Integration of Repair and Remediation Methods into Pipe Material Selection Software

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RESEARCH & DEVELOPMENT

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16. Abstract

This report presents the latest enhancements to the Pipe Assessment and Selection Software (PASS), developed in partnership with the North Carolina Department of Transportation (NCDOT). These improvements integrate new structural requirements, historical repair and rehabilitation methods, and mitigation strategies to provide comprehensive guidance on culvert pipe service life. The updated NCDOT pipe material selection guide now incorporates dynamic adjustments based on structural specifications, enabling engineers to automatically modify fill heights and parameters to align with NCDOT standards. PASS employs a weighted average approach to evaluate historical repair and rehabilitation methods and map their applicability to different pipe materials. This systematic method allows engineers to assess compatibility with existing infrastructure and select the most suitable repair strategies based on design life, corrosion resistance, and cost-effectiveness. The inclusion of mitigation strategies allows engineers to factor subsurface exposure into their analysis. The software models the effects of various mitigation approaches, such as flowable fill, compacted clay liners, geosynthetic clay liners, and polymeric liners, to assess their impact on extending service life. Advanced one-dimensional modeling enables PASS to calculate optimal mitigation strategies by considering exposure conditions, soil properties, and chloride concentrations. A service life evaluation model is also included in PASS to predict the longevity of different pipe materials under varied environmental and structural conditions. This analysis ensures engineers can align rehabilitation measures with NCDOT standards and provide cost-effective solutions. A detailed user manual guides NCDOT engineers through the software's features and capabilities, ensuring seamless implementation into their workflow. With PASS, engineers can evaluate project-specific parameters efficiently and select the most suitable pipe materials while ensuring optimal repair, rehabilitation, and mitigation strategies. Overall, the enhancements to PASS deliver a versatile tool that supports improved decision-making, aligns with NCDOT standards, and promotes sustainable transportation infrastructure. The software empowers engineers to better assess and maintain culvert pipes, reducing long-term maintenance costs and strengthening the state's infrastructure network.

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Executive Summary:

This report provides a comprehensive overview of the latest improvements to the Pipe Assessment and Selection Software (PASS), an advanced tool that aids in the selection and evaluation of culvert pipes for the North Carolina Department of Transportation (NCDOT). Developed in close collaboration with NCDOT, PASS was refined and expanded to incorporate new structural requirements, historical repair and rehabilitation methods, and mitigation strategies that help predict and extend the service life of critical infrastructure.

The updated PASS includes a reconstructed NCDOT pipe material selection guide that seamlessly integrates current structural requirements and specifications. Users can now dynamically adjust fill heights and other parameters by selecting from drop-down menus that automatically change based on project details. This dynamic functionality simplifies the process of aligning pipe materials with NCDOT standards, allowing engineers to make faster and more accurate decisions.

In addition, the software incorporates a comprehensive catalog of historical repair and rehabilitation methods used by NCDOT. An updated mapping of these methods and their applicability to various pipe materials has been integrated, allowing engineers to understand previous practices and assess compatibility with existing infrastructure. By using a weighted average approach, PASS provides systematic criteria for evaluating rehabilitation measures, enabling users to select the most suitable repair strategies based on project-specific requirements such as design life, corrosion resistance, and cost-effectiveness.

The report also details the incorporation of subsurface exposure mitigation strategies into PASS. The updated software models the effectiveness of various mitigation approaches, such as flowable fill, compacted clay liners, geosynthetic clay liners, and polymeric liners, in extending service life. Each strategy has been evaluated using advanced models that account for different exposure conditions, soil characteristics, and chloride concentrations. The findings from this modeling have been programmed into PASS, empowering engineers to factor these elements into their decision-making process.

Furthermore, PASS includes a service life evaluation model that allows users to predict the longevity of different pipe materials under varied environmental and structural conditions. This comprehensive analysis supports the selection of the best rehabilitation approach, helping NCDOT engineers optimize their strategies to minimize maintenance costs and downtime.

To ensure the updated PASS is user-friendly and ready for implementation, the report provides a detailed user manual. This guide walks engineers through the software's various features, ensuring that NCDOT staff can confidently navigate and apply the software in their daily operations.

In conclusion, the enhancements made to PASS create a versatile tool that now integrates repair, rehabilitation, and mitigation strategies, offering a holistic approach to pipe assessment and selection. These updates will empower NCDOT engineers to quickly analyze and evaluate project-specific parameters, optimizing the selection, maintenance, and longevity of the department's vital transportation infrastructure. The expanded capabilities of PASS will improve decision-making

processes, align closely with NCDOT standards, and ultimately contribute to the state's resilient and sustainable infrastructure network.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1. Background

Every year, a significant number of culvert pipes are installed in North Carolina. While the selection process considers the loading and structural requirements of these pipes, the influence of environmental exposure on their lifespan has received limited attention. In a previous research project (2020-022: Durability of Pipe Materials in Soils), our team developed a pipe selection software to predict the service life of commonly used pipe materials based on their exposure conditions. Geographic Information System (GIS) data has been correlated with GPS coordinates across North Carolina. The software includes various pipe materials used by NCDOT, such as reinforced concrete, galvanized steel, aluminized steel, cast iron, mild steel, aluminum alloy, and polymeric pipes.

Our collaboration with the NCDOT Steering Committee, led by Mr. Cabell Garbee, Chair of the Steering Committee, has been instrumental in refining the software to meet NCDOT's requirements. The research team presented and deliberated on the preliminary software draft with NCDOT colleagues, incorporating their feedback into the final version, which has received positive responses. Through discussions with NCDOT colleagues during meetings, we've identified additional elements for incorporation into the software. Notably, these include:

- The ongoing software development currently focuses on material types and exposure conditions in the selection process. However, there is a need to incorporate NCDOT's structural demands to provide a single software solution that fulfills both durability and structural requirements for NCDOT engineers and users.
- The current selection guide lacks an estimation of potential service life extension through repair and rehabilitation. Enhancing the guide to encompass varied rehabilitation approaches would enable engineers to comparatively assess repair strategies in terms of their projected impact on service life.
- The current guide does not account for the influence of subsurface exposure mitigation methods on the service life of installed pipes. For instance, using backfill that differs from native soil can affect a culvert's service life. Incorporating mitigation strategies is crucial to accurately assess service life.

This project aims to address these supplementary aspects, expanding the software's versatility. The goal of this research initiative is an upgraded pipe selection guide that integrates structural requisites, repair techniques, and mitigation strategies into a comprehensive tool1.2. Research Objectives and Tasks

The specific objectives of the research project included the following:

(i) Compile the existing structural prerequisites for pipe selection and incorporate them into the evolving pipe selection guide.

(ii) Gather and organize the array of repair and rehabilitation methods employed by NCDOT, assessing the suitability of these methods with distinct pipe material types.

(iii) Construct a service life evaluation model grounded in diverse repair approaches and integrate this model into the ongoing pipe selection software.

(iv) Document NCDOT's mitigation techniques and devise mechanisms to factor in their impact on the service life of installed pipes.

2. Updates on PASS Since the Previous Version

Figure 1 shows the user interface of the "Instruction" tab. The red box in **Figure 1** highlights different tabs, each color-coded for clear differentiation. This intuitive design ensures that users can easily identify various sections within the software. The instructions associated with each tab are also marked using the same colors, maintaining consistency and aiding navigation. The "Instruction" tab provides comprehensive guidance for different aspects of the software, helping users understand the process. The color-coding offers a visual cue that simplifies the identification of specific sections, making it straightforward for users to locate the information they need. This clear and organized design enhances user experience by reducing the learning curve and improving workflow efficiency. Engineers and other professionals can quickly navigate through the software's multiple features, adjusting as necessary to align with the unique requirements of their projects. Ultimately, this design facilitates a seamless, user-friendly experience that ensures engineers have the information they need to make informed decisions efficiently.

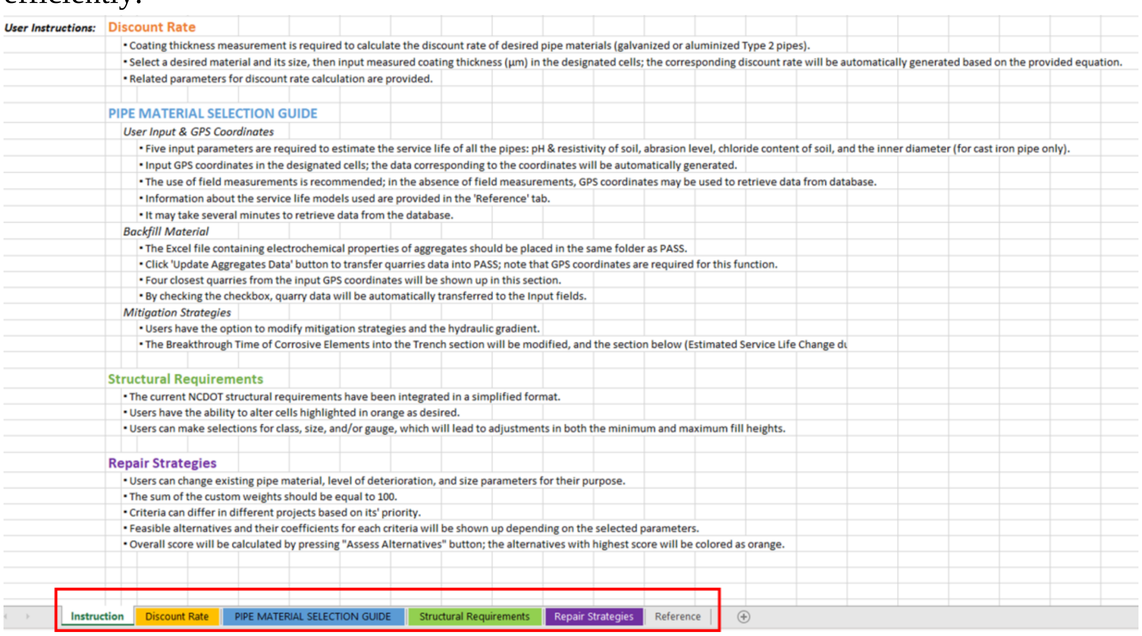

Figure 1. Color coded tabs and color-coded instructions with the same colors.

The user interface, footnotes, and acronyms have been updated since the previous version of PASS to ensure greater clarity and usability. In the "Pipe Material Selection Guide" tab, a new figure has been added that illustrates the environmental guidelines for different pipe materials.

This comprehensive figure helps users easily identify viable options by providing a visual representation of the relationship between the materials and the varying levels of pH, resistivity, and maximum abrasion. As shown in **Figure 2**, these guidelines serve as a reference point that enables engineers and project planners to make informed decisions when selecting appropriate pipe materials.

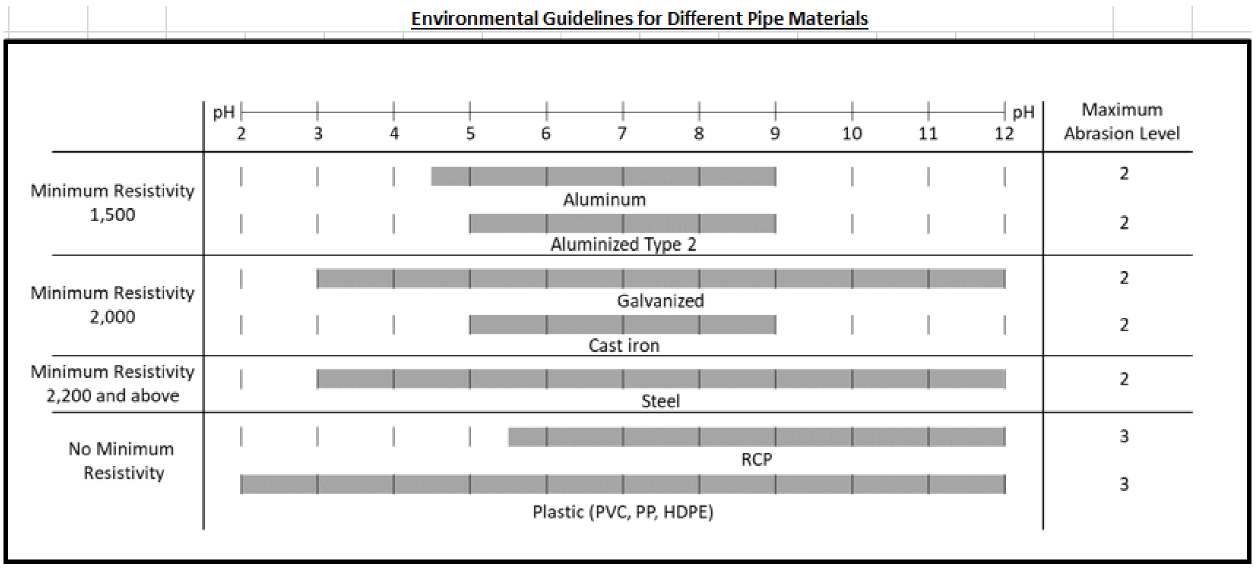

Figure 2. Environmental guidelines for different pipe materials in “Pipe Material Selection Guide” tab.

In the "Discount Rate" tab of the PASS software, comprehensive footnotes and detailed notes have been strategically added to each section to enhance clarity and provide users with in-depth guidance, as illustrated in **Figure 3**. These additions are designed to elaborate on the complexities and nuances associated with calculating discount rates for various pipe materials. Each footnote and note serves as a helpful resource, explaining the criteria and methodology used in the calculations, thus ensuring that users have a clear understanding of how discount rates are determined based on different variables.

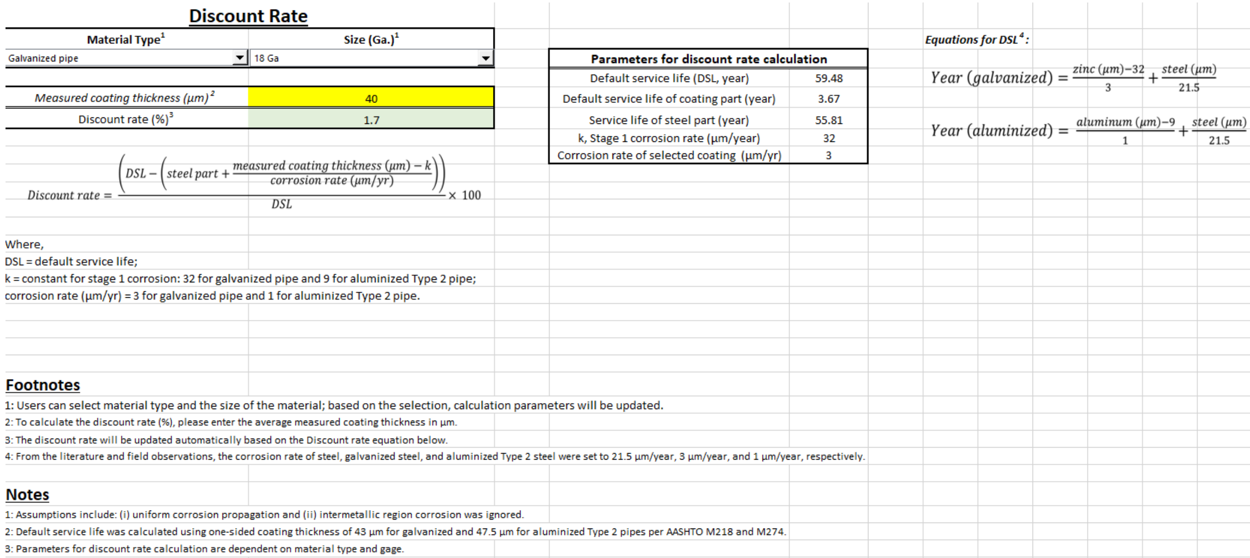

Figure 3. Footnotes and notes added in the “Discount Rate” tab.

Throughout RP 2022-02, new tabs—namely "Structural Requirements" and "Repair Strategies"—and a new section, titled "Estimated Service Life Change due to Mitigation Strategies," were introduced in the "Pipe Material Selection Guide" tab. These additions significantly enhance the functionality and comprehensiveness of the software by providing users with additional resources to evaluate and plan their projects effectively.

The "Structural Requirements" tab is designed to help engineers apply current structural standards relevant to different types of pipe materials. By outlining the specific load-bearing requirements, installation parameters, and safety considerations, this tab ensures that users can easily align their material selection and project designs with NCDOT guidelines.

The "Repair Strategies" tab provides a focused understanding of the repair and rehabilitation methods available for maintaining and extending the service life of pipe infrastructure. Within this tab, users can find information tailored to different pipe materials and conditions, allowing them to identify optimal strategies for repair/rehabilitation.

The "Estimated Service Life Change due to Mitigation Strategies" section in the “Pipe Material Selection Guide” tab delivers valuable insights into the impact of mitigation measures on the overall longevity of the infrastructure. By modeling and analyzing the effects of different strategies, such as flowable fill or geosynthetic clay liners, this section helps engineers understand how specific mitigation practices can extend the service life of culvert pipes and other infrastructure components.

3. Integration of Current Structural Requirements into PASS

Figure 4 presents the current "NCDOT Pipe Material Selection Guide." The "Fill Tables" row highlights the minimum and maximum fill heights for various materials, categorized by both classes (for reinforced concrete pipes) and sizes (covering corrugated steel, corrugated aluminum, HDPE, PP, and PVC pipes). The second to fifth rows assess the suitability of different pipe materials under varying drainage conditions and installation environments.

The guide has now been integrated into the PASS system, as illustrated in **Figure 5**. Structural requirements and specifications have been programmed into the guide's software to facilitate user interaction and decision-making. When users click on the orange-colored cells, a variety of options will appear in drop-down menus, as shown in **Figure 6**. The minimum and maximum fill heights will automatically adjust according to the sizes of the selected pipe materials. Additionally, the structural requirements will adapt based on the chosen installation locations. This update ensures that the guide provides dynamic, context-sensitive information, enhancing its utility and accuracy in project planning.

NCDOT PIPE MATERIAL SELECTION GUIDE

FILL TABLES

RCP[1] (REINFORCED CONCRETE) AASHTO M170

CLASS II MIN.[4]	CLASS II MAX.	CLASS III MIN.[4]	CLASS III MAX.	CLASS IV MIN.[4]	CLASS IV MAX.	CLASS V MIN.[4]	CLASS V MAX.
2.0′	10.0′	2.0′	20.0′	1.0′	30.0′	1.0′	40.0′

(FOR FILLS > 40′ & < 80′ USE LRFD DIRECT DESIGN METHOD. NOTE: DIRECT DESIGN METHOD RCP PIPES MUST HAVE A MINIMUM DIAMETER OF 36″.)

WHEN FILL HEIGHTS (NOT INCLUDING THE PAVEMENT STRUCTURE AND CURB) FOR RCP RUNNING PARALLEL TO AND UNDER CURB AND GUTTER, EXPRESSWAY GUTTER, SHOULDER BERM GUTTER AND ADJACENT TO MEDIAN BARRIER ARE 1′ OR LESS, SPECIFY CLASS IV RCP.

WHEN THE FILL HEIGHTS (FROM TOP OF PIPE TO SUBGRADE) FOR RCP RUNNING UNDER/ACROSS THE PAVEMENT ARE 1′ OR LESS, SPECIFY CLASS V RCP.

SPECIFY A SINGLE CLASS OF RCP IN A SINGLE RUN OF PIPE.

CSP[2] (CORRUGATED STEEL) AASHTO M36 2 ⅔ X ½ CORRUGATION[3]

SIZE	MIN.[4]	MAXIMUM (Ga) 16	14	12	10	8
12″	1.0′	204′	256′			
15″	1.0′	162′	204′			
18″	1.0′	135′	169′	239′		
24″	1.0′	100′	126′	178′		
30″	1.0′	79′	100′	142′		
36″	1.0′	65′	83′	117′	152′	
42″	1.0′	55′	70′	100′	130′	160′
48″	1.0′	48′	61′	87′	113′	139′
54″	1.0′		54′	77′	100′	123′
60″	1.0′			69′	90′	111′
66″	1.0′				81′	100′
72″	1.0′				74′	91′
78″	1.0′					81′
84″	1.0′					69′

CAAP (CORRUGATED ALUMINUM) AASHTO M196 2 ⅔ x ½ CORRUGATION[3]

SIZE	MIN.[4]	MAXIMUM (Ga) 16	14	12	10	8
12″	1.0′	123′	155′	218′	281′	344′
15″	1.0′	98′	123′	174′	224′	275′
18″	1.0′	81′	102′	144′	187′	228′
24″	1.0′	60′	76′	108′	139′	171′
30″	1.0′		60′	85′	111′	136′
36″	1.0′		50′	71′	92′	113′
42″	1.0′			60′	78′	96′
48″	1.0′			52′	68′	84′
54″	1.0′			46′	50′	74′
60″	1.0′				50′	62′
66″	1.0′					51′
72″	1.0′					41′

HDPE AASHTO M294; PP[7] ASTM F2881, ASTM F2764, OR AASHTO M330; PVC–ASTM F949 AASHTO M304

HDPE SIZE	HDPE MIN.[4]	HDPE MAX.	PP SIZE	PP MIN.[4]	PP MAX.	PVC SIZE	PVC MIN.[4]	PVC MAX.
12″	2.0′	20′	12″	1.0′	20′	12″	2.0′	30′
15″	2.0′	20′	15″	1.0′	20′	15″	2.0′	30′
18″	2.0′	20′	18″	1.0′	20′	18″	2.0′	30′
24″	2.0′	20′	24″	1.0′	20′	24″	2.0′	30′
30″	2.0′	17′	30″	1.0′	20′	30″	2.0′	30′
36″	2.0′	17′	36″	1.0′	20′	36″	2.0′	30′
42″	2.0′	17′	42″	1.0′	20′			
48″	2.0′	17′	48″	1.0′	20′			
54″	2.0′	17′	54″	NA	NA			
60″	2.0′	17′	60″	1.0′	20′			

		RCP[1]	CSP[2]	CAAP	HDPE / PP[7] / PVC
OPEN END CROSS PIPES	INTERSTATE[5]	CAN BE USED	USE ONLY IF PIPE SLOPE IS GREATER THAN 10%	USE ONLY IF PIPE SLOPE IS GREATER THAN 10%	DO NOT USE
	PRIMARY[5]	CAN BE USED	CAN BE USED	CAN BE USED	USE ONLY IF TRAFFIC <10000 ADT & <200 DUALS & <100 TTST
	SECONDARY	CAN BE USED	CAN BE USED	CAN BE USED	CAN BE USED
STORM DRAIN SYSTEMS	INTERSTATE	CAN BE USED	USE ONLY AT SYSTEM INLETS & SYSTEM OUTLET IF PIPE SLOPE IS GREATER THAN 10%	USE ONLY AT SYSTEM INLETS & SYSTEM OUTLET IF PIPE SLOPE IS GREATER THAN 10%	DO NOT USE
	PRIMARY	CAN BE USED	USE ONLY AT SYSTEM INLETS & SYSTEM OUTLET IF PIPE SLOPE IS GREATER THAN 10%	USE ONLY AT SYSTEM INLETS & SYSTEM OUTLET IF PIPE SLOPE IS GREATER THAN 10%	USE ONLY IF TRAFFIC <10000 ADT & <200 DUALS & <100 TTST
	SECONDARY	CAN BE USED	USE ONLY AT SYSTEM INLETS & SYSTEM OUTLET IF PIPE SLOPE IS GREATER THAN 10%	USE ONLY AT SYSTEM INLETS & SYSTEM OUTLET IF PIPE SLOPE IS GREATER THAN 10%	CAN BE USED
TRANSVERSE MEDIAN PIPES	INTERSTATE	CAN BE USED	USE ONLY IF PIPE SLOPE IS GREATER THAN 10%	USE ONLY IF PIPE SLOPE IS GREATER THAN 10%	DO NOT USE
	PRIMARY	CAN BE USED	CAN BE USED	CAN BE USED	USE ONLY IF TRAFFIC <10000 ADT & <200 DUALS & <100 TTST
	SECONDARY	CAN BE USED	CAN BE USED	CAN BE USED	CAN BE USED
SLOPE DRAINS[6]	INTERSTATE	DO NOT USE	CAN BE USED	CAN BE USED	CAN BE USED
	PRIMARY	DO NOT USE	CAN BE USED	CAN BE USED	CAN BE USED
	SECONDARY	DO NOT USE	CAN BE USED	CAN BE USED	CAN BE USED
SIDE DRAINS	INTERSTATE	CAN BE USED	CAN BE USED	CAN BE USED	CAN BE USED
	PRIMARY	CAN BE USED	CAN BE USED	CAN BE USED	CAN BE USED
	SECONDARY	CAN BE USED	CAN BE USED	CAN BE USED	CAN BE USED

NOTES

1– RCP IS NOT ALLOWED FOR GRADES >10%
2– FOR COUNTIES LISTED IN ARTICLE 310 OF THE STANDARD SPECIFICATIONS CSP IS NOT ALLOWED. IN OTHER COUNTIES, CSP REQUIRES AN ACCEPTABLE COATING IN ACCORDANCE WITH 1032.
3– FOR DIFFERENT CORRUGATIONS AND ARCH PIPES REFER TO ROADWAY DESIGN MANUAL AND MANUFACTURERS SPECIFICATION.
4– MINIMUM FILL HEIGHT IS MEASURED FROM TOP OF PIPE TO SUBGRADE. MINIMUM COVER IS 1FT WHEN PIPE IS USED AS A SIDE DRAIN.
5– WHERE SITE CONDITIONS ALLOW: INCREASE PIPE DIAMETER OF OPEN END CROSS PIPES AND SECTIONS OF STORM SEWER SYSTEMS ACTING AS OPEN END CROSS PIPES, A MINIMUM OF ONE SIZE FOR FUTURE REHABILITATION. THIS IS IN ADDITION TO UPSIZING TO COMPENSATE FOR BURYING INVERTS FOR WILDLIFE PASSAGE.
6– FOR PIPE RUNS WITH GREATER THAN 12′ VERTICAL DROP TO DOWNSTREAM STRUCTURE, PROVIDE A MEANS TO REDUCE RISK OF UNINTENDED ENTRY INTO UPSTREAM END OF PIPE.
7– FILL HEIGHTS SHOWN WERE CALCULATED USING AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS. JUSTIFY FILL HEIGHT OR DESIGN DEVIATIONS WITH STRUCTURAL DESIGN BASED ON AASHTO LRFD BRIDGE DESIGN OR ASTM STANDARDS. SUBMIT DESIGN SEALED BY AN NC PE FOR REVIEW & APPROVAL BY NCDOT.

INSTALLATION OF ALL PIPE TYPES IS SUBJECT TO THE INSTALLATION METHODS FOUND IN THE STANDARD DRAWINGS, STANDARD SPECIFICATIONS, HYDRAULICS GUIDELINES, AND CONTRACT DOCUMENTS; ACCOUNTING FOR SITE CONDITIONS SUCH AS SOIL PROPERTIES.

ALL PIPES TYPES ARE SUBJECT TO THE MAXIMUM AND MINIMUM FILL HEIGHT REQUIREMENTS AS FOUND IN THE ROADWAY DESIGN MANUAL. THE APPROPRIATE CLASS OF PIPE FOR RCP AND GAUGE THICKNESS FOR CSP/CAAP SHOULD BE SELECTED BASED ON FILL HEIGHT.

SITE SPECIFIC CONDITIONS MAY LIMIT A PARTICULAR MATERIAL BEYOND WHAT IS IDENTIFIED IN THE TABLE. THESE CONDITIONS INCLUDE, BUT ARE NOT LIMITED TO, ABRASION, ENVIRONMENTAL, SOIL RESISTIVITY AND PH, HIGH GROUND WATER AND SPECIAL LOADING CONDITIONS. THE HYDRAULIC DESIGN ENGINEER WILL DETERMINE IF ADDITIONAL RESTRICTIONS ARE NECESSARY.

DEFINITIONS

SIDE DRAINS– STORM DRAIN PIPES RUNNING PARALLEL TO THE ROADWAY TO INCLUDE PIPES IN THE MEDIANS, OUTSIDE DITCHES, DRIVEWAYS AND UNDER SHOULDER BERM GUTTER ALONG OUTSIDE SHOULDERS GREATER THAN 4′ WIDE. MAY OR MAY NOT BE OPEN ENDED. 1′ MINIMUM COVER FOR ALL SIDE DRAIN PIPE IN ACCORDANCE WITH STANDARD SPECIFICATION SECTION 310.

STORM DRAIN SYSTEMS– LATERAL DRAIN PIPE UNDER CURB AND GUTTER, EXPRESSWAY GUTTER AND SHOULDER BERM GUTTER (WITH SHOULDERS 4′ WIDE OR LESS) THAT CONNECT DRAINAGE STRUCTURES AND IS NOT OPEN ENDED. ALSO INCLUDES CROSS DRAIN CONNECTING TWO OR MORE SYSTEMS OR SYSTEM OUTLETS. ONLY PIPE WITH SMOOTH WALL INSIDE WALLS WILL BE ALLOWED FOR STORM DRAIN SYSTEMS.

TRANSVERSE MEDIAN PIPES– SHALLOW CROSS DRAIN PIPE THAT COLLECTS DRAINAGE IN A MEDIAN DITCH OR CURB SECTION AND DEPOSITS IT OUTSIDE DITCHES OR NATURAL DRAINAGE CHANNELS. MAY OR MAY NOT BE OPEN ENDED.

ALTERNATE PIPE– PIPE IN WHICH MATERIAL IS UNSPECIFIED ON THE DRAINAGE SUMMARY SHEET AND DRAINAGE PLANS.

HDPE– HIGH DENSITY POLYETHYLENE

PP– POLYPROPYLENE

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Figure 4. Current structural requirements in NCDOT

Structural Requirements

		RCP		CSP		CAAP		HDPE		PP		PVC	
		CLASS	Class 3	Size (in) Gauge	48 10	Size (in) Gauge	24 12	Size (in)	15	Size (in)	24	Size (in)	12
	Min (ft)	2		1		1		2		1		2	
	Max (ft)	20		113		108		20		20		30	
Open end cross pipes	Primary	Can be used		Use only if pipe slope is greater than 10%		Use only if pipe slope is greater than 10%		Use only if traffic <10000 ADT & <200 DUALS & <100 TTST					
Storm drain systems	Primary	Can be used		Use only at system inlets & system outlet if pipe slope is greater than 10%		Use only at system inlets & system outlet if pipe slope is greater than 10%		Use only if traffic <10000 ADT & <200 DUALS & <100 TTST					
Transverse median pipes	Primary	Can be used		Use only if pipe slope is greater than 10%		Use only if pipe slope is greater than 10%		Use only if traffic <10000 ADT & <200 DUALS & <100 TTST					
Slope drains	Interstate	Do not use		Can be used		Can be used		Can be used					
Side drains	Primary	Can be used		Can be used		Can be used		Can be used					

Figure 5. Reconstructed NCDOT pipe material selection guide that will be included in the PASS program.

Structural Requirements

		RCP		CSP		CAAP		HDPE		PP		PVC	
		CLASS	Class 3	ize (in) Gauge	48 10	Size (in) Gauge	24 12	Size (in)	15	Size (in)	24	Size (in)	12
	Min (ft)	2	Class 2 Class 3	1		1		2		1		2	
	Max (ft)	2	Class 4 Class 5	113		108		20		20		30	
Open end cross pipes	Primary	Can be used		Use only if pipe slope is greater than 10%		Use only if pipe slope is greater than 10%		Use only if traffic <10000 ADT & <200 DUALS & <100 TTST					
Storm drain systems	Primary	Can be used		Use only at system inlets & system outlet if pipe slope is greater than 10%		Use only at system inlets & system outlet if pipe slope is greater than 10%		Use only if traffic <10000 ADT & <200 DUALS & <100 TTST					
Transverse median pipes	Primary	Can be used		Use only if pipe slope is greater than 10%		Use only if pipe slope is greater than 10%		Use only if traffic <10000 ADT & <200 DUALS & <100 TTST					
Slope drains	Interstate	Do not use		Can be used		Can be used		Can be used					
Side drains	Primary	Can be used		Can be used		Can be used		Can be used					

Figure 6. Example of a drop-down menu in an orange-colored cell.

3. Integrating Repair and Rehabilitation Methods into the Software

3.1. Historical Repair and Rehabilitation Approaches Used by NCDOT

The research team has carefully reviewed the historical data provided by the NCDOT on pipe repair approaches used across the state. The data are spatially represented on the map shown in **Figure 7**. As an example, 24% of documented repairs were completed using cured-in-place pipe (CIPP), and 51% of repairs utilized centrifugally cast concrete pipe (CCCP) in North Carolina from 2003 to 2018.

In terms of the physiographic regions, specifically Division 3 (Coastal Plain), all pipe rehabilitations were primarily conducted using CIPP, with few exceptions, probably due to the high chloride content typically present in the coastal plain region. In Halifax and Johnston Counties in Division 4, however, a paved invert was used for the restoration of reinforced concrete pipes. In Dare County, Division 1, slip-lining with centrifugally cast fiberglass composite pipe was utilized. In Pitt County, Division 2, joint repairs were made using oakum rope injection grouting behind the joints. Many of the rehabilitation measures in Wake County, Division 5 (Piedmont region), were performed using CCCP. Within the Mountain region, various repair approaches were employed, including CIPP and CCCP.

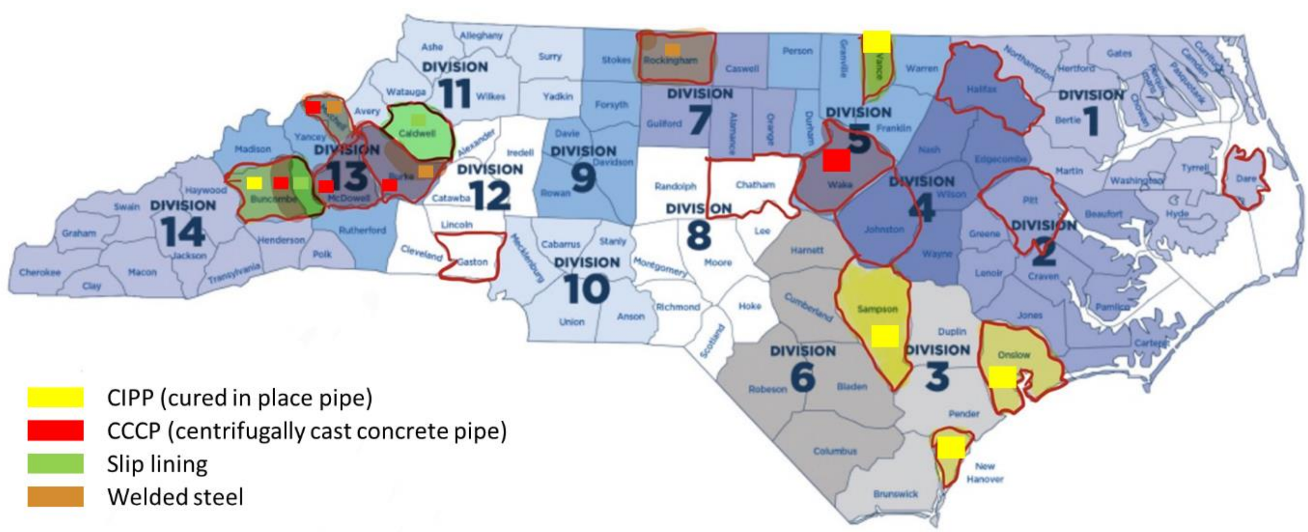


Figure 7. Mapping of different rehabilitation approaches used by NCDOT (2003 – 2018)

3.2. Cataloging Repair and Rehabilitation Approaches Used by NCDOT

The NCDOT pipe liner manual was reviewed and summarized as follows [1–3].

Category A – Cured-In-Place Pipe (CIPP) liners

- Can be installed in pipes of any material and any cross-section (circular or non-circular).
- Suitable for use with or without corrugations on the inside surface of the pipe.
- Corrugations are sometimes filled with cement grout prior to applying the liner.
- Conventional CIPP lining is applicable to pipe diameters between 6 in. and 108 in., and for installation lengths ranging from 10 ft to nearly 3000 ft.
- Smaller diameters (e.g., 4 in pipes) can also be CIPP relined in some cases.
- Composite CIPP linings are typically used in pipes with a diameter of 48 inches or larger, although composite CIPP linings can sometimes be used in 36 in. pipes as well.


(a)


(b)

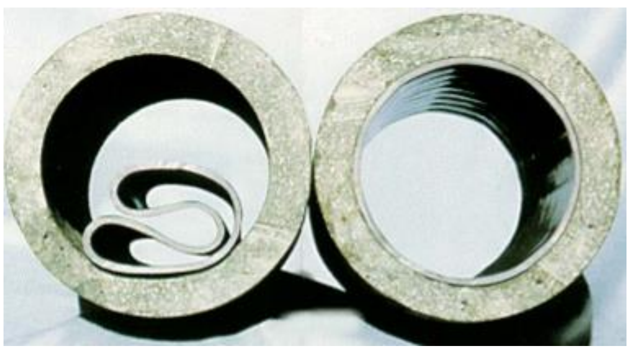
Figure 8. Examples of CIPP installation options: (a) pull-in-and-inflate, and (b) liner inversion (Courtesy of Insituform Technologies, Inc.)

Table 1. Pros and cons of category A liners.

Pros	Cons
- No need for excavation and grouting - Installation of a one-piece product with no joints can provide an estimated 50-year service life (per one manufacturer) - CIPP is a proven technology that has been used for over 30 years. - Often cost effective and causes minimal disruption to traffic. - Small diameter installations can be completed quickly, sometimes in a single day.	- Need to bypass flow - Custom-made tube is required for each installation. - Highly trained personnel and specialty equipment are required. - A prolonged liner cure is needed for large diameter pipes. - Potential for thermal pollution (if hot water is used to accelerate resin cure) - Potential for adverse environmental impact (if styrene-based resins are used)

Category B - Fold and Form flexible liners

- Most common for circular pipes with diameters from 6 in. to 24 in.
- Some non-circular culvert shapes can also be rehabilitated, e.g., elliptical.
- Lengths up to 1500 ft. can be relined.
- Applicability is not limited by culvert pipe type or condition unless the pipe has already collapsed (these liners can rehabilitate deteriorated pipes with ovality up to 10%, soil voids, and with offsets and bends).
- Deep pipes exceeding 30 ft. below grade have been rehabilitated.
- Can be installed in corrugated culvert pipes, however, the installation cannot be performed in live flow conditions.



(a)

(b)

Figure 9. Fold and Form liners: (a) folded and final shapes, and (b) insertion of a folded liner (Courtesy of Ultraliner)

Table 2. Pros and cons of category B liners.

Pros	**Cons**
- No need for excavation or grouting - One piece (jointless) final product with an expected minimum 50-year service life (according to one manufacturer). - Installation is straight-forward and fast, with minimal traffic disruption. Equipment and work procedures are relatively simple. - The liner is manufactured in a controlled environment under stable conditions and the installation process does not change the	- Diameter is limited to about 30 in. - Need to bypass flow (installations cannot be performed in live flow conditions) - Installation lengths are limited by pull-in forces or coil lengths. This is not typically an issue with culvert rehabilitation. - Chemical grouting may be required at liner ends

physical properties of the liner material (no curing of resins or similar). - No hazardous chemicals are used, and no refrigeration is required during transportation or storage of materials. - Reduction of cross area of culvert pipe is minimal, while flow capacity remains the same, or is even improved, due to the liner's smooth surface.	

Category C – HDPE, PE, PVC, PP, solid wall slip liners

- Applies to circular pipes in a wide range of diameters.
- Pipes with inner diameters of 4 in. to 63 in. can be repaired with continuous sliplining.
- Pipes with inner diameters of 4 in. to 152 in. can be repaired with segmental sliplining. Lengths over 5000 ft. have been sliplined.
- Custom shapes are possible with segmental sliplining, however, diameter changes may prevent the use of this method.
- The method is typically limited to straight pipe alignment, however, continuous sliplining can accommodate gradual bends.
- Can be applied to any culvert pipe material and shape.
- Corrugations on the inside surface do not hinder the use of this method.
- Pipe condition is generally not a limitation (e.g., pipe can be corroded, deformed, and even near collapse).
- Can be performed in live flow conditions and flow bypass is seldom required.

(a)

(b)

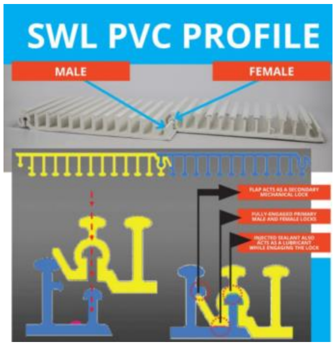
Figure 10. Examples of sliplining: (a) large diameter sliplining, and (b) live insertion sliplining (Courtesy of Hobas Pipe USA)

Table 3. Pros and cons of category C liners.

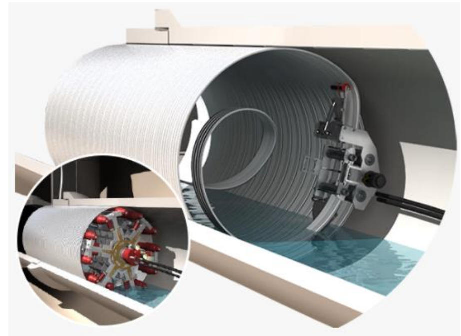
Pros	Cons
- Simple installation in concept (slide a new pipe inside an old pipe). - Rehabilitate practically any pipe size - Variety of sliplining pipes are available on the market - No need for bypassing flow in most cases - Often offers an economical rehabilitation option for culverts - Capable of accommodating large radius bends - Does not involve chemical processes and may be environmentally safer relative to other procedures.	- Need for excavation of pits (although with shorter culvert lengths, digging access pits may be avoided) - Grouting of the annular space is generally required. - Reduction in cross-section (reduced flow), however, flow capacity can sometimes be recovered, or even increased, due to smooth interior surface of slipliner pipe. - Need for a sufficient work area (this can be very significant). - Numerous joints can be created with segmental sliplining, whereas with continuous sliplining the number of joints can be limited to only few - Cannot accommodate tight bends or turns.

Category D – HDPE, PVC, PP corrugated, profile wall, steel reinforced, or spirally wound slip liners

- Strips for winding can be made of PVC or HDPE (for deform and reform liners).
- Strips come in a variety of profiles with external ribs to increase the liner stiffness and to anchor the liner in the cement grout if grout is used for annular space grouting.
- The PVC strip can include steel reinforcement, though this is typically used for larger diameter liners (30in. or more).
- Covers a diameter range of 6 in to 180 in.
- Maximum drive length is dependent on several variables and project specifics, and is typically limited to about 650 ft.
- Applicability is not limited by culvert pipe type, shape, corrugations on the inside surface, or condition.
- Installation can be performed in live flow conditions.



(a)



(b)

Figure 11. Examples of spirally wound slip liners: (a) self-interlocking of male and female edges of the approach (Courtesy of Infrastructure Product Group), and (b) a rotating winding machine that traverses through the pipeline (courtesy of SEKISUI SPR Americas, LLC)

Table 4. Pros and cons of category D liners.

Pros	Cons
- No need for excavation, storage or handling of pipes onsite - No need to bypass flow (for most applications) - Installation is generally quick and quiet - Ability to accommodate large radius bends and diameter changes - Does not involve chemical processes and is more likely to be environmentally safe	- Usually, a need for grouting the annular space (unless diameter expansion has been applied) - Causes a reduction in flow area, although flow capacity can often be recovered or even increased due to smooth interior surface of the liner pipe. - Ends of the relined pipe require watertight sealing.

Category E - Sprayed-on liners

- Cementitious liners
  - Applicable to circular pipes with a diameter from 12 in. to 140 in.
  - Reinforced cement mortar lining is only applicable in many-entry pipes.
  - Maximum installation length is about 650 ft in robotic applications and about 50 to 60 ft in man-entry applications (depends on safety regulations).
  - Corrugations in the pipe do not hinder the use of shotcrete, but the pipe must be empty and clean (no live flow).
- Polymer-based liners
  - Applicable in all pipe shapes and types, but the pipes must be empty, dry, and clean
  - Spincasting is applicable in smaller diameter circular pipes, typically in a range between 3 in. and 36 in. Lengths up to 700 ft. are realistic.
  - In man-entry pipes, the method is applicable in any pipe size and shape, and the installation length is typically limited to 450 ft (depending on safety regulations)

(a)

(b)

Figure 12. Examples of sprayed-on liners: (a) cementitious liners (Courtesy of Curtis Concrete Pumping), and (b) polymer-based coatings and liners (Courtesy of Epoxytec Intl, Inc.)

Table 5. Pros and cons of category E liners.

Pros	Cons
Cementitious liners	
- Cement mortar lining – ability to provide protection against corrosion and abrasion, restore flow capacity, and provide structural repair if sufficient material thickness is used - No excavation is required	- Relatively long setting time and a relatively slow strength gain of the installed liner - Culvert must be completely free of water and flow bypass may be required - Extensive surface preparation is needed in most cases
Polymer-based coatings and liners	
- Ability to provide protection against corrosion (some provide structural enhancement) - No excavation is required	- Must be completely free of water and flow bypass may be required - Extensive surface preparation is essential for successful application with some systems

3.3. Compatibility Check for the Repair and Rehabilitation Methods with the Available Types of Pipe Materials

Information presented in two FHWA Reports (report numbers: FHWA-CFL/TD-05-003 and FHWA-SC-17-01) suggests a weighted average approach for the selection of pipe rehabilitation measures [4,5]. The suggested approaches allow users to select different criteria and decide the relative importance of each selected criterion. The information is then integrated and compiled into the approach best suited for a given pipe type and site conditions.

The weighted average approach encompasses nine different performance criteria according to the report by Thornton et al. (report #: FHWA-CFL/TD-05-003) [4]. As shown in **Table 6**, a rating of '1 to 5' is used in the weighted average method, with a value of 1 indicating the worst performance and a value of 5 indicating the best performance for each alternative 'j' and for each criterion 'i'. Since performance criteria may vary from project to project, users can select the most appropriate criteria for a given project before ranking the relative performance of each repair option according to the selected criteria. The method outlined in **Table 6** allows users to assign high ratings to the criteria that are most important to the project's objectives.

Table 6. Alternative rating scales as presented by Thornton et al. (2005) [4]

Alternative (j)	**Sliplining**		**Close-fit lining**		**Spirally Wound Lining**	**Cured-in-place lining**		**Spray-on lining**	
Criterion (i)	Segmental Method	Continuous Method	Deformed /Reformed Method	Fold and Form Method		Inversion Method	Pulled-in-place Method	Cement-mortar System	Epoxy system
Design Life	4	4	4	3	3	5	5	1	2
Capacity Reduction	2	2	5	5	5	5	5	4	4
Abrasion and Corrosion Resistance	3	3	3	4	4	4	4	1	2
Installation Time	5	3	3	3	4	2	2	1	1
Flow Bypass Requirements	4	4	1	3	4	1	1	1	1
Digging Requirements	5	1	3	3	3	2	2	5	5
Cost	4	4	3	3	2	1	1	5	5
Safety	4	3	3	3	3	3	3	5	5
Environmental Concerns	4	4	3	3	4	1	1	1	1

With the criteria rankings assigned, **Equation (1)** is used to determine the overall score for each repair alternative, thus identifying the optimal approach for the selected inputs. In the equation, S_j represents the overall score for rehabilitation alternative 'j', W_i is the weight of the criterion "i," and $R_{i,j}$ denotes the relative importance of criterion 'i' for alternative 'j'. The overall score S_j will range from 1 to 5, as the summation of the normalized weights must equal 1.

$$S_j = \sum_{i=1}^{n} W_i \times R_{i,j} \qquad \text{Equation (1)}$$

As an example, it is necessary to identify normalized weights for the selected performance criteria. In this scenario, we assume that design life, abrasion and corrosion resistance, installation time, cost, safety, and environmental concerns are the most important factors for a hypothetical project. These criteria are assigned the normalized weights shown in the first column (W) of **Table 7**. The normalized weights are then multiplied by the performance rankings and summed for each repair option. The overall scores indicate that sliplining emerges as the best option, while cement-mortar spray-on lining is identified as the least favorable option in this hypothetical case.

Table 7. Example of using the weighted average method [4]

W	Alternative (j)	Sliplining		Close-fit lining		Spirally Wound Lining	Cured-in-place lining		Spray-on lining	
	Criterion (i)	Segmental Method	Continuous Method	Deformed /Reformed Method	Fold and Form Method		Inversion Method	Pulled-in-place Method	Cement-mortar System	Epoxy system
0.35	Design Life	4	4	4	3	3	5	5	1	2
-	Capacity Reduction	2	2	5	5	5	5	5	4	4
0.15	Abrasion and Corrosion Resistance	3	3	3	4	4	4	4	1	2
0.1	Installation Time	5	3	3	3	4	2	2	1	1
-	Flow Bypass Requirements	4	4	1	3	4	1	1	1	1
-	Digging Requirements	5	1	3	3	3	2	2	5	5
0.2	Cost	4	4	3	3	2	1	1	5	5
0.1	Safety	4	3	3	3	3	3	3	5	5
0.1	Environmental Concerns	4	4	3	3	4	1	1	1	1
1	**Overall Score**	**3.95**	**3.65**	**3.35**	**3.15**	**3.15**	**3.15**	**3.15**	**2.20**	**2.70**

In a similar vein, Report No. FHWA-SC-17-01 selects five criteria for pipe rehabilitation decision-making, in contrast to the nine used in FHWA-CFL/TD-05-003 [4,5]. These criteria are cost, design life, capacity, traffic impact, and environmental impact. For a more comprehensive evaluation of various alternatives, the approach in FHWA-SC-17-01 synthesizes alternative ratings for two general repair types (semi-structural and full-structural) across three size ranges of base culvert materials, including reinforced concrete pipe (RCP) and corrugated metal pipe (CMP): less than 36 inches, 36-60 inches, and 60-120 inches [5]. While FHWA-SC-17-01 also employs the weighted average method, its approach slightly differs from that in FHWA-CFL/TD-05-003 [4,5]. In FHWA-SC-17-01, derived ratings are developed using the pairwise comparison procedures of the Analytical Hierarchy Process (AHP) and the number of chosen criteria [5]. Additionally, this process considers open-cut and pipe bursting methods, which are not utilized by NCDOT.

Based on the literature review, various rehabilitation methods including cured-in-place-pipe lining (CIPP), Deformed/Reformed, Fold and Form, slip lining (SL), spiral wound liner (SWL), and spray-on methods (cement mortar/epoxy) were assessed in conjunction with the reported custom weights method. While the report by Thornton et al. (report #: FHWA-CFL/TD-05-003) suggested nine different performance criteria, factors related to safety and environmental concerns were not included in this analysis, as these factors can vary substantially from site to site and from contractor to contractor [4].

To identify an appropriate rehabilitation approach, users first need to select the following parameters: 1. Existing pipe material, 2. Level of deterioration, and 3. Pipe size, according to the alternatives shown in **Figure 13**. These input parameters were adopted based on the information provided in Report No. FHWA-SC-17-01 [5].

Figure 14 displays the adopted criteria suggested by Thornton et al. (2005), including "Custom weights" section that users can adjust to reflect the condition of their project. The total of the custom weights should equal '100%' [4].

After selecting the parameters and determining the custom weights, the calculated overall scores and applicable alternatives will be displayed adjacent to the criteria section, as shown in **Figure 15**. The cell with the highest score(s) will be colored orange, and the alternative(s) in these orange cells will be identified as the best option(s), as demonstrated in **Figure 16**.

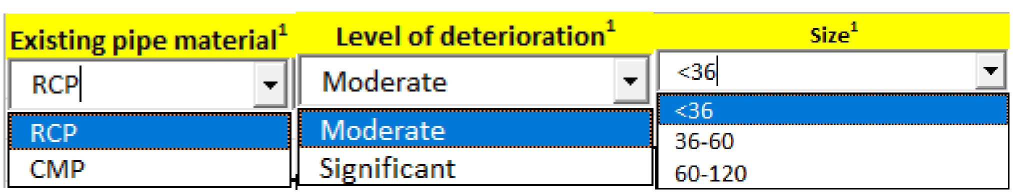


Figure 13. Parameters needed to be selected by users.

Custom weights[2] (%)	Criteria[3]
16	Design life
14	Abrasion and corrosion resistance
27	Installation time
8	Flow bypass requirements
13	Digging requirements
22	Cost
100	**Overall score[5]**

Figure 14. Incorporated criteria and custom weights input section.

Alternatives[4]						
Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
1	2	5	5	4	3	3
4	4	5	5	5	5	5
1	2	4	4	3	4	4
1	1	2	2	3	3	4
1	1	1	1	1	3	4
5	5	2	2	3	3	3
230	273	331	331	318	355	376

Figure 15. Performance ratings and calculated overall scores for applicable alternatives.

Existing pipe material[1]	Level of deterioration[1]	Size[1]
CMP	Significant	<36

Custom weights[2] (%)	Criteria[3]	Alternatives[4]				
		SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL
30	Design life	4	4	5	5	3
30	Abrasion and corrosion resistance	2	2	5	5	5
18	Installation time	3	3	4	4	4
2	Flow bypass requirements	5	3	2	2	4
10	Digging requirements	4	4	1	1	4
10	Cost	5	1	2	2	3
100	Overall score[5]	334	290	406	406	390

Existing pipe material[1]	Level of deterioration[1]	Size[1]
RCP	Moderate	<36

Custom weights[2] (%)	Criteria[3]	Alternatives[4]						
		Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
10	Design life	1	2	5	5	4	3	3
10	Abrasion and corrosion resistance	4	4	5	5	5	5	5
10	Installation time	1	2	4	4	3	4	4
5	Flow bypass requirements	1	1	2	2	3	3	4
5	Digging requirements	1	1	1	1	1	3	4
60	Cost	5	5	2	2	3	3	3
100	Overall score[5]	370	390	275	275	320	330	340

Figure 16. Examples of orange-colored (best) options based on input custom weights.

The footnotes for items in **Figure 16** that contain superscripts have been updated, as shown in **Figure 17**. **Figure 18** provides explanations for the acronyms used in **Figure 16** for easy reference. When the sum of the "Custom weights" assigned to the various criteria for selecting repair and rehabilitation measures does not equal '100', an error message box will pop up. This error message is illustrated in **Figure 19**. Additionally, the reference tab has been updated accordingly (see **Figure20 and Figure 21**).

Footnotes
1. Users can change existing pipe material, level of deterioration, and size parameters for their purpose.
2. The sum of the custom weights should be equal to 100.
3. Criteria can differ in different projects based on its' priority.
4. Feasible alternatives and their coefficients for each criteria will be shown up depending on the selected parameters.
5. Overall score will be calculated by pressing "Assess Alternatives" button; the alternatives with highest score will be colored as orange.

Figure 17. Footnotes for reference.

Acronyms	
CIPP	Cured-in-place-pipe
SWL	Spiral wound liner
SL	Slip lining

Figure 18. Acronyms for reference.

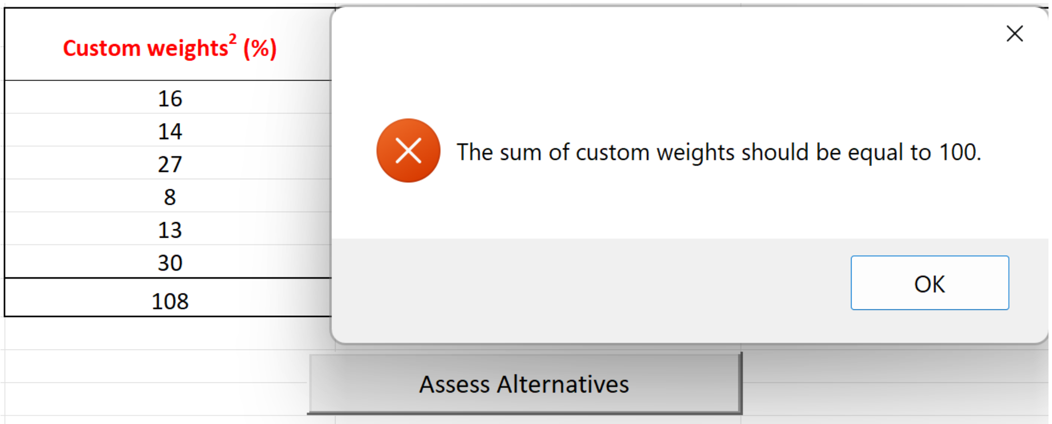


Figure 19. Pop-up error message box when the sum of the weights is not equal to 100.

Feasible repair/rehabilitation approaches according to pipe materials, level of deteriorations, and sizes of original pipe

Existing pipe material	Level of deterioration	Size	Feasible approaches						
RCP	Moderate	<36	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
RCP	Moderate	36-60	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	SWL		
RCP	Moderate	60-120	Spray-on lining-cement-mortar	Spray-on-epoxy	SWL				
RCP	Significant	<36	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL		
RCP	Significant	36-60	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL		
RCP	Significant	60-120	SL-segmental	SL-continuous	SWL				
CMP	Moderate	<36	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
CMP	Moderate	36-60	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	SWL		
CMP	Moderate	60-120	Spray-on lining-cement-mortar	Spray-on-epoxy	SWL				
CMP	Significant	<36	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL		
CMP	Significant	36-60	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL	Spray-on lining-cement-mortar	Spray-on-epoxy
CMP	Significant	60-120	SL-segmental	SL-continuous	SWL	Spray-on lining-cement-mortar	Spray-on-epoxy		

Figure 20. Updated reference tab: feasible repair/rehabilitation approaches regarding pipe materials, level of deterioration, and sizes of original pipe.

Adopted criteria and criterion weights to calculate scores for different alternatives

Criteria	Alternatives								
	Sliplining-segmental	Sliplining-continuous	Deformed/Reformed	Fold and Forl	Spirally Wound Lining	CIPP-inversion	CIPP-pulled-in-place	Spray-on lining-cement-mortar	Spray-on-epoxy
Design life	4	4	4	3	3	5	5	1	2
Capacity Reduction	2	2	5	5	5	5	5	4	4
Abrasion and Corrosion Resistance	3	3	3	4	4	4	4	1	2
Installation Time	5	3	3	3	4	2	2	1	1
Flow Bypass Requirements	4	4	1	3	4	1	1	1	1
Digging Requirements	5	1	3	3	3	2	2	5	5
Cost	4	4	3	3	2	1	1	5	5

Figure 21. Updated reference tab: adopted criteria and criterion weights to calculate scores for different alternatives

4. Integrating Mitigation Methods of Adverse Subsurface Exposure Factors for Installed Pipes into the Software

4.1 Introduction

Work in this section investigates the impact of various mitigation strategies on the transport of chloride and sulfate ions towards installed pipes. Our goal was twofold: (i) to estimate how chloride accumulation impacts the service life of a typical, unmitigated in-ground pipe, and (ii) to estimate the impact of mitigation strategies on extending in-ground pipe service life. The primary focus will be on evaluating the potential for chloride as a primary exposure element related to corrosion. Modeling is conducted to assess chloride transport with the installation of mitigation measures. The four mitigation scenarios considered herein for lining the pipe trench include flowable fill, compacted clay layer, geosynthetic clay liner, and polymeric liner.

The modeling employed the 1-D advection-diffusion model [6]. This widely accepted modeling equation is relatively simple to use and can be readily programmed into the Excel platform for future use by NCDOT. The evaluation of mitigation strategies involved comparing the predicted transport behavior of chloride assuming several mitigation measure scenarios. Chloride was used herein as a marker for elements influencing deterioration of concrete and metallic pipes. A baseline scenario, utilizing native soil backfill, was utilized as the reference (baseline) case for comparative assessment of the efficacy of the proposed mitigation measures. Modeling effort then simulated scenarios where the native backfill is replaced with alternative materials possessing lower hydraulic conductivity to mitigate the migration of chloride in solution into the pipe trench.

4.2 Background

Chloride is deposited onto the earth's surface from the atmosphere. There are two means by which atmospheric chloride deposition occurs: wet deposition and dry deposition [7]. Wet deposition occurs when chloride-containing precipitation falls to the earth's surface, while dry deposition occurs when particulate chloride is deposited by the force of gravity and varying wind flows [7]. The primary source of atmospheric chloride is marine aerosols; therefore, coastal soils typically exhibit higher chloride levels relative to inland ecosystems. Other sources of atmospheric chloride include wildfires, volcanic emissions, coal combustion, and traffic emissions [8].

To examine the distribution of chloride deposition across North Carolina, we used the Total Deposition Maps produced by the National Atmospheric Deposition Program's (NADP) Total Deposition Science Committee (TDEP). TDEP's Total Deposition maps account for both wet and dry deposition of chemical species. The maps are created using three sources of data including the measured wet data from NADP, the measured dry data from the EPA's Clean Air Status and Trends Network (CASTNET), and modeled deposition velocities from the Community Multiscale Air Quality model (CMAQ). We used the TDEP's reported total chloride deposition data from 2000 – 2018 to estimate the maximum potential chloride level in North Carolina groundwater. **Figure 22** shows maximum potential groundwater chloride concentrations as distributed across the three geologic regions of North Carolina. Maximum values are observed in the Coastal Plain region of the states with the highest concentration of 800 mg/l observed in the coastal areas. The lowest concentration (less than 160 mg/L) is observed for the Piedmont and the Mountain geologic regions of North Carolina.

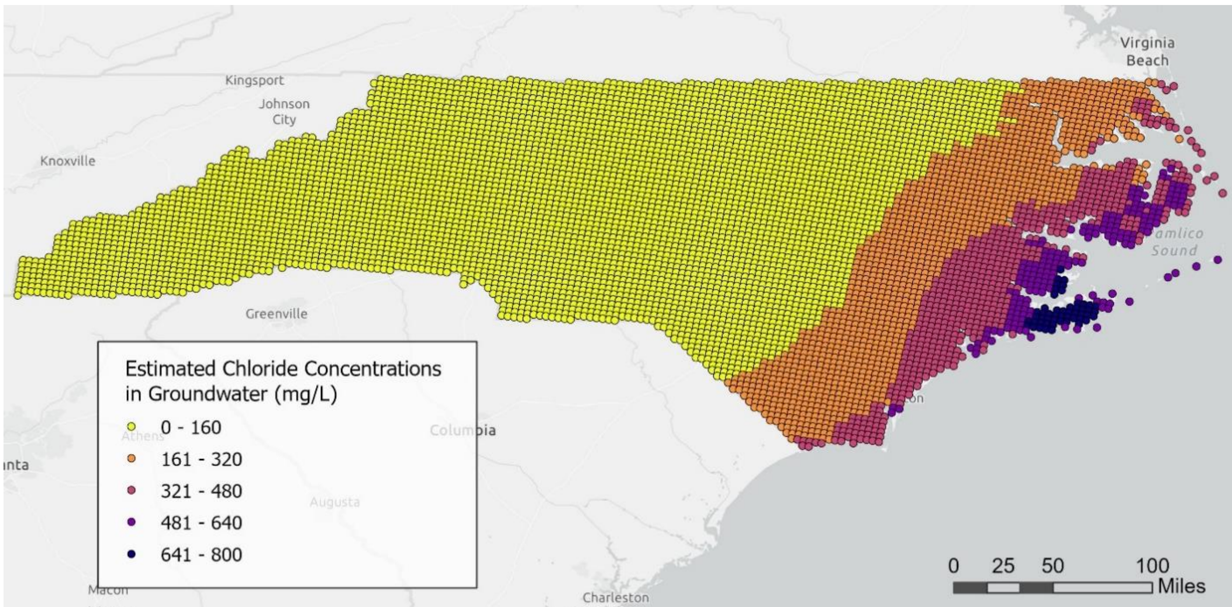


Figure 22. Estimated groundwater chloride concentrations in North Carolina.

The data shown in **Figure 23** is a histogram depicting the distribution of groundwater chloride levels across the state. The data plot is skewed towards the lower end of concentration vales and conforms to a lognormal distribution form. For the analyses herein, however the higher chloride concentration of 600 mg/l will be used since its occurrence in the Coastal Plain area is noted from **Figure 22**.

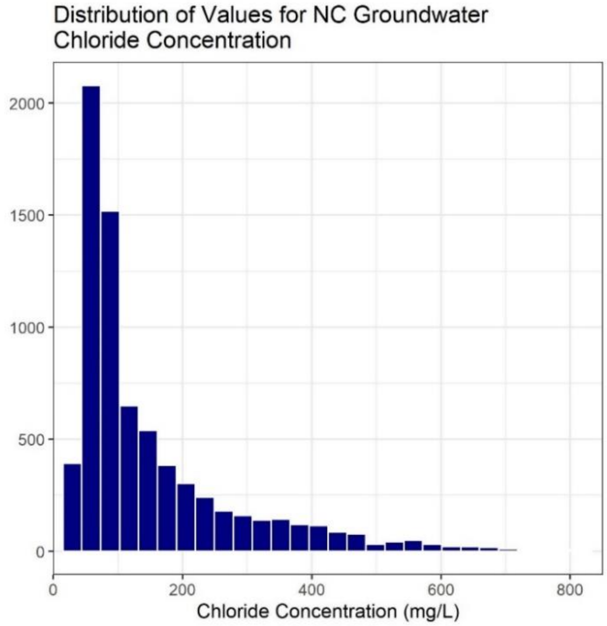


Figure 23. Frequency of chloride concentration level occurrence across North Carolina.

4.3. Modeling Approach

Solute transport through porous media is defined by two distinct mechanisms, advection and dispersion. Advection occurs when groundwater flow carries solutes through a flow domain. Dispersion, on the other hand, occurs when solutes mix with local groundwater. Specifically, dispersion occurs when solute molecules spread unevenly, which alters the degree of solute mixing (and transport) throughout the system. Often, both advective and dispersive processes occur simultaneously and influence the rate and magnitude of solute transport within the porous media. The governing equation by Ogata and Banks (1961) [6] provides the basis for the 1-D model incorporating advection-dispersion transport in porous media. **Equation (2)** models the time (t) it takes for a specified chloride concentration (C) to travel a certain distance (x).

$$C(x,t) = \frac{C_0}{2}\left[erfc\left(\frac{x - v_x t}{2\sqrt{D_x t}}\right) - \exp\left(\frac{v_x x}{D_x}\right) erfc\left(\frac{x + v_x t}{2\sqrt{D_x t}}\right)\right] \qquad \text{Equation (2)}$$

Where:

$$erfc(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-u^2}du;\ v_x = \frac{(k \times i)}{n};\ D_x = a_x v_x + D^*$$

$$D^* = \tau \times D_d; D_x = a_x v_x + D^*; D^* = \tau \times D_d$$

The definition of each parameter specified in **Equation (2)** is shown in **Table 8**.

Table 8. Parameter definitions.

Parameters	Definitions
C_0	Initial chloride concentration (e.g. mg/l)
x	Location down-gradient of the source
v_x	Seepage velocity (e.g., m/sec)
D_x	Hydrodynamic dispersion coefficient (e.g., m^2/s)
t	Time (e.g., sec)
k	Hydraulic conductivity (e,g., m/sec)
i	Hydraulic gradient (e.g., m per m)
n	Effective porosity (unitless)
a_x	Dispersivity (e.g., m)
D^*	Effective diffusion (e.g, m^2/s)
τ	Tortuosity (unitless)-accounts for the random pores network distribution within soil matrix.
D_d	Diffusion coefficient including Tortuosity (e.g., m^2/s)

4.4. Modeling Scenarios

The transport of chloride in the subsurface was modeled as a base case and scenarios representing mitigation measures (with various iterations for each). The four mitigation measures considered herein include the use of flowable fill, compacted clay lining of the trench, geosynthetic clay liner, and synthetic polymeric membrane liners.

For all scenarios, the initial chloride concentration (C_0) was set to 600 mg/L (i.e., extreme case; representative of NC coastal region, from the 19 years of chloride deposition data in PASS). The modeling objective was to estimate the time (t) it takes to achieve 5% of "Co" chloride concentration breaking through into the pipe trench (i.e. C/C_0 = 5%, or C = 30 mg/L) at a location "x" representing the location of the pipe within the trench. The 30 mg/L concentration was a conservative selection. In **Figure 24**, Uhlig and Revie (1985) have shown that as the concentration of the chloride in solution increases above zero, the corrosion rate in parallel increases; as the chloride concentration reaches 3% by weight (30,000 mg/L), the highest corrosion rate is reached and then the rate begins to decrease with an increase in concentration beyond 3% [9]. In the modeling herein a 30 mg/L of chloride solution (i.e. 0.1% of the 3% chloride concentration corresponding to the highest corrosion rate) is used to represent the onset of the corrosion process within the pipe trench.

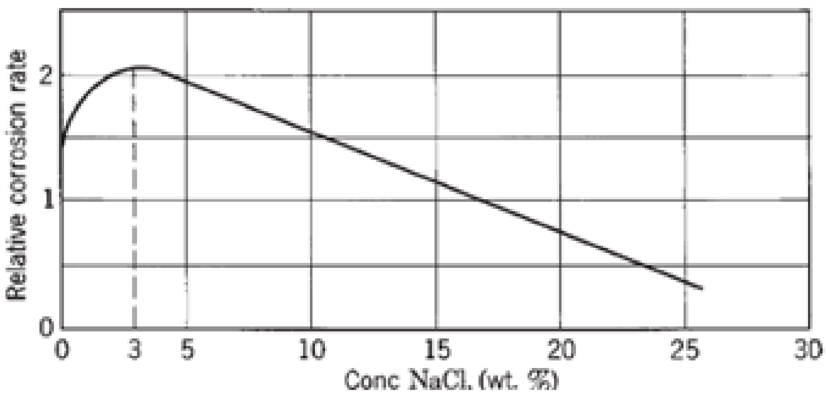


Figure 24. Effect of sodium chloride concentrations on iron pipe corrosion [9].

4.4. Mitigation Strategies

As mentioned earlier, the four mitigation scenarios considered herein include flowable fill, synthetic liner, and compacted clay lining of the trench. Several factors influence chloride transport with the use of flowable fill, synthetic liners, and compacted clay lining of the trench to retard the ingress of the chloride solution into the pipe trench. These factors include the distance a chloride ion travels (distance), the mitigation approach's hydraulic conductivity (seepage resistance to flow), the potential damage of the approach during installation, and the hydraulic gradient driving the flow. **Table 9** summarizes these unique inputs for each scenario.

To demonstrate the efficacy of a mitigation measure, a baseline scenario (Base Case) with a hydraulic conductivity of 1.0 x 10-7 m/s and a gradient of 0.01 (i.e. 1%) was utilized in the analyses. The "base case" scenario is taken to represent an unmitigated flow situation. In the case of the lined system, the distance (x) a chloride travels and breaks through into the pipe trench is assumed to be the same as the thickness of the liner itself. To estimate the hydraulic gradient of flow toward the pipe trench, we made a simplifying assumption of the water level difference between the outside and inside of the trench is = 6 inches (0.153 m).

Table 9. Input parameters depicting the hydraulic parameters used in the transport model.

Lined Mitigation Strategy	Inches (m)	Hydraulic Conductivity (m/s)	Gradient (length/length)
Based case (unmitigated flow)	-	1×10^{-7}	0.01

Flowable fill	-	1 x 10^{-8}	0.001
			0.01
			0.1
Compacted clay: intact	6 (0.1524)	1 x 10^{-10}	1
Compacted clay: defective	6 (0.1524)	1 x 10^{-9}	1
GCL: intact	0.5 (0.0127)	1 x 10^{-12}	12
GCL: defective	0.5 (0.0127)	1 x 10^{-11}	12
Membrane: intact	0.06 (0.0015)	1 x 10^{-14}	100
Membrane: defective	0.06 (0.0015)	1 x 10^{-13}	100

4.4.1. Flowable Fill

Flowable fill is an alternative backfill known for its high compressive strength. Flowable fill is composed of water, cement, fly ash, and fine aggregates, although the mix proportions vary [10]. Among its many advantages (high strength, low compressibility, low cost), flowable fill is also favorable because of its relatively low permeability compared to granular soils. Permeability values for flowable fill typically range from 1 x 10-6 m/s to 1 x 10-9 m/s [11,12]. Typically, flowable fills with a higher proportion of fines will have a lower permeability [13]. Low permeability reduces flow of contaminants from the external environment to the pipe, increasing pipe longevity.

4.4.2. Clay Liners

Installation of Compacted clay liners (CCLs) as a part of the pipe trench construction will necessitate that the side slopes will be relatively flat, CCLs are constructed from native soils or mixing soils with bentonite clay to obtain a low permeability value. If clay material is locally available, they can be cost-effective solutions as lining layers. The permeabilities of clay liners typically range between 1 x 10^{-9} to 1 x 10^{-10} m/s and have minimum thickness of 6” (0.157 m) to accommodate the construction process. While CCLs have relative low permeability value, they are susceptible to damage from freeze-thaw cycles and desiccation cracking, per Koerner and Daniel (2020) [14].

Geosynthetic clay liners (GCLs) are another type of clay barrier that can mitigate liquid migration. Essentially, GCLs are constructed by sandwiching a layer of bentonite clay between two layers of geotextiles. GCLs are often used to mitigate pollutant transport to the environment, particularly in landfills, reservoirs, and around underground storage tanks. GCLs are laid side-by-side with a certain amount of overlap to minimize leaks between layers. A key advantage of GCLs is their ability to self-heal after experiencing freeze-thaw cycles and desiccation. GCLs are not undamageable, however; because they are relatively thin (as little as 0.2" or 0.0508 m) thick, they are susceptible to damage from punctures and inadequate overlap of seams, especially during installation. Also, failure to install GCLs with adequate overlay distance at the seams can result in increased permeability [14]. Hydraulic permeabilities (k) of GCLs average between 1 x 10^{-10} and 1 x 10^{-12} m/s.

4.4.3. Synthetic Membrane Liners (also referred to as Flexible Membrane Liners)

Polymeric membrane liners, also referred to as "geomembranes," are defined by ASTM D5889 as, "a low permeability synthetic membrane liner or barrier used with any geotechnical engineering-related material so as to control fluid (or gas) migration in a human-made project, structure or system" [15]. Membrane liners are constructed from very thin sheets of polymeric synthetic resins. Membrane liners hydraulic conductivities, assuming no installation damages, range from 1 x 10^{-12} to 1 x 10^{-15} m/s.

Table 10. Hydraulic conductivity values of mitigation measured used in modeling.

Mitigation measures	**Values in m/s (ft/min)**
Flowable fill	1.00×10^{-7} (1.97×10^{-5})
Clay lining	1.00×10^{-8}, 1.00×10^{-9}, 1.00×10^{-10}, and 1.00×10^{-11} (1.97×10^{-6}, 1.97×10^{-7}, 1.97×10^{-8}, and 1.97×10^{-9})
Membrane lining	$1.00\times10^{-11}$and 11.00×10^{-12} (1.97×10^{-9}, 1.97×10^{-10})

4.5. Analysis Cases

We modeled five unique scenarios: an unmitigated "Base Case" scenario, Flowable Fill backfill, CCL system, GCL system, and Membrane-Lined system. For the Flowable Fill scenario, we modeled chloride accumulation for three different groundwater hydraulic gradients of 0.001 (0.1%), 0.01 (1%), and 0.1 (10%). For the CCL, GCL, and Membrane-Lined systems, we also modeled scenarios for intact versus defective liners. Our modeled scenarios are summarized as follows:

- Base case
- Flowable Fill *(0.1%, 1%, and 10%)*

- CCL (*both intact and defective)*
- GCL (*both intact and defective)*
- Membrane-Lined *(both intact and defective)*

In addition, the following simplifying assumptions were made to facilitate the use of the one-dimensional model:

i) Chloride flow occurs in one dimension (x)

ii) Chloride breakthrough is occurring along the total length of the pipe trench.

iii) Hydraulic gradients remain constant with time.

iv) The trench backfill is initially chloride-free.

v) The width of the trench *(excluding additional width for the pipe)* is 3 ft, in accordance with NCDOT standards (Division 03 Pipe Culverts.pdf (ncdot.gov))

vi) The soil porosity (n) is 0.25.

The approach of modeling chloride transport differed for unlined systems (*base case scenario, flowable fill)* versus lined systems (*clay-lined, membrane-lined)*. For unlined systems, a mass flux breakthrough into the pipe trench was used to compute the time it took for the water inside the trench to reach the critical concentration threshold of 30 mg/L assumed herein. For lined systems, chloride solute flow was modeled in two steps. In step one, the fixed-gradient advection-dispersion equation was used to model chloride solute flow through a given lining type. In step two, a mass flux model was used to estimate the time it took for the water inside the trench to reach the critical chloride concentration. These two approaches are described in detail in the sections below.

4.5.1. Unlined Systems

For both the Base Case and the Flowable Fill scenarios, a mass flux model was used to estimate the time required for the water inside the pipe trench to reach the specified critical concentration threshold of 30 mg/L. **Figure 25** shows a schematic of an unlined system.

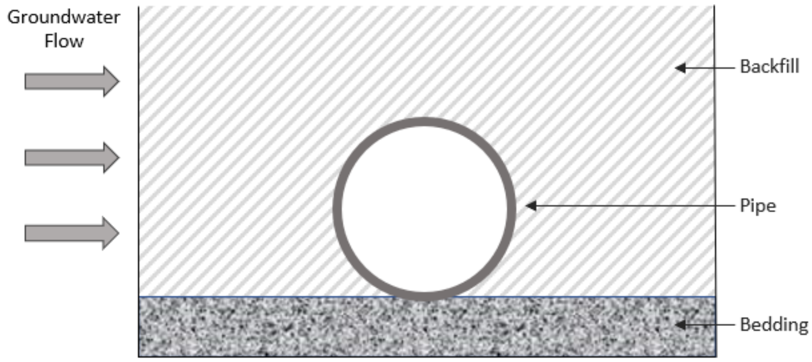


Figure 25. An unlined, in-ground pipe system; it is not drawn to scale.

The following procedure was used to estimate the chloride mass flux into the trench and demonstrate how the solute concentration is computed. Note that these methods were also used for step two of the lined systems model:

i. First, the groundwater flow rate (Q)was calculated as $Q\_ = (k \times i)/n \times (A \times n)$

k = hydraulic conductivity of the backfill, i = hydraulic gradient, n= soil porosity, and A = cross-sectional area of the trench boundary, assumed to be 1 ft x 1 ft

ii. Next, the volume of groundwater entering the trench for a particular timestep was found:

$V\_i = Q(t\_i - t\_(i-1))$, V_i = volume of groundwater entering the trench at timestep "i"

t_i = timestep

Accordingly, the mass of chloride entering the trench for each timestep (m_i) was computed and then summed to compute the mass breaking through the trench per given time period.

$\sum m\_i = V\_i \times Co$

The total chloride mass inside the trench was calculated for each timestep, and this was tracked until the trench concentration reached the critical corrosive threshold of 30 mg/L. The trench was assumed to have a pure water volume of 0.75 ft^3 (21.25 L), per ft of length and assuming 1 ft of water ponding inside the trench:

$1\,ft \times 1\,ft \times 3\,ft \times 0.25 = 0.75\,ft^3$

$C = (\sum m_i) / (21.25\ L)$

For the Base Case scenario, a hydraulic conductivity of 1.0 x 10^{-7} m/s and a gradient of 0.01 (1%) were assumed. For the Flowable Fill scenario, a hydraulic conductivity of 1.0 x 10^{-8} m/s was assumed, and three different gradients were modeled: 0.1%, 1%, and 10%.

4.5.2. Lined Systems

The lined systems (CCLs, GCLs, and Membrane-Lined) were modeled in two steps. The first step used the advective-dispersion equation to model chloride transport through the trench liner, and the second step used a mass flux approach, described above, to model chloride accumulation inside the pipe trench. **Figure 26** shows a generic schematic of a lined trench system.

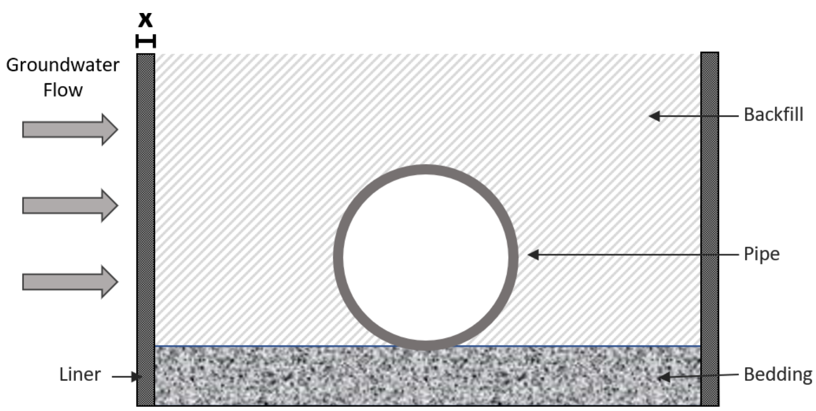


Figure 26. A lined, in-ground pipe trench system.

Step one of the approaches modeled chloride solute ingresses into the trench liner system using **Equation (2)**. In addition, the dispersity (α) of the transported solute depends on the length of the flow path (x). Neuman (1990) [16] concluded that for systems shorter than 100 m, dispersity and flow path can be described using **equation (3)**:

$\alpha\_x = 0.0169\ (x)^{1.53}$ Equation (3)

Table 11 summarizes the magnitude of the parameters that were held constants for all lined systems.

Table 11. Parameters used for all lined scenarios.

C_0	Initial Chloride Concentration	600	mg/L
$C(x,t)$	Final Chloride Concentration at location x	30	mg/L
n	Porosity	0.25	--
D_d	Diffusion Coefficient	2.03×10^{-9}	m^2/s
τ	Tortuosity	0.15	--

Input parameters including the distance (x), hydraulic permeability (k), and the hydraulic gradient (i) were unique to each lined scenario. **Table 12** summarizes these input parameters for each lined mitigation scenario. The distance chloride traveled (x) corresponds to the assumed thickness of the liner, and thereby the relatively high hydraulic gradient values in **Table 12**. The hydraulic gradient across the liner was assumed to increase as liner permeability decreased; thus, membrane-liners are modeled with the highest gradient, GCLs a moderate gradient, and CCLs the lowest gradient. Also, for the intact versus defective scenarios, defective liners were assumed to have higher hydraulic conductivities by one order of magnitude.

Table 12. Unique inputs for lined scenarios.

Lined Mitigation Strategy	**x** (in)	**Hydraulic Conductivity** (m/s)	**Gradient (length/length)**
Clay Liners			
Compacted Clay: Intact	6	1×10^{-10}	1
Compacted Clay: Defective	6	1×10^{-9}	1
GCL: Intact	0.5	1×10^{-12}	12
GCL: Defective	0.5	1×10^{-11}	12
Membrane Liners			
Intact	0.06	1×10^{-14}	100
Defective	0.06	1×10^{-13}	100

Step two of the lined-systems model estimated the time it took for the chloride concentration inside the trench to reach the critical corrosive threshold. As was previously described, the chloride concentration that emerged through the liner ($C\_(x, t)$) was used to calculate the mass flux of chloride at each timestep. The mass flux methods for step two of the lined systems model are identical to the methods for step one of the unlined systems. The chloride concentration inside the trench was tracked until it reached the 30 mg/L threshold.

4.6. Results & Discussion

Figure 27 shows the time for the chloride solute to break through the trench and reaches the pipe location, without any mitigation strategies in place, and assuming a backfill hydraulic conductivity = $1x10^{-7}$ m/sec ($1.971x10^{-5}$ ft/min) and a hydraulic gradient of 0.01 (1%). without any mitigation strategies in place. The data indicates that chloride concentration can reach critical levels in a pipeline trench within a timeframe of 132 days under the conditions specified in the base case scenario.

In comparison, the results for the case of utilizing flowable fill as the backfill of the pipe trench is shown in **Figure 28**. The results indicated that depending on the hydraulic gradient driving the solute toward the trench, the time to reach critical chloride concentration can increase by one order of magnitude compared to the base case under the hydraulic gradient of 1%. The time is significantly extended to over two hundred years when the site hydraulic gradient is 0.1% was assumed in the analyses. Depending on the magnitude of hydraulic gradient, using flowable fill as a backfill material can significantly extend, the time it takes for chloride ions to reach critical concentrations in a pipeline trench and extend service life by reducing chloride-induced corrosion.

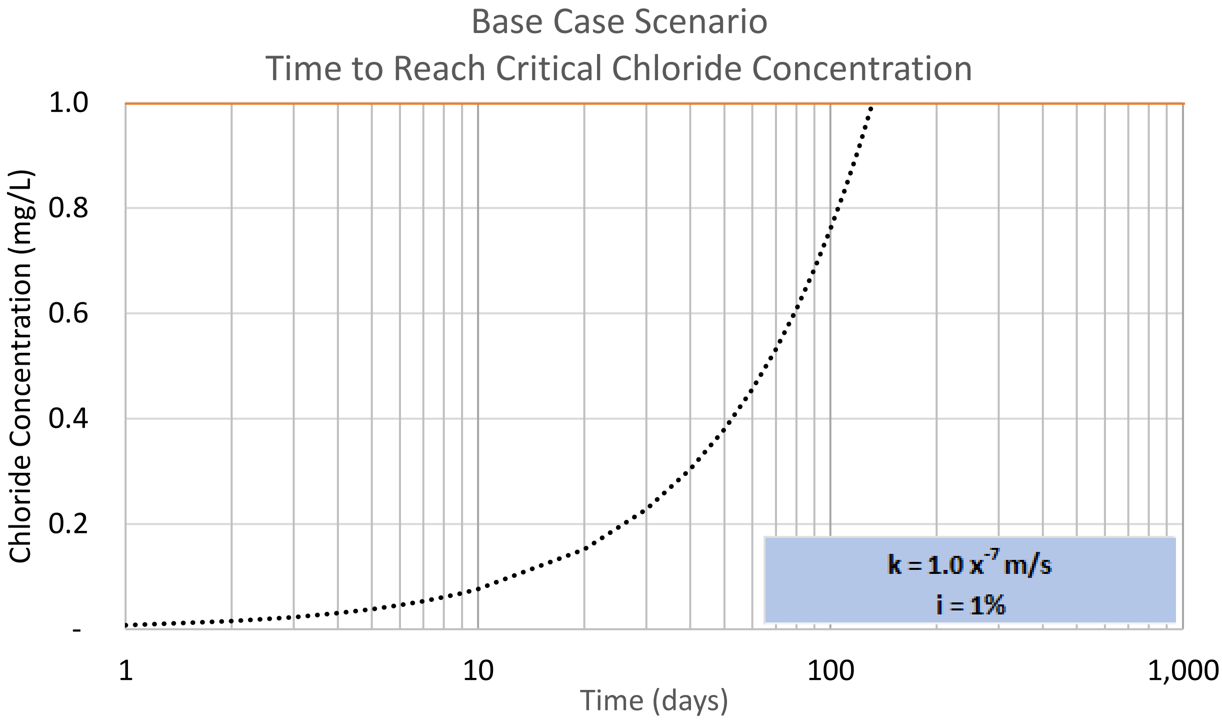


Figure 27. Case with pipe trench filled with select fill with no provision for mitigation measure.

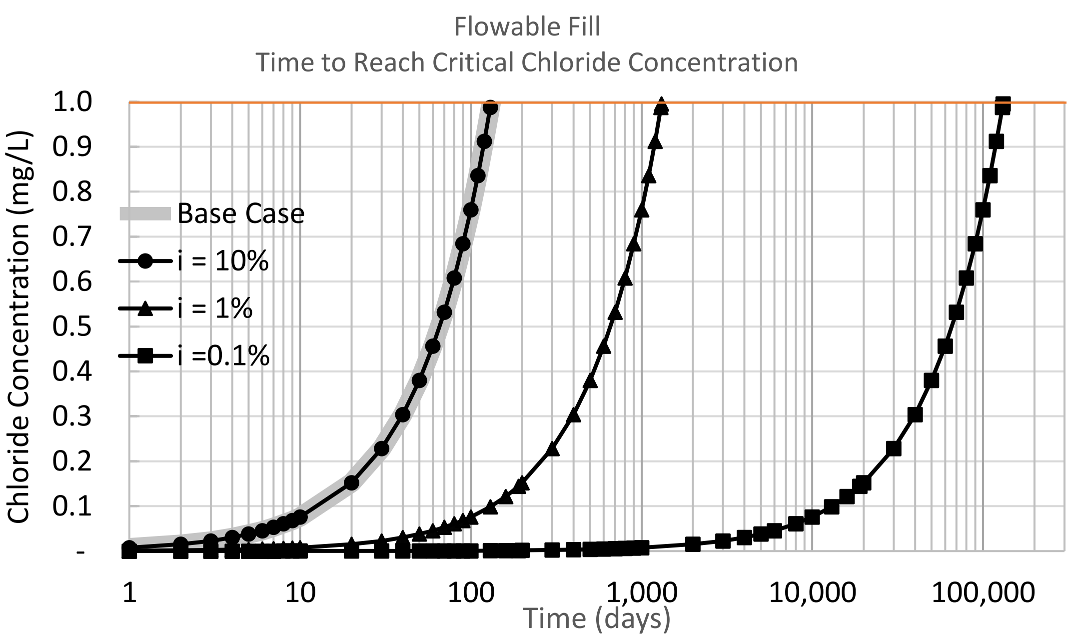


Figure 28. Case with flowable fill used as pipe trench backfill.

As discussed earlier, the use of clay liner can be in the form of CCL or GCL. As shown in **Figure 29**, the use of the CCL also demonstrates a substantial improvement over the base case in terms of delaying the time to chloride concentrations inside the trench leading to the onset of accelerated corrosion rate. Under the hydraulic gradient magnitude of 100% (i.e. 6 inches of water ponding outside the trench and 6 inches of flow path,) and assuming the CCL does not experience desiccation cracking, the critical concentration is reached in 8000 days compared to less than 1300 days in the case of utilizing flowable fill. The use of CCL, however, is not as effective as flowable fill if desiccation cracking occurs leading to an increase in the permeability by one order of magnitude. In this case, the time to reach the critical chloride concentrations is on the order of 500 days.

As the thickness of the mitigation measure, in the form of trench lining layer, decreases the hydraulic gradient significantly increases. The lining system including GCL, and flexible membrane liners provide the advantages of relatively less labor-intensive installation, quality assurance of the material conducted by the manufacturer, and the benefit of accumulate performance data over the years.

Under a gradient of 12% and permeability of 1 x 10-12 m/sec (see **Table 12**), the results of utilizing intact GCL, and GCL with potential defects are show in **Figure 30**. Even with assuming the GCL permeability to increase by one order of magnitude, the time to reach critical chloride concentration is on the order of 5000 days, which is five times the estimated time with the use of flowable fill as the backfill for the pipe trench.

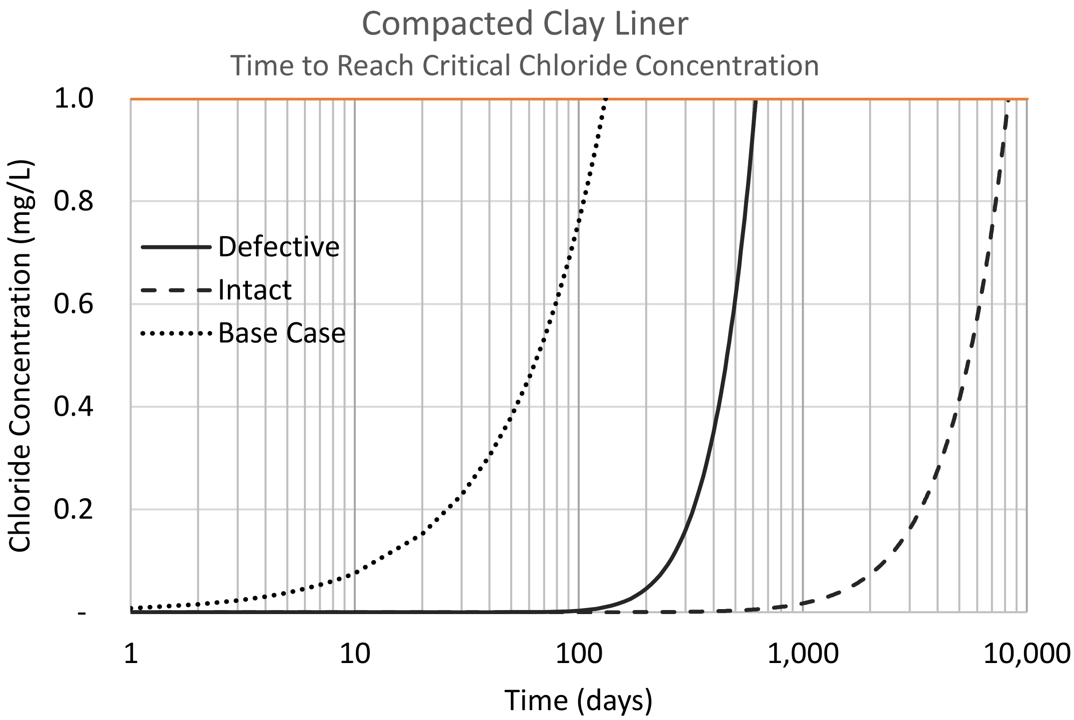


Figure 29. Case of lining the pipe trench with a 6- inch layer of compacted clay.

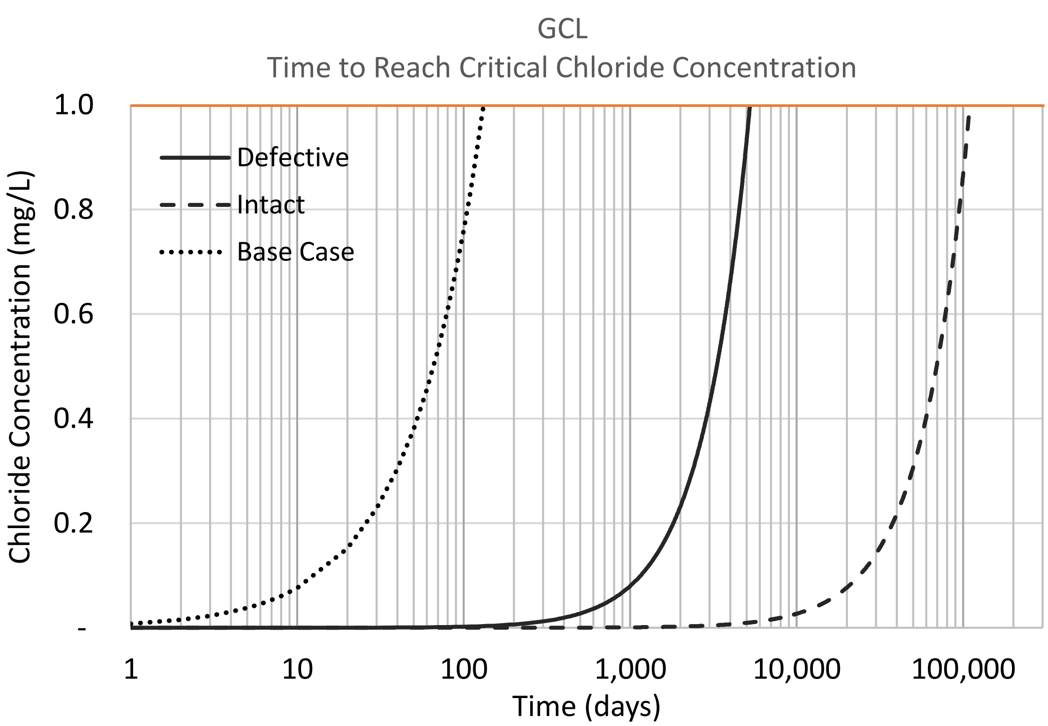


Figure 30. Case with geosynthetic clay liner as lining material for the pipe trench.

Flexible membranes provide the lowest hydraulic conductivity when properly installed. They are easier and faster to install than GCLs. FMLs, however, are susceptible to punctures and tears during installation and may not conform well to uneven surfaces.

Figure 31 shows the performance of chloride solute breakthrough time when flexible membrane is installed. Given the model assumptions and limitation, the data suggests that if the membrane is intact, no chloride breakthrough is observed in 130,000 days (~356 years); this is approximately the same time for the chloride concentration to reach critical levels if the liner is assumed to be defective such that the hydraulic conductivity is increased by one order of magnitude (i.e. from 1 x 10^{-14} to 1 x 1 x 10^{-13} m/sec.)

While using a flexible membrane as a trench liner yielded the longest time for chloride ions to reach critical concentrations in the pipeline trench, service life of polymeric membranes is governed by other environmental factors. Rowe and Ewais (2015) [17] explored how climate impacts the degradation of exposed high-density polyethylene (HDPE) membranes by examining membranes exposed at two locations for varying durations: nearly 16 years in a warm-hot climate slope at a mine facility, and 6 years in a mild-cold climate at a research site. The results revealed faster depletion of antioxidants (and therefore degradation in membrane properties) at the warm-hot slope compared to exposure at the research site. Accordingly, the authors concluded that the research site's membrane (exposed to a milder climate) is estimated to have an antioxidant depletion time between 20 and 54 years, while the membrane at the mine facilities (warmer climate) reached their nominal failure point based on stress crack resistance (SCR) but did not actually rupture. The most literature on lifetime of polymeric membranes however comes from the use of membranes in liner systems of landfills. As membranes are made of synthetic polymer chains, yield strength and SCR are most affected by aging. With time and depending on exposure conditions, a SCR significantly decreases from its initial value (i.e. the value at the time the membrane was manufactured) with a wide range of SCR reduction across the different polymer type from which a given membrane is made (e.g. polyethylene versus polypropylene.) An average decrease of 63% from the initial value was reported by Rowe et al (2019) [18]. More recently, Rowe et al (2024) [19] examined the effect of textured versus smooth membrane surface on the integrity of high-density polyethylene (HDPE) membranes immersed in synthetic municipal solid waste leachate over an approximately 8-year period. The results show significantly faster antioxidant depletion (and therefore faster degradation in properties) in the textured portion compared to the smooth edge. The authors estimated nominal failure of membrane was reached at 75°C after six years of immersion in the simulated leachate. Combined with data obtained at 85°, the authors extrapolated the expected time to nominal failure at 40°C to be 360 years for textured HDPE membrane and 680 years for smooth HDPE membrane.

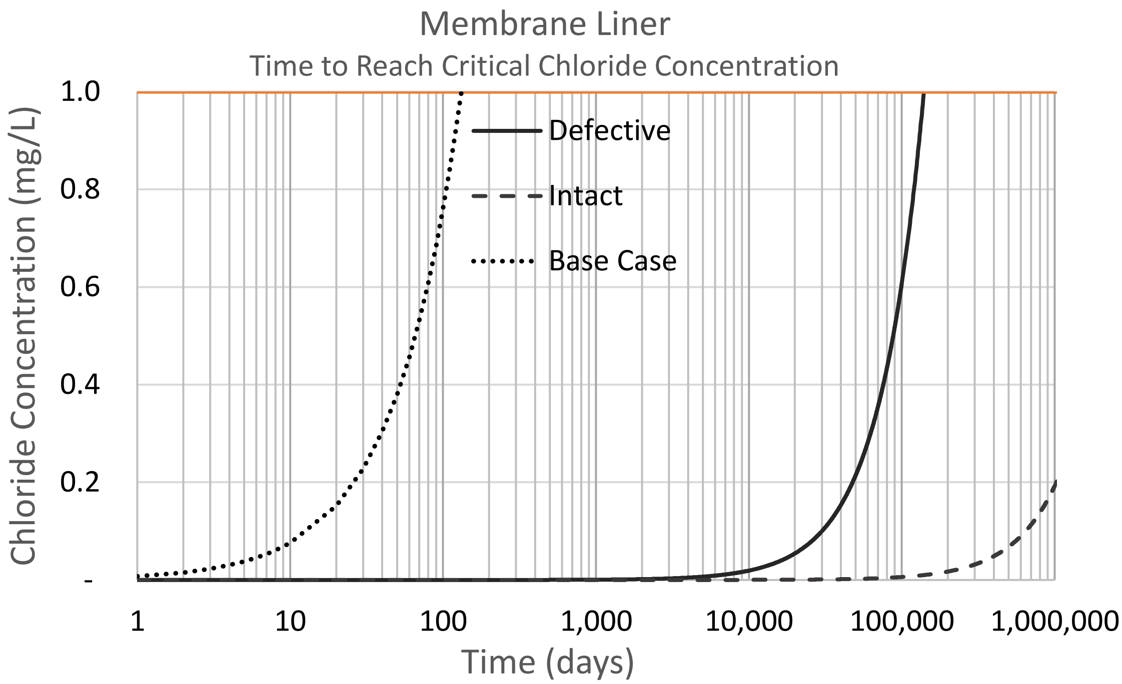


Figure 31. Case for use of polymeric membrane (flexible membrane) for lining the trench.

4.7. Summary

Work in the section investigated different methods to prevent chloride from reaching and corroding pipelines. One-dimensional (1-D) model for simulating chloride transport through porous media was utilized in the analyses. The model utilizes the Ogata and Banks (1961) [6] equation to estimate the time (t) required for a specific chloride concentration (C) to travel a defined distance (x) within the porous media. The model incorporates two principal mechanisms governing solute movement: advection and dispersion. Advection represents the bulk transport of chloride by the flowing groundwater, and dispersion accounts for the mixing of chloride with the surrounding pore water. A summary of the results is shown in **Table 13**.

The breakthrough times for corrosive flow entering the trench, exceed 200 years for the following mitigation measures: flowable fill with a gradient of 0.1, intact GCL with a gradient of 12, intact membrane with a gradient of 100, and defective membrane with a gradient of 100). The presence of defects in the liner drastically reduces the breakthrough time. Without mitigation strategies in place, chloride can reach critical levels within a short timeframe (around 132 days) under the assumed conditions. Flowable fill, used as a backfill material, can increase this timeframe by an order of magnitude depending on the hydraulic gradient driving the flow toward the pipe trench. Lining the trench with compacted clay (CCL) also offers substantial improvement, but its effectiveness can be substantially reduced if the clay is susceptible to desiccation cracking. Geosynthetic clay liners (GCLs) and Flexible membrane liners (FMLs) offer the lowest long-term mitigation when properly installed.

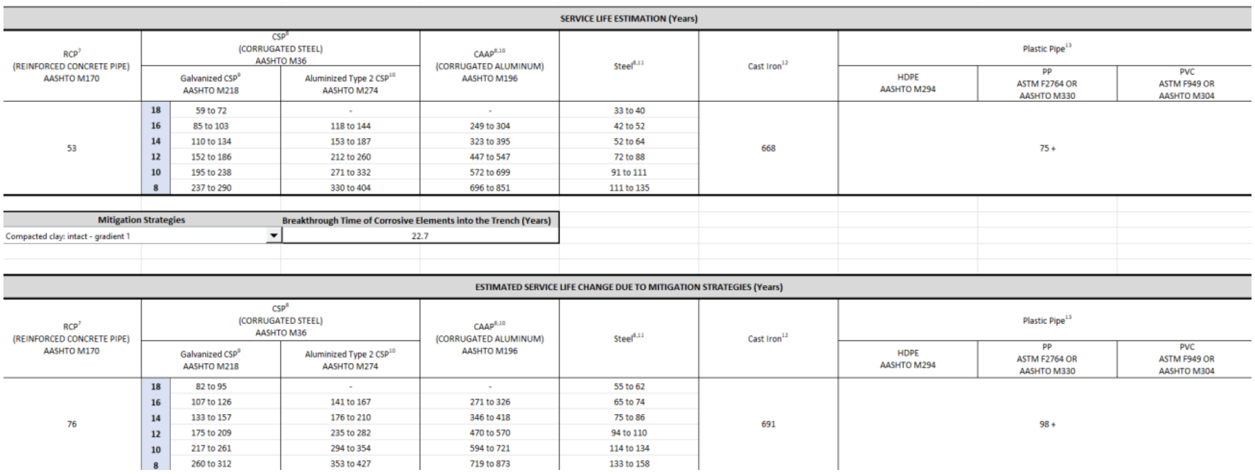
For critical applications or those with severe chloride exposure, an intact GCL might be preferred due to its potential “self-healing” feature. However, if ease of installation is a major concern, flexible membranes represent the best choice given that measures are taken to minimize puncture during backfilling of the pipe trench. Aspects such as aging, environmental cracking, and degradation of flexible membrane are not normally a concern but need to be considered when deciding upon the membrane material type (e.g. high-density polyethylene versus polyvinyl chloride or propylene.)

All the mitigation strategies investigated in this study can be effective in delaying chloride transport and extending the service life of pipelines. The effectiveness of these mitigation measures is further enhanced by being less permeable than the surrounding soil media. Water will preferentially flow through the path of least resistance, and the less permeable mitigation layer will lead to diverting flow around the trench. However, the 1-D model is not capable of capturing such preferential flow paths. The model assumes uniform flow throughout the domain, and it may not accurately represent the complex flow patterns that can develop around the mitigation layer due to permeability differences. It should be noted that in addition to the 1-D modeling assumption, factors such as specific corrosion salt properties, and compact clay desiccation can all influence breakthrough times.

Table 13. Summary of modeling results in terms of time for chloride concentration to reach critical levels in pipeline trench.

Mitigation Strategy	**x** (in)	**Hydraulic Conductivity** m/s (ft/min)	**Gradient** **length/length**	**Time** (d)	**Time** (y)
Base Case *Unmitigated flow*	---	1 x 10^{-7} (1.97x10^{-5})	0.01	130	0.36
Flowable Fill	---	1 x 10^{-8} (1.97x10^{-6})	0.1 0.01 0.001	130 1,310 131,000	0.36 3.6 360
Clay Liners					
Compacted Clay: Intact	6	1 x 10^{-10} (1.97x10^{-8})	1	8,280	22.7
Compacted Clay: Defective	6	1 x 10^{-9} (1.97x10^{-7})	1	617	1.69
GCL: Intact	0.5	1 x 10^{-12} (1.97x10^{-10})	12	109,000	300
GCL: Defective	0.5	1 x 10^{-11} (1.97x10^{-9})	12	5,240	14.4
Membrane Liners					
Intact	0.06	1 x 10^{-14} (1.97x10^{-12})	100	2,990,000	8,192
Defective	0.06	1 x 10^{-13} (1.97x10^{-11})	100	139,000	381

Based on the modeling results, the "Pipe Material Selection Guide" section has been updated, as shown in **Figure 32**. Users can now select mitigation strategies with varying gradients, as detailed in **Figure 33**. The breakthrough time of corrosive elements into the trench, measured in years, will be automatically updated. The estimated service life and the breakthrough time will be added and displayed in the section titled "Estimated Service Life Change due to Mitigation Strategies (years)". To maintain practical relevance in long-term planning, any breakthrough times exceeding 200 years are capped at 200 years, as illustrated in **Figure 34**. **Figure 35** shows the auto-calculation of the estimated service life due to mitigation strategies. The values in the green highlighted boxes are summed up, and the results are displayed in the red highlighted box.



SERVICE LIFE ESTIMATION (Years)

RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
53	18	59 to 72	-	-	33 to 40	668	75 +		
	16	85 to 103	118 to 144	249 to 304	42 to 52				
	14	110 to 134	153 to 187	323 to 395	52 to 64				
	12	152 to 186	212 to 260	447 to 547	72 to 88				
	10	195 to 238	271 to 332	572 to 699	91 to 111				
	8	237 to 290	330 to 404	696 to 851	111 to 135				

Mitigation Strategies	Breakthrough Time of Corrosive Elements into the Trench (Years)
Compacted clay: intact - gradient 1	22.7

ESTIMATED SERVICE LIFE CHANGE DUE TO MITIGATION STRATEGIES (Years)

RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
76	18	82 to 95	-	-	55 to 62	691	98 +		
	16	107 to 126	141 to 167	271 to 326	65 to 74				
	14	133 to 157	176 to 210	346 to 418	75 to 86				
	12	175 to 209	235 to 282	470 to 570	94 to 110				
	10	217 to 261	294 to 354	594 to 721	114 to 134				
	8	260 to 312	353 to 427	719 to 873	133 to 158				

Figure 32. Updated user interface of "Pipe material selection guide" section.

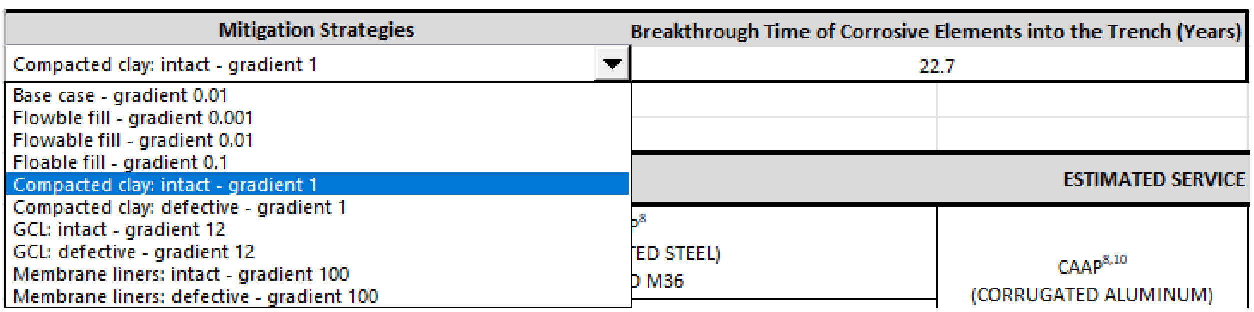


Figure 33. Updated mitigation strategies section.

Mitigation strategies and expected additional service life

Mitigation Strategies	Hydraulic Gradient	Breakthrough Time of Corrosive Elements into the Trench (Years)
Base case	0.01	0.36
Flowable fill	0.001	200
Flowable fill	0.01	3.6
Flowable fill	0.1	0.36
Compacted clay: intact	1	22.7
Compacted clay: defective	1	1.69
GCL: Intact	12	200
GCL: Defective	12	14.4
Membrane: intact	100	200
Membrane: defective	100	200

Figure 34. Updated reference tab based on the results in **Table 13**.

SERVICE LIFE ESTIMATION (Years)

RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
53	18	59 to 72	-	-	33 to 40	668	75 +		
	16	85 to 103	118 to 144	249 to 304	42 to 52				
	14	110 to 134	153 to 187	323 to 395	52 to 64				
	12	152 to 186	212 to 260	447 to 547	72 to 88				
	10	195 to 238	271 to 332	572 to 699	91 to 111				
	8	237 to 290	330 to 404	696 to 851	111 to 135				

Mitigation Strategies	Breakthrough Time of Corrosive Elements into the Trench (Years)
GCL: defective - gradient 12	14.4

ESTIMATED SERVICE LIFE CHANGE DUE TO MITIGATION STRATEGIES (Years)

RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
68	18	74 to 87	-	-	47 to 54	682	89 +		
	16	99 to 118	132 to 159	263 to 318	57 to 66				
	14	124 to 149	168 to 202	338 to 409	66 to 78				
	12	167 to 201	227 to 274	462 to 561	86 to 102				
	10	209 to 252	286 to 346	586 to 713	106 to 126				
	8	251 to 304	345 to 418	710 to 865	125 to 150				

Figure 35. Auto-calculation of estimated service life due to mitigation strategies.

6. Findings and Conclusions

This research project has successfully integrated essential structural requirements and advanced repair/rehabilitation methodologies into the PASS software, aligning it closely with NCDOT's operational needs. Through detailed analysis and integration, the software now offers:

- Dynamic Adjustment Capabilities: Incorporating NCDOT's current structural requirements enables the software to dynamically adjust based on user inputs, significantly enhancing its utility for project planning.

- Expanded Repair Options: The software now includes a comprehensive catalog of both historical and contemporary repair methods, allowing for systematic evaluation against various pipe materials.
- Decision Support System: Utilizing a weighted average method, based on detailed performance criteria, allows users to prioritize based on critical factors specific to each project, enhancing decision-making accuracy.
- Mitigation Strategy Modeling: New mitigation strategies have been modeled and integrated to combat subsurface exposure factors, crucial for extending the service life of infrastructures such as pipes.
- Validation and Practical Application: The enhancements have been validated through field applications and feedback from NCDOT, affirming the software's effectiveness in improving infrastructure resilience and longevity.

The integration of detailed structural requirements and comprehensive repair strategies into the PASS software represents a significant advancement in the tools available to NCDOT engineers and planners. This project has not only enhanced the functionality of the PASS software but has also established a robust framework for ongoing improvements and updates. The enhanced PASS software is now better equipped to support the planning, maintenance, and enhancement of transportation infrastructure, ultimately contributing to more durable and cost-effective infrastructure solutions across North Carolina. The continuous application and iterative refinement of this software will ensure that it remains an essential component of NCDOT's infrastructure management toolkit, leading to improved decision-making and longer-lasting infrastructure.

Overall, the enhancements are expected to augment the versatility of the final software, transforming it into a comprehensive tool that addresses both material selection and repair strategy considerations for transportation infrastructure in North Carolina.

7. Recommendations

We recommend:

- Using Pipe Assessment and Selection Software (PASS), which was developed in consultation with NCDOT. This software estimates the service life of different pipes under various exposure conditions.
- Applying PASS with actual field-measured data (pH, resistivity, and chloride content). If such measurements are unavailable, GPS coordinates provide an alternative method for retrieving input parameters.
- Utilizing the reconstructed "Structural Requirements" tab incorporated into PASS. When users click on the orange-colored cells, a variety of options will appear in drop-down menus.
- Employing the weighted average method included in PASS. After selecting parameters and determining custom weights, the calculated overall scores and applicable alternatives will be displayed adjacent to the criteria section.
- Using the "Estimated Service Life Change due to Mitigation Strategies" section. The breakthrough time of corrosive elements into the trench, measured in years, will be automatically updated. The estimated service life and breakthrough time will be added and displayed in the section titled "Estimated Service Life Change due to Mitigation Strategies (years)".

8. Implementation and Technology Transfer Plan

The major outcomes of the present project are: (i) the Pipe Assessment and Selection Software (PASS) and (ii) a training video. Both are implementation-ready and programmed in an Excel spreadsheet, making them ready for use by NCDOT. The training video is designed to expedite training and implementation. To ensure continuous improvement, PASS will receive regular updates and upgrades based on user feedback and technological advancements. Additionally, the research team will provide ongoing training to keep users informed about the latest features and best practices.

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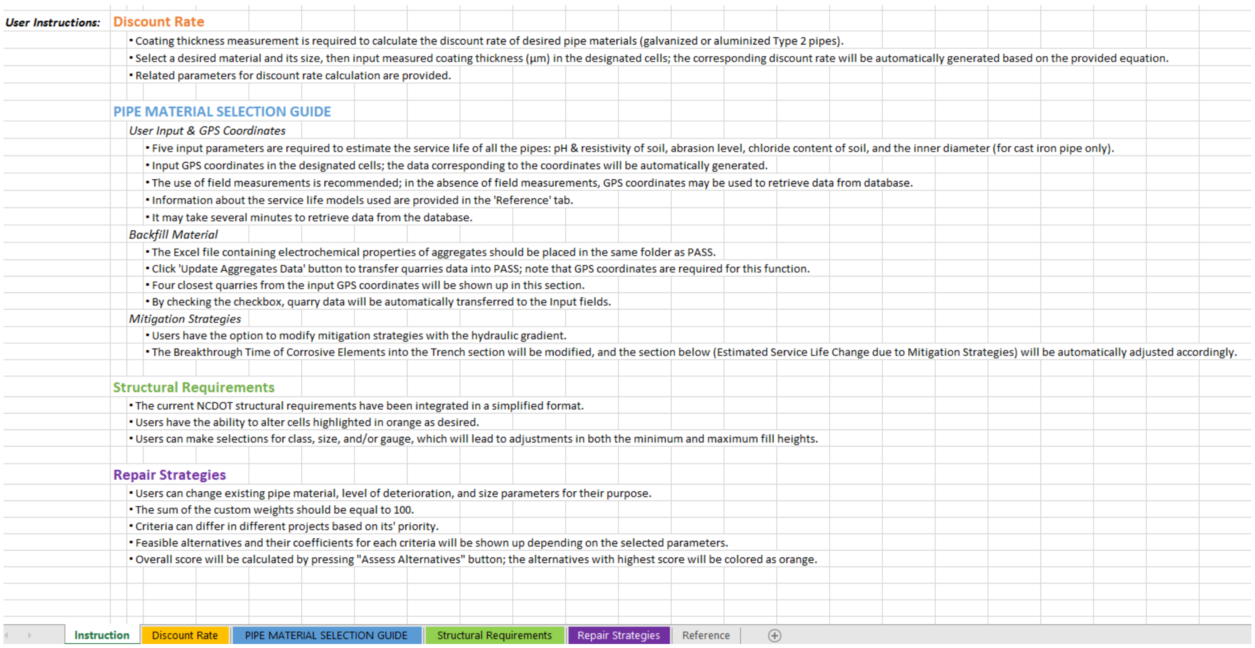
APPENDIX:
PASS user manual

Usage of PASS – instruction and reference tab:

PASS consists of six different tabs: instruction, discount rate, pipe material selection guide, structural requirements, repair strategies, and references. **Figure 1** displays the instruction tab, which provides a brief overview of the PASS program. The references tab, shown in **Figure 2**, contains the information used to develop each tab.



User Instructions: Discount Rate

- Coating thickness measurement is required to calculate the discount rate of desired pipe materials (galvanized or aluminized Type 2 pipes).
- Select a desired material and its size, then input measured coating thickness (μm) in the designated cells; the corresponding discount rate will be automatically generated based on the provided equation.
- Related parameters for discount rate calculation are provided.

PIPE MATERIAL SELECTION GUIDE

User Input & GPS Coordinates

- Five input parameters are required to estimate the service life of all the pipes: pH & resistivity of soil, abrasion level, chloride content of soil, and the inner diameter (for cast iron pipe only).
- Input GPS coordinates in the designated cells; the data corresponding to the coordinates will be automatically generated.
- The use of field measurements is recommended; in the absence of field measurements, GPS coordinates may be used to retrieve data from database.
- Information about the service life models used are provided in the 'Reference' tab.
- It may take several minutes to retrieve data from the database.

Backfill Material

- The Excel file containing electrochemical properties of aggregates should be placed in the same folder as PASS.
- Click 'Update Aggregates Data' button to transfer quarries data into PASS; note that GPS coordinates are required for this function.
- Four closest quarries from the input GPS coordinates will be shown up in this section.
- By checking the checkbox, quarry data will be automatically transferred to the Input fields.

Mitigation Strategies

- Users have the option to modify mitigation strategies with the hydraulic gradient.
- The Breakthrough Time of Corrosive Elements into the Trench section will be modified, and the section below (Estimated Service Life Change due to Mitigation Strategies) will be automatically adjusted accordingly.

Structural Requirements

- The current NCDOT structural requirements have been integrated in a simplified format.
- Users have the ability to alter cells highlighted in orange as desired.
- Users can make selections for class, size, and/or gauge, which will lead to adjustments in both the minimum and maximum fill heights.

Repair Strategies

- Users can change existing pipe material, level of deterioration, and size parameters for their purpose.
- The sum of the custom weights should be equal to 100.
- Criteria can differ in different projects based on its' priority.
- Feasible alternatives and their coefficients for each criteria will be shown up depending on the selected parameters.
- Overall score will be calculated by pressing "Assess Alternatives" button; the alternatives with highest score will be colored as orange.

Instruction | Discount Rate | PIPE MATERIAL SELECTION GUIDE | Structural Requirements | Repair Strategies | Reference

Figure 1. Instruction tab of PASS.

Acceptable ranges for different pipe materials

Material	pH (soil)	Resistivity (Ohm-cm)	In Soil: Chloride (%)	In Soil: Sulfate (%)	Abrasion level
Reinforced concrete pipe (RCP)	5.5 < pH < 12.0	All	< 0.5	< 0.5	< 3
Galvanized CSP	3.0 < pH < 14.0	R > 2,000	< 0.2	< 0.2	< 2
Aluminized Type 2 CSP	5.0 < pH < 9.0	R > 1,500	< 0.2	< 0.2	< 2
Aluminum	4.5 < pH < 9.0	R > 1,500	< 0.5	< 0.5	< 2
Steel pipe	3.0 < pH < 14.0	R > 2,200	< 0.05	< 0.05	< 2
Cast iron pipe	5.0 < pH < 9.0	R > 2,000	< 0.05	< 0.05	< 2
Plastic (PVC, PP, HDPE)	1.25 < pH < 15.0	All	-	-	< 3

Abrasion level (FHWA)

Abrasion level (FHWA)	Degree of abrasion	General site characteristics
Level 1	Non-abrasion	No bedload regardless of velocity; or storm sewer applications
Level 2	Low abrasion	Minor bed loads of sand and gravel and velocities of 5ft./sec or less
Level 3	Moderate abrasion	Bed loads of sand and small stone or gravel with velocities between 5 and 15ft./sec
Level 4	Severe abrasion	Heavy bed loads of gravel and rock with velocities exceeding 15ft./sec

Instruction | Discount Rate | PIPE MATERIAL SELECTION GUIDE | Structural Requirements | Repair Strategies | Reference

Figure 2. Reference tab of PASS.

Usage of PASS – discount rate:

Coating thickness measurement is required to calculate the discount rate of desired pipe materials (galvanized or aluminized Type 2 pipes). An average of a minimum of 10 measurements (as opposed to 3) of coating thickness is recommended.

Figure 3 shows the platform that engineers can use to calculate the discount rate of desired pipe materials. After selecting their desired material types and sizes, the discount rate in percent will be automatically calculated in the green box once engineers input the averaged coating thickness (um) from their measurements.

Figure 4 shows the variable parameters for discount rate calculation in PASS. Different values will change according to the types and sizes of pipes.

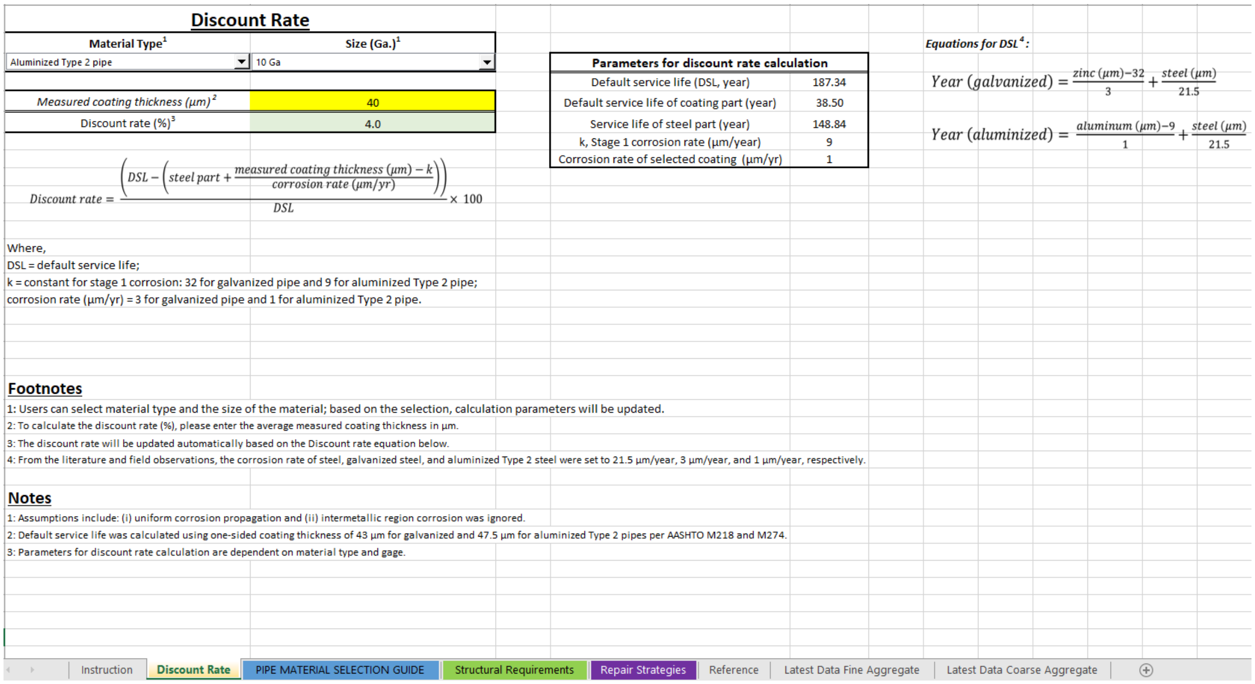


Figure 3. Discount rate calculation user interface in PASS.

Parameters for discount rate calculation	
Default service life (DSL, year)	187.34
Default service life of coating part (year)	38.50
Service life of steel part (year)	148.84
k, Stage 1 corrosion rate (µm/year)	9
Corrosion rate of selected coating (µm/yr)	1

Figure 4. Variable parameters for discount rate calculation.

Usage of PASS – Pipe material selection guide tab:

In **Figure 5**, users can input the GPS coordinates of their project in the section highlighted in a red box. It should be noted that the longitude value should be negative. By pressing the “GET the values of pH, resistivity, and chloride” button, the values for the project coordinates will be populated. For example, entering Raleigh coordinates (-78.638, 35.779) will result in a pH of 6.2, a resistivity of 10,000 ohm-cm, and a low chloride concentration, as shown in **Figure 6**. To consider abrasion and cast-iron pipes, users need to input the abrasion level and the nominal diameter (inner diameter) of the cast iron pipe, as shown in **Figure 6**. Once these values are provided, the estimated service life for different materials with various gauges will be presented in the service life estimation (year) section, as shown in **Figure 7**.

GPS COORDINATES[2]	
LONGITUDE	LATITUDE
-78.638	35.779

*Note that the value of longitude should be negative

GET the values of pH, resistivity, and chloride

USER INPUT[1]				
pH	Resistivity (ohm-cm)	Abrasion level[3]	Chloride[4]	Nominal Diameter (in) of Cast Iron[5]

Figure 5. PASS example – inputting GPS coordinates and pushing the button.

Raleigh coordinates

GPS COORDINATES[2]	
LONGITUDE	LATITUDE
-78.638	35.779

*Note that the value of longitude should be negative

GET the values of pH, resistivity, and chloride

USER INPUT[1]				
pH	Resistivity (ohm-cm)	Abrasion level[3]	Chloride[4]	Nominal Diameter (in) of Cast Iron[5]
6.2	10000	1	Low	16

Figure 6. PASS example – getting parameters and inputting abrasion level and nominal diameter (inside diameter) of cast iron pipe.

USER INPUT[1]				
pH	Resistivity (ohm-cm)	Abrasion level[3]	Chloride[4]	Nominal Diameter (in) of Cast Iron[5]
6.2	10000	1	Low	16

SERVICE LIFE ESTIMATION (Years)									
RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
33.4	**18**	49.6	-	-	23.8	140.1	75 +		
	16	62.0	86.4	224.2	31.0				
	14	80.5	112.3	291.5	38.1				
	12	111.5	155.5	403.6	52.4				
	10	142.5	198.8	515.7	66.7				
	8	173.5	242.0	627.8	81.0				

Figure 7. PASS example – getting a service life estimation.

Definition of service life of each material:

The following definitions for service life of different materials are used.

i. Reinforced concrete pipe (RCP): time to corrosion initiation plus 6 years (Life-365)
ii. Galvanized pipe: 25% removal of the thickness of the culvert wall at the invert (AISI method)
iii. Aluminized Type 2 pipe: the time of first perforation (complete penetration) is the service life end point (FDOT method)
iv. Aluminum pipe: time of first perforation (complete penetration) is the service life end point (FDOT method)
v. Steel pipe: number of years from installation until the deterioration reaches the point of perforation at any location on the pipe (CALTRANS method)
vi. Cast iron pipe: time of first perforation (complete penetration) is the service life end point (Rajani model, 2000)
vii. Plastic pipes: service life is independent of the environmental conditions, rather it has to do with initial field loadings or slow crack growth (creep/rupture mechanism).

Updating information of quarries:

Since the physiochemical aggregates data can be continuously updated, PASS was programmed to transfer the Excel data from the original dataset into two separate tabs: "Latest data on fine aggregate" and "Latest data on coarse aggregate," as shown in **Figure 8**. The original dataset file must be named "**ElectroChemical Aggregates.xlsm**" and be in **the same folder** as the PASS program. Please note that these files (PASS and the quarries data) should be located on a local hard drive, not in shared folders such as OneDrive or Google Drive. After inputting the project GPS coordinates and pressing the "Update Aggregate Data" button highlighted in red in **Figure 9**, engineers can select the material type and description that fit their objectives.

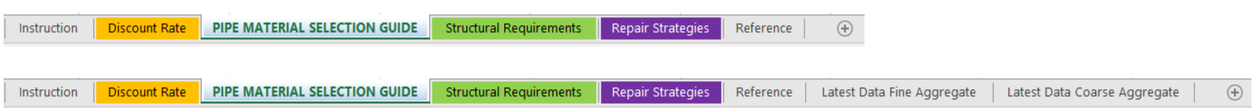


Figure 8. PASS example – tabs before and after recalling physiochemical data of aggregates.

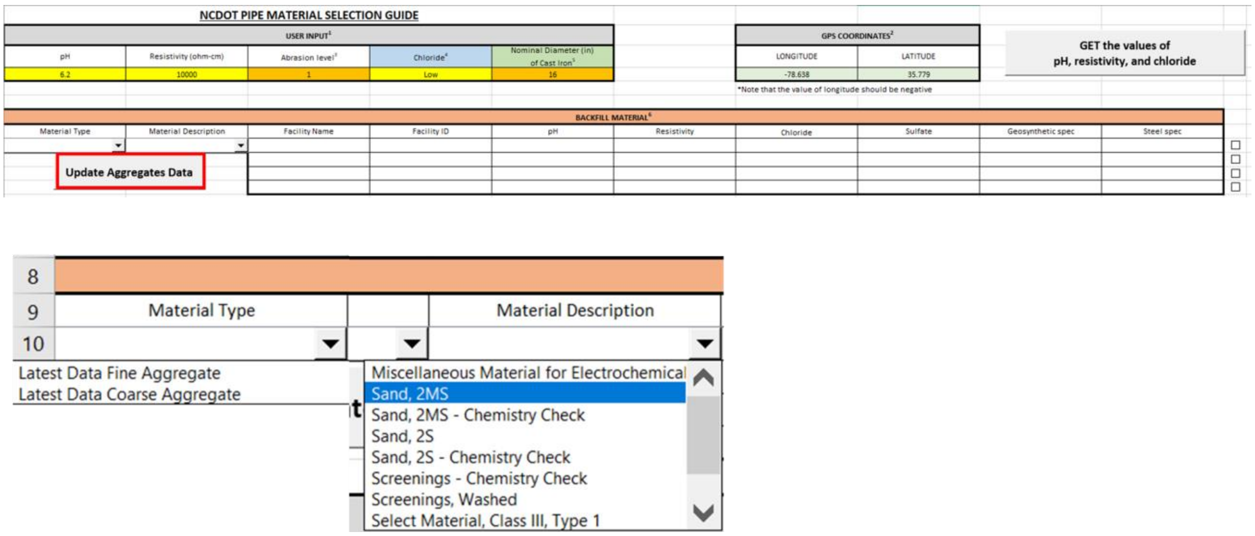


Figure 9. PASS example – recalling physiochemical data of aggregate and selecting material type and material description.

PASS will automatically identify the four closest quarries to a given project location based on the GPS coordinates, selected Material Type, and Material Description, as shown in **Figure 10**. Next to the identified quarries, there are checkboxes. By selecting one of these boxes, the achievable parameters (pH, resistivity, and chloride concentration) will be updated based on the selected quarry's conditions. The service life estimation section will then be adjusted to reflect the updated conditions, as shown in **Figure 11**.

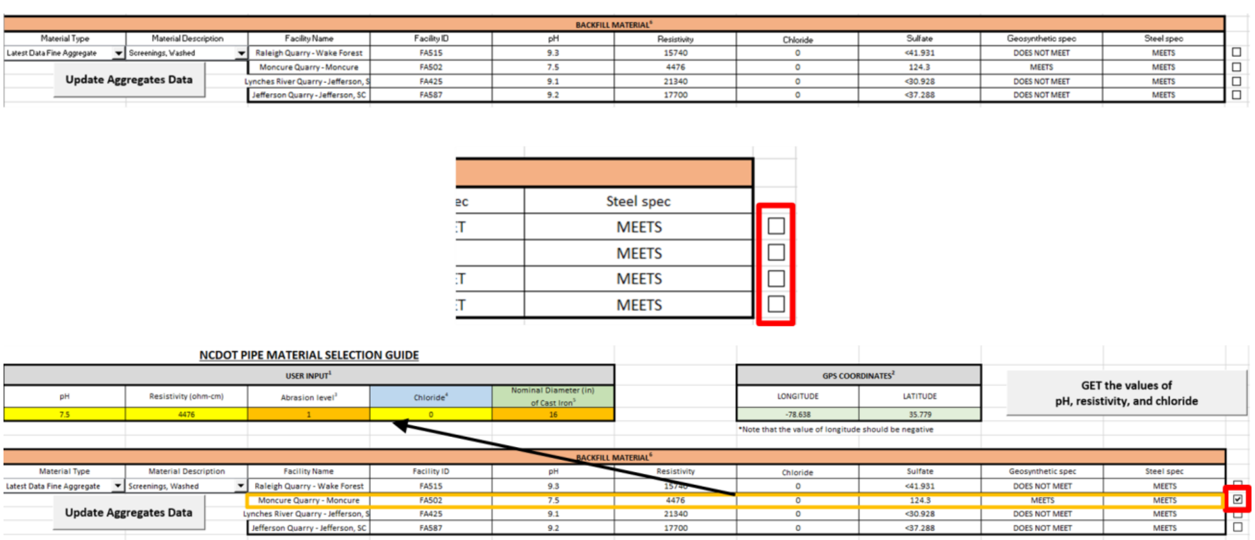
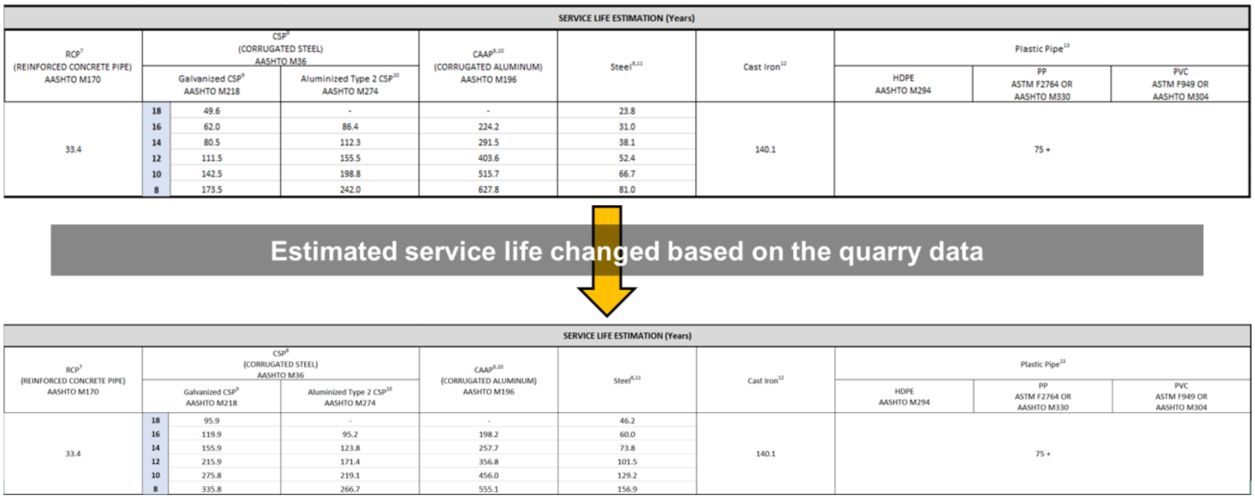


Figure 10. PASS example – identified four closest quarries and recalling the condition of selected quarry.



SERVICE LIFE ESTIMATION (Years)									
RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
	18	49.6	-	-	23.8				
	16	62.0	86.4	224.2	31.0				
33.4	14	80.5	112.3	291.5	38.1	140.1	75 +		
	12	111.5	155.5	403.6	52.4				
	10	142.5	198.8	515.7	66.7				
	8	173.5	242.0	627.8	81.0				

SERVICE LIFE ESTIMATION (Years)									
RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
	18	95.9	-	-	46.2				
	16	119.9	95.2	198.2	60.0				
33.4	14	155.9	123.8	257.7	73.8	140.1	75 +		
	12	215.9	171.4	356.8	101.5				
	10	275.8	219.1	456.0	129.2				
	8	335.8	266.7	555.1	156.9				

Figure 11. PASS example – service life estimation before and after checking quarry data.

Mitigation strategies:

Users can select various mitigation strategies with different gradients (ft/ft) as shown in **Figure 12**. The values in the green highlighted boxes are summed up, and the results are displayed in the red highlighted box, as shown in **Figure 13**.

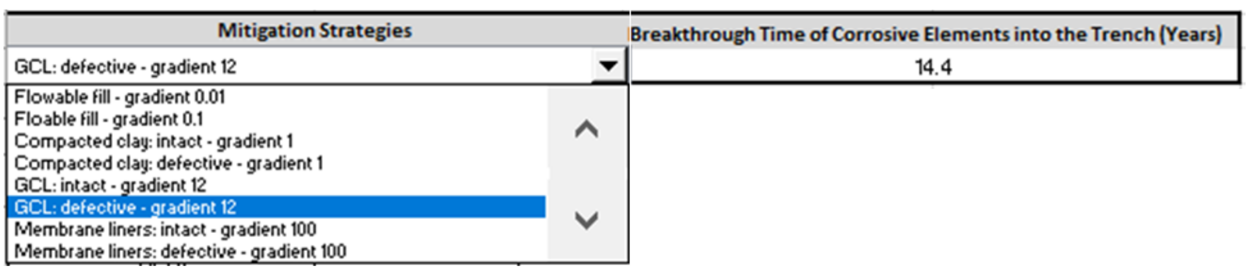


Figure 12. PASS example – service life estimation before and after checking quarry data.

SERVICE LIFE ESTIMATION (Years)									
RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
53	18	59 to 72	-	-	33 to 40	668	75 +		
	16	85 to 103	118 to 144	249 to 304	42 to 52				
	14	110 to 134	153 to 187	323 to 395	52 to 64				
	12	152 to 186	212 to 260	447 to 547	72 to 88				
	10	195 to 238	271 to 332	572 to 699	91 to 111				
	8	237 to 290	330 to 404	696 to 851	111 to 135				

Mitigation Strategies	Breakthrough Time of Corrosive Elements into the Trench (Years)
GCL: defective - gradient 12	14.4

ESTIMATED SERVICE LIFE CHANGE DUE TO MITIGATION STRATEGIES (Years)									
RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196	Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274				HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
68	18	74 to 87	-	-	47 to 54	682	89 +		
	16	99 to 118	132 to 159	263 to 318	57 to 66				
	14	124 to 149	168 to 202	338 to 409	66 to 78				
	12	167 to 201	227 to 274	462 to 561	86 to 102				
	10	209 to 252	286 to 346	586 to 713	106 to 126				
	8	251 to 304	345 to 418	710 to 865	125 to 150				

Figure 13. PASS example – service life estimation before and after checking quarry data.

Usage of PASS – structural requirements:

The current guide has now been integrated into the PASS system, as illustrated in **Figure 14**. Structural requirements and specifications have been integrated into the guide's software to improve user interaction and decision-making. When users click on the orange-colored cells, a variety of options will appear in drop-down menus, as shown in **Figure 15** and **Figure 16**. The minimum and maximum fill heights will automatically adjust according to the sizes of the selected pipe materials. Additionally, the structural requirements will adapt based on the chosen installation locations. This update ensures that the guide provides dynamic, context-sensitive information, enhancing its utility and accuracy in project planning.

Structural Requirements

		RCP	CSP	CAAP	HDPE	PP	PVC
		CLASS: Class 3	Size (in): 48 Gauge: 10	Size (in): 24 Gauge: 12	Size (in): 15	Size (in): 24	Size (in): 12
	Min (ft)	2	1	1	2	1	2
	Max (ft)	20	113	108	20	20	30
Open end cross pipes	Primary	Can be used	Use only if pipe slope is greater than 10%	Use only if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Storm drain systems	Primary	Can be used	Use only at system inlets & system outlet if pipe slope is greater than 10%	Use only at system inlets & system outlet if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Transverse median pipes	Primary	Can be used	Use only if pipe slope is greater than 10%	Use only if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Slope drains	Interstate	Do not use	Can be used	Can be used	Can be used		
Side drains	Primary	Can be used	Can be used	Can be used	Can be used		

Figure 14. Reconstructed NCDOT pipe material selection guide that will be included in the PASS program.

Structural Requirements

		RCP	CSP	CAAP	HDPE	PP	PVC
		CLASS: Class 3	Size (in): 48 Gauge: 10	Size (in): 24 Gauge: 12	Size (in): 15	Size (in): 24	Size (in): 12
	Min (ft)	2	1	1	2	1	2
	Max (ft)	2	113	108	20	20	30
Open end cross pipes	Primary	Can be used	Use only if pipe slope is greater than 10%	Use only if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Storm drain systems	Primary	Can be used	Use only at system inlets & system outlet if pipe slope is greater than 10%	Use only at system inlets & system outlet if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Transverse median pipes	Primary	Can be used	Use only if pipe slope is greater than 10%	Use only if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Slope drains	Interstate	Do not use	Can be used	Can be used	Can be used		
Side drains	Primary	Can be used	Can be used	Can be used	Can be used		

Class 2
Class 3
Class 4
Class 5

Figure 15. Example of a drop-down menu in an orange-colored cell.

Structural Requirements

		RCP	CSP	CAAP	HDPE	PP	PVC
		CLASS: Class 3	Size (in): 48 Gauge: 10	Size (in): 24 Gauge: 12	Size (in): 15	Size (in): 24	Size (in): 12
	Min (ft)	2	1	1	2	1	2
	Max (ft)	20	113	108	20	20	30
Open end cross pipes	Primary	Can be used	Use only if pipe slope is greater than 10%	Use only if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Storm drain systems	Primary	Can be used	Use only at system inlets & system outlet if pipe slope is greater than 10%	Use only at system inlets & system outlet if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Transverse median pipes		Can be used	Use only if pipe slope is greater than 10%	Use only if pipe slope is greater than 10%	Use only if traffic <10000 ADT & <200 DUALS & <100 TTST		
Slope drains	Interstate	Do not use	Can be used	Can be used	Can be used		
Side drains	Primary	Can be used	Can be used	Can be used	Can be used		

Interstate
Primary
Secondary

Figure 16. Example of a drop-down menu in an orange-colored cell.

Usage of PASS – repair strategies:

To determine the most suitable rehabilitation method, users should set the following parameters based on the options in **Figure 17**: 1. Type of pipe material, 2. Degree of deterioration, and 3. Diameter of the pipe. **Figure 18** illustrates the criteria proposed by Thornton et al. (2005), which includes a "Custom weights" section that users can modify to match the specific conditions of their project. The sum of these custom weights must total 100% [4].

Upon setting these parameters and customizing the weights, the system will compute and display the overall scores along with the relevant rehabilitation options next to the criteria section, as depicted in **Figure 19**. The cell containing the highest score(s) will be highlighted in orange, and the option(s) within these orange cells will be designated as the optimal choice(s), as shown in **Figure 20**.

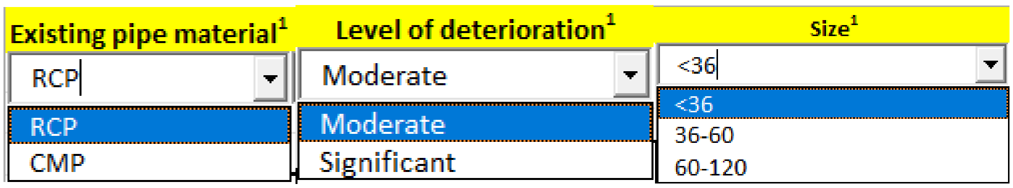


Figure 17. Parameters needed to be selected by users.

Custom weights[2] (%)	Criteria[3]
16	Design life
14	Abrasion and corrosion resistance
27	Installation time
8	Flow bypass requirements
13	Digging requirements
22	Cost
100	**Overall score[5]**

Figure 18. Incorporated criteria and custom weights input section.

Alternatives[4]						
Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
1	2	5	5	4	3	3
4	4	5	5	5	5	5
1	2	4	4	3	4	4
1	1	2	2	3	3	4
1	1	1	1	1	3	4
5	5	2	2	3	3	3
230	273	331	331	318	355	376

Figure 19. Performance ratings and calculated overall scores for applicable alternatives.

Existing pipe material[1]	Level of deterioration[1]	Size[1]
CMP	Significant	<36

Custom weights[2] (%)	Criteria[3]	Alternatives[4]				
		SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL
30	Design life	4	4	5	5	3
30	Abrasion and corrosion resistance	2	2	5	5	5
18	Installation time	3	3	4	4	4
2	Flow bypass requirements	5	3	2	2	4
10	Digging requirements	4	4	1	1	4
10	Cost	5	1	2	2	3
100	**Overall score[5]**	334	290	406	406	390

Existing pipe material[1]	Level of deterioration[1]	Size[1]
RCP	Moderate	<36

Custom weights[2] (%)	Criteria[3]	Alternatives[4]						
		Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
10	Design life	1	2	5	5	4	3	3
10	Abrasion and corrosion resistance	4	4	5	5	5	5	5
10	Installation time	1	2	4	4	3	4	4
5	Flow bypass requirements	1	1	2	2	3	3	4
5	Digging requirements	1	1	1	1	1	3	4
60	Cost	5	5	2	2	3	3	3
100	**Overall score[5]**	370	390	275	275	320	330	340

Figure 20. Examples of orange-colored (best) options based on input custom weights.

The annotations corresponding to superscripted items (**Figure 20**) can be found below the section as shown in **Figure 21**. **Figure 22** offers definitions for the acronyms found in **Figure 20** for quick reference. If the 'custom weight' assigned across different criteria for choosing repair and rehabilitation measures does not total '100,' an error message will appear. This error message is displayed in **Figure 23**. Additionally, corresponding references can be found in the reference tab, as shown in **Figure 24** and **Figure 25**.

Footnotes
1. Users can change existing pipe material, level of deterioration, and size parameters for their purpose.
2. The sum of the custom weights should be equal to 100.
3. Criteria can differ in different projects based on its' priority.
4. Feasible alternatives and their coefficients for each criteria will be shown up depending on the selected parameters.
5. Overall score will be calculated by pressing "Assess Alternatives" button; the alternatives with highest score will be colored as orange.

Figure 21. Footnotes for reference.

Acronyms	
CIPP	Cured-in-place-pipe
SWL	Spiral wound liner
SL	Slip lining

Figure 22. Acronyms for reference.

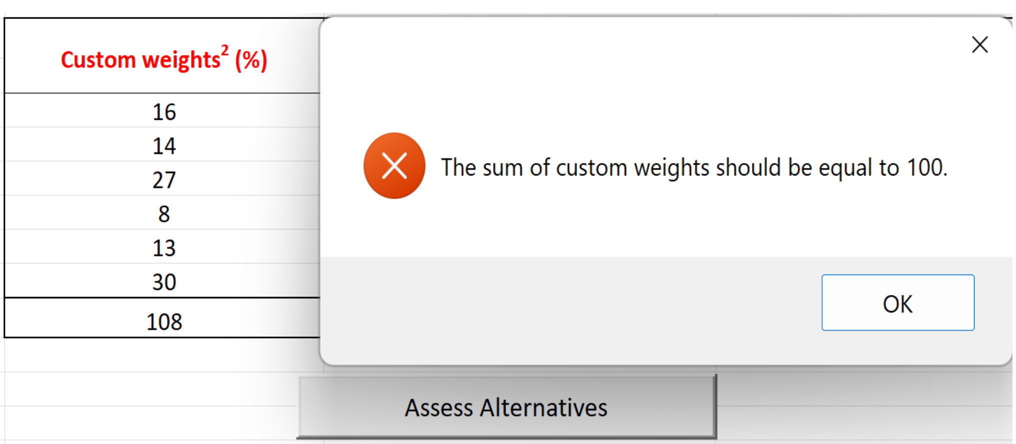


Figure 23. Pop-up error message box when the sum of the weights is not equal to 100.

Feasible repair/rehabilitation approaches according to pipe materials, level of deteriorations, and sizes of original pipe

Existing pipe material	Level of deterioration	Size	Feasible approaches						
RCP	Moderate	<36	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
RCP	Moderate	36-60	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	SWL		
RCP	Moderate	60-120	Spray-on lining-cement-mortar	Spray-on-epoxy	SWL				
RCP	Significant	<36	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL		
RCP	Significant	36-60	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL		
RCP	Significant	60-120	SL-segmental	SL-continuous	SWL				
CMP	Moderate	<36	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	Deformed/Reformed	Fold and Form	SWL
CMP	Moderate	36-60	Spray-on lining-cement-mortar	Spray-on-epoxy	CIPP-inversion	CIPP-pulled-in-place	SWL		
CMP	Moderate	60-120	Spray-on lining-cement-mortar	Spray-on-epoxy	SWL				
CMP	Significant	<36	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL		
CMP	Significant	36-60	SL-segmental	SL-continuous	CIPP-inversion	CIPP-pulled-in-place	SWL	Spray-on lining-cement-mortar	Spray-on-epoxy
CMP	Significant	60-120	SL-segmental	SL-continuous	SWL	Spray-on lining-cement-mortar	Spray-on-epoxy		

Figure 24. Updated reference tab: feasible repair/rehabilitation approaches regarding pipe materials, level of deterioration, and sizes of original pipe.

Adopted criteria and criterion weights to calculate scores for different alternatives

Criteria	Alternatives								
	Sliplining-segmental	Sliplining-continuous	Deformed/Reformed	Fold and Forl	Spirally Wound Lining	CIPP-inversion	CIPP-pulled-in-place	Spray-on lining-cement-mortar	Spray-on-epoxy
Design life	4	4	4	3	3	5	5	1	2
Capacity Reduction	2	2	5	5	5	5	5	4	4
Abrasion and Corrosion Resistance	3	3	3	4	4	4	4	1	2
Installation Time	5	3	3	3	4	2	2	1	1
Flow Bypass Requirements	4	4	1	3	4	1	1	1	1
Digging Requirements	5	1	3	3	3	2	2	5	5
Cost	4	4	3	3	2	1	1	5	5

Figure 25. Updated reference tab: adopted criteria and criterion weights to calculate scores for different alternatives.