D2990-17	Declared Value, but not less than 10,000 psi Declared Value, but not less than 250,000 psi Declared Value – Qualification Test by 3rd Party
Compressive Strength **Compressive Modulus** **Compressive Creep**	ASTM D695-15 ASTM D695-15 ASTM D2990-17	Declared Value, but not less than 8,000 psi Declared Value, but not less than 300,000 psi Declared Value – Qualification Test by 3rd Party

Conclusions and Recommendations

- SAPL surface preparation, environmental conditions, bonding and quality of installation are very important
- Both polymeric and cementitious SAPLs were able to increase the structural capacity of the fully invert deteriorated CMPs
- Design equations were verified with experimental testing results
- FEM showed reasonable accuracy for polymeric circular and arch shapes. The FE model for cementitious circular and arch may need more work.
- More studies are recommended to refine design equations (considering effects of CMP's length, culvert diameter or span of above 120 in., hydrostatic pressure, etc.)
- More advanced FEM simulations are needed to improve the analysis of post-failure behaviors
- This research can be extended for different culvert shapes, depths and loading conditions
- Testing is needed to assess reduced strength of field aged SAPLs after 5 and 10 years of service

Substrate Preparation IS the key!



Implementation

- Results of this project to be implemented and monitored under active traffic with lining a deteriorated CMP culvert divided in two or more sections
- Each section lined with different polymeric and cementitious/geopolymer SAPL
- Developed design equations and performance specifications presented in Chapters 8 and 9 of this report should be used by the contractor
- Strategies to overcome potential risks and obstacles will be identified during this implementation
- Improvement in the quality of installation should be compared with recently installed SAPLs
- Soil movement around the culvert should be monitored at least for one year
- Surface settlement, infiltration, and condition of invert should be monitored and documented
- Additional numerical methods using FEM can expand results of field evaluation to other scenarios

Questions

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