# DEVELOPMENT OF A FRAMEWORK FOR DESIGN AND INSTALLATION OF CEMENTITIOUS SPRAY APPLIED PIPE LININGS IN RENEWAL OF CORRUGATED METAL CULVERTS

By

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Abstract

DEVELOPMENT OF A FRAMEWORK FOR DESIGN AND INSTALLATION OF CEMENTITIOUS SPRAY APPLIED PIPE LININGS IN RENEWAL OF CORRUGATED METAL CULVERTS

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Millions of culverts under road embankments provide drainage for U.S. transportation network system and are in need of maintenance, repair, and renewal. Over time culverts, like any other asset, deteriorate due to many factors. *Spray applied pipe lining (SAPL)* is one of the trenchless technology methods applicable for culverts renewal. In the SAPL method, polymers or cementitious materials are sprayed by machine or manually in different lifts to achieve required thickness based on the design criteria. The scope of this dissertation includes reinforced concrete pipe and corrugated metal pipe (RCP and CMP) culverts renewal with cementitious and polymer SAPLs. The objectives of this dissertation are to develop a framework for design and installation of SAPL. Due to lack of standards for structural design of SAPL, different vendors and contractors have come up with different design methodologies. Data collected through this research shows that with the same material properties, different thicknesses were applied with similar host culvert conditions. The methodology used in this dissertation includes literature review, evaluation of contractors' practices, survey of U.S. departments of transportations (DOTs) and Canadian

transportation agencies, and numerical analysis of deteriorated CMP lined with cementitious SAPL. The results of this dissertation show that (1) Different contractors/vendors use different design equations, (2) CMP culverts with deteriorated inverts and RCP culverts with longitudinal cracking and joint separation are the most common reasons for considering condition of a culvert as fully deteriorated, (3) The most common installation problems in cementitious SAPLs are longitudinal and circumferential cracking, hairline cracking, and cracking at joints, (4) The expected design life of SAPL is 50 to 75 years, (5) The structural behavior of SAPLs is related to many variables, such as, soil embedment of the host culvert, SAPL thickness, and shapes of host culvert, and (6) Compared with circular-shape CMP lined with cementitious SAPL, a lined arch-shape CMP deflects in the range of 15 to 40% more than circular-shape.

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# Chapter 1: Introduction and Background

A culvert is a structure that is used for passing storm water under an embankment, such as, highways, roads, railroads, etc., and acts either as a part of a drainage system or as a lone drainage structure. Not only does a culvert pass the water, but also it carries the loads dead and live loads, therefore, design and construction of culverts are complex.

The United States uses the world's biggest transportation network system including approximately 47,000 miles of the national highway system, more than 2 M miles of paved roadway, and more than 1.5 M miles of unpaved roadway (Najafi et al. 2008).

Culverts assets routinely require inspection, maintenance, repair, and renewal. Failure of these systems is costly for DOTs, both directly due to the replacement of the failed system and indirectly the social costs. The variety in material types, shapes, embedment materials, types of roads and location, and environmental conditions make every single culvert unique in terms of its behavior and durability as well as renewal (Najafi and Salem 2008).

## 1.1 Culvert Classifications

Culverts are commonly classified based on hydraulic behavior (flow control) and structural behavior (flexibility or rigidity of material), and are classified by materials shapes and sizes as follow:

### 1.1.1 Hydraulic Behavior (Flow Control)

The hydraulic behavior of a culvert is related to location, position, train topography (ground slope), and geometry. The engineer makes the design strategy when a special need is required. The publication FHWA-NHI-06-086, 2006, states that right-of-way (ROW), debris and dissipater cost are some of the issues for selecting the types of flow control in a culvert. Figure 1.1 illustrates major flow conditions which may happens in a culvert (VDOT 2017).

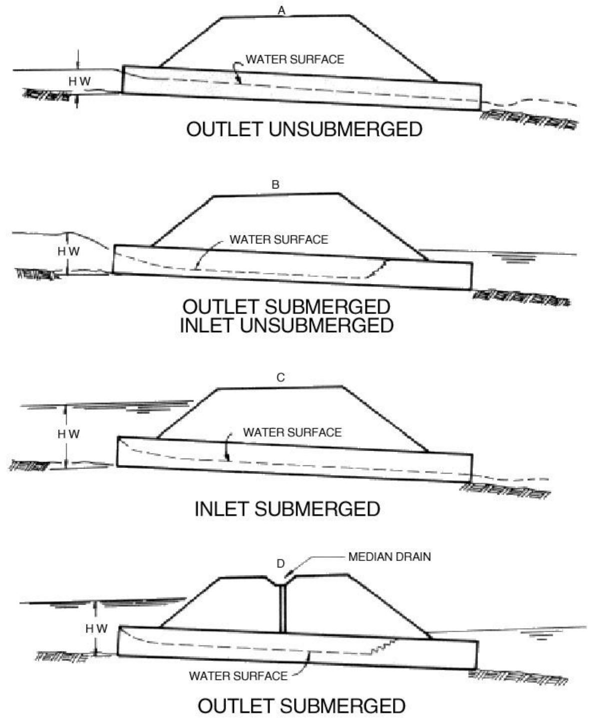

Figure 1.1. Major Types of Flow Control
Source: VDOT 2017

### 1.1.2 Materials

In general, culverts are constructed of concrete, metal, and thermoplastics, such as, polyvinyl chloride (PVC), and high density polyethylene (HDPE). Culverts in the mountainous roads are commonly excavated as a tunnel for which rocks bear the dead loads directly if the mechanism of rock failure has been studied, or a shotcrete liner with/without reinforcement are applied to the culvert tunnel. Within the concept of a metal culvert, mostly corrugated metal is used. Some other materials are also used in culvert construction, such as, brick, vitrified tile (clay), corrugated plastic, steel casing, stone, timber, and corrugated aluminum (Ohio DOT 2017). Table 1.1 presents some common culvert materials.

### 1.1.3 Shapes

Culverts are made either single or multi-cells/multiple in different shapes such as, circular, arch, horizontal or vertical elliptical, box and mix shapes.

Table 1.1. Different Materials Used in Culverts

| | |
|---|---|
| **Plain or Reinforced Concrete**<br>Source: FHWA-HIF-12-026 |  |
| **Corrugated Metal Pipe (CMP)**<br>Source: www.cuire.org<br>- CMP Non-Sectional Plate<br>- CMP Sectional Plate |  |
| **Cast or Ductile Iron**<br>Source: U.S. PIPE<br>Available at:<br>https://www.uspipe.com/products/ductile-iron-pipe |  |
| **Corrugated Aluminum Alloy**<br>Source: Armtec<br>Available at: https://drainage.armtec.com |  |

### 1.1.4 Culvert Size

The inside diameter of a circular pipe culvert is considered its span. The geometry of arch shapes culverts defines by two parameters, which are "S," the span of an arch shape and "R," the inside height (rise) (see Figure 1.2). Ohio DOT (2017) states that with multiple culverts, the span would be from inside of the left culvert through the other inside of the right culvert as illustrated in Figure 1.4.

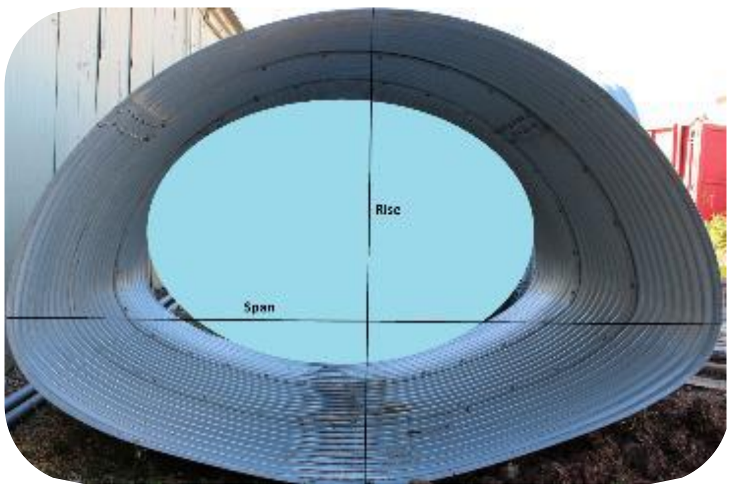


Figure 1.2. An Arch CMP culvert.
Source: Adapted from www.cuire.org

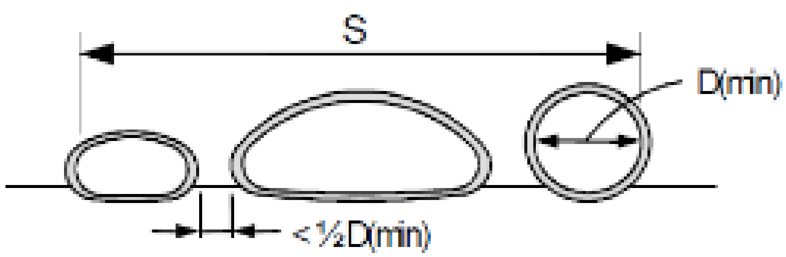


Figure 1.3. Definition of Span and Diameter in a Multi-cell Culvert
Source: ODOT 2017

### 1.1.5 Culverts Renewal Design Classifications

For purpose of this dissertation, a deteriorated culvert needs to be renewed to carry loads. In addition, renewed culverts need to be considered for flow capacity, sedimentation (especially bed load), head, and end walls, and so on. As noted above (Sec. 1.2), the hydraulics of culverts have impacts on the structural capacity. The following sections describe structural and hydraulic considerations for culverts:

1.1.5.1 Hydraulics

The Manning “n” factor and slope are the main variables when a culvert is designed for outlet unsubmerged flow control. A steep slope happens in rare topography as the culvert passed normally across the road; therefore, considering an appropriate manning “n” factor has an important impact on the hydraulic of a culvert. After several years of usage, the manning is changed due to corrosion or tuberculation, and has a consequence on flow discharge as well as strength.

1.1.5.2 Structural

Culverts are designed to bear the entire load from the embankment and traffic, such as soil and pavement loads (dead loads), truck loads (live loads), and hydrostatic loads. Each culvert has a unique loading capacity dependent on location, topography, types of natural soil, bedding, embedment and backfilling, pavement thickness and material, and hydraulic behavior/flow control. All these aspects, in conjunction with soil pipe structure interactions, make design of culverts a complex process with a variety of variables.

1.1.6 Structural Behavior of Culverts

Corrugated metal pipe (CMP) and thermoplastic culverts follow flexible pipe design procedures and reinforced concrete pipe (RCP) culverts follow rigid pipe design procedures. According to Moser and Folkman (2008), flexible pipes can deflect up to 7% of diameter, with metal pipes deflecting up to 5% not considering lag deflection. The rigid pipe deflection is related to the safety factors which defined based on the width of cracks.

1.1.7 Soil-Pipe Interaction

#### 1.1.7.1 Soil Types/Classes Appropriate for Culvert inside Embankments

Traditionally, granular soil is preferred for bedding, embedment and backfilling of culverts; however, if natural and in-place soil satisfies the design needs, a combination of natural soil with granular soil can be used due to the cost of transportation of specific soils. ASTM D2321 – 14 2014, considered using soil of all classes (class I, II, III and IV) for culverts based on AASHTO soil groups except class V for embedment.

#### 1.1.7.2 Selecting Soil Type for This Dissertation

AASHTO (2002), Standard Specifications for highway bridges, considers appropriate granular soil identifications for Highway Bridge design (Table 1.2). This data is used in this dissertation for calculating the ultimate load bearing capacity of soil.

Table 1.2. Typical Range of $E_s$ and υ for Granular Soil Materials
Adapted from AASHTO 2002

| **Soil Types** | **Young's Modulus, $E_s$ (ksf)** | **Poisson's Ratio, υ (Dimensionless)** |
|---|---|---|
| Loose Sand | 200 – 600 | 0.2 – 0.35 |
| Medium Dense Sand | 600 – 1,000 | 0.2 – 0.35 |
| Dense Sand | 1,000 – 1,600 | 0.3 – 0.4 |
| Loose Gravel | 600 – 1,600 | 0.2 – 0.35 |
| Medium Dense Gravel | 1,600 – 2,000 | 0.2 – 0.35 |
| Dense Gravel | 2,000 – 4,000 | 0.3 – 0.4 |

### 1.1.8 Culvert Installation Methods

#### 1.1.8.1 Trenching

In this method, the pipe/culvert is placed inside of an excavated narrow trench on a bedding material, which is usually a loose granular sand or control low strength material (CLSM). In this case, pipe/culverts may have some impact from the trench walls. AASHTO LRFD Bridge Design

Specifications (2017), presents four types of soil materials and compactions for a standard trench installation.

1.1.8.2 Projection or Embankment

In this method, the pipe/culvert is placed on a bedding material in a wide or infinite side. Then the hunching areas is backfilled concurrently with the other parts of embankment in a defined width. Normally, culverts underneath of roads or railroads are installed using this method. AASHTO LRFD Bridge Design Specifications (2017), presents four types of soil materials and compactions for a standard embankment installation.

1.1.9 Culvert Deterioration

FHWA-CFL/TD-10-005 (2010) rates conditions of existing culverts as:

1. "Good, like new, with little or no deterioration, structurally sound and functionally adequate,
2. Fair, some deterioration, but structurally sound and functionally adequate,
3. Poor, significant deterioration and/or functional inadequacy, requiring repair action that should, if possible, be incorporated into the planned roadway project,
4. Critical, very poor conditions that indicate possible imminent failure that could threaten public safety, requiring immediate repair action, and
5. Unknown, all or part of the culverts is inaccessible for assessment or a rating cannot be assigned."

1.1.9.1 Partially deteriorated

According to ASTM F-1216-16 (2016), the term *"partially deteriorated"* is used when a pipe has enough strength to support soil and live loads, but it cannot bear hydrostatic loads.

1.1.9.2 Fully deteriorated

According to ASTM F-1216-16 (2016), the term *"fully deteriorated"* is used for the condition of a pipe, which cannot bear soil, live and hydrostatic loads.

1.1.9.3 Invert lost (invert deteriorated culvert)

The most common problem with CMP culverts is invert corrosion to the point that the whole invert is lost as shown in Figure 1.4.

Figure 1.4. An Invert Corroded CMP Culvert
Source: cuire.org

1.1.10 Rehabilitations and Renewals Methods

Several methods are developed since 1970 for rehabilitations and renewals of gravity conduits. The four most common methods, which make a liner pipe inside a culvert, are cured-in-place pipe (CIPP), sliplining (SL), modified sliplining (MSL), and SAPL, as shown in Table 1.5 and described in below sections.

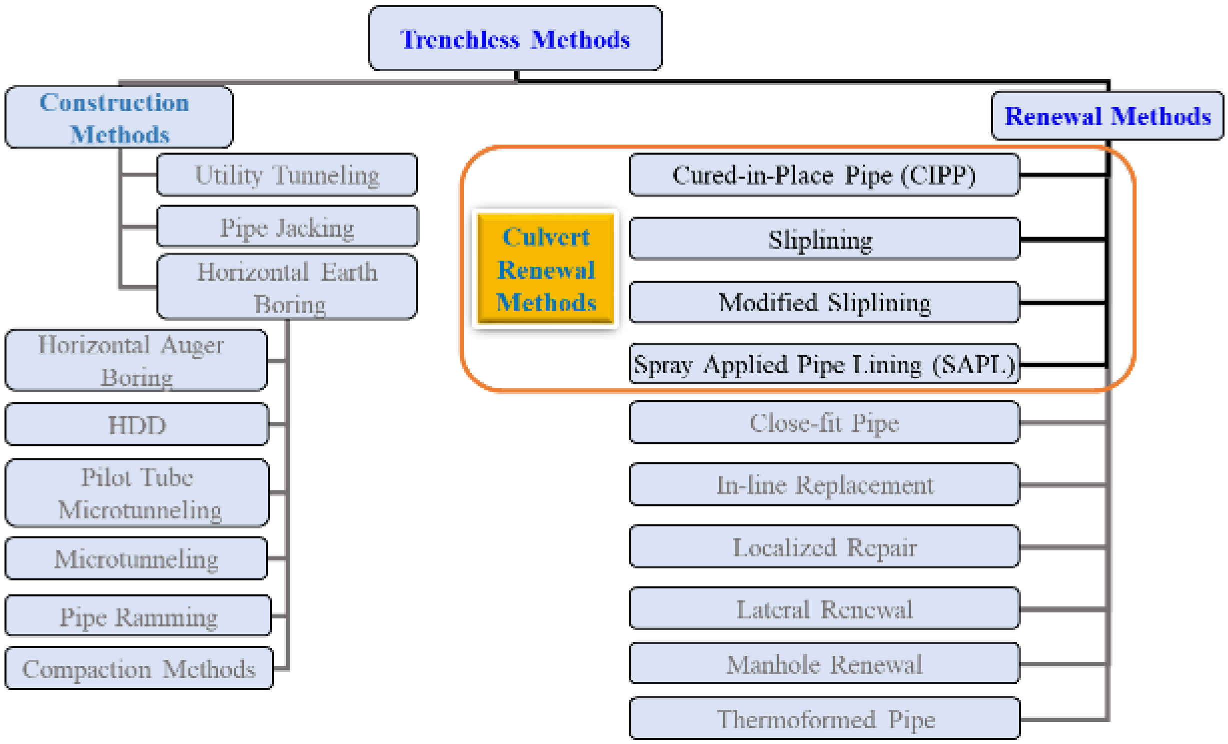


Figure 1.5. Culvert Renewal Methods within Trenchless Technology Methods
Source: Adapted from Najafi and Gokhale (2005)

1.1.10.1 Cured in Place Pipe (CIPP)

The most common method for pipe rehabilitation is cured-in-place pipe (CIPP), "which involves the insertion of a resin-impregnated fabric tube into an existing pipe by use of water inversion or winching" (Najafi 2016). The fabric is a polyester felt, fiberglass reinforced, or similar. Usually water, steam, or ultraviolet (UV) light is used for curing. This method can be used for structural or non-structural purposes. Table 1.3 presents the main characteristics of the CIPP method. Figures 1.6 and 1.7 show the inverted-in-place and winched-in-place methods.

Table 1.3. Main Characteristics of CIPP Methods
Source: Najafi 2016

| Method | Diameter Range (in.) | Maximum Installation (ft) | Liner Material | Applications |
|---|---|---|---|---|
| Inverted-In-Place | 3-120 | 3,000 | Thermoset Resin/ Fabric Composite | Gravity and Pressure Pipelines |
| Winched-In-Place | 4-54 | 1,000 | Thermoset Resin/ Fabric Composite | Gravity and Pressure Pipelines |

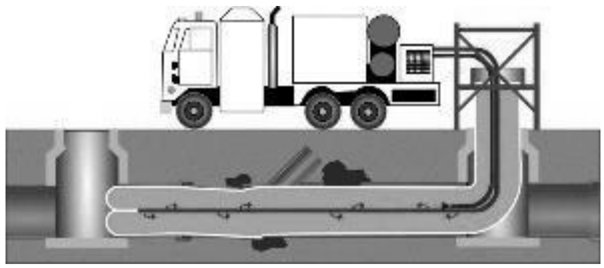
Figure 1.6. CIPP Inverted-In-Place Installation Method
Source: Google Images

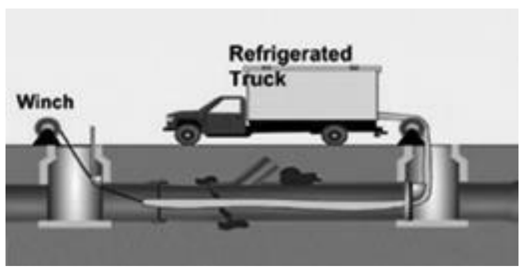

Figure 1.7. CIPP Winched-In-Place Installation Method
Source: Google Images

1.1.10.2 Sliplining (SL)

Sliplining (SL) is the practice of placing a new pipe inside the old host pipe. "This method is mainly used for structural applications when the existing pipe does not have joint settlements or misalignments. In this method, a new pipeline of smaller diameter is inserted into the existing pipe and usually the annulus space between the existing pipe and new pipe is grouted" (Najafi 2016). Segmental SL and Continuous SL are the two main categories in this method. There will be a significant hydraulic loss because of this method. Table 1.4 presents the main characteristics of the SL method. Figures 1.8 and 1.9 show the segmental and continuous SL methods.

Table 1.4. Main Characteristics of Sliplining (SL) Methods
Source: Najafi 2016

| Method | Diameter Range (in.) | Maximum Installation (ft) | Liner Material | Applications |
|---|---|---|---|---|
| Segmental | 4-158 | 1,000 | HDPE, PVC, and GRP | Gravity Pipelines |
| Continuous | 4-63 | 1,000 | HDPE and PVC | Pressure Pipelines |

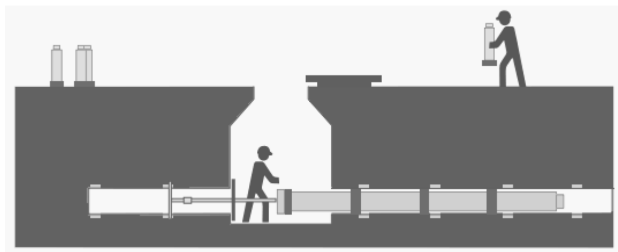

Figure 1.8. Segmental SL Method
Source: Google Images

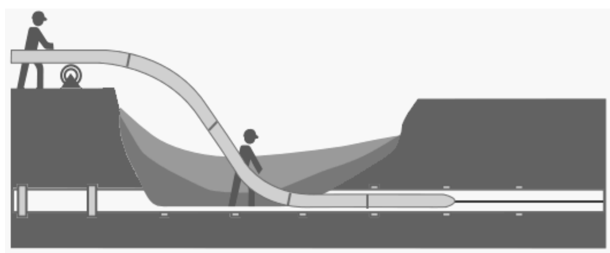

Figure 1.9. Continuous SL Method
Source: Google Images

#### 1.1.10.3 Modified Sliplining (MSL)

Modified sliplining (MSL) is applicable for large diameter (worker-entry) gravity pipes including culverts (Najafi, 2016). The scope of using this method is for both structurally and non-structurally applications. It is applicable for different shapes and is used in sewer lines. “MSL liners (panels) usually have tongue-and-groove joints that are sealed with either rubber sealing rings or polyurethane or epoxy filler” (Najafi, 2016). There will be reduction in cross-sectional area of the pipe, which must be compared with any improvements due to a better coefficient of roughness of the lined pipe. As a conclusion of using this method, it is useful when the culvert needs structural rehabilitation.  Table 1.5 shows the main characteristics of the MSL method.

Table 1.5. Main Characteristics of MSL Methods
Source: Najafi 2016

| Method | Diameter Range (in.) | Maximum Installation (ft) | Liner Material | Applications |
|---|---|---|---|---|
| Panel Lining | >48 | varies | GRP | Gravity Pipelines |
| Spiral Wound | 36 -100 | 1,000 | PE and PVC | Gravity Pipelines |

1.1.10.4 Spray Applied Pipe Lining (SAPL)

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. The SAPL is applied inside of a culvert for the application of 1) non-structural (control/stop the corrosion), 2) semi-structural (increase the load bearing capacity as a composite structural behavior of host culvert and SAPL), and 3) structural application (the liner works as a standalone structure which is a new culvert inside the old host culvert). The type of deterioration is dependent upon the existing structure under consideration. According to Najafi (2013), the main objective of a structural renewal is to inhibit further deterioration and the process 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 polyurea.

Cementitious SAPLs including cementitious and geopolymer are categorized as rigid SAPLs, and polymeric materials including polyurea, polyurethane, and epoxy are categorized as flexible SAPLs. When the SAPL is applied inside of a culvert, four combinations of flexibility/rigidity might be applicable in a renewed culvert.

1) Flexible culvert with flexible liner, (ex. a CMP lined by a polymeric SAPL material),
2) Flexible culvert with rigid liner, (ex. a CMP lined by a cementitious SAPL material),

3) Rigid culvert with flexible liner, (ex. an RCP lined by a polymeric SAPL material), and
4) Rigid culvert with rigid liner, (ex. an RCP lined by a cementitious SAPL material).

## 1.2 Need Statement

Several failures have occurred over the surface of highways and roads due to failure of deteriorated culverts. These failures not only cause costly replacement of the culverts but also involves social costs due to traffic disruptions and costs to commuting public. Fatality have also resulted in a few cases. As stated above, different methods are available to structurally rehabilitate or renew a fully or partially deteriorated culvert.

Ohio DOT (2017), states that field applications of protective coating is a need for maintenance of culverts. Davidson et al. (2008) recommended that a range of lined culverts needs to be analyzed in future studies to get load resistance validation. Najafi and Osborn (2008) recommended making a framework for the renewal of a culvert. They stated that it would have a significant impact to design the future life of existing culverts. NCHRP Synthesis 303 (2002) states that several studies on the load capacity and soil-culvert structure interaction are accomplished over the last 75 years, however, “specifications for pipe lining need to be developed.” Marr (2012) conducted surveys showing a lack of study on culvert design, performance specifications, material selection, soil-culvert structure interaction issues, rehabilitation and so on. NCHRP Synthesis 519 (2018) summarized trenchless technologies for culvert renewal including CIPP, SL, MSL, in-line replacement (ILR), spray-in-place pipe (SIPP), and close-fit pipe (CFP). DOTs planned for future research project on these methods. One of these projects has already started entitled “Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits,” which is to cover culvert and storm water drainage structures. Syar et al. (2019)

mentioned that there is a need of structural design equations for culvert renewal method using SAPLs.

Due to lack of standard practice, the SAPL application including both design and performance specifications is defined by different vendors. This dissertation will provide a framework for structural design of cementitious SAPLs in deteriorated CMPs.

## 1.3 Objectives

As stated above, the main objective of this dissertation is to provide a framework for design and installation of cementitious SAPLs in deteriorated CMPs. The secondary objectives are:

- To analyze data from existing cementitious SAPL projects and compare with ASTM and literature.
  - To investigate SAPL problems in three parts of pre, during, and post installation,
  - To analyze structural behavior of cementitious SAPL culverts in both circular and arch shape CMPs.
  - To make a comparison between the structural behavior of SAPLs for circular and arch shape conditions.

## 1.4 Scope

Table 1.6presents scope of this dissertation.

Table 1.6. Research Scope

| Culvert | Included | Not Included |
|---|---|---|
| Shape | Circular, Pipe Arch | Any other shapes |
| Materials | CMP, RCP | Any other materials |
| Soil* | poorly graded sand (SP), poorly graded gravel (GP) | Any other types of soil or any other combination of soils |
| Loads | Soil (dead) load, H-20 truck (live) load | Seismic load |
| SAPL Materials | Cementitious, and Polymeric (only in papers I and III) | Polymeric in papers II and IV |

Culverts are usually constructed with granular materials. For this dissertation, poorly graded sand (SP) and poorly graded gravel (GP) were selected for numerical analysis which is presented in Chapter 6. ASTM defines SP as Class II soils, which includes poorly graded sands and gravelly sands with little or no fines. More than 50 percent of this soil type passes a No. 4 sieve and more than 95 percent is retained on No. 200 sieve.

## 1.5 Methodology

As a paper-based dissertation, Figure 4.7 presents methodology of this research.

**Chapter 1** **General Introduction**

- Definitions of Culverts, Culverts' Deteriorations, Rehabilitions and Renewals
- SAPL
- Hypotesis

**Chapter 2** **Literature Review**

**Chapter 3** **Paper I**

- Evaluation of Literature on Design and Performance of Spray Applied Pipe Linings for Renewal of Culverts and Drainage Structures

**Chapter 4** **Paper II**

- An Investigation of Contractors' Practices for Application of Spray Applied Pipe Liners for Renewal of Deteriorated Corrugated Metal Pipe Culverts

**Chapter 5** **Paper III**

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

**Chapter 6** **Paper IV**

- Evaluation of Load Bearing Capacity of Lined Deteriorated Corrugated Metal Pipes Using Laboratory Testing and Numerical Analysis

**Chapter 7** **Conclusions and Recommendations for Future Research**

Figure 1.10. Dissertation Methodology

## 1.6 Hypothesis

Main hypotheses: Thin wall thickness of cementitious SAPL behaves like a flexible material.

The secondary hypothesis of this dissertation can be summarized as follows:

- There is a direct relationship between the thickness of cementitious SAPL and the diameter of the host culvert.

- The contractors’ practices design equations (thicknesses’ formula), for cementitious SAPL application, followed ASTM F 1216-16.
- SAPL cementitious materials has a design life more than 50 years.

## 1.7 Chapter Summary

This chapter presented an introduction to culverts and drainage structures. Background materials were included on culvert installation considering structural and hydraulic capacities. A discussion of common renewal/rehabilitation methods including CIPP, Sliplining, and SAPL were included. Research objectives, scope, methodology and hypothesis were presented.

## 1.8 Co-Authors’ Contributions

### 1.8.1 Chapter 3, Paper I

Evaluation of Literature on Design and Performance of Spray Applied Pipe Linings for Renewal of Culverts and Drainage Structures

1. Jalalediny Korky, Seyedmohammadsadegh: Primary Author
2. Najafi, Mohammad: Supervisor
3. Syar Jeffery: Co-author – Revising paper
4. Nandyala Vasudeva Kaushik: Co-author – Summarizing parts of reports and papers

### 1.8.2 Chapter 4, Paper II

An Investigation of Contractors’ Practices for Application of Spray Applied Pipe Liners for Renewal of Deteriorated Corrugated Metal Pipe Culverts

1. Jalalediny Korky, Seyedmohammadsadegh: Primary Author
2. Najafi, Mohammad: Supervisor

### 1.8.3 Chapter 5, Paper III

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

1. Jalalediny Korky, Seyedmohammadsadegh: Primary Author

2. Najafi, Mohammad: Supervisor

### 1.8.4 Chapter 6, Paper IV

Evaluation of Load Bearing Capacity of Lined Deteriorated Corrugated Metal Pipes Using Laboratory Testing and Numerical Analysis

1. Jalalediny Korky, Seyedmohammadsadegh: Primary Author

2. Najafi, Mohammad: Supervisor

## 1.9 References

AASHTO LRFD Bridge Design Specification. (2017). “AASHTO LRFD Bridge Design Specifications,” 8th Edition, September 2017. Publication Code: LRFD-8. ISBN: 978-1-56051-654-5. American Association of State Highway and Transportation Officials.

AASHTO. (2002). “Standard Specification for Highway Bridges,” 17th Edition, ISBN: 156051-171-0

ASTM (American Society for Testing and Materials). (2016). “Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube,” Standard ASTM F1216-16. ASTM, West Conshohocken, PA.

ASTM (American Society for Testing and Materials). (2014). “Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications,” Standard ASTM D2321-14. ASTM, West Conshohocken, PA.

Davidson. S.J., Kang, J., Uday, K.V., Brian, P., and Balaji, T. (2008). “PVA Fiber Reinforced Shotcrete for Rehabilitation and Preventative Maintenance of Aging Culverts”. Alabama

Department of Transportation, Project 930-657, https://rosap.ntl.bts.gov/view/dot/17333, Date Accessed April 24, 2018.

FHWA-CFL/TD-10-005. (2010). "Culvert Assessment and Decision-Making Procedures Manual," Publication No. FHWA-CFL/TD-10-005. U.S. Department of Transportation, Federal Highway Administration, and Central Federal Lands Highway Division, 12300 West Dakota Avenue, Lakewood, CO 80228.

FHWA-NHI-15-047. (2015). "Load and Resistance Factor Design (LRFD) for Highway Bridge Superstructures," Reference Manual, Publication No. FHWA-NHI-15-047. U.S. Department of Transportation, Federal Highway Administration.

FHWA-HIF-12-026. (2012). "Hydraulic Design of Highway Culverts," Publication No. FHWA-HIF-12-026. Hydraulic Design Series Number 5. U.S. Department of Transportation, Federal Highway Administration.

Federal Highway Administration (FHWA) and National Highway Institute (NHI). (2006). "Hydraulic Design of Energy Dissipators for Culverts and Channels," Prepared for U.S. Department of Transportation, Hydraulic Engineering Circular No. 14, 3rd Edition.

Marr J. (2012). "A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota," Final Report No. MN/RC 2012-27. Minnesota Department of Transportation. Research Services. Office of Policy Analysis, Research, & Innovation. Performing Organization: University of Minnesota.

Moser A. P. and Folkman S. (2008). "Buried Pipe Design," 3rd Edition. ISBN 978-0-07-147689-8. McGraw-Hill.

Najafi M. and Gokhale S. (2005). "Trenchless Technology – Pipeline and Utility Design, Construction and Renewal," McGraw-Hill.

Najafi M. and Osborn L. (2008). “Trenchless Renewal of Culverts and Storm Sewers,” ASCE Pipelines Congress 2008.

Najafi M. and Salem O. (2008). “Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures” Access at CUIRE.org, July, 26, 2019: http://www.uta.edu/ce/cuire/MRUTC0715%20Trenchless%20Technology%20Final%20Report%2012-08-08.pdf

Najafi M., Salem O., Bhattachar D., Salman B. and Patil R. (2008). “An Asset Management Approach for Drainage Infrastructure and Culverts” Access at CUIRE.org, July, 26, 2019: http://www.uta.edu/ce/cuire/MSU-UTA-UC%20CULVERT%20ASSET%20MANAGEMENT%20FINAL%20REPORT%20June%2030-2008%20R1.pdf

Najafi M. (2016). “Pipeline Infrastructure Renewal and Asset Management,” McGraw-Hill, New York, NY

NCHRP Synthesis 303 (2002). “Assessment and Rehabilitation of Existing Culverts,” National Cooperative Highway Research Program (NCHRP). Transportation Research Board – The National Academies. Washington, D.C. 2002.

NCHRP Synthesis 519 (2018). “The Renewal of Stormwater Systems Using Trenchless Technologies,” National Cooperative Highway Research Program (NCHRP). Transportation Research Board – The National Academies. Washington, D.C. 2018.

Ohio Department of Transportation, (2017). “Culvert Management Manual.” ODOT.

Najafi M., Salem O., Salem S., Bhattachar D., Salman B., Patil R., and Claderon D. (2008). “An Asset Management Approach for Drainage Infrastructures & Culverts” Prepared for: for the Midwest Regional University Transportation Center, Wisconsin Department of

Transportation, Hill Farms. State Transportation Building. 4802 Sheboygan Avenue Madison, WI 53706.

Syar J. and Najafi M. (2018). “Update of the Use of Spray-Applied Pipe Linings as a Structural renewal for Gravity Storm Water Conveyance Conduits.” Trenchless Technology Magazine, June 2018.

Syar J., Najafi M., Kohankar. Z., Jalalediny Korky S. and Tehrani A. (2019). “Use of Spray Applied Pipe Linings as a Structural Renewal for Gravity Storm Water Conveyance Conduits,” North American Society for Trenchless Technology (NASTT), NASTT’s 2019 No-Dig Show, Chicago, Illinois, March 17-20, 2019.

Virginia Department of Transportation, (2017). “Virginia Drainage Manual,” VDOT.

# Chapter 2: Literature Review

## 2.1 Introduction and Background

This chapter presents previous studies on culvert rehabilitations/renewals using spray applied pipe linings (SAPLs). After presentation of standards and construction guidelines for culvert renewals with trenchless technologies, past studies on soil-pipe structure interaction are discussed.

## 2.2 Standards and Construction Guidelines

### 2.2.1 Culvert

The Federal Highway Administration (FHWA) (2012) considered culverts as buried structures with a span less than 20 ft for circular shapes (diameter less than 20 ft). This publication has updated a previous edition with adding culvert repair and rehabilitation as well as software solutions and aquatic organism passage.

The Federal Highway Administration (FHWA) for Federal Land Highway (FLH) (2010) defines a culvert assessment tool. The objective of this tool is "to provide FHWA FLH personnel with project-level guidelines for assessing the condition and performance of existing roadway culverts within the extents of a planned roadway project. This procedure applies to culverts with a span of less than 20 feet." FLH (2010) considers conditions for a culvert as Good, Fair, Poor, Critical, and Unknown.

Nationally, culverts are buried structures with spans less than 20 ft. Ohio DOT (2017) has specifications that reduces this span to 10 ft in the interest of public safety and 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. Additionally, they define culvert as 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."

As stated in Chapter 1, ASTM F-1216-16 divides existing pipe conditions into two classes: "partially deteriorated" condition and "fully deteriorated" condition. The assignment of a partially or a fully deteriorated design procedure depends upon the existing condition of the existing pipe or its expected structural contribution over the liner design period.

ASCE (2007) states that the term "fully deteriorated" is fundamentally flawed. The existing pipe structure, even in its fully deteriorated state, is holding the soil and live loads. In fact, a fully deteriorated culvert may not be fully collapsed. However, most design methodologies used in practice today follow ASTM F1216-16.

The terms "partially deteriorated" may not be applied to most culverts, since culverts are usually installed above ground inside the road embankment and may not be subjected to hydrostatic loading.

### 2.2.2 Culvert Renewals Methods and Materials

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.

NCHRP (2002) has a synthesis of highway practice over the assessment and rehabilitation of existing culverts entitled SYNTHESIS 303. “This synthesis study was initiated to determine the state of the practice of pipe assessment, the selection of appropriate repair or rehabilitation methods, and the management aspects of a pipe/culvert program.” The methodology of this publication was based on a survey that collected data from local, state, and federal transportation agencies. Results of the survey show that there are no comprehensive methods/manuals for repair; therefore, personal experiences were used for repair. As a conclusion of this study and survey results, most of the respondents wanted to rehabilitate the existing culvert rather than replace it. Respondents requested the need for SAPLs.

Wagener and Leagjeld (2014) studied culvert rehabilitation methods and practices. The main objective of their research was to develop the best practices guidelines for rehabilitation and replacement methods for deteriorating culverts. The methodology of this research includes the collection of survey data from state of Minnesota and other states. The most common culvert rehabilitation and repair methods identified during the survey program were included. The authors state that culvert repair process includes these steps: (1) Identify the problem, (2) Determine the causes of deterioration, (3) Evaluate the hydraulic condition, (4) Evaluate the structural condition, (5) Evaluate repair, rehabilitation, and replacement options, (6) Implement the design, and (7) Maintain the repairs. Culverts with diameters greater than 36 in. can be repaired with paved inverts because personnel entry is possible. SAPL can be applied to culverts at early stages of deterioration to increase the service life.

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. The type of deterioration is dependent upon the 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 epoxy, polyurethane, and polyuria. All these different types of SAPLs have advantages and limitations.

### 2.3 Soil-Pipe-Structure-Interaction

Watkins et al. (1982) analyzed the effects of loads on buried corrugated polyethylene pipes. Their objective was to determine a relationship between pipe deflection and height of soil cover for a 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. The authors did not consider impact of a dense embedment to increase load bearing capacity. However, in the design theory of flexible pipe, only the prism of soil above the pipe is considered.

Bian et al. (2012) studied on the effect of the burial depth. A full-scale model test of concrete culvert in a soil box with dimensions of 50 ft x 16.7 ft (15 m x 5 m) and 20 ft (6 m) in depth was performed. The culvert was covered under various depths of the granular soil. Pressure cells were used to measure pressure above the crown at different burial depths. A convergence gauge was used to measure the change in the profile of the culvert and a rebar stress gauge was used to measure the structural response. Vehicle loads were applied in steps of 2.25 kips (10 kN) to a maximum load of 15.7 kips (70 kN). The experiment concluded that, under various load conditions, the load from the vehicle tire decreases to about 10% with increase of each 3.3 ft (1.0 m) depth of the soil fill. Their conclusion is different from Boussinesq's curve, which is cited by Moser and Folkman (2008). Boussinesq's curve showed that in 3 ft depth of soil cover, only 30% of the load from vehicles is distributed on the pipe.

Soil-Structure interaction shows a significant effect during the design of a reinforced concrete liner. Jenkins and Drake (2017) studied this effect by using finite element modelling (FEM) on these concrete liners inside of corrugated circular and pipe-arch culverts. The objective of their study was to compare the results of the simplified design analysis as indicated in Australian design codes with the FEM by considering soil-structure interaction of culverts under train (live) load. Their methodology included a simplified frame design analysis of multi-cell 11.5 ft (3.5 m) diameter circular pipes and multi-cell 26 x 13 ft (8 x 4 m) pipe-arch sections, without considering soil-structure interaction according to Australian design codes. A two-dimensional finite element modeling of the soil-structure interaction was considered and the host pipe was removed. The finite element results depicted that a substantial reduction in bending moments compared with the simplified analysis. Reduction in bending moment was approximately 65% for circular culverts, and 50% for arch culvert under dead load and live load. It was concluded that soil-structure interaction significantly improves the structural efficiency of the reinforced concrete liner. The authors mentioned that soil-structure interaction shows significant effect during the design of reinforced concrete liner. It seemed that the authors considered the lined CMP as a rigid pipe.

However, in the design theory of a rigid pipe, the settlement of soil on the sides of the pipe is more than the soil above the pipe (Moser and Folkman 2008). .

Elastic buckling is a significant parameter in the design of culverts. Moore et al. (1995) studied the rehabilitation of three-collapsed corrugated steel plate culverts consisting of 37 ft (11.28 m) span horizontal ellipses located in Elgin Country, Canada. The objective of this study was to investigate the major cause for the culvert failure and monitoring of the construction during rehabilitation. Their methodology included a geotechnical investigation around the pipes to check the construction deficiencies and analysis of structural stability. The result of this investigation showed that the failure was not because of construction practice. They found that the culverts were barely stable with respect to elastic buckling, which was a fault in the original design. The steps taken to implement the repairs were selection of construction equipment, sequence of excavation, concreting, and backfilling operations. Elastic buckling is a significant parameter in the design of culverts and can be prevented by appropriate depth and density of the soil cover. A proper soil-pipe-structure-interaction study can show the load sharing among embedment, soil cover, bedding, and the structure (pipe).

## 2.4 SAPL Materials

### 2.4.1 Fiber Reinforced Concrete

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 D-load testing of full-scale composite host pipe with liner. Finite Element Modelling (FEM) indicated that the optimum thickness would be 1-in. Figure 2.1 illustrates the results of FEM. An analytical approach was derived for designing the required liner thickness. The authors concluded that PVA offers intriguing and unique characteristics that would minimize the required liner thickness, while providing tension, strength, rigidity, and ductility. Authors used three-edge bearing tests (D-Load tests) and ignored the impact of soil-pipe-structure interactions.

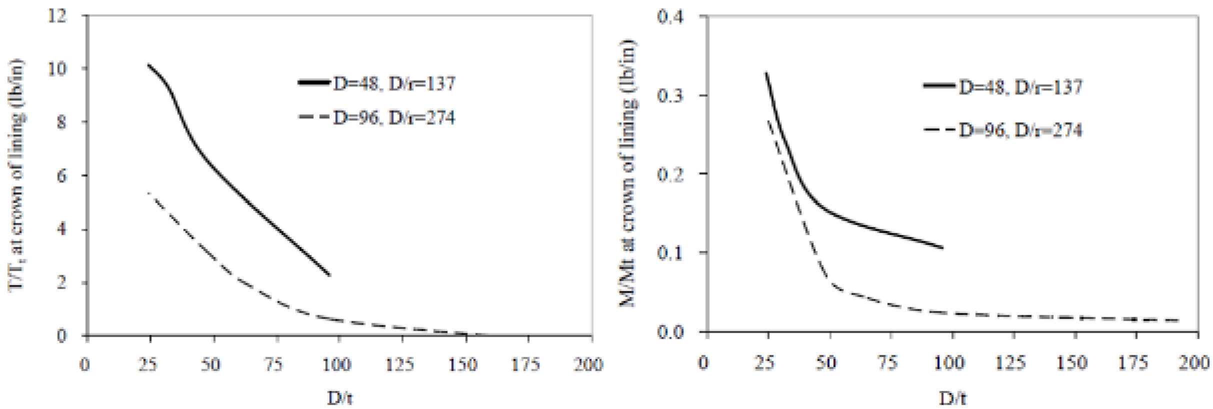


Figure 2.1. Axial Forces, T (left) and Bending Moments, M (right) at the CMP Crown
Source: Davidson et al. (2008)

### 2.4.2 Geo-polymers

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 within poorly graded sandy gravel (GP-SP). Both culverts were instrumented with strain gauges and string potentiometers (cable 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. According to FHWA-RD-94-096 (1995) – Culvert Repair Manual-Vol1-010551 – and AASHTO LRFD Bridge Design Specification (2017), when a culvert is covered by less than 2 ft, it is considered a shallow depth culvert; therefore, none of these sample tests represent shallow depth culverts. Under a soil cover of 83-in. (~7 ft), the impact of truck load is negligible. In fact, based on AASHTO, the designer can ignore the impact of truck load when it comes to deeper than an 8 ft soil cover (AASHTO LRFD bridge design 2017).

Moore and Garcia (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 with 3 and 2-in. thicknesses of SAPL were applied for these tests. Figure 2.2 illustrates the crack patterns for 3 and 2-in. thicknesses, respectively. 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- and 2- in. liner thicknesses that were specified.

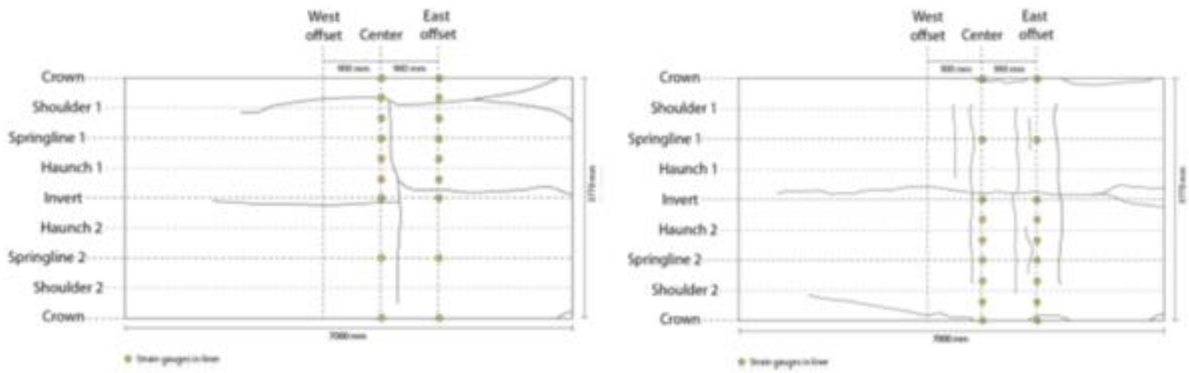


Figure 2.2. Cracks Pattern for 3-in. (left) and 2-in. (right) Liner Thicknesses
Source: Moore and Garcia (2015)

Royer and Allouche (2016) conducted laboratory testing of RCP and CMP with and without SAPL. The tests were performed on 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. D-Load values were scaled assuming Type IV bedding factor ($B_f$) of 1.5. 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. Authors used D-Load tests and ignored the impact of soil-pipe-structure interactions. According to Moser and Folkman (2008), the maximum allowable deflection for a CMP is 5%. The authors continued testing on the ovalities from 5% to

12%. It seems that authors believe in the possibility of renewal for up to 12% ovality. The authors considered that a geo-polymer SAPL renewed culvert behaves like a rigid pipe.

Royer and Iseley (2017) reexamined above laboratory testing with a different bedding factor. D-Load values were scaled assuming Type IV bedding factor ($B_f$) of 2.5. Figure 2.3 illustrates effects of different percentages of ovality in geo-polymer liner. Authors provided same recommendations as above.

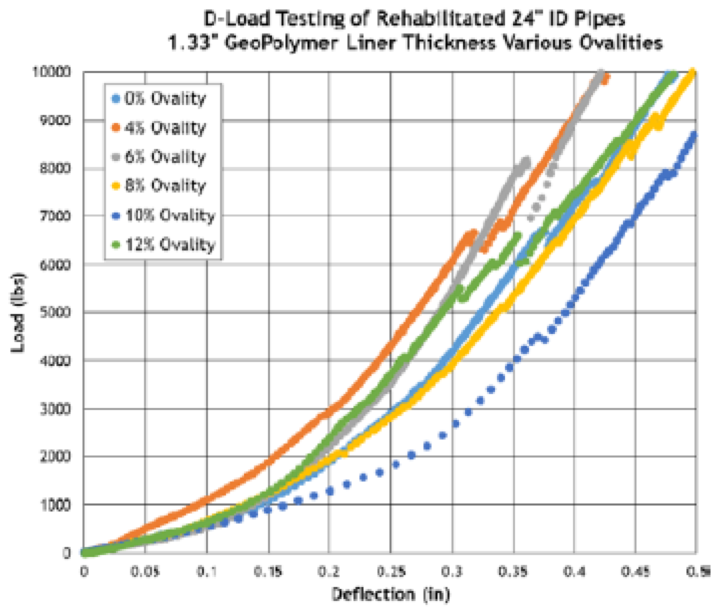


Figure 2.3. Effect of Ovality on 24-in. Rehabilitated CMP
Source: Royer and Iseley (2017)

Matthews et al. (2014) presented a report to the U.S. Environmental Protection Agencies (EPA) entitled "Performance Evaluation of an Innovative Fiber Reinforced Geo-polymer Spray Applied Mortar for Large Diameter Wastewater Main Rehabilitation in Houston, Texas." The objective of this report was to describe the performance of a fiber reinforced geo-polymer spray applied mortar as a structural lining in a 60 in. circular reinforced concrete pipe (RCP) under 25 ft soil cover. "A lining thickness of approximately 3.3 in. was sprayed in the pipe, which is more than the design minimum value of 1.9 in. The third-party test results for compressive strength averaged 8,635 psi at 28 days, which is slightly above the manufacturer stated 8,000 psi at 28 days. However, the samples collected by the research team tested under the manufacturer-stated conditions (e.g., measured at 7,881 psi or 1.5% below specification for compressive strength). Based on the lower density of the mixture, it was hypothesized that the lower values in these samples were attributable to light rain experienced during sample collection."

The design methodology used was for resisting against hydrostatic pressure (Eq. 2.1) and soil loads (Eq. 2.2).

$$t_{pd}{}^{2.5} = N \frac{P_w l r^{1.5} (1-\mu^2)^{0.75}}{0.807E} \quad \text{(Eq. 2.1)}$$

$t_{pd}$ = minimum thickness required, partially deteriorated pipe (in.)

$P_w$ = external hydrostatic pressure due to groundwater (psi) = 0.433($H_w$+$D$/12)

$H_w$ = height of ground water above pipe (ft)

$D$ = inside diameter of the host pipe (in.)

$l$ = effective length caused by surface traffic wheels (in.)

$r$ = inside radius of the host pipe (in.) = $D$/2

$\mu$ = Poisson's ratio of concrete (0.15)

$N$ = safety factor (2.0 default)

$E$ = initial long-term modulus of elasticity (ksi) = 2,000

$$t_{fd}{}^{2.5} = N \frac{W_t l r^{1.5} (1-\mu^2)^{0.75}}{0.807E} \quad \text{(Eq. 2.2)}$$

$t_{fd}$ = minimum thickness required, fully deteriorated pipe (in.)

$W_t$ = total loads (psi) = $P_w$ + $W'_s$

$W'_s$ = soil and live loads (psi) = $W_c$/12/$D$

$W_c$ = loads on pipe (lb/ft) = $C_d \times w_s \times (B_d/12)^2$

$C_d$ = load coefficients

$ku'$ = soil coefficients

$H$ = depth of cover from ground surface to top of pipe (ft)

$B_d$ = width of trench (inches) = $D$ + 24 in.

$w_s$ = unit weight of soil (lb/ft$^3$)

Authors concluded that the fiber reinforced geo-polymer SAPL used in this study is structurally applicable instead of full replacement.

### 2.4.3 Resin-based

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 polyurea SAPL increases the compressive strength of RCP. Authors used external coating and internal spraying, which are not usable for the application of renewal of existing culverts. Authors used D-Load tests and ignored the impact of soil-pipe-structure interactions.

### 2.4.4 Cementitious

Kampbell (2016) studied lining large diameter pipes with cementitious materials. The objective of this paper was to discuss the performance considerations of design and development of a new generation of cementitious material to be used as SAPL. Kampbell presented the characteristics of these materials by describing thixotropy, permeability, modulus of rapture, thin-shell toughness, and freeze-thaw performance. The author concluded that due to soil structure behavior under hydrostatic and live loads, SAPL needs a comprehensive evaluation of site conditions.

## 2.5 Invert Paving

Sargand et al. (2015) studied a CMP arch culvert based on the level of corrosion in Muskingum County, Ohio. 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. Results show that under service load, there is no difference between paved and original CMP. Figures 2.4 and 2.5 show longitudinal strain at the peak and valley of CMP before and after paving.

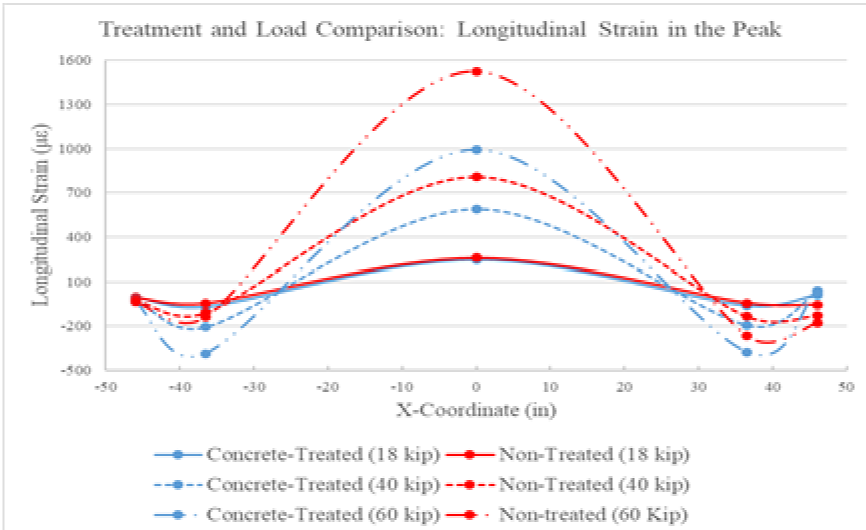


Figure 2.4. Comparision of Longitudinal Strain at Peak of Corrugation before and after Paving – Source: Sargand et al. (2015)

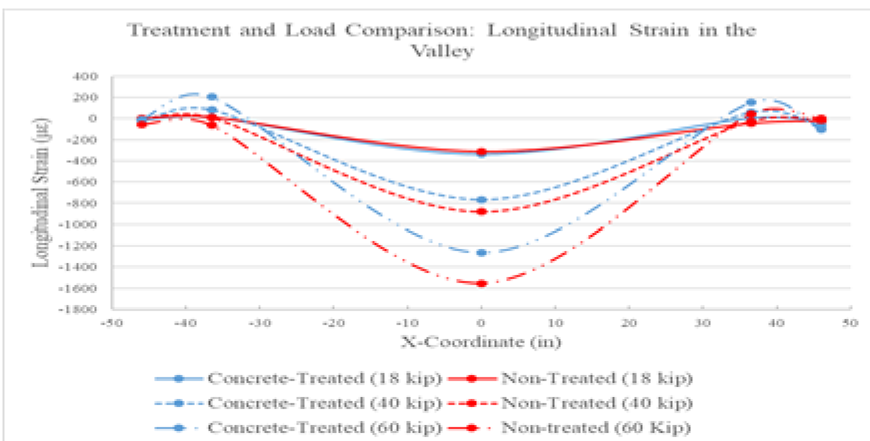


Figure 2.5. Comparision of Longitudinal Strain at Valley of Corrugation before and after Paving – Source: Sargand et al. (2015)

Tetreault et al. (2018) analyzed a shallow depth horizontal 5.3-ft span and 4.3-ft rise ellipse CMP culvert (1.6 m span and 1.35 m rise). Their objectives were to examine the corroded ellipse culvert behavior before and after paved invert rehabilitation under service load and to check the ultimate load bearing capacity. Experimental methodology included first putting an intentionally corroded elliptical culvert under 1.5 ft (0.45 m) of soil cover with service load of a tandem axle wheel pad. Second, the invert of the culvert was paved with concrete and tested under load. Figure 2.6 illustrates the schematic of CMP culvert position for the soil box testing.

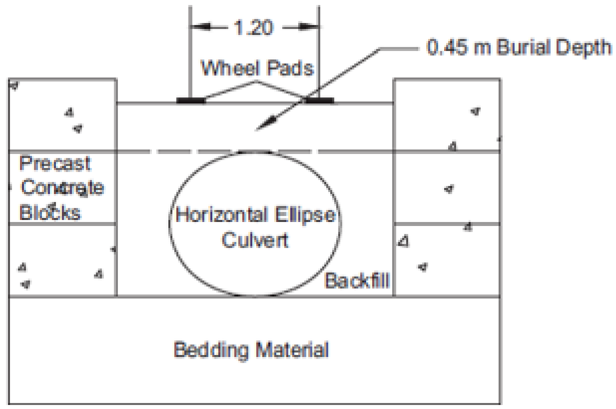


Figure 2.6. Cross Section of Culvert Position and Load Applied
Source: Tetreault et al. (2018)

In this study, the thickness of a CMP culvert was reduced in different locations by 10 to 20%. A poorly graded sandy gravel (AASHTO soil classification GP-SP) was selected for embedment and bedding with 95% of standard Proctor. However, in another part of this paper, the authors mentioned that loose material was used for bedding. The selected rehabilitation methodology was paving the invert with a 4-in. (100 mm) thickness of concrete layer in 5.3 ft (1.6 m) of the inside sector of the horizontal ellipse with a 4 x 4 galvanized mesh. A 23- by 10-in. (600-

by 25-mm) steel load pad was used for service load and a 37- by 14-in. (950- by 370-mm) wooden load pad was used for ultimate load. The conclusions were:

- The loading zone area is more critical,
- The corrosion at the invert of the horizontal ellipse did not have a significant impact on the performance of the culvert under service loads,
- The paved invert rehabilitation technique seemed to improve the structural performance of the horizontal ellipse under service loads,
- The bending capacity increased from 180 Kips (800 KN) to 214 Kips (950 KN), and
- Both intact and rehabilitated horizontal ellipse culverts experienced similar failure mechanisms. The intact culvert failed under 298 Kips (1,325 KN) and rehabilitated culvert failed under 360 Kips (1,600 KN).

Masada et al. (2017) studied structural contribution of paving invert of culvert. Two field studies at Ohio University's outdoor loading tests facilities were performed to obtain data. The study continued by engineering analysis and computer simulations. Selecting a suitable culvert in the field was based on cover depth over the crown between 1 to 2 ft, span 5 to 10 ft, no or little sediment, shallow flow depth if it is normal, moderate to severe deterioration (perforations) on the invert or interface area in the haunch, and good site accessibility. The culvert was tested under an

H-20 gravel loaded truck before and after paving in different loading position. Figure 2.7 illustrates the position of wheel loading over the culvert after paving the invert.

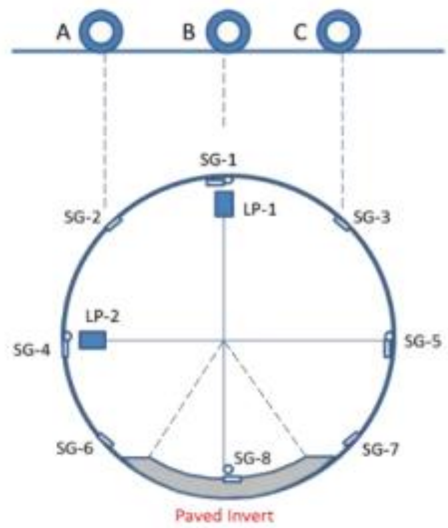


Figure 2.7. Culvert Loading Positions in the Field
Source: Masada et al. (2017)

The authors continued testing in an outdoor site with a 60-in. diameter CMP, 16-ft length and 2-2/3 in. (pitch) corrugation by ½ in. (depth). This CMP had a thickness of 0.109 in. (gage 12) and the pipe wall moment of inertia was 3.425 x $10^{-3}$ $in^4$/ft. This CMP was tested three times, including baseline performance, removal of 1/3 of the bottom and after paving CMP. The authors presented the following results:

- More settlement of the soil cover and more deflection when the CMP invert is severely deteriorated.
- After removing the invert, the load capacity of CMP dropped to 73% (considering a 60-in. CMP).
- A dominant failure mode was observed in both situations, when the invert was paved by #4 rebars and with extra steel reinforcement.
- The structural behavior of a paved CMP culverts can be considered similar to the original CMP

## 2.6 Welding #4 rebars to the CMP is recommended to get 100% of structural capacity due to providing better bonding.Chapter Summary

Many structural and construction issues such as applicability of the host culvert conditions must be investigated. This chapter presented an overview of past literature. The depth of soil cover and the embedment have a significant impact on the bearing capacity of a culvert; therefore, analysis of the structural application of a SAPL is also related to the depth of soil cover. A summary of the critiques is presented in Table 2.1.

Table 2.1. Summary of Important Critiques

| Topic | Publication | Critique |
|---|---|---|
| Deterioration | ASTM F1216 | A "fully deteriorated" is not a collapsed culvert |
| Soil-pipe-structure-interaction | Watkins et. al (1982) | Dense embedment needs to be investigated for load bearing capacity |
| | Bian et al. (2012) | A remarkably different with Boussinesq's curve |
| | Jenkins and Drake (2017) | Whether a lined CMP behaves like a rigid pipe or not |
| SAPL Materials | Davidson et al. (2008) | Three-edge bearing tests (D-Load tests) ignores the impact of soil-pipe-structure interactions |
| | Moore and García (2013) | A soil cover of 83-in. (~7 ft), is not representative of a shallow culvert |
| | Royer and Allouche (2016) | D-Load tests<br>A geo-polymer SAPL culvert is a rigid pipe |
| | Masada et al. (2017) | Functionality in paved, deteriorated CMP structural |

## 2.7 References

AASHTO LRFD Bridge Design Specification. (2017). "AASHTO LRFD Bridge Design Specifications," 8th Edition, September 2017. Publication Code: LRFD-8. ISBN: 978-1-56051-654-5. American Association of State Highway and Transportation Officials.

ASCE (American Society of Civil Engineers). (2007). Pipeline Infrastructure Task Committee. "Emerging Concepts for the Design of Pipeline Renewal Systems," ASCE Pipeline Division. Available at: https://www.uta.edu/ce/cuire/Emerging%20Concepts%20in%20Pipeline_Renewal_Design%20Final%20Version.pdf, Date Accessed June 21, 2018.

ASCE (American Society of Civil Engineers). (2010). "Trenchless Renewal of Culverts and Storm Sewers." Prepared by: The Pipeline Infrastructure Committee, ASCE, Reston, VA.

ASTM (American Society for Testing and Materials). (2016) "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube," Standard ASTM F1216-16. ASTM, West Conshohocken, PA.

Bian X., Tang X., Shen W., Ling D., Chen Y. (2012). "An Experimental Study on a Culvert Buried in Granular Soil Subjected to Vehicle Loads," Journal of Advances in Structural Engineering.

Davidson. S.J., Kang, J., Uday, K.V., Brian, P., and Balaji, T. (2008). "PVA Fiber Reinforced Shotcrete for Rehabilitation and Preventative Maintenance of Aging Culverts". Alabama Department of Transportation, Project 930-657, https://rosap.ntl.bts.gov/view/dot/17333, Date Accessed April 24, 2018.

Federal Highway Administration (FHWA). (2012). "Hydraulic Design of highway Culverts." 3rd Edition, Publication No. FHWA-HIF-12-026. U.S. Department of Transportation.

Federal Highway Administration (FHWA) for Federal Land Highway (FLH) (2010). "Culvert Assessment and Decision-making Procedures Manual." Publication No. FHWA-CFL/TD-10-005. U.S. Department of Transportation. Central Federal Lands Highway Division, 12300 West Dakota Avenue, Lakewood, CO 80228.

García, B. D., and Moore I. D. (2015). "Performance of Deteriorated Corrugated Steel Culverts Rehabilitated with Sprayed-On Cementitious Liners Subjected to Surface Loads." *Tunneling and Underground Space Technology*, Vol. 47, No. 3, 2015, pp. 222–232.

Jenkins, D. and Drake, L. (2017) "Corrugated Steel Culvert Lining Systems – Innovative Analysis and Design Methods." 10th Austroads Bridge Conference, Melbourne, Victoria, Australia.

Kampbell, E. (2016). "Lining Large Pipes with the New Generation of Cementitious Lining Materials," ASCE Pipelines 2016.

Masada, T., Hurd, J. and Fekrat, A. Q. (2017), "Structural Benefits of Concrete Paving of Steel Culvert Inverts." Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. Report No. FHWA/OH-2017-21

Matthews, J. C., Condit, W., Vaidya, S. and Stowe, R. (2014). "Performance Evaluation of an Innovative Fiber Reinforced Geopolymer Spray-Applied Mortar for Large Diameter Wastewater Main Rehabilitation in Houston, Texas." A Report Prepared for U.S. Environmental Protection Agency (EPA). EPA/600/R-14/443.

Moore, I. D. and García, B. D. (2013). "Measured Response of Two Deteriorated Metal Culverts Repaired with Sprayed Cementitious Liners." Report on performance of the GeoSpray liner system for the 407 ETR, November 2013, 117pp, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.719.7274&rep=rep1&type=pdf , Date Accessed April 24, 2018.

Moore, I. D. and García, B. D. (2015). "Ultimate Strength Testing of Two Deteriorated Metal Culverts Repaired with Spray-On Cementitious Liners." Transportation Research Record: *Journal of the Transportation Research Board*, No. 2522, 2015, pp. 139-147, https://trrjournalonline.trb.org/doi/pdf/10.3141/2522-14, Date Accessed April 24, 2018.

Moore, R.G., Bedell, P.R. and Moore I.D. (1995), "Design and Implementation of Repairs to Corrugated Steel Plate Culverts." ASCE Journal of Performance of Constructed Facilities, Vol 9, No.2.

Najafi, M. (2016). "Pipeline Infrastructure Renewal and Asset Management," McGraw-Hill, New York, NY.

Najafi, M. (2005). "Trenchless Technology: Pipeline and Utility Design, Construction and Renewal," McGraw-Hill, New York, NY.

NCHRP SYNTHESIS 303. (2002). "Assessment and Rehabilitation of Existing Culverts," A Synthesis of highway Practice. National Cooperative Highway Research Program (NCHRP). Transportation Research Board of the National Academes.

ODOT (2017). Ohio Department of Transportation, Culvert Management Manual, http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Culvert%20Management/Culvert%20Management%20Manual/Culvert%20Management%20Manual%20October%202017%2011-9-17.pdf, Date Accessed April 24, 2018.

Royer, J. R., and Allouche, E. (2016). "Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Stormwater Conduits." NASTT, Dallas, Texas. WM-T6-03

Royer, J. R., and Iseley, T. (2017). "Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Storm Water Conduits, Part II – CMP Culvert Analysis." NASTT, Washington, D.C., TM2-T3-04

Sargand, S., Khoury, I., Jordan, B., and Hussein H. (2015). "Ultimate Load Capacity of Corrugated Steel Pipe with Extreme Corrosion." *Prepared for* Ohio Department of Transportation (Ohio DOT). Prepared in cooperation with the Ohio DOT and the U.S. Department of Transportation, Federal Highway Administration.

Szafran, J. and Matusiak, A. (2017), "Structural Behavior and Compressive Strength of Concrete Rings Strengthened with a Polyuria Coating System." Monograph from Scientific Seminar

Organized by Polish Chapters of International Association for Shell and Spatial Structures, University Science and Technology. Civil, Architecture and Environmental Engineering, Lodz University of Technology, Poland, https://www.researchgate.net/publication/321484765_Structural_behaviour_and_compressive_strength_of_concrete_rings_strengthened_with_a_polyurea_coating_system, Date Accessed April 24, 2018.

Tetreault J., Hoult N. A. and Moore I. D. (2018). "Pre- and post-rehabilitation behavior of a deteriorated horizontal ellipse culvert." Canadian Geotech Journal Vol. 55, 2018. Published at www.nrcresearchpress.com/cgi

Tian Y., Cassidy J. M. (2008). "Modeling of Pipe-soil Interaction and its Application in Numerical Simulation," International Journal of Geo-mechanics.

Wagener, B.D. and Leagjeld, E. E. (2014). "Culvert Repair Best Practices, Specifications and Special Provisions – Best Practices Guidelines", Published by Minnesota Department of Transportation.

Watkins, R. K. and Reeve, R. C. (1982) "Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe." Advanced Drainage Systems, Inc., Columbus, Ohio, http://onlinepubs.trb.org/Onlinepubs/trr/1983/903/903-014.pdf, Date Accessed April 24, 2018.

# Chapter 3: Evaluation of Literature on Design and Performance of Spray Applied Pipe Linings for Renewal of Culverts and Drainage Structures[1]

## 3.1 Abstract

Different studies show that design and implementation of culvert renewal and rehabilitation is complex due to the depth of soil cover, traffic loads, type of embedment, culvert material and age, etc. Spray Applied Pipe Linings (SAPLs) are one of the renewal methods for deteriorated culverts and drainage structures used for semi-structural applications. This paper provides a review of literature to identify the capabilities of SAPLs and to select an appropriate process based on physical properties and type of application. Many structural and construction issues, such as the applicability of the host culvert conditions, must be investigated. This literature review concludes that SAPLs have potential for renewing deteriorated culvert pipes and can be used as semi-structural applications.

## 3.2 Introduction

Drainage infrastructure systems (culvert, storm sewer, outfall and related drainage elements) are buried underground and need 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 traffic disruptions and social costs. Further challenges are the variety in available pipe material types, shapes, embedment materials, types of roads, wide geospatial distribution and environmental exposures that make every single culvert unique (Najafi et al., 2008).

[1] This paper is published in the ASCE Pipeline conference, July 2019, Nashville, US.

The Ohio DOT (2017) defines a culvert 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.” The Federal Highway Administration (FHWA) (2012) considers culverts as buried structures with spans of less than 20 ft for arch shapes (diameter less than 20 ft for circular shapes). The Ohio DOT (2017) considered a culvert to have a span or diameter less than 10 ft.

### 3.2.1 Culvert Renewal Methods

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

Najafi 2013 summarized renewal/rehabilitation methods based on the maximum length of installation, range of diameters and type of material as shown in Table 3.1. This paper focuses on spray applied pipe linings as described in the following sections.

Table 3.1. Application of Trenchless Renewal Methods
(Adapted from Najafi 2013)

| Trenchless Renewal Method | Diameter Range (in.) | Maximum Installation (ft) | Liner Material |
|---|---|---|---|
| Cured-in-Place Pipe (CIPP) | 4 – 120 | 1,000 – 3,000 | Thermoset resin/fabric composite |
| Sliplining | 4 – 100 | 1,000 – 2,000 | HDPE, PVC, GRP |
| Spray-in-Place Pipe (SIPP) | 4 – 180 | 500 | Cement mortar, geo-polymer epoxy, polyurea, polyurethane |
| Pipe Bursting | 4 – 48 | 1,000 | HDPE, DI, PVC, VCP and GRP |

### 3.2.2 Spray Applied Pipe Linings

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. The type of deterioration is dependent upon the existing structure under consideration. According to Najafi (2013), the main objective of a structural renewal is to inhibit further deterioration and to 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 polyuria. All these different types of SAPLs have advantages and limitations.

## 3.3 Methodology

### 3.3.1 Liner/Pipe/Soil Structure Interaction

#### 3.3.1.1 Impact of Soil Cover on the Buried Pipes

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 the 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. The results showed that side fill material at certain densities restrained the pipe without significant effects from height of soil cover.

Bian et al. (2012) studied the effect of pipe burial depth. A full-scale model test of a concrete culvert in the test box 50 ft x 16.7 ft (15 m x 5 m) in plan area and 20 ft (6 m) in depth was performed. The culvert was covered under various depths of the granular soil. Pressure cells were used to measure the pressure above the crown at different burial depths. A convergence gauge was used to measure the change in the profile of the culvert and a rebar stress gauge was used to measure the structural response. Vehicle loads were applied in steps of 2.25 kips (10 KN) to a maximum load of 15.7 kips (70 KN). The experiment concluded that, under various load conditions, the load from the vehicle tire decreases about 10% with the increase of each 3.3 ft (1.0 m) depth of the soil fill.

Soil-Structure interaction shows significant effect during the design of reinforced concrete liner. Jenkins and Drake (2017) studied this effect by using finite element modelling (FEM) on these concrete liners inside of corrugated circular and pipe-arch culverts. The objective of their study was to compare the results of the simplified design analysis as indicated in Australian design codes with the FEM by considering soil-structure interaction of culverts under train (live) load. Their methodology included a simplified frame design analysis of multi-cell 11.5 ft (3.5 m) diameter circular pipes and multi-cell 26 x 13 ft (8 x 4 m) pipe-arch sections, without considering soil-structure interaction according to Australian design codes. In the two-dimensional finite element scheme, modeling the soil-structure interaction was considered and the host pipe was removed. The finite element results depicted that a substantial reduction in bending moments compared with the simplified analysis. The reduction in bending moment was approximately 65% for circular culverts, and 50% for arch culvert under dead load and live load, respectively. It was concluded that soil-structure interaction significantly improves the structural efficiency of the reinforced concrete liner.

Tian and Cassidy (2008) studied three different, but related models, to model the pipe-soil interactions viz., Elastoplastic Model (EP), Bounding Surface Model (BS) and Bubble Model (BM). The EP model is based on conventional plasticity theory and uses a combined loading yield surface to define allowable loading conditions, a hardening law to describe the expansion of this surface with embedment, an elasticity matrix to define elastic response of increments inside the yield surface and a flow rule to describe elastoplastic event. The Bounding Surface Model (BS) improves upon the EP model by considering the nonlinear behavior of soil even under small loading conditions, which in the EP model fall into the purely elastic zone. The bubble model (BM) which accounts for the kinematic hardening under small cyclic loads further improves upon the BS model. It consists of a small yield surface travelling inside the outer bounding surface with the soil behavior inside the small yield surface assumed purely elastic. This paper concludes that the EP model is only suitable for normally loaded cases, where the current load point is exactly on the bounding surface, whereas, the BM and BS models are applicable for increments inside the bounding surface and for cyclic loading cases.

Elastic buckling is a significant parameter in the design of culverts. Moore et al. (1995) studied the rehabilitation of three-collapsed corrugated steel plate culverts consisting of 37 ft (11.28 m) span horizontal ellipses located in Elgin Country, Canada. The objective of this study was to investigate the major cause for the culvert failure and monitoring of the construction during rehabilitation. Their methodology included the geotechnical investigation around the pipes to check the construction deficiencies and analysis of structural stability. The result of this investigation showed that the failure was not because of construction practice. They found that the culverts were barely stable with respect to elastic buckling, which was a fault in the original design. The steps taken to implement the repairs were selection of construction equipment, sequence of excavation, concreting and backfilling operations. Table 3.2 summarizes above studies and presents the relationship of soil cover depth and embedment to the load bearing capacity of the culvert.

Table 3.2. Impact of Embedment and Soil Cover on the Load Bearing Capacity of Culvert

| Pipe/Culvert Material and Size | Load Types/ Failure Load | Impact of Embedment and Soil Cover on the Load Bearing Capacity of Pipe/Culvert | Author | Year |
|---|---|---|---|---|
| Corrugated Polyethylene Pipe | Truck Load | Embedment at certain densities restrained the pipe without significant effects from height of soil cover. | Watkins et al. | 1982 |
| Concrete Culvert | Vehicle Load | Load from the vehicle wheel decreases approximately 10% with increase of each 3.3 ft depth of the soil cover. | Bian et al. | 2012 |
| Horizontal Ellipse-shaped Corrugated Steel Culvert | Elastic Buckling | The culverts were barely stable with respect to elastic buckling | Moore et al. | 1995 |

### 3.3.2 Cementitious SAPL Materials

#### 3.3.2.1 SAPL Applications by Using Fiber Reinforced

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 D-load testing of full-scale composite host pipe with liner. Finite Element Modelling (FEM) indicated that the optimum thickness would be one in. Figure 3.1 illustrates the results of FEM. An analytical approach was derived for designing the required liner thickness. The authors concluded that PVA offers intriguing and unique characteristics that would minimize the required liner thickness, while providing tension, strength, rigidity and ductility.

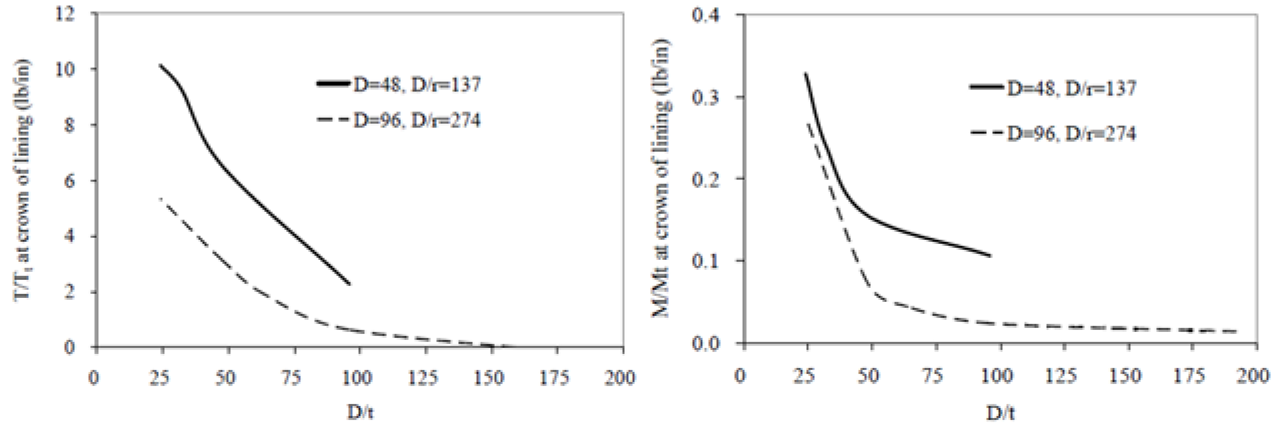


Figure 3.1. Axial Forces, T (left) and Bending Moments, M (right) at the CMP Crown
Source: Davidson et al. (2008)

3.3.2.2 SAPL Application by Using Geo-polymers

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 gradually over these lined CMPs. Geo-polymer material with 2- and 3-in. thicknesses was used as the SAPL and included 48- and 83-in. soil covers, respectively. Results showed that deteriorated CMPs with SAPLs survived H-20 and HL-93 loads. The loading continued until the lined CMPs failed. The first crack was at a loading of 146 kips, and then with increasing loads, larger cracks started at 169-180 kips.

Moore and Garcia (2015) analyzed the 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 with 3 and 2-in. thicknesses of SAPL were applied for these tests. The maximum measured SAPL strain was approximately 10% of the yield strain. The 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- and 2- in. liner thicknesses that were specified.

Royer and Allouche (2016) conducted laboratory testing of RCP and CMP with and without SAPL. The tests were performed on 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 a 12% deformation. Compressive strength tests were conducted as per ASTM C39, tensile tests as per ASTM C307 and flexural strength tests as per C78. D-Load values were scaled assuming Type IV bedding factor (Bf) of 1.5. 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.

Royer and Iseley (2017) conducted laboratory testing above with a different bedding factor. D-Load values were scaled assuming Type IV bedding factor (Bf) of 2.5. The authors provided the same recommendations as above.

Matthews et al. (2014) presented a report to the U.S. Environmental Protection Agencies (EPA) entitled “Performance Evaluation of an Innovative Fiber Reinforced Geo-polymer Spray Applied Mortar for Large Diameter Wastewater Main Rehabilitation in Houston, Texas.” The objective of this report was to describe the performance of a fiber reinforced geo-polymer spray applied mortar as a structural lining in a 60 in. circular reinforced concrete pipe (RCP) under 25 ft soil cover. “A lining thickness of approximately 3.3 in. was sprayed in the pipe, which is more than the design minimum value of 1.9 in. The third-party test results for compressive strength averaged 8,635 psi after 28 days, which is above the manufacturer stated claim of 8,000 psi at 28 days. However, the samples collected by the research team tested under the manufacturer-stated guidelines (e.g., measured at 7,881 psi or 1.5% below specification for compressive strength). Based on the lower density of the mixture, it was hypothesized that the lower values in these samples were attributable to light rain experienced during sample collection." The design methodology used was for resisting against first, hydrostatic pressure Eq. (3.1) and soil loads Eq. (3.2). The authors concluded that the fiber reinforced geo-polymer SAPL used in this study is structurally applicable for repair of deteriorated culverts.

$$t_{pd}^{2.5} = N\frac{P_w l r^{1.5}(1-\mu^2)^{0.75}}{0.807E} \qquad \text{Eq. (3.1)}$$

Where:

$t_{pd}$ = minimum thickness required, partially deteriorated pipe (in.)

$Pw$ = external hydrostatic pressure due to groundwater (psi) = 0.433($Hw$+$D$/12)

$Hw$ = height of ground water above pipe (ft)

$D$ = inside diameter of the host pipe (in.)

$l$ = effective length caused by surface traffic wheels (in.)

$r$ = inside radius of the host pipe (in.) = D/2

$\mu$ = Poisson's ratio of concrete (0.15)

$N$ = safety factor (2.0 default)

$E$ = initial long-term modulus of elasticity, 2,000 ksi

$$t_{fd}^{2.5} = N\frac{W_t l r^{1.5}(1-\mu^2)^{0.75}}{0.807E} \qquad \text{Eq. (3.2)}$$

Where:

$t_{fd}$ = minimum thickness required, fully deteriorated pipe (in.)

$W_t$ = total loads (psi) = $Pw + W'_s$

$W'_s$ = soil and live loads (psi) = $W_c/12/D$

$W_c$ = loads on pipe (lb/ft) = $C_d \times w_s \times (B_d/12)2$

$C_d$ = load coefficient

$ku'$ = soil coefficient

$H$ = depth of cover from ground surface to top of pipe (ft)

$B_d$ = width of trench (in.) = $D$ + 24 in.

$w_s$ = unit weight of soil (pounds/cubic ft)

Selvakumar et al. (2014) used the above study to evaluate technologies that have the potential to reduce costs and increase the effectiveness of the operation, maintenance, and renewal of aging water distribution and wastewater collection systems. The main objectives of this study were: (a) to use an innovative large-diameter structural rehabilitation technology on a severely deteriorated pipe located beneath a large open storm water channel, and (b) to assess the new technology by an independent third party. The authors once again concluded that the geo-polymer could be used as a structural alternative instead of traditional repair and replacement methods.

### 3.3.3 Resin-based SAPL Materials

Szafran and Matusiak (2017) studied the 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. The 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.

Allouche 2017 studied maximizing the service life of culverts by rehabilitation while minimizing direct costs and traffic disruptions. The objectives of their research were 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 (SAPL) of metal pipes was part of this study, which explained 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 the host culvert.

## 3.4 Chapter Conclusions

The literature review concludes that SAPLs have potential for renewing deteriorated culvert pipes and can be used as semi-structural applications. Many structural and construction issues such as applicability of the host culvert conditions must be investigated. The depth of soil cover and the embedment have a significant impact on the bearing capacity of a deteriorated culvert and will impact application of a SAPL accordingly. Different SAPL thicknesses are tested for cementitious/geo-polymer and polymeric materials by researchers. Results of these studies showed that a comprehensive testing and evaluations are needed to develop a methodology for proper SAPL design based on culvert conditions and SAPL material properties.

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## 3.6 References

Allouche E. (2017). "Culvert Rehabilitation to Maximize Service Life While Minimizing Direct Costs and Traffic Disruption," Active Research, NCHRP 14, Louisiana Tech University.

Bian X., Tang X., Shen W., Ling D., Chen Y. (2012). "An Experimental Study on a Culvert Buried in Granular Soil Subjected to Vehicle Loads," Journal of Advances in Structural Engineering.

Davidson. S.J., Kang, J., Uday, K.V., Brian, P., and Balaji, T. (2008). "PVA Fiber Reinforced Shotcrete for Rehabilitation and Preventative Maintenance of Aging Culverts". Alabama Department of Transportation, Project 930-657, https://rosap.ntl.bts.gov/view/dot/17333, Date Accessed April 24, 2018.

Federal Highway Administration (FHWA). (2012). "Hydraulic Design of highway Culverts." 3rd Edition, Publication No. FHWA-HIF-12-026. U.S. Department of Transportation.

Jenkins, D. and Drake, L. (2017) "Corrugated Steel Culvert Lining Systems – Innovative Analysis and Design Methods." 10th Austroads Bridge Conference, Melbourne, Victoria, Australia.

Moore, I. D. and García, B. D. (2013). "Measured Response of Two Deteriorated Metal Culverts Repaired with Sprayed Cementitious Liners." Report on performance of the GeoSpray liner system for the 407 ETR, November 2013, 117pp, Moore, I. D. and García, B. D. (2015). "Ultimate Strength Testing of Two Deteriorated Metal Culverts Repaired with Spray-On Cementitious Liners." Transportation Research Record: Journal of the Transportation Research Board, No. 2522, 2015, pp. 139-147,

Moore, R.G., Bedell, P.R. and Moore I.D. (1995), "Design and Implementation of Repairs to Corrugated Steel Plate Culverts." ASCE Journal of Performance of Constructed Facilities, Vol 9, No.2.

Najafi, M. (2005). "Trenchless Technology: Pipeline and Utility Design, Construction and Renewal," McGraw-Hill, New York, NY.

Najafi, M. (2013). "Trenchless Technology: Planning, Equipment, and Methods" McGraw-Hill, New York, NY.

Najafi, M., Salem, S., Bhattachar, D., Salman, B., and Patil, R. (2008). "An Asset Management Approach for Drainage Infrastructure and Culverts." Midwest Regional University Transportation Center, Madison, WI, http://www.wistrans.org/mrutc/files/06-08_FR.pdf, Date Accessed April 24, 2018.

Najafi, M., and Osborn, L., (2008). "Trenchless Renewal of Culverts and Storm Sewers." ASCE International Pipelines Conference 2008, July 22-27, 2008, Atlanta, Georgia.

Najafi, M. (2016). "Pipeline Infrastructure Renewal and Asset Management," McGraw-Hill, New York, NY.

NCHRP SYNTHESIS 303. (2002). "Assessment and Rehabilitation of Existing Culverts," A Synthesis of highway Practice. National Cooperative Highway Research Program (NCHRP). Transportation Research Board of the National Academes.

ODOT (2017). Ohio Department of Transportation, Culvert Management Manual, http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Culvert%20Management/C ulvert%20Management%20Manual/Culvert%20Management%20Manual%20October%202017%2011-9-17.pdf, Date Accessed April 24, 2018.

Royer, J. R., and Allouche, E. (2016). "Laboratory Testing and Analysis of Geo-polymer Pipe-lining Technology for Rehabilitation of Sewer & Stormwater Conduits." NASTT, Dallas, Texas. WM-T6-03

Royer, J. R., and Iseley, T. (2017). "Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Storm Water Conduits, Part II – CMP Culvert Analysis." NASTT, Washington, D.C., TM2-T3-04

Selvakumar, A., Matthews, J.C. and Condit, W. (2014). "Demonstration of an Innovative Large Diameter Sewer Rehabilitation Technology in Houston, Texas," NASTT 2014 NO-Dig Show, Orlando, Florida.

Szafran, J. and Matusiak, A. (2017), "Structural Behavior and Compressive Strength of Concrete Rings Strengthened with a Polyuria Coating System." Monograph from Scientific Seminar Organized by Polish Chapters of International Association for Shell and Spatial Structures, University Science and Technology. Civil, Architecture and Environmental Engineering, Lodz University of Technology, Poland,

https://www.researchgate.net/publication/321484765_Structural_behaviour_and_compressive_strength_of_concrete_rings_strengthened_with_a_polyurea_coating_system,

Date Accessed April 24, 2018.

Tian Y., Cassidy J. M. (2008). "Modeling of Pipe-soil Interaction and its Application in Numerical Simulation," International Journal of Geo-mechanics.

Watkins, R. K. and Reeve, R. C. (1982) "Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe." Advanced Drainage Systems, Inc., Columbus, Ohio, http://onlinepubs.trb.org/Onlinepubs/trr/1983/903/903-014.pdf, Date Accessed April 24, 2018.

# Chapter 4: An Investigation of Contractors' Practices for Application of Spray Applied Pipe Liners

## 4.1 Abstract

Spray applied pipe lining (SAPL) is one of the trenchless technology renewal methods, which has the capability to be applied in gravity storm sewers and culverts. SAPL is currently known as a renewal trenchless method for enhancement of structural properties of the host culvert, as well as protection against corrosion. In this method, materials sprayed by a machine/hand in different lifts can achieve the required thickness based on the design criteria. The structural capability of the renewed culvert is related to properties of the SAPL materials and its thickness and culvert geometry and conditions. Due to lack of a standard practices for structural design of this method of trenchless technology, different vendors and contractors have come up with various design methodologies. Data collected through this study show that with the same material properties, different thicknesses were applied with similar host culvert conditions. The objective of this paper is to compare data from existing cementitious SAPL projects with existing ASTM standard for cured-in-place pipe (CIPP) and literature. This data presents materials and thicknesses of SAPLs, and diameters, shapes and materials of host culvert; however, some factors, such as depth of soil cover, type of pavement, and percentage of host pipe deterioration are not included. Two statistical models are used to analyze data including box plots (whisker plots), and upper and lower control limits in four categories of diameters. The results of this paper show that an appropriate thickness for cementitious SAPL lined inside a deteriorated corrugated metal pipe (CMP) culvert needs consideration of several variables, such as, diameter, depth of soil cover, embankment conditions, SAPL bonding with host culvert and other factors as described in this paper. A comparison between data from contractors' practices, literature and ASTM standard provides potential critical and unsafe zones. Results of this paper show that using ASTM CIPP

standard for calculation of the SAPL wall thickness may not be applicable and contractors' design calculations need to be investigated for structural stability.

## 4.2 Introduction and Background

Drainage infrastructure systems (culvert, storm sewer, outfall, and related drainage elements) are buried underground and need special attention in terms of proactive/preventive asset management and rehabilitation/renewal strategies. A culvert is a structure that is used for passing a moderate amount of water under an embankment, such as, highways, roads, railroads, etc., with the span of less than 10 ft (Ohio DOT, 2017). However, FHWA 2012 considers a culvert's diameter/span to be up to 20 ft. Culverts are constructed with different materials and geometric shapes, using materials such as, concrete, steel, PVC, HDPE, and corrugated metal pipe (CMP), corrugated HDPE and in shapes of box, circular, pipe arch, vertical/horizontal ellipse, etc. According to ASTM – A760/A760M 2015, CMPs are classified into 10 types. This classification discusses the shape (circular or arch), the type of corrugation (annular or helical), the smoothness of inside of the CMP, and the flatness of the arch CMPs. This paper focuses on circular CMP culverts.

Several methods are developed for pipe/culvert rehabilitations/renewals. The installation of a liner to renew the culvert requires proper selection of the renewal method, material and thickness as well as host culvert inspection and preparation (Jalalediny Korky et al. 2019b).

*Spray Applied Pipe Lining (SAPL)* is a trenchless technology method that is used when a pipe/culvert needs to be rehabilitated/repaired/renewed. Not only does SAPL enhance structural properties of host culvert, but also protects it against the corrosion. In this method, materials sprayed by spin-cast or manually at different passes can achieve the required thickness based on the design criteria. The common types of SAPL materials are cementitious materials, geo-polymers, fiber reinforced concrete, and resin-based materials. This paper is based on contractors' practices for cementitious SAPL culverts.

The objective of this paper is to compare data from existing cementitious SAPL projects with existing ASTM standard for cured-in-place pipe (CIPP) and literature. This data presents materials and thicknesses of SAPLs, and diameters, shapes and materials of host culvert; however, some factors, such as depth of soil cover, type of pavement, and percentage of host pipe deterioration are not included. Two statistical models are used to analyze data including box plots (whisker plots), and upper and lower control limits in four categories of diameters.

The inverts of many CMP culverts are corroded after years of service. According to ASTM – F1216-16 2016 a corroded culvert is considered partially deteriorated if the liner is designed to carry the hydrostatic loads. When a corroded culvert cannot carry dead loads (pavement and soil loads), live loads (truck load), and hydrostatic loads it is considered fully deteriorated. The methodology involved in this paper is based on the fully deteriorated application.

This paper is focused on the thickness of SAPL with the assumption that the physical properties of the SAPL satisfies the minimum thickness criterion.

## 4.3 Literature Review

Davidson et al. (2008) studied polyvinyl alcohol (PVA) fiber reinforced concrete. The goal of their paper was to analyze the use of PVA fiber reinforced concrete on corrugated metal pipes (CMPs) to rehabilitate using SAPL. They evaluated the soil-structure interaction of cementitious liners for CMPs by D-load testing of full-scale composite host pipe (d = 48 in.) with 1.5 in. thickness of liner. In order to find a relationship between thickness and the other parameters, they used FEM.

Matthews et al. (2014) described the performance of a fiber reinforced geo-polymer spray applied mortar as a structural lining in a 60 in. circular reinforced concrete pipe (RCP) under 25 ft of soil cover. This pipe was lined with 3.3 in. thickness approximately, which is more than the design minimum value of 1.9 in. geo-polymer material with compressive strength of 8,635 psi at 28 days was used in this project. Because of the uncertainty of the design equation, they were not satisfied by 1.9 in., and they applied 3.3 in., which is two times more than the calculated value.

Royer and Allouche (2016) and Royer and Iseley (2017) recommended a minimum thickness of liner for geo-polymer materials which are 1-in. for pipes smaller than 54-in. and a minimum of 1.5-in. for larger pipes. Moore and Garcia (2015) applied 2 in. and 3 in. of Geo-polymer liner in a 48 in. diameter partially deteriorated pipe. They applied different thicknesses for different depths of soil cover in the laboratory tests. They consider these two thicknesses for 48-in. and 83-in. soil covers depth, respectively. The results showed that deteriorated CMPs with SAPLs (2 in. and 3 in. thicknesses for 48 in. and 83 in. soil cover) survived H-20 and HL-93 loads. The loading continued until the lined CMPs failed. The first crack was at a loading of 146 kips, and then with increasing loads, larger cracks started at 169-180 kips.

Allouche (2017) studied maximizing the service life of culverts by rehabilitation while minimizing direct costs and traffic disruptions. Spray-on coating of metal pipes is part of this study which explains SAPLs used with different thicknesses. One of the case studies was a 60-in. pipe with a length of 1,800 ft, which was sprayed with polyurethane at a thickness of 0.3-in. (300 mils)

Huynh et al. (2017) presented wet-mix sprayed ultra-high-performance fiber reinforced concrete (UHPFRC) using this method for the rehabilitation of corrugated metal pipe (CMP) culverts. They stated that wet spraying of an ultra-thin UHPFRC is applicable in the range of 1.2 to 2.3 in. (3 to 6 cm). The product, as a semi-rigid material, increases the structural capacity of the culvert after curing time. The results of their study showed that this application/material is applicable for large diameter CMP culvert as it had a reasonable result after being tested on a 10 ft (3 m) CMP.

Sargand et al. (2015) studied a CMP arch culvert based on the level of corrosion in Muskingum County, Ohio. This case study included replacement of invert with concrete on an arch pipe shape CMP (S = 93”, R = 71”), which is equivalent with an 86” diameter circular shape. 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.

Masada et al. (2017) studied the question of what would be the structurally contribution of paving the invert of culvert? A 60-in. diameter CMP was tested three times, including baseline performance, removal of 1/3 of the bottom and after paving CMP with concrete in a range of 3 to 6 in. thickness with #4 rebars. Table 4.1 presents a summary of above literature.

Table 4.1. Summary of Thickness and SAPL Materials vs. the Host Pipe Materials and Diameters

| Host Pipe Diameter (in.) | Host Pipe Material | Thickness of SAPL (in.) | SAPL Material | Author | Year |
|---|---|---|---|---|---|
| 48 | CMP | 1.5 | Fiber Reinforce Conc. | Davidson et al. | 2008 |
| 60 | RCP | 3.3 | Cementitious/Geo-polymer | Matthews et al. | 2014 |
| ≤54<br>>54 | RCP and CMP | 1.0<br>1.5 | Cementitious/Geo-polymer | Royer and Allouche, and Royer and Iseley | 2016<br>2017 |
| 48 | CMP | 2.0<br>3.0 | Cementitious/Geo-polymer | Moore and Garcia | 2015 |
| 60 | CMP | 0.3<br>(300 mils) | Polyurethane | Allouche | 2017 |
| 120 (3 m) | CMP | 1.2 (3 cm)<br>2.3 (6 cm) | wet-mix sprayed ultra-high-performance fiber reinforced concrete (UHPFRC) | Huynh et al. | 2017 |
| Equivalent 84 | CMP Arch | 2.0<br>5.0 | Paving by Reinforced Concrete | Sargand et al. | 2015 |
| 60 | CMP | 4.0<br>6.0 | Paving by Reinforced Concrete | Masada et al. | 2017 |

## 4.4 Methodology

In this study, first the existing data (contractors’ practices) is analyzed. Second, based on ASTM F1216-16, the required thicknesses for different pipe diameter are obtained. Third, a ratio of the contractors' practices (thickness of the existing data) and the minimum required thicknesses provided by literature is developed. Fourth, a statistical analysis (independent sample mean comparison) including test of normality and T-test was accomplished.

### 4.4.1 Step 1 – Contractors' Practices Data Analysis

#### 4.4.1.1 Data Collection

Data were collected from the existing SAPL culvert projects, including material and thickness of liner, as well as diameter, shape, and material of host culvert.

#### 4.4.1.2 Assumptions:

The assumptions for bounding data are: 1) The strength of the host pipe is considered negligible because the liner is supposed to act as a standalone structure. 2) The depth of soil above the crown has a non-linear impact on the design (thickness) of SAPL when the soil is partially washed out. The existing data did not have soil characteristics details; therefore, a constant value is exhibited for the depth of soil above the crown. In addition 3) Data did not consider the type and thickness of the pavement, which may distribute the loads over the culvert. As a conservative assumption, the impact of the pavement on distributing the load and on the culvert was not considered.

#### 4.4.1.3 Categorization and Process

SAPL data, including circular and arch pipe shapes (circular equivalent), was categorized into four categories of diameters (four groups of datasets). First, due to the dispersion of the data, specifically the ratio of thickness of liner to the internal diameter of host culvert, a box-and-whisker plot was used to get the best statistical results of data. This technique provides the maximum, minimum, median and quartiles. This method is useful when there is a need of making comparison between the distributions of many groups of datasets. The box-and-whisker method also is capable to identify if there is any outlier of data.

Upper and lower control limit charts was the second statistical method of data analysis in this study. These charts present upper and lower thresholds for considering the structural design. Devore (2012) has stated that control charts are used for monitoring the products, which is the thickness of the liner in this paper. Data were processed based on the same categories of diameters in four upper lower limit charts. Traditionally, control charts are used for monitoring the quality of manufacturing products. Different thicknesses used by different vendors are monitored in this study; therefore, this statistical technique and process to identify a result of product might be matched to this research.

For both methods, box-and-whisker, and Control Charts, the data categorized based on the existing culvert diameters including less than 48 in. (small), bigger than 48 in. and less than 60 in. (medium), bigger than 60 in. and less than 84 in. (large), and extra-large size which is bigger than 84 in. The size of culvert in this research is limited to 10 ft (120 in.)[2] (Table 4.2).

Table 4.2. Culverts Categorization

| Size | Range |
|---|---|
| Small | $D \leq 48$ in. |
| Medium | 48 in. $< D \leq 60$ in. |
| Large | 60 in. $< D \leq 84$ in. |
| Extra-large | 84 in. $< D \leq 120$ in. |

#### 4.4.1.4 Minimum Thickness on Contractors' Practices

Figure 4.1 is a box-and-whisker plot for cementitious materials which, illustrates minimum thickness as 1-in. for diameter less than 84 in. and 1.5-in. for diameter bigger than 84 in., Figure

[2] Federal Highway Administration (FHWA) (2012) considered culverts as buried structures with span less than 20 ft for circular shapes (diameter < 20 ft); however, some DOTs, such as, the Ohio DOT has local laws that have reduced this span to 10 feet in the interest of public safety.

4.2 is the same graph for geo-polymer liner, which illustrates that pipes less than 60 in. diameter have a minimum of 1-in. SAPL thickness. This figure shows that there is a gap of the minimum thickness between pipes with less than 60 in. and bigger than 60 in. diameter, since minimum SAPL thickness for pipes bigger than 60 in. diameter is 2.5 in. This plot does not have whiskers in any categories of diameters. Figure 4.3 illustrates box-and-whisker plot for rigid SAPL materials including both cementitious and geo-polymer for circular and arch shape (equivalent to circular) culverts.

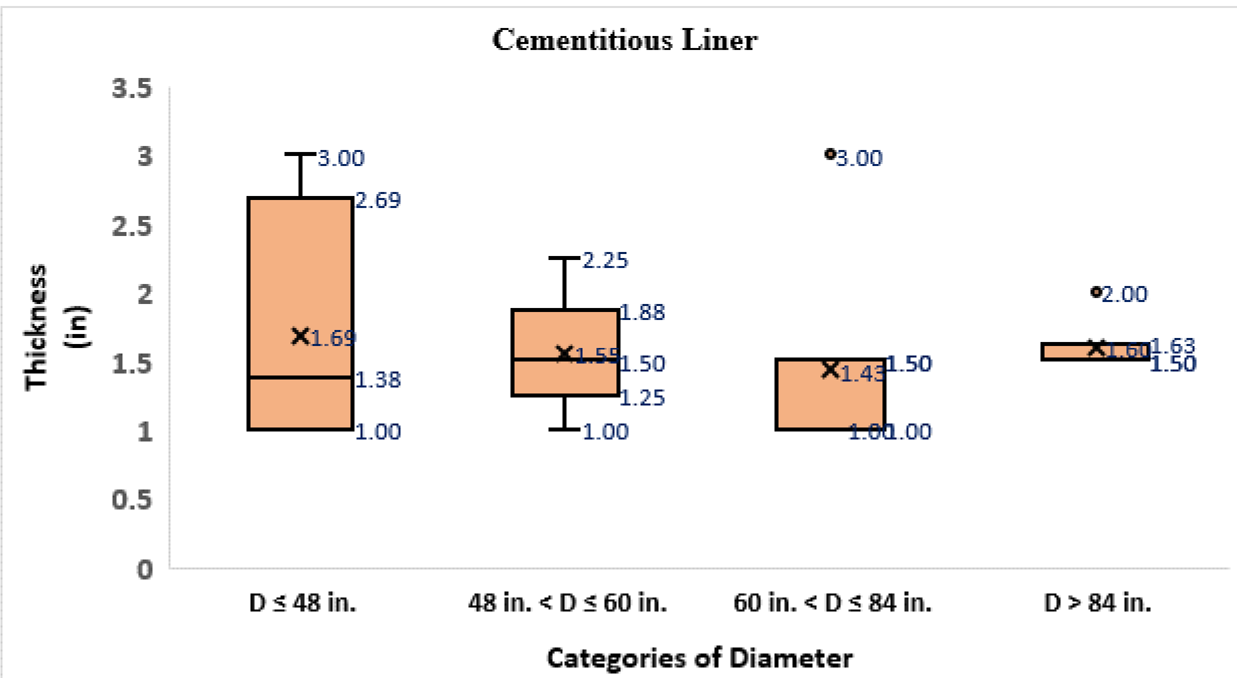



Figure 4.1. Variability of Thickness on Four Categories of Diameter Culverts Lined by Cementitious Material

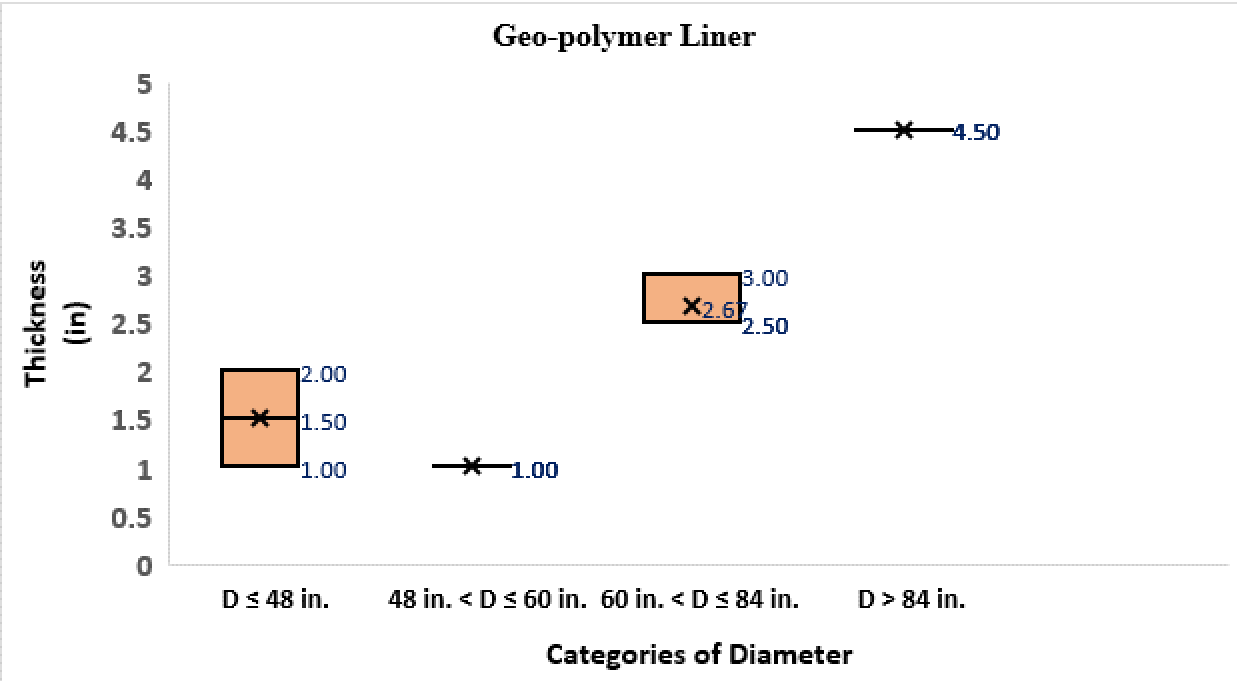



Figure 4.2. Variability of Thickness on Four Categories of Diameter Culverts Lined by Geo-polymer Material

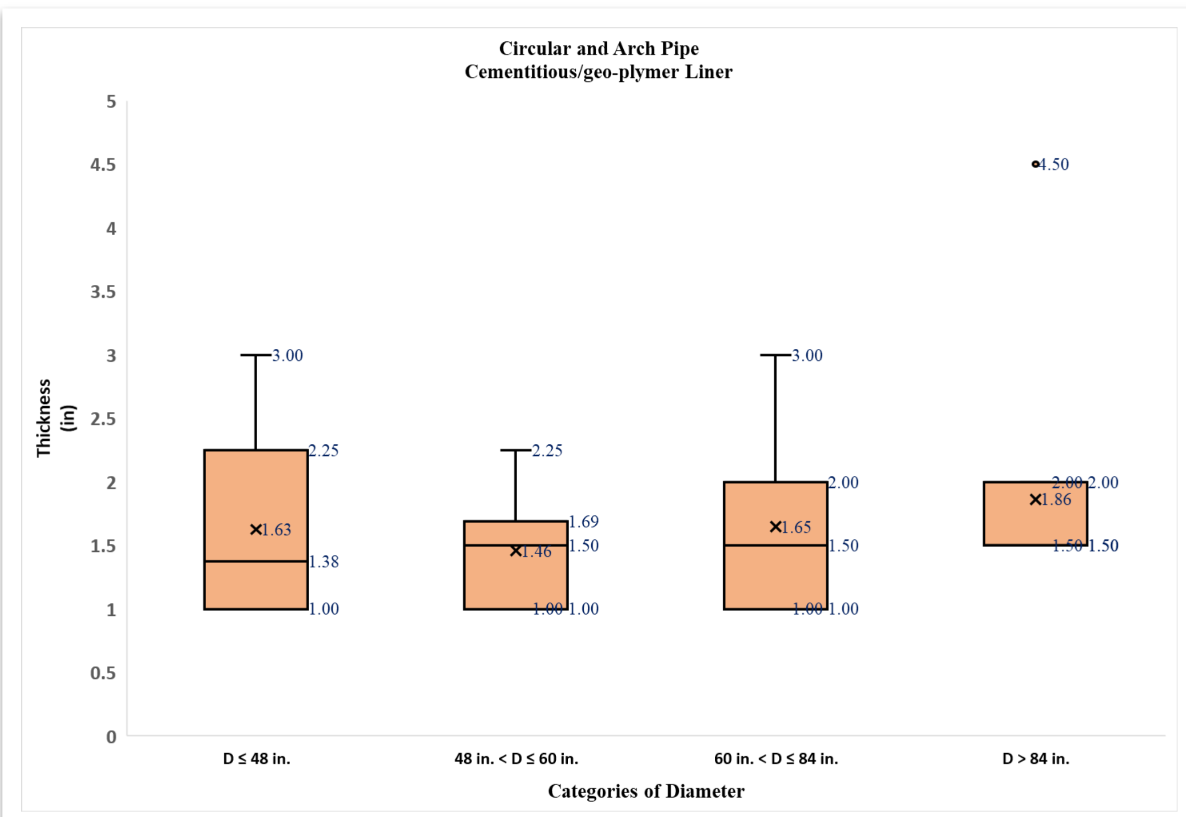



Figure 4.3. Variability of Thickness on Four Categories of Diameter Culverts Lined by Rigid Materials

### 4.4.2 Step 2 – Minimum Required Thickness Based on ASTM F1216-16

Considering 2 ft of cover including flexible pavement over a 60 in. diameter fully deteriorated CMP pipe, the required thickness for SAPL liner based on ASTM F1216-16 is 1.6 in. This thickness is calculated without considering watertable above the crown. With considering watertable in the level of road surface, the minimum of thickness is 1.8 in. A spreadsheet analysis is developed to conduct trial and error calculation to obtain required thickness for different pipe dimeters. These calculations are based on Equation 4.1, which is extract from Equation X1.3, ASTM F1216-16 considering fully deteriorated gravity pipe. Table 4.3 presents different thicknesses versus diameters based on ASTM F1216-16 with assumptions described below.

Table 4.3. Calculated SAPL Thickness Based on ASTM F1216 -16

| **D** (in.) | 30 | 36 | 42 | 48 | 54 | **60** | 64 | 66 | 72 | 78 | 84 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **T** (in.) | 0.9 | 1.1 | 1.3 | 1.4 | 1.6 | **1.8** | 1.9 | 2 | 2.1 | 2.3 | 2.5 | 3.5 |

$$q_t = \frac{1}{N}[32\ R_w\ B'E'_s\ C\left(\frac{E_L I}{D^3}\right)]^{1/2} \qquad (4.1)$$

where:

$q_t$ = Total External Pressure on Pipe, psi (MPa).

= $0.433H_w + wHR_w/144 + W_s$, (English Units),

$R_w$ = Water Buoyancy Factor (0.67 min) = $1 – 0.33\ (H_w/H)$,

W = Soil Density, lb.ft3 (KN/m3),

$W_s$ = Live Load, psi (Mpa),

$H_w$ = Height of Water above Top of Pipe, ft (m)

H = Height of Soil above Top of Pipe, ft (m),

B’ = Coefficient of Elastic Support = 1/ (1 + 4e−0.065H) (English Units),

I = Moment of Inertia of CIPP, in.$^4$/in. (mm$^4$/mm) = $t^3/12$,

$t$ = Thickness of CIPP per in.

$C$ = Ovality Reduction Factor = $\left(\left[1 - \frac{\Delta}{100}\right] / \left[1 + \frac{\Delta}{100}\right]^2\right)^3$

$\Delta$ = Percentage Ovality of Original Pipe =

$$100 \times \frac{(Mean\ Inside\ Diameter - Minimum\ Inside\ Diameter)}{Mean\ Inside\ Diameter}$$

$N$ = Factor of safety

$E'_s$ = Modulus of Soil Reaction, psi

$E_L$ = Long-term Modulus of Elasticity for CIPP[3], psi

$D$ = Mean Inside Diameter of Original Pipe, in.

The CIPP design from Eq 1 (Eq X1.3, ASTM F1216-16) should have a minimum thickness as calculated by $\frac{EI}{D^3} = \frac{E}{12(DR)^3} \geq 0.093$ (English Units)

where:

$E$ = Initial Modulus of Elasticity[4], psi

The below values were selected for calculating and conformity of the ASTM F1216-16 using cementitious material to obtain the minimum thicknesses considering fully deteriorated 60 in. gravity circular conduit:

- Soil Density: w = 120 lb/ft$^3$
- Modulus of Soil Reaction: $E'_s$ = 1,000 psi (Min per ASTM D3839)
- Modulus of Elasticity for Cementitious Material: E = 3,155 ksi

[3] $E_L$ is equal to E = 3,155 ksi

[4] Initial Modulus of elasticity (E) is obtained after curing time (normally = 28 days)

Figure 4.4 illustrates the changes of the slope of line regarding depth of soil above the crown with a constant H-20 truck load based on ASTM F1216-16. Similar analysis is used for one ft cover (minimum cover including the flexible pavement which is one (1) ft per AASHTO LRFD bridge design) for two options, without and with watertable above the crown, which provides the worst-case scenario.

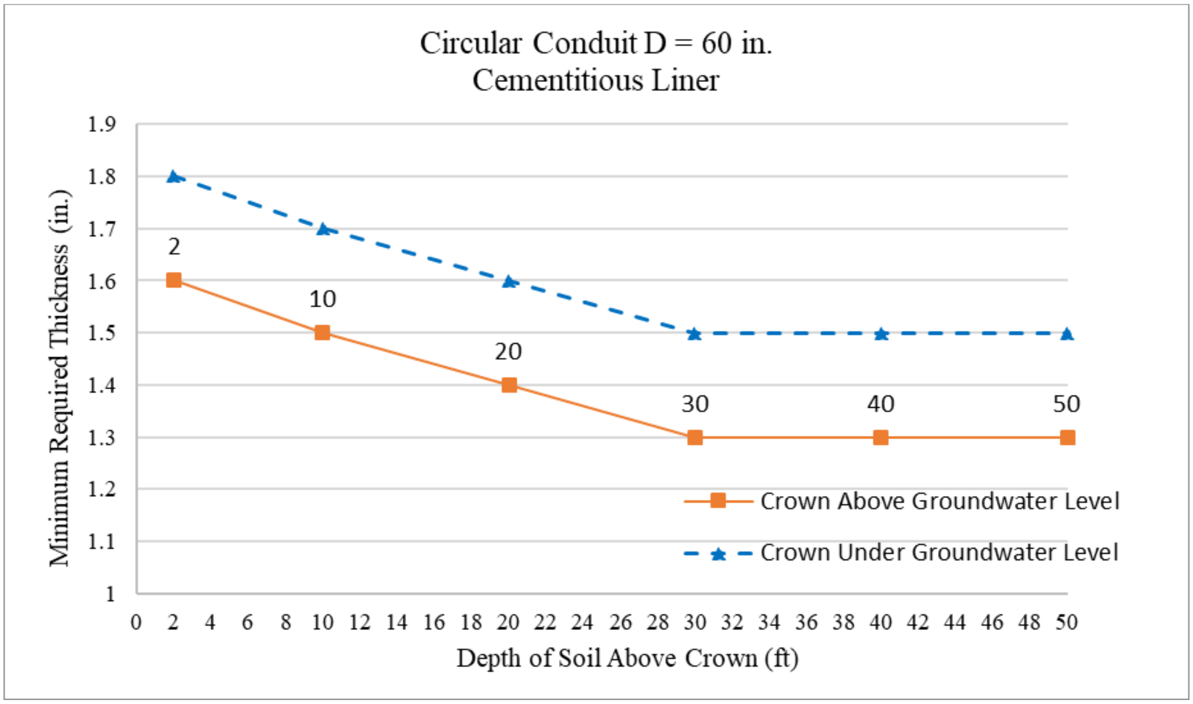



Figure 4.4. Minimum Thickness Required for Cementitious Liner without Ground Water Based on ASTM F1216-16

Comparing Figure 4.4, the thickness of the liner needs to increase by approximately 15% with considering groundwater. Figure 4.4. shows that after 30 ft of depth of soil cover, soil carried (distributed) the loads under influence of soil arch phenomena; therefore, the thickness of the liner (here is CIPP) would be constant. Figure 4.5 illustrates the required thickness of SAPL versus changes in the diameter of the culvert based on ASTM F1216-16. Again, the minimum thicknesses are calculated in a trial and error spreadsheet, and are categorized in (D ≤ 48 in, 48 in. < D ≤ 60 in., 60 in. < D ≤ 84 in., and D > 84 in.) in comparable with the above-mentioned box-and-whisker plots as follows (all other conditions remain the same):

- For small diameter (less than 48 in.), the thickness is 1.4 in.,
- Medium diameter (between 48 in. to 60 in.), the thickness is 1.8 in.,
- Large diameter (between 60 in. to 84 in.), the thickness is 2.5 in.
- Extra-large diameter (above 84 in.), the thickness is 3.5 in.

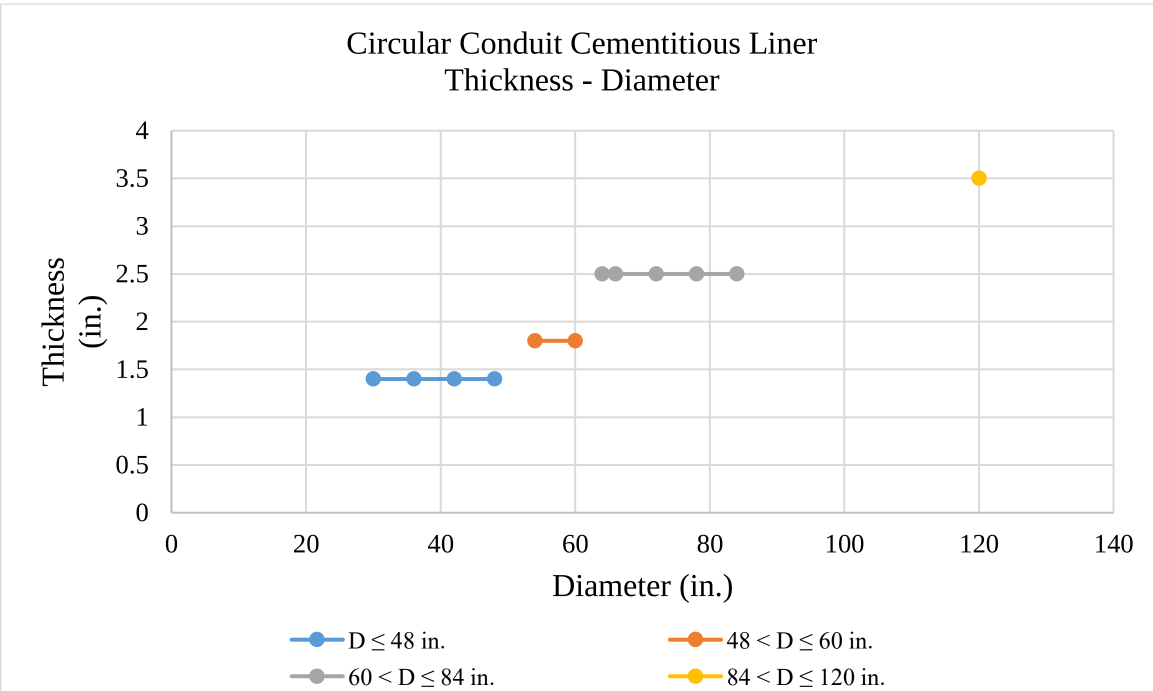



Figure 4.5. Minimum Thickness Required for Cementitious Liner Adjusted Data to Minimum Requirement of ASTM F1216-16

### 4.4.3 Step 3 – Thickness Ratio Data Analysis

The second statistical analysis was based on the upper and lower limitations, which are presented in Figure 4.6. This statistical model is used for data quality control.

Devore (2012), stated that several factors can impact on the product, which is the thickness of SAPL. If data is in the range of upper and lower lines, the process is in control, which does not mean, "design criteria had been satisfied." In fact, using upper lower control for thickness requirements of SAPL is a comparison between design equations used by different vendors with assuming similarity in site and host culvert conditions and methods. Devore (2012) presented different techniques for upper lower control plot, such as, the $\bar{X}$ chart based on known parameter values, $\bar{X}$ charts based on estimated parameters, and so for.

Hines and Montgomery (1981) recommended upper control limit (UCL) and lower control limit (LCL) based on $\bar{X}$ and $\bar{R}$. They suggested:

$$UCL = \bar{\bar{X}} + A_2\bar{R} \tag{4.2}$$

$$LCL = \bar{\bar{X}} - A_2\bar{R} \tag{4.3}$$

Table 4.4 presents the $A_2$ based on the numbers of data (Hines and Montgomery 1981), and Table 4.5 presents $\bar{X}$ , $\bar{R}$ and $A_2$ for small, medium, large and extra-large culvert size.

Table 4.4. Average and Range Charts
Source: Hines and Montgomery (1981)

| n | $A_2$ | n | $A_2$ |
|---|---|---|---|
| 2 | 1.880 | 7 | 0.419 |
| 3 | 1.023 | 8 | 0.373 |
| 4 | 0.729 | 9 | 0.337 |
| 5 | 0.577 | 10 | 0.308 |
| 6 | 0.483 | | |

Table 4.5. $\bar{X}$ , $\bar{R}$ and $A_2$ for Four Categorize of Diameters

| Culvert Diameter Size | $\bar{X}$ | $\bar{R}$ | $A_2$ |
|---|---|---|---|
| Small | 1.35 | 1 | 0.483 |
| Medium | 1.3 | 0.5 | 0.483 |
| Large | 1.647 | 2 | 0.308 (n > 10) |
| Extra-large | 1.6 | 0.5 | 0.308 (n > 10) |

For calculating the UCL and LCL, results of Table 4.5 are applied in Eq. 4.2 and 4.3. For instance, for small size (D < 48 in.):

$UCL = 1.625 + 0.483 * 2 = 2.59$ in.

$LCL = 1.625 - 0.483 * 2 = 0.659$ in.

Table 4.6 presents UCL and LCL for all categorizes of culvert diameter.

Table 4.6. UCL and LCL for Small, Medium, Large and Extra-large Culverts

| Culvert Diameter Size | *UCL* | *LCL* |
|---|---|---|
| Small | 2.59 | 0.66 |
| Medium | 2.06 | 0.86 |
| Large | 2.26 | 1.03 |
| Extra-large | 2.78 | 0.94 |

SAPL thickness calculated by ASTM F1216-16 is compared with contractors' practices. For instance, in the category of small size culvert (diameter less than 48 in.), the upper limit of SAPL thickness, based on the contractors' practices, is 2.59 in. (see Table 4.6 and Figure 4.6); though, the need of thickness, based on ASTM F1216-16, is 1.4 in. (from Figure 4.5). Thus, the ratio between the results of thickness calculated based on ASTM F1216-16 and this upper limitation of thickness obtained by contractors' practices, would be the *opportunity*[5] (certainty) for a future SAPL project (Eq. 4 – less than 1.0). On the other words, the structure is not at *risk*[6].

To continue using upper lower control charts, the ratio between the result of thickness calculated by using ASTM F1216-16, which is 1.4 in., and the lower limitation of thickness obtained by contractors' practices, which is 0.66 in., would be the *risk* (uncertainty) (Eq. 4.5 – more than 1.0). Therefore, the structure can be considered to be under risk. Briefly, below is the number for above example of host culverts with diameters less than 48 in.:

Thickness based on upper limit = 2.59 in.

Thickness based on lower limit = 0.66 in.

Thickness based on literature = 1.00 in.

Thickness based on ASTM F1216-16 = 1.4 in. (Figure 4. 5)

#### 4.4.3.1 Minimum Required Thickness from Literature

If the lower limit is smaller than the minimum thicknesses, which is presented by the literature, then the designer/contractor should use the minimum thicknesses based on the literature. Therefore, in the denominator of equation 5, potential designer should put 1.00 instead of 0.66.

$$R = \frac{1.4}{2.59} = 0.54 \quad (4.4)$$

$$R = \frac{1.4}{1.00} = 1.4 \quad (4.5)$$

In some situations, Equations 4.4 and 4.5 might be more than 1.0, so that it is considered as a risk. In the results and discussion and contribution to the knowledge of this paper, it is

[5] *Opportunity* is a terminology which is used as an antonym of *risk* in statistical books. Here Opportunity means that the contractor's design equation gives bigger thickness of SAPL than ASTM, thus the thickness is in safe zone.

[6] *Risk* = risk of design equation that was developed by contractor. It is in unsafe zone in comparison with ASTM.

explained what the condition of a lined culvert would be when equations 4 and 5 are more than 100%.

The upper and lower graphs show that there is an integrity of design for liner thickness in larger diameter size of culverts, yet in smaller sizes, such as, less than 48 in. and between 48 and 60 in., a wide range of data was observed.

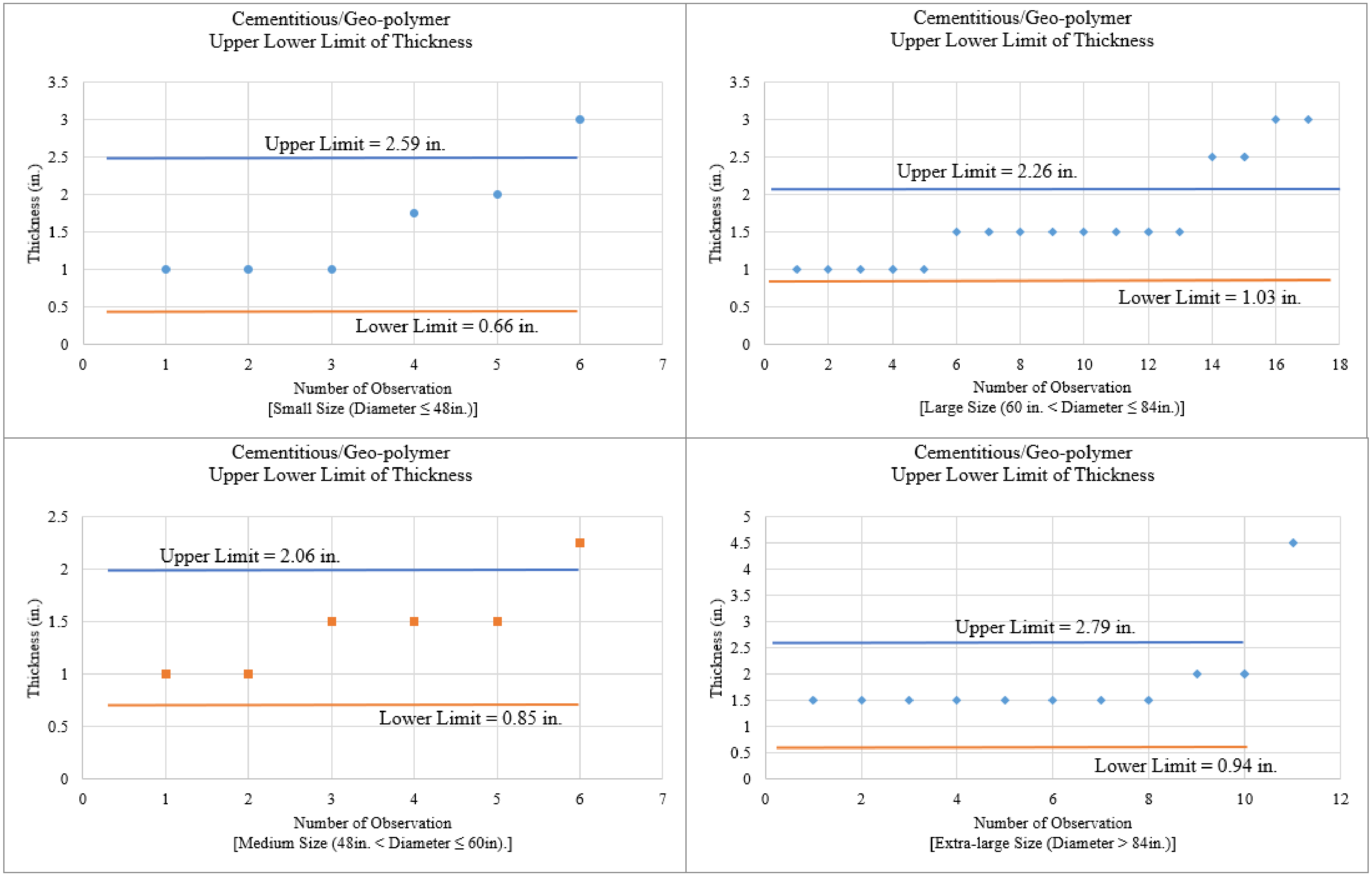



Figure 4.6. Upper and Lower Limitation of Data

#### 4.4.4 Step 4 – Independent Sample Mean Comparison

##### 4.4.4.1 Test of Normality (Appendix 4.A)

The data used in this study include practitioners' choice of liner thickness and a thickness that is calculated by ATSM F1216-16 regarding the diameter of the pipe.

When the data is normally distributed, then the T-test is valid. T-test is a standard way to compare means of samples from populations with normal distribution (Devore, 2015).

There are some specific statistical tests for investigating the normality of the data. One of them that has shown to be very powerful for the populations with unknown mean and variance is the Anderson and Darling test (Pettitt, 1977). XLSTAT software was used to test the normality of the SAPLs' thicknesses of contractors' practice (CP) and the SAPLs' thicknesses that are calculated based on ASTM F1216-16 for each pipe diameter. The test shows that both groups of thicknesses can be considered normal at a 1% significance level.

##### 4.4.4.2 T-Test (Appendix 4.A)

The T-test showed that there is no statistically significant difference between the liner thickness that is calculated by ASTM F1216-16 and what contractors use in practice ($t = 1.077$, P-value = 0.287).

##### 4.4.4.3 Data Plot

Part of data which has a minimum SAPL thickness for different host CMPs' diameters including contractors' practices, literature and calculated thicknesses based on ASTM F1216-16 are presented in Figure 4.7, which illustrates the dispersion of data. Appendix 4.B presents the data in pie charts.

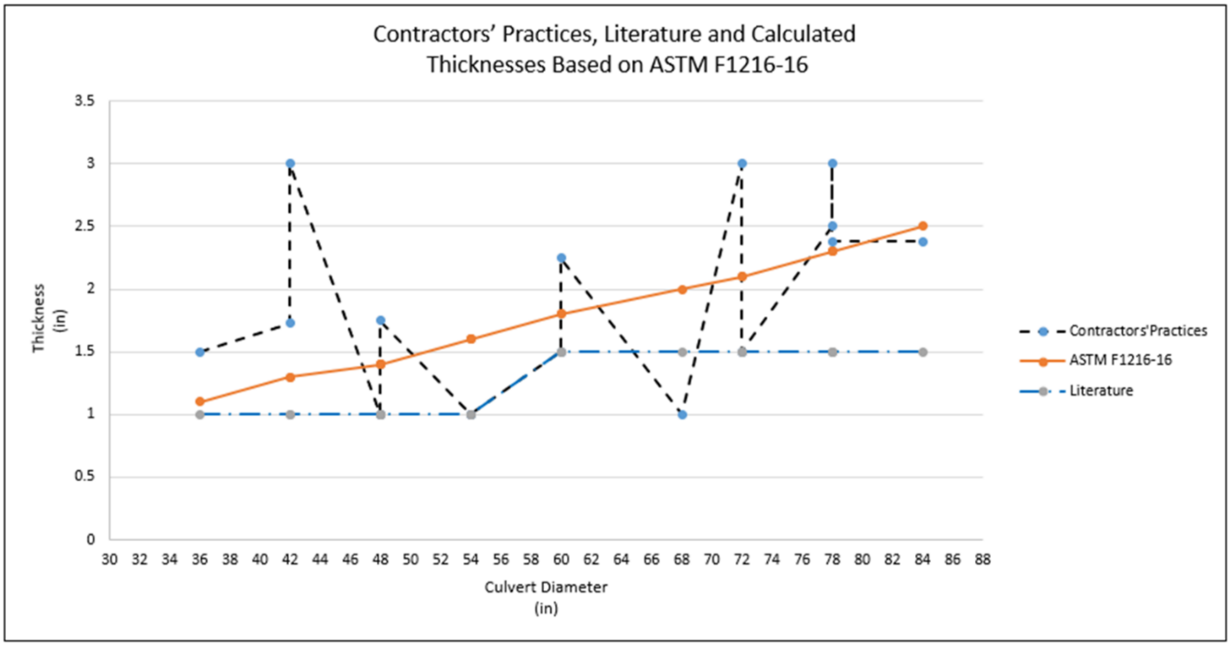



Figure 4.7. Data Plot of Minimum SAPL Thickness for Different Host Pipe Diameters Including Contractors' Practices, Literature and ASTM F1216-16

## 4.5 RESULTS AND DISCUSSION:

Comparing existing data from the literature and from calculating the minimum thicknesses based on ASTM F1216-16, demonstrates that using ASTM F1216-16 for thin wall cementitious liner – in the worst-case scenario – makes a high percentage of risks. Table 4.6 presents the thickness based on the worst-case scenario in three conditions including literature, ASTM F1216-16 calculation, and contractors' practices data.

The amount of opportunity (certainty) in Table 4.6 presents how safe the SAPL is designed, and the amount of risk (uncertainty) in this table presents the critique for future design. In the case of larger diameters, there is a higher risk compared with ASTM F1216-16.

Table 4.7. Risk and Opportunity Percentages of Contractors' Practices Data with ASTM F1216-16 and Literature

| **Category of Culvert Diameter (in.)** | **Worst Case Scenario for Thickness of Liner Cementitious and Geo-polymer** | | | | | |
|---|---|---|---|---|---|---|
| | **Literature** | **Contractors' Practices Data** | | **ASTM F1216-16** | **Status** | |
| | | Lower Limit (Fig. 7) | Upper Limit (Fig. 7) | | (Eq. 4) | (Eq. 5) |
| **D ≤ 48** | 1 | 0.66 | 2.59 | 1.4 | 0.54 (Opportunity) | 1.4 (Risk) |
| **48 < D ≤ 60** | 1.5 in. (D > 54) | 0.85 | 2.06 | 1.8 | 0.87 (Opportunity) | 1.2 (Risk) |
| **60 < D ≤ 84** | 1.5 | 1.03 | 2.26 | 2.6 | 1.15 (Risk) | 1.73 (Risk) |
| **D > 84** | 1.5 | 0.94 | 2.79 | 3.5 | 1.25 (Risk) | 2.33 (Risk) |

The same calculations for calculating the percentage of risk with considering ASTM F1216-16 worst case scenario were completed for thicknesses extracted from literature, which are 1.4, 1.2, 1.73 and 2.33 for small (D ≤ 48 in.), medium (48 in. < D ≤ 60 in.), large(60 in. < D ≤ 84 in.) and extra-large (D > 84 in.) respectively.

In all the categories of diameters, the lower limits were smaller than the minimum thicknesses presented by literature, so that the minimum thicknesses based on literature was used in Eq. 4.5 (refer to column Eq. 5 in Table 4.6). For example, for D ≤ 48 in.:

$$\frac{\text{ASTM F1216} - 16}{\text{Greater of "}\mathit{Lower\ Limit\ of\ Contractor's\ Practice,}\text{" and "}\mathit{Literature}\text{"}}$$

$$= \frac{1.4}{Greater\ of\ 1.0\ in.\ (Literature)\ and\ 0.66\ in.(Lower\ Limit)} = \frac{1.4}{1.0} = 1.4$$

Same as above-mentioned calculation, for upper limit of contractors' practices, can be performed since all numbers in upper limit are bigger than all numbers of literature (see Table 4.6). Where (see Eq. 4 in Table 4.6):

$$\frac{\text{ASTM F1216} - 16}{\text{Greater of "}\mathit{Upper\ Limit\ of\ Contractor's\ Practice,}\text{" and "}\mathit{Literature}\text{"}}$$

$$= \frac{1.4}{Greater\ of\ 1.0\ in.\ (Literature)\ and\ 2.59\ in.(Upper\ Limit)} = \frac{1.4}{2.59} = 0.54$$

Some of the existing deteriorated culverts might have been lined as partially deteriorated as Figures 4.1, 4.2 and 4.3 show wide ranges of thickness applied for the same diameters; however, in this study all the cases were considered as fully deteriorated.

## 4.6 Contribution to The Body of Knowledge

Result of making a comparison between data from contractors' practices, literature and standard (ASTM F1216-16), shows critical and unsafe zones (see Figure 4.8).

Considering that the safety factor equals 4.2, extra-large projects are located inside of the unsafe zone (see Figure 4.8); however, all other categories of diameter are located in the critical zone when ASTM F1216-16 is considered as the only existing standard. The categories of diameters less than 60 in. *might* be in a safe zone, if the results of the existing literature are accepted as a valid data.

The average thicknesses of all four categorizes of culvert size can be considered as centerline $\bar{\bar{X}}$ for all data:

$$\bar{\bar{X}} = \frac{\bar{X}_1 + \bar{X}_2 + \ldots + \bar{X}_k}{k}$$

$$\bar{\bar{X}} = \frac{1.63 + 1.46 + 1.65 + 1.86}{4} = 1.65\ in.$$

A rough thickness requirement for all four categorizes of culvert size can be considered as a weighted average from the upper limit ($\overline{ULC}$) for all data.

$$\overline{ULC} =$$

$$= \frac{ULC_{small} * No._{small} + ULC_{medium} * No._{medium} + ULC_{large} * No._{large} + ULC_{ex.-large} * No._{ex.-large}}{No._{small} + No._{medium} + No._{large} + No._{ex.-large}}$$

$$= \frac{2.59 * 5 + 2.06 * 6 + 2.26 * 17 + 2.79 * 11}{5 + 6 + 17 + 11} = 2.4\ in$$

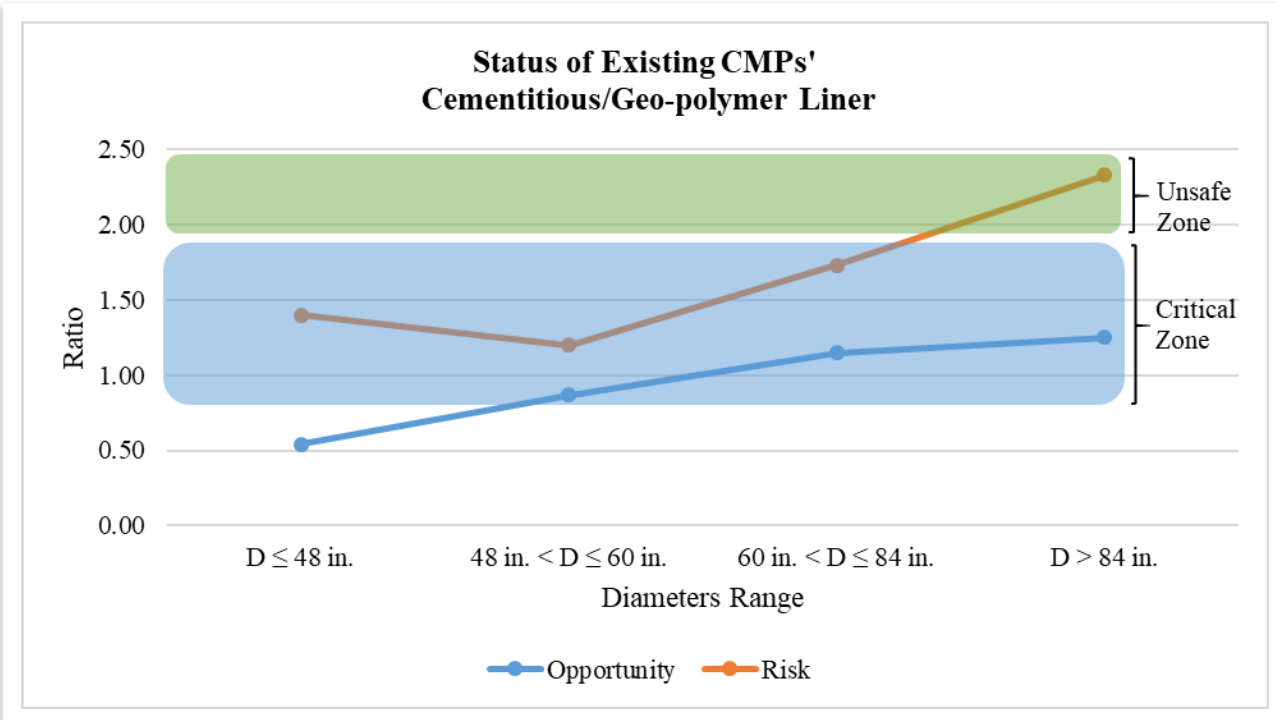



Figure 4.8. Critical and Unsafe Zones Based on a Comparison between ASTM F1216 Literature and Contractors' Practices

## 4.7 Chapter Conclusions

Results of this study showed that a valid design equation/standard needs to be developed for thin cementitious liner. The following should be considered for developing the standard:

- Considering no structural capacity from the host pipe for fully structurally application,
- A realistic assumption for soil density based on the actual compaction,
- Considering groundwater level in the surface of embankment (conservative design),
- Exclude the negative impact of soil arch due to possibility of washing out fine aggregates,
- Taking the real Modulus of elasticity of liner material based on valid laboratories' testing, and

- It is predicted that the thickness of liner does not have a direct relation with the diameter of existing culvert.

## 4.8 Limitations and Recommendations for Future Study

As a thin-wall liner, cementitious SAPL material needs to be investigated for cracks. The cracks must be analyzed either at crown, in the springline or at invert. Recognition of circumferential and longitudinal cracks should be investigated as well. This paper did not cover the construction performance specifications. Site conditions, thick liner (liner thicker than 3 in. that needs to be controlled for shrinkage), extremely narrow cover depth (less than 1 ft), fluctuation of underground watertable, and seismic loads need study.

There were not enough data using polymeric SAPL for CMP renewal when this study was undertaken; therefore, statistical modeling/analysis would not be constructible.

## 4.9 Acknowledgments

This research was conducted under a pool funded project from seven Department of Transportations. The author would like to thank the Ohio Department of Transportation and six other DOTs for funding this project and providing data. I would like to thanks to Vausdeva Kaushik Nandyala for organizing data. Also, I would like to thanks to Dr. Mostafa Ghandehari for assistance on the statistical analysis of this research.

## 4.10 Chapter References

AASHTO (American Association of State Highway and Transportation Officials). (2017) AASHTO LRFD Bridge Design Specification, 8th Edition, LRFD-8. AASHTO, Washington, DC 20001.

ASTM (American Society for Testing and Materials). (2016). “Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube,” Standard ASTM F1216-16. ASTM, West Conshohocken, PA.

ASTM (American Society for Testing and Materials). (2015). “Standard Specification for Corrugated Steel Pipe, Metallic-Coated for Sewers and Drains,” Standard ASTM A760. ASTM, West Conshohocken, PA.

ASTM (American Society for Testing and Materials). (2015). “Standard Guide for Underground Installation of “Fiberglass” (Glass-Fiber Reinforced Thermosetting-Resin) Pipe,” Standard ASTM D3839-14. ASTM, West Conshohocken, PA.

Contech. (2017). “Corrugated Metal Pipe Solution.” www.contechES.com, Contech Engineering Solutions LLC. 9025 Center Polnte Dr. Suite 400, West Chester, OH 45069, U.S.

Contech. (2015). “230 – CSP Round Standard Backfill Detail AASHTO.” www.contechES.com, Contech Engineering Solutions LLC. 9025 Center Polnte Dr. Suite 400, West Chester, OH 45069, U.S.

Davidson. S.J., Kang, J., Uday, K.V., Brian, P., and Balaji, T. (2008). “PVA Fiber Reinforced Shotcrete for Rehabilitation and Preventative Maintenance of Aging Culverts”. Alabama Department of Transportation, Project 930-657, https://rosap.ntl.bts.gov/view/dot/17333, Date Accessed April 24, 2018.

Devore, J. L., (2012). “Probability and Statistics for Engineering and the Science,” Book, Eighth Edition., ISBN-13: 978-0-73352-6., ISBN-10: 0-538-73352-7.

Devore, J. L., (2015). “Probability and Statistics for Engineering and the Science,” Book, Eighth Edition.

Federal Highway Administration (FHWA). (2012). “Hydraulic Design of highway Culverts.” 3rd Edition, Publication No. FHWA-HIF-12-026. U.S. Department of Transportation.

Federal Highway Administration (FHWA) for Federal Land Highway (FLH) (2010). “Culvert Assessment and Decision-making Procedures Manual.” Publication No. FHWA-CFL/TD-10-005. U.S. Department of Transportation. Central Federal Lands Highway Division, 12300 West Dakota Avenue, Lakewood, CO 80228.

Jalalediny Korky, S., Najafi, M., Syar, J. and Nandyalal, V.K. (2019a). “Evaluation of Literature on Design and Performance Guidelines of Spray Applied Pipe Linings.” ASCE Pipeline Conference, 2019, Nashville, U.S.

Jalalediny Korky, S., Homing Ni, A., Najafi, M., Malek M., M. and Serajiantehrani, R. (2019b). “Design and Installation of Water Pipeline Renewals.” NASTT’s 2019 No-Dig Show Conference. Chicago, Illinois, U.S.

Havens, B. T., Klaiber, F. W., Lohnes, R. A., and Zachary, L. W. (1995). “Longitudinal Strength and Stiffness of Corrugated Metal Pipe.” Transportation Research Board, Issue Number 1514. ISSN: 0361-1981. Available at: http://worldcat.org/issn/03611981

Hines W. W., and Montgomery D. C. (1981). “Probability and Statistics in Engineering and Management Science,” 3rd Edition.

Matthews, J. C., Condit, W., Vaidya, S. and Stowe, R. (2014). “Performance Evaluation of an Innovative Fiber Reinforced Geopolymer Spray-Applied Mortar for Large Diameter Wastewater Main Rehabilitation in Houston, Texas.” A Report Prepared for U.S. Environmental Protection Agency (EPA). EPA/600/R-14/443.

Moore, I. D. and García, B. D. (2015). "Ultimate Strength Testing of Two Deteriorated Metal Culverts Repaired with Spray-On Cementitious Liners." Transportation Research Record: *Journal of the Transportation Research Board*, No. 2522, 2015, pp. 139-147.

Najafi, M., Salem, S., Bhattachar, D., Salman, B., and Patil, R. (2008). "An Asset Management Approach for Drainage Infrastructure and Culverts." Midwest Regional University Transportation Center, Madison, WI, http://www.wistrans.org/mrutc/files/06-08_FR.pdf, Date Accessed April 24, 2018.

National Corrugated Steel Pipe Association (NCSPA). (2008). "Corrugated Steel Pipe Design Manual," First Edition. 14070 Proton Road Suite 100 LB 9 Dallas, TX 75244.

ODOT (2017). Ohio Department of Transportation, Culvert Management Manual.

Pettitt, A. N. (1977). "Testing the Normality of Several Independent Samples Using the Anderson-Darling Statistic." Journal of the Royal Statistical Society. Series C (Applied Statistics), 26(2), 156-161.

Royer, J. R., and Allouche, E. (2016). "Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Stormwater Conduits." NASTT, Dallas, Texas. WM-T6-03.

Royer, J. R., and Iseley, T. (2017). "Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Storm Water Conduits, Part II – CMP Culvert Analysis." NASTT, Washington, D.C., TM2-T3-04.

Sargand, S., Khoury, I., Jordan, B., and Hussein H. (2015). "Ultimate Load Capacity of Corrugated Steel Pipe with Extreme Corrosion." *Prepared for* Ohio Department of Transportation (Ohio DOT). Prepared in cooperation with the Ohio DOT and the U.S. Department of Transportation, Federal Highway Administration.

## 4.11 Appendix 4.A

**Test of Normality**

**Test of Normality of Practitioners' Selected Thickness**

Anderson-Darling test (Current Design):

| | |
|---|---|
| $A^2$ | 0.929 |
| p-value (Two-tailed) | 0.015 |
| alpha | 0.01 |

H0: The variable from which the sample was extracted follows a Normal distribution.

Ha: The variable from which the sample was extracted does not follow a Normal distribution.

At $\alpha = 0.01$, we cannot reject the null hypothesis.

**Test of Comparison between Thicknesses of Contactors' Practice and Thicknesses Based on ASTM F1216-16**

**T-Test for Two Independent Samples/Two-Tailed Test:**

95% confidence interval on the difference between the means:

[ -0.805, 0.243 [

| | |
|---|---|
| Difference | -0.281 |
| t (Observed value) | -1.077 |
| \|t\| (Critical value) | 2.011 |
| DF | 48 |
| p-value (Two-tailed) | 0.287 |
| alpha | 0.05 |

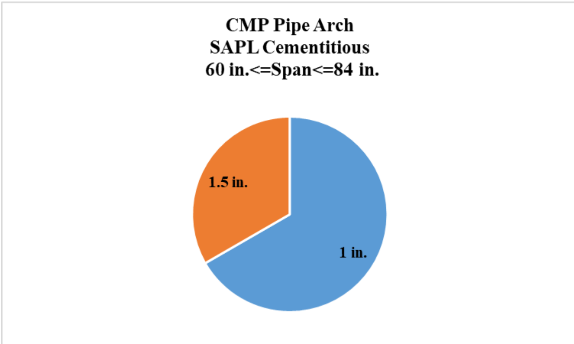
H0: The difference between the means is equal to 0.

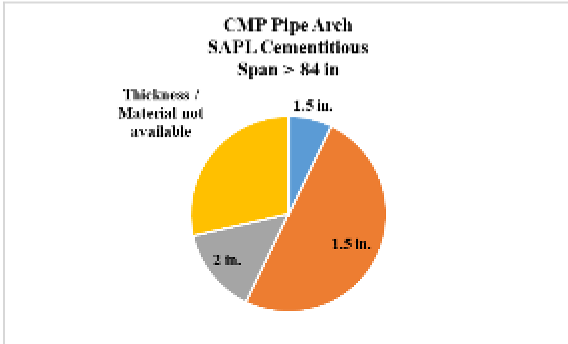
Ha: The difference between the means is different from 0.

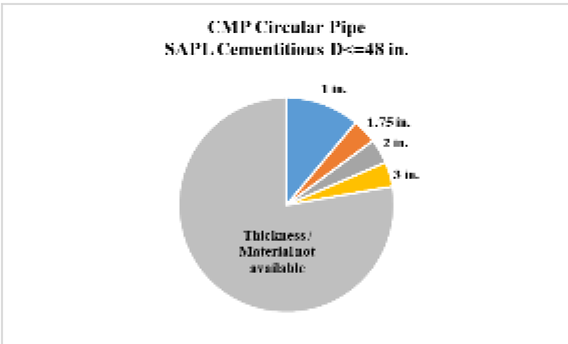
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

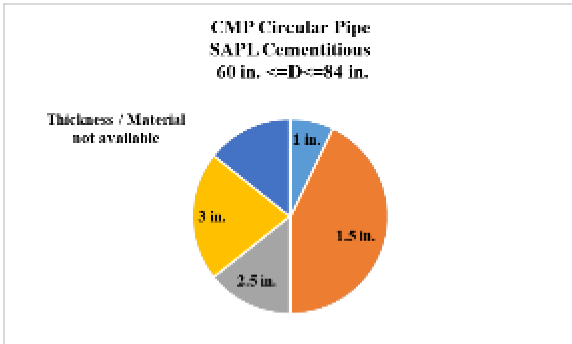
4.12 Appendix 4.B

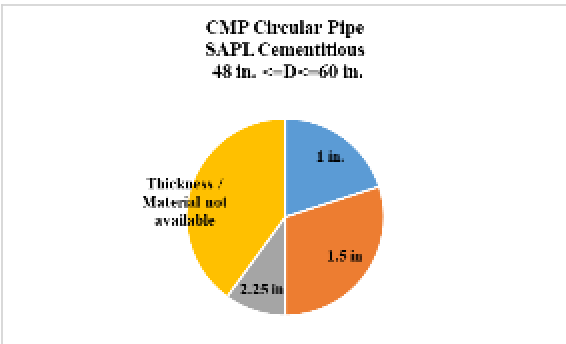
## Summary of Data in Pie Chart

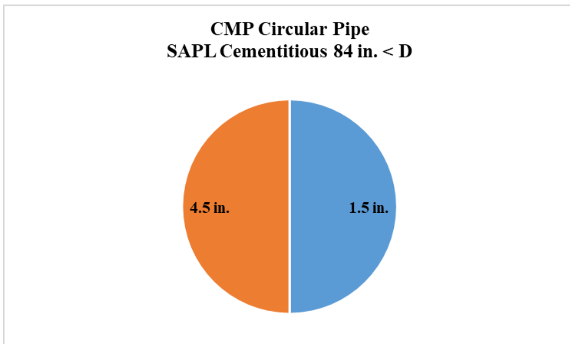


# Chapter 5: Survey of Structural Design Methodology for Spray Applied Pipe Liners (SAPLs) in Culverts

## 5.1 Abstract

Spray applied pipe linings (SAPLs) are trenchless renewal methods for extending the life of old and deteriorated culverts and drainage structures. Since December 2017, a research project to evaluate structural application of cementitious and polymeric SAPLs is ongoing at the University of Texas at Arlington, Center for Underground Infrastructure Research and Education (CUIRE). The objective of this project is to develop design methodologies and equations for structural application of SAPLs for circular pipe arch culverts. As part of this project, a survey was conducted for collecting data from state Departments of Transportation (DOTs) and Canadian transportation agencies regarding their experiences with SAPLs. Out of 52 DOT and 8 Canadian, a total of 32 DOT and one Canadian responded to this survey (overall: 33/60). The survey included three parts: (1) considerations for SAPL application, (2) issues during SAPL application and (3) issues after SAPL application. The survey was limited to Corrugated Metal Pipe (CMP) and Reinforced Concrete Pipe (RCP) culverts, circular and arch shapes. The methodology for this paper consists of analyzing the survey results to investigate DOT concerns with SAPL installations, such as performance and quality. Additional considerations include SAPL hydraulic and structural analysis and effects of SAPL installation on the annual daily traffic (ADT). The results of this paper show that CMP culverts with deteriorated inverts and RCP culverts with longitudinal cracking and joint separation are the most common reasons for considering a culvert fully deteriorated. The bonding between SAPLs and host conduits was one of the design considerations. The top three considerations in cementitious SAPLs were (1) longitudinal and circumferential

cracking, (2) hairline cracking with rust bleeding through cracks, and (3) cracking at joints. For polymer SAPL, respondents did not report any issues because of lack of experience with these materials. According to this survey, the expected design life of SAPL is expected to be 50 to 75 years.

## 5.2 Introduction and Background

A culvert is a structure which allows passage of moderate amount of water under an embankment, such as, highways, roads, railroads, etc. with the span of less than 10 ft (Ohio DOT, 2017), and less than 20 ft (FHWA, 2012). Culverts 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. Further challenges are the variety in material types, shapes, backfill materials, and types of roads, wide geospatial distribution and environmental exposures that makes every single culvert unique (Najafi et al., 2008, and Jalalediny Korky et al., 2019a). Several methods have been developed for pipe/culvert rehabilitations/renewals. The installation of a liner to renew the culvert requires proper selection of renewal method, material and thickness as well as host culvert inspection and preparation (Jalalediny Korky et al. 2019b). *Spray Applied Pipe Lining (SAPL)* is a trenchless rehabilitation/renewal method which increases the remaining useful life of the culvert by using spun application on the existing host culvert pipe. A structural SAPL works with the host culvert to inhibit further deterioration and can structurally renew deteriorated culvert and drainage structures.

A Transportation Research Synthesis (TRS) 1510 (2016) presents repair techniques for large corrugated metal pipe based on a survey of practice and literature review. The survey was published by the Minnesota Department of Transportation (MnDOT). The objective of this survey was to perform repair or rehabilitation that provides continuous structural support for traffic loads. The survey included large diameter CMPs which were repaired by using epoxy or cementitious SAPLs, sliplining or cured-in-place pipe methods. This survey covered the following eight topics:

1. Repair techniques
2. Frequency and extent of large-diameter repairs
3. Potential environmental concerns
4. Roadblocks precluding the use of certain repairs
5. Structural issues before repair
6. Structural issues after repair
7. Life-cycle cost-effectiveness
8. Pending research

In TRS 1510 (2016), Michigan DOT stated multiple areas of concerns, including the loading conditions not considered in design assumptions and inadequate coverage of liner support material. Both Indiana and Michigan DOTs reported a failed rehabilitation effort and presented concerns about a product used in a rehabilitation project (TRS, 2016). They reported experience with rehabilitating culverts by using CIPP, concrete paved inverts, sliplining, and SAPL methods.

Wagener and Leagield (2014) presented best practices for culvert repairs. The objective of their work was to provide guidelines for engineers to select culvert repair methods. After web surveys and personnel interviews among MnDOT personnel, survey was distributed to other DOTs and sent to AASHTO Research Advisory Committee (AASHTO RAC). The best practices guidelines was prepared based on the results of the survey.  These guidelines include:

- Rehabilitation of culvert, including, paved invert, cured-in-place pipe (CIPP), sliplining and centrifugally cast concrete mortar liner.
- Repair of culvert, including, spall repair, joint repair methods and filling voids outside the culvert.
- Rehabilitation methods, including, spirally wound liners, close-fit liners and shotcrete.
- Other repair methods, including, joint sealing with internal packers, corrugated steel pipe (CSP) seam repair, invert plating, sprayed coatings and linings, slab jacking, compaction grouting and replacement of culvert using open cut methods.
- Replacement of a culvert using trenchless replacement methods, including, pipe jacking, and horizontal directional drilling and pipe bursting (Wagener and Leagield, 2014).

As a summary, above report included types of culverts, deterioration, rehabilitation/renovation with trenchless technologies, structural behavior and life cycle.

## 5.3 Methodology

A survey was conducted as part of an NCHRP pool-funded research project at the Center for Underground Infrastructure Research and Education (CUIRE), the University of Texas at Arlington (UTA) for gathering data from DOTs in the North of America agencies to investigate applicability of SAPLs for structural renewal of culverts (Appendix 5.A). Figures 5.1 and 5.2 present U.S. DOTs and Canadian transportation agencies who responded to this survey.

The main objective of the survey was to investigate DOT experiences with SAPL for culvert renewal in three parts of pre, during, and post installation. The secondary objectives of survey were:

- Which DOTs used or plan to use SAPLs.
- Existing SAPL specifications.

- Applicability of SAPLs for structural renewal.
- Environmental and host culvert requirements for SAPL application.
- The quality of SAPL installations.


Figure 5.1. U.S. Survey Respondents


Figure 5.2. Canadian Survey Respondents

The methodology of this paper includes the following:

1) Present survey responses for:
    a. CMP and RCP (host culvert materials),
    b. Circular and Arch Pipe shapes, and
    c. SAPL materials.
2) Discussion and analysis of each question,
3) Survey reliability check, and
4) Survey validity check,

As stated previously, survey questions were categorized in three parts: part A – considerations before SAPL, for design of SAPL application; part B – considerations during

SAPL, for performance construction specifications of SAPL; and part C – considerations after SAPL installations, for maintenance and lifecycle of SAPL.

### 5.3.1 Questionnaire Development and Reviewers

Three consultant engineers and seven DOTs administrators reviewed the survey questionnaire.

## 5.4 Survey Questions

### 5.4.1 Part A) Considerations BEFORE SAPL (Questions A.1 through A.12)

#### 5.4.1.1 Question A.1 – Decision Making Priorities When Using SAPL

The objective of this question was to find what the priorities are when a culvert rehabilitates with SAPL. Figures 5.3 and 5.4 illustrate the priorities set by the respondents based on their experiences for CMP and RCP culvert, respectively. Overall, for both RCP and CMP, durability, hydraulic capacity, impact to travelling public, project economics, minimum thickness, contractor experience, and project schedule are all major considerations. Some respondents stated other priorities, which included fish passage, host culvert condition, feasibility, and benefit/cost ratio for both RCP and CMP renewals.

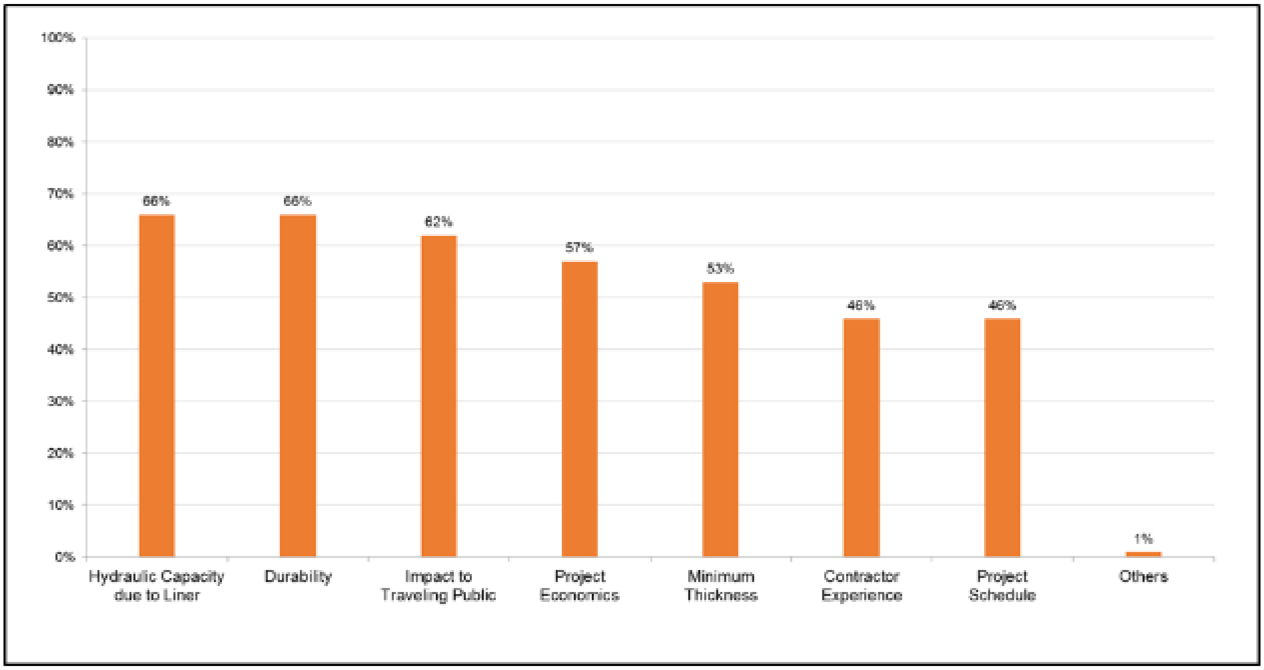



Figure 5.3. Decision Making Priorities for Selecting SAPL for RCP Culverts (17 Respondents)

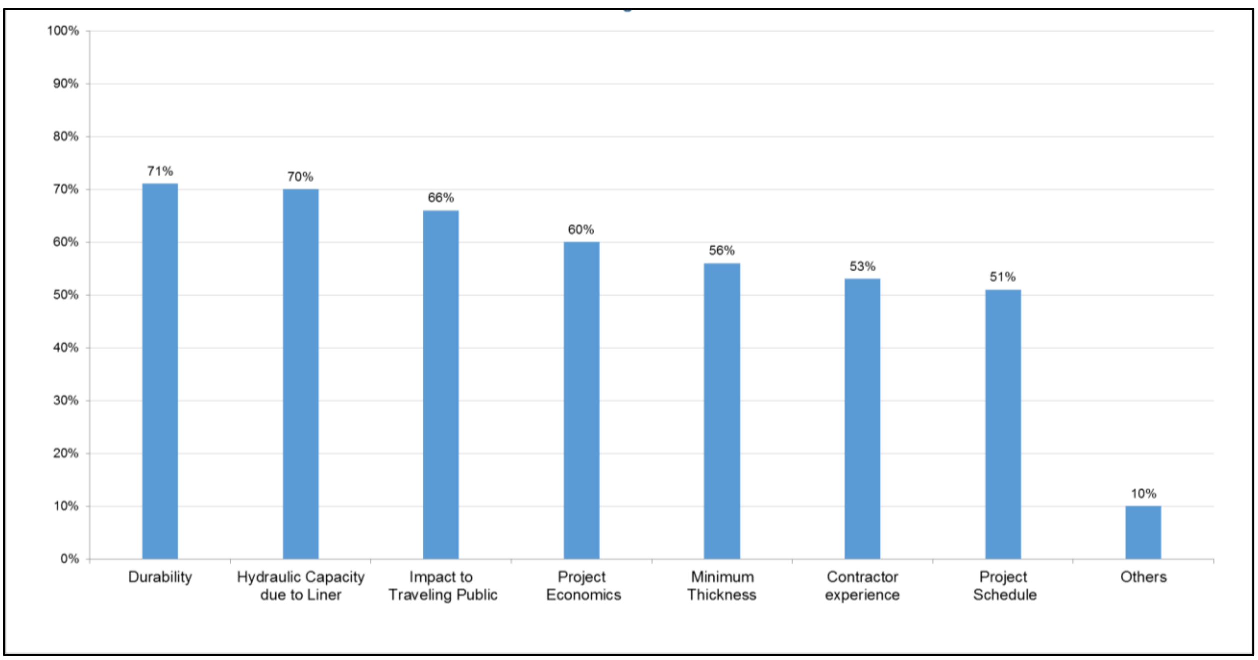



Figure 5.4. Decision Making Priorities for Selecting SAPL for CMP Culverts (20 Respondents)

#### 5.4.1.2 Question A.2 – The Main Reasons for Selecting Fully Structural SAPL

The objective of this question was to find top reasons for selecting a structural SAPL. Figures 5.5 and 5.6 illustrate priorities selected by respondents for structural application of SAPL for RCP and CMP culverts respectively. More than 80% of the respondents considered longitudinal cracking and circumferential cracking the most common problems for fully structurally application of SAPL in RCP culverts. Invert loss or erosion, joint separation and delamination are the second important categories of RCP pipes, which need to be lined as fully structural application according to 70% of respondents' viewpoint. Spalling also might be considered as a reason for fully structural application as more than 60% of the respondents have considered it. Environmental footprint impacts and large diameter RCP are also some of the noticeable factors.

The most common CMP culvert problem to apply a structural SAPL is invert loss. Respondents ranked invert loss as the first issue for selecting SAPL and access to culvert as the second ranked parameter. Survey results showed that 74% of the respondents ranked deflection/ovality/flattening/racking as the third reason. Respondents ranked conservative design to avoid future failures as the fourth reason. Additionally, respondents ranked other priorities which inluded corrosion and environmental footprint

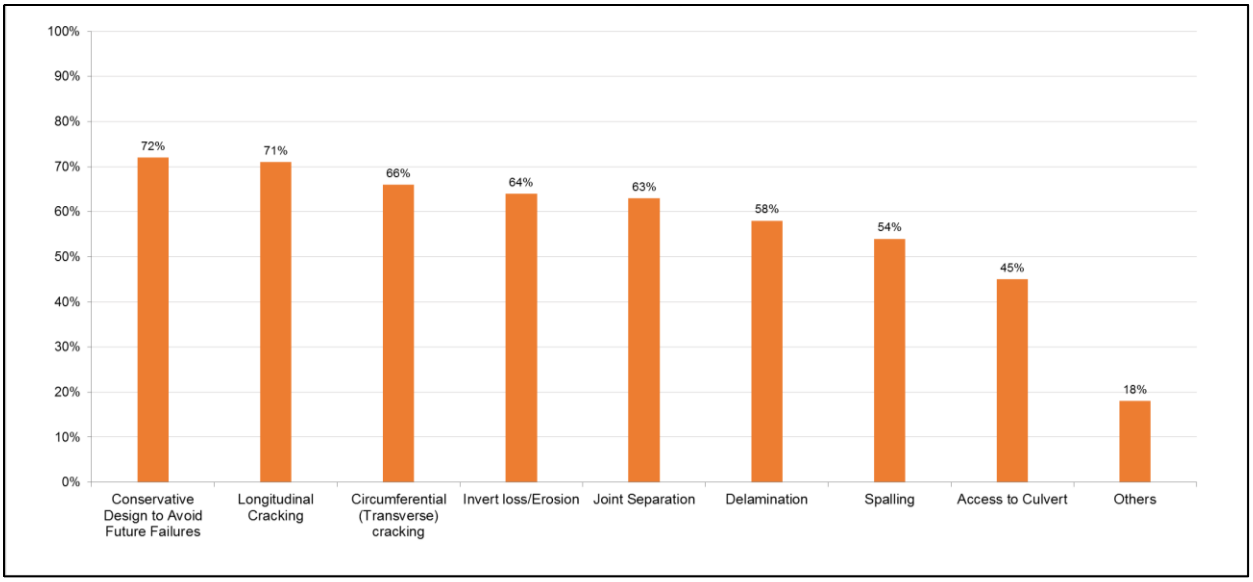



Figure 5.5 – Reasons for Selecting Structural SAPL for RCP Culverts
(17 Respondents)

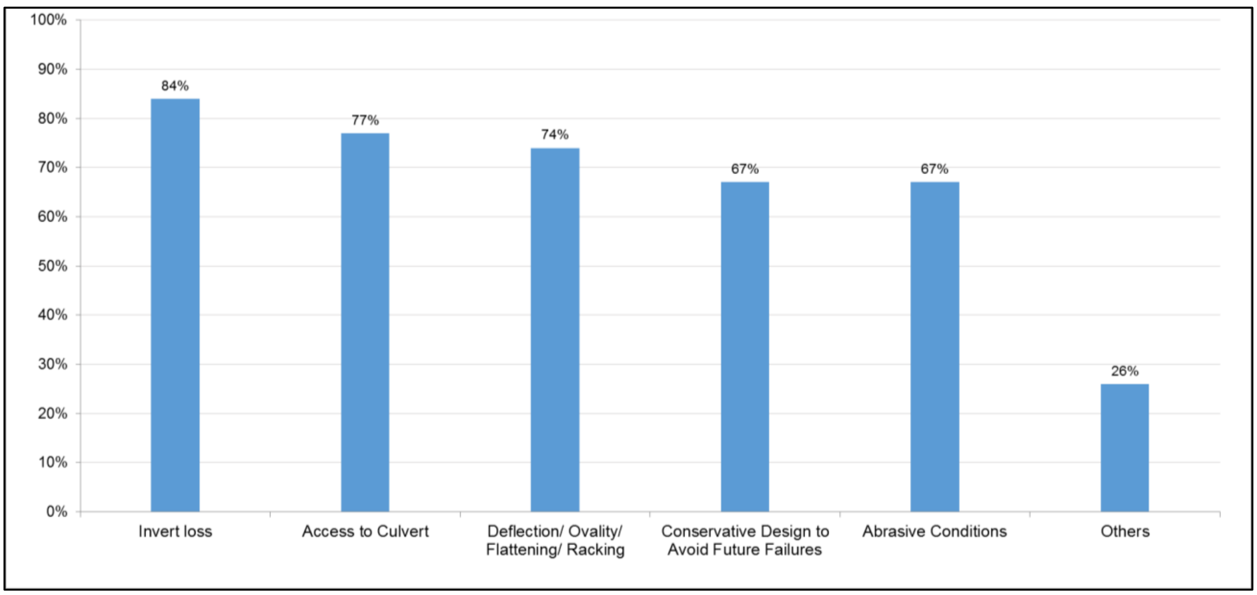



Figure 5.6 – Reasons for Selecting Structural SAPL for CMP Culverts
(13 Respondents)

#### 5.4.1.3 Question A.3 – Conditions for Considering a Culvert as a "Fully Deteriorated" Culvert

The objective of this question was to get the DOTs' opinion and experiences for considering a culvert fully deteriorated as shown in Table 5.1.

Table 5.1. Reasons for a Culvert to be identified as Fully Deteriorated with "1" Highest Priority

| RCP | | | | CMP | |
|---|---|---|---|---|---|
| Circular | | Pipe Arch | | Circular and Pipe Arch | |
| Issues | Rank | Issues | Rank | Issues | Rank |
| Longitudinal Cracking and Joint Separation | 1 | Longitudinal Cracking and Joint Separation | 1 | Corrosion at Invert | 1 |
| Erosion, Pop-outs and Delamination | 2 | Circumferential Cracking, Pop-outs and Delamination | 2 | Deflection/Ovality and Seam Defects/Cracks | 2 |
| Circumferential Cracking and Spalling | 3 | Erosion and Spalling | 3 | Abrasion | 3 |
| Corrosion | 4 | Corrosion, Abrasion and Honeycombs | 4 | | |
| Abrasion and Honeycombs | 5 | Scaling and Efflorescence | 5 | | |
| Scaling | 6 | | | | |
| Efflorescence | 7 | | | | |

5.4.1.4 Question A.4 – Limitation of SAPL Due to Culvert and Site Conditions (19 Respondents)

The objective of this question was to take characteristics of culvert in conjunction with the site conditions before SAPL. The responses were categorized in three conditions: i) common conditions for both RCP and CMP, ii) specific conditions for RCP, and iii) specific conditions for CMP.

i) Most of the respondents considered the Culvert Conditions for both RCP and CMP based on size, shape, level of deterioration, hydraulic capacity, partially collapsed, host pipe condition related to its viability as a "form," mostly shape (deflection) and alignment (joints), and past performance. Site conditions for both CMP and RCP included high ADT, utilities, detours, manholes on each end (limited access), high bed load that could crack SAPL, site access, high groundwater and infiltration, deep cover and culvert no longer aligned as originally installed, flowing water and Aquatic Organism Passage (AOP) and environmental issues.

ii) Specific conditions for RCP included joint separation or movement that is likely to continue, large offset of joints, and collapsed pipe with longitudinal cracking and joint minor separation and cracks.

iii) Specific conditions for CMP included significant deviation from original shape, severe deflection/ovality and completely rusted out on the bottom.

5.4.1.5 Questions A.5 and A.6 – Factors for Making Decision to Use SAPL

The objective of this question was to find decision making process for selection of cementitious or polymeric materials. Results are divided into four categories as following:

i. Circular CMP with cementitious/polymeric materials (Figure 5.7)
ii. Pipe arch CMP with cementitious/polymeric materials (Figure 5.8)
iii. Circular RCP with cementitious/polymeric material (Figure 5.9)
iv. Pipe arch RCP with cementitious/polymeric material (Figure 5.10)

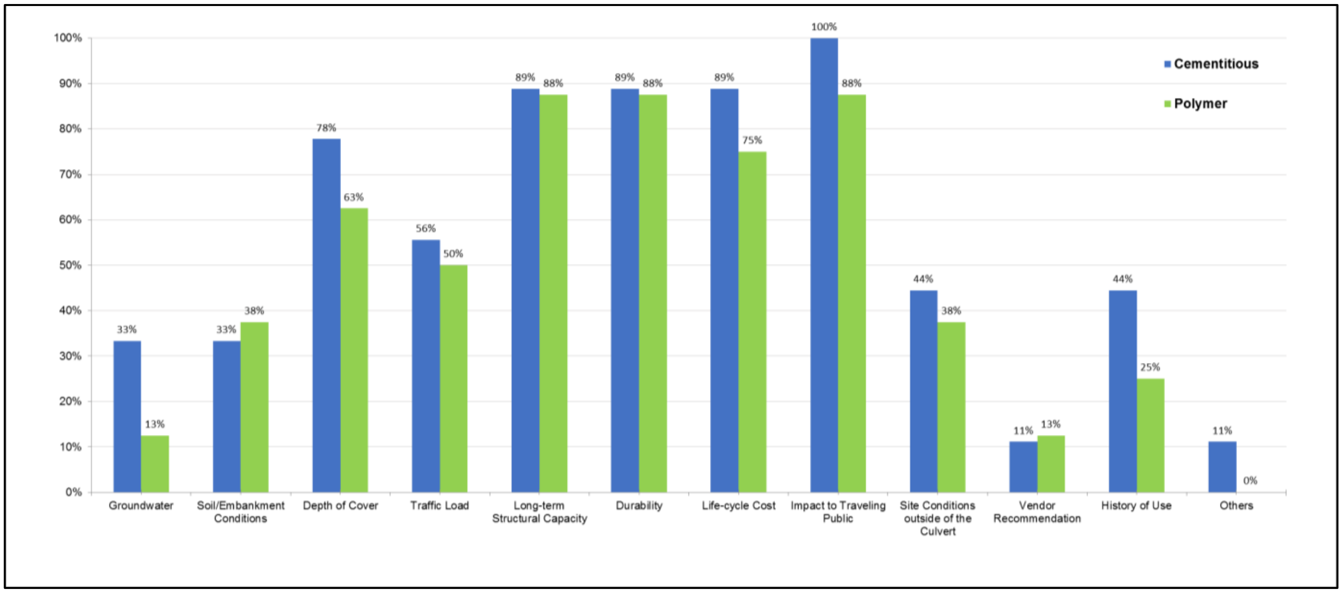



Figure 5.7. Factors Influencing Circular CMP
(No. of Respondents: Cementitious = 8; Polymer = 8)

*i. Circular CMP with cementitious/polymeric materials:*

Figure 5.7 illustrates that respondents considered *impact to traveling public*, *life-cycle cost*, *durability* and *long-term structural capacity* as the four important factors for selecting SAPL.

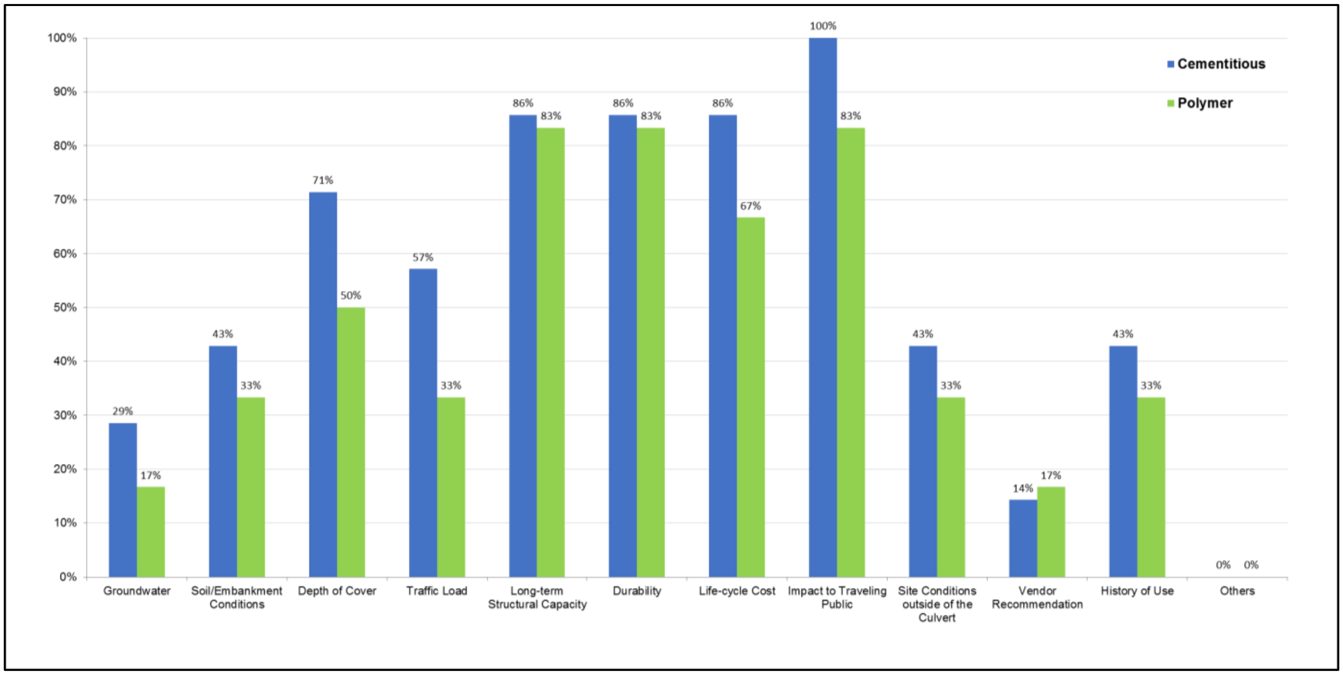



Figure 5.8. Factors Influencing Pipe Arch CMP
(No. of Respondents: Cementitious = 7; Polymer = 6)

*ii. Pipe arch CMP with cementitious/polymeric materials:*

Figure 5.8 illustrates that the pipe arch CMP has same influencing factors. Respondents believed that *impact to traveling public*, *life-cycle cost*, *durability* and *long-term structural capacity* are the most important factors for making decision in application of SAPL.

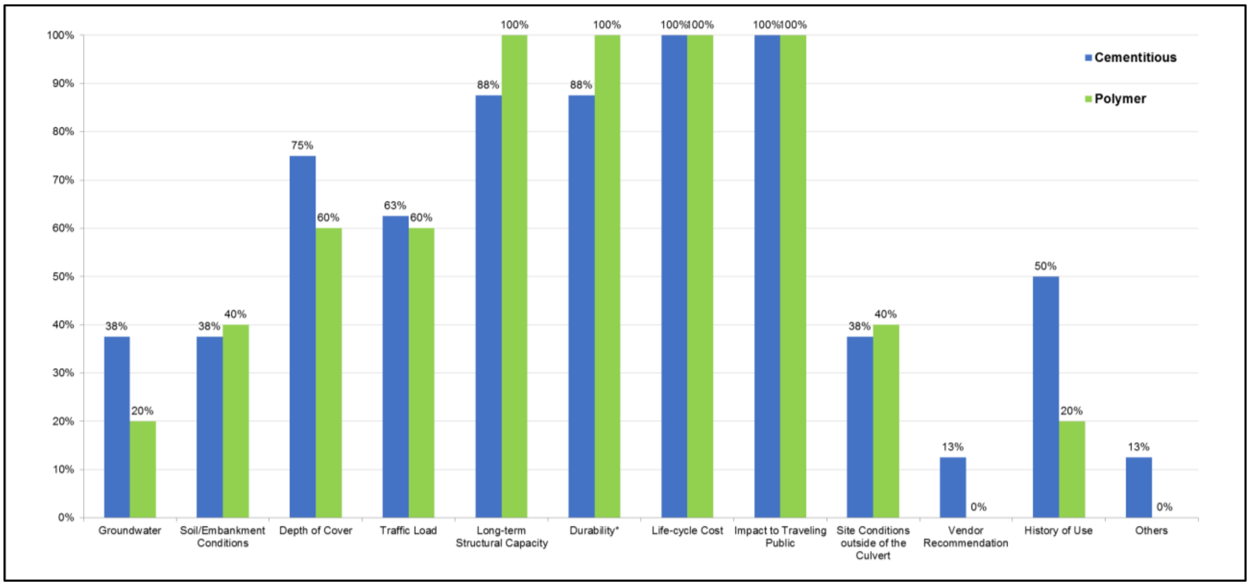


Figure 5.9. Factors Influencing Circular RCP
(No. of Respondents: Cementitious = 7; Polymer = 5)

*iii. Circular RCP with cementitious/polymeric materials:*

Figure 5.9 illustrates that respondents considered *impact to traveling public*, *life-cycle cost*, *durability* and *long-term structural capacity* as the four important factors for making decisions regarding the application of SAPL.

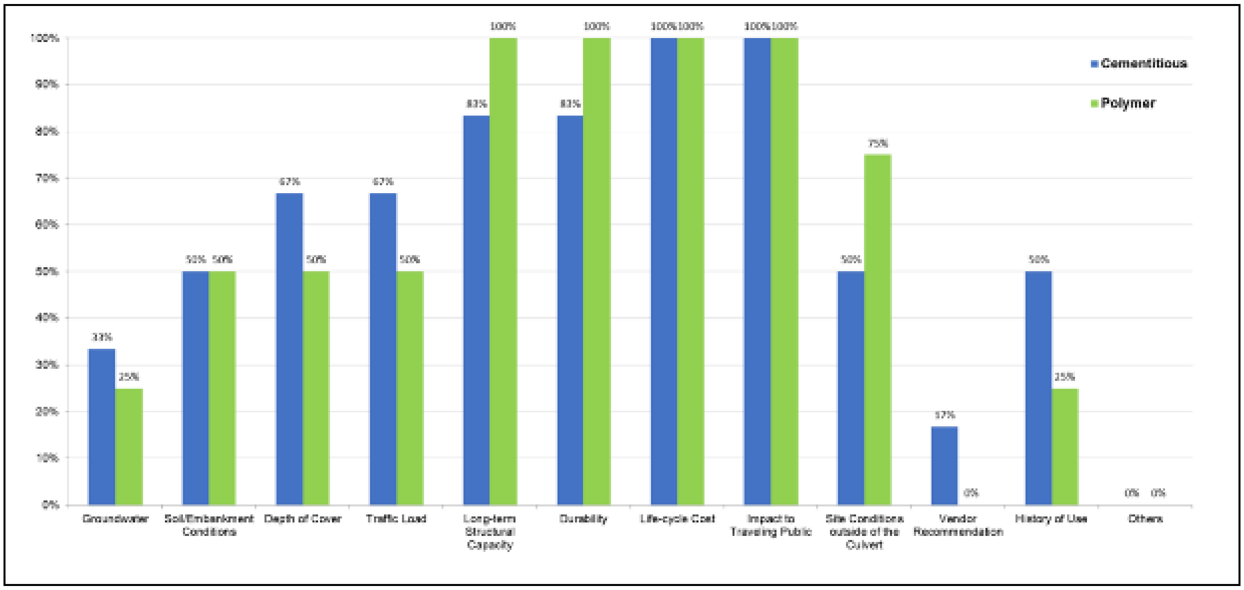



Figure 5.10. Factors Influencing Pipe Arch RCP
(No. of Respondents: Cementitious = 6; Polymer = 4)

*iv. Pipe arch RCP with cementitious/polymeric materials:*

Like circular RCP, Figure 5.10 illustrates that pipe arch RCP has the similar result for considering influencing factors. Respondents believed that *impact to traveling public*, *life-cycle cost*, *durability* and *long-term structural capacity* as the four important factors for making decisions regarding the application of SAPL.

5.4.1.6 Question A.7 – Percentage of Existing Culverts Based on Shape

Figure 5.11 illustrates that 86% of the existing culverts are circular and 14% are pipe arch.

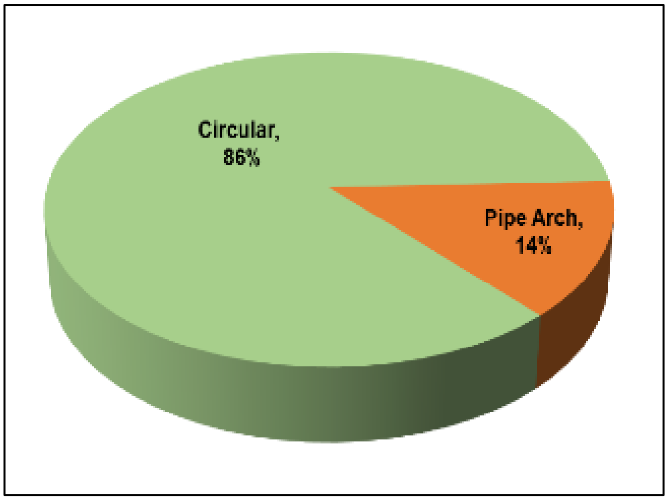



Figure 5.11. Percentage of Existing Culverts
(15 Respondents)

5.4.1.7 Question A.8 – Priority of Material Selection

Table 5.2 presents which material is more likely to be used for SAPL based on 15 responses.

Table 5.2. SAPL Materials Ranking with "1" the Highest Priority

| Material | Rank |
|---|---|
| Cementitious | 1 |
| Geo-polymer | 2 |
| Polyurethane | 3 |
| Polyurea | 4 |
| Epoxy | 4 |

5.4.1.8 Question A.9 – Prohibited SAPL Materials

Approximately 70% of the respondents (among 14 respondents) responded "None" to this question; however, three of the DOTs had limitations on using cementitious SAPL materials.

5.4.1.9 Question A.10 – SAPL Permitted Reinforcement Materials

Figure 5.12 illustrates permitted SAPL reinforcement materials.

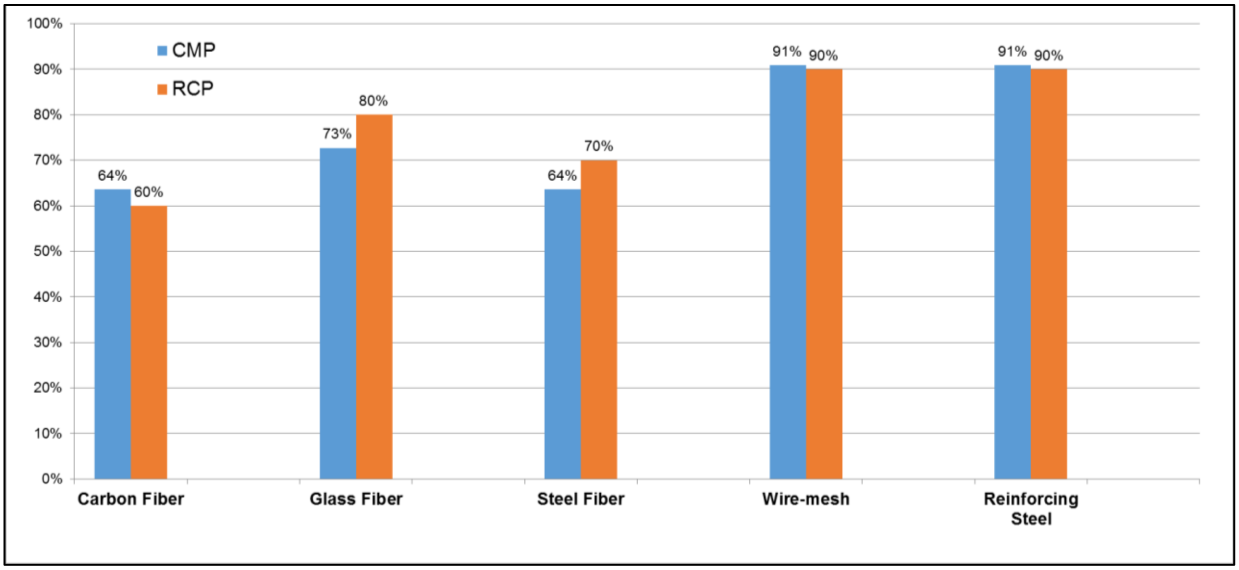



Figure 5.12. Permitted Reinforcement Materials
(10 Respondents)

For CMP culverts, 90% of respondents considered using *reinforcing steel* and *wire-mesh*, 80% considered using *glass fiber*, and 70% considered using *carbon fiber* and *steel fiber*. For RCP culverts, 100% of respondents considered using *reinforcing steel* and *wire-mesh*, 88% considered using *glass fiber*, and 75% considered using *carbon fiber* and *steel fiber*. Overall, using traditional reinforcement, such as, *reinforcing steel* and *wire mesh* are most likely to be used for both CMP and RCP culverts.

#### 5.4.1.10 Question A.11 – Necessity of Considering Adhesion of SAPL with the Host Culvert for Structural Application

Figures 5.13 and 5.14 illustrate what percentage of the respondents that believed adhesion of cementitious and polymer SAPLs to the host culvert is required.

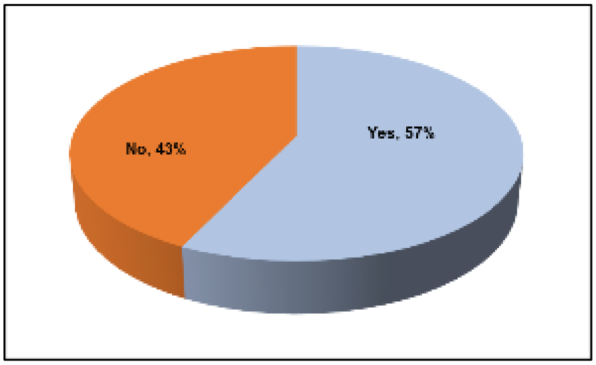


Figure 5.13. Required Adhesion in Cementitious Materials
(15 Respondents)

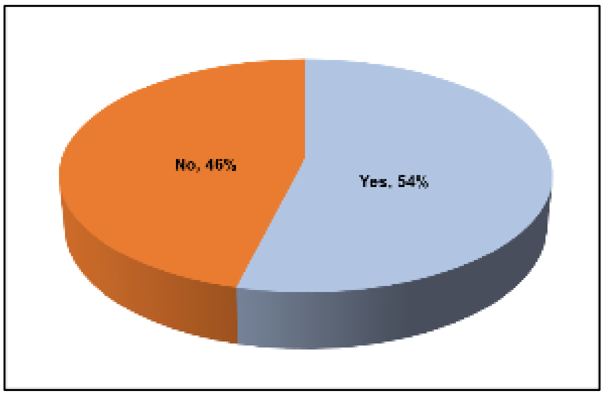


Figure 5.14 – Required Adhesion in Polymeric Materials
(14 Respondents)

Adhesion for cementitious materials has been selected more than polymeric materials. The reason behind of this selection, might be a concern regarding bearing load capacity of cementitious SAPL as a standalone structure.

According to Z-test, Z score = 0.329, which means the frequencies of "Yes" and "No" are not significantly difference from each other.

P value = 0.742 >>> 0.05

Therefore, based on results of survey, there is no justification for using adhesion or not.

5.4.1.11 Question A.12 – Minimum Thickness Requirement for SAPL

Figures 5.15 and 5.16 illustrate what percentage of the respondents required a minimum thickness for cementitious and polymer SAPLs.

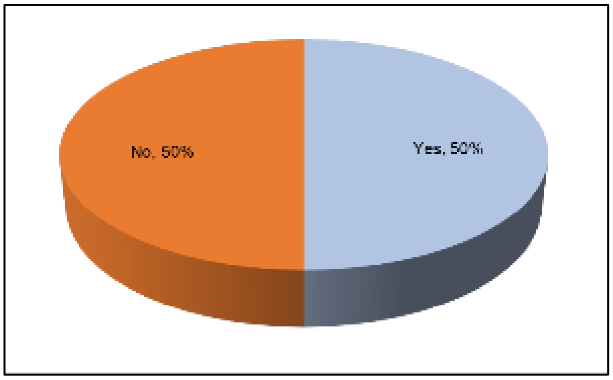


Figure 5.15. Minimum Thickness Requirement in Cementitious Material (11 Respondents)

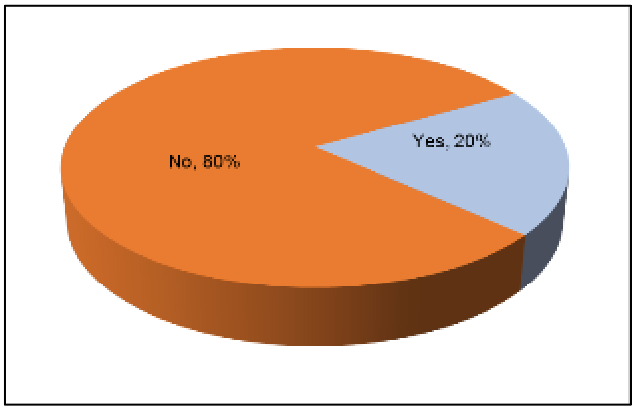


Figure 5.16. Minimum Thickness Requirement in Polymeric Material (9 Respondents)

Considering the required minimum of thickness for cementitious materials more than polymeric materials shows that the respondents had concerns over maintaining a uniform thickness for cementitious SAPLs and consideration that thicker cementitious SAPL provide more bearing capacity as a standalone structure.

5.4.2 Part B) Considerations DURING SAPL Installations (Questions B.1 through B.3)

5.4.2.1 Question B.1 – Type of Weather Conditions Prohibiting Installation of SAPL

According to respondents, during installation, when SAPL projects encounters cold weather, wetness and freeze/thaw conditions, cementitious material is prohibited and polymeric SAPLs are more resistant. In hot weather and humid conditions, cementitious SAPLs are considered to have a better performance and polymeric SAPLs are prohibited (Figure 5.17).

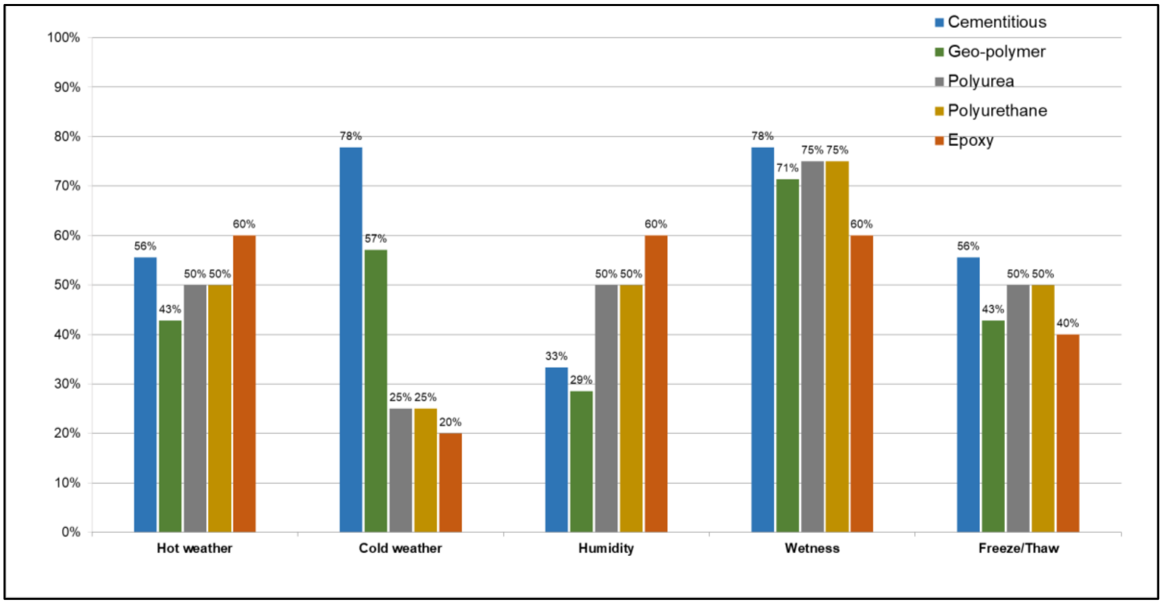



Figure 5.17. Prohibited Weather Conditions
(9 Respondents)

According to Figure 5.17, SAPL installations in cold weather can impact cementitious and geo-polymer SAPLs.

5.4.2.2 Question B.2 – Jurisdiction Having a Protocol for QA/QC of SAPL Installation, Testing and Inspection (12 Respondents)

Respondents selected NO to this question and they stated that a standard construction specification for installation and materials selections must be prepared.

5.4.2.3 Question B.3 – Jurisdiction Having Additional Safety Protocols in Addition to OSHA Confined Space Entry (21 Respondents)

According to respondents, there are no additional safety protocols in addition to OSHA standards for SAPL projects.

5.4.3 Part C) Considerations AFTER SAPL Installations (Questions C.1 through C.3)

The main concerns for renewed SAPL culverts after installation were proper thickness and quality of installation.

#### 5.4.3.1 Question C.1 – Tools and Techniques to Measure the Thickness of SAPL (16 Respondents)

Nails and cores, and yardstick were considered by two respondents. One other respondent stated that based on SAPL product, the thickness measurement will be selected. One other respondent recommended that contractor must check the thickness in at least three locations around the culvert circumference each 20 ft apart by depth gauges. The depth gauges would have to be in place in inner surface of culvert before spraying and would remain after installation.

Twelve respondents stated that they did not use any tools.

#### 5.4.3.2 Question C.2 – Type of Problems After SAPL Application (7 Respondents)

Cementitious:

- Longitudinal and circumferential cracking
- Hairline cracking with rust bleeding through cracks
- Cracking at joints
- Spalling
- Delamination
- Rough application
- Rust-through
- Slumping from ceiling
- Buildup of material due to poor installation
- Lack of uniform application
- Groundwater infiltration before cure time.
- Cracking and infiltration of groundwater through the centrifugally cast concrete pipe (CCCP) (another term for cementitious SAPL) was observed approximately one year after installation,

Geo-polymer:

- Leaking groundwater
- Cracking at joints
- Spalling
- Delamination
- Rough application
- Rust-through
- Slumping from ceiling
- Buildup of material due to poor installation

#### 5.4.3.3 Question C.3 – Expected SAPL Design Life

Figure 5.18 illustrates that, according to respondents, most probable design life is between 50 to 75 years.

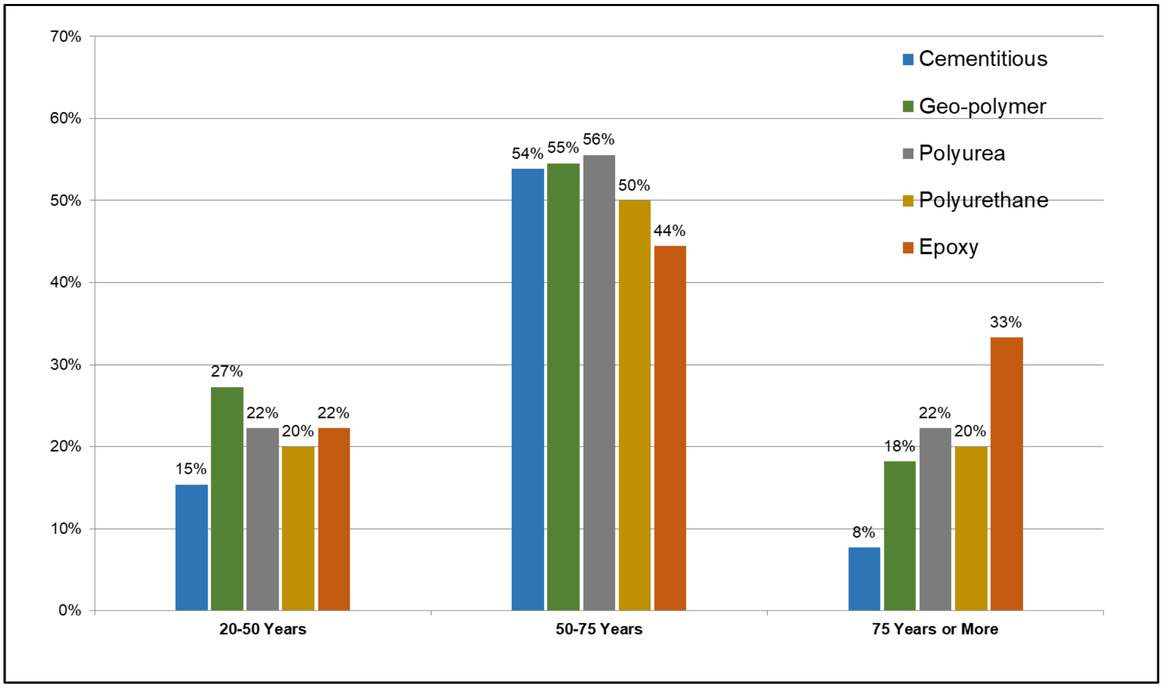



Figure 5.18. Expected Design Life
(17 Respondents)

When I pulled data on cementitious and geo-polymer, the proportions were not statistically equal. More specifically, the proportion that mentioned 50 – 75 years, was significantly greater than the other two groups (25 – 50 and 75 – 100 years).

P value =0.028 < 0.05

It means that, based on this result, the expected design life for a cementitious SAPL is 50 – 75 years.

## 5.5 Chapter Conclusions

DOTs preferred using SAPL due to less impact to traveling public and less space requirements for installation compared with the other trenchless renewal methods; however, most of the respondents expressed concerns about SAPL structural capabilities. Respondents have used cementitious SAPLs for many years, and they preferred to use it in future due to their past experiences.

CMP culverts with deteriorated inverts and RCP culverts with longitudinal cracking and joint separation are the most common reasons for considering a culvert in a fully deteriorated condition. The bonding between SAPL and host conduits was not the only point of consideration for the design methodology, as there were several other issues to be considered with respect to rehabilitation of deteriorated culverts. Survey results showed that respondents expected to have a design methodology and equations as well as construction guidelines and specifications for SAPL. The SAPL specifications and design guidelines would help vendors and contractors in proper execution of culvert renewals.

## 5.6 Survey Reliability, Validity and Accuracy

### 5.6.1 Reliability

To compare the survey results an alternate-form reliability test was conducted (Litwin 1995). It is important to make questions which are not identical. Litwin (1995) stated that in an alternate-form reliability test, the survey designer must use the same vocabulary level in the same level of difficulty.

#### 5.6.1.1 Internal Consistency

For example in questions 3, the respondents were asked to select the conditions under which they consider culvert to be fully deteriorated. As an example, here is the answer to two identical items. These two items are *Erosion*[7] and *Abrasion*[8]. In the glossary of the questionnaire, it was specifically explained that these two terms are equivalent. Table 5.3 presents results of consistency check for question 3. As it can be seen, the answers are identical in 86% of times, which implies that there is a good internal consistency in our responses.

---

[7] Erosion = Wearing or grinding away of culvert material by water laden with sand, gravel or stones; generally referred to as abrasion.

[8] Abrasion = Abrasion is the gradual wearing away of the culvert wall due to the impingement of bed load and suspended material.

Table 5.3. Internal Consistency Check

| Question | Responses Based on the State DOTs | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Erosion | N/A | 0 | 0 | 1 | 1 | N/A | 1 | 0 | N/A | 1 | 0 | 0 | 1 | 1 | N/A | 1 | N/A | 0 | 0 | N/A | N/A |
| Abrasion | N/A | 0 | 0 | 0 | 1 | N/A | 0 | 0 | N/A | 1 | 0 | 0 | 1 | 1 | N/A | 0 | N/A | 0 | 0 | N/A | N/A |

### 5.6.2 Validity of Survey Data

The objective of validation of the survey data is to check how the results of data has been measured. Litwin (1995) defined types of validity for a survey as: face, content, criterion, concurrent, predictive, construct and convergent validity. The validity of this survey was established multiple times as follow:

1) Before distribution, survey was sent to three professionals who were remarkably involved with culvert design and performance specifications as well as pipe renewal and trenchless technologies to control whether the questionnaire is valid or not, and
2) The report of survey result was sent to 7 DOTs to check validation of face, content, criterion, concurrently, predictively, constructively and convergent of the survey results.

### 5.6.3 Survey Accuracy Analysis

Freedman et al. (1998) discussed how a survey can be protected from bias. They presented different biases based on the method of survey and number of respondents. Biases in this survey can fall into following three categories:

- Non-response bias
- Selection bias
- Simple random sampling

When the number of responses is less than the number of respondents, there is a non-response bias. Sometimes the proportion of non-responded questions is small enough that does not harm the analysis. Table 5.4 presents different parts/questions representing non-response biases for all three parts (A, B and C) of the survey.

Table 5.4. Probability of Non-response Biases*

<table>
<tr><th>Part</th><th>Question</th><th colspan="2">Non-response Bias</th></tr>
<tr><td rowspan="13">A) Before SAPL</td><td>1</td><td colspan="2">44%</td></tr>
<tr><td>2</td><td colspan="2">53%</td></tr>
<tr><td>3</td><td colspan="2">58%</td></tr>
<tr><td>4</td><td colspan="2">42%</td></tr>
<tr><td>5</td><td colspan="2">76%</td></tr>
<tr><td>6</td><td colspan="2">82%</td></tr>
<tr><td>7</td><td colspan="2">45%</td></tr>
<tr><td>8</td><td colspan="2">52%</td></tr>
<tr><td>9</td><td colspan="2">42%</td></tr>
<tr><td>10</td><td colspan="2">70%</td></tr>
<tr><td>11</td><td colspan="2">58%</td></tr>
<tr><td rowspan="2">12</td><td>Cementitious</td><td>67%</td></tr>
<tr><td>Polymer</td><td>73%</td></tr>
<tr><td rowspan="7">B) During SAPL</td><td rowspan="5">1</td><td>Cementitious</td><td>73%</td></tr>
<tr><td>Geo-polymer</td><td>79%</td></tr>
<tr><td>Polyurea</td><td>88%</td></tr>
<tr><td>Polyurethane</td><td>88%</td></tr>
<tr><td>Epoxy</td><td>85%</td></tr>
<tr><td>2</td><td colspan="2">64%</td></tr>
<tr><td>3</td><td colspan="2">36%</td></tr>
<tr><td rowspan="7">C) After SAPL</td><td>1</td><td colspan="2">52%</td></tr>
<tr><td>2</td><td colspan="2">61%</td></tr>
<tr><td rowspan="5">3</td><td>Cementitious</td><td>61%</td></tr>
<tr><td>Geo-polymer</td><td>67%</td></tr>
<tr><td>Polyurea</td><td>73%</td></tr>
<tr><td>Polyurethane</td><td>70%</td></tr>
<tr><td>Epoxy</td><td>73%</td></tr>
</table>

*The following examples show how probability of non-response biases is calculated:

Example 1, Question A11: The minimum probability of non-response biases in this part is 42%. With assuming that 42% of the respondents did not have enough knowledge or motivation to answer this question, removing the 42% probability of non-response biase from this part would not be a wrong assumption. In fact in question A11, 58% of the respondents did not respond. It means 58% - 42% = 16%, and 100% - 16% = 84%. It means that the results of this question do not have a high probability of non-response bias. It is important that this does not mean that if all the respondents answered, as results had only 16% difference.

Example 2, Question A3: 36% of the respondents did not respond to this question. Following the method described in Example 1 above, 36% - 36% (minimum in part B) = 0%. It shows that there is no probability of non-response bias in comparison with other questions in this part of survey; however, the result of this question may have non-response biases.

In this survey, the respondents were state DOTs so vendors, contractors, designers, consultant engineering firms and so on were not represented. Consequently, this survey might have *selection biases*.

Obviously, the number of respondents is one of the most factors for relying on the result of any survey. Discussion on biases is also related to the number of respondents. Figure 5.19 presents the average number of the respondents to each parts of this survey.

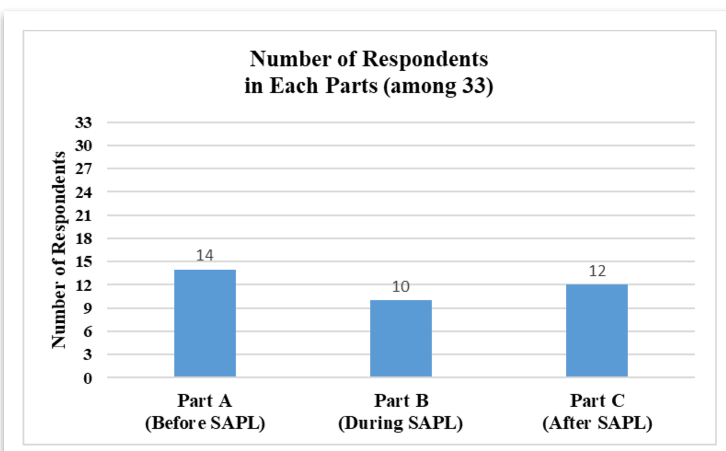



Figure 5.19. Average Number of Respondents for Each Part of the Survey with a Total Number of 33

## 5.7 Chapter Conclusions

Conclusions of this paper are summarized below:

- Compared with the other rehabilitations' solution, SAPL is a durable liner which increases the hydraulic capacity without having impact on traveling public,
- SAPL is applicable for both RCP and CMP culverts,
- RCP host culverts must be assessed for large offset of joints and longitudinal cracking (Culvert Conditions), and not to use SAPL if the result of assessment over these criteria is positive,
- CMP host culverts must be assessed for sever deflection/ovality (Culvert Conditions), and not to use SAPL if the result of assessment over these criteria is positive,
- SAPL Preferred material for circular and arch CMP and RCP culverts is *cementitious*,
- Prior to the construction of SAPL, separated joints must be repaired,
- Respondents expected long-term durability and usage from renewals' techniques including SAPL, and they expected a 50 – 75 year design life for this trenchless method,

## 5.8 Limitations and Recommendation for Future Research

1. The survey was limited to corrugated metal pipe (CMP) and reinforced concrete pipe (RCP) culverts, with circular and pipe arch. The questions regarding the host materials did not cover:
    a. Diameter of culvert,
    b. Sizes/gages of the corrugations of CMP[9],
    c. Thickness of RCP,

[9] CMP culverts are made with different sizes/gages of corrugations, such as, 2 2/3 x ½ in., 3 x 1 in., 5 x 1 in. and ¾ x ¾ x 7½ annular or helical (Contech).

   d. RCP reinforcement,
   e. Percentage of deterioration

2. In general, two types of materials are used in the SAPL applications, rigid (cementitious) and flexible (polymeric) materials. In case of cementitious, cementitious and geo-polymer materials were addressed in the survey; and, in case of polymeric materials, polyurethane, polyurea and epoxy were considered in the survey.
3. Reinforcement materials limited to carbon fiber, glass fiber, steel fiber, wire-mesh and reinforcing steel.

## 5.9 Acknowledgments

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## 5.10 References

Federal Highway Administration (FHWA). (2012). "Hydraulic Design of highway Culverts." 3rd Edition, Publication No. FHWA-HIF-12-026. U.S. Department of Transportation.

Freedman D., Pisani R., Purves R., (2007). "Statistics." 4th Edition.

Jalalediny Korky, S., Najafi, M., Syar, J. and Nandyalal, V.K. (2019a). "Evaluation of Literature on Design and Performance Guidelines of Spray Applied Pipe Linings." ASCE Pipeline Conference, 2019, Nashville, U.S.

Jalalediny Korky, S., Homing Ni, A., Najafi, M., Malek M., M. and Serajiantehrani, R. (2019b). "Design and Installation of Water Pipeline Renewals." NASTT's 2019 No-Dig Show Conference. Chicago, Illinois, U.S.

Litwin M. S. (1995). "How to Measure Survey Reliability and Validity," The Survey Kit, Volume 7. SAGE Publications, INC. ISBN: 0-8039-5704-1.

Najafi M., Wallace R. and Boxter R. (2008). "Case Study: Hydraulic Analysis of a Corrugated Metal Pipe (CMP) CIPP-Lined Culvert," North American Society for Trenchless Technology (NASTT) No-Dig Show 2008, Dallas. Texas.

Ohio Department of Transportation (ODOT). (2017). "Culvert Management Manual."

Transportation Research Synthesis (TRS) 1510. (2016). "Large Corrugated Metal Pipe Repair Techniques: A Survey of Practice and Related Resources." Minnesota Department of

Transportation, Office of Transportation System Management, Research Service Management, Research Services and Library. Prepared by CTC & Associates.

Wagener B. D. and E. E. Leagield. (2014). "Culvert Repair Best Practices, Specifications and Special Provisions – Best Practices Guidelines." A Published Report by Minnesota Department of Transportation, Prepared by CAN Consulting Engineers.

http://www.lrrb.org/PDF/201401.pdf.

## 5.11 Appendix 5.A

SURVEY (SAMPLE)

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*

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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.<br>- Circumferential (Transverse) cracking<br>- 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. |

# Chapter 6: Evaluation of Load Bearing Capacity of Deteriorated Corrugated Metal Pipes Renewed with Spray Applied Linings Using Laboratory Testing and Numerical Analysis

## 6.1 Abstract

Spray applied pipe lining (SAPL) is one of the available trenchless renewal methods for culverts and drainage structures. Corrugated metal pipe (CMP) culverts are the most common deteriorated culverts. Usually, CMP corrosion starts and develops from invert, which is under flow most of the time. SAPLs include cementitious and geo-polymer, polyurethane, polyurea, and epoxy. Each of these materials have their own physical properties and structural behavior. The objectives of this paper are to determine the residual strength of deteriorated (invert-cut) CMP culverts for both circular and arch shapes, to analyze structural behavior of cementitious SAPLs with different thicknesses, and to make a comparison between the structural behavior of circular and arch shapes cementitious SAPL. Finite element modeling (FEM) using two-dimensional PLAXIS software is used for evaluating the failure modes of the invert-cut CMPs with and without SAPL under H-20 truck service loads. First, circular, and arch shape intact CMPs with shallow cover are analyzed and then CMPs with corroded invert were modeled and verified with laboratory soil box testing. Then, FEM models are developed for cementitious SAPLs for both circular and arch shapes CMPs for two types of embedment, poorly graded sand and poorly graded gravel. The results of this paper show that invert lost circular or arch shape CMP fails under service load, and structural behavior of a CMP with cementitious SAPL is significantly related to thickness of SAPL, and arch shapes lined CMP behaves more flexible than circular lined CMP.

## 6.2 Keywords

Corrugated Metal Pipe (CMP), CMP Culvert Deterioration, Culvert Renewal, Spray applied pipe lining

## 6.3 Introduction and Background

A culvert is a structure, which allows passage of moderate amount of water under an embankment, such as, highways, roads, railroads, etc. Different entities defined different size criteria considering an opening underneath of a road as culvert. For instance, the OhioDOT (2017) defined the maximum span (diameter) of a culvert less than 10 ft, however, FHWA (2012) considered culverts to be less than 20 ft. Making corrugation on metal sheets increases the stiffness and moment of inertia of material. Thus, vendors offered corrugated metal pipe (CMP) culverts from early 20$^{th}$ century. From that time, a tremendous change has been exhibited in the design, construction and coating of this type of culvert. CMPs are susceptible to corrosion at invert. Invert has a significant impact on the strength of a CMP culvert, therefore, when a CMP loses the invert, the structural capacity is undermined. Spray applied pipe lining (SAPL) is one of the trenchless renewal methods available for culverts and drainage structures. This method is recognized as semi-structural or structural application. Materials for SAPLs are divided into two general types, cementitious and polymer. Recently, vendors under category of cementitious material present geo-polymer, which is a mix of Portland cement, fly ash and polymer. Polyurethane, polyurea, and epoxy are three types of polymeric materials. A research of the needs on the structural capacity and behavior of invert lost CMPs before and after the application of SAPL was the main reason for this dissertation. When invert is lost, the soil structure interaction of culvert will not follow design criteria, and culvert will lose its strength, therefore, it needs to be renewed. The objectives of this paper are:

1. To determine residual strength of deteriorated (invert lost) CMP culverts for both circular and arch shapes,
2. To analyze the structural behavior of cementitious SAPL culverts in both circular and arch shapes with different thicknesses, and
3. To make a comparison between the structural behavior of circular and arch shapes cementitious SAPL – CMP in different thicknesses.

## 6.4 Literature Review

Watkins et al. (1982) analyzed the effects of loads on buried corrugated polyethylene pipes to determine a relationship 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. Pipes were deflected less than 5%. Results showed that side fill material at certain densities restrained the pipe without significant effects from height of soil cover. They stated that uniform load distribution happened when pipes are buried in a minimum soil cover.

Havens et al. 1995 studied longitudinal strength and stiffness of bare corrugated steel pipe not embedded into soil. They made actual tests on two closed end CMP samples with 4 ft and 6 ft diameters. Each pipe sample was loaded under a service load and failure load. The service load was simulated by putting sandbags on the top of the CMPs, and water added to the inside of the CMPs incrementally to fail the CMPs. They presented moment – deflection graphs for bottom and top of the CMPs for both service and failure loads. The mid-span CMPs deflection was in a range of 1.5 in. to 2.3 in. before yield moment and more than a range of 5.4 in. to 10.7 in. under ultimate moment. The first and second specimen collapsed after 11% and 15% deflection respectively. They concluded that their experimental tests results verified the theory of design.

Royer and Allouche (2016) and Royer and Iseley (2017) conducted laboratory testing of RCP and CMP with and without SAPL. The tests were performed on 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 different percentages of deformation as a realistic preparation before applying SAPL. The results show that with a thickness of 1.33 in. of geo-polymer SAPL, the 24-in diameter pipe – with 0% ovality – deflected by 0.4 in. under 5000 lbs. D-load test.

Li et al. 2018 proposed a new method of rehabilitation using thin-walled polyhedral pipe liners encased in a circular pipe. Polyhedral liners rehabilitate the pipes with increasing the strength supporting hydrostatic pressure. They discussed elastic buckling under uniform external pressure. They compared their analytical results with numerical analysis. They concluded that the analytical buckling pressure was in agreement with FE modeling; however, according to the authors it needs experimental tests verification. They stated that, the strength of an octagon polyhedral liner is ten times more than a cylindrical liner, the enhanced factor has a relationship with the numbers of sides in the polygon base shape of a polyhedral, and a cylindrical liner is more stable than a polyhedral liner if post-buckling occurs. Finally, they recommended a bigger safety factor for polyhedral liner in comparison with cylindrical.

Tetreault et al. 2017 tested an ellipse-shaped corroded corrugated metal culvert and compared the results with an intact one. The culvert was embedded with a combination of sand and gravel with an average of 92% compaction. It was tested first without any action, and then after rehabilitation (paved invert method). They did not observe a significant difference between the behaviors of intact and deteriorated culvert under service load, which is 82.5 kips[10]. However,

[10] Maximum Service Load – Tandem Axel – CSA (2014) = 367 KN ~= 82.5 kips

they reported that the failure strength capacity of the paved invert culvert and the corroded culvert were 360 and 298 kips respectively.

Masada et al. (2017) studied the structurally contribution of invert paving (a method of rehabilitation) considering the impact of H-20 truck load on the deteriorated (invert lost) culvert. First, a large size shallow cover (1 to 2 ft) culvert in the field was selected. The culvert was tested under an H-20 gravel loaded truck before and after rehabilitating. Another in-door test setup was performed to test a 60-in. diameter CMP in conditions of intact, invert lost (1/3 of the bottom), and after rehabilitation by paving. The results showed that 1) In comparison between intact and invert lost, soil cover is settled and CMP deflected more when invert was cut, 2) after removing the invert, the load capacity of CMP dropped to 73%, and 3) the structural behavior of a paved CMP culverts can be considered similar to the original CMP.

## 6.5 Methodology

First, intact CMP and deteriorated CMP culverts (invert lost/invert cut) were modeled and verified by laboratory testing. Secondly, finite element modeling (FEM) was developed to test cementitious SAPL with invert cut CMP. Numerical models considered different combinations of two types of soil embedment including poorly graded sand and poorly graded gravel with different densities for foundation, bedding, embedment, and cover.

### 6.5.1 Part A – Laboratory Testing

#### 6.5.1.1 A1. Test Facility

A soil box at the Center for Underground Infrastructure Research, and Education (CUIRE) at the University of Texas at Arlington (UTA) was used for laboratory testing. Figure 6.1 shows the soil box frame and actuator. The 25-ft by 12-ft plan and 10-ft depth created an ideal area for soil pipe interaction testing. In this research, in each test, three 6-ft diameter circular CMPs or 6-ft equivalent arch-shape were placed back to back with a wooden wall separator as shown in Figure 6.2a.

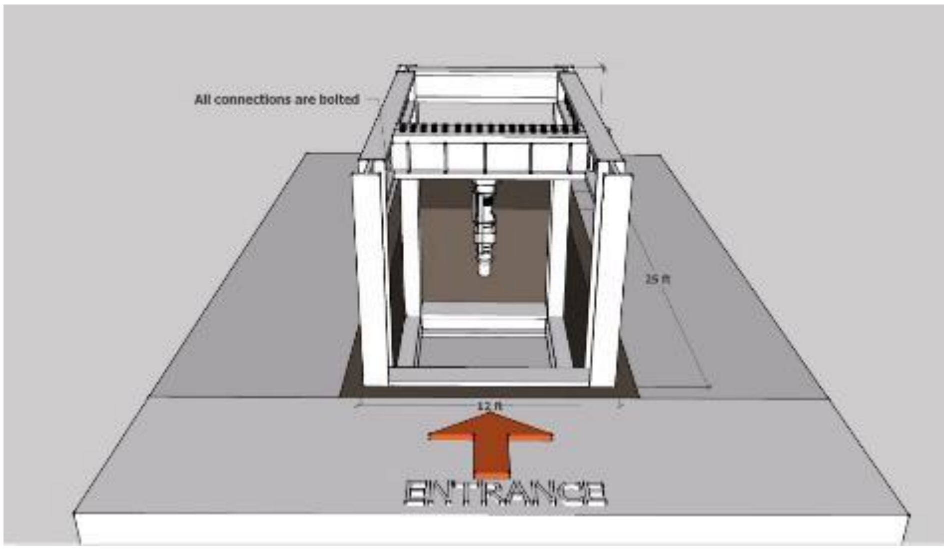



Figure 6.1. Soil Box Detail

6.5.1.2 A2. Test Procedures

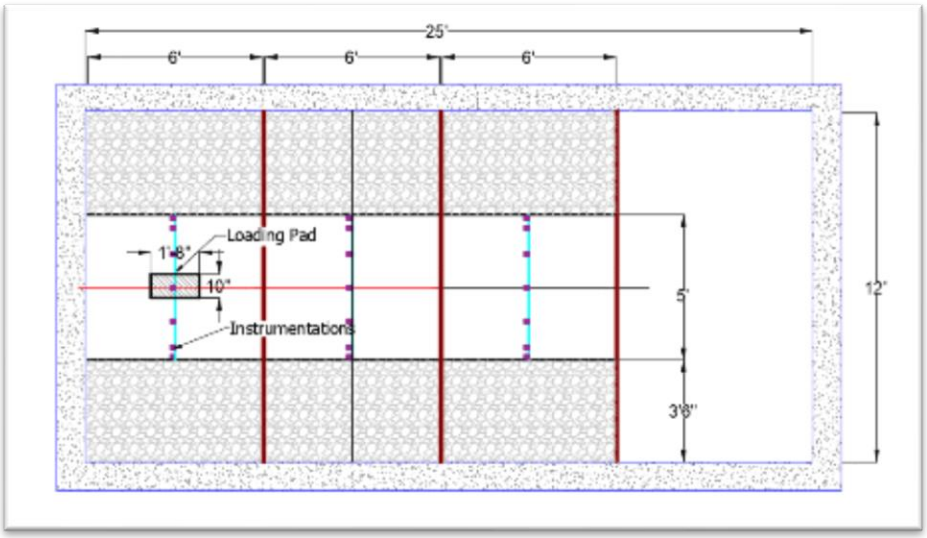
The test procedure was followed through following steps:

Step 1. Soil box filled by 20 in. of gravel to make a foundation for testing. Above this foundation, 4 in. loose sand was placed to for bedding. Then the soil box was separated by wooden walls.

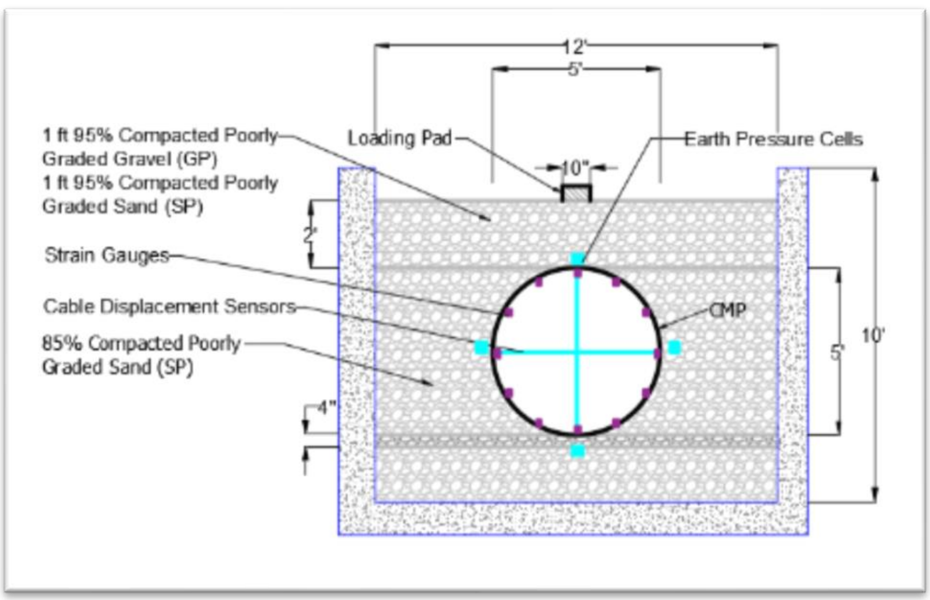
Step 2. A bared CMP was placed inside of the soil box and instrumented by strain gages. Figure 6.2a shows the plan view of placing the intact CMP and Figure 6.2b illustrates a cross section of CMP inside soil box with strain gages and soil embedment.

Step 3. Figure 6.2a, illustrates the layout of the CMPs from left to right including a bared CMP, an invert-cut arch shape CMP and an invert-cut circular CMP. Figure 6.3 illustrates how the invert is cut and separated for circular and arch CMPs.

Step 4. Load was applied to three CMPs separately. Figure 6.2a shows the position of load pad.




**(a)**




**(b)**

Figure 6.2. CMP Sample Instrumentation Details
(a) Plan View of CMP Specimen inside the Soil Box; (b) Cross Section of CMP Specimens

6.5.1.3 A2. CMP Selection: Shape, Size, Dimension, and Cut Invert Deterioration Simulation

The DOTs have used CMPs for near a century and deteriorate over time from bottom (invert). For simulating a corroded CMP (an invert lost CMP), The CMP sample was cut in the invert in the factory and was connected with wood blocks and bolts for both circular and arch shaped (see Figure 6.3). This method helped to keep the CMP shaped for placing inside of the soil box with original configuration. It also kept the original shape during soil embedment. Before applying the service (truck) load, the invert-cut was unbolted, and the invert was removed (see Figure 6.3). The CMP samples contained 2-2/3 in. (pitch) x ½ in. (depth) (12 gages) 60 in. diameter circular CMP and 71(span(S)) by 47(rise(R)) arch shape CMPs (see Figure 6.4). An arch shape with S=71 x R=47 in. is equivalent to 60-in. circular shape. In the all tests, the width (arc) of invert cut was 15 in. plus the wood block separator (see Figure 6.3).

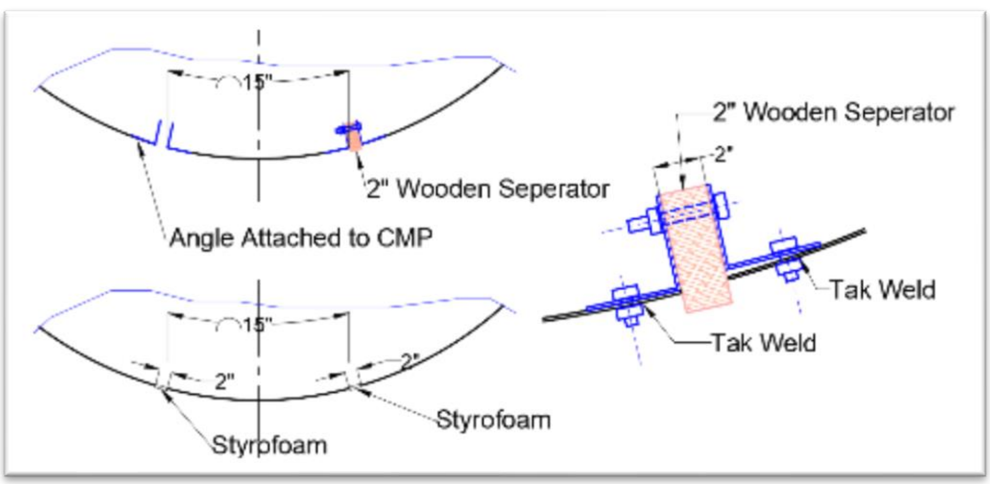



Figure 6.3. Simulating Invert Lost CMPs for Laboratory Testing

6.5.1.4 Plan for SAPL Tests

For SAPL tests, the invert part will be kept, and Styrofoam will be placed in the gap to provide surface for the lining (see Figure 6.3).

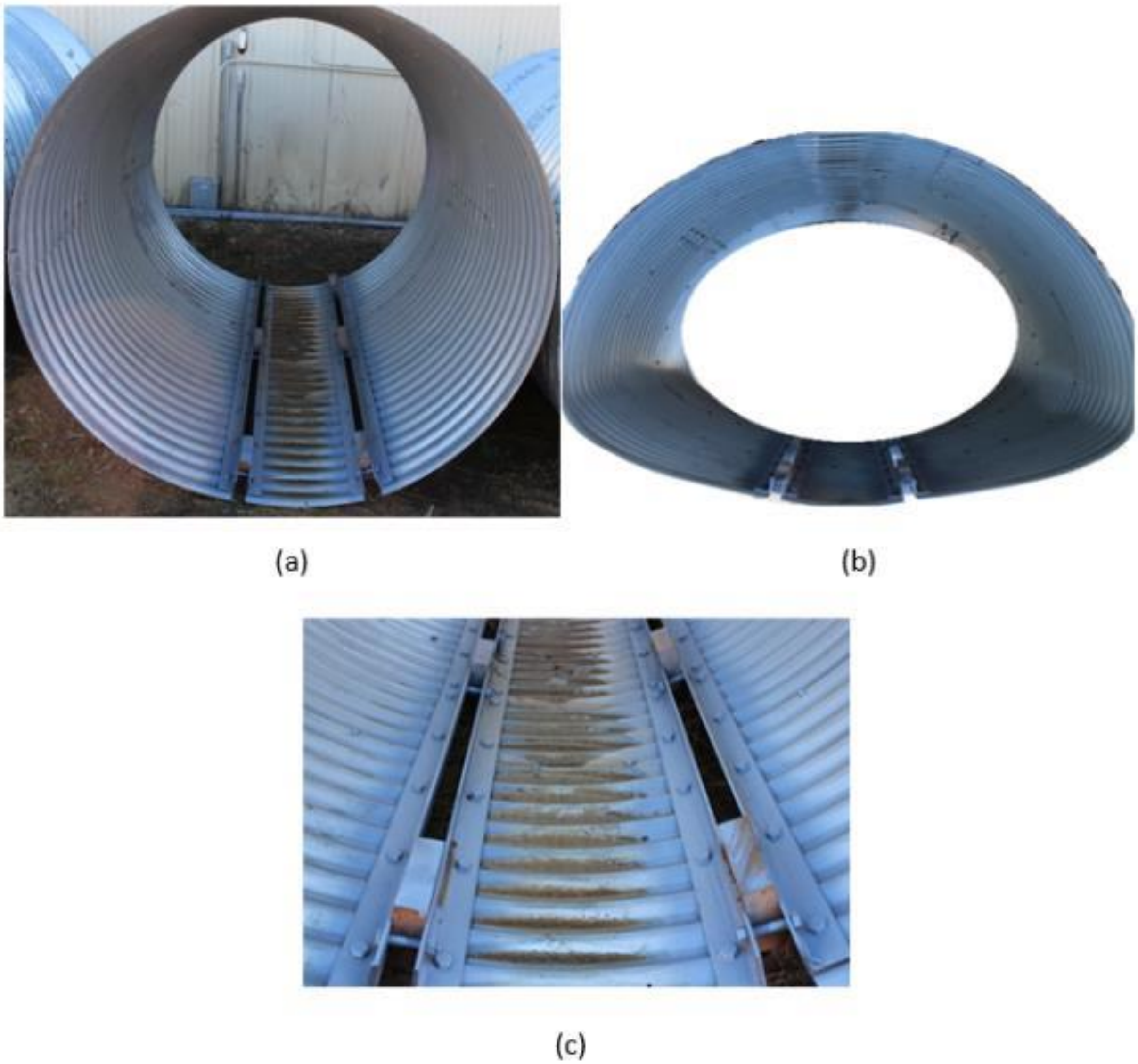



Figure 6.4. a) An Invert Cut Circular CMP (D = 60 in.), b) An Invert Cut Arch Shape CMP (S = 71 in. R = 47 in.), and c) Details of Invert Cut for CMP Sample

#### 6.5.1.5 A3. Soil Material Selection

Selecting embedment soil materials for a culvert depends on existing materials and are specified by different standards and agencies, such as, AASHTO, ASTM, local departments of transportation (DOTs), and CMP manufacturers. The Corrugated Steel Pipe Design Manual (2008) states that the best backfill and embedment materials are sandy and gravelly soils (GW, GP, GM, SW). This manual considers 90% compaction of standard Proctor unit weight.

Two types of soil were selected based on workability in laboratory testing including poorly graded sand (SP) and poorly graded gravel (GP). Types of materials and percentage of compactions are presented in Table 6.1.

Table 6.1. Naming of Materials Based on Percentages of Compaction

| Materials Nomination | Poorly Graded Sand | | | Poorly Graded Gravel |
|---|---|---|---|---|
| Compaction | ≤ 85% | 85%< ≤95% | ≥95% | ≥95% |
| Material | M2 | M3 | M1 | M4 |

6.5.2 Part B – Numerical Modeling

6.5.2.1 B1. Geometry of Soil

All of the models were developed in accordance with lab testing. Different parts included 20 in. foundation, 4 in. bedding, 5 ft embedment, and 24 in. of cover.

Figure 6.5 (a and b) shows how a Circular CMP and an Arch CMP are embedded. Models were developed in following order:

- One stage, including foundation, bedding, embedment and backfilling;
- Four stages, with separating foundation, bedding, embedment and backfilling with *incremental load impacts*;
- Nine stages, including one 20-in foundation (M1), one 4-in layer for bedding (M2), Five 12-in layers for pipe-zone (M3), and two 12-in. layers of backfilling (a combination of M1, M3 and M4) (Tables 6.2 and 6.3). Again, *incremental load impacts* were applied to all the layers.

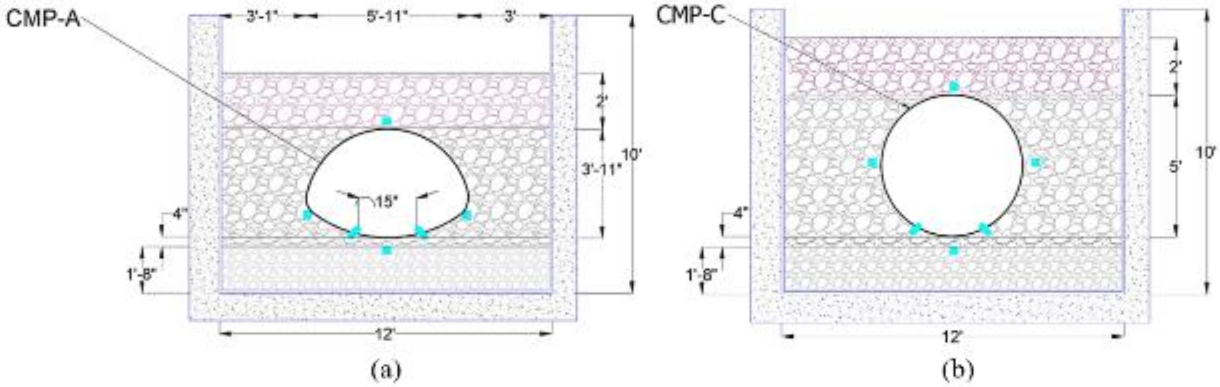



Figure 6.5. a) Arch CMP, b) Circular CMP

Table 6.2. Materials Used in Models for Circular CMP

| **Pipe Soil Interaction** | | **Materials (M#) Model I** | **Materials (M#) Model II** | **Materials (M#) Model III** |
|---|---|---|---|---|
| $2^{nd}$ layer of cover | 12-in. | M1 | M4 | M4 |
| $1^{st}$ layer of cover | 12-in. | M1 | M3 | M4 |
| Circular Pipe Zone | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| Bedding | 4-in. | M2 | M2 | M2 |
| Foundation | 20-in. | M1 | M1 | M1 |

Table 6.3. Materials Used in Models for Arch CMP

| **Pipe Soil Interaction** | | **Materials (M#) Model I** | **Materials (M#) Model II** | **Materials (M#) Model III** |
|---|---|---|---|---|
| $2^{nd}$ layer of cover | 12-in. | M1 | M4 | M4 |
| $1^{st}$ layer of cover | 12-in. | M1 | M3 | M4 |
| Arch Pipe Zone | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| | 12-in. | M3 | M3 | M3 |
| Bedding | 4-in. | M2 | M2 | M2 |
| Foundation | 20-in. | M1 | M1 | M1 |

#### 6.5.2.2 B2. Soil Characteristics and Physical Properties

As mentioned above, granular soil is preferred for bedding, embedment, and backfilling. The most important granular soil parameters are dry unit weight, angle of internal friction (P), and Modulus of elasticity. Table 6.5 presents physical properties of materials for M1, M2, M3, and M4. In addition to unit weight and internal friction angle, which are measured in the laboratory, soil Modulus of elasticity must be determined.

#### 6.5.2.3 B3. Impact of Depth of Soil Cover

The impact of soil cover on the bearing capacity of an H-20 service load is related to the depth of the culvert. Different studies showed that after 10 ft of soil cover the impact of the service load will be negligible and can be ignored. Moser and Folkman (2008) presented a Boussinesq curve, which shows that only 44% of the live load transferred to the culvert in 2 ft of cover.

#### 6.5.2.4 B4. Soil Modulus Elasticity (Young's Modulus or E)

The U.S. Department of the Interior Bureau of Reclamation (2015) presented two tables for the Modulus of elasticity for different types of soil, which are listed for embedment material parameters and native trench wall material. The CMP culverts were installed in trench embedment; therefore, the amount of E and/or E' for granular materials were selected and adapted from this reference (see Table 6.4).

Different soil models, such as, the Linear Elastic model, Mohr-Coulomb model, Hardening Soil model, etc., have equipped Plaxis. The Hardening Soil model is an adaptive model to granular materials with no fines, which was selected for modeling in this research.

A low deflection of soil-CMP-interaction stopped the analysis under the service load for elastic soil behavior, therefore, the load increment option activated based on the Duncan soil model to consider the behavior of soil by unloading and reloading. The Duncan soil model considered a hyperbolic curve for stress-strain relationship, $E_{ur}$ is presented by Eq. 5.1 (Moser and Folkman, 2008):

$$E_{ur} = K_{ur} P_a \left(\frac{\sigma_3}{P_a}\right)^n \tag{5.1}$$

where $K_{ur}$ is the unloading-reloading constant and $E_{ur}$ is the unloading-reloading modulus (psi). $P_a$ is atmospheric pressure used for dimensional purposes (psi); $\sigma_3$ is minor principle stress (confining pressure) (psi), and n is the elastic modulus exponent. Considering pre-deflections of soils in the parallel models demonstrate that Eq. 1 is valid for passing the soil-CMP-interaction module.

Table 6.4. Embedment Material Parameters
Adapted from M-25 (2015)

| **Soil Classification of Embedment (USCS)** | **Percent Compaction of Embedment (E') (psf)** | | |
|---|---|---|---|
| | Uncompacted/ Low Compaction ≥75% to 85% | Moderate ≥85% to 95% | High ≥95% |
| Sands, gravels with more than 12% fines GC, GM, SC, SM (or any soil beginning with one of these symbols [i.e. SC/CL]) | E' = 200 | E' = 1,000 | E' = 2,500 |
| Sands, gravels with 12% or less fines GW, GP, SW, SP, or any soil beginning with one of these symbols (i.e. GP-GM). Does not apply to SP soils with ≥50% fine sand (passing No. 40 sieve). | E' = 500 | E' = 2,000 | E' = 4,000 |

Table 6.5. Soil Properties for FEM

| Parameter | Name | Sand ≤85% Compaction | ≤85% Sand <95% Compaction | Sand ≥95% Compaction | Gravel ≥95% Compaction | Unit English |
|---|---|---|---|---|---|---|
| **General** | | | | | | |
| Material model | Model | Hardening Soil | Hardening Soil | Hardening Soil | Hardening Soil | -- |
| Drainage type | Type | Drained | Drained | Drained | Drained | -- |
| Soil unit weight above p.l. | $\gamma_{unsat}$ | 79 | 88 | 103 | 120 | $Lb/ft^3$ |
| Soil unit weight below p.l. | $\gamma_{sat}$ | 96 | 106 | 125 | 130 | $Lb/ft^3$ |
| **Parameters** | | | | | | |
| Secant Stiffness in standard drained triaxial test | $E_{50}^{ref}$ | $0.432 \times 10^5$ | $1.152 \times 10^5$ | $1.58 \times 10^5$ | $5.68 \times 10^5$ | $Lb/ft^2$ |
| Tangent stiffness for primary oedometer loading | $E_{oed}^{ref}$ | $0.432 \times 10^5$ | $1.152 \times 10^5$ | $1.58 \times 10^5$ | $5.27 \times 10^5$ | $Lb/ft^2$ |
| Unloading / reloading stiffness | $E_{ur}^{ref}$ | $1.3 \times 10^5$ | $3.456 \times 10^5$ | $4.7 \times 10^5$ | $1.7 \times 10^6$ | $Lb/ft^2$ |
| Power for stress-level dependency of stiffness | m | 0.5 | 0.5 | 0.5 | 0.5 | - |
| Friction angle | φ’ | 31 | 31 | 31 | 45 | $^o$ |
| Dilatancy angle | ψ | 1.0 | 1.0 | 1.0 | 1.0 | $^o$ |
| Poisson’s ratio | υ’ | 0.2 | 0.2 | 0.2 | 0.2 | - |
| **Groundwater** | | | | | | |
| Horizontal permeability | $K_x$ | 3.28 | 3.28 | 3.28 | 3.28 | Ft/day |
| Vertical permeability | $K_y$ | 3.28 | 3.28 | 3.28 | 3.28 | Ft/day |
| **Interfaces** | | | | | | |
| Interface strength type | Type | Rigid | Rigid | Rigid | Rigid | - |
| Interface strength | $R_{inter}$ | 1.0 | 1.0 | 1.0 | 1.0 | - |
| **Initial** | | | | | | |
| $K_0$ determination | | Automatic | Automatic | Automatic | Automatic | - |
| Lateral earth pressure coefficient | $K_{0,x}$ | 0.485 | 0.485 | 0.485 | 0.485 | - |
| Over-consolidation ratio | OCR | 1.0 | 1.0 | 1.0 | 1.0 | - |
| Pre-overburden ratio | POP | 0.0 | 0.0 | 0.0 | 0.0 | - |

#### 6.5.2.5 B5. CMP Characteristics and Physical Properties

ASTM A760 is used for selecting physical properties of Corrugated Metal Pipes (CMP).

5.6.3.1.B6. Cementitious SAPL Characteristics and Physical Properties

The minimum amount of $f'_c = 8{,}000\ psi$ is selected for SAPL due to differences between products by different vendors. Models repeated with 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 in. thicknesses.

#### 6.5.2.6 B7. H-20 Service Load

According to AASHTO LRFD Bridge Design (2017), a shallow underground conduit passing crossroads must be designed based on an H-20 truckload, which is simulated at 32,000 lb on the back-axel equivalent to 16,000 lb on two wheels. For a two-dimensional model, the load is defined as a line-load with the length of 10 in. (the load pad size in laboratory testing is 10 by 20 in., while the length is located parallel to the length of samples). After applying factors, the total factored service load on the load pad is 23,952 lb.

Considering the length of pad as 20 in., 17,245 lb/ft/ft is the linear amount of H-20 factored service load.

### 6.5.3 Part C – Results of Modelling

Models were developed in the steps of, 1) Intact Circular CMP, 2) Invert Lost Circular CMP, and 3) Circular SAPL – CMP. Then models were developed in the same order for pipe arch shapes. A flowchart (Figure 6.6) presents the models' development.

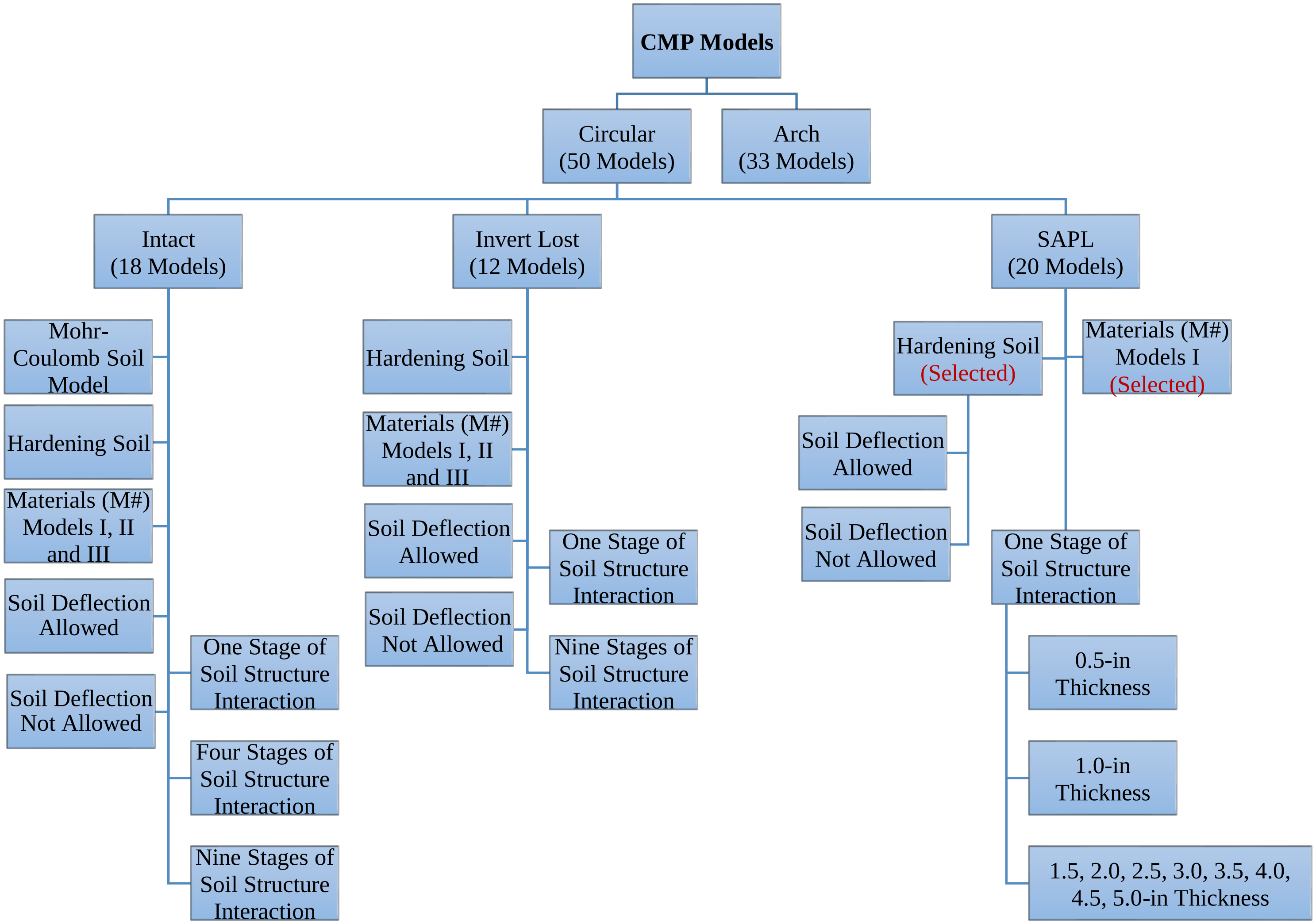



Figure 6.6. Order of Modeling for 60 in. Circular and 71 by 47 in. Arch CMP

#### 6.5.3.1 C1. Results of Intact Circular CMP (under Service Truck Load)

Plaxis models were developed for two soil conditions:

- Soil displacement restricted failure (soil deflection not allowed in Figure 6.6)
- Soil displacement controlled (soil deflection allowed in Figure 6.6).

#### 6.5.3.2 C1.1. Results of Intact Circular CMP (under Service Truck Load in the Condition of Soil displacement restricted failure)

The absolute displacement value of an intact circular CMP under service load increases when the soil physical properties changed. With increasing density, friction angle and modulus of elasticity of soil, more energy is absorbed by the pipe before soil is punched/failed (see Table 6.6 and Figure 6.7).

Table 6.6. Absolute Displacement Value of an Intact Bare Circular CMP under Service Load

| Model | Cover Material (under Service Load) | | Absolute Value of CMP Displacement (in) |
|---|---|---|---|
| Bare CMP | 1 ft Sand with 85% and 1 ft Sand with 95% compaction | Model I | 0.3665 |
| | 1 ft Sand with 85% and 1 ft Gravel with 95% compaction | Model II | 0.5047 |
| | 2 ft Gravel with 95% compaction | Model III | 0.5929 |

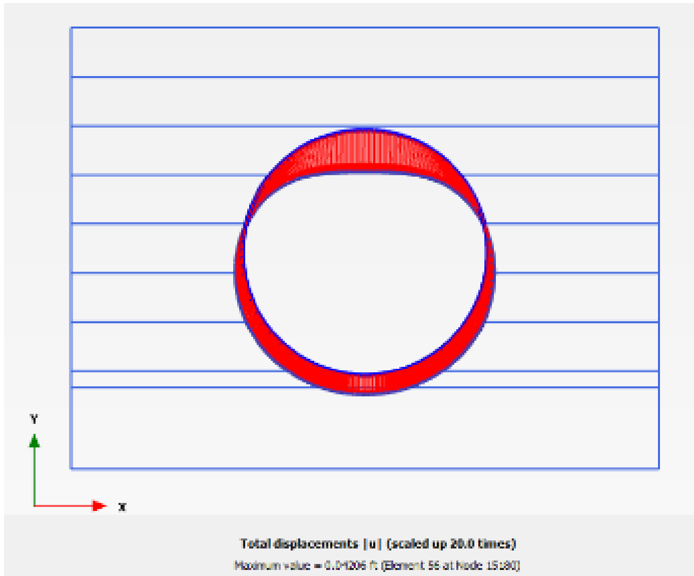



Figure 6.7. CMP Displacement under Service Load (PLAXIS)
Soil Cover: One-foot Sand with 85% and one-foot Gravel with 95% compaction (Model II)

#### 6.5.3.3 C1.2. Results of Intact Circular CMP (under Service Truck Load in the Condition of Soil displacement controlled) – Appendix 6.A

The absolute displacement value of an intact circular CMP under service load with Model II soil cover (one ft sand with 85% and one ft gravel with 95% compaction) is equal 4.3824 in.

#### 6.5.3.4 C1.3. Verification of Results of FE

The absolute deflection value of CUIRE laboratory test on a bare circular CMP is approximately 4.3 in., which verifies the numerical analysis. Figure 6.8 shows the deflection of CMP at the end of the loading procedures.

Figure 6.8 Bare CMP Deflection

6.5.3.5 C2. Results of Invert Lost Circular CMP (under Service Truck load – Soil Cover Load)

The service load caused failure to invert lost circular CMP; therefore, the invert lost circular CMP had been modeled only for 2 ft of soil cover load. Table 6.7 presents the absolute displacement value of an invert lost circular CMP for different soil properties before the truck load.

Table 6.7. Absolute Displacement Value of an Invert Lost Circular CMP under 2 ft Soil Load

| Model | Cover Material (before Service Load) | | Absolute Value of CMP Displacement (in) |
|---|---|---|---|
| Bare CMP | 1 ft Sand with 85% and 1 ft Sand with 95% compaction | Model I | 0.3278 |
| | 1 ft Sand with 85% and 1 ft Gravel with 95% compaction | Model II | 0.3167 |
| | 2 ft Gravel with 95% compaction | Model III | 0.3215 |

#### 6.5.3.6 C3. Results of Cementitious SAPL inside a Circular Cut Invert CMP (under Service Truck Load)

Different soil materials and densities were simulated. Using gravel with more density increases the load bearing capacity of the soil/pipe system. Maximum bearing capacity was acquired by using 2 ft of gravel (Model III). However, due to installation of load cells, one-foot sand with 85% and one-foot gravel with 95% compaction (Model II) were selected for laboratory testing and followed by FEM. Plaxis models were developed from 0.5-in. thickness to 5.0-in. thickness of SAPL for two conditions:

- Soil displacement restricted failure (soil deflection not allowed in Figure 6.6)
- Soil displacement controlled (soil deflection allowed in Figure 6.6).

Table 6.8 presents the absolute value of displacement in both of the above conditions. Figure 6.9 illustrates an invert lost SAPL – CMP. Figure 6.10 is a sample of displacement for 0.5 in. thickness of cementitious materials. It shows both deflection of invert cut portion, which was lined by SAPL, and other part, which is a composite of CMP and SAPL.

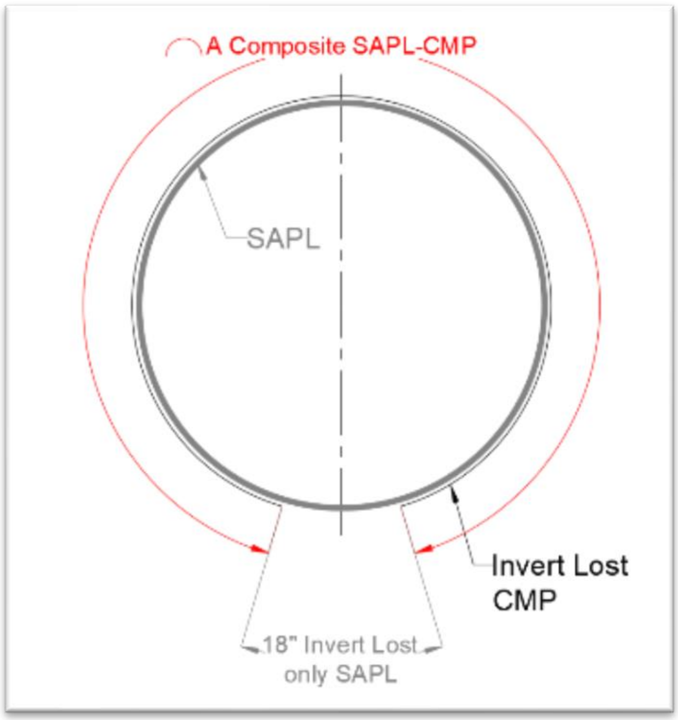
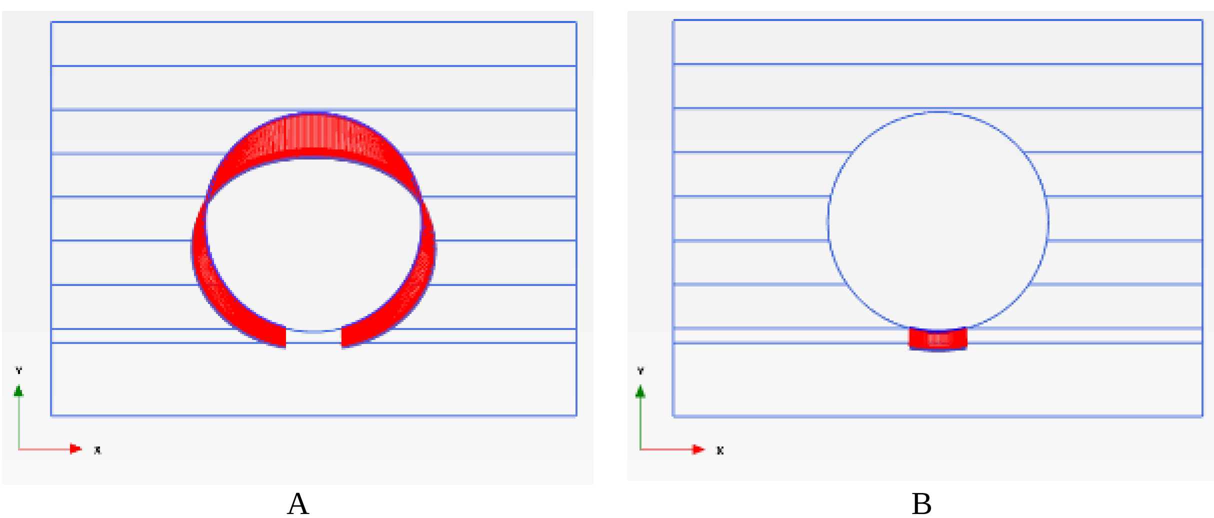


Figure 6.9. An Invert Lost SAPL – CMP



A) 2.4012 in. SAPL – CMP Displacement on Crown and
B) 1.0327 in. only SAPL Displacement on Invert

Figure 6.10. Total Displacement under Service Load on a Lost Invert Circular CMP with 0.5-in. Thickness of Cementitious SAPL

Table 6.8. Absolute Displacement Value of different thicknesses of SAPL

| SAPL Thickness (in.) | Absolute Value of SAPL-CMP Displacement (in) | Absolute Value of SAPL (Invert lost) Displacement (in) | Absolute Value of SAPL-CMP Displacement (in) | Absolute Value of SAPL (Invert lost) Displacement (in) |
|---|---|---|---|---|
| | Soil Displacement Controlled | | Soil Displacement Restricted Failure | |
| 0.5 | 2.4012 | 1.03272 | 0.6294 | 0.4412 |
| 1.0 | 2.1108 | 1.1316 | 0.6322 | 0.4804 |
| 1.5 | 1.962 | 1.1929 | 0.6084 | 0.4947 |
| 2.0 | 1.8696 | 1.2336 | 0.5952 | 0.5105 |
| 2.5 | 1.7496 | 1.2132 | 0.6319 | 0.5461 |
| 3.0 | 1.716 | 1.2456 | 0.6459 | 0.5691 |
| 3.5 | 1.6896 | 1.2696 | 0.6646 | 0.5929 |
| 4.0 | 1.6728 | 1.2948 | 0.6654 | 0.5935 |
| 4.5 | 1.6608 | 1.3164 | 0.6748 | 0.6287 |
| 5.0 | 1.6548 | 1.338 | 0.6997 | 0.6455 |

#### 6.5.3.7 C4. Discussion of the Results of Cementitious SAPL inside a Circular Cut Invert CMP (under Service Truck Load)

#### 6.5.3.8 C4.1. Soil Displacement Restricted Failure

SAPL – CMP with invert lost, which has only SAPL, both deflected more with increasing thickness of SAPL; however, the slope of the tangent for SAPL (the invert part) is steeper than the slope of the tangent of the SAPL – CMP. Figure 6.11 illustrates how deflection varies with increasing SAPL thickness for the condition of soil displacement restricted failure.

#### 6.5.3.9 C4.2. Soil Displacement Controlled

When soil is allowed to be deformed, the SAPL – CMP deflection decreased with increasing thickness of SAPL. However, the deflection of the invert portion, with SAPL only, increased by increasing the thickness of SAPL. Figure 6.11 illustrates how deflection varies with increasing the SAPL thickness for the condition of soil displacement controlled. According to Figure 6.11, with less than 1.2-in. SAPL, the lined culvert behaves in a flexible manner (Zone 1), and with more than 2.4-in. SAPL, the lined culvert behaves in a rigid manner (Zone 3). Semi-rigid behavior happened when the thickness of liner was between 1.2-in. to 2.4-in (Zone 2). Figure 6.12 does not cover the cracks of cementitious materials. In fact, the performance limitations must be considered when this graph is used. Moser and Folkman (2008) considered the design of semi-rigid or semi-flexible pipes based on deflection of flexible pipes.

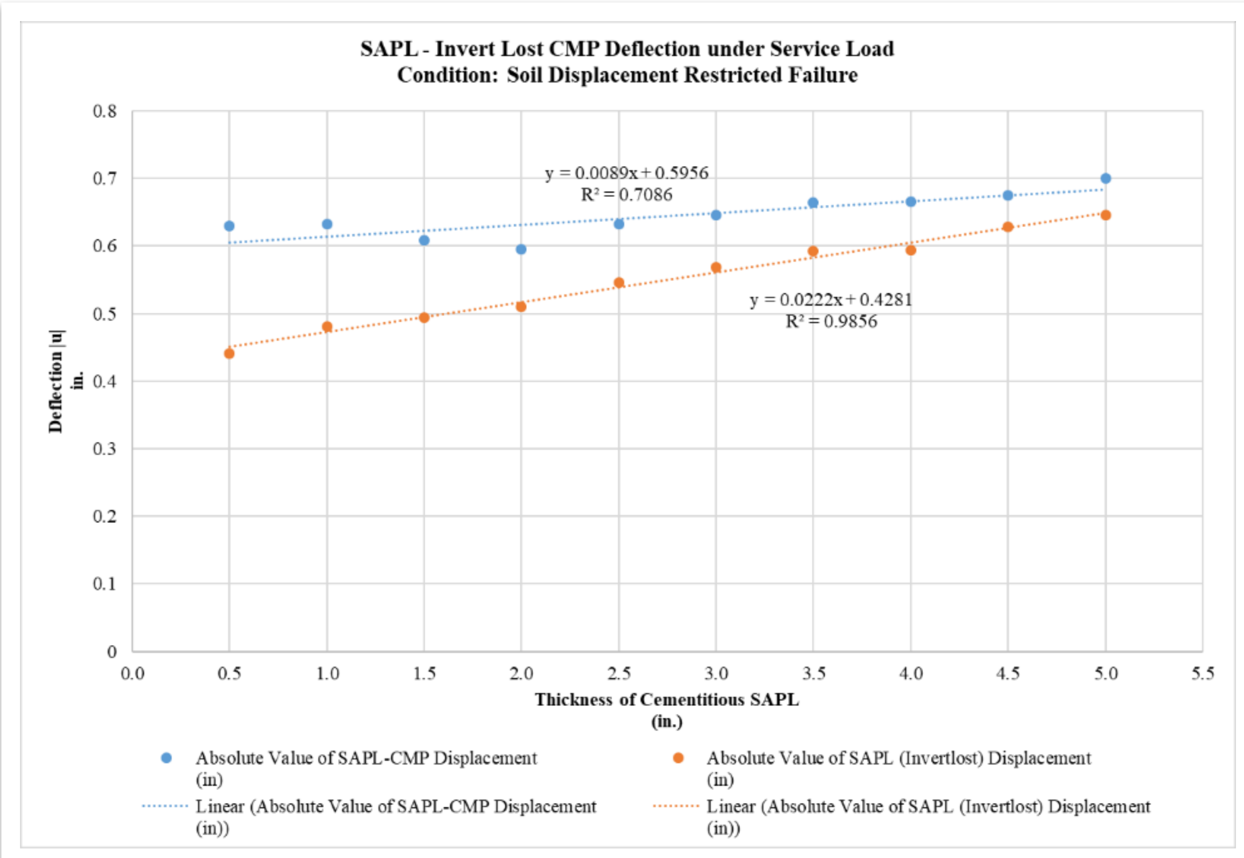



Figure 6.11. Variance of Thicknesses (in.) vs. Deflection (in.) for Circular CMP SAPL Invert Lost under Condition of Soil Displacement Restricted Failure

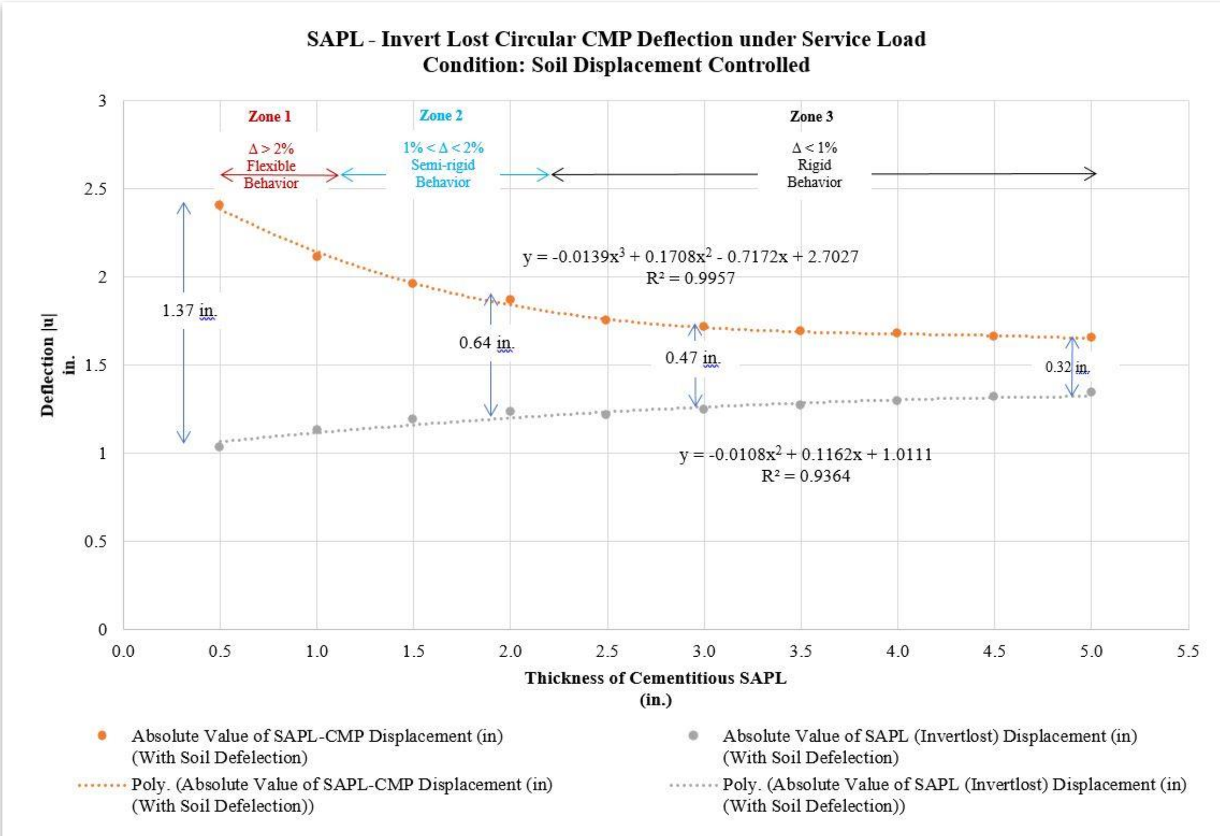
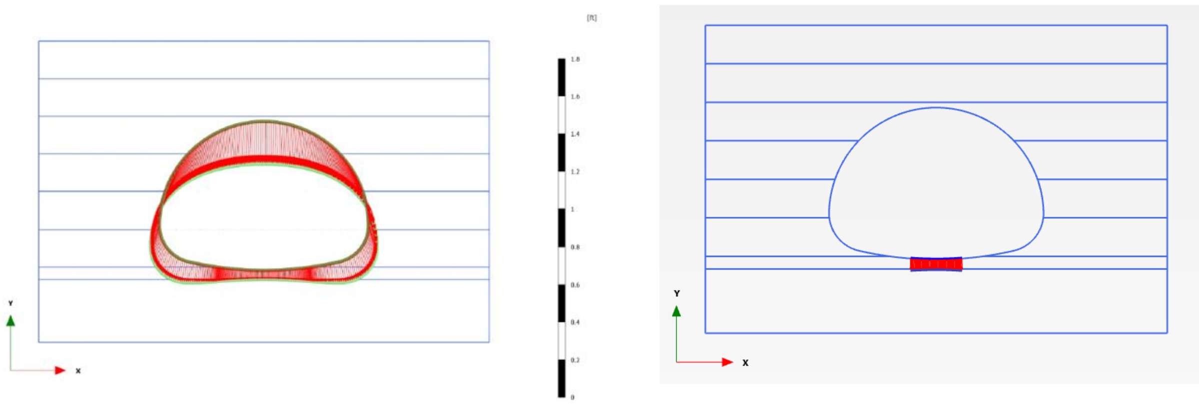



Figure 6.12. Variance of Thicknesses (in.) vs. Deflection (in.) for Circular SAPL – CMP Invert Lost under Condition of Soil Displacement Controlled

6.5.3.10 C5. Results of Cementitious SAPL inside an Arch Cut Invert CMP (under Service Truck Load)

Similar circular, one-foot sand with 85%, and one-foot gravel with 95% compaction (Model II) are selected for laboratory testing and followed by FEM. Models were developed from 0.5-in. thickness to 5.0-in. thickness of SAPL. Figure 6.13 is a sample of displacement for 0.5 in. thickness of cementitious materials. It shows both deflection of the invert cut portion, filled by SAPL, as a composite of CMP and SAPL.



A B

A) 2.7132 in. SAPL CMP Displacement on Crown and
B) 0.7159 in. only SAPL Displacement on Invert
Figure 6.13. Total Displacement under Service Load on a Lost Invert Arch CMP with 0.5-in. Thickness of Cementitious SAPL

#### 6.5.3.11 C5.1. Discussion of the Results of Cementitious SAPL inside an Arch Cut Invert CMP (under Service Truck Load) in Condition of Soil Displacement Controlled

Again, like circular, in arch shape, the SAPL – CMP deflection decreased with increasing the thickness of SAPL. However, deflection of the invert, which has only SAPL, increased by increasing the thickness of SAPL. Figure 6.14 illustrates variance of deflection with increasing the SAPL thickness for the condition of soil displacement controlled. According to the Figure 6.14, with less than 2.0-in. SAPL, the lined culvert behaves in a flexible manner (Zone 1), and more than 4.5-in. SAPL, the lined culvert behaves in a rigid manner (Zone 3). Semi-rigid behavior happened when the thickness of liner was between 2.0-in. to 4.5-in. (Zone 2). Again, similar to the circular, the Figure 6.14 graph does not cover the cracks of cementitious materials. In fact, the performance limitations must be considered when this graph is used.

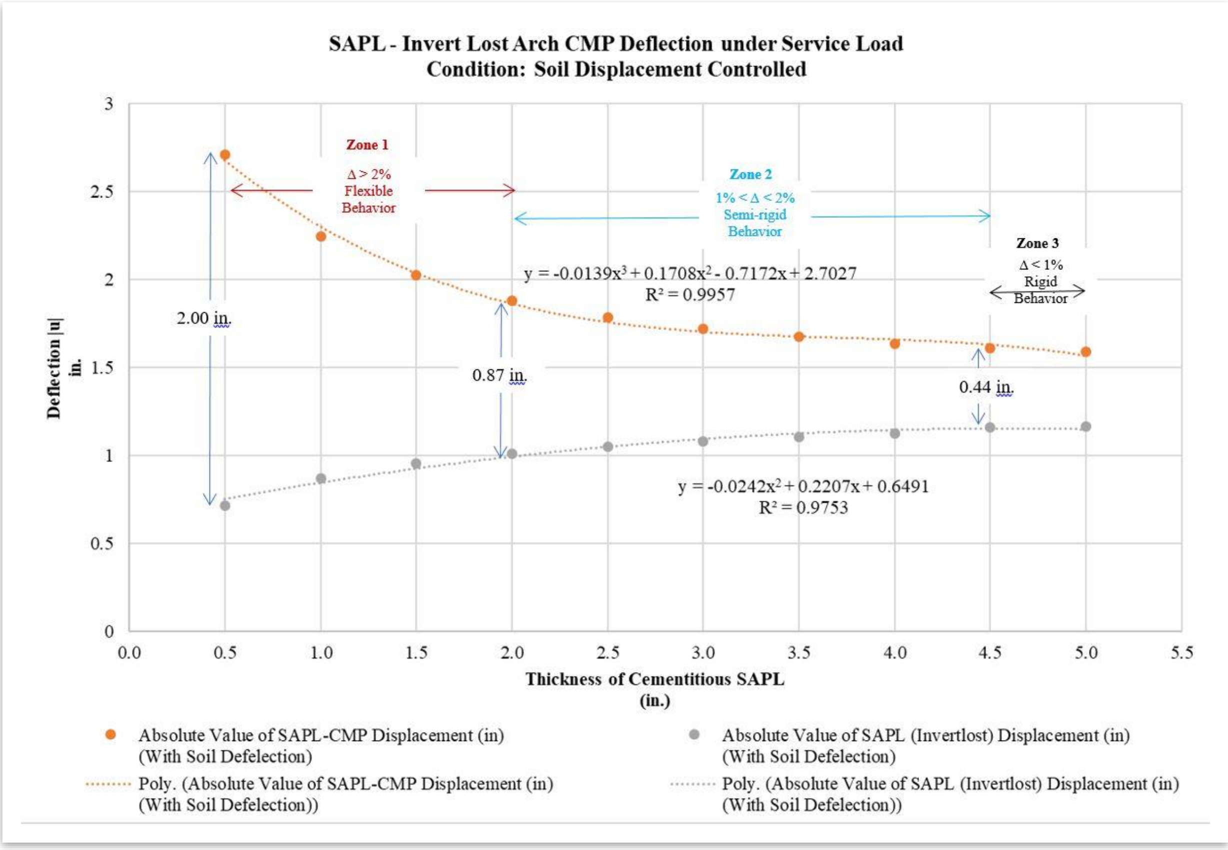



Figure 6.14. Variance of Thicknesses (in.) vs. Deflection (in.) for Arch Shape SAPL – CMP Invert Lost under Condition of Soil Displacement Controlled

6.5.3.12 C6. Comparison between Circular and Arch Shape Cementitious SAPL

Figure 6.15 shows a comparison between deflection of arch shapes and circular shapes SAPL – CMP with different thicknesses.

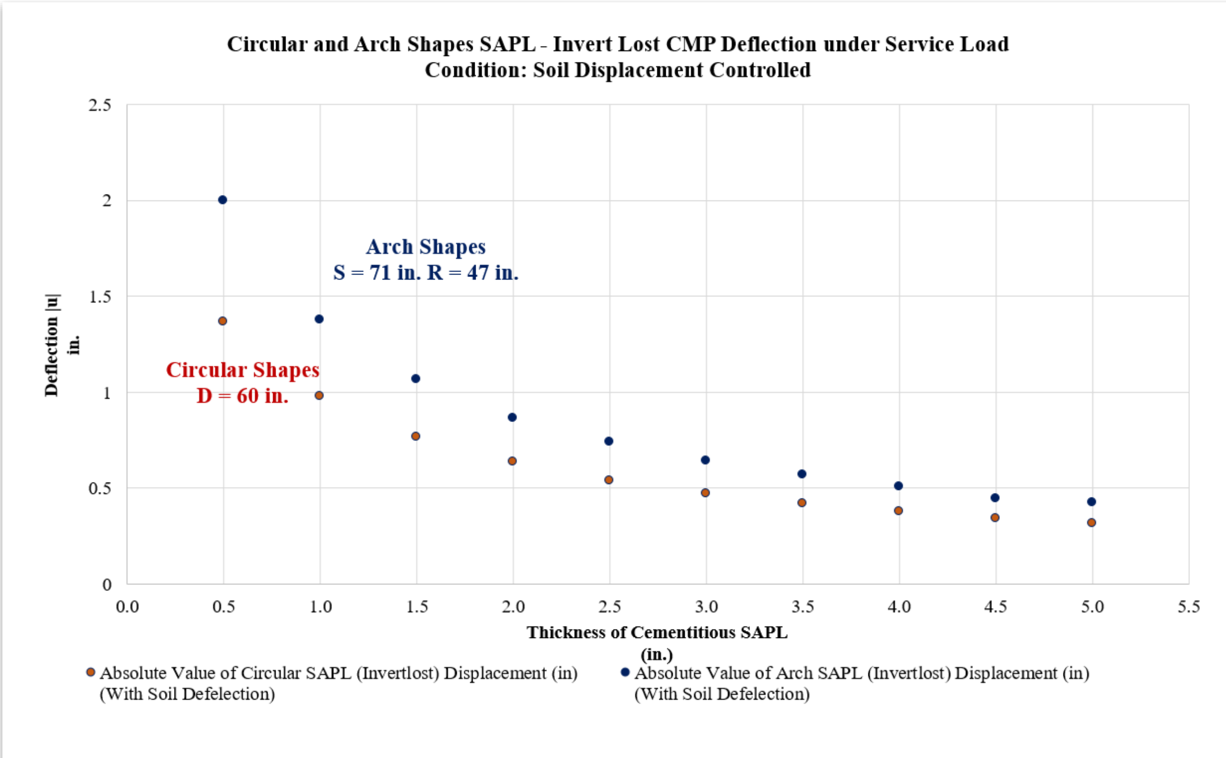



Figure 6.15. Deflection of Arch Shapes and Circular Shapes SAPL – CMP with Different Thicknesses

## 6.6 Chapter Conclusions

The structural behavior of intact CMPs, invert lost CMPs, and SAPL – CMP invert lost culverts in circular and arch pipe shapes were analyzed by FEM. This paper showed that the structural capacity of deteriorated (invert lost) CMPs increased by cementitious SAPL. The structural behavior of an invert lost CMP – cementitious SAPL is complex because of two parameters: (1) cementitious SAPL in the invert part, and (2) composite of metal and cementitious SAPL for the rest of the CMP. Other conclusions are:

- There is a linear relationship between increasing thicknesses of cementitious SAPL and pipe deflection before the soil was punched or failed.
- When soil was allowed to deflect (soil is under failure mode or punched), with increasing the thickness of cementitious SAPL, the pipe deflection decreased.

- A circular 60-in. CMP with
    - Less than 1.2 in. cementitious, SAPL behaves as flexible pipe,
    - More than 2.4 in. cementitious, SAPL behaves as rigid pipe, and
    - More than 1.2 in. and less than 2.4 in. cementitious, SAPL behaves as semi-flexible or semi-rigid pipe.

## 6.7 Contributions to The Body of Knowledge

The following are contributions of this paper to develop a structural design methodology of cementitious SAPL:

- The structural behavior of a CMP cementitious SAPL is related to the thickness of SAPL.
- At least 2.15 in. thickness of cementitious SAPL for a 60 in. circular CMP shallow depth[11] culvert needs to prevent flexible behavior of system.
- The arch shape SAPL – CMPs behave flexibly and semi-flexibly with different thicknesses of cementitious SAPL less than 4.5 in. Therefore, it is recommended not to use cementitious SAPL for an arch shaped shallow depth culvert without reinforcements.

## 6.8 Limitations and Recommendations for Future Research

A variety of culverts are under operations with different issues; thus, the following are the main needs of future studies:

- This study was limited to one size circular and one size arch shape. For future research, it is recommended to consider the impact factor of the host culvert's size. For the same SAPL thickness, the size of the host culvert will determine whether the composite culvert behaves flexibly or rigidly.

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[11] FHWA – Culvert Repair Manual-Vol1-010551 considered shallow depth as 0 to 2 ft.
AASHTO LRFD Bridge design considered less than 2 ft as shallow depth.

- This study is limited to one physical properties of SAPL cementitious materials. However, different vendors/contractors have their own materials with different *f'c* and other physical properties.
- This study did not cover reinforcements.
- This paper considered only one type of deterioration at culvert invert.

## 6.9 References:


AASHTO (American Association of State Highway and Transportation Officials). (2017). "AASHTO LRFD Bridge Design Specification," 8th Edition, LRFD-8. AASHTO, Washington, DC 20001.

Corrugated Steel Pipe Design Manual. (2008). Published by: National Corrugated Steel Pipe Association.

FHWA-RD-94-096 (1995). "Culvert Repair Practice Manual." Volume I. Publication No. FHWA-RD-94-096. U.S. Department of Transportation. Federal Highway Administration.

FHWA-HIF-12-026. (2012). "Hydraulic Design of Highway Culverts," Publication No. FHWA-HIF-12-026. Hydraulic Design Series Number 5. U.S. Department of Transportation, Federal Highway Administration.

Havens B. T., Klaiber F. W., Lohnes R. A. and Zachary L. W. (1995). "Longitudinal Strength and Stiffness of Corrugated Steel Pipe," Transportation Research Record 1514.

Li Z., Tang Y., Tang F., Chen Y. and Chen G. (2018). "Elastic Buckling of Thin-walled Polyhedral Pipe Liners Encased in a Circular Pipe under Uniform External Pressure," Available at: https://doi.org/10.1016/j.tws.2017.11.019

Masada T., Hurd J. and Fekrat, A. Q. (2017). "Structural Benefits of Concrete Paving of Steel Culvert Inverts." Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. Report No. FHWA/OH-2017-21

Masada T. (2017). “Structural Benefits of Concrete Paving of Steel Culvert Inverts.” Final Report. Prepared for the Ohio Department of Transportation. State Job Number 135248

Moser A. P. and Folkman S. (2008). “Buried Pipe Design.” 3rd Edition, Utah State University, ISBN: 978-0-07-147689-8. Logan, Utah, U.S.

M-25 (2015). “Methods for Prediction of Flexible Pipe Deflection,” 2nd Edition. RECLAMATION Managing Water in the West. U.S. Department of the Interior Bureau of Reclamation.

ODOT (2017). Ohio Department of Transportation, Culvert Management Manual. Available: http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Culvert%20Management/Culvert%20Management%20Manual/Culvert%20Management%20Manual%20October%202017%2011-9-17.pdf,

PLAXIS 2D. (2017). “Tutorial Manual.” Available: https://www.plaxis.com/support/manuals/plaxis-2d-manuals/

Royer, J. R., and Allouche, E. (2016). “Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Stormwater Conduits.” NASTT, Dallas, Texas. WM-T6-03.

Royer, J. R., and Iseley, T. (2017). “Laboratory Testing and Analysis of Geopolymer Pipe-lining Technology for Rehabilitation of Sewer & Storm Water Conduits, Part II – CMP Culvert Analysis.” NASTT, Washington, D.C., TM2-T3-04.

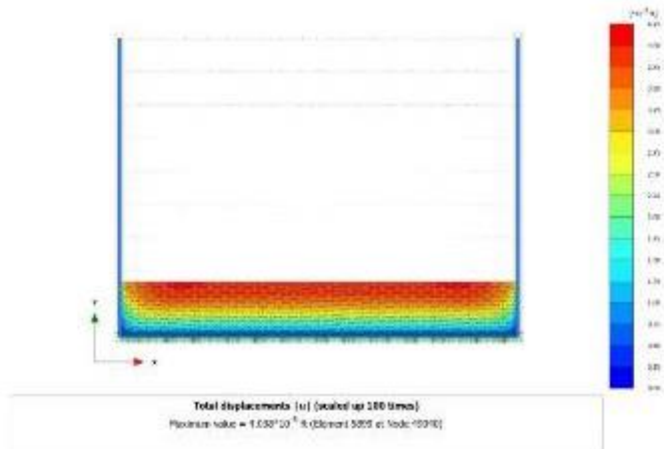
Tetreault J., Neil A. H. and Moore I. D. (2016). "Pre- and Post-rehabilitation Behavior of a Deteriorated Horizontal Ellipse Culvert." Can. Geotech. J. 55: 329-342. Published at www.nrcreasearchpress.com/cgi on 18 July 2017.

Watkins, R. K. and Reeve, R. C. (1982) "Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe." Advanced Drainage Systems, Inc., Columbus, Ohio, http://onlinepubs.trb.org/Onlinepubs/trr/1983/903/903-014.pdf, Date Accessed April 24, 2018.

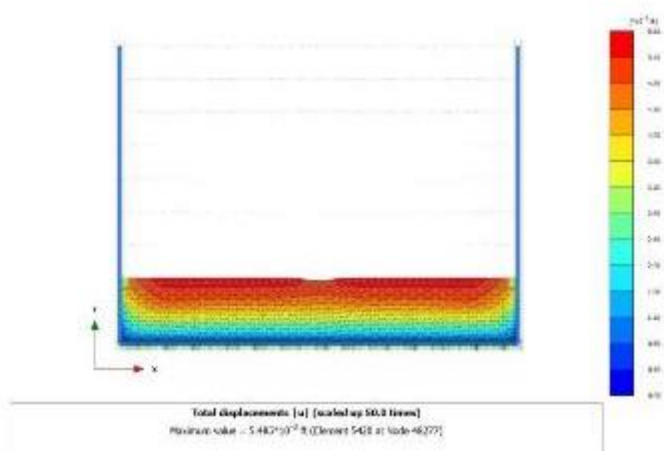
## 6.10 Appendix 6.A

Results of Intact Circular CMP (under Service Truck Load in the Condition of Soil displacement controlled)

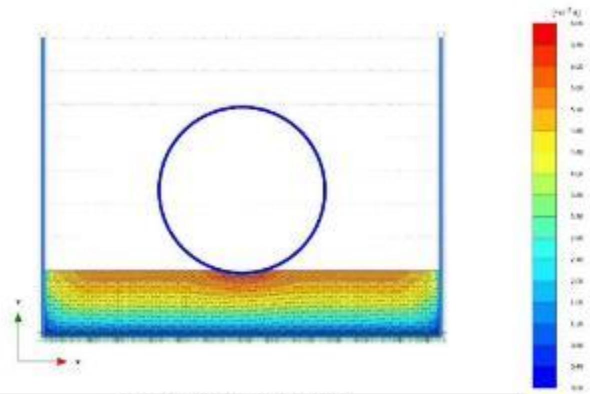
**2.1.1.1.1 Calculation results, Phase_1 [Phase_1] (1/9), Total displacements |u|**




**2.1.1.1.2 Calculation results, Phase_2 [Phase_2] (2/15), Total displacements |u|**

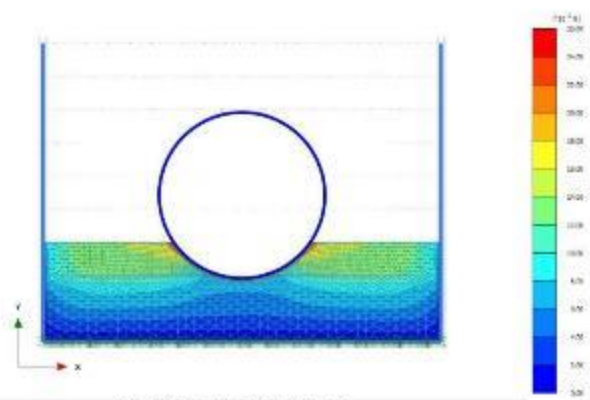


**2.1.1.1.3 Calculation results, Phase_3 [Phase_3] (3/18), Total displacements |u|**



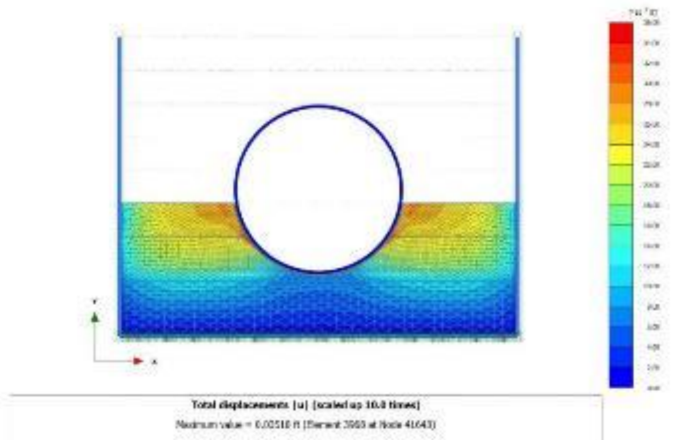
Total displacements |u| (scaled up 50.0 times)
Maximum value = 5.669*10^-3 ft (Element 5314 at Node 34166)

**2.1.1.1.4 Calculation results, Phase_4 [Phase_4] (4/38), Total displacements |u|**

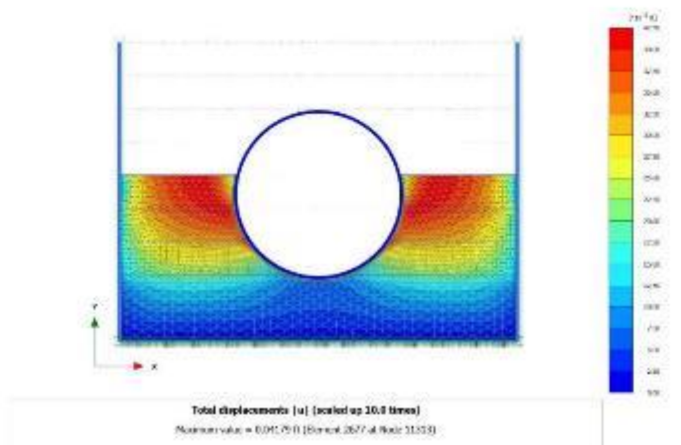


Total displacements |u| (scaled up 20.0 times)
Maximum value = 0.00523 ft (Element 4772 at Node 29350)

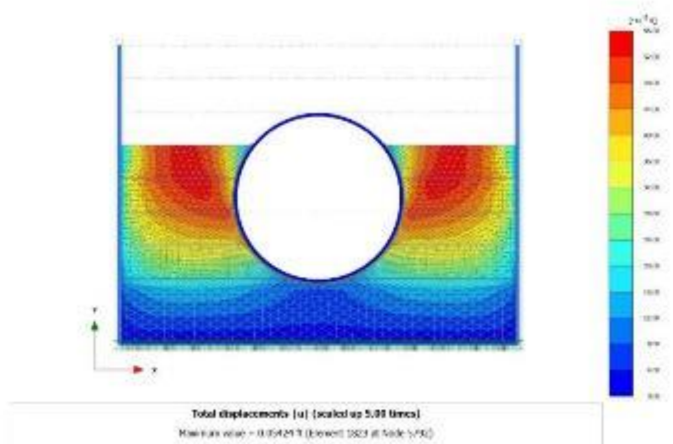
### 2.1.1.1.12 Calculation results, Phase_5 [Phase_5] (5/352), Total displacements |u|



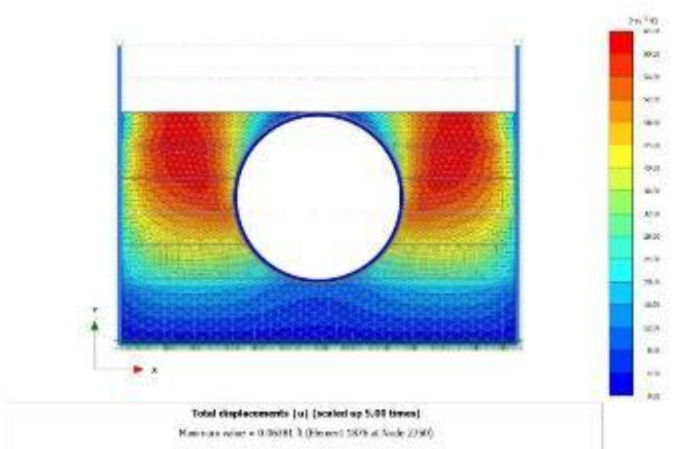

### 2.1.1.1.5 Calculation results, Phase_6 [Phase_6] (6/52), Total displacements |u|



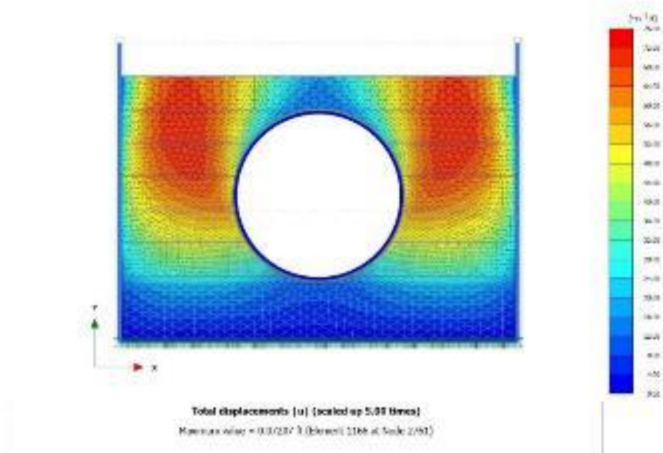
### 2.1.1.1.6 Calculation results, Phase_7 [Phase_7] (7/86), Total displacements |u|



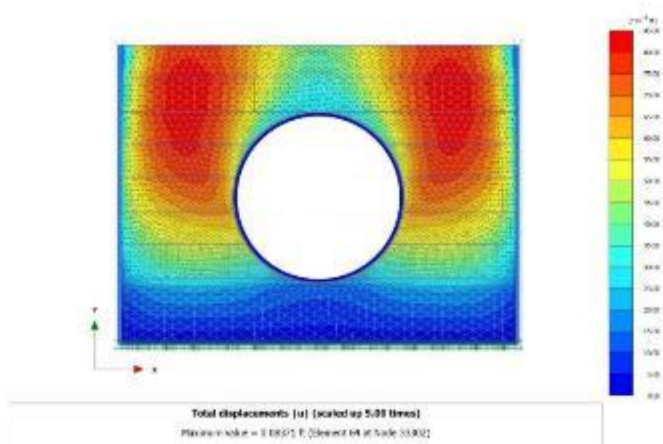

### 2.1.1.1.7 Calculation results, Phase_8 [Phase_8] (8/101), Total displacements |u|



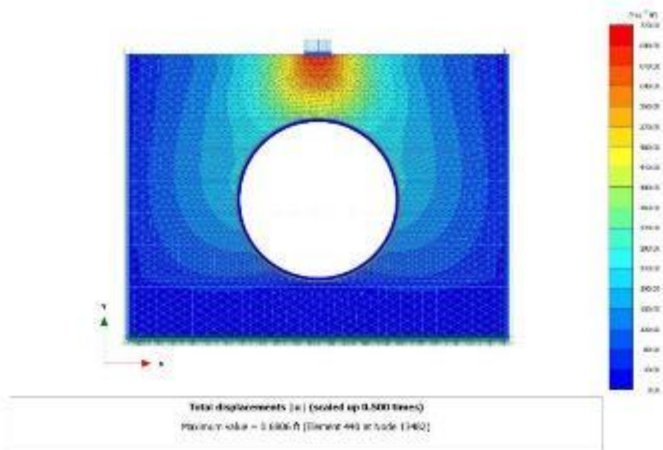
#### 2.1.1.1.8 Calculation results, Phase_9 [Phase_9] (9/114), Total displacements |u|



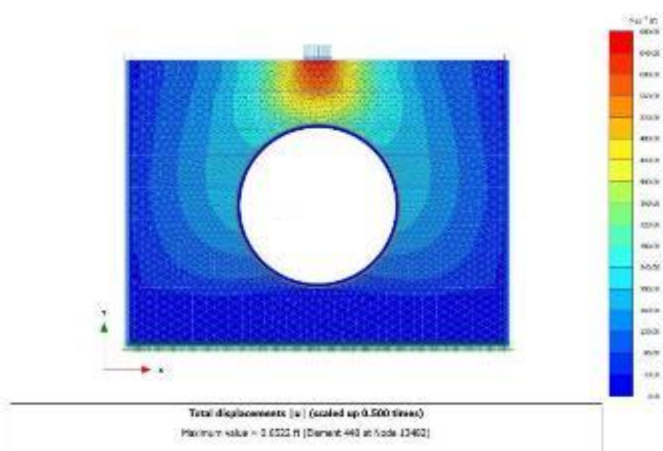

#### 2.1.1.1.9 Calculation results, Phase_10 [Phase_10] (10/132), Total displacements |u|



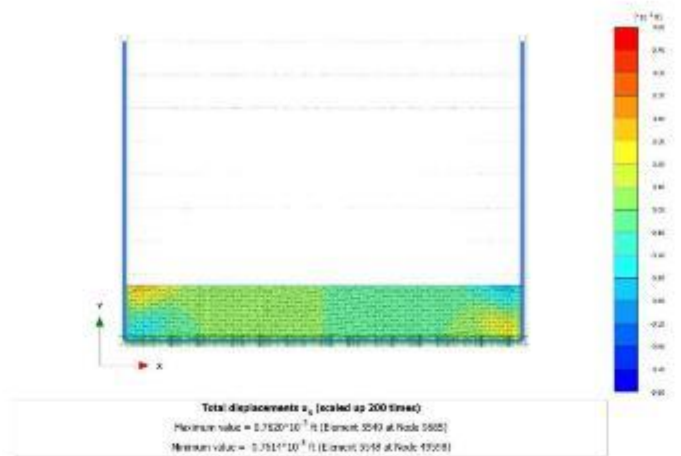
**2.1.1.1.10 Calculation results, Phase_11 [Phase_11] (11/133), Total displacements |u|**



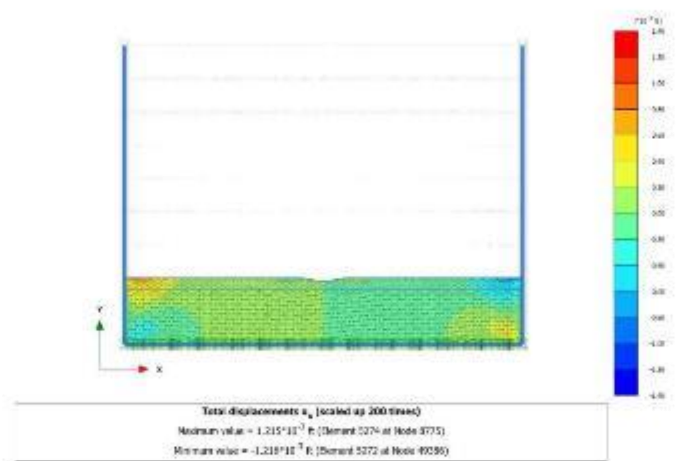

**2.1.1.1.11 Calculation results, Phase_12 [Phase_12] (12/318), Total displacements |u|**



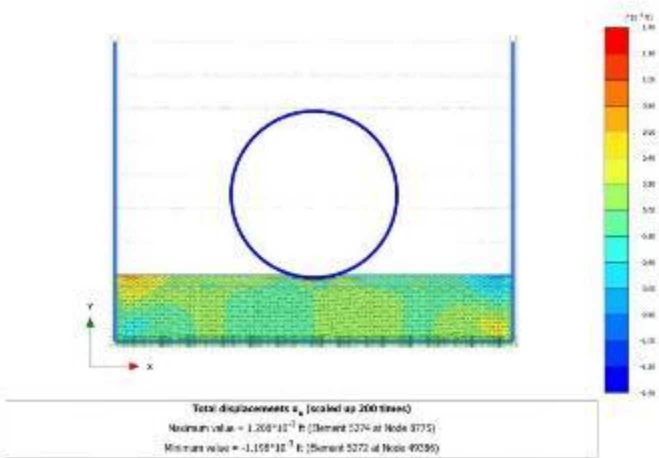
**2.1.1.2.1 Calculation results, Phase_1 [Phase_1] (1/9), Total displacements $u_x$**



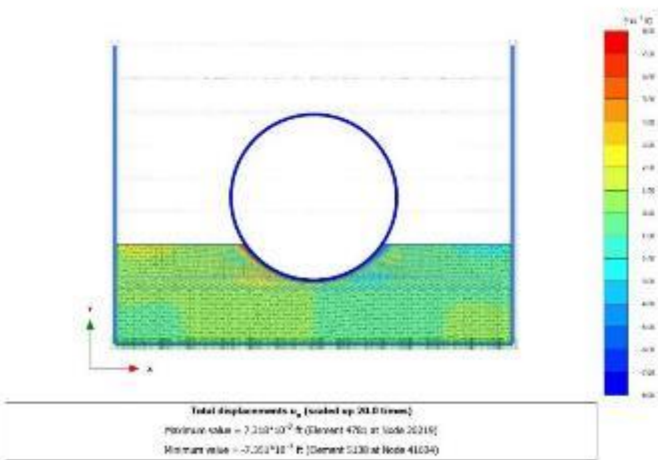

**2.1.1.2.2 Calculation results, Phase_2 [Phase_2] (2/15), Total displacements $u_x$**



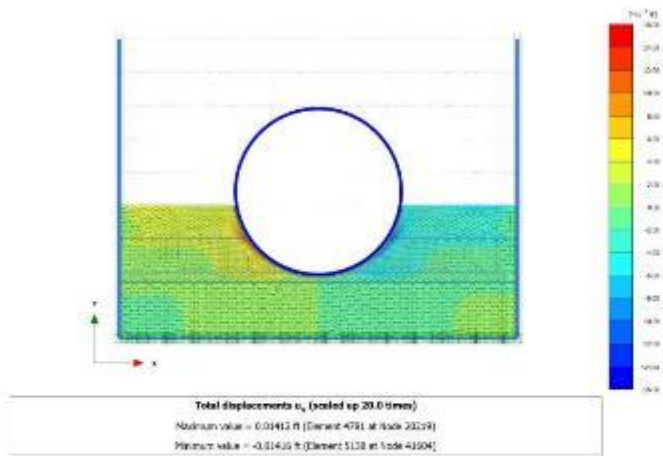
### 2.1.1.2.3 Calculation results, Phase_3 [Phase_3] (3/18), Total displacements $u_x$



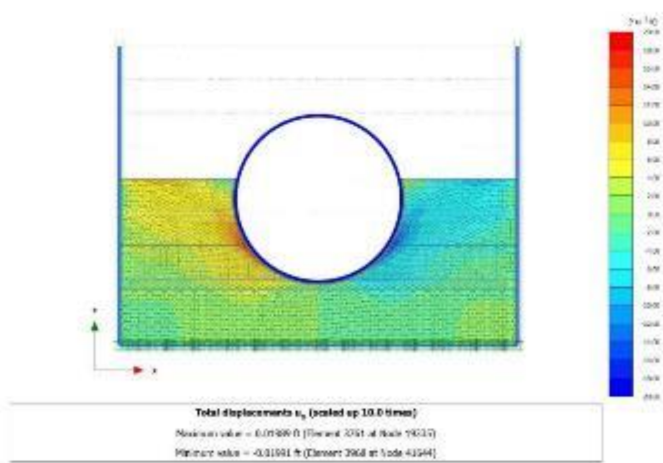

### 2.1.1.2.4 Calculation results, Phase_4 [Phase_4] (4/38), Total displacements $u_x$



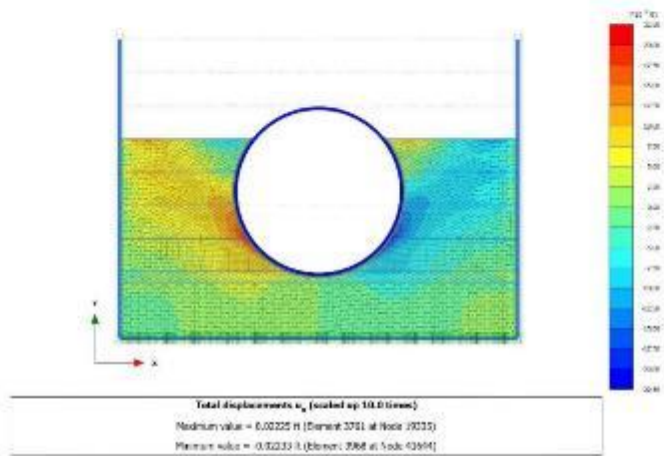
**2.1.1.2.12 Calculation results, Phase_5 [Phase_5] (5/352), Total displacements $u_y$**



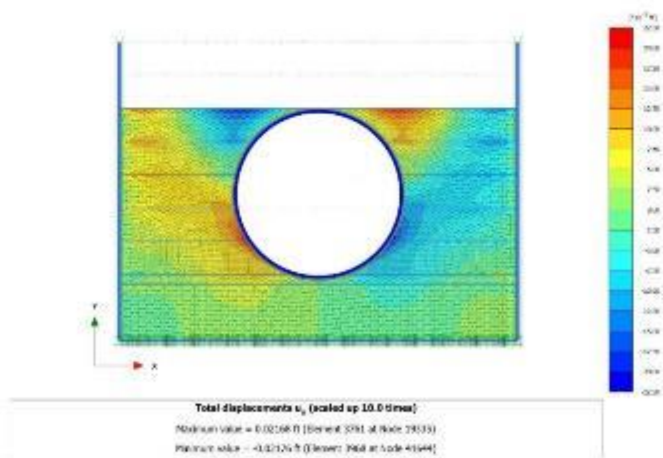

**2.1.1.2.5 Calculation results, Phase_6 [Phase_6] (6/52), Total displacements $u_y$**



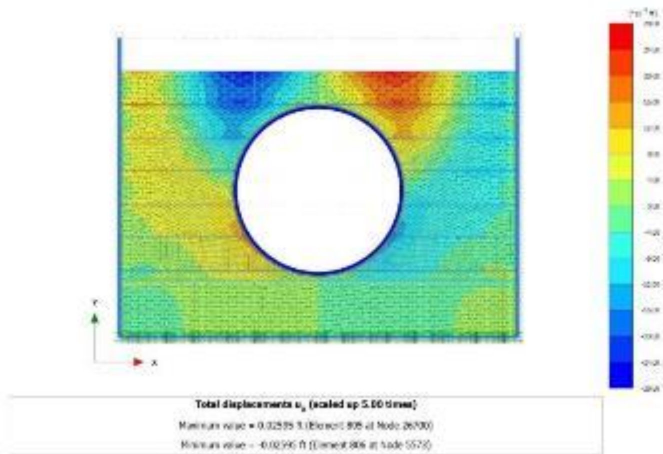
### 2.1.1.2.6 Calculation results, Phase_7 [Phase_7] (7/86), Total displacements $u_y$



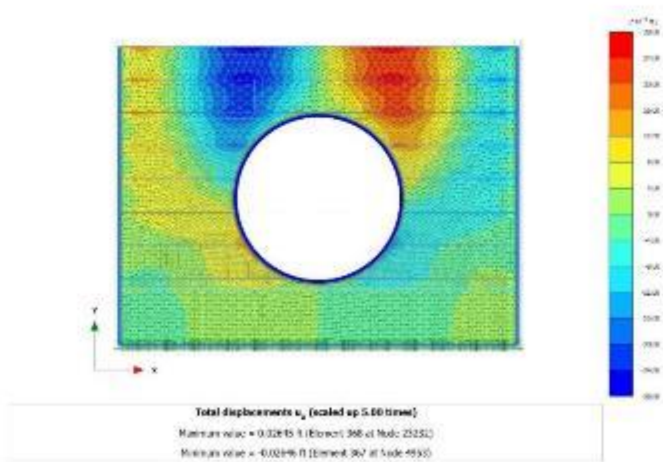

### 2.1.1.2.7 Calculation results, Phase_8 [Phase_8] (8/101), Total displacements $u_y$



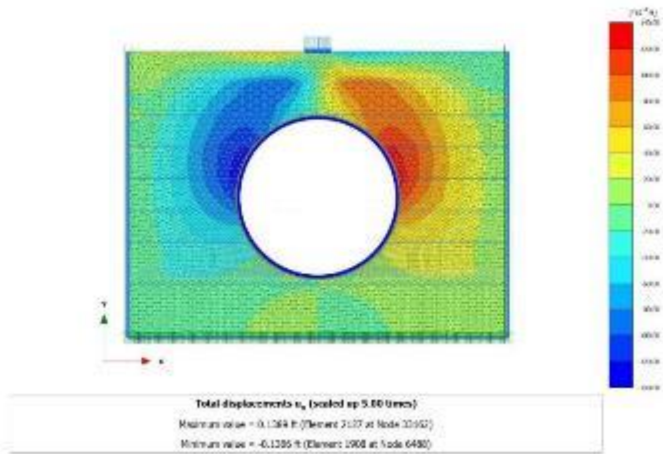
#### 2.1.1.2.8 Calculation results, Phase_9 [Phase_9] (9/114), Total displacements $u_y$



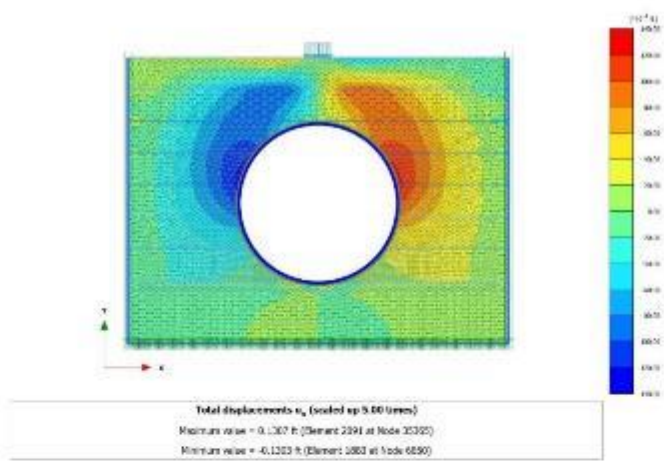

#### 2.1.1.2.9 Calculation results, Phase_10 [Phase_10] (10/132), Total displacements $u_y$



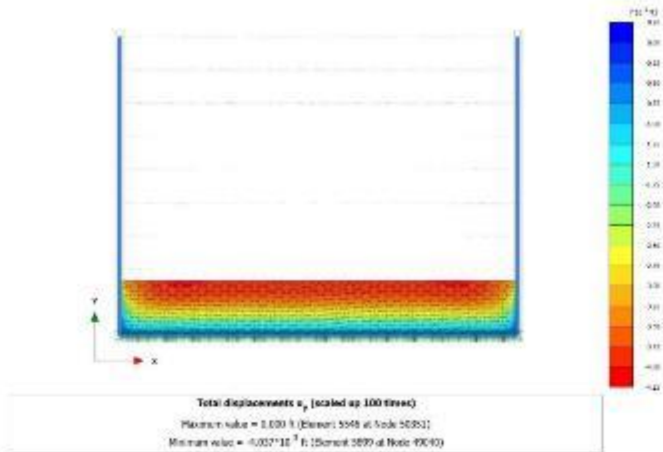
**2.1.1.2.10 Calculation results, Phase_11 [Phase_11] (11/133), Total displacements $u_x$**



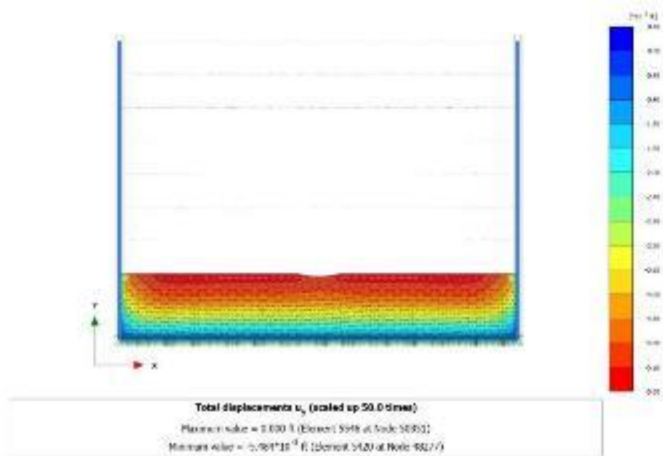

**2.1.1.2.11 Calculation results, Phase_12 [Phase_12] (12/318), Total displacements $u_x$**



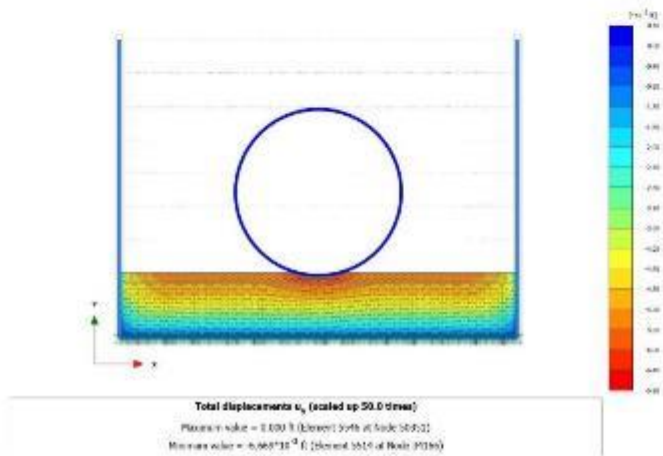
### 2.1.1.3.1 Calculation results, Phase_1 [Phase_1] (1/9), Total displacements $u_y$



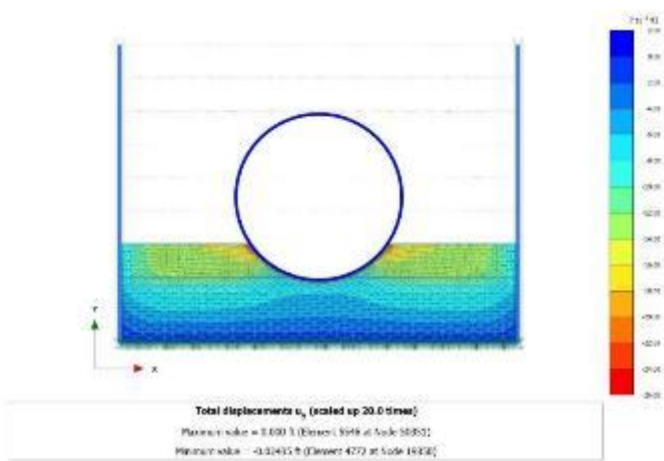

### 2.1.1.3.2 Calculation results, Phase_2 [Phase_2] (2/15), Total displacements $u_y$



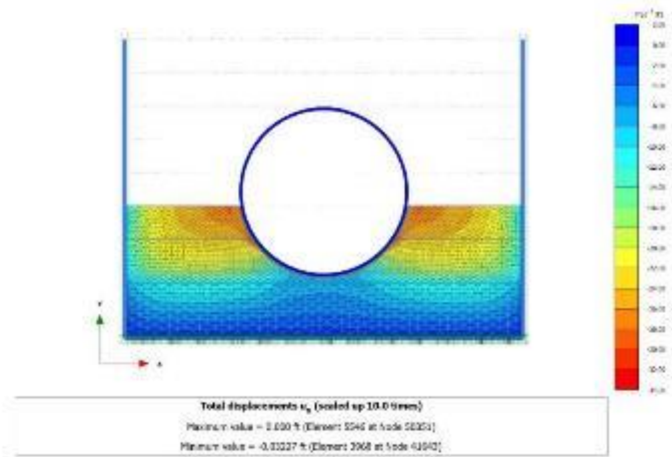
#### 2.1.1.3.3 Calculation results, Phase_3 [Phase_3] (3/18), Total displacements $u_y$



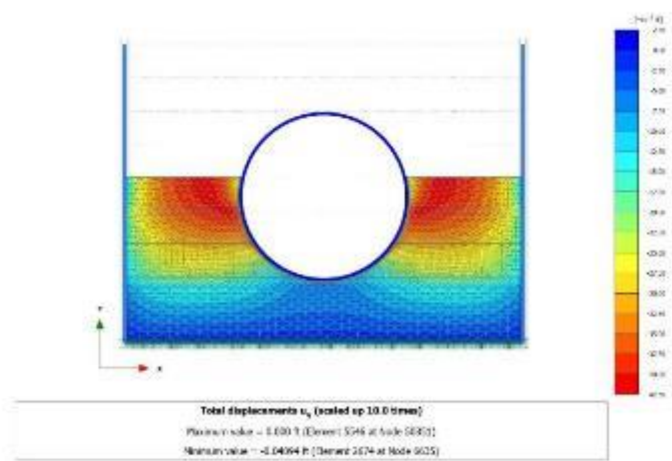

#### 2.1.1.3.4 Calculation results, Phase_4 [Phase_4] (4/38), Total displacements $u_y$



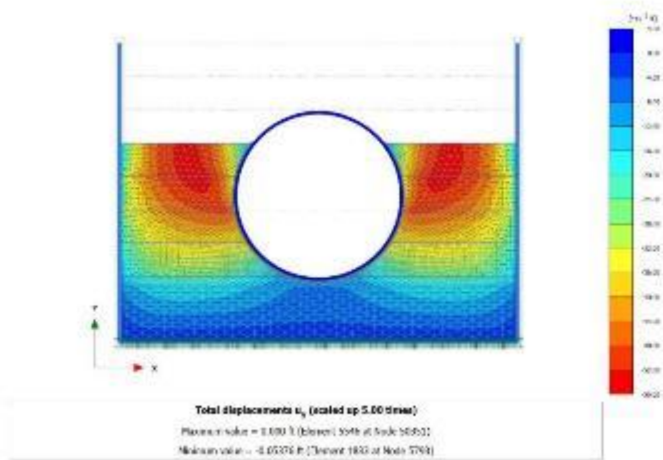
**2.1.1.3.12 Calculation results, Phase_5 [Phase_5] (5/352), Total displacements $u_y$**



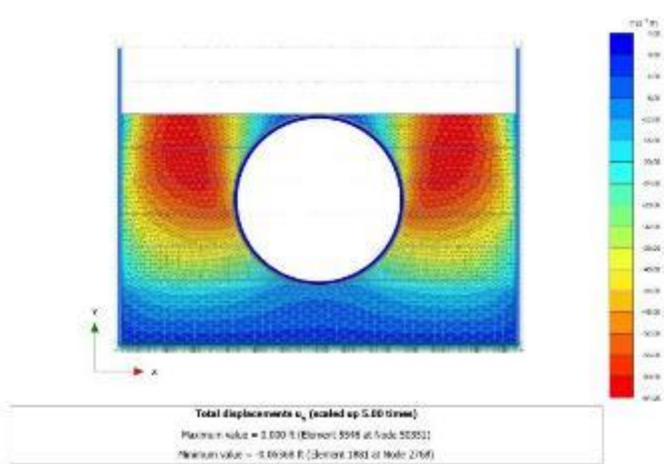

**2.1.1.3.5 Calculation results, Phase_6 [Phase_6] (6/52), Total displacements $u_y$**



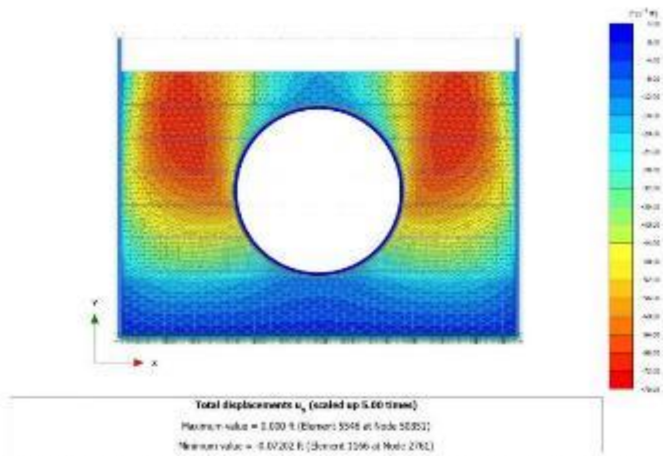
### 2.1.1.3.6 Calculation results, Phase_7 [Phase_7] (7/86), Total displacements $u_y$



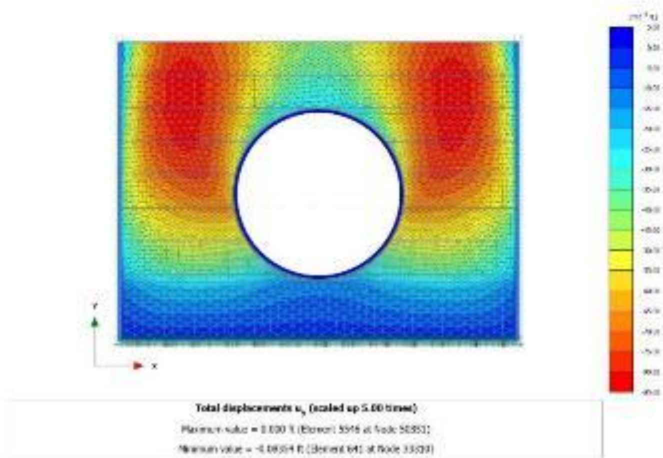

### 2.1.1.3.7 Calculation results, Phase_8 [Phase_8] (8/101), Total displacements $u_y$



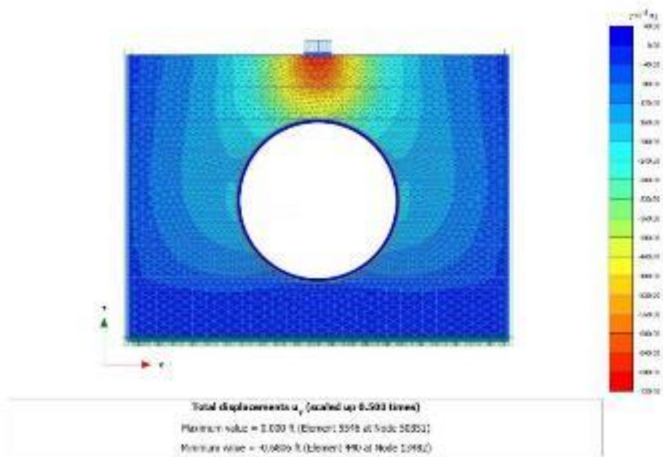
**2.1.1.3.8 Calculation results, Phase_9 [Phase_9] (9/114), Total displacements $u_y$**



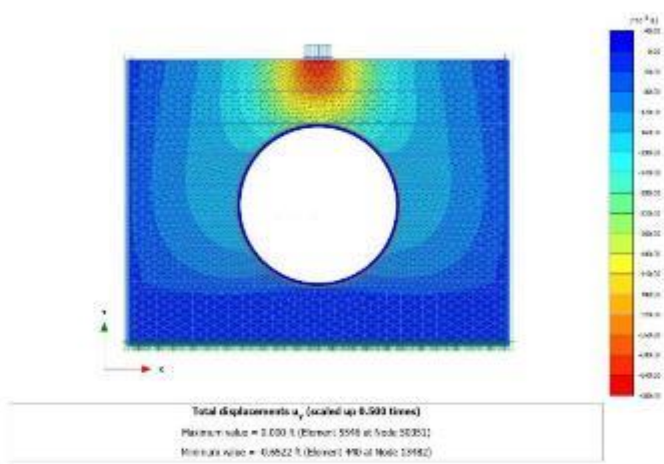

**2.1.1.3.9 Calculation results, Phase_10 [Phase_10] (10/132), Total displacements $u_y$**



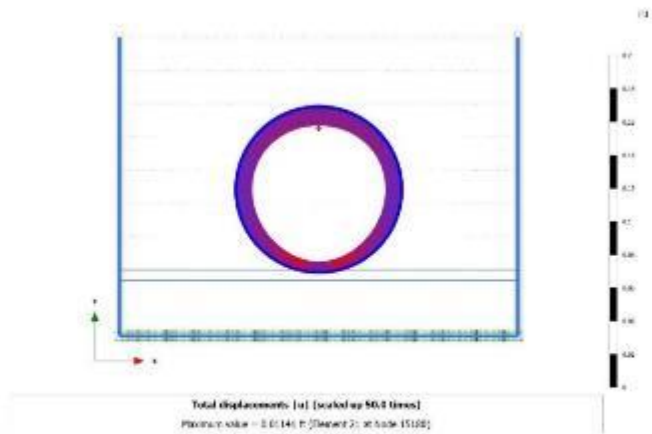
### 2.1.1.3.10 Calculation results, Phase_11 [Phase_11] (11/133), Total displacements $u_y$



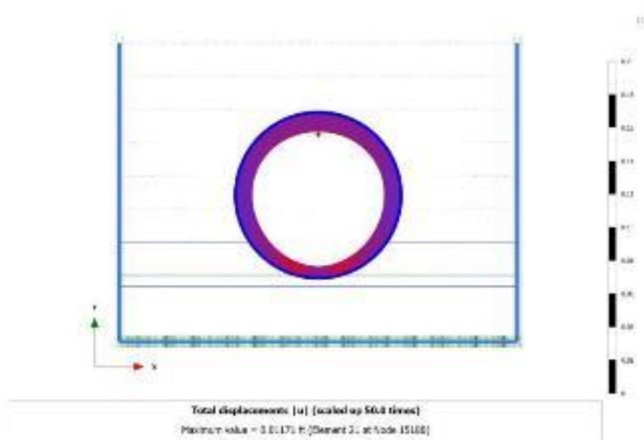

### 2.1.1.3.11 Calculation results, Phase_12 [Phase_12] (12/318), Total displacements $u_y$



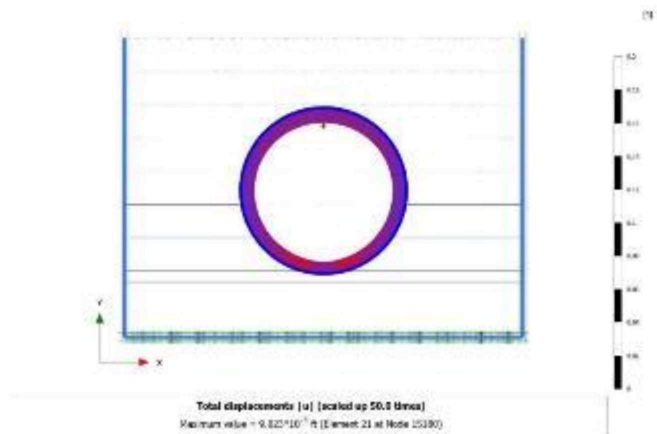
### 3.1.1.1.1.3 Calculation results, Plate, Phase_3 [Phase_3] (3/18), Total displacements |u|



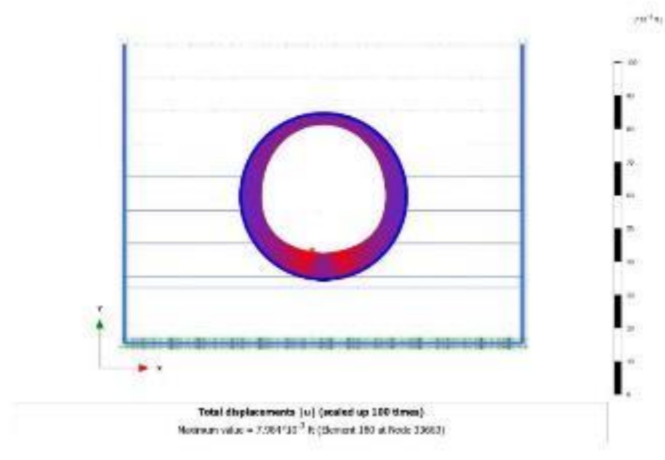

### 3.1.1.1.1.4 Calculation results, Plate, Phase_4 [Phase_4] (4/38), Total displacements |u|



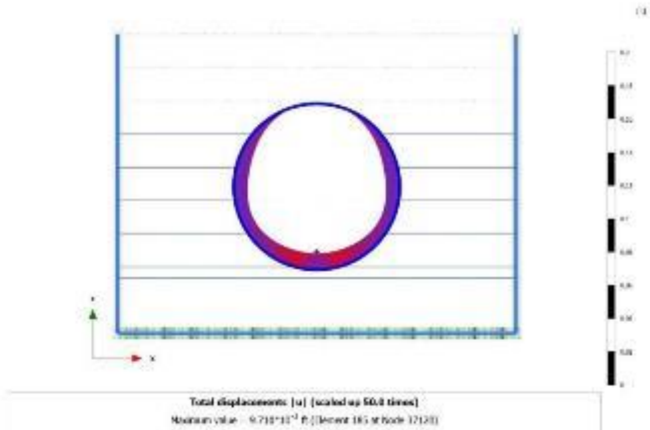
## 3.1.1.1.1.12 Calculation results, Plate, Phase_5 [Phase_5] (5/352), Total displacements |u|



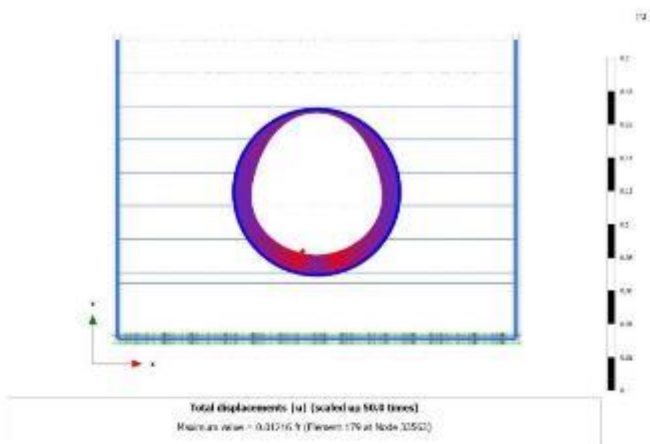

## 3.1.1.1.1.5 Calculation results, Plate, Phase_6 [Phase_6] (6/52), Total displacements |u|



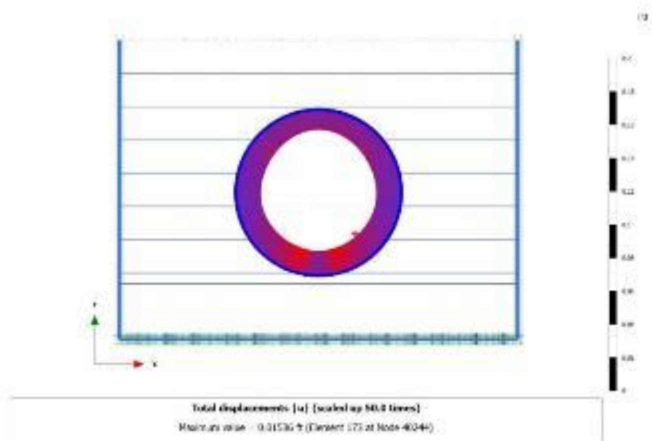
### 3.1.1.1.1.6 Calculation results, Plate, Phase_7 [Phase_7] (7/86), Total displacements |u|



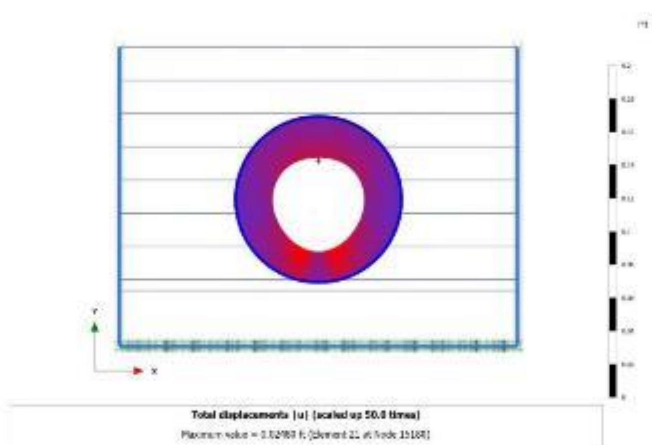

### 3.1.1.1.1.7 Calculation results, Plate, Phase_8 [Phase_8] (8/101), Total displacements |u|



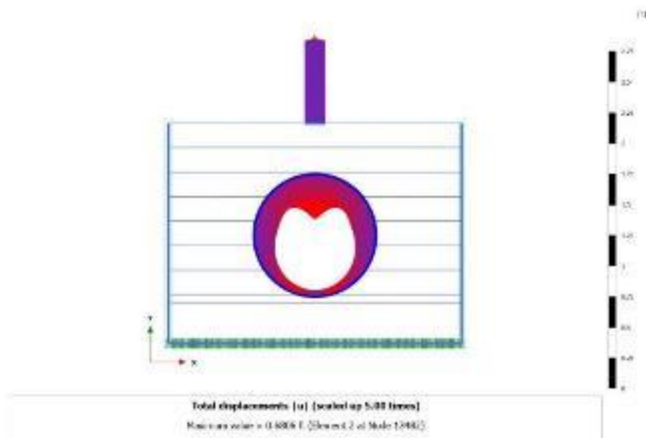
**3.1.1.1.1.8 Calculation results, Plate, Phase_9 [Phase_9] (9/114), Total displacements |u|**



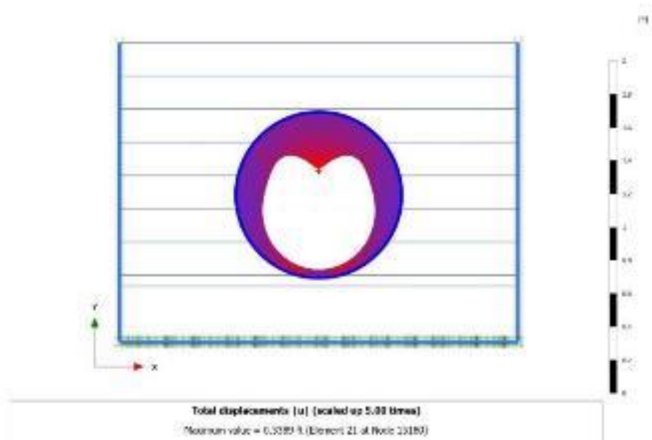

**3.1.1.1.1.9 Calculation results, Plate, Phase_10 [Phase_10] (10/132), Total displacements |u|**



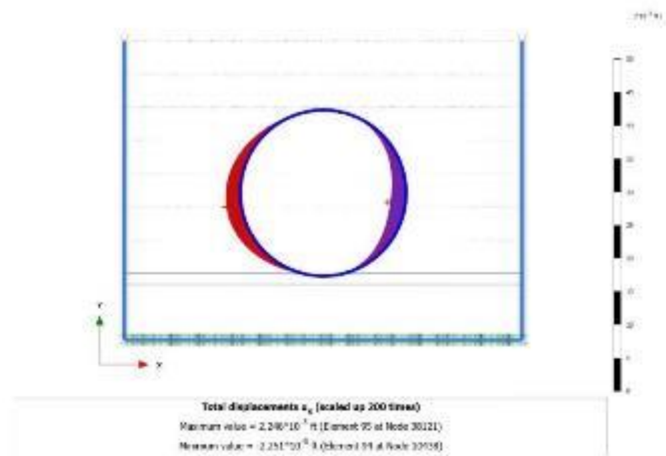
**3.1.1.1.1.10 Calculation results, Plate, Phase_11 [Phase_11] (11/133), Total displacements |u|**



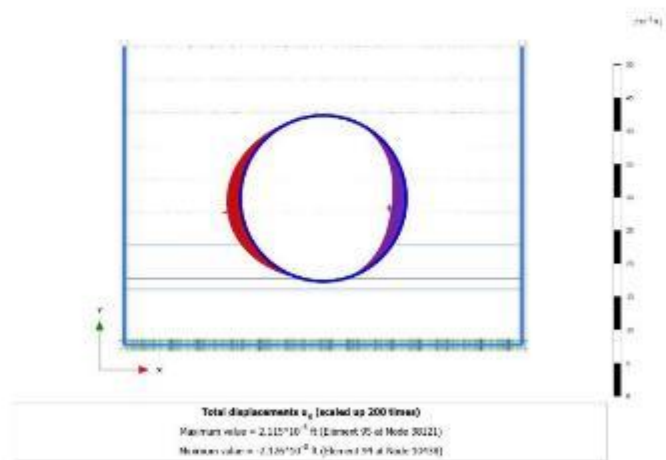

**3.1.1.1.1.11 Calculation results, Plate, Phase_12 [Phase_12] (12/318), Total displacements |u|**



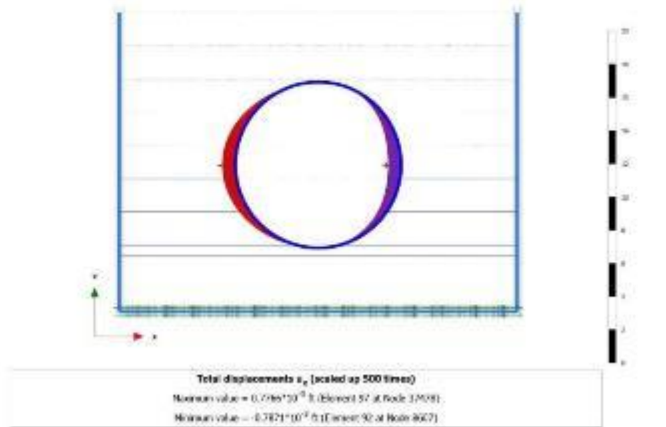
**3.1.1.1.2.3 Calculation results, Plate, Phase_3 [Phase_3] (3/18), Total displacements $u_x$**



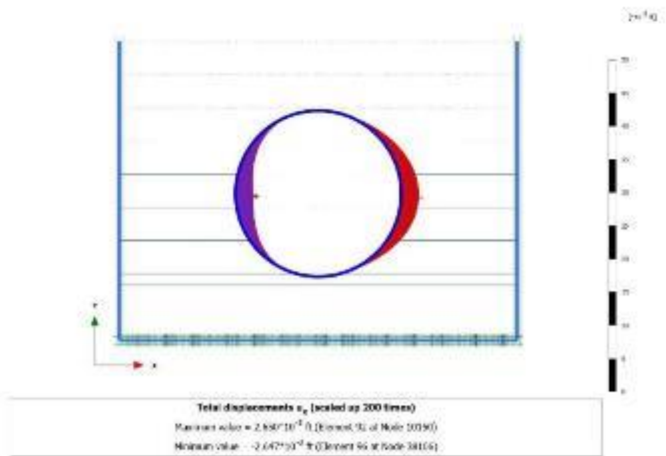

**3.1.1.1.2.4 Calculation results, Plate, Phase_4 [Phase_4] (4/38), Total displacements $u_x$**



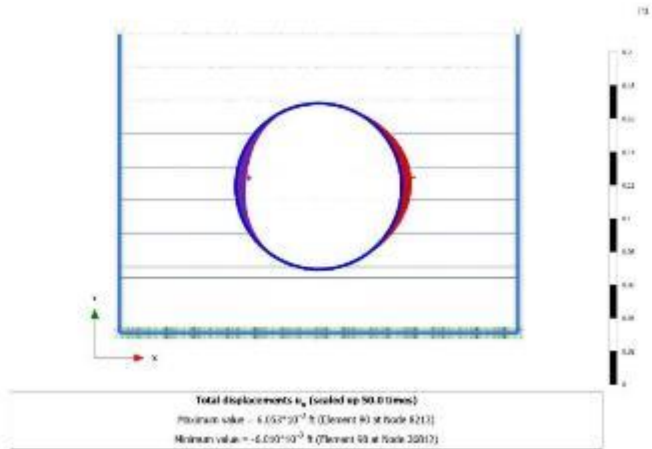
**3.1.1.1.2.12 Calculation results, Plate, Phase_5 [Phase_5] (5/352), Total displacements $u_x$**



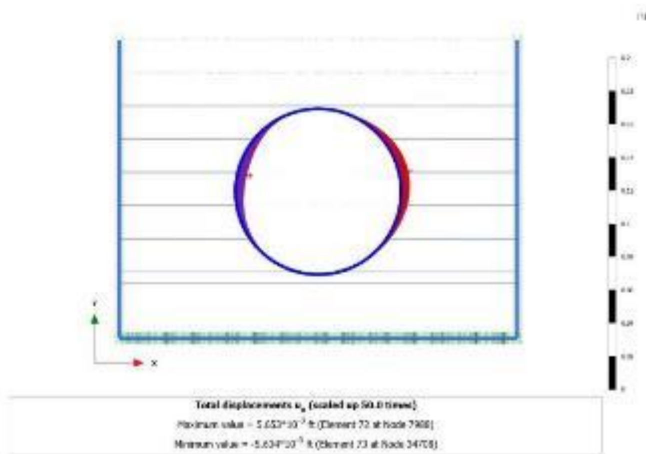

**3.1.1.1.2.5 Calculation results, Plate, Phase_6 [Phase_6] (6/52), Total displacements $u_x$**



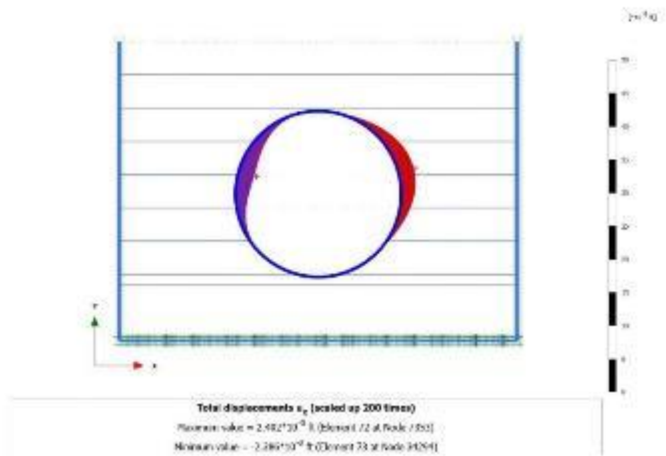
**3.1.1.1.2.6 Calculation results, Plate, Phase_7 [Phase_7] (7/86), Total displacements $u_x$**



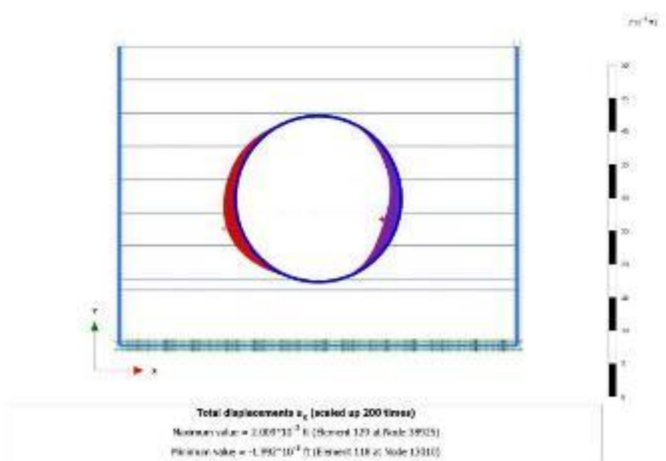

**3.1.1.1.2.7 Calculation results, Plate, Phase_8 [Phase_8] (8/101), Total displacements $u_x$**



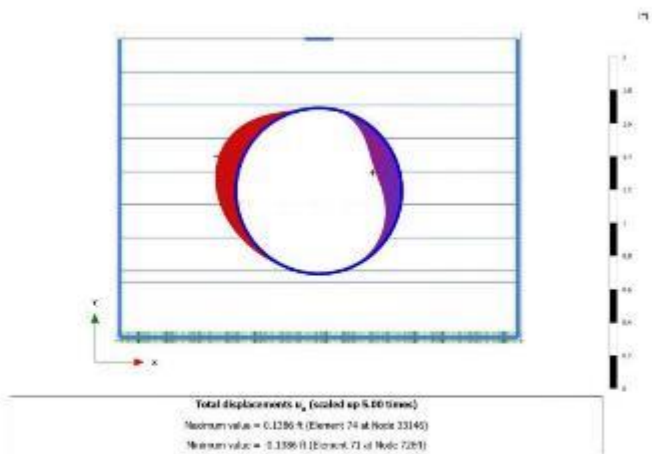
### 3.1.1.1.2.8 Calculation results, Plate, Phase_9 [Phase_9] (9/114), Total displacements $u_x$



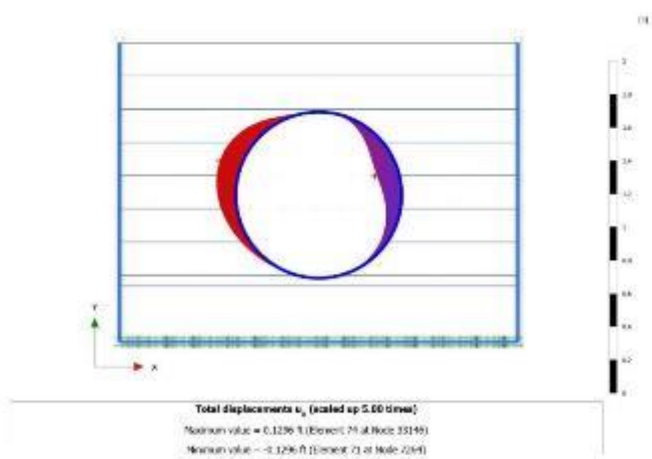

### 3.1.1.1.2.9 Calculation results, Plate, Phase_10 [Phase_10] (10/132), Total displacements $u_x$



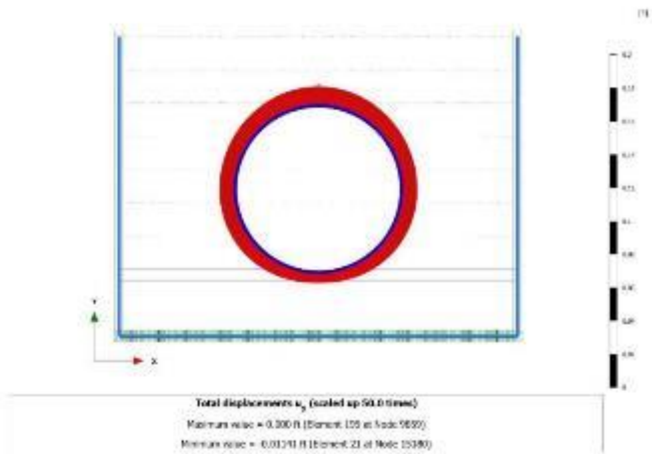
**3.1.1.1.2.10 Calculation results, Plate, Phase_11 [Phase_11] (11/133), Total displacements $u_x$**



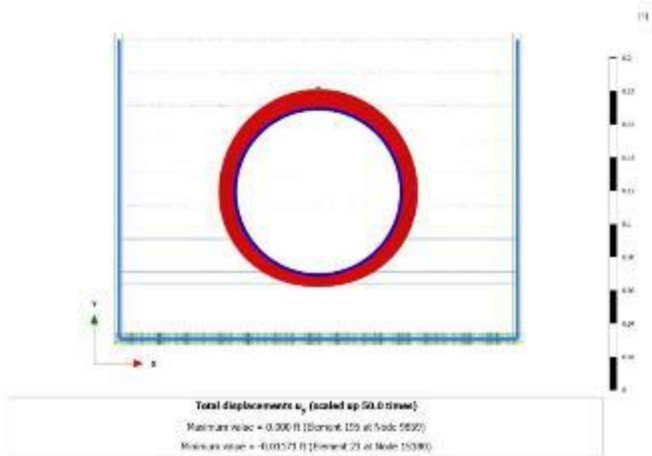

**3.1.1.1.2.11 Calculation results, Plate, Phase_12 [Phase_12] (12/318), Total displacements $u_x$**



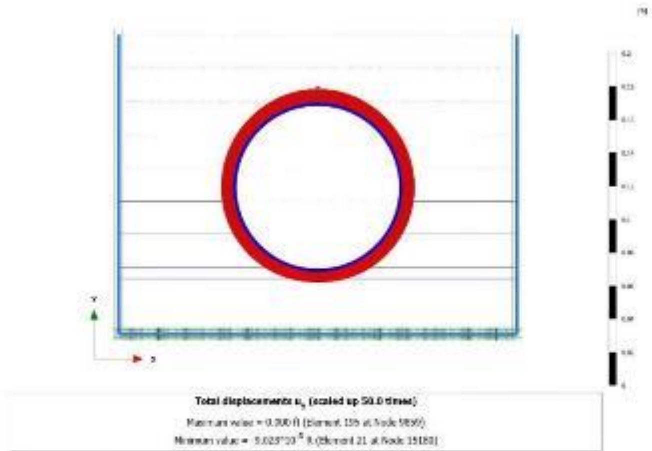
**3.1.1.1.3.3 Calculation results, Plate, Phase_3 [Phase_3] (3/18), Total displacements $u_y$**



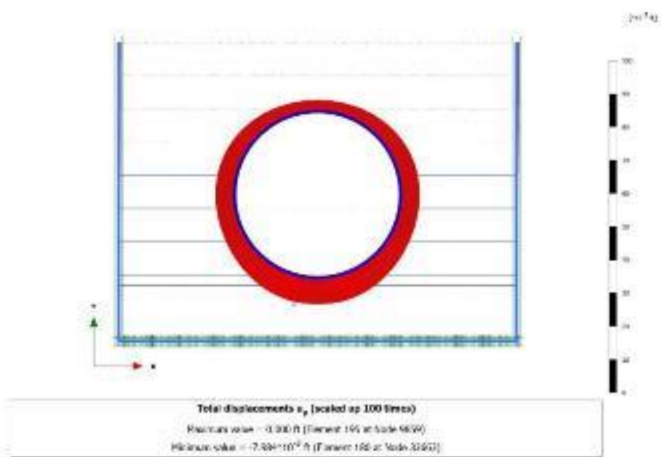

**3.1.1.1.3.4 Calculation results, Plate, Phase_4 [Phase_4] (4/38), Total displacements $u_y$**



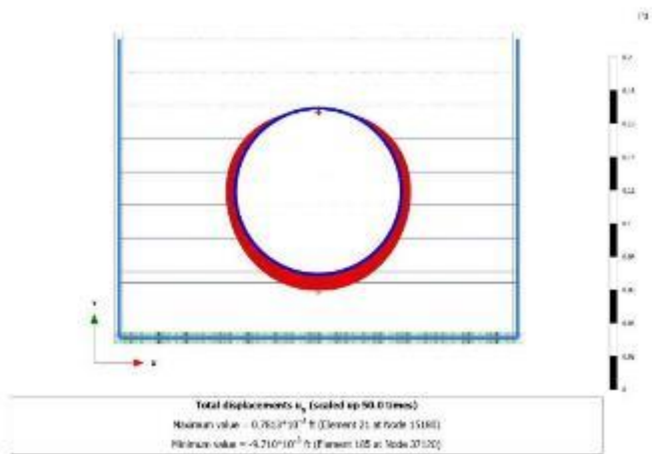
**3.1.1.1.3.12 Calculation results, Plate, Phase_5 [Phase_5] (5/352), Total displacements $u_y$**



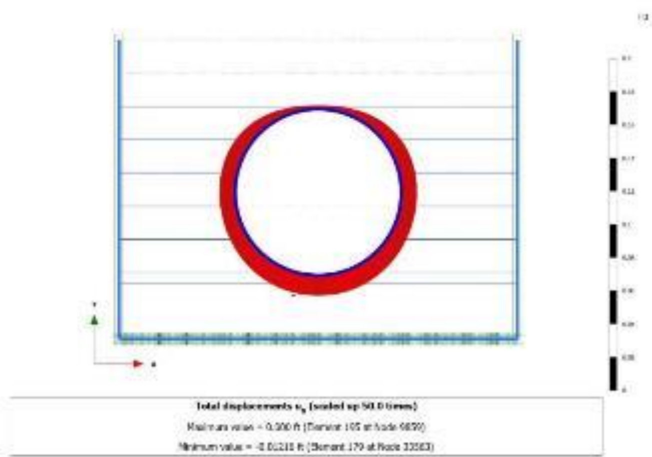

**3.1.1.1.3.5 Calculation results, Plate, Phase_6 [Phase_6] (6/52), Total displacements $u_y$**



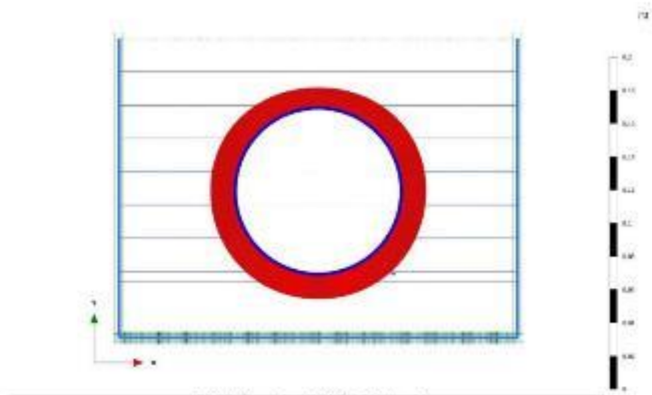
**3.1.1.1.3.6 Calculation results, Plate, Phase_7 [Phase_7] (7/86), Total displacements $u_y$**




**3.1.1.1.3.7 Calculation results, Plate, Phase_8 [Phase_8] (8/101), Total displacements $u_y$**



**3.1.1.1.3.8 Calculation results, Plate, Phase_9 [Phase_9] (9/114), Total displacements $u_y$**

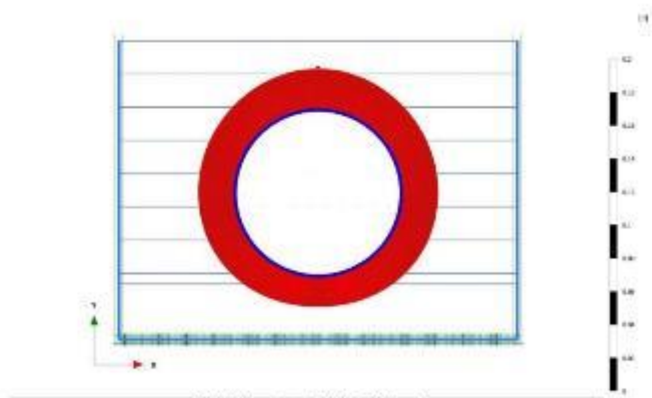


Total displacements $u_y$ (scaled up 50.0 times)

Maximum value = 0.000 ft (Element 195 at Node 9699)

Minimum value = -0.01536 ft (Element 173 at Node 40744)

**3.1.1.1.3.9 Calculation results, Plate, Phase_10 [Phase_10] (10/132), Total displacements $u_y$**

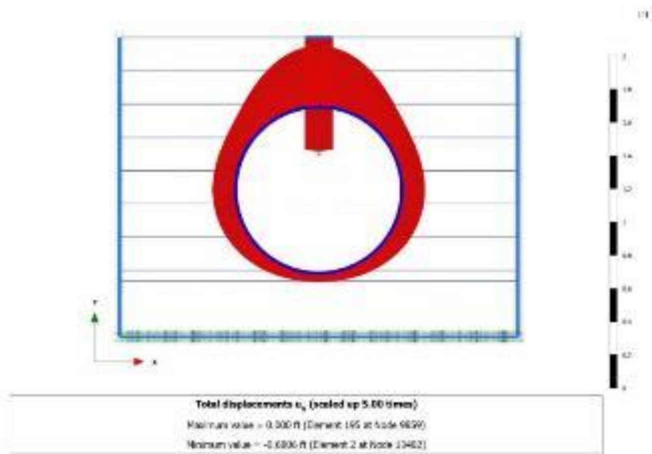


Total displacements $u_y$ (scaled up 50.0 times)

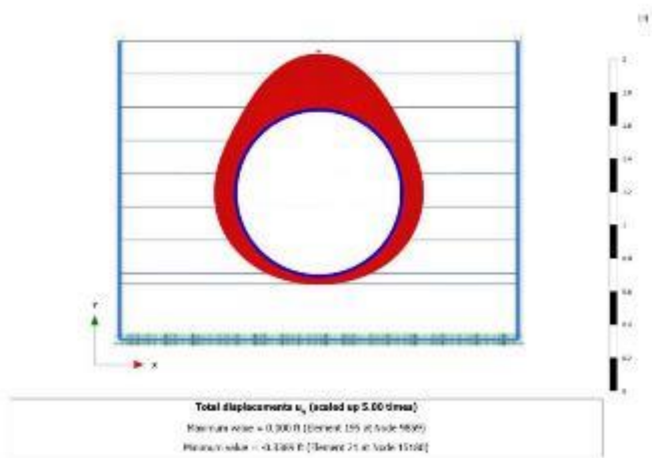
Maximum value = 0.000 ft (Element 195 at Node 9699)

Minimum value = -0.02480 ft (Element 21 at Node 15180)

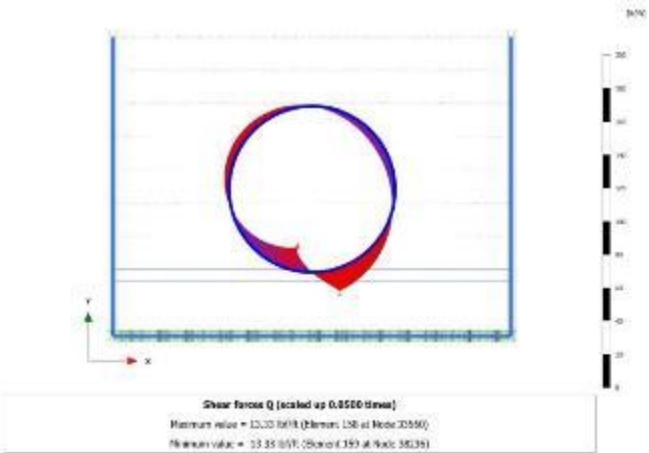
### 3.1.1.1.3.10 Calculation results, Plate, Phase_11 [Phase_11] (11/133), Total displacements $u_y$



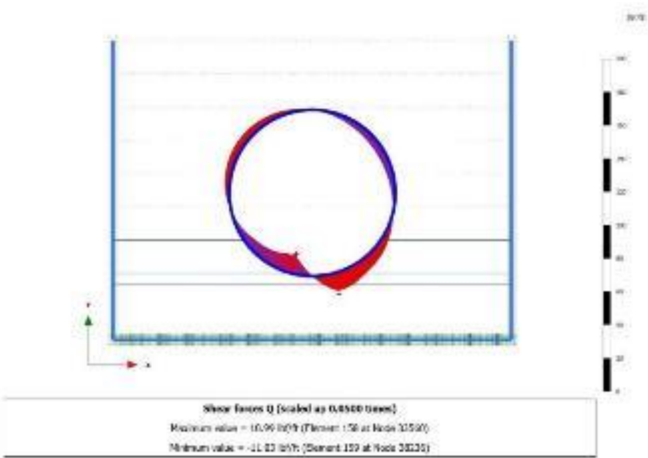

### 3.1.1.1.3.11 Calculation results, Plate, Phase_12 [Phase_12] (12/318), Total displacements $u_y$



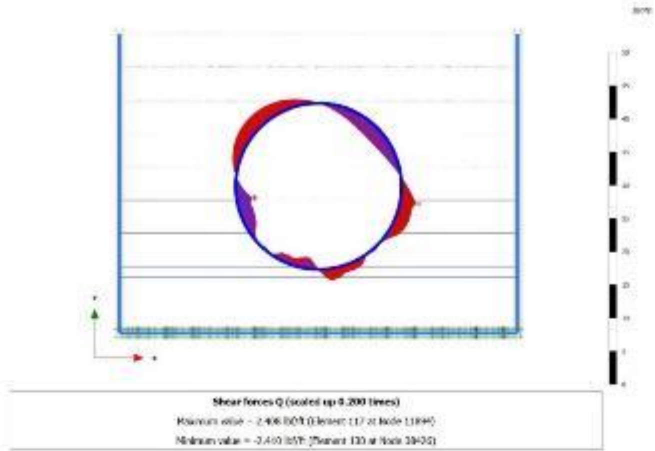
3.1.2.1.3 Calculation results, Plate, Phase_3 [Phase_3] (3/18), Shear forces Q



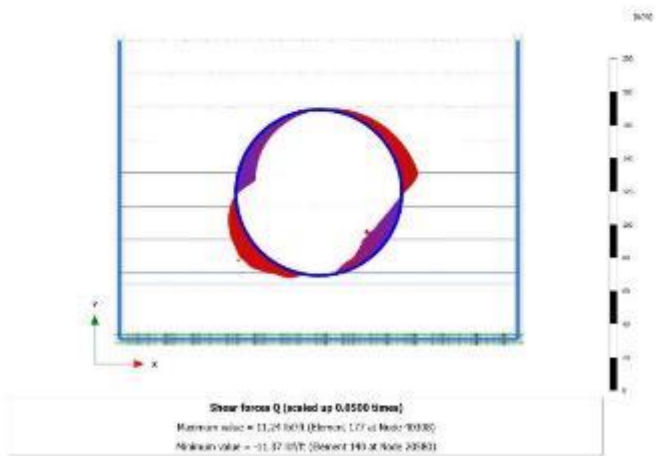

3.1.2.1.4 Calculation results, Plate, Phase_4 [Phase_4] (4/38), Shear forces Q



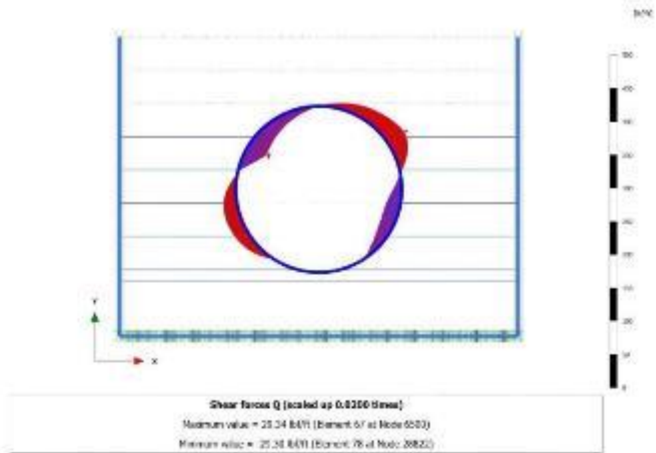
### 3.1.2.1.12 Calculation results, Plate, Phase_5 [Phase_5] (5/352), Shear forces Q



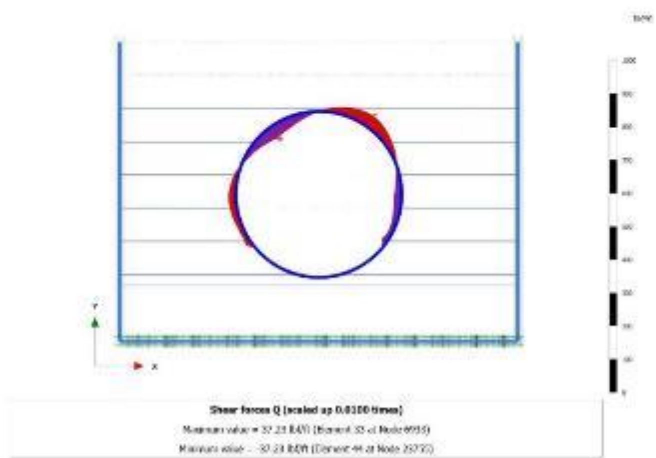

### 3.1.2.1.5 Calculation results, Plate, Phase_6 [Phase_6] (6/52), Shear forces Q



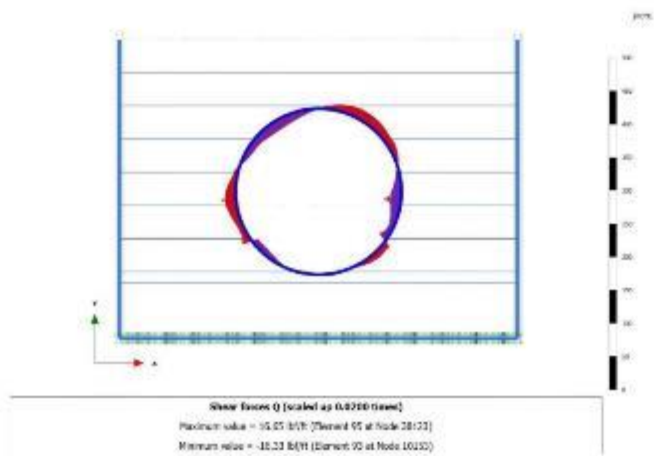
### 3.1.2.1.6 Calculation results, Plate, Phase_7 [Phase_7] (7/86), Shear forces Q



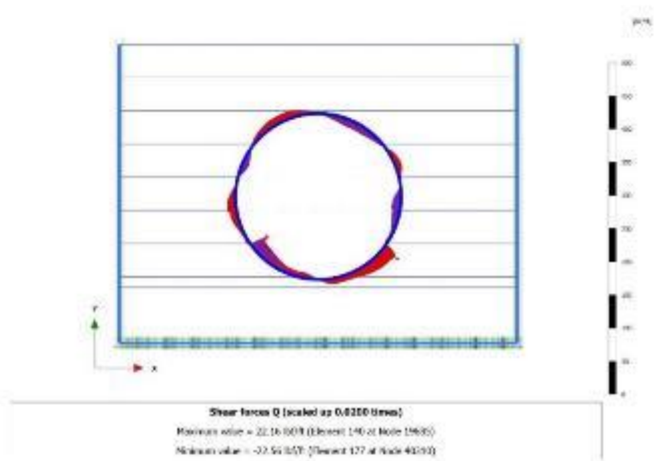

### 3.1.2.1.7 Calculation results, Plate, Phase_8 [Phase_8] (8/101), Shear forces Q



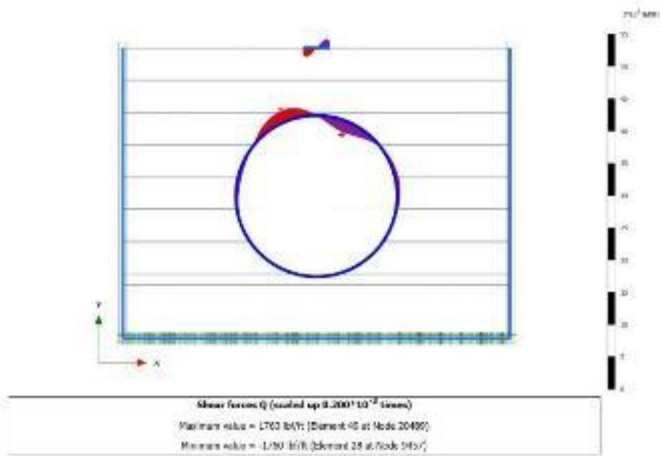
### 3.1.2.1.8 Calculation results, Plate, Phase_9 [Phase_9] (9/114), Shear forces Q



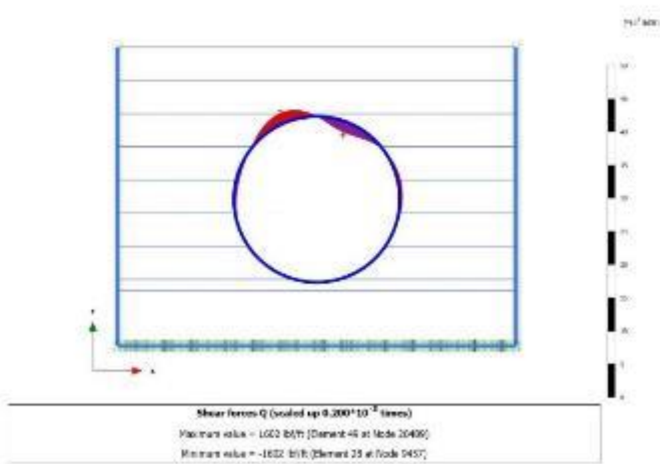

### 3.1.2.1.9 Calculation results, Plate, Phase_10 [Phase_10] (10/132), Shear forces Q



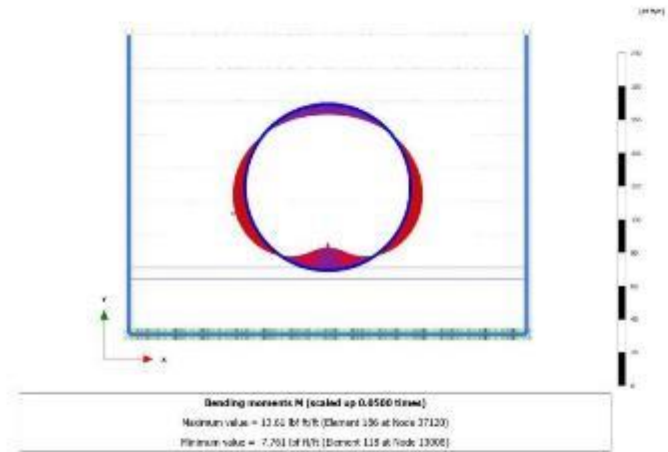
**3.1.2.1.10 Calculation results, Plate, Phase_11 [Phase_11] (11/133), Shear forces Q**



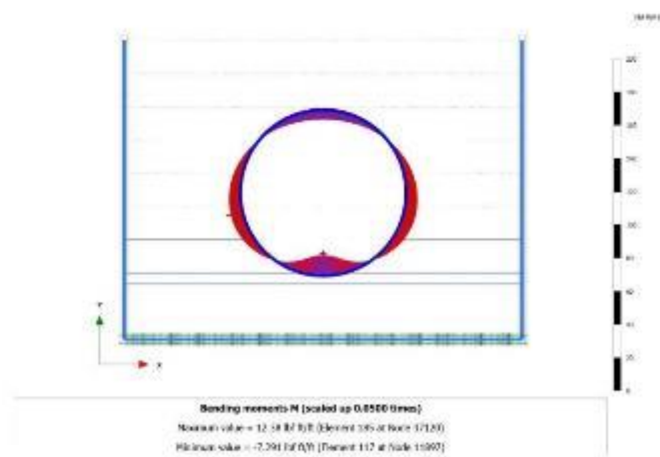

**3.1.2.1.11 Calculation results, Plate, Phase_12 [Phase_12] (12/318), Shear forces Q**



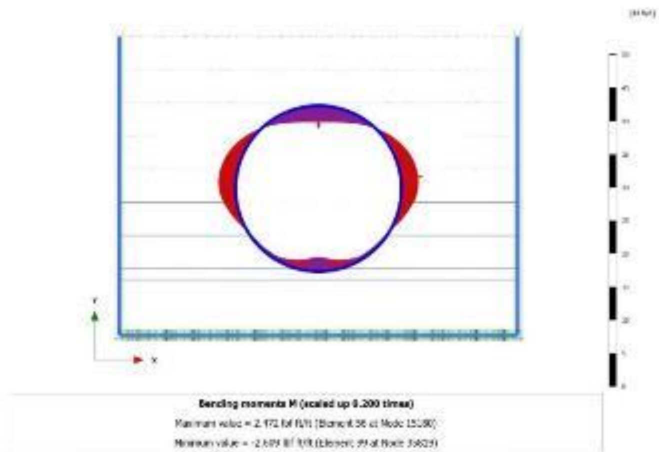
**3.1.2.2.3 Calculation results, Plate, Phase_3 [Phase_3] (3/18), Bending moments M**



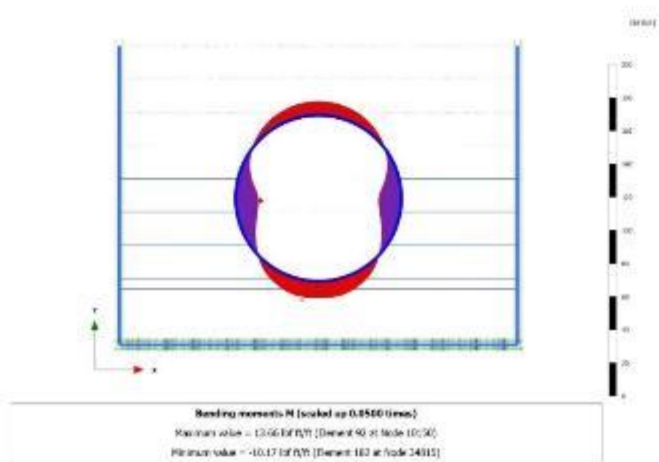

**3.1.2.2.4 Calculation results, Plate, Phase_4 [Phase_4] (4/38), Bending moments M**



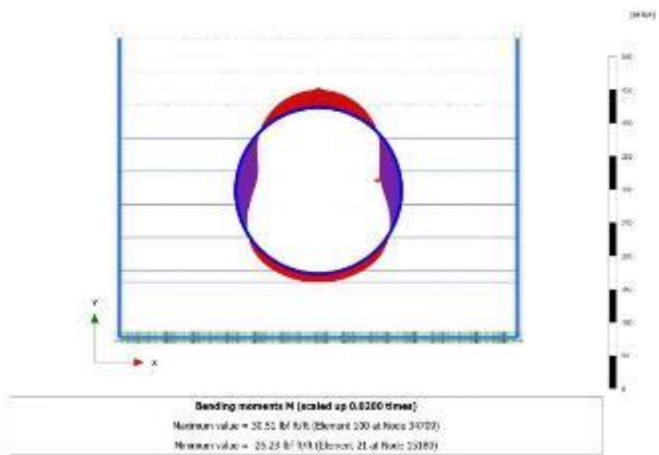
### 3.1.2.2.12 Calculation results, Plate, Phase_5 [Phase_5] (5/352), Bending moments M



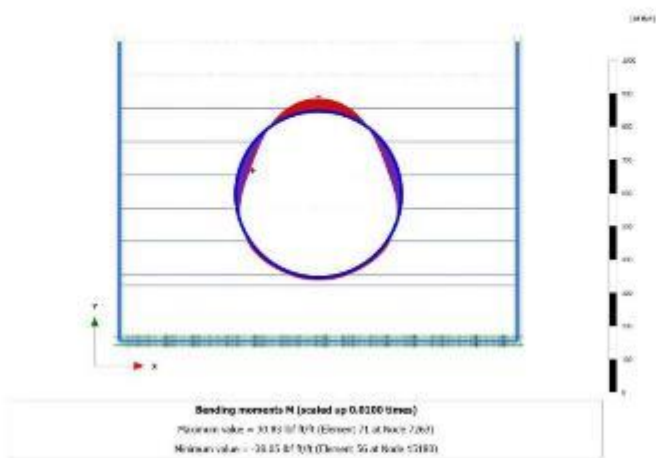

### 3.1.2.2.5 Calculation results, Plate, Phase_6 [Phase_6] (6/52), Bending moments M



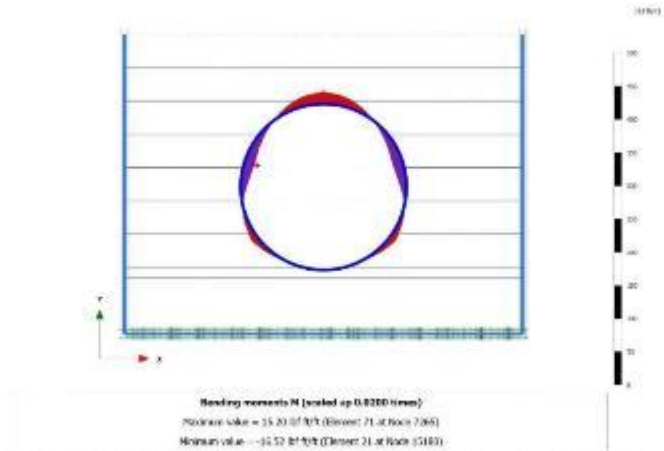
**3.1.2.2.6 Calculation results, Plate, Phase_7 [Phase_7] (7/86), Bending moments M**



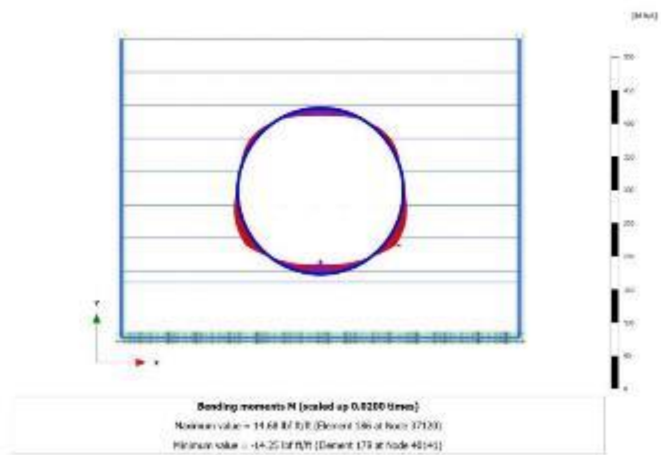

**3.1.2.2.7 Calculation results, Plate, Phase_8 [Phase_8] (8/101), Bending moments M**



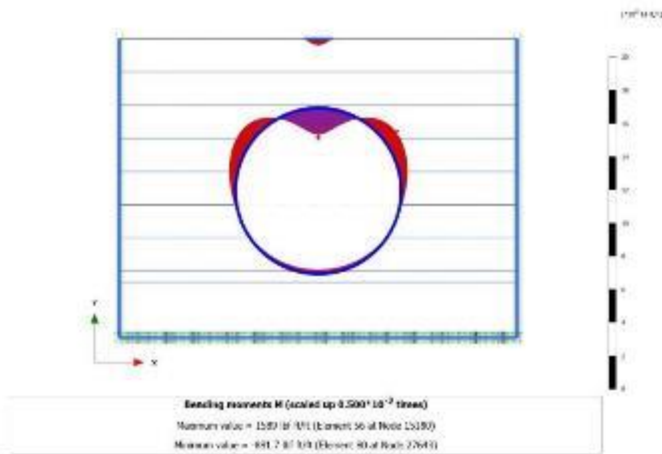
### 3.1.2.2.8 Calculation results, Plate, Phase_9 [Phase_9] (9/114), Bending moments M



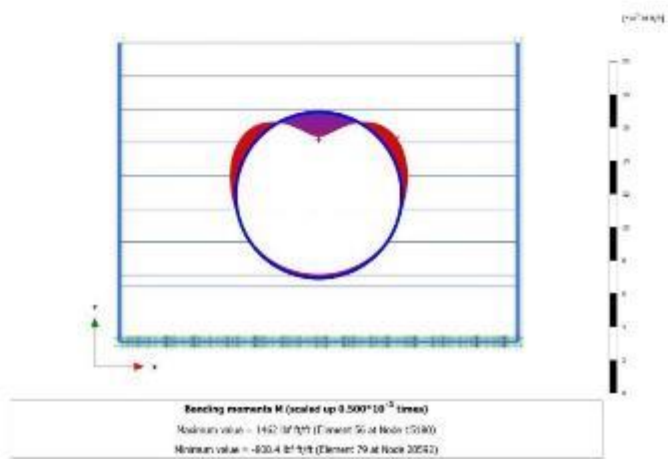

### 3.1.2.2.9 Calculation results, Plate, Phase_10 [Phase_10] (10/132), Bending moments M



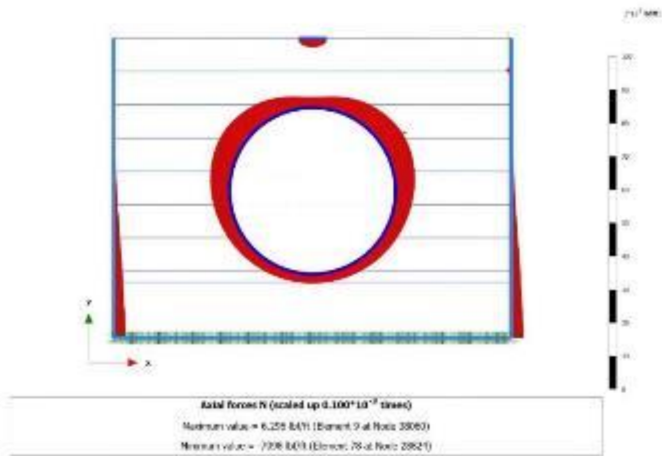
**3.1.2.2.10 Calculation results, Plate, Phase_11 [Phase_11] (11/133), Bending moments M**



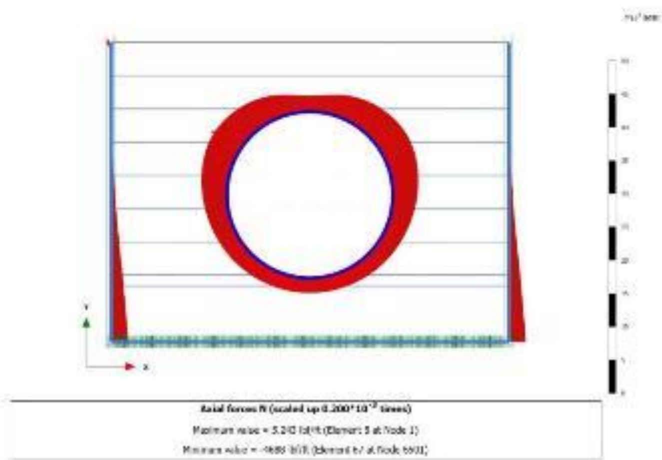

**3.1.2.2.11 Calculation results, Plate, Phase_12 [Phase_12] (12/318), Bending moments M**



### 3.1.2.3.10 Calculation results, Plate, Phase_11 [Phase_11] (11/133), Axial forces N




### 3.1.2.3.11 Calculation results, Plate, Phase_12 [Phase_12] (12/318), Axial forces N



## Chapter 7: Conclusions and Recommendations for Future Studies

*Culvert* is a composite structure that is used for passing storm water under an embankment as a part of a drainage system and bears loads from embankment and vehicles. Overtime, culverts deteriorate and need repair and/or renewal. This dissertation focused on renewal of circular and arch shape CMP and RCP culverts using SAPLs. The primary SAPL materials fall into two broad categories: (1) cementitious SAPLs including cementitious and geopolymer, which are categorized as rigid liners, and (2) polymeric SAPLs including polyurea, polyurethane, and epoxy, as flexible liners. Figure 7.1 illustrates research methodology.

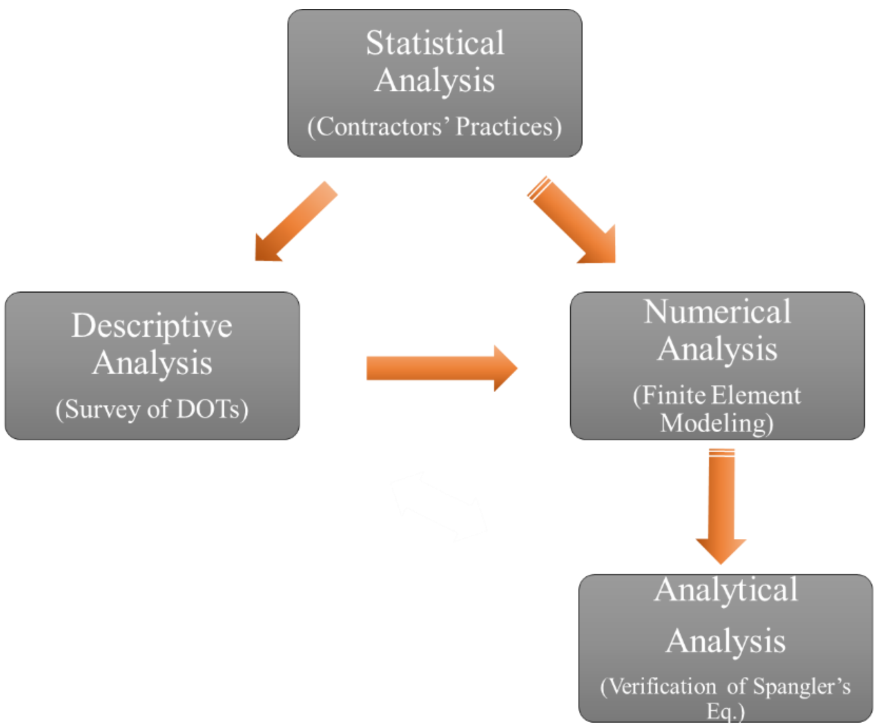



Figure 7.1 Dissertation Research Methodology

### 7.1 Conclusions

The information obtained in the literature review indicated that depth of soil cover and the embedment have a significant impact on the bearing capacity of a renewed SAPL culvert. Some studies discussed SAPL thicknesses for cementitious/geo-polymer and polymeric materials; however, a gap in literature was found for calculating the appropriate thickness of SAPL.

Analyzing contractors' practices on the design of SAPL showed variations in design and installations.

The results of a DOT survey conducted for this research concluded that SAPL is applicable for RCP and CMP culverts for both circular and arch shapes. Joint offset and longitudinal cracking of RCP and ovality of CMP culverts are the main criteria for assessing an existing culvert to be deteriorated. The survey respondents indicated that they have experienced longitudinal and circumferential cracking, hairline cracking with rust bleeding through cracks, cracking at joints, spalling, delamination, rough application (corrugation issues), rust-through, slumping from crown, buildup of material due to poor installation, lack of uniform application, groundwater infiltration before cure time, and leaking groundwater. Most respondents did not have much experience with polymer SAPLs.

The structural behavior of SAPLs is mainly dependent on thickness, physical properties of SAPL, conditions and soil embedment and the host culvert. Four combinations of flexibility/rigidity applicable in a renewed culvert are:

- Flexible culvert with flexible liner (i.e., a CMP – lined by a polymeric SAPL material),
- Flexible culvert with rigid liner (i.e., a CMP – lined by a cementitious SAPL material),
- Rigid culvert with flexible liner (i.e., an RCP – lined by a polymeric SAPL material), and
- Rigid culvert with rigid liner (i.e., an RCP – lined by a cementitious SAPL material).

Results of numerical analysis indicated that increasing thickness of cementitious SAPLs provide more rigidity and stiffness to host CMP culverts. Current SAPL design considers selecting rigid or flexible procedures based on type of SAPL materials. Results of this dissertation showed that even with cementitious materials, the composite system of SAPL and CMP) behave like a flexible material. Cementitious SAPL – CMP might behave like a flexible, semi-rigid, or rigid system.

## 7.2 Framework

As part of this dissertation, a framework for analysis of host culverts and application of a cementitious SAPL over CMP was prepared as shown in Figure 7.2. This framework includes three parts:

### 7.2.1 Culvert Assessment Framework

The first step of design/installation of SAPL would be recognition of host culvert conditions to determine whether the culvert is *partially deteriorated* or *fully deteriorated*[12]. This dissertation did not consider partially deteriorated culverts, so the framework considers fully deteriorated condition.

### 7.2.2 Culvert – SAPL Materials

Two types of rigid and flexible materials for both host culvert and SAPL were studied in this dissertation. Therefore, four combinations of *rigid culvert – rigid SAPL, rigid culvert – flexible SAPL*, *flexible culvert – flexible SAPL*, and *flexible culvert – rigid SAPL* are applicable. This framework considers *flexible culvert – rigid SAPL*.

[12] Partially and fully deteriorated were defined in the first chapter.

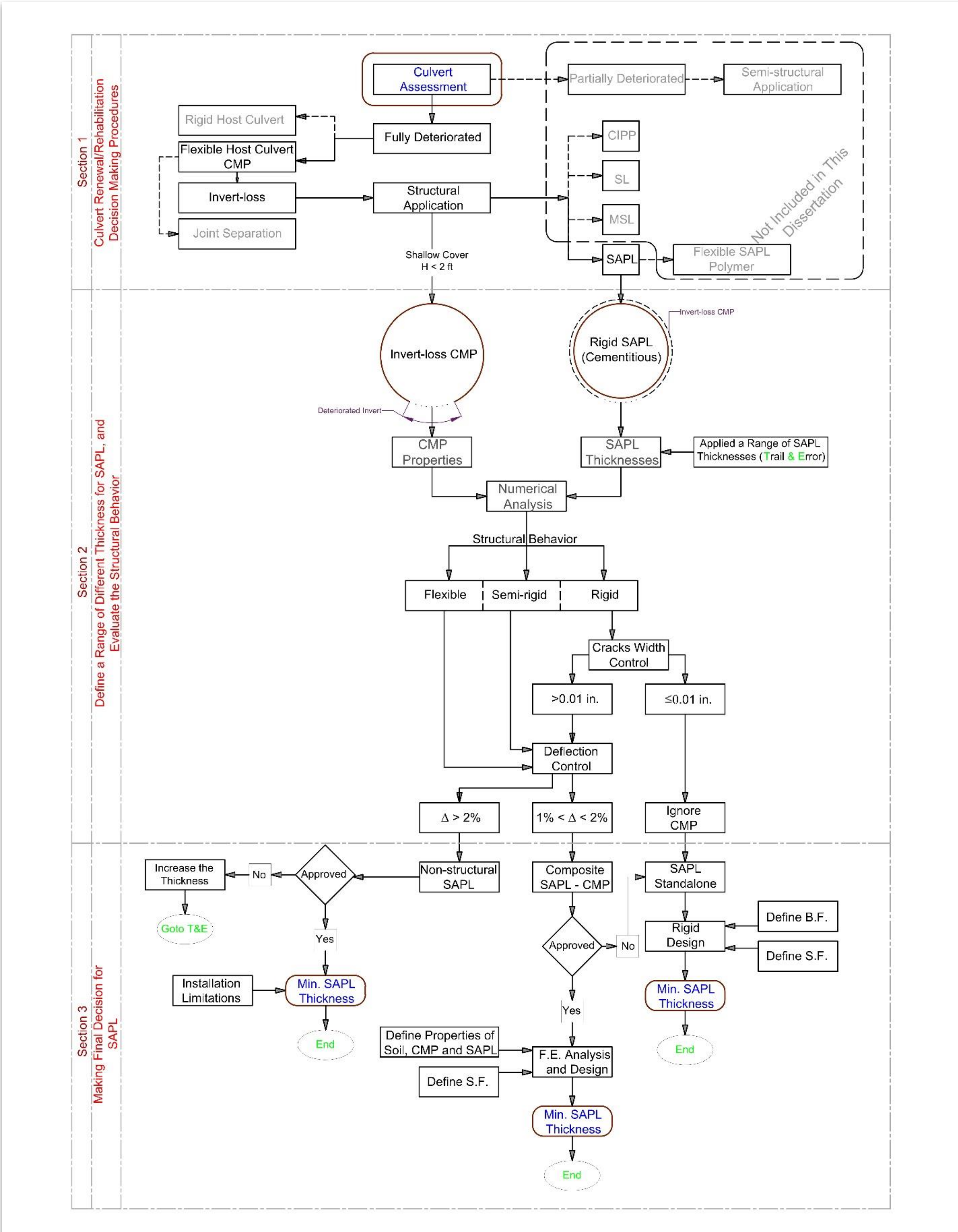



Figure 7.2. A Framework for Cementitious SAPL – CMP

## 7.3 Recommendations for Future Research

As a thin-wall liner, cementitious SAPL material needs to be investigated regarding cracks. SAPL cracks must be analyzed either underneath the crown, in the springline, or above the invert. Investigation of circumferential and longitudinal cracks related to site condition, a thick liner (thicker than 3 in.), shallow cover depth (approximately 2 ft), and seismic loads are recommended.

This dissertation investigated structural analysis of an invert-lost deteriorated CMP in both circular and arch shape. For a future study, analysis of the structural behavior for other types of culverts is necessary. Future studies can cover different materials, shapes, and sizes of the host culvert with different SAPLs.