Final Report

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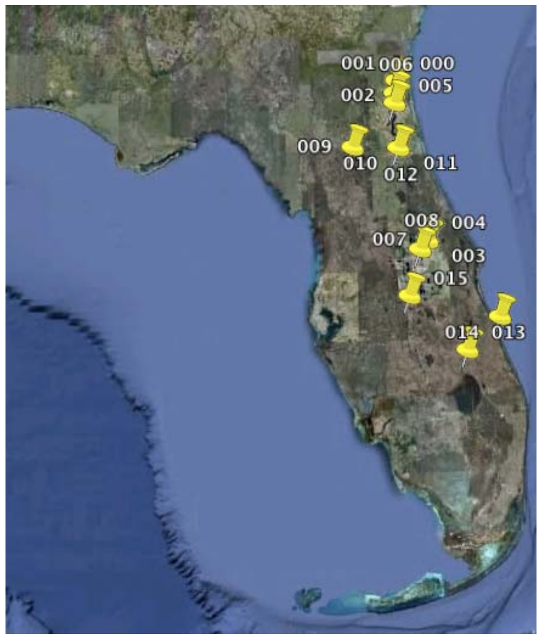
Durability of In-situ Pipe Repair



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Prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation.

SI (MODERN METRIC) CONVERSION FACTORS (from FHWA)

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

The Florida Department of Transportation constructs, manages and maintains a significant portion of the pipe infrastructure system in the state of Florida, which results in significant investment of time and funds each year. Finding and implementing the most effective repair methods is vital to utilizing the available resources effectively. The goal of the following research document is to identify these repair methods and the situations in which they are most successful, enhancing the durability and effectiveness of the entire pipe networks. The research team conducted a full literature review detailing pipe repair methods and solutions, describing their use, longevity and efficiency. After the completion of the literature review, commonly used repair methods were identified, and associated drainage pipe repairs throughout the state were investigated while compiling a database of the pipe repairs completed during the past fifteen years. From this database, the selected repair sites were identified based on four major repair types for review. The research team conducted sixteen pipe inspections using closed-circuit television (CCTV) video recording and obtained soil samples at repair sites to observe the longevity and ultimate effectiveness of the existing repairs. Based on the analysis of the 15 years of observed data and existing literature, recommendations for utilization of the various repair types were created, which can enhance and update the current Pipe Repair Matrix used by the Florida Department of Transportation to determine effective repairs for certain situations.

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Pipe, Repair, Durability, In-situ, Rehabilitation	No restrictions.

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) is interested in enhancing its current Pipe Repair Matrix with supporting research documentation to more efficiently utilize construction and maintenance funds by finding out which pipe repair methods are most effective within given situations. The objective of the researchers was to provide FDOT with a restructured Pipe Repair Matrix for determining exactly which repair to use in certain scenarios. A review of existing data and creation of a pipe repair database for recent pipe repair within the state of Florida were completed. After determining which sites would be inspected, the research team traveled around the state of Florida to perform site visits. Once all inspections were completed, the University of Florida (UF) research team began analyzing the field data to determine the findings of the research. It was determined by the UF research team that overall the best repairs observed, given proper installation, were pipe liners (for larger repair issues) and band seals (for joint issues). In this report, the research team provided FDOT with a pipe repair flowchart to determine what type of repair to use in given instances, along with a detailed report of each repair as a whole to explain reasons to use, or not, a given type of repair. Also provided was a table showing repair ratings for each repair analyzed, along with a detailed explanation of observations during each inspection. FDOT will benefit from the performed research by implementing the flowchart and recommendations provided by the UF research team when considering pipe repairs and utilizing the recommendations for organizing pipe repair data. This research project has also created a database of pipe repair sites to allow further research to be performed on more sites and different pipe materials throughout the state of Florida in order to supplement the findings of this report.

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CHAPTER 1
INTRODUCTION

The Florida Department of Transportation (FDOT) has spent approximately 9.5 million dollars on pipe repair and rehabilitation in the past five years alone. This expenditure represents a significant recurring investment in FDOT's pipe and culvert assets over time. Simply put, FDOT wants to identify the repair methods and strategies that will result in the wisest use of these funds. To invest these construction and maintenance dollars wisely, effective methodologies for the in-situ repair of optional drainage conduit types are vital to FDOT's mission.

Our research will focus on determining which of the commercially available pipe repair technologies are most effective in extending pipe longevity, without sacrificing hydraulic flow capacity. FDOT created a Pipe Repair Matrix webpage as linked within the FDOT Office of Construction website. This webpage serves as a "toolbox" for specialty engineers, Construction Engineering and Inspection (CEI) personnel, and contractors to use in selecting the best in-situ pipe repair method for various optional pipe material applications. Our research will augment and enhance the body of knowledge conveyed in the Pipe Repair Matrix webpage for all categories of optional drainage pipe materials allowed by FDOT.

The objectives of this research project included the following:

a) Develop a database that will contain the last 15 years' worth of various pipe materials and their respective repairs implemented by seven districts;
b) Assist FDOT in compiling a list of potential project review sites that will be selected from the database and which will contain each of the optional pipe types, along with their associated repair methods;

c) Conduct closed circuit television (CCTV) inspection and laser profiling observations that will be used to evaluate in-situ repairs; the current condition of the repairs; and the condition of the pipes;

d) Collect field data on infiltration of water or sediment, debris accumulations, corrosion of metal (aluminum or steel) pipes and their repairs, staining, cracking or deflection, alignment, seams and joints, pitting, shapes, and thickness of pipes associated with repairs, as well as the general appearance of the repair;

e) Collect data on the influence of in-situ soil properties on these repairs through soil sampling and testing to determine their pH and electrical conductivity and other properties that contribute to pipe material degradation; and

f) Develop criteria based on field data that will be used to analyze and eventually be incorporated into the FDOT Standard Specifications and the Pipe Repair Matrix.

A more detailed explanation of the above objectives is presented in Section 2 (Research Approach).

A brief review of contemporary pipe repair literature revealed that little work has been done on developing a pipe management system to determine long-term durability of various pipe repair methods. The Ohio Department of Transportation conducted an 11-year study of 1,616 culverts and concluded the life expectancy of culvert pipe to be between 10 and 35 years before significant deterioration occurred (Meegoda et al. 2009). In National Cooperative Highway Research Program (NCHRP) Synthesis 254, the Arizona and Mississippi Departments of Transportation (DOTs) reported a menu of choices associated with the desired service life (Gabriel and Moran 1998). The parameters evaluated were the performances of different pipe materials, such as steel, aluminum, concrete, and polyethylene, under various environmental conditions. The study reported that different states adopt their own repair strategy to meet their needs from experience with various products. In NCHRP Synthesis 303 (Transportation Research Board 2002), the Federal Highway Administration (FHWA) developed a Culvert Management System (CMS) computer software program containing five modules: 1) inventory of the culverts; 2) condition and ratings; 3) work needs (repair or rehabilitation); 4) work funding and prioritization; and 5) scheduling (time of the year and whether in-house or contract). The New York State Department of Transportation (NYSDOT) takes individual culvert rating data and summarizes them into an annual culvert inspection report. NYSDOT also stores its culvert data in a centralized database. Potter (1988) and Potter and Schindler (1988) suggested that life cycle cost analysis (LCCA) be used to determine the relative economic rating of design alternatives of U.S. Army drainage structures. The use of LCCA can improve the pipe and material selection process and can be done for each site. Once the service life of a drainage material is selected, the procedures for LCCA are established and published in U.S. Army technical manuals (Potter 1988).

There have been a number of studies on abrasion, corrosion, and durability of various types of pipes. From using charts and graphs developed through these studies, it can be determined what type of pipe to use to replace an existing pipe. With these studies as resources, FDOT could benefit from guidelines for a preventive maintenance program to inventory and inspect pipes on a regular schedule. Another issue is centralized pipe data at the appropriate management level, such that analysis can be performed to determine when to schedule pipe inspections, schedule corrective maintenance action, and generate history and deterioration curves for various conditions.

The Wyoming DOT's special provision for pipe liner installation NCHRP 303 (Transportation Research Board 2002) and NYSDOT specifications are examples that could be referred to in setting a strategy for developing specifications, as well as the American Society for Testing and Materials' (ASTM) A849-00 specification for post-applied linings in a manufacturer's plant and A979/A979M-97 specifications for field-installed linings.

From the literature search, the most commonly reported method of permanent structural stabilization is lining. It is the preferred method by most agencies. In 1985, the FHWA evaluated various repair methods under the experimental project program to determine the best method to rehabilitate pipe on the Skyline Drive in Virginia (Beucler 1985). They concluded that the inverted resin impregnated felt tube process was the method that should be used to rehabilitate these 50-year-old pipes. Sukley and St. John (1994) reported on the performance of the polyester fiber-felt, thermosetting resins, and polyurethane pipe rehabilitation process used on a Pennsylvania Department of Transportation (PennDOT) project over a 9-year study period. The "pipe in pipe" performed satisfactorily and saved PennDOT an estimated $170,000. In addition, the liner improved the flow characteristics (i.e., lower pipe friction *n-value*) in the pipe and required little excavation. In 1997, Okpala and Anderson reported that slip liners were cost-beneficial when compared with excavating and replacing a deteriorating pipe. At one site, they indicated that a 52% savings was achieved over the estimated cost of excavating and replacing.

The NCHRP Synthesis 303 (Transportation Research Board 2002) study was initiated to determine the state-of-practice of pipe assessment, the selection of appropriate repair or rehabilitation methods, and the management aspects of a pipe program. The study reports on information collected regarding the state-of-the-practice for plastic, concrete, and metal pipes and their appurtenances, such as inlets, outlets, joints, access holes, junction boxes, wingwalls, endwalls, and headwalls. It also provides information on how transportation agencies have incorporated pipe assessment and corrective work (repair or rehabilitation) into a pipe management system and eventually into a layered transportation management system. Rehabilitation specification and methods of record keeping of field reports are presented as well. The study determines what management systems and methods are being used by transportation agencies to predict the service life of pipes. As mentioned earlier, the FDOT Construction Office has developed a Pipe Repair Matrix (FDOT 1996-2010). It is a guidance document for selecting various repair methods.

CHAPTER 2
LITERATURE REVIEW

2.1 Stormwater Culvert and Pipe Material

2.1.1 Concrete Culverts

Concrete is one of the oldest materials used in the construction industry. Concrete culverts are either cast-in-place or precast. Cast-in-place culverts are constructed as one unit without connected joints, which makes these culverts vulnerable to cracking due to their length and rigidity. These culverts should be inspected regularly for signs of chemical attack or abrasion (Najafi et al. 2008). The underside of the top slab, the invert slab, and the water line on the walls are the most likely areas to be damaged. Freeze-thaw action can also damage concrete culverts, particularly the headwalls and wingwalls. Since precast concrete culverts are manufactured under controlled conditions, these pipes have better quality in uniformity and density compared to cast-in-place culverts. Generally, concrete culverts are classified as rigid structures because they do not deform appreciably under the applied loads. Uneven or excessive loads will cause such structures to crack rather than bend (Ballinger and Drake 1995a). Figure 2-1 presents an overview of standard concrete pipe shapes in a range of sizes and common uses (AASHTO 1991).

The most common durability problems associated with concrete culverts are abrasion, corrosion, cracks, spalling, invert deterioration, joint defects and misalignment (in precast concrete culverts), and footing problems (in arch-type cast-in-place culverts). Figure 2-2 is an example of a corroded concrete pipe (Oberdorfer AG 2010).

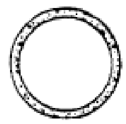
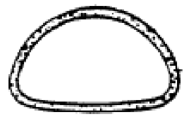
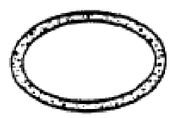
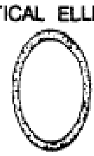
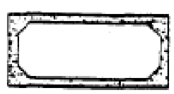
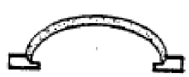
SHAPE	RANGE OF SIZES	COMMON USES
CIRCULAR 	12 to 180 inches reinforced 4 to 36 inches non-reinforced	Culverts, storm drains, and sewers.
PIPE ARCH 	15 to 132 inches equivalent diameter	Culverts, storm drains, and sewers. Used where head is limited.
HORIZONTAL ELLIPSE 	Span x Rise 18 to 144 inches equivalent diameter	Culverts, storm drains, and sewers. Used where head is limited.
VERTICAL ELLIPSE 	Span x Rise 36 to 144 inches equivalent diameter	Used where lateral clearance is limited.
RECTANGULAR (box sections) 	Span 3ft to 12ft	Culverts, storm drains, and sewers. Used for wide openings with limited head.
ARCH 	Span 24ft to 41ft	Culverts and storm drains. For low, Wide waterway enclosures.
FLAT TOP 3-SIDED 	Span 14ft to 35ft	Culverts and storm drains. For low, Wide waterway enclosures.
ARCH TOP 3-SIDED 	Span 16ft to 36ft	Culverts and storm drains. For low, Wide waterway enclosures.

Figure 2-1. Standard concrete shapes, range of sizes, and common uses (AASHTO 1991).

Figure 2-2. Corrosion of concrete pipe at a joint (Oberdorfer AG 2010).

The *Federal Highway Administration (FHWA) Culvert Repair Practices Manual, Vol. II*, provides a detailed description for each of these problems and is summarized below (Ballinger and Drake 1995b; Najafi et al. 2008).

Improper handling during installation, improper gasket placement, and movement or settlement of the pipe sections may cause circumferential cracks in the joint area. These cracks may lead to leakage even though they are covered by gaskets. If differential movement between pipe sections or other problems is not observed, and the cracks are not open or spalling, they may be considered a minor problem. Severe joint cracks are similar in significance to separated joints and should be repaired, accordingly (Ballinger and Drake 1995a). The repair procedures for cracks involve sealing and patching.

Spalling may be defined as the cracking and detaching of concrete (Najafi et al. 2008). In precast concrete pipe, spalls often occur along the edges of either longitudinal or transverse cracks when the crack is due to overloading or poor support rather than simple tension cracking (Ballinger and Drake 1995a). Also, as reinforcing bars corrode, they tend to expand and apply pressure on the concrete surrounding them. Detached concrete parts should be replaced by patching as a proper method of repair.

Concrete culverts usually exhibit high resistance to corrosive environments; however, invert deteriorations are also a common type of problem faced with concrete culverts. Deteriorated parts of the inverts should be repaired by paving the invert or applying proper coating materials, such as vitrified clay tiles. If abrasion is an important factor causing the deterioration of the invert, installing a neutralization basin would be a proper method of repair (Najafi et al. 2008). Figure 2-3 shows the damage that an abrasive flow can have on the inside of a concrete pipe (Oberdorfer AG 2010).

Figure 2-3. Damage from abrasive flow (Oberdorfer AG).

Joint defects are commonly seen in concrete culverts and can lead to minor problems or more serious problems. Joint defects include leakage (exfiltration and infiltration), cracks, and joint separation. Exfiltration, in which water flows out through the walls of the pipe, for example, through cracks or loose joints, is a cause of minor leakage that may not always be a significant problem unless soils are quite erosive. According to Ballinger and Drake (1995a), infiltration of water can lead to settlement, misalignment, and scouring problems if it carries fine-grained soil particles from the surrounding backfill. This can eventually cause cracks and openings at the joints. Application of structural adhesives, chemical grouting, and sealing are appropriate methods of repair for cracked joints. Open joints may be sealed with similar methods unless the opening is wide. Wide openings can be repaired by installing steel bands and covering with shotcrete.

Another problem experienced with precast concrete culverts is misalignment. Uneven settlement of the surrounding soil, improper installation techniques and undermining might be factors leading to misalignment. If misalignment is detected, excavating and relaying the culvert would be an appropriate solution (Najafi et al. 2008).

There might also be footing problems on arch-type, cast-in-place concrete culverts with independent footings. Scour and undermining of footings might be reasons for this type of problem. The appropriate solution for this type of problem is underpinning of the foundation. Underpinning is accomplished by excavating beneath the existing footing and constructing another footing underneath (Najafi et al. 2008).

One of the most comprehensive concrete culvert evaluations was performed in the "Ohio Culvert Durability Study" in which a total of 545 concrete culverts were inspected and statistical analysis of those culverts was performed. According to the observations and results given in this report, concrete culverts were found to have different behaviors depending on pH levels. The life of a culvert is significantly dependent on the pH of water in contact with the concrete, especially pH values less than 7, whereas slope, flow velocity, and abrasion also showed significant but minor effects on the concrete rating. The most significant negative effect was observed when the pH was less than 7, which constitutes an acidic flow. As the acidity increased (decreasing pH), the concrete rating was found to be decreasing much more rapidly. Below a pH level of 4.5, additional protection was suggested for the concrete culverts. Other significant variables determined as part of this study include pipe slope, sediment depth (positive), and age (negative) (Salem et al. 2008).

Some of the protection methods for concrete culverts were also inspected during this project. According to inspections made by Midwest Regional University Transportation Center (Madison, WI), vitrified clay liner plates were observed to perform very well in extremely acidic conditions, whereas concrete field paving was also found to be successful in extending the life of the pipe in acidic conditions. However, coal tar pitch coating was applied in some concrete culverts in Ohio, but according to the investigations of the Midwest Regional University Transportation Center, this type of coating performed poorly and did not last longer than 5 years in any of the sites (Salem et al. 2008).

According to the results of the inspection made by the Ohio Research Institute for Transportation and the Environment (ORITE) in which 25 concrete culverts were inspected, the service life was determined as 70 to 80 years. Salem et al. (2008) determined that age, pH, and abrasiveness were significant parameters which were affecting the culvert rating. They also added that cast-in-place box culverts and reinforced concrete circular/elliptical pipe culverts had exhibited similar performances.

Concrete culverts usually do not face structural problems due to their rigidity, if they are designed according to the specifications; however, the soil conditions adjacent to the concrete pipes can create problems. For example, Heger and Selig (1994) investigated two case studies in rigid pipe installation failures. According to the results of their investigation, soft soil adjacent to the pipe under high fills can cause increased earth loads on the structure, and they suggested that soft soils should be removed from each side of the culvert for a distance of at least one diameter (Salem et al. 2008).

In summary, according to the studies presented, the performance of concrete culverts depends on the pH of the flow, age of the culvert, sediment depth, slope, the presence of roadway deicing salts and the soil strata next to the culvert. Concrete culverts may be considered more durable than metal culverts, but they are heavier and the installation process is harder. Corrosion and abrasion may still be a major problem in some of the extremely corrosive environments. This condition may lead to durability problems, slabbing, spalling, and joint problems in precast concrete culverts (Salem et al. 2008).

Concrete Pipe Standards:

- ASTM C1417 / C1417M -08 Standard Specification for Manufacture of Reinforced Concrete Sewer, Storm Drain, and Culvert Pipe for Direct Design
- ASTM C76 / C76M -10a Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe
- ASTM C655 / C655M -09 Standard Specification for Reinforced Concrete D-Load Culvert, Storm Drain, and Sewer Pipe
- ASTM C507 / C507M -10a Standard Specification for Reinforced Concrete Elliptical Culvert, Storm Drain, and Sewer Pipe
- ASTM C506 / C506M -10a Standard Specification for Reinforced Concrete Arch Culvert, Storm Drain, and Sewer Pipe
- ASTM C985 / C985M -04e1 Standard Specification for Nonreinforced Concrete Specified Strength Culvert, Storm Drain, and Sewer Pipe
- ASTM C14 / C14M -07 Standard Specification for Nonreinforced Concrete Sewer, Storm Drain, and Culvert Pipe

- ASTM C877M -02(2009) Standard Specification for External Sealing Bands for Concrete Pipe, Manholes, and Precast Box Sections (Metric)
- ASTM C990 -09 Standard Specification for Joints for Concrete Pipe, Manholes, and Precast Box Sections Using Preformed Flexible Joint Sealants
- ASTM C76; C789; C850; C507; C17; C506; C428; C663
- AASHTO M170; M259; M207; M86; M206; M217
- Federal SS-P-331
- ACI 346

2.1.2 Metal Culverts

2.1.2.1 Corrugated *Metal Culverts*

Culverts made from corrugated aluminum pipe (CAP), corrugated steel pipe (CSP), corrugated aluminized steel pipe (CASP), spiral rib aluminum pipe (SRAP), spiral rib steel pipe (SRSP) and spiral rib aluminized steel pipe (SRASP) are classified as metal culverts by the FDOT Pipe Repair Matrix (FDOT 2010a). Generally, corrugated steel and aluminum culverts are considered as flexible culverts, because they respond to and depend upon the soil backfill to provide structural stability and support to the culvert. Therefore, apart from corrosion and abrasion, backfill gradation and compaction are also important in the performance of metal culverts (Najafi et al. 2008).

Joint defects in corrugated metal pipes, invert deterioration of corrugated metal pipe and structural metal pipes, shape distortions, and cracked and distorted seams in structural plates are some of the most common problems associated with corrugated metal culverts. *FHWA Culvert Repair Practices Manual* provides a detailed description for each of these problems and is summarized below (Ballinger and Drake 1995a; Najafi et al. 2008).

Infiltration and exfiltration of water and soil through or from a culvert could be caused by joint defects and may lead to significant problems. This situation may cause loss of support and disturb the soil-pipe interaction necessary for the survival of the pipe. Joint separation may indicate a lack of slope stability. Indications of joint defects include open joints, deflection, seepage at the joints, and surface sinkholes over the culvert. In order to repair joint defects in metal pipes and pipe-arches, excavation and exterior repair, grouting or installation of interior seals methods may be used (Ballinger and Drake 1995a; Najafi et al. 2008).

Durability problems are the most common cause for the replacement of metal pipe culverts. Durability of culvert material refers to the ability of a material to resist corrosion and abrasion. Corrosion and abrasion of corrugated metal culverts can be a serious problem. Abrasion can accelerate corrosion by wearing away protective coatings on a metal culvert. Corrosion is the deterioration of metal due to electrochemical or chemical reactions. Metal culverts are subject to corrosion in certain aggressive environments. Progression of invert deterioration may cause loss of structural integrity of a culvert and may cause the culvert to fail. In order to repair deteriorated inverts of metal culverts, methods such as invert paving with concrete, steel armor plating, or converting a pipe-arch culvert into an arch-type culvert can be used (Ballinger and Drake 1995a; Najafi et al. 2008).

Metal culverts may have shape distortions due to asymmetrical loading. This loading might be the result of poor installation or poor design. Shape changes in the culvert provide a direct indication of the inadequacy and instability of the supporting soil envelope, since the corrugated metal culvert depends on the backfill or embankment to maintain its proper shape and stability. When the backfill does not provide required support, the culvert will deflect, settle, or distort.

Minor horizontal and vertical misalignment is generally not a significant problem in corrugated metal structures unless it causes shape or joint problems. Occasionally, culverts are intentionally installed with a change in gradient. If the rate of shape distortion is not progressing with time, then there is no need for a corrective action. If shape distortion is progressing with time, then temporary bracing; excavation and backfilling; and reshaping might be used as a repair method (Ballinger and Drake 1995a). Figure 2-4 presents on overview of standard corrugated steel culvert shapes (Ballinger and Drake 1995a).

Corrugated Metal Culvert Standards:

- ASTM A926 -03(2008) Standard Test Method for Comparing the Abrasion Resistance of Coating Materials for Corrugated Metal Pipe
- ASTM A762 / A762M -08 Standard Specification for Corrugated Steel Pipe, Polymer Precoated for Sewers and Drains
- ASTM B744 / B744M -05 Standard Specification for Aluminum Alloy Sheet for Corrugated Aluminum Pipe
- ASTM B864 / B864M -08 Standard Specification for Corrugated Aluminum Box Culverts
- ASTM A807 / A807M -02(2008) Standard Practice for Installing Corrugated Steel Structural Plate Pipe for Sewers and Other Applications
- ASTM A142; C700; C479 (NCHRP 1978)
- AASHTO M36; M167; M245; M64; M65 (NCHRP 1978)
- American Iron and Steel Institute (AISI) Typ 409 (NCHRP 1978)
- Federal WW-P-405; WW-P-421; SS-P-361 (NCHRP 1978)

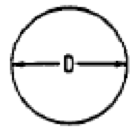
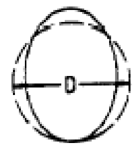
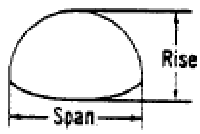
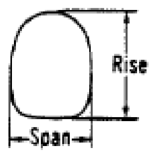
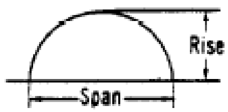
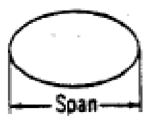
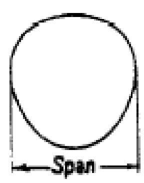
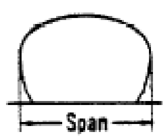
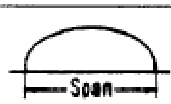
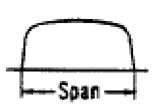
Shape		Range of Sizes	Common Uses
Round		6 in. – 26 ft.	Culverts, subdrains, sewers, service tunnels, etc. All plates same radius. For medium and high fills (or trenches).
Vertically–elongated (ellipse) 5% is common		4 – 21 ft. nominal; before elongating	Culverts, sewers, service tunnels, recovery tunnels. Plates of varying radii; shop fabrication. For appear–ance and where backfill compaction is only moderate.
Pipe–arch		Span x Rise 17 in. x 13 in. to 20 ft. 7 in. x 13 ft. 2 in.	Where headroom is limited. Has hydraulic advantages at low flows. Corner plate radius. 18 inches or 31 inches for structural plate.
Underpass*		Span x Rise 5 ft. 8 in. x 5 ft. 9 in. to 20 ft. 4 in. x 17 ft. 9 in.	For pedestrians, livestock or vehicles (structural plate).
Arch		Span x Rise 6 ft. x 1 ft. 9 1/2 in. to 25 ft. x 12 ft. 6 in.	For low clearance large waterway opening, and aesthetics (structural plate).
Horizontal Ellipse		Span 7 – 40 ft.	Culverts, grade separations, storm sewers, tunnels.
Pear		Span 25 – 30 ft.	Grade separtaions, culverts, storm sewers, tunnels.
High Profile Arch		Span 20 – 45 ft.	Grade separtaions, culverts, storm sewers, tunnels, ammo ammunition magazines, earth covered storage.
Low Profile Arch		Span 20 – 50 ft.	Low–Wide waterway enclosures, culverts, storm sewers.
Box Culverts		Span 10 – 26 ft.	Low–Wide waterway enclosures, culverts, storm sewers.
Specials		Various	For lining old structures or other special purposes. Special fabrication.

Figure 2-4. Standard corrugated steel culvert shapes (Ballinger and Drake 1995a).

2.1.2.2 Corrugated *Metal Structural Plate Culverts*

Individual corrugated metal structural plates are formed, curved, and galvanized at the factory, then assembled and bolted together at the job site to construct the large corrugated metal culverts which can be found in circular pipe, arch, or pipe-arch structures. Corrugated metal structural plate culverts have longitudinal seams throughout the structure. Asymmetrical forces and faulty assembling may cause distortion and cracks on the seams which might be repaired by reversing lap joints, welding reinforcing bars, shotcreting beams, and excavating (Najafi et al. 2008; Ballinger and Drake 1995a).

Corrugated metal arch culverts may have either a natural streambed or a bottom part. The arch structure is connected to the concrete foundation below the flow line. Undermining of corrugated metal arch culvert foundations may lead to settlement, rotation, distortion and failures (Najafi et al. 2008; Ballinger and Drake 1995a).

As previously stated, corrugated metal arch culverts usually have the original soil as the streambed. If there is an excess amount of debris and sedimentation, the culvert should be cleaned out with proper equipment. If there is scouring and lowering of the streambed, then the streambed material should be changed with an appropriate material (Najafi et al. 2008; Ballinger and Drake 1995a).

A summary of the common problems and repair methods for corrugated metal culverts and concrete culverts (Najafi et al. 2008) are shown in Figure 2-5.

Corrugated Metal Structural Plate Culvert Standards:

- ASTM A761 / A761M -04(2009) Standard Specification for Corrugated Steel Structural Plate, Zinc-Coated, for Field-Bolted Pipe, Pipe-Arches, and Arches
- ASTM B790 / B790M -00(2006) Standard Practice for Structural Design of Corrugated Aluminum Pipe, Pipe-Arches, and Arches for Culverts, Storm Sewers, and Other Buried Conduits

- ASTM A760 / A760M -09 Standard Specification for Corrugated Steel Pipe, Metallic-Coated for Sewers and Drains
- ASTM B745 / B745M -97(2005) Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains
- AASHTO M167 (NCHRP 1978)
- Federal WW-P-405 (NCHRP 1978)

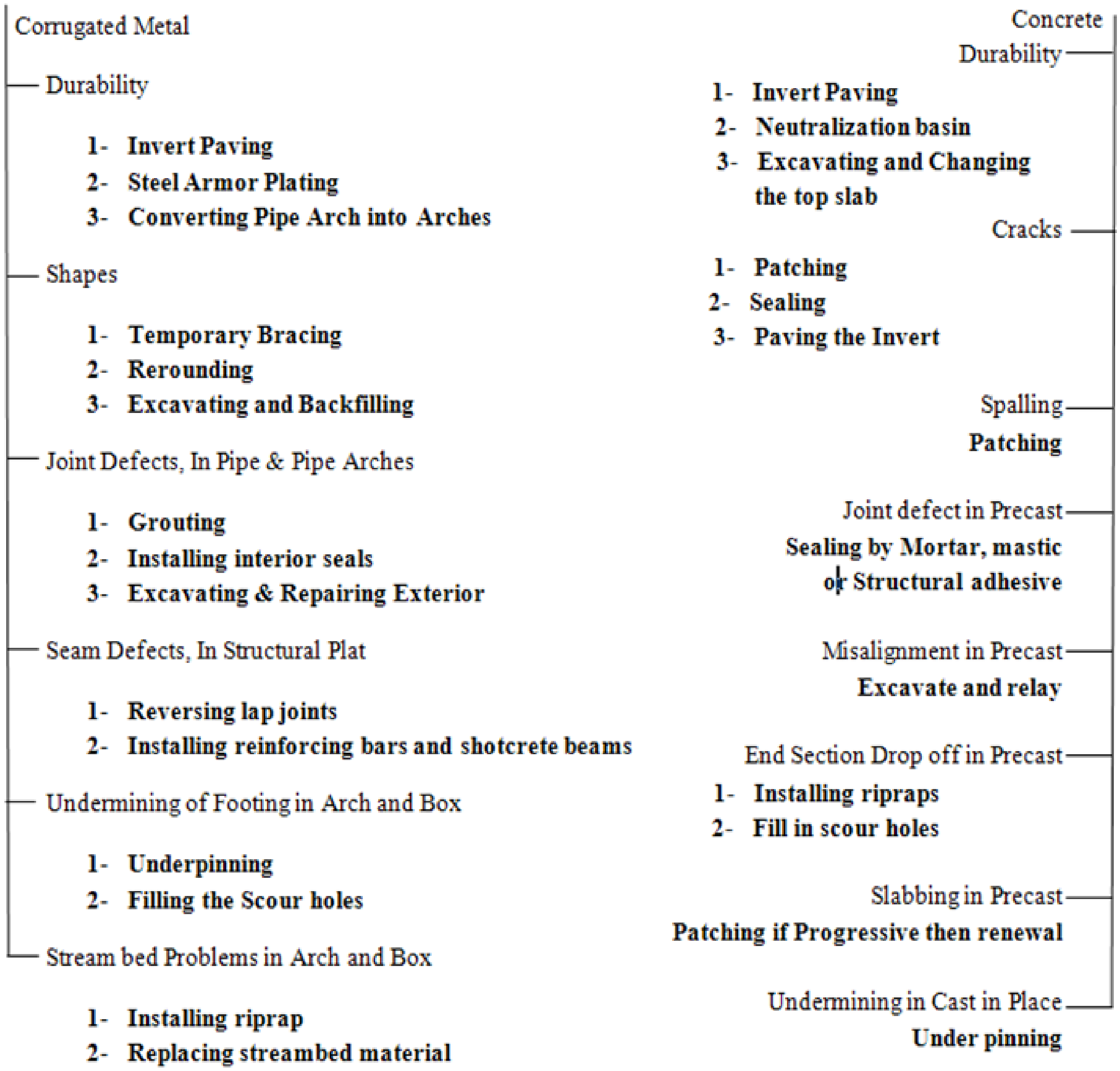


Figure 2-5. Overview of common problems and repair methods for corrugated metal culverts and concrete culverts (Najafi et al. 2008).

Corrugated Metal Structural Plate Culvert Standards:

- ASTM A761 / A761M -04(2009) Standard Specification for Corrugated Steel Structural Plate, Zinc-Coated, for Field-Bolted Pipe, Pipe-Arches, and Arches
- ASTM B790 / B790M -00(2006) Standard Practice for Structural Design of Corrugated Aluminum Pipe, Pipe-Arches, and Arches for Culverts, Storm Sewers, and Other Buried Conduits
- ASTM A760 / A760M -09 Standard Specification for Corrugated Steel Pipe, Metallic-Coated for Sewers and Drains
- ASTM B745 / B745M -97(2005) Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains
- AASHTO M167 (NCHRP 1978)
- Federal WW-P-405 (NCHRP 1978)

2.1.2.3 Aluminum *Culverts*

Aluminum has been used as a construction material for drainage structures for approximately 50 years in the United States. Aluminum culverts are the choice of designers at many sites because these culverts have better corrosion resistance when compared to other metal culverts (Najafi et al. 2008).

Advantages of Aluminum (Ring 1984):

- light weight makes them ideal for shipping
- broad range of size and shapes
- thickness of the sheets and also the corrugations can be selected from a wide range in order to obtain the required strength
- easy and fast assembly and installation procedures
- better resistance to corrosion than steel pipes in salty water

Disadvantages of Aluminum:

- corrugation roughness decreases the rate of flow except for the smooth-lines pipes
- abrasion may cause loss of material, in the case of significant presence of sand and/or rock in a high velocity stream
- generally more expensive than steel pipes
- installation procedures must be handled more carefully compared to steel pipes due to higher flexibility
- sensitivity to live and dead loads compared to the steel pipes due to higher flexibility

Bellair and Ewing (1984) investigated and compared the metal-loss rates observed in uncoated steel and aluminum culverts in New York. The field survey included 190 galvanized steel culverts and 35 aluminum culverts. According to their findings, aluminum culverts showed significantly better performance than uncoated steel culverts throughout the state and with the application of statistical analysis to the field data, they reached the conclusion that 35 mm thickness of material was satisfactory for a 70-year design life, which was already within the minimum thickness requirement (Najafi et al. 2008).

In summary, aluminum culverts and aluminum coated culverts can be considered to have better corrosion resistance compared to steel culverts, if they are used on the sites within the design limits; although installation and backfilling procedures should be handled with greater care due to the higher flexibility (Najafi et al. 2008).

Aluminum Standards:

- ASTM B790/B790M-00 (2006) Standard Practice for Structural Design of Corrugated Aluminum Pipe, Pipe-Arches, and Arches for Culverts, Storm Sewers, and Other Buried Conduits
- ASTM B744/B744M-05 Standard Specification for Aluminum Alloy Sheet for Corrugated Aluminum Pipe
- ASTM B745/B745M-97 (2005) Standard Specification for Corrugated Aluminum Pipe for Sewer Drains
- ASTM B746/B746M-02 (2007) Standard Specification for Corrugated Aluminum Alloy Structural Plate for Field-Bolted Pipe, Pipe-Arches, and Arches

2.1.3 Plastic Culverts

Technological improvements in materials science have enabled pipe manufacturers to produce lightweight and durable pipes from polymers. Plastic pipes are classified as flexible pipes and can be manufactured with the desired durability to withstand the effects of corrosion and abrasion; however, installation and backfilling procedures must be handled with care. Similar to other flexible culvert types, plastic culverts also depend on the soil–structure interaction in terms of structural stability. Improper design and/or installation techniques may lead to deflections and misalignments in plastic culverts (Najafi et al. 2008).

In a study carried out by Gassman et al. (2002), 45 HDPE pipes were inspected and deflections measured with respect to AASHTO and ASTM specifications in South Carolina. According to those inspections, it was observed that 36% percent of the pipes exhibited minor cracks, punctures or bulges; however, the pipes were still in the circular shape. The reason for these deflections and cracks was explained as improper installation techniques, such as poor bedding of soils and inadequate backfilling (Najafi et al. 2008).

A similar study performed by Adams et al. (1989) in which one 24″ diameter corrugated polyethylene pipe was placed under 95′ of fill. According to the results of this study, the pipe was observed to remain in its circular shape and the vertical diameter decrease was observed to be around 4 percent whereas the horizontal diameter increase was observed to be around 0.4 percent. The earth pressure was also measured at the crown section of the pipe and it was determined to be only 20 percent of the vertical embankment pressure. This study shows the significance of soil pipe interaction (Najafi et al. 2008).

ORITE has inspected ten thermoplastic pipes in Ohio for the project “Risk Assessment and Update of Inspection Procedure for Culverts” which included a study of six circular high density polyethylene (HDPE) and four circular polyvinylchloride (PVC) pipes. According to the results, the authors stated that the most frequently observed problems were the deflection of the pipes for more than 7.5%, followed by the localized buckling and misalignment problems at joints. The authors further stated that with proper design and installation, these pipes could be in service for at least 20 years (Najafi et al. 2008).

2.1.3.1 Polyethylene *Pipes*

Polyethylene pipes are not susceptible to galvanic corrosion associated with electro-chemical attack. Polyethylene pipes are also not corroded by pH extremes, salts, or other chemically induced corrosion. Typically, polyethylene pipes are more abrasion resistant than concrete and metal pipes. In fact, in testing in both the United States and Europe, polyethylene has demonstrated wear rates up to 10 times less than steel (Gabriel 2010).

<u>*Polyethylene Standards*</u>:

- ASTM D2239-03 Standard Specification for Polyethylene (PE) Plastic Pipe (SIDR-PR) Based on Controlled Inside Diameter
- ASTM F1055-98(2006) Standard Specification for Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing
- ASTM D3261-10a Standard Specification for Butt Heat Fusion Polyethylene (PE) Plastic Fittings for Polyethylene (PE) Plastic Pipe and Tubing
- ASTM F2306/F2306M-08 Standard Specification for 12 to 60 in. [300 to 1500 mm] Annular Corrugated Profile-Wall Polyethylene (PE) Pipe and Fittings for Gravity-Flow Storm Sewer and Subsurface Drainage Applications
- ASTM F894-07 Standard Specification for Polyethylene (PE) Large Diameter Profile Wall Sewer and Drain Pipe
- ASTM F405-05 Standard Specification for Corrugated Polyethylene (PE) Pipe and Fittings
- ASTM F810-07 Standard Specification for Smoothwall Polyethylene (PE) Pipe for Use in Drainage and Waste Disposal Absorption Fields
- ASTM F667-06 Standard Specification for Large Diameter Corrugated Polyethylene Pipe and Fittings
- ASTM F405
- AASHTO M252

2.1.3.2 High *Density Polyethylene Pipes*

High density polyethylene (HDPE) pipes are effective for drainage of hostile effluents, such as acid rain, acidic mine wastes, aggressive landfill leachates and effluents with high concentrations of road salts, fuels, and motor oils. Laboratory studies indicate that only a negligible increase in abrasive wear of HDPE pipes may be expected when the pH drops from neutral (pH = 7) to medium-low acidic conditions (pH = 4). A reported field study showed that HDPE pipe is unaffected by acid mine run-off of pH levels ranging from 2.55 to 4 (Gabriel 2010).

HDPE Standards:

- ASTM F2619/F2619M-07 Standard Specification for High-Density Polyethylene (PE) Line Pipe
- ASTM F2737-10 Standard Specification for Corrugated High Density Polyethylene (HDPE) Water Quality Units
- ASTM F2487-06 Standard Practice for Infiltration and Exfiltration Acceptance Testing of Installed Corrugated High Density Polyethylene Pipelines
- ASTM F1759-97(2010) Standard Practice for Design of High-Density Polyethylene (HDPE) Manholes for Subsurface Applications
- ASTM D2513 – Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing and Fittings
- ASTM F714 - Standard Specification for Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Outside Diameter
- ASTM D3035 - Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter
- ASTM F1533 – Standard Specification for Deformed Polyethylene (PE) Liner
- AWWA C-901 & C-906 – Standard for PE Pressure Pipe and Tubing

2.1.3.3 Polyvinylchloride *Pipes*

Polyvinylchloride (PVC) is a noncorrosive pipe material that is commonly used in trenchless pipe repair. PVC is also not vulnerable to deterioration from low resistivity soils. These pipes are also well suited for sanitary sewers because they are resistant to most wastewater chemicals found in sewage lines. Furthermore, PVC is resistant to abrasion and erosion. When compared to other thermoplastics, PVC is less prone to sagging and ponding because of its higher modulus of elasticity (Uni-Bell PVC Pipe Association 2007). While strong, PVC pipes are also flexible, which can lead to the development of fewer cracks or breaks. Certain additives in PVC are, however, susceptible to bacteria-induced corrosion, though PVC is resistant to bacteria attack. Certain solvents such as aromatic and chlorinated hydrocarbons, ketones and esters can cause cracking in PVC (Zhao 1998).

PVC Standards:

- ASTM F1735-09 Standard Specification for Poly (Vinyl Chloride)(PVC) Profile Strip for PVC Liners for Rehabilitation of Existing Man-Entry Sewers and Conduits
- ASTM D1784-08 Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds
- ASTM D1785-06 Standard Specification for Poly(Vinyl Chloride) (PVC) Plastic Pipe, Schedules 40, 80, and 120
- ASTM D2729-03 Standard Specification for Poly(Vinyl Chloride) (PVC) Sewer Pipe and Fittings
- ASTM D3034-08 Standard Specification for Type PSM Poly(Vinyl Chloride) (PVC) Sewer Pipe and Fittings
- ASTM F512-06 Standard Specification for Smooth-Wall Poly(Vinyl Chloride) (PVC) Conduit and Fittings for Underground Installation
- ASTM F679-08 Standard Specification for Poly(Vinyl Chloride) (PVC) Large-Diameter Plastic Gravity Sewer Pipe and Fittings
- ASTM F794-03(2009) Standard Specification for Poly(Vinyl Chloride) (PVC) Profile Gravity Sewer Pipe and Fittings Based on Controlled Inside Diameter
- ASTM D2122 – Standard Test Method for Determining Dimensions of Thermoplastic Pipe and Fittings
- ASTM D2412 - Standard Test Method for Determination of External Loading
- Characteristics of Plastic Pipe by Parallel-Plate Loading
- ASTM F1871 – Standard Specification for Folded/Formed Poly (Vinyl Chloride) Pipe Type A for Existing Sewer and Conduit Rehabilitation
- ASTM D2444 – Impact Resistance
- ASTM D790 – Flexural Properties
- ASTM D638 – Tensile Properties
- ASTM D2680; ASTM D2751; ASTM D3033; ASTM D3034
- AASHTO M264

2.2 INSPECTION of Pipe Culvert Repairs

Pipe culvert inspections are performed to verify their condition and make decisions on necessary maintenance, repair, renewal, or replacement activities (Najafi et al. 2008). Culvert inspection requires a combination of skills, experience, proper equipment, knowledge of installation methods and design criteria, and an intimate knowledge of the host pipe materials and repair methods themselves. Culvert barrel inspection criteria and rating methods were developed by the Federal Highway Administration (Arnoult 1986; Ballinger and Drake 1995a, 1995b), the Federal Emergency Management Agency (FEMA 2005), and the Ohio Department of Transportation (Najafi et al. 2008). There does not appear to be any published criteria or methodologies for inspecting the conduit repair itself, which differs from that of inspecting the host pipe. This section lists the relevant inspection criteria for host pipes that are made of corrugated metal, concrete, and thermoplastics materials.

2.2.1 Concrete Host Pipe Inspection

Concrete host pipe should be checked for:

- cracking
- scour and abrasion
- settlement
- joint separation or misalignment
- corrosion of reinforcing steel
- discoloration and scaling

2.2.2 Corrugated Metal Host Pipe Inspection

Corrugated metal host pipe should be checked for:

- corrosion
- scour and abrasion
- coating loss

- perforations
- cracking
- joint separation or misalignment
- seam misalignment
- shape changes and deflection
- undermining of ends or interior sections

2.2.3 Thermoplastic (PVC or HDPE) Host Pipe Inspection

PVC and HDPE host pipe should be checked for:

- joint separation or misalignment
- shape changes, deflection, and buckling
- seam misalignment
- settlement
- scour and abrasion
- splitting or cracking

2.2.4 Specialized Pipe Inspection Equipment

Generally, conduits with diameters 36″ or larger can be inspected by man-entry, if proper Occupational Safety and Health Administration (OSHA) precautions are taken. Conduits with diameters smaller than 36″ are generally considered inaccessible for man-entry and require specialized inspection equipment (FEMA 2005). The most widely used method of specialized pipe inspection is closed circuit television inspection (CCTV) consisting of a camera mounted on a tethered or autonomous robotic crawler. CCTV inspection is preferred over man entry for safety reasons (Najafi et al. 2008). Man-entry is not recommended due to various hazards that may be encountered, such as poor air quality, confined space, animals, poisonous plants, insects, etc.

Various add-ons to CCTV equipment include:

- sonar or ultrasound for inspecting conduit surfaces that are below the water line

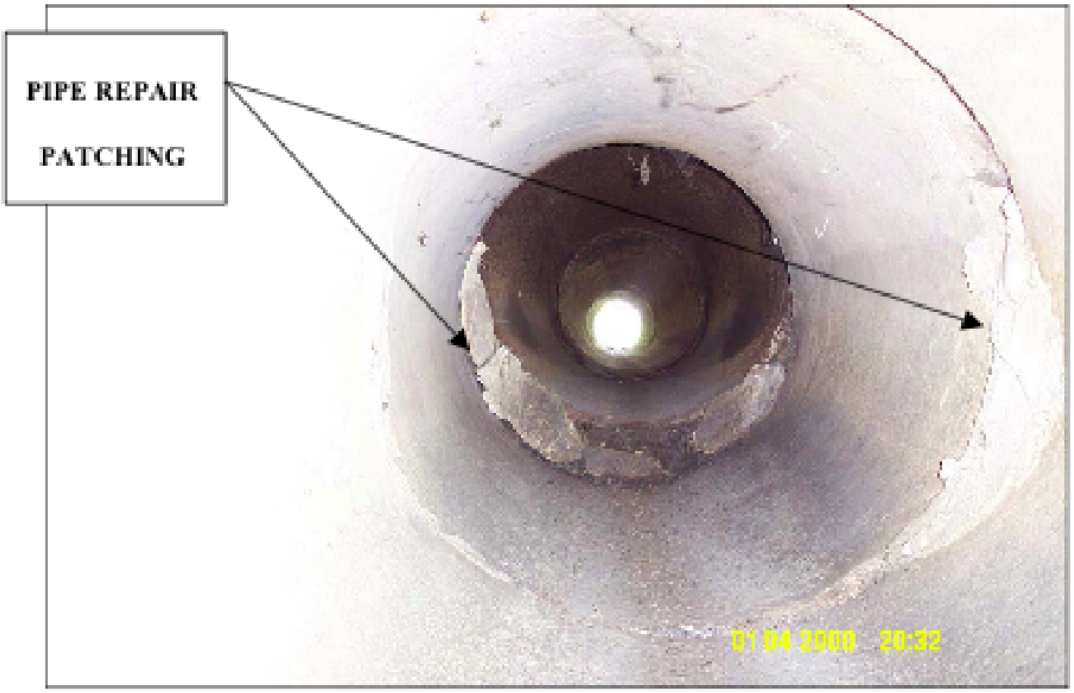
- laser-based scanning
- sewer scanning evaluation technology (SSET) – three-dimensional scanning and imaging of the pipe

2.3 Assessment and Evaluation of Culvert Pipe Repairs

The Delaware and Illinois Departments of Transportation (DelDOT and ILDOT, respectively) have published recent internal memorandums to help culvert inspectors recognize and assess culvert repairs through a series of photo images (DelDOT 2009; ILDOT 2010). Delaware also developed a set of pipe defect terms to classify defects in terms of structural, operation/maintenance, and construction features (DelDOT 2009). The terms closely resemble those of the National Association of Sewer Services Companies (NASSCO) Pipeline Assessment and Certification Program (PAPC).

Figures 2-6 and 2-7 show examples of various pipe repair defects detected by CCTV inspection. The assessment of the durability of in-situ pipe repairs is more accurately determined by CCTV inspection of the actual repair point using available advanced technologies such as sonar, laser scanning, and sewer scanning evaluation technology (SSET). Figure 2-8 is a form developed by the DelDOT for calibrating and measuring pipe defects as viewed from CCTV video logs.

Typical problems associated with the interior of conduits include deterioration, obstructions, joint offsets and separations, defective joints, and cracking. Assessment and evaluation of pipe repair defects will depend on the ability of the inspector to detect those areas through training on what to look for by repetitive viewing of photos of pipe and pipe repair defects. Inspectors should also become familiar with pipe inspection techniques of published FHWA, FEMA, and respective state DOT standards.



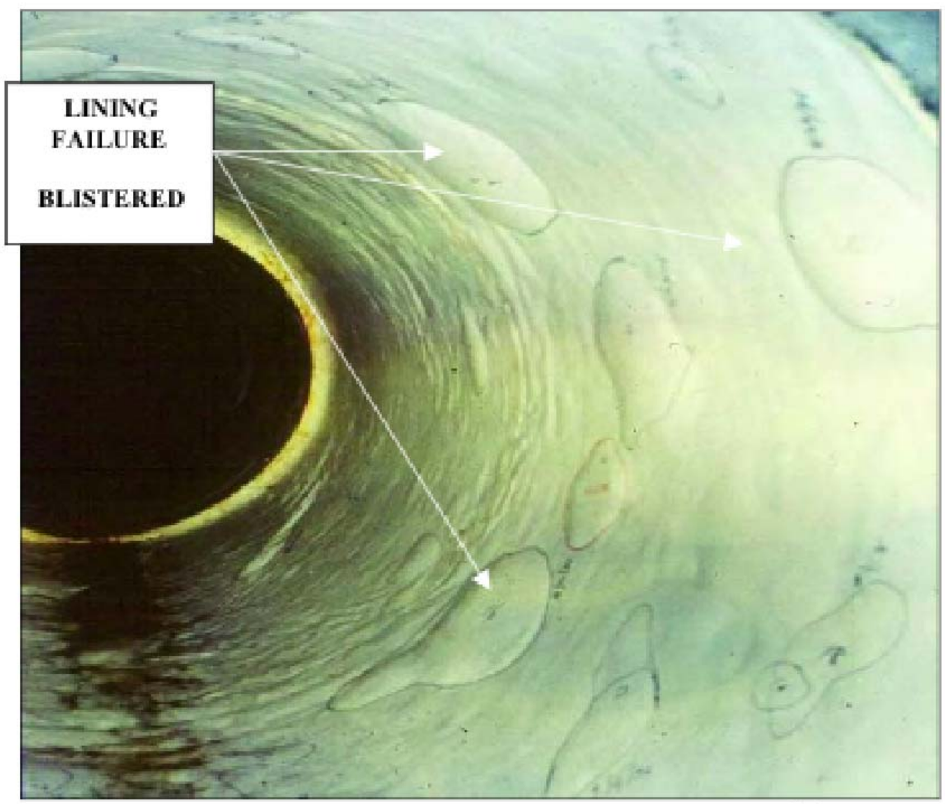
Original pipe section(s) repaired by patching.

Original pipe section(s) repaired using localized liner.

Figure 2-6. Pipe repairs by patching (above) and lining (below) (DelDOT 2009).

CT

Lining no longer formed to original cross surface
- Wrinkled (not smooth) Defective Surface



CT

Lining surface has been damaged (not smooth).

Figure 2-7. Failed lining repairs (DelDOT 2009).

IN-PIPE DEFECT MEASUREMENT RECORD

PAGE __1__ of ____

CCTV Monitor Screen Size of Installed Pipe Defects

This table records the CCTV Monitor screen size (to 1/32 inch) of pipe defects as viewed by the same CCTV camera/configuration as used to develop the calibration information used for comparison.

PROJECT/NUMBER: ____________ **DATE OF INSPECTION:** ____________

PROJECT NAME: ____________ **CONTRACTOR:** ____________

CCTV EQUIPMENT INFORMATION

CCTV COMPANY/VEHICLE INFORMATION

COMPANY NAME: ____________ **PHONE:** ____________

OPERATOR NAME: ____________ ____________

CCTV VEHICLE #: ____________ Vehicle Manufacturer: ____________

Camera Manufacturer: ____________ Camera Manufactuer Model #: ____________

MONITOR INFORMATION

Diagonal Screen Size: ____________ Full Screen Image: Yes / No (Circle)

If not full screen image, explain: ____________

I assure that the following measurments are as accurate as possible using the camera and vehicle described above.

____________ ____________

SIGNED (CCTV Operator) DATE OF CALIBRATION:

CALIBRATION INFORMATION USED FOR COMPARISON

DATE OF CALIBRATION: **ATTACH CALIBRATION CHART TO THIS RECORD**

INSPECTION OBSERVATION RECORD

Tracking Indicator	PIPE **Size/Type**	PIPE **Position**	**MONITOR SIZE** (1/32 in.) of In-pipe Defect Image	+/- Value	**DEFECT COMMENTS**

Figure 2-8. Form for recording calibrated CCTV measurements of pipe defects (DelDOT 2009).

2.4 Repair and Rehabilitation Methods

2.4.1 Introduction

As pipes and culverts age, they deteriorate and probability of failure increases with time. Even to date, there is no simple way to accurately predict when a culvert will fail or require service. This requires agencies to inspect these structures for signs of degradation and conduct periodic condition assessments to investigate failure risks. Once a functional and/or structural deficiency is identified, the agency must decide if the pipe can be rehabilitated or if it should be replaced. This decision is made difficult because many pipes and culverts run through heavy traffic areas (both vehicular and pedestrian) where traditional pipe replacement strategies may not be an option. The selected repair method must be applicable to the current conditions of the pipe and the problems encountered (Najafi et al. 2008).

In-situ pipe repairs, a form of trenchless rehabilitation, are non-intrusive construction methods which minimize the impact felt by the surrounding environment. These methods consist of various processes to maintain or upgrade the structural conditions and flow characteristics of existing underground pipes and culverts (Najafi et al. 2008).

A technically viable rehabilitation solution must meet the following criteria at the minimum (Najafi et al. 2008):

1. It must solve the problem in a manner which maintains all the required performance parameters of the system.
2. It must continue to solve the problem for the design life of the rehabilitated system.
3. It must comply with any relevant codes, standards, or regulations.
4. It must be capable of implementation at an acceptable level of risk and achieve adequate quality.
5. It must allow future maintenance by the utility entity or public agency.

Presently, a general classification system for the available trenchless rehabilitation methods consists of various kinds of relining, coating, and point repair techniques. Relining methods could be further categorized into segmental and continuous lining techniques such as sliplining, cured-in-place pipe, spiral wound lining (grout-in-place pipe), and fold-and-form lining (formed-in-place pipe) (Najafi et al. 2008).

2.4.2 Sliplining

2.4.2.1 Method *Introduction*

Sliplining is one of the more effective ways to restore a culvert to a functional state. Depending on the materials and techniques used for the sliplining, it may be possible to restore the structural strength of deteriorated culverts. Sliplining is the process of inserting a new pipeline into an existing culvert and grouting the annular space. Material of the new pipeline should be different from the existing pipe, which is more resistant to environmental factors in order to eliminate the previously faced problems. Considering that sliplining decreases the total cross sectional area of a culvert, the new pipe material should be smoother and have a lower Manning's roughness coefficient in order to avoid a reduction in flow capacity (Najafi et al. 2008).

Typically, most existing pipes can be repaired by sliplining, including host pipes made from various types of plastics such as polyethylene, high density polyethylene (HDPE) and polyvinyl chloride (PVC), as well as concrete, fiberglass, steel or aluminum (Ballinger and Drake 1995a).

According to Ballinger and Drake (1995a), the proper selection of the most appropriate material will depend upon many factors, including:

- type, kind, and size of the existing culvert

- structural and functional (hydraulic) conditions and adequacy of the existing culvert
- site-specific conditions
- urban or rural location
- flat or mountainous terrain
- amount and velocity of water passing through the culvert at the time of the work
- effluent characteristics
- design life requirements
- service life assigned
- economic factors including the cost of materials, labor and equipment
- expected maintenance

Advantages of Sliplining (Najafi 2005):

- expensive specialized equipment is not needed
- simple technique
- can be used for both structural and nonstructural purposes
- existing flow does not restrict the process
- corrosion resistant
- improved interior surface improves flow characteristics

Limitations of Sliplining (Najafi 2005):

- reduction in pipe diameter
- grouting is required

2.4.2.2 Installation *Methods*

In order to have a successful sliplining, the existing culvert must be inspected for any bends or irregularities, which may obstruct the pulling or pushing of the new pipe. Once the inspections are completed, the host pipe should be cleaned and prepared for sliplining. The new pipe segments should be joined together, inserted into the existing pipe and positioned. The final step is to grout the annular space between the new lining pipe and the old culvert. Grouting must be completed in phases in order to prevent the new lining material from floating and to have good bonding between the new lining material and the old culvert (Salem et al. 2008).

According to *FDOT Standard Specifications for Road and Bridge Construction 2010*, Section 431 (FDOT 2010b), one or a combination of the following methods can be used to slipline a culvert:

- sliplining
- pulling/pushing
- spiral winding
- paneling
- coating or bursting

The annular space between the interior of the host pipe and the exterior of the liner must be sealed or grouted according to the liner manufacturer's written instructions.

The Minnesota Department of Transportation (Mn/DOT) conducted a study on sliplining deteriorated culverts with a variety of materials in order to compare their constructability and costs with open-cut methods (Johnson and Zollars 1992). The findings of this study were:

- Smooth polyethylene pipes had debonding problems due to differences in coefficients of thermal expansion and due to the completion of the grouting process in only one step (which caused floating of the liner);
- Spiral ribbed polyvinyl chloride had inexpensive material cost but installing the ribbed liner through the culvert was difficult. PVC exhibited brittle behavior in cold weather;
- Fiberglass liners had high material costs. Even though the installation was smooth, pushing through corrugated metal exhibited problems. Fiberglass liners are quite heavy, which makes it difficult to handle, compared to other liners; and
- Installation of a spiral ribbed coated steel arch was the most difficult and time consuming. Ribs on the liner were caught on the rivets and corrugation on the older culvert. Although it was the hardest to install, spiral ribbed coated steel arch provided the least flow capacity loss.

2.4.2.3 General *Sliplining*

Liners can be installed by joining discrete lengths, panels or segments of pipe liner in a manhole or other access point and inserting the liner into the host pipe. After installing a liner inside an existing culvert, the annular gap between the liner and the host pipe should be filled with grout. Figure 2-9 shows a cross section of rehabilitated pipe that has been sliplined and has had the annular space between the liner and the host pipe grouted. Grout materials usually range from Portland cement-based mortar to controlled low strength material (CLSM), which is a title that has been established for this class of materials by the American Concrete Institute Technical Committee 229. CLSM is usually a mixture of cement, fly ash, fine sand, and water. Grout may not need to have the strength of structural concrete, but rather only the strength of well compacted soil (Ballinger and Drake 1995a). Grouting should be completed in phases in order to prevent floating of the renewal pipe and to improve the bond between the host and new pipe. Grouting in lifts helps to minimize flotation.

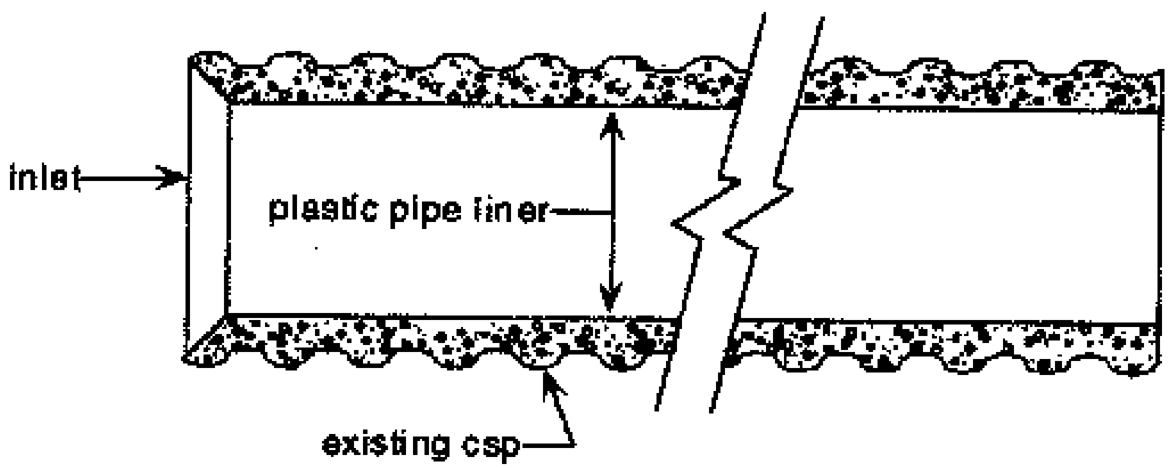


Figure 2-9. Grouting the annular space between a new pipe and the host pipe (Caltrans 2003b).

<u>Sliplining Using Precast Concrete Pipes</u>. Precast concrete has the advantage of being handled easier than metal sections because they may be cast in shorter sections. Precast concrete can be pulled into the culvert and connected inside the culvert, thus minimizing the amount of work space needed outside of the culvert.

Sliplining Using Steel Pipes. Corrugated pipes and pipe arches must be prefabricated to the desired length or assembled by connecting them together at the job site. If multiple sections are being used, then they can be connected together outside of the culvert and pulled or pushed into the existing structure. Also, if conditions permit, individual sections may be pulled through and assembled inside the existing culvert using tabs for alignment and grout to hold position. Structural plates can also be used for lining. In that case, the outside dimensions of liner must be sufficiently smaller than the existing culvert so that workmen may handle fastening the bolts from both the inside and the outside. Installation of steel or aluminum pipe liner should be in accordance with the manufacturer's written instructions (FDOT 2010b).

Sliplining Using Plastic Pipes – Overview. Polyethylene, high density polyethylene and polyvinyl chloride (PVC) plastic pipes, are available in great diversity for lining culverts. Plastic pipes can be fabricated in several ways. They can have a corrugated outer surface or corrugations on both the inner and outer surfaces. Others are smooth on the inside or on both sides. Plastic pipes also differ in type of installation. Some are folded for insertion and then expanded into shape with hot water, such as Nu-Pipe and U-Liner. Plastic pipes may be connected in several ways, but the most common are either snapped together or fusion bonded. Usually, sections of plastic pipe are connected together prior to their installation in a culvert. The Pipe Liners Incorporated system is manufactured in a circle. It is deformed into a U-shape while it is still hot and, at the site, is expanded with steam after insertion (Ballinger and Drake 1995a).

Sliplining Using Polyethylene Pipes. Polyethylene pipe liners should be installed in accordance with ASTM F-585. The manufacturer's written instructions may be substituted for ASTM F-585 with written permission from the Engineer (FDOT 2010b).

Sliplining Using High Density Polyethylene Pipes. High density polyethylene pipes (HDPE) may be either a fusion-welded continuous pipe or a segmental pipe which is a string of discrete pipe barrels connected by joints (e.g., threaded, snap-together, welded, or similar joints) (Salem et al. 2008). High density polyethylene pipe liner should be installed in accordance with ASTM F-585. The manufacturer's written instructions may be substituted for ASTM F-585 with written permission from the Engineer (FDOT 2010b).

Sliplining Using Polyvinyl Chloride Pipes. Polyvinyl chloride pipe liner should be installed in accordance with ASTM F-1698 (FDOT 2010b).

Sliplining Using Fiberglass Pipes. Fiberglass pipes are generally more expensive than plain unreinforced plastic pipe and they are more routinely used to line pipelines. The largest, and strongest, of such pipe is filament wound with glass fibers in a polyester resin. The connections of fiberglass pipe include O-ring seals, with one being used for low pressure applications and two being used for high pressure applications. Another type of fiberglass pipe is made with a combination of glass fibers and a sand-resin mixture that produces a strong, but somewhat heavier and less expensive pipe (FDOT 2010b).

Fiberglass Standards:

- ASTM D5685 -05 Standard Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe Fittings
- ASTM D3567 -97(2006) Standard Practice for Determining Dimensions of Fiberglass (Glass-Fiber-Reinforced Thermosetting Resin) Pipe and Fittings
- ASTM D3754 -06 Standard Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer and Industrial Pressure Pipe
- ASTM D3840 -01(2005) Standard Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Fittings for Nonpressure Applications
- ASTM D3517 -06 Standard Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe
- ASTM D2992 -06 Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings

- ASTM 2996
- ASTM 2997

Fiberglass, steel or aluminum pipe liner should be installed in accordance with the manufacturer's written instructions (FDOT 2010b).

2.4.2.4 Sliplining *by Pulling/Pushing*

The liner should be installed in accordance with the manufacturer's written instructions. The end of the pipe liner should be protected using a device that uniformly distributes the applied load around the perimeter of the liner. Also, the applied load should be monitored continuously, and the liner should not be stretched by more than 1% of its original length. For liner lengths of 100′ or less, the end protection device may be omitted, with written permission from the Engineer. Furthermore, liner ends should not be sealed, nor grouting begun prior to 24 hours after liner installation (FDOT 2010b). Figure 2-10 illustrates how a pipe can be rehabilitated by either the pull insertion method or the push insertion method (Caltrans 2003b).

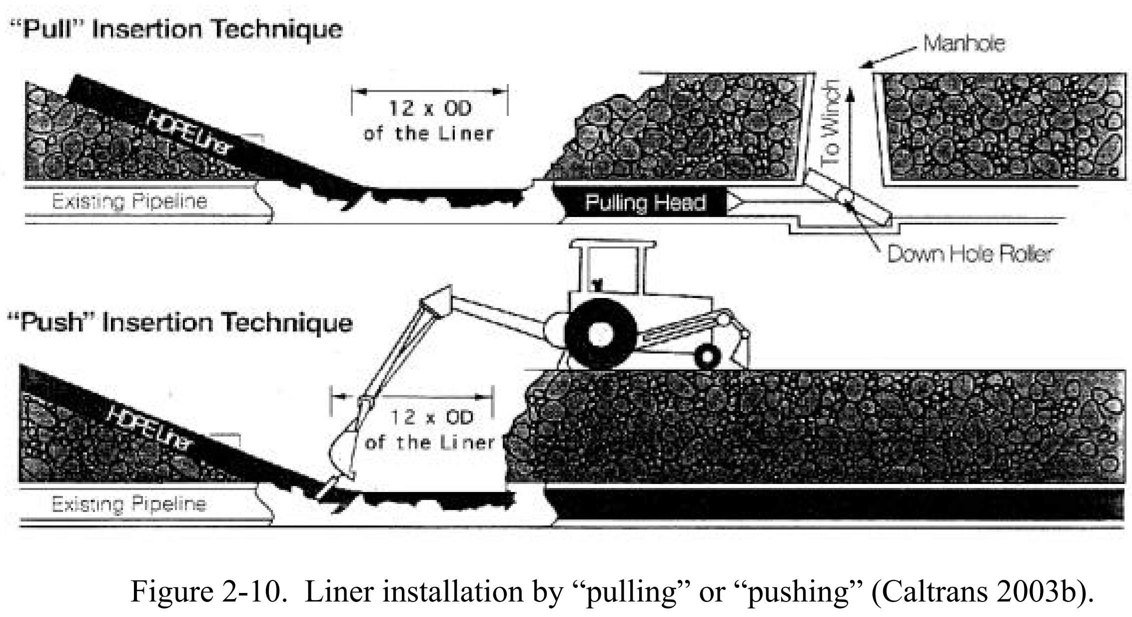


Figure 2-10. Liner installation by "pulling" or "pushing" (Caltrans 2003b).

2.4.2.5 Sliplining *by Spiral Winding*

Typically, spiral wound liners are strips, approximately 12″ wide, made from either polyethylene, polyvinylchloride, or polypropylene, though PVC is most commonly used, which are helically wound inside the pipe at the job site. As the strips are wound, they are interlocked by either snapping into place or by using a sealant. For increased structural stability, a band of steel can also be wound in with the liner strips. The winding can be done either manually or mechanically. Manual winding usually takes place inside man-entry size pipes, while mechanical winding can occur either inside the existing pipe or outside the pipe. Figure 2-11 shows a pipe being repaired by mechanically spiral winding the new liner into the host pipe. The continuous spiral lining is watertight and fits very closely to the host pipe. If there is annular space between the new liner and the existing culvert, it should be grouted (Najafi et al. 2008).

Figure 2-11. Liner installation by spiral wound method (Caltrans 2003b).

<u>Advantages of Spiral Wound Pipe</u> *(Najafi 2005)*:

- large bends can be accommodated
- pipes are not stored on the job site
- mobilization costs are low

Limitations of Spiral Wound Pipe *(Najafi 2005)*:

- skillful personnel are needed
- annular space should be grouted
- special winding machine and skilled personnel are required

Spiral Winding Standards:

- ASTM F1698-02 standard - Details of the spiral wound pipe renewal method
- ASTM F1741-08Standard Practice for Installation of Machine Spiral Wound Poly (Vinyl Chloride) (PVC) Liner Pipe for Rehabilitation of Existing Sewers and Conduits
- ASTM F1697-09Standard Specification for Poly(Vinyl Chloride) (PVC) Profile Strip for Machine Spiral-Wound Liner Pipe Rehabilitation of Existing Sewers and Conduit
- ASTM F1741 -08 Standard Practice for Installation of Machine Spiral Wound Poly (Vinyl Chloride) (PVC) Liner Pipe for Rehabilitation of Existing Sewers and Conduits
- Pipe liner should be installed in accordance with ASTM F-1698 or ASTM F-1741 (FDOT 2010b)

2.4.2.6 Sliplining *by Paneling*

Large diameter noncircular drainage structures can be renewed by panel lining. Depending on the strength of the existing pipe and the concrete, panel linings can be designed either as a self-supporting pipe or as a pipe fill in the annular space. In this type of renewal, workers enter the pipe and install the panels manually. Figure 2-12 shows a worker installing a non-circular panel section (TI 2009). Reductions in the cross sectional area may be significant (Najafi et al. 2008).

Advantages of Panel Lining *(Najafi 2005)*:

- panel lining can be used in any shape of pipe
- chemical and abrasive resistant liners can be installed
- can be installed under restricted flow conditions

Limitations of Panel Lining *(Najafi 2005)*:

- only worker entry pipes can be renewed by this method
- grouting must be applied to the annular space

Figure 2-12. Pipe rehabilitation by paneling (TI 2009).

Pipe liner should be installed in accordance with the manufacturer's written instructions. Limit paneling to host pipes having 90″ or greater internal diameter. Panels should not be placed where a liner joint will lie along or near the crown of the host pipe (FDOT 2010b).

2.4.2.7 Sliplining *by Spray-on Cement Mortar Lining*

Cement mortar consists of well-mixed Portland cement, sand, and water, yielding a dense, homogenous layer. Cement mortar is primarily used for lining the internal surface of potable water steel pipelines. This coating protects the pipe's surface through its alkaline cement environment, which protects the steel, and thus, prevents corrosion. Cement mortar lining is also used to protect cast iron, concrete, and brick pipelines, ranging in size from 4″ to 22′ in diameter. The lining provides a relatively smooth interior surface layer that spans joints and repairs damaged or corroded inverts. It also can fill voids under eroded inverts and open joints between segments of a culvert (Ballinger and Drake 1995a). It is applied by either using a rotating machine or by using shotcrete. The rotating machine helps to fix the mortar to the face of the culvert by centrifugal force. Figure 2-13 is a schematic view of the spray-on cement mortar lining repair method (Caltrans 2003b). The cement mortar lining is relatively thin and decreases the hydraulic roughness, therefore, it does not contribute to significant hydraulic loss and can actually improve flow characteristics. If reinforcing bars or steel mesh is placed before the application of a mortar lining, this can add to the structural strength of the culvert (Ballinger and Drake 1995a). Culverts that are 36″ or larger can accommodate a reinforced cement mortar lining with welded-wire mesh. Spray-on-lining requires only small amounts of additional space at each end of the pipe; however, stream flow will need to be diverted through the culvert. Spray-on-lining costs depend on the lining material; structural reinforcement required; the site location and access; and the availability of specialty contractors. Spray-on-lining provides a structural (or nonstructural) rehabilitation of pipes that can accommodate a small-to-moderate reduction in diameter (Piehl 2005). The coating should be of sufficient thickness in order to create the alkaline environment at the mortar/steel interface. Insufficient coating of the mortar

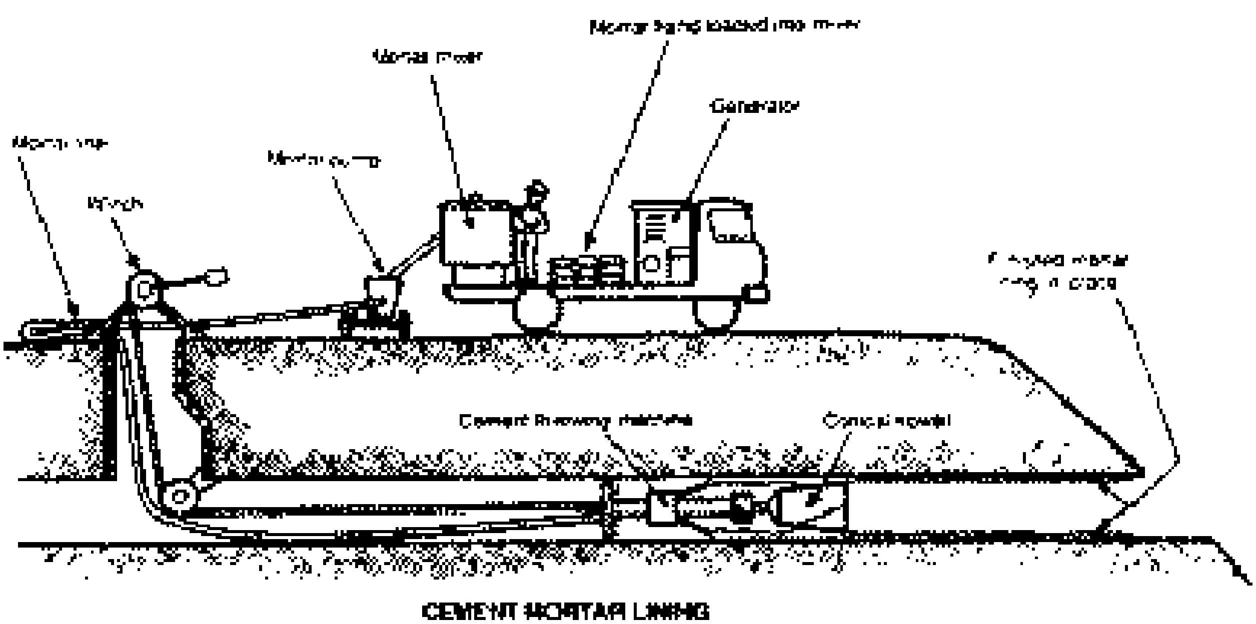


Figure 2-13. Schematic of cement mortar lining installation (Caltrans 2003b).

over the metal will cause the mortar to crack. Although cement mortar can be used in trenchless pipe repairs, it is not appropriate for pipes that leak, or for corroded pipes that have significant thickness reduction (ISTT 2005).

Advantages of this Method:

- elimination of leakage
- reduced surface roughness
- improved flow capacity
- improved corrosion resistance

Disadvantage of this Method:

- limited durability of the cementitious coating
- some agencies have found that the liner does not bond to the existing culvert
- cracking and loss of function have been noted as the liner may crack and separate from the existing culvert periphery

Cement Mortar Standards:

- AWWA C602: Standard for Cement-Mortar Lining of Water Pipelines in Place—4 In. (100 mm) and Larger
- ASTM F2719-09: Standard Practice for Installation of Polyethylene (PE) and Encapsulated Cement Mortar Formed in Place Lining System (FIPLS) for the Rehabilitation of Water Pipelines
- ASTM C398-98 (2008): Standard Practice for Use of Hydraulic Cement Mortars in Chemical-Resistant Masonry
- ASTM C399-98e1 (2008): Standard Practice for Use of Chemical-Resistant Resin Mortars
- ASTM F2551-09: Standard Practice for Installing a Protective Cementitious Liner System in Sanitary Sewer Manholes

Use of materials and installation of the pipe liner should be in accordance with the manufacturer's written instructions (FDOT 2010b).

2.4.2.8 Sliplining *by Non-Cementitious Coatings*

Spray-on linings do not always have to be cementitious based, they can also be resinous materials such as epoxies. These non-cementitious spray-on linings are applied in the same fashion as cementitious linings, with a rotating machine spinning at a constant rate applying the lining. Field application can be applied either on the surface or below the surface. The moisturized environment for below surface repair methods has posed problems to the repair process. Moisture prevents the coating from curing completely and also weakens the ability of the coating to bond to the pipe's structure. Various coatings with high moisture tolerance, such as epoxies, urethane and urea, have been shown to overcome this problem. Nonetheless, the effects of moisture during underground pipe repair process should be noted. Resinous materials are not used for structural rehabilitation projects.

Properties Determining Pipe Longevity and Durability:

1. cathodic disbondment (CD) resistance
2. ability to conduct cathodic protection (CP) currents
3. CP is able to target the disbanded area and continue to protect the pipe, in the event disbondment occurs
4. low CP shielding
5. allows CP to reach disbanded location more easily
6. corrosion resistance
7. abrasion tolerance
8. pH tolerance

Types of Pipe Coating – Aluminum. Aluminum is a common coating discoverable in steel pipes. As a hard alloy, aluminum can possess tiny fissures; however, this alloy is capable of providing cathodic protection which contributes to its durability (Ballinger and Drake 1995a). With erosion protection to prevent the corrosion of steel pipes, this coating depicts excellent corrosion and moderate abrasion. Both these resistant factors reinforce the longevity of the pipe.

Unfortunately, this coating suffers under severe abrasion, therefore, it will perform most idealistically in the absence of notable abrasion. It also does not cooperate well with heavy metals such as iron, copper, etc., and its performance is less competent in highly acidic environments.

Compared to aluminum coatings, galvanized coatings experience faster corrosion and more frequent environmental setbacks. Studies indicate that in normal environments, the service life of aluminum coated steel pipes exceeds 75 years, whereas galvanized coatings situate near the 50 year mark (AK Steel 1995).

Aluminum Coating Standards:

- AASHTO M274 (Aluminized Steel Type 2 material)
- AASHTO M36 and ASTM A 760 (conduit, pipe)
- AASHTO Standard Bridge Design Specifications, Section 12 (structural design) and ASTM A 796
- ASTM A 798 (Installation)
- ASTM A929 / A929M – Standard Specification for Steel Sheet, Metallic-Coated by the Hot-Dip Process for Corrugated Steel Pipe

Types of Pipe Coating – Epoxy. Made from polymers, epoxy coatings are mainly applied on the interior of copper and steel pipes to deliver safe and potable drinking water by protecting against corrosion. In effectively controlling the corrosion rates of pipes, epoxy coatings contribute to a longer life span of 40 to 60 years for the pipes (USACE 1999). Compared to aluminum coated pipes, epoxy coatings have higher abrasion resistance. However, their brittle properties can attract more impact damages (Ault and Ellor 2000). Regrettably, new epoxy coatings may not easily intermingle with the existing pipes and may be a more expensive approach to pipe repairs (Salem et al. 2008). A laboratory study evaluated galvalume coating, aluminum coating, and epoxy coating under extremely low pH levels and concluded epoxy coating to have the most excellent results (Ault and Ellor 2000).

Epoxy Coating Standards:

- ANSI/NSF 61 Drinking Water System Components-Health Effects
- ANSI/AWWA C210-97 Liquid-Epoxy Coating systems for the Interior and Exterior of Special Sections, Connections, and Fittings for Steel Water Pipes

Types of Pipe Coating – Galvalume (Aluminum-Zinc). Galvalume is composed of an aluminum-zinc alloy with 43.4 percent zinc, 1.6 percent silicon, and 55 percent aluminum. It can be applied on steel and concrete pipes. Normally, when exposed to surroundings, the zinc-abundant areas tend to corrode first; however, due to the coating's dendritic properties, corrosion eventually fills in the interdendritic spaces and, as a result, effectively decreases the corrosion rate by four times. Conversely, the aluminum-abundant areas are rarely affected by the environment and act as a barrier coat, whereas the zinc-enriched areas provide protection against rusting and shearing. Fortunately, with the predominant percentage of aluminum, the galvalume coating can reach up to 400° C (750° F) with no discoloration and approximately up to 650° C (1200° F) with minimal oxidation and scaling (GalvInfo Center 2010). In laboratory experience, galvalume outshined galvanized coatings and aluminum coatings in cyclic standing water and corrosion, abrasion, and salt spray resistance (Ault and Ellor 2000).

Galvalume (Aluminum-Zinc) Coating Standards:

- ASTM A792/A792M-09a Standard Specification for Steel Sheet, 55 % Aluminum-Zinc Alloy-Coated by the Hot-Dip Process
- AZ50 [AZM150]
- AZ55 [AZM165]
- AZ60 [AZM180]

Types of Pipe Coating – Polyurethane. One hundred percent (100%) solid rigid aromatic polyurethanes consist of two components: an isocyanate-rich solution and a polyol-rich solution, which is also identified as the ASTM D16 Type V polyurethane coating. The term "100% solids" indicates that the coating resins remain in the liquid state until it is converted, 100%, to a solid film after application. The term “rigid” indicates the physical characteristic of the polyurethanes. This rigid characteristic allows the polyurethanes to have exceptional adhesion and corrosion protection of metals (Guan 2003). In addition, this structure of the polyurethanes provides the coating film with superior resistance to chemicals, water penetration, cathodic disbondment, and temperature extremes (Guan 2000). These attributes follow the list of standards listed above and promote the longevity of the 100% solid rigid aromatic polyurethanes.

A primary health concern when handling 100% solid aromatic polyurethanes is the isocyanates monomer (a powerful irritant that causes inflammation) in the resin. However, most isocyanates used today in 100% solids polyurethane coatings are of the MDI (Diphenylmethane Di-isocyanate) type, which is used to decrease the level of isocyanate monomer in the finished system. As a result, the polyurethane systems are safer to use compared to many epoxy systems (Guan 2001).

The process for applying the 100% solid rigid aromatic polyurethanes coating follows the standard of pipe preparations before the coating can be applied as noted above. The 100% solid rigid polyurethane field-applied coating is made of a sprayable resin and a castable type resin. The sprayable resin includes a 1:1 mixing ratio of a polyiocyanate-rich component and a polyo-rich component. As the coating is being applied, it should be tested for the standards listed above. These standards provide the physical requirements for the pipe to function correctly.

Polyurethane Coating Standards:

- ASTM D4541 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers
- ASTM D4060-10 Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser
- ASTM G95-07 Standard Test Method for Cathodic Disbondment Test of Pipeline Coatings (Attached Cell Method)

- ASTM D714-02 (2009) Standard Test Method for Evaluating Degree of Blistering of Paints
- ASTM D522-93a (2008) Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings
- ASTM G14-04 Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)
- ASTM B117-09 Standard Practice for Operating Salt Spray (Fog) Apparatus
- ASTM D570-98 (2010) -e1 Standard Test Method for Water Absorption of Plastics

2.4.2.9 Sliplining *by Bursting*

In-line replacement of buried pipes involves trenchless procedures in which the deteriorated pipe is replaced with a new pipe having the same or larger diameter. In-line replacement can be performed either by fracturing and splitting the existing pipe and inserting a new pipe namely by pipe bursting, or by destroying and removing the existing pipe, namely by pipe removal (Najafi 2004). Figure 2-14 illustrates the sliplining by pipe bursting process (All American Trenchless Technologies 2010).

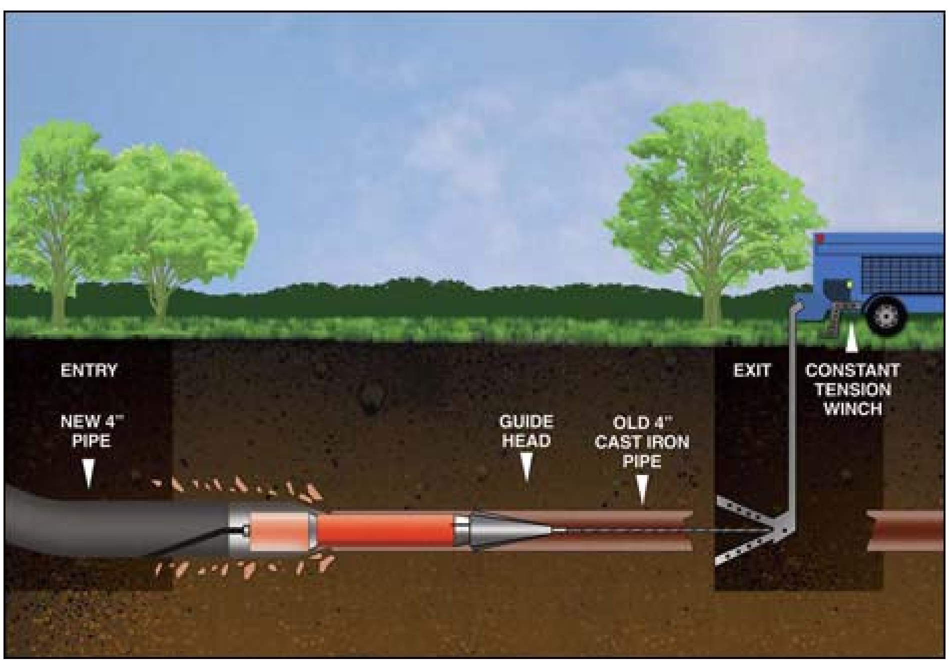


Figure 2-14. Sketch of pipe bursting process (All American Trenchless Technologies 2010).

The pipe liner should be installed in accordance with the manufacturer's written instructions. Also, bursting should be limited to vitrified clay or concrete cross drain or side drain pipe having no lateral connections or risers. Furthermore, bursting should be limited to locations where no part of the host pipe passes within 5′ of any buried utility or pavement base material (FDOT 2010b).

Advantages of Pipe Bursting Methods:

The in-line replacement methods offer the following advantages (Najafi 2004):

- in-line replacement methods can be used to renew a wide range of pipe types
- diameter of the pipe can be increased
- renewed pipe has the same alignment with the existing pipe
- existing pipe does not have to be disposed, if pipe bursting is employed

Limitations of the In-line Replacement Methods:

Some of the limitations of the in-line replacement methods are as follows (Najafi 2004):

- shafts may be required for insertion and reception
- construction equipment over the ground needs working space
- lateral service connections should be established by open cut excavation
- renewal should be performed while the flow is diverted
- nearby utilities and structures may be damaged, if excessive ground movements and vibrations are present in the job site

2.4.2.10 Close-*fit Pipe*

In this type of renewal, the pipe is manufactured before being brought to the job site, which increases the quality of the finished product. Close-fit pipes are generated by modifying the cross sectional area of polyethylene pipes, inserting them to the host pipe and returning the cross sectional area back to the pipe's original shape by applying pressure. Modifying of the cross sectional area is accomplished by using a machine to mechanically fold the pipe into a U or H shape and holding the pipe in this shape with temporary restraining bands (Najafi et al. 2008).

Three types of close fit pipe rehabilitation approaches, thermoformed, fold-and-form, and swagelining and rolldown, will be examined in the following sections.

Advantages of Close-fit Pipe (Najafi 2005):

- new pipe is produced at a controlled environment
- minimal reduction in the existing pipe area
- mechanically folded pipes can accommodate 45-degree bends

Limitations of Close-fit Pipe (Najafi 2005):

- diameter and installation range is limited
- large working space is needed
- flow usually needs to be bypassed

Sliplining with Thermoformed Pipes. To provide a tightly fitting chemical and abrasion resistant pipe, polyvinyl chloride or polyethylene pipes are thermoformed inside the host pipes. In order to insert the new pipes they are either "deformed and reformed," "fused and expended," or "fold-and-formed." Figure 2-15 shows a pipe liner being mechanically deformed at the job site prior to installation (Caltrans 2003b). After insertion, the new pipe is heated and pressurized according to the manufacturer's specifications. In order to assure a tight fit, the pipe needs to be cooled first and then depressurized (Salem et al. 2008).

Advantages of Thermoformed Pipe (Najafi 2005):

- new pipe is produced at a controlled environment (factory), therefore quality is higher and installation is faster
- cross sectional reduction is minimal
- can provide a design life of a new pipe

Limitations of Thermoformed Pipe (Najafi 2005):

- diameter range is limited
- bypassing the existing flow is required in many cases
- large working space may be required for some type of installations

Figure 2-15. Liner being mechanically deformed prior to installation (Caltrans 2003b).

Sliplining with Thermoformed Pipes Standards:

- The details of deformed and reformed type of renewal can be found in the ASTM F1606-05 standard and the details of the fold-and-formed type of renewal can be found in the ASTM F1867-98 standard.
- Manufacturer of the pipe clearly mark diameter measurements at 5-ft. intervals or less to meet the ASTM D 2122 specifications.
- In order to comply with the applicable specifications and standards, samples should be collected from the beginning and end of every reel produced, which should meet following standards.
- ASTM D256 & D 2444: Impact resistance
- ASTM D 2412: Flattening to 60%
- ASTM D 2412: Pipe Stiffness at 5% Deflection
- ASTM D 2152: Acetone Immersion
- ASTM F 1057: Heat Reversion
- ASTM D 638: Tensile Strength
- ASTM D 790: Flexural Modulus

Sliplining with Fold-and-Form Pipes. Fold-and-form technology uses HDPE or polyvinyl chloride (PVC) plastic pipe materials with properties that allow pipe deformation. The pipe lining is folded into a U or H shape that reduces its cross sectional area before insertion into the existing pipe. The liner reverts to its original round shape when subjected to pressure and/or heat. Figure 2-16 illustrates the cross section of a fold-and-form pipe prior to inflation (left pipe) and after inflation (right pipe) (Caltrans 2003b). The annular space between the old pipe and the liner may require grouting, unless the old pipe and the new pipe fit closely together. The method may be structural or nonstructural, depending on the flexural modulus (stiffness) of the material after curing and the structural-dimension ratio of the pipe. With PVC, the fold-and-form method typically is limited to 24″ diameter pipe. HDPE is used with folded pipe technology up to 36″ in diameter. This method may be useful when hydraulic conditions allow a small decrease in the size of the pipe’s upstream opening. Pipes with an abrupt bend, such as those with differential settlement problems, may restrict use. Grouting of the annular space may or may not be necessary, depending on how close the liner fits the old pipe (Piehl 2005).

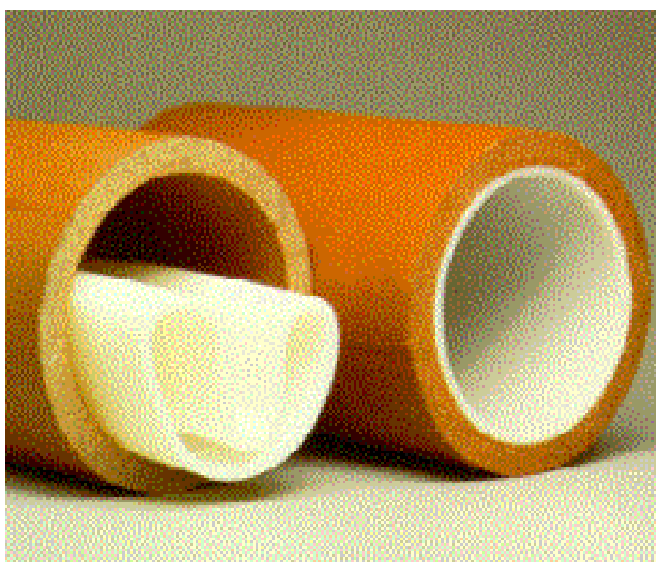


Figure 2-16. Fold-and-form PVC liner before (left) and after (right) heat and pressure are applied (Caltrans 2003b).

Advantages of the Fold-and-Form Pipe:

- can repair even severely corroded pipes
- risk of damage or disruption to buried utilities is minimized
- improves flow characteristics

Limitations of the Fold-and-Form Pipe:

- risk of lining reverting back to original shape
- stresses in the liner can cause the liner to move within the pipe
- existing flow needs to be bypassed

Sliplining with Fold-and-Form Pipes Standards:

- ASTM F 1504 – Standard Specification for Folded Poly (Vinyl Chloride) (PVC) Pipe for Existing Sewer and Conduit Rehabilitation
- ASTM D 1784 – Standard Specification for Rigid Poly (Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds
- ASTM F 1867 - Standard Practice for Installation of Folded/Formed Poly (Vinyl Chloride) (PVC) Pipe Type A for Existing Sewer Conduit Rehabilitation
- ASTM F 1871 – Standard Specification for Folded/Formed Poly (Vinyl Chloride) Pipe Type A for Existing Sewer and Conduit Rehabilitation
- ASTM F 1947 – Standard Practice for Installation of Folded Poly (Vinyl Chloride) (PVC) Pipe into Existing Sewers and Conduits
- ASTM D 3034 – Standard Specification for Type PSM Poly (Vinyl Chloride) (PVC) Sewer Pipe and Fittings

Sliplining by Swagelining and Rolldown. Swagelining and rolldown methods use HDPE or PVC plastic pipe with properties that allow pipe deformation. In swagelining technique, with close-fit pipes, the contractor temporarily reduces the pipe diameter by pulling the pipe string through one or more dies, which may be heated. Figure 2-17 illustrates the schematic of the swagelining process and an actual installation being performed (IPS 2010). In the rolldown technique, similar to swagelining, the contractor temporarily reduces the pipe diameter by mechanical rolling. Both techniques may require grouting of the annular space between the old pipe and the liner, unless the old pipe and the new pipe fit snugly. Both methods may be structural or nonstructural, depending on the flexural modulus of the material and the structural dimension ratio of the pipe. Stream bypass might be necessary prior to installation. Swagelining and rolldown are appropriate repair methods when hydraulic conditions allow for a small decrease in the size of the pipe's upstream opening. Pipes with an abrupt bend, such as with differential settlement problems, may not be suitable for swagelining and rolldown methods (Piehl 2005).

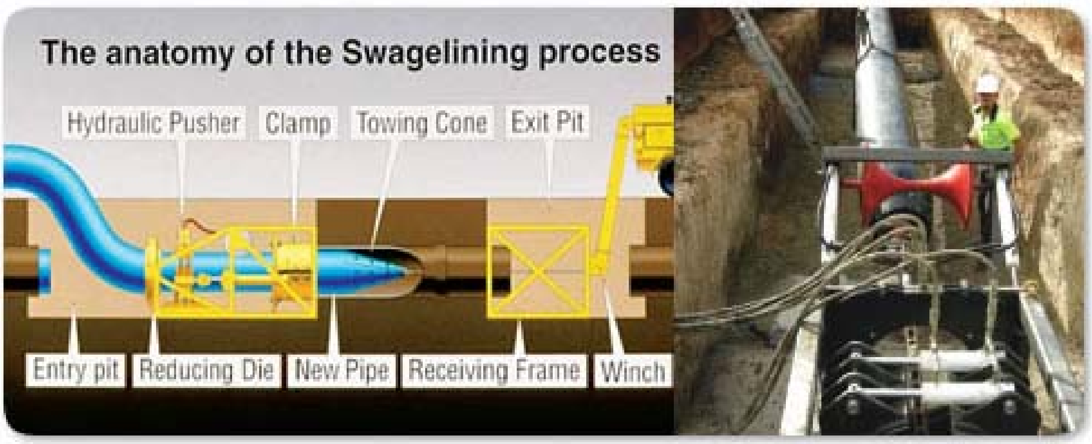


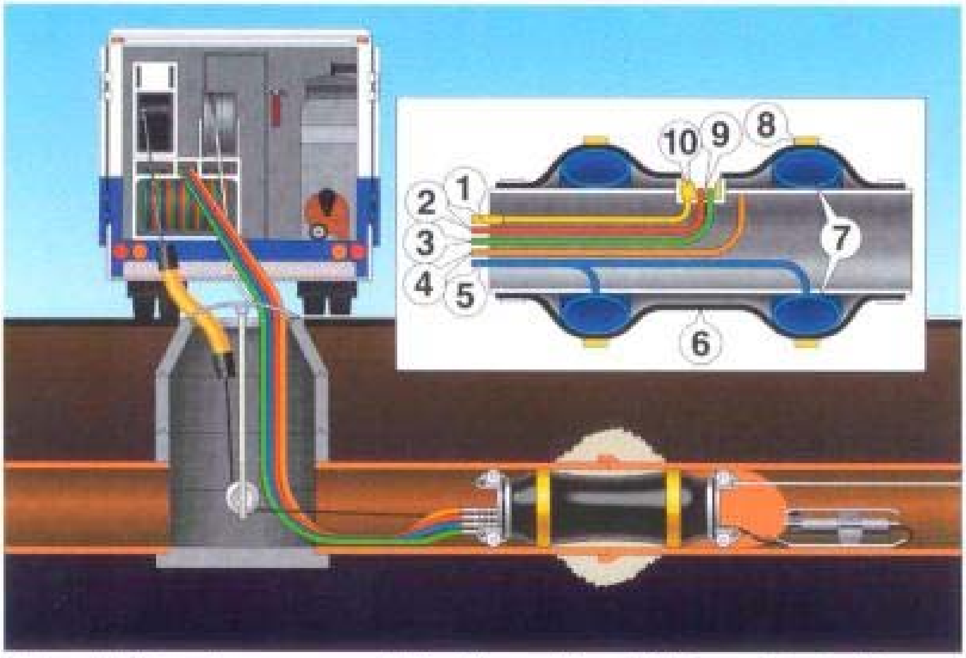
Figure 2-17. Schematic of swagelining process (IPS 2010).

Limitations (Piehl 2005):

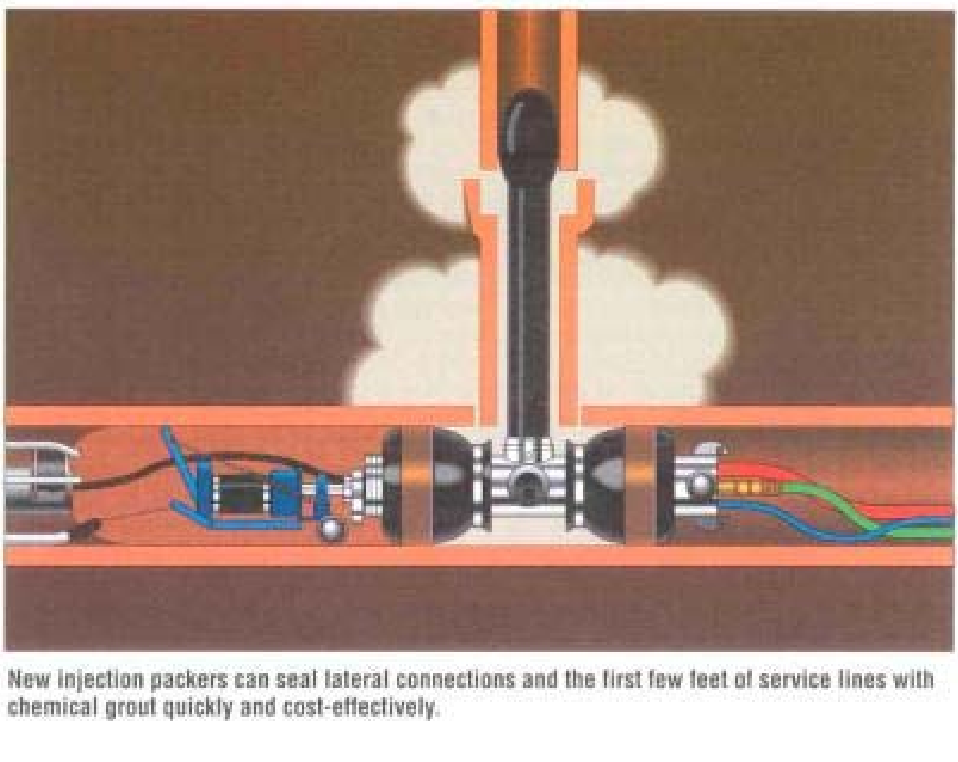
- Currently limited to 48″-diameter pipe
- Flow bypass may be required
- Grouting may be required

2.4.2.11 Sliplining *by Pressurized Grouting*

Chemical Grouting. After coming into practice during the 1960s, the cost-effectiveness and reliability of chemical grouting has expanded its use to many different pipe systems. All chemical grouts listed here are considered "permanent," having a life expectancy of between 25 to 30 years, if applied correctly. Figure 2-18 shows the various components involved in the chemical grouting process as well as a schematic view of chemical grouting rehabilitation being



Modern injection packers are very sophisticated, consisting of; (1) Pressure Sensing Line, (2) Chemical "A" Line, (3) Chemical "B" and Air Pressure Line, (4) Sleeve Air Line, (5) End Seal Air Line, (6) Sleeve, (7) End Seal Elements, (8) Sealing Pads, (9) Chemical Injection Ports, (10) Pressure Sensor Element.



New injection packers can seal lateral connections and the first few feet of service lines with chemical grout quickly and cost-effectively.

Figure 2-18. Schematic view of chemical grouting being applied to a damaged pipe (Caltrans 2003c).

performed (Caltrans 2003c). The drawback is that it often requires the guidance of an experienced professional engineer to apply some of these grouts properly.

Chemical grouting is most commonly used for leaking problems. In the case of leakages, chemical grouting seems to be the only cost-effective method of solving the problem. However, it can be helpful in structural and corrosion problems as well (Oetting 2005).

Materials commonly used for chemical grouting include:

- acrylamide
- acrylate
- polyurethane
- epoxies
- concrete

Chemical Grouting Standards:

- ASTM F2304-03 Standard Practice for Rehabilitation of Sewers Using Chemical Grouting
- ASTM F2454-05 (2010) Standard Practice for Sealing Lateral Connections and lines from the mainline Sewer Systems by the Lateral Packer Method, Using Chemical Grouting
- ASTM F2414-04 Standard Practice for Sealing Sewer Manholes Using Chemical Grouting
- ANSI/NSF Standard 61: Drinking Water System Components -- Health Effects

Acrylamide Grout. Acrylamide grout, which requires approximately 10% acrylamide, is effective in reaching lower levels of permeability than most cement grouts. It is determined by the Department of Energy in report RAP86-69 to have a half-life of 115 years, although durability varies upon conditions. For example, acrylamide can shrink when exposed to constant ultraviolet (UV) rays and degrades more quickly over time, if exposed to constant freeze-thaw or wet-dry cycles. It is usually not a practical or preferred solution for potable water systems.

There have been recent concerns and a few reports published over the association of acrylamide with cancer (NCI 2010). As a result, it is not recommended to be used near potable water systems.

Acrylate Grout. Known for its extremely low permeability (even lower than polyurethane grout in most cases) and resistivity to extreme pHs, acrylate grout provides an ideal option in containing pipes used for transporting hazardous waste.

Unless required for use in extreme conditions such as high/low pH, acrylamide grout usually provides an equally reliable, easier-to-use, more durable alternative to acrylate grout. Acrylate grout has set times that are more difficult to control and has significantly lower durability in comparison.

Polyurethane Grout. Although it does not adhere to concrete, stretch in a moving crack, or stabilize soil effectively, polyurethane grouts can be used as joint filler and have demonstrated a life expectancy of 175 years when not exposed to UV rays.

> *Hydrophilic* – Hydrophilic polyurethane grout is effective for cracks, but not recommended for moving cracks since it often does not stick to cement. Additionally, it is usually only used in underground structures that are usually wet, as hydrophilic gels are prone to shrinkage in dry environments. Some forms of this grout, if used according to the ANSI 61 standards, can even be applied to potable water systems.
>
> *Hydrophobic* - Hydrophobic polyurethane grout is effective for sealing cracks—including moving cracks, stabilizing soil, and creating a water-resistant, movement-resistant barrier between the culvert and the soil. Some hydrophobic grouts are approved for use in potable water systems as well. Although they are optimized under conditions of warmer water with lower pressure, their use is often extended to drier areas since hydrophobic grouts do not require water to function properly.

Epoxies. Epoxy resins are almost completely UV resistant and non-toxic. Additionally, they can be engineered to have chemical resistance or heat resistance. After being cured, they form a material with resistance to pressure as high as 1000 psi. Although epoxies demonstrate great tensile strength and easily adhere to concrete, their life expectancy varies greatly, as these systems are prone to failure in areas of movement and seismic activity. This is rarely an issue in Florida, since most parts are not seismically active.

Concrete Grout. The most common material used for concrete grouting is Portland cement. It is optimized in drier conditions or in water with a pH of approximately 7, as cement grout is quite permeable in higher and lower pH levels.

Numerous sources suggest that concrete can be engineered to have a life expectancy ranging from 70 years (the minimum federal standard) to over 100 years depending on the water-to-cement ratio and other factors (The American Concrete Pipe Association). Some sources even suggest that Portland cement used for grouting can last thousands of years based on chemical modeling estimations (Alcorn et al. 1990). Of course, these may not reflect practical conditions and that number may be considerably lower.

2.4.2.12 Cost *Considerations*

Sliplining costs range from 55 to 80% of the cost of replacing the pipe by traditional open cut method and the following observations have been made:

- If concrete invert lining lasted for four years or more, its use would be more economical than replacing the pipe (Meegoda et al. 2009).
- Invert lining (concrete) would cost 35% more than the cost of slip lining (aluminum), but the slip-lined pipe would last for 50 years (Meegoda et al. 2009).
- Increasing the thickness of plates forming the invert is an economical strategy for extending service life of pipes (Meegoda et al. 2009).
- Cost savings for sliplining a pipe decreases as the depth of the pipe increases, and therefore, sliplining is not a cost effective strategy for deep installation (Okpala and Anderson 1997).

2.4.3 Cured-in-Place Pipe (CIPP)

2.4.3.1 Method *Introduction*

Cured-in-Place Pipe (CIPP) is a process by which a deteriorated culvert is lined with a continuous liner composed of a liquid thermosetting resin-saturated material (Piehl 2005). This type of lining eliminates the future joint defects and provides a corrosion and abrasion resistant invert, thereby having the advantage of lining without joints. The host pipe to be lined by the CIPP method is not required to be circular in shape and CIPP can be used in the pipes with bends. However, the existing flow should be bypassed and the cost can be high due to specially produced tube and a carefully monitored curing process (Salem et al. 2008). CIPP can provide structural (or nonstructural) rehabilitation of existing pipe, depending on the thickness of the liner. Increased wall thickness yields higher strength, but also higher weight which can cause the liner to buckle. The styrene monomer-based resins (polyester and vinylester) in the liner are potentially toxic before they are cured. Nontoxic epoxy resins may better suit a sensitive environment (Piehl 2005). Cured-in-place liners are not suitable for use in abrasive environments, but do perform well in environments where there are considerable temperature fluctuations, differences in diameters and cross sections, bends, and requirements for chemical resistance (WERF 2000).

Advantages of CIPP (Najafi 2005):

- grouting is not necessary
- smooth interior surface enabling an increase in flow capacity
- lining noncircular shapes is possible
- lining can be accomplished even in the presence of bends

Limitations of CIPP (Najafi 2005):

- tube is custom made for each project
- existing flow must be diverted
- successful installation depends highly on the curing process
- can be expensive
- potentially hazardous to the environment

2.4.3.2 *Installation Method*

Workers invert or drag a watertight needle-punched felt-fabric tube saturated with catalyzed polyester, vinylester, or epoxy resin into the pipe. The host pipe should be inspected and cleaned prior to using CIPP as a renewal method. The CIPP flexible tube should then be ordered according to the unique project requirements. Once the tube is brought to the job site, it should be installed using the inversion method or by using a winch. With the inversion method, workers affix one end of the fabric tube on the end of the culvert, while water pressure is used to invert the tube, thereby inserting the tube into the culvert and pressing it against the inside (Salem et al. 2008). Curing takes place by heating and recirculating the water; however, this water must be properly disposed of because of environmental hazards. The pipe also can be cured with ultraviolet light, air, or steam. CIPP liners can be structural or nonstructural, depending on the thickness of the liner (Piehl 2005). Figure 2-19 is an illustration of the before, during, and after cured-in-place pipe repair method (MDWS 2008).

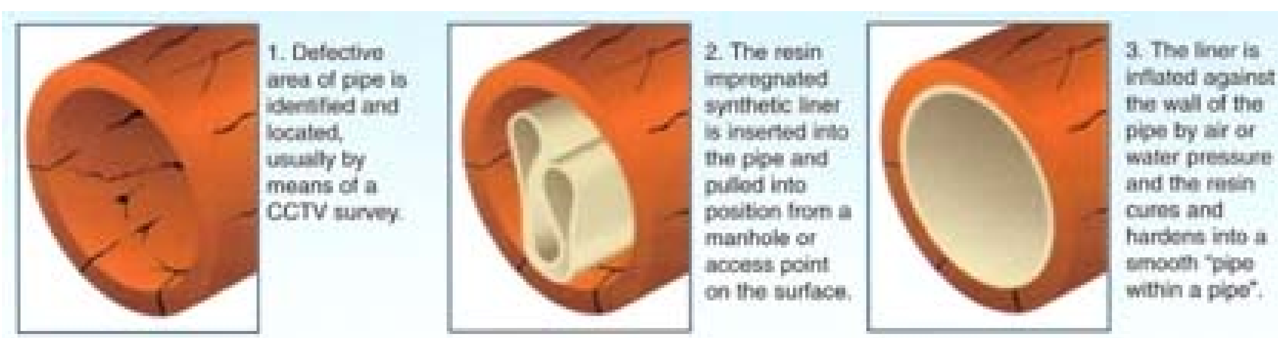


Figure 2-19. Cured-in-place pipe process (MDWS 2008).

2.4.3.3 Installation *Standards*

- A resin impregnated felt tube pipe liner should be installed into the host pipe, and cure in place, in accordance with ASTM F-1216.

- Details of the cured-in-place pipe renewal procedure can be found in ASTM F1216 07b (installation by inversion) and ASTM F1743-96 (installation by pulling in place) standards.
- The testing requirements to determine if the installed CIPP meets the performance requirements are outlined in ASTM F 1216, ASTM F 1743 and ASTM D 5813.
- The chemical resistance properties of the material used in CIPP should meet the requirements of the chemical resistance test in ASTM F 1216.
- Among some of the quality control procedures, it is recommended by the ASTM D5813 that for each inversion designated by the owner, a specified number of CIPP samples must be required.
- ASTM F2019-03 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)
- ASTM F2019-00 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)
- ASTM D5813-04 Standard Specification for Cured-in-Place Thermosetting Resin Sewer Piping Systems

2.4.3.4 Cost *Considerations*

CIPP costs range from $100 per linear foot (perhaps less for large quantities) for 18″ diameter pipe to $800 or more per linear foot for large-diameter pipe (Piehl 2005). As diameters get larger, costs tend to rise more rapidly because of the weight and cost of material, plus the greater difficulty of installation (WERF 2000). This method is comparable to the conventional open-cut method in terms of price. This method is justifiable to be performed in urban areas where space and disruption is critical and at locations where significant reduction in hydraulic capacity in not permissible (Salem et al. 2008).

2.4.4 Internal Seals

Internal seal method offers structural solutions where a segment of the pipe or a pipe joint fails. It can be used for both nonworker entry pipes as small as 6″ and worker entry pipes as large as 110″ (Najafi 2004). It is important to prepare the surface of the damaged area to ensure proper adhesion with the sealing sleeve. Figure 2-20 is a cross section drawing of an internal seal inside a concrete pipe (Trelleborg AB 2010).

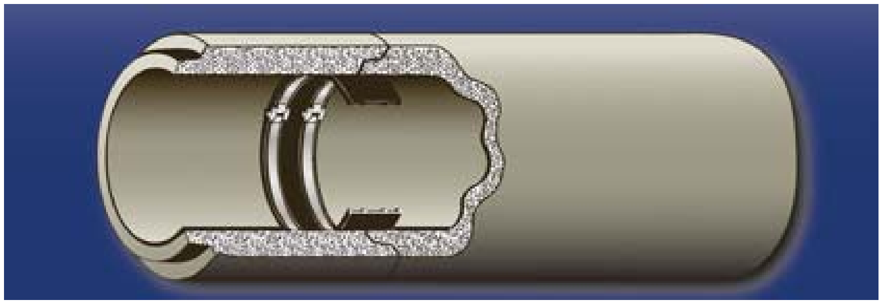


Figure 2-20. Cross section of pipe repaired with internal seals (Trelleborg AB 2010).

Advantages of Internal Sealing (Najafi 2004):

- method offers structural solutions
- method can be applied to solve problems such as pipe breakage, joint settlement, and longitudinal cracks
- gravity sewers, culverts, and pressure pipes can be repaired without excavation

Limitations of Internal Sealing (Najafi 2004):

- internal sleeve may cause a hydraulic loss due to decreased cross sectional area
- method is only applicable to circular pipes

2.4.5 Point Cured-in-Place Pipe (CIPP)

Point CIPP method provides a structural solution to repair a failed section of a pipe. The methodology of point CIPP is similar to the CIPP renewal method in which the whole pipe is being renewed, but instead only a section is repaired. The lining material is applied to the desired location by use of an inflatable packer and cured by the use of hot water or steam (Najafi 2004). The liner should not be heated before it is pressured to the surface of the existing pipe. Figure 2-21 illustrates how the point cured-in-place pipe repair method is installed (Perma-Liner Industries 2010).

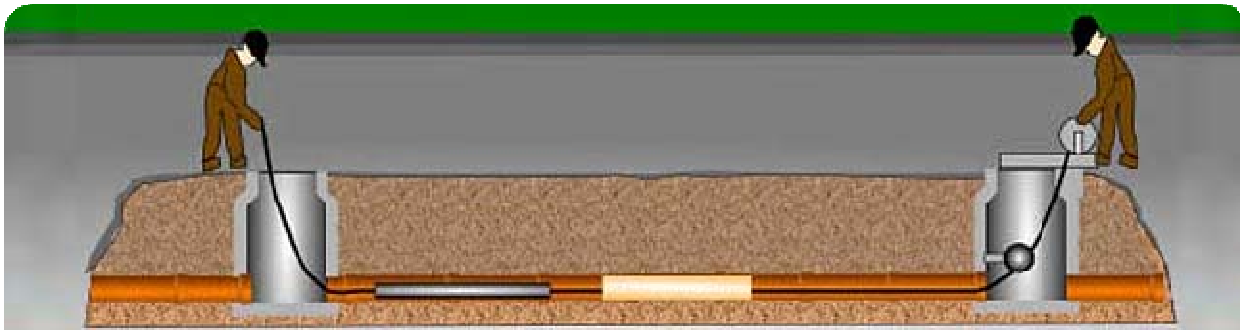


Figure 2-21. Point repair using cured-in-place pipe method (Perma-Liner Industries 2010).

<u>Advantages of Point CIPP</u> *(Najafi 2004)*:

- defective pipe sections between 3′ and 50′ of length with diameters up to 60″ can be repaired
- point CIPP adheres to the existing pipe tightly and eliminates infiltration
- repair procedure may usually be performed without diverting the existing flow
- method offers structural solution to the defective pipe segment
- lining does not obscure the flow due to tapered smooth ends

<u>Limitations of Point CIPP</u> *(Najafi 2004)*:

- method does not improve the structural condition of the pipe as a whole
- point CIPP method may be more expensive than other point source repairs
- hydraulic capacity may be slightly decreased due to lining

<u>Point CIPP Standards</u>:

- wall thickness design and installation of CIPP utilizing the pull-in and invert through process is described in ASTM F 1743 (ASTM 2003)

2.4.6 Invert Paving

Invert paving is a common procedure to protect deteriorating inverts of culverts from further degradation due to corrosion and abrasion. If the deterioration has reached a point where the loss of material from the invert section is endangering the structural integrity of the culvert, reinforcing steel should be welded while paving the invert. Various concrete types such as

Portland cement concrete, steel fiber reinforced concrete, and high-strength concrete can be used for invert paving procedures (Salem et al. 2008).

The detailed explanation of invert paving procedure can be found in FHWA's *Culvert Repair Practices Manual, Volume 2* (Ballinger and Drake 1995b). According to this manual, the procedure starts with diverting the flow. Water flow to the culvert should not be allowed until the concrete has cured for 48 hours. The culvert should be cleaned thoroughly and the reinforcing steel should be placed on the culvert. The amount of the reinforcing steel to be placed should be adequate to restore the structural strength of the culvert. Concrete should be placed on the invert covering an adequate percentage of the cross sectional area depending on the geometry of the culvert. Finally, the surface of the pavement should be smoothened and concrete should be properly cured before returning it to service (Ballinger and Drake 1995b). Figure 2-22 is a schematic view of the recommended application of invert paving (Caltrans 2003c).

Advantages of Invert Paving:

- cost of repair is low
- no need for special equipment

Limitation of Invert Paving (Salem et al. 2008):

- durability of the paved section is usually limited

Invert Paving Standards:

- ASTM A849-00 (2005) Standard Specification for Post-Applied Coatings, Pavings, and Linings for Corrugated Steel Sewer and Drainage Pipe
- ASTM A979/A979M-03 (2009) Standard Specification for Concrete Pavements and Linings Installed in Corrugated Steel Structures in the Field

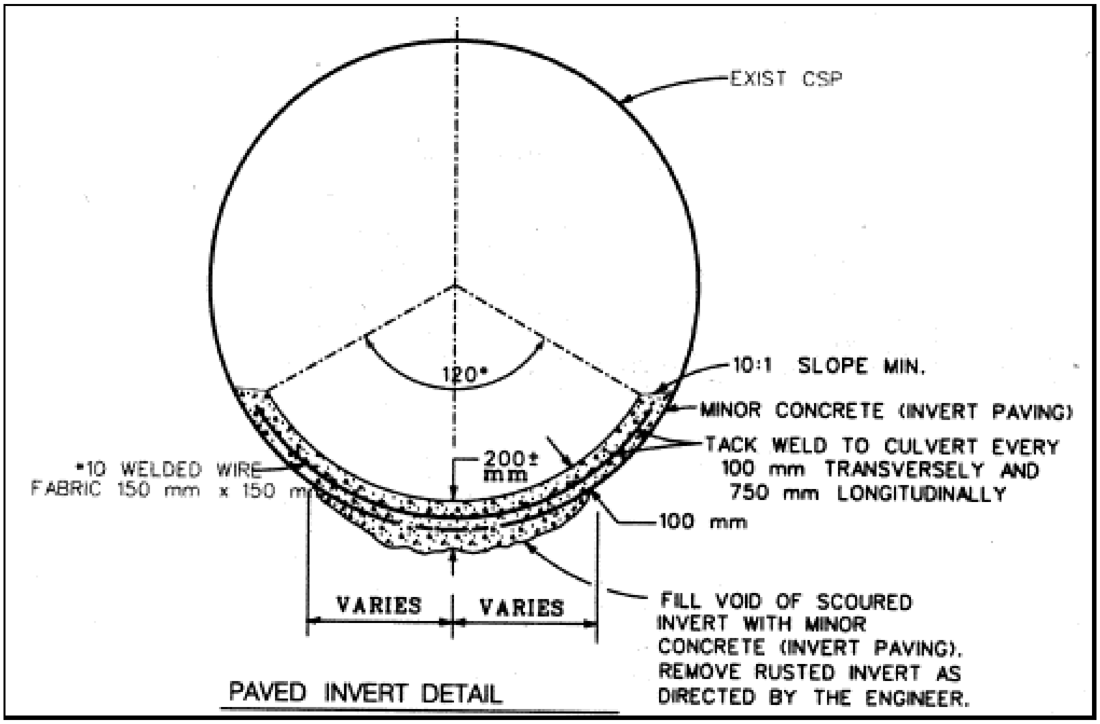


Figure 2-22. Invert paving schematic (Caltrans 2003c).

2.4.7 Concrete Collars

Concrete collars are an external type of pipe repair often used for joining two pipes together and providing a soil-tight repair. Although concrete collars are useful for high density polyethylene pipes, they can often be substituted by using snap couplers, split band couplers, or even metal connection bands in the case of metal pipes.

A significant amount of variation in durability occurs depending on the prevalence of concrete-corrosive chemicals, such as sulfates, present in and around the pipe. The average service life of concrete in German sewers was observed to be at 70 years (*Durability of Building Materials and Components* 1999). With more modern advances in concrete technology since then, the durability today can be assumed to be even higher.

Concrete also degrades faster in acidic environments, so collars installed in pipes used for transporting water of lower pH would most likely experience a shorter service life than collars exposed to neutral pH water.

2.5 Soil Chemistry and Properties

2.5.1 Soil Chemistry and Pipe Material

A number of textbooks covering the principles of soil and water chemistry have been published in recent years (Bohn et al. 2001; Essington 2004; McBride 1994; Sparks 2003; Sposito 2008). These books convey in detail the physicochemical phenomena that are most pertinent to pipe durability in soils: (i) potential to conduct electrical current (resistivity or its reciprocal, electrical conductivity); (ii) acid-base reactions (pH), and (iii) oxidation-reduction potential (Eh; "redox"). Other soil factors often noted as playing a role in pipe corrosion, including activities of sulfides and chlorides (Palmer 1989), generally act upon pipe integrity via their effects on the properties of resistivity, pH, and redox. Hence, those properties are reviewed below according to their impact on pipes in contact with soil material.

2.5.2 Soil Properties

2.5.2.1 Resistivity

"Resistivity" (ohm-cm) is a measure of a soil's resistance to conduct an electric current (Palmer 1989). It is the inverse of electrical conductivity (EC), the latter being an indirect measure of soil salinity (total solute concentration) that is problematic in agriculture (Corwin and Lesch 2003). Hence, resistivity declines as ionic strength increases since it is the ions in soil solution that serve to conduct electric current in soils. Resistivity at a given ionic strength decreases with increasing temperature.

High resistivity is a favorable property of soils with respect to metal pipe durability because corrosion rate of metal s in the pipe directly relates to the magnitude of electric current that can be maintained in the vicinity of the pipe (Palmer 1989). Resistivity is influenced by soil composition (Liu et al. 2010a). Soils with high soluble salt concentrations (saline soils) are particularly corrosive. They are mainly restricted to arid regions where salts have not been leached from the soil (Donner and Grossl 2002; Lynn et al. 2002). Such soils would tend to have a high concentration of anions such as chloride, sulfate, and carbonates associated with these salts. The role of soil as an electrolyte is to maintain the flow of electrons from an anodic zone in the pipe–which is undergoing oxidation and corrosion–to a cathodic (chemically reducing) zone of the pipe. The increase in rate of corrosion as temperature increases is attributable in part to the decrease in resistivity (Benmoussa et al. 2006). Salt concentrations are generally low (and resistivity high) in soils of humid regions where salts have been leached, with the exception of coastal marshes.

Accuracy of in-situ resistivity measurement is of paramount importance (Benson 2002) given the key role of this property in pipe corrosion. Research addressing pipe durability and corrosion processes (Choi et al. 2006; Doyle et al. 2003; Gan et al. 1994; Khan 2004; Khare and Nahar 1997; Li et al. 2007; Osella and Favetto 2000; Sagues et al. 2000; Scully and Bundy 1985; Summerson 1984), or modeling these processes (Alamilla et al. 2009; Chin and Sabde 2000; Redaelli et al. 2006; Velazquez et al. 2009), consistently invokes resistivity as a critical variable. Mitigating the risk of pipe corrosion commonly involves the introduction of a barrier or agent that enhances resistivity (cathodic protection) (Anis and Alfons 1994; Benedict et al. 1997; Bhardwaj et al. 2004; Gan et al. 1994; Schwerdt 1965).

2.5.2.2 Hydrogen *Ion Activity (pH)*

The negative $\log_{10}$ of the hydrogen ion activity (pH) is an indicator of the spectrum of acidity to alkalinity that is represented in soils. Many inferences can be drawn about soils from this single measure, e.g., degree of development, parent material, nutrient availability, speciation of metals, lime requirement, suitability of soils for many uses, etc. (Bohn et al. 2001; Essington 2004; McBride 1994; Sparks 2003). Aluminum and iron, metals common to soils and pipes, are sensitive to pH such that its effects on pipes can require mitigation (e.g., Hirsch 1984; Hurd 1984). They tend to be soluble at low and high pH (<4 and >8.5). Hence, extremes in acidity and alkalinity are problematic for pipe durability (Palmer 1989).

The components that control pH are those that undergo buffering hydrolytic or dissolution reactions. Hydrolytic reactions of aluminum in soils of humid regions would tend to buffer in the range of pH 4.7 (Bohn et al. 2001). However, "life" and the organic acids it generates also influence pH in humid region soils. The pH of soils in arid and semi-arid regions is not controlled by aluminum but rather by carbonates or soluble salts which tend to maintain pH in the neutral to alkaline range (pH >7).

The pH of most soils falls within the range of 4-8 such that metal solubility is minimal. However, exceptions occur in some coastal regions where sulfidic materials are drained and in arid regions with sodic-saline soils. Extreme acidity (pH<3.5; sulfuric acid formation) can result from the oxidation of iron-sulfide-rich coastal sediments (Fanning et al. 2002). Sulfur oxidation involves its transformation from a valence of -2 to +6. That change in sulfur oxidation state transforms it from an anion coordinating iron (sulfide) in the mineral structure to a cation coordinated by oxygen (sulfate). Hence the presence of sulfate in soils or soil solutions is often associated with extreme acidity and a hostile environment for metal and concrete pipes, particularly in coastal regions. Another exception, on the alkaline end of the spectrum, is saline-sodic soils which can have pH > 8.5 due to the chemical nature of salts that can accumulate in arid climates (Donner and Grossl 2002). Obviously, pipes in soil environments with these extremes in pH would be highly vulnerable to corrosion. Concrete pipes would be particularly sensitive to extreme acidity.

2.5.2.3 Oxidation-*Reduction ("Redox") Potential*

Soils vary in redox potential (i.e., E_h) largely as a consequence of their hydrologic setting. That is because saturated conditions drive chemical reduction by drastically restricting the rate of oxygen diffusion into the soil. Redox reactions in soils are driven by microbial oxidation of organic matter. The eventual depletion of oxygen in water- saturated soil results in a lowering of E_h and the need for alternative electron acceptors of lower energy yield (Vepraskas and Faulkner 2001).

A generalized soil half-cell reaction (e^- = electron) can be written as follows:

$$\text{a (oxidants)} + \text{b } H^+ + \text{n } e^- \Rightarrow \text{c (reductants)} + \text{d } H_2O$$

The following equation (a form of the Nernst equation) expresses the physical chemistry of this generalized redox reaction:

$$E_h = E^0 - (RT/nF) \ln [[\text{reductant}^c]/[\text{oxidant}^a][H^b]] \qquad (2.1)$$

where E_h is electrode potential (calibrated to Pt/H_2, mV), E^0 is standard electrode potential (unit activity, STP), R is gas constant, T is temperature (K), F is Faraday constant, n = number of electrons transferred, and [ ] is activity of chemical species in mol/L, and "a", "b", and "c" exponents are the coefficients for reactants.

The other "half cell" to complete the redox loop would be the generation of electrons in the oxidation or organic matter. In effect, organic matter and microbial activity are a necessary part of the process (Kajiyama and Okamura 1999; Li et al. 2001b). Half-cell reduction reactions for successive (top to bottom) electron acceptors in soils include the following, usually in this sequence, to the extent that components are present:

$4e^- + O_2 + 4H^+$	$\rightarrow$ $2H_2O$	E_h about +350
$12e^- + 12H^+ + 2NO_3$	$\rightarrow$ $N_2 + 6H_2O$	E_h about +220
$2e^- + 4H^+ + MnO_2$	$\rightarrow$ $Mn^{+2} + 2H_2O$	E_h about +200
$e^- + 3H^+ + Fe(OH)_3$	$\rightarrow$ $Fe^{2+} + 3H_2O$	E_h about +120
$8e^- + 10\ H^+ + SO_4^{2-}$	$\rightarrow$ $H_2S + 4\ H_2O$	E_h about −150
$8e^- + 8\ H^+ + CO_2$	$\rightarrow$ $CH_4 + 2\ H_2O$	E_h about −150

The equations above show that redox- and acid-base reactions are related processes in soils. In effect, reduction involves both hydrogen ions and electrons. Corrosion of pipes involves redox-potential driven electron transfers from anodic reduced zones that are undergoing oxidation to cathodic zones, by virtue of electric current in the soil and pipe system (Palmer 1989). The mechanism commonly involves electrons moving from reduced soil zones to zones that are more oxygenated; oxygen depolarizes hydrogen gas that would otherwise tend to arrest the process by building up at the cathodic zone. Studies of pipe corrosion commonly implicate redox potential as facilitated by low resistivity (Anis and Alfons 1994; Gan et al. 1994; Khare and Nahar 1997; Li et al. 2001a; Velazquez et al. 2009).

The reduction of manganese- and iron oxides results in their dissolution and the mobilization of these metals. They can be immobilized in more oxidized soil zones to which they diffuse. Zones of metal depletions and concentrations that result from redox processes in soils are referred to as "redoximorphic features" (Vepraskas and Faulkner 2001). These features are indicators of season high water saturation in the soil (Morgan and Stolt 2006). Some data have been reported to indicate that there is a significant temperature dependency for soil redox processes (Rabenhorst and Castenson 2005).

2.5.2.4 *Soil Type*

Soil physicochemical properties as conveyed by "soil type" are key factors in the durability of pipes (Charalambous and Cotton 2007; Liu et al. 2010b; Palmer 1989; Sagues et al. 2000; Seica et al. 2002). Soil variation in these properties is captured in soil taxonomic categories (e.g., order, suborder, great group, subgroup, family, and series; proceeding from highest to lowest level of generalization) (Soil-Survey-Staff 1999). Typically, "soil type" is used synonymously with "soil series"; soil series are intended to convey distinctions in use and management between otherwise similar soils. Soils of a series would tend to have similar composition and properties. Principles of kinetics (Sparks 2003) as well as mineral equilibrium (Karathanasis 2002) dictate the transformation of parent materials and the ultimate composition of soils. Soil composition, in turn, dictates how "hospitable" the soil, or material derived from it, will be to artifacts placed within it (to include pipes).

Soils vary spatially in their properties according to classical factors of soil formation: climate, parent material, topography, organisms, and time (Jenny 1994). Hence, soils differ at local, regional, and continental scales in accordance with these factors (Lynn et al. 2002). Soil map units are devised to convey spatial variation of soils on the landscape. They are generally named by the series that dominates a given delineation. A lot can be inferred about the suitability of a soil for various uses from soil maps (Jarvis and Hedges 1994).

A large Florida soils database was created under the auspices of the Florida Soil Survey Program conducted jointly by the United States Department of Agriculture (USDA)-Natural Resources Conservation Service, the University of Florida Soil and Water Science Department, and the FDOT. The physical, chemical, and mineralogical data are in individual county soil survey reports that also contain the county soil maps. These data can also be retrieved in electronic form at the following URL: http://flsoils.ifas.ufl.edu/.

2.6 Pipe Durability and Failure

A literature search was conducted on the field use of state-of-the-art pipe diagnostic technologies, such as robotic closed circuit television (CCTV) inspection with laser profiling and three-dimensional laser imaging. The results indicate that the following determinations can be evaluated and defects coded according to the Pipeline Assessment and Certification Program (PACP):

- length and width measurement of all cracks within the pipe
- measurement of all pipe joints
- deflection measurements, pipe deformation measurements, leaks, debris or other damage or defects.
- crack measurements
- detection of corrosion areas
- ovality
- sediment
- plan and profile

2.6.1 Corrosion

The results from the literature review pertaining to concrete pipes are:

- If pH is relatively neutral and sulfate levels are low, the base service life is 100 years.
- Applicability is a function of the diameter, fill height, trench conditioning, type of concrete, and environmental factors including velocity (type and amount of bed load), as well as pH, sulfate, and chloride levels.
- Resistivity does not directly impact the service life of concrete pipe.

The service life of galvanized steel pipes is related to soil resistivity, pipe thickness, and the pH of the water flowing through the pipe, and the soils in which the pipes are installed. These parameters were identified by previous research and were found to be valid parameters.

The AISI service lives predicted from existing published handbooks and publications are more than three times longer than the observed service lives. The predicted service lives systematically deviate from the measured service lives.

On the average, the service lives predicted by Caltrans service life relationships for steel pipes are in agreement with observed service lives. Caltrans service life estimates over-predict effects of gage thickness. The thickness multiplier suggested by Caltrans assumes a linear relationship between corrosion and pipe thickness. The data from Colorado sites suggest a power relationship. The effects due to increased thickness occur at a reduced rate.

For aluminum pipes, the salt content of the surrounding soil was found to be a primary factor affecting the service life. Three of the failure sites had aluminum pipes of the same size and age.

While the site with low chloride concentration exhibited little damage after 26 years of operation, sites with high sulfate and chloride concentrations showed dramatic reduction in service life. After 26 years of operation, the pipes were riddled with perforations.

For concrete pipes, the existing literature presents ranges of salt contents to define the corrosivity of the environment. For the Colorado failure cases, these limits were exceeded by an order of magnitude. Even under these extreme conditions, the structural integrity of the pipe was not totally compromised.

Other factors such as flow duration, geographic location, etc., are expected to affect the service life of steel pipes. The AISI has most recently introduced “hardness” of water as an additional parameter along with resistivity. The effects of these factors could not be studied due to the sample size of service life data.

2.6.2 Abrasion

The final step to determine the service life in metal pipes is to analyze for abrasion potential due to the flow of water and sediment. According to Caltrans approach, in determining the abrasion potential, the five-year design velocities used to check for a potential abrasive environment. Where low bedloads are present, higher velocities are not of concern. Abrasive velocities should be evaluated on the basis of frequency and duration. Invert protection/ productive coatings can be applied for different abrasive environments.

2.6.3 Structural

The most common materials used in culvert conduits are reinforced concrete, corrugated steel, and corrugated high-density polyethylene. Other materials that may be found in culvert conduits are corrugated aluminum, non-reinforced concrete, ribbed polyvinyl chloride (PVC), welded steel, timber, and masonry.

These various pipe materials will have differing types of response to applied load. Based on this response, the pipe material can be categorized as either rigid or flexible. This distinction in behavior is important not only in understanding how a pipe will perform under various soil and live load conditions, but will also affect failure mechanisms and repair considerations.

The flow chart in Figure 2-23 offers a general guide to the thought process and factors involved in selecting allowable alternative materials in accordance with HDM Topic 853.

If the culvert material is rigid (usually reinforced concrete), the load is carried primarily by the structure walls. It is very important to have uniform bedding to distribute the load reaction around the lower periphery of the pipe. Adequate support is critical in rigid pipe installations, or shear stress may become a problem. Excavation, backfill and culvert beddings

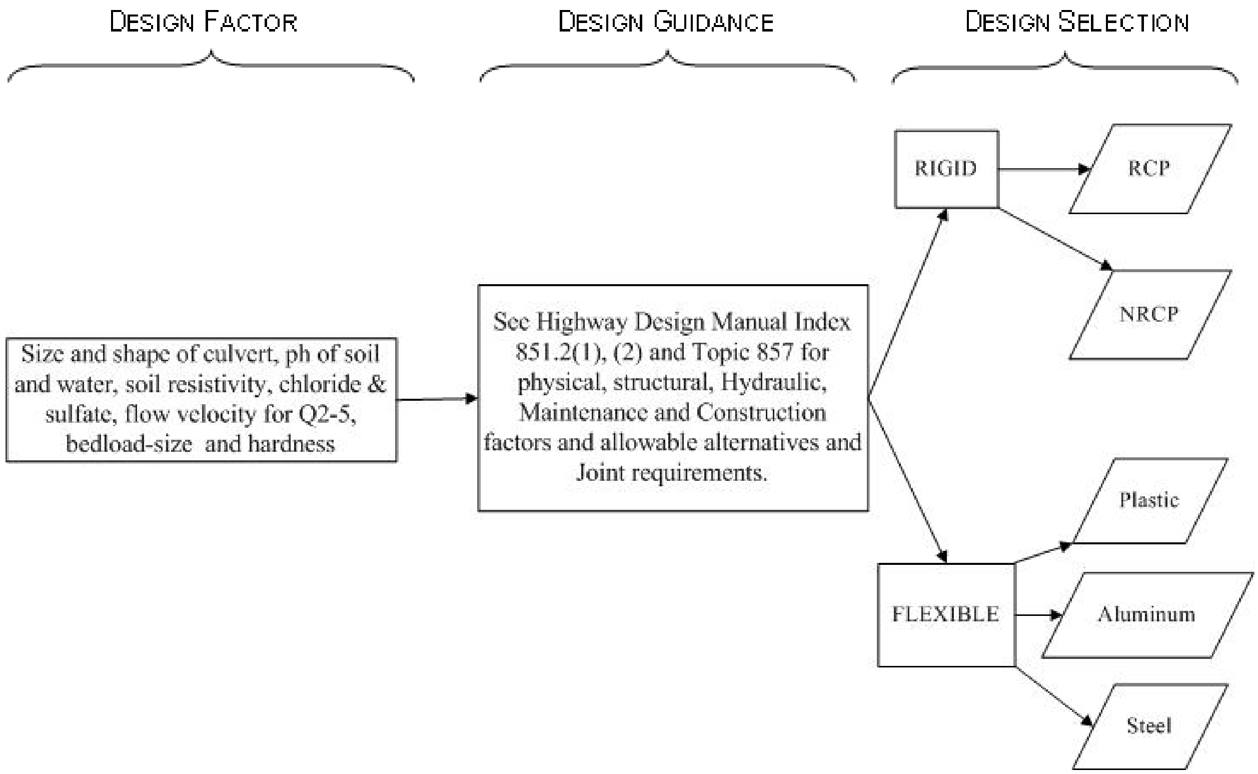


Figure 2-23. Flow chart for selecting alternative pipe materials (Caltrans 2003a).

shall conform to the details shown on the Standard Specifications. In addition, slurry cement backfill or controlled low strength material (CLSM) may be used in lieu of structure backfill.

If the culvert material is flexible (usually metal or plastic), a soil-pipe interaction must be present in order that the pipe is able to transfer the bulk of the load to the surrounding soil. In other words, the soil, not the pipe, carries and supports most of the live and dead load. Suitable backfill material and adequate compaction are of critical importance – especially below the springline. A well-compacted soil envelope of adequate width is needed to develop the lateral pressures required to maintain the shape of the culvert. The width of the soil envelope is a function of the strength of the surrounding in-situ soil and the size of the pipe.

2.6.4 Functional

The major findings of the literature review may be summarized under the categories that follow.

2.6.4.1 Steel *Pipe*

- service life is a function of pH and resistivity levels
- service life (SL) can be expressed as:

$$SL = (\text{Thickness}/1.3\text{mm}) * SL_b + C(\text{Coating})$$

where SL_b = base service life determined from resistivity-pH-service life chart;
C = a constant that is a function of coating type; and
Thickness = gage thickness of pipe in mm.

2.6.4.2 Aluminum *Pipe*

- service life is a function of thickness and coating
- if pH level is between 5 and 9 and resistivity is greater than 500 ohm-cm, then

$$SL = (\text{Thickness}/1.5\text{mm}) * SL_b + C(\text{Coating})$$

where SL_b = base service life of 50 years;
C = a constant with a value of 20 years if coating is present, if not, $C = 0$; and
Thickness = gage thickness of pipe in mm.

2.6.4.3 Concrete *Pipe*

- if pH is relatively neutral and sulfate levels are low, the base service life is 100 years.
- applicability is a function of the diameter, fill height, trench conditioning, type of concrete, and environmental factors including velocity (type and amount of bed load), as well as pH, sulfate, and chloride levels.
- resistivity does not directly impact the service life of concrete pipe.

2.6.4.4 Plastic *HDPE*

- expected service life is 75 years
- pH and resistivity are rarely constraints
- functions well for all levels of pH (1.25 to 14) and for all values of resistivity
- applicability if a function of diameter (18″ to 36″), joints, and fill height (less than 30′)

2.6.4.5 Galvanized *Steel*

- service life is a function of pH and resistivity

2.6.5 Deflection

The laser profiler is used for verification and measurement of the following:

- ovality
- corrosion
- material loss
- diameter
- build-up
- sediment depth
- life expectancy

Laser profiling is an advanced technique for determining the accurate surface profile of a pipe or other structure. The method projects a laser generated source onto the interior of a pipe or structure wall to determine accurate measurement of the structure. Laser profiling uses include:

- determination of the structural shape, cross sectional area and defects
- estimation of debris quantity
- calculation of pipe capacity before and/or after cleaning
- rehabilitation/replacement design information to improve selection of method
- post rehabilitation verification of lining and subsequent capacity

How the laser profiler works can be broken down into several steps (refer to Figure 2-24):

1. A ring of laser light is projected onto the internal pipe surface.
2. Laser image is in the field of view of the camera while the camera moves through the pipe.
3. Analysis is performed on the ring of light using the Laser Profiler software to build a digital pipe profile.
4. For use with live or pre-recorded video (tape, CD, or DVD) Ovality - The Ovality function calculates the "q" (as per ASTM F 1216, the internationally recognized standard for CIPP rehabilitation).

5. Capacity - The Capacity (X-sectional Area) function calculates the cross-sectional area for each profile and normalizes the results against the expected internal pipe area.
6. Interface with CCTV software.

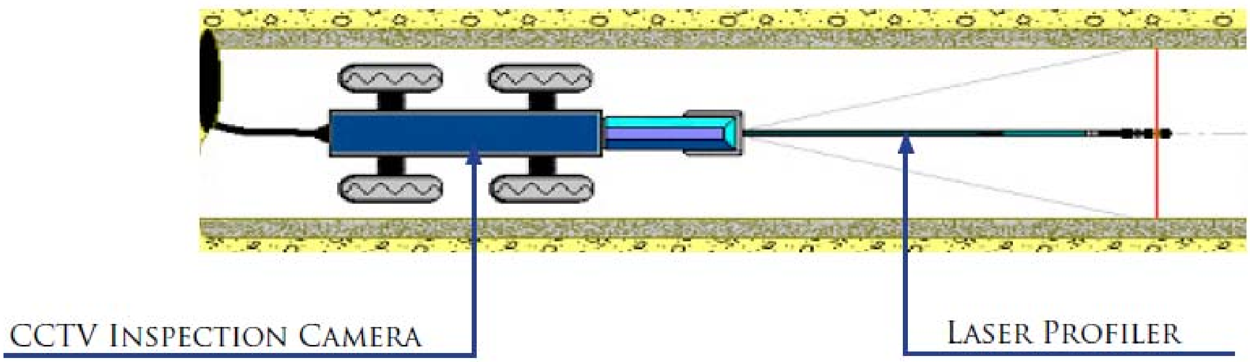


Figure 2-24. Laser profiler (Cues, Inc. 2010).

In the automated analysis, the software uses machine vision. Machine vision is used to find the video image of the laser profile (red laser line). Each frame of the inspection video is analyzed to build a digital profile of the pipe as shown in Figure 2-25.

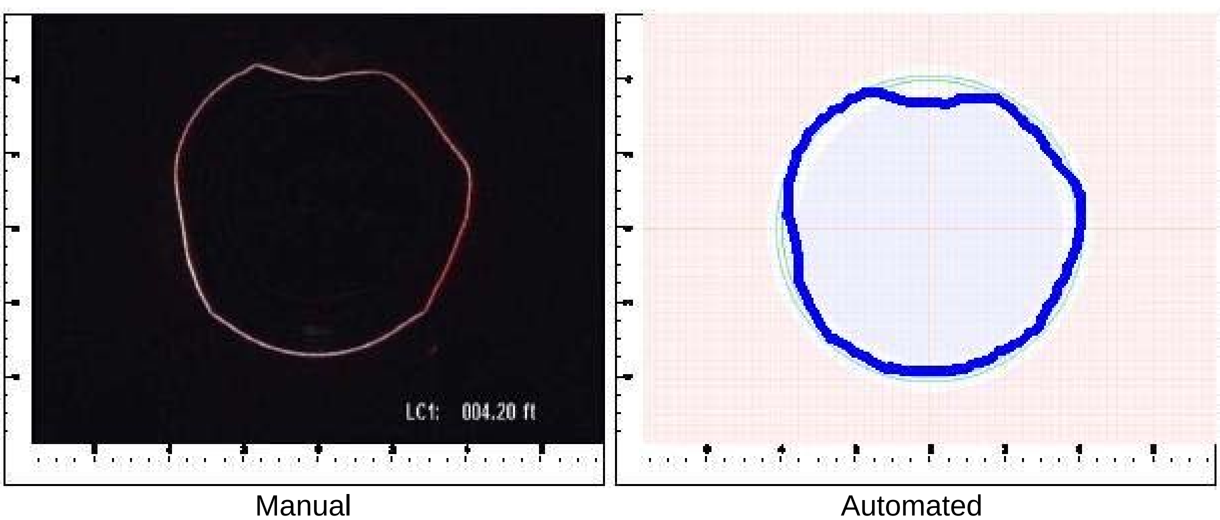


Figure 2-25. Examples of quantifying lift in liner using both the manual and automated digital measurement methods (Cues Inc. 2010).

The Laser Profiler is a stand-alone, snap-on tool for use with a CCTV survey system/ camera to collect survey data and create pipeline reports, including fault measurements and internal pipeline features.

It attaches to existing CCTV crawler camera, using machine vision software to analyze CCTV images. The Laser Profiler measures pipe size, laterals, water levels and other features. Performs automatic analysis of pipe ovality and capacity at a rate of 30 times per second.

The Laser Profiler enables the contractor, municipality, or engineer to determine internal pipeline conditions such as corrosion loss as shown in Figures 2-26, 2-27 and 2-28 before, during, or after rehabilitation, for use within 5″ to 72″ pipe diameters.

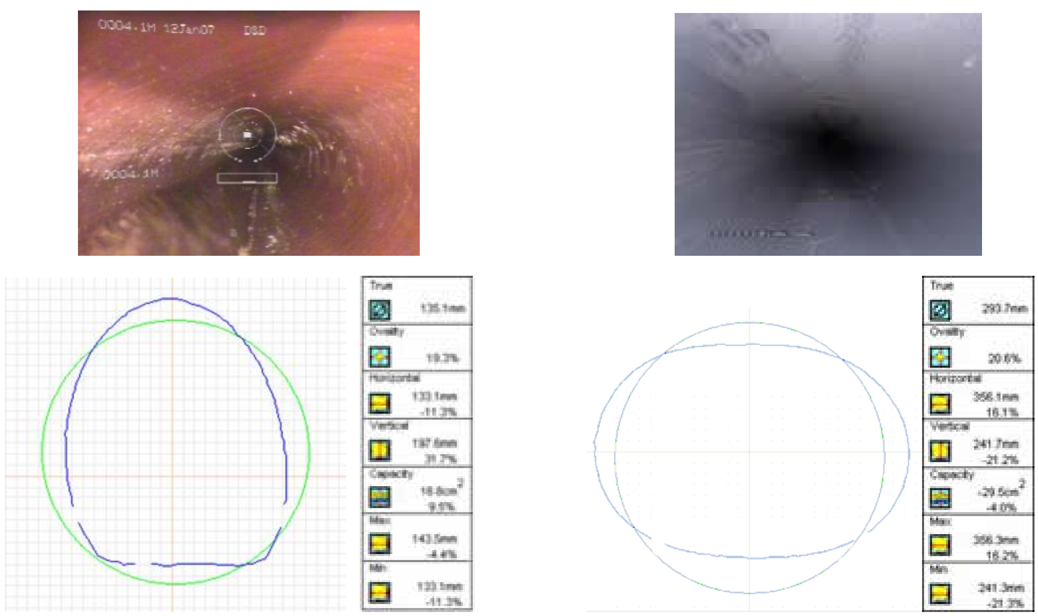


Figure 2-26. Corrosion loss: Laser profiling provides details data that would otherwise be overlooked (Atlas Inspection Technologies, Inc. 2010).

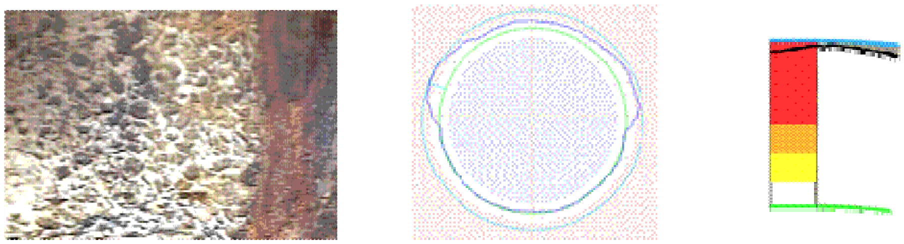


Figure 2-27. Laser profiling image above shows corrosion to 41 mm on original pipe wall (Atlas Inspection Technologies, Inc. 2010).

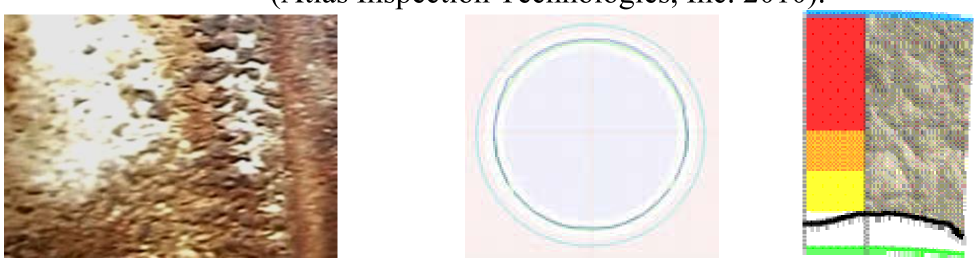


Figure 2-28. Laser profiling image above shows corrosion to 7 mm on pipe wall (Atlas Inspection Technologies, Inc. 2010).

The laser profiler is not intended to replace conventional CCTV inspections, but to gather data about the pipe ovality, slopes and other information that are beyond the capabilities of standard CCTV methods. Purely visual data is often insufficient to determine actual pipe shape and ovality deflects.

The system laser profiler measures the interior ovality of any type of pipe to assist in accurately verifying the overall condition of an existing pipeline or to confirm that installation of new pipe meets ovality specifications, see Figure 2-29 below:

Figure 2-29. Cross-sectional coloring easily locates sections of pipe where user defined ovality and capacity thresholds are exceeded (Maverick Inspection Ltd. 2009).

2.7 Summary of Repair and Rehabilitation Methods

Table 2-1 presents a summary of various repair and rehabilitation methods and their average service life. It can be seen from this table that the majority of repair methods last 50 years, with the exception of grouting and internal seal methods.

Table 2-2 provides a comparison of what the FDOT has decided to implement as acceptable pipe rehabilitation methods versus the methods various other states are using to repair pipes. As shown, sliplining and cured-in-place pipes are the most commonly used repair methods, followed by fold-and-form pipe liners. However, there is little consistency between the states with respect to the rest of the repair methods. It should also be noted that not all states have readily available pipe repair methods data (Caltrans 2003a; FDOT 2010a; Hollingshead 2009; Iowa DOT 2006; McCullouch 1992; Mirshahi 2008; NYSDOT 2006; ODOT 2005; Stains 2010).

Table 2-1. Summary of Various Repair Methods with Their Average of Service Life (Salem et al. 2008; AK Steel 1995)

No.	Repair Method	Material Used	Advantages	Disadvantages	Diameter and Length	Average Additional Service Life (Years)
1	Sliplining	Concrete, Metal, PE, HDPE, PVC, Fiberglass	-Expensive specialized equipment is not needed -Simple -Corrosion resistance -Improves both structural and nonstruct characteristics -Existing flow does not restrict the process -Improves flow characteristics and improves flow	-Reduction in pipe diameter -Grouting is required	Diameter: Segmental: 24 – 160 (in) Continuous: 4 – 63 (in) Length: Segmental and Continuous: 1000 (ft)	52
2	Sliplining by Spiral Winding	PE, PVC, PP	-Large bends can be used -Pipes are not stored on the job site -Mobilization costs are low	-Skillful personell are needed -Annular space should be grouted	Diameter: 6 – 108 (in) Length: 1000 (ft)	50
3	Sliplining by Paneling	GRP, PE, PVC, PP, PVDM	-Can be used in any shape of pipe -Chemical and abrasive resistant liners can be used -Can be installed under restricted flow conditions	-Only applicable on worker entry pipes -Annular space must be filled with grouting	Diameter: More than 48 inches Length: Varies	40
4	Sliplining by Spray- on Cement Mortar Lining	Cement mortar	-Improvement of flow capacity and corrosion resistance -Elimination of Leakage -Reduction of surface roughness	-Limited durability -Bonding problems has been observed between the liner and the existing culvert -Problems of cracking and loss of function as the liner may crack and separate from the existing culvert periphery has been observed	Diameter: Varies Length: Varies	50
5 *	Aluminum Coating	Aluminum	-Excellent corrosion and moderate abrasion protection	-Not very good under severe abrasion -Does not cooperate well with heavy metals such as iron, copper, etc.	Diameter: Varies Length: Varies	75
6	Epoxy Coating (Non-Cementitious Coating)	Polymer	-Protection against corrosion -Compared to aluminum coated pipes, epoxy coatings have higher abrasion resistance -Better results under extremely low pH	-Has brittle properties -New epoxy coatings may not easily intermingle with the existing pipes.may be a more expensive approach to pipe repairs -Relativly expensive	Diameter: Varies Length: Varies	50

Table 2-1. Summary of Various Repair Methods with Their Average of Service Life, continued.

No.	Repair Method	Material Used	Advantages	Disadvantages	Diameter and Length	Average Additional Service Life (Years)
7	Sliplining by Pipe Bursting	PE, PP, PVC, GRP (Glass-reinforced Plastic)	-Methods can be used to renew a wide range of pipe types -Diameter of the pipe can be increased -The renewed pipe has the same alignment with the existing pipe -The existing pipe does not have to be disposed	-Shafts may be required for insertion and reception -Construction equipment over the ground needs working space -Lateral service connections should be established by open cut excavation -Flow should be diverted -Nearby utilities and structures may be damaged if excessive ground movements and vibrations are present in the job site	Diameter: 4 – 48 (in) Length: 1500 (ft)	55
8	Sliplining with Close-Fit Pipe	HDPE, MDPE	-The new pipe is produced in a controlled environment Minimal reduction in the existing pipe area -Useful in eliminating internal corrosion problems -Mechanically folded pipes can accommodate 45 degree bends	-The diameter and installation range is limited -A large working space is needed -Usually the flow needs to be bypassed	Diameter: Close-fit Structural: 3 – 24 (in) Close-fit Nonstructural: 3 - 63 (in) Length: Structural and Nonstructural : 1000 (ft)	50
9	Grouting (Najafi Sep. 2008)	Chemical gel grouts, cement based grouts	-Infiltration and exfiltration problems can be eliminated -Low cost	-Does not enhance the structural condition of the whole pipe -Durability of the grout is usually limited	Diameter: Varies Length: Varies	20
	Cured in Place Pipe (CIPP)	Fiberglass, polyester, etc.	-Smooth interior space enables an increase in flow capacity -Grouting is not necessary -Lining noncircular shapes is possible -Lining can be accomplished even in the presence of bends	-The tube is custom made for each project -Existing flow must be diverted -Successful installation depends highly on the curing process -It can be expensive -Potentially hazardous to the environment	Diameter: Inverted in place: 4 – 108 (in) Winched in place: 4 – 108 (in) Length: Inverted in place: 3000 (ft) Winched in place: 1500(ft)	45
10	Internal Seals	Special Sleeves	-Can solve problems such as pipe breakage, joint settlement and longitudinal cracks -Offers structural solutions -Gravity sewers, culverts, and pressure pipes can be repaired without excavation	-Internal sleeve may cause a hydraulic loss due to decreased cross sectional area -Is only applicable to circular pipes	Diameter: 6 - 110 (in) Length: N/A	28

Table 2-1. Summary of Various Repair Methods with Their Average of Service Life, continued.

No.	Repair Method	Material Used	Advantages	Disadvantages	Diameter and Length	Average Additional Service Life (Years)
11	Point CIPP	Fiberglass, polyester, etc.	-Defective pipe sections between 3 ft and 50 ft of length with diameters up to 60 inches can be repaired -Point CIPP adheres to the existing pipe tightly and eliminates infiltration -May usually be performed without diverting the existing flow -Offers structural solution to the defective pipe segment -Lining does not obscure the flow due to tapered smooth ends	-Does not improve the structural condition of the pipe as a whole -May be more expensive than other point source repairs -Hydraulic capacity may be slightly decreased due to lining.	Diameter: 4 -60 (in) Length: 50 (ft)	50

*Note: The source of the information shown in the above table is (Salem et al. 2008) with the exception of Repair Method row number 5, Aluminum Coating, which is (AK Steel 1995).

Table 2-2 Comparison of Various State DOT Approaches to Pipe Repair/Rehabilitation

Florida (FDOT 2010a)	**California** (Caltrans 2003a)	**Ohio** (Stains 2010)	**Virginia** (Mirshahi 2008)	**Utah** (Hollingshead and Tullis 2009)	**Iowa** (Iowa DOT 2006)	**Oregon** (ODOT 2005)	**New York** (NYSDOT 2006)	**Indiana** (McCullouch 1992)
Sliplining	Sliplining	Sliplining	Sliplining	Sliplining	Sliplining	Sliplining	Sliplining	Sliplining
	Cured-in-place pipe	Cured-in-place pipe	Cured-in-place pipe	Cured-in-place pipe	Cured-in-Place Pipe	Cured-in-place pipe	Cured-in-place pipe	Cured-in-place pipe
Fold and Form Pipe	Fold and Form Pipe		Fold and Form Pipe	Fold and Form Pipe	Fold and Form Pipe	Fold and Form Pipe		
	Deform and Reform Pipe			Deform and Reform Pipe	Deform and Reform Pipe			
	Spiral Wound Pipe	Spiral Wound Pipe		Spiral Wound Pipe		Spiral Wound Pipe		
	Cement Mortar Lining			Cement Mortar Lining			Cement Mortar Lining	Cement Mortar Lining
	Spray on Polymer Lining		Spray on Polymer Lining					
Chemical Grouting	Chemical Grouting							Chemical Grouting
	Invert Paving						Invert Paving	
Internal Joint Seals	Internal Joint Seals							
Metal Armor Plating	Steel Armor Plating							
Mastic Banding					Mastic Banding			
Concrete Collar								
Welding								
Coupler								
	Panel Lining							

CHAPTER 3
RESEARCH APPROACH

3.1 Task 1 – Collect Data on the Durability of In-situ Pipe Repairs

3.1.1 Task 1a – Conduct Literature Review

The Florida Department of Transportation (FDOT) has spent $9.5 million over the past five years on repair and rehabilitation of its pipe and culvert assets. In order to find more efficient ways to spend these funds, FDOT wants to identify the most effective repair methods and strategies. As the availability of funds for reconstruction, repair, and rehabilitation becomes scarce, finding the most efficient pipe repair methods is vital.

The goal of this research is to find the most durable and economically feasible pipe repair technologies. The following summarizes the literature review which is based on compiled contemporary information on pipe repair methods and their durability.

This literature review (see Chapter 2) has focused on the long-term durability of various in-situ pipe repairs. It is organized by type of pipe material including concrete, metal, and plastic. At the end of each pipe material discussion, standards and specifications are presented. Similarly, the sections on inspection of pipe repairs are organized by type of pipe material. This is followed by an assessment of the pipe repairs. Next, several repair and rehabilitation methods are discussed followed by advantages, disadvantages, and standards and specifications for each method. For certain methods, installation methods are also discussed. Furthermore, soil chemistry and properties for various soil types are discussed, including soil resistivity, hydrogen ion activity (pH), and oxidation reduction potential. Finally, the report discusses the pipe durability and failure due to corrosion, abrasion, structural and functional failure, and deflection for various pipe materials. At the end of this literature review, a summary of repair and rehabilitation methods is provided including the material used, advantages and disadvantages, the applicable diameters and lengths of pipe, and average additional service life. The summary also includes a comparison of other states' repair methods with Florida's repair methods. A glossary of important terms can be found in Appendix A.

3.1.2 Task 1b – Conduct Survey of District Construction and Maintenance Project Files of Pipe Repair Data from the Last 15 Years

Once the literature review was completed, the research team, upon the instruction and with the approval of FDOT Project Manager Larry Ritchie, sent emails to contacts within each FDOT District containing a project introduction letter, which included instructions for assisting the research team in compiling data, and a sample spreadsheet, which included the information the research team was looking for on each pipe repair (see project letter in Appendix B). A large amount of data was returned quickly from District 5, and some from District 2, but no data were provided by other districts.

3.1.2.1 *Problems Encountered in Collecting the Essential Pipe Repair Data*

Most of the districts responded that they were not able to provide even minimal data, as the files for the pipe repair projects were scattered, difficult to find, and unorganized. Also, the districts all made it clear that it would be nearly impossible to get host pipe installation dates, as this information is not recorded or maintained.

Locating the project files proved to be much more difficult than originally projected as many of these pipe repair projects are side projects attached to much larger construction or maintenance projects, and thus, not recorded on their own merit. Therefore, the research team began contacting project managers, using their knowledge of recent projects to locate files. Still, this process did not turn up as much data as was hoped, and after a few months, information on only about 20 useful repair projects had been gathered.

3.1.2.2 *Obtaining the Essential Pipe Repair Data Elsewhere*

The next and most successful idea came from Larry Ritchie in October 2010, who suggested that we use FDOT's electronic database to look up daily work reports and search for key words such as "liner," "grout," "pipe repair," etc. However, the research team's application for access to the database was denied. Larry Ritchie took it upon himself to run these searches and forward the search reports to the research team. Over the course of the next few months, the research team reviewed thousands of pages of search data, pulling project numbers from the daily work report notes based on work described, and finally, by the beginning of January 2011, was able to compile a fairly comprehensive pipe repair data set for the last 15 years.

In short, the most time-consuming portion of the project was the data acquisition, which has now led to a large database of possible review sites which can be found in Appendix C. This database led the research team to recommend that further research be explored using these possible review sites to expand on the findings of this project.

3.2 Task 2 – Prepare a List of Potential Review Sites for Each District

Upon completion of the compilation of the pipe repair data in Task 1b, the project files were organized and sorted. The research team had over 100 relevant projects that included pipe repair during the past 15 years. The research team organized the data by district, date, and repair type. The criteria used to narrow down these sites to a comprehensive list of potential review sites were in the following order:

1. Type of Repair
2. Date of Repair
3. Pipe Diameter

The research team created a list of potential sites using these criteria and included as many different repair types as possible, while trying to keep only the oldest repairs and a variety of pipe diameters. The research team held a teleconference with Larry Ritchie to approve the list of potential sites and decided that the scope of the project would need to be limited, due to the amount of time spent on acquiring and organizing the repair data, leaving a much shorter time frame for site visits. The research team and Larry Ritchie came up with four major repair types (liners, grout, sectional repairs, and sleeves and bands) and decided the goal would be to have at least four sites for each repair type. The final list of potential sites included 16 sites, four in each of the four repair types.

Through the scheduling and visiting of sites, the list was forced to change due to lack of information on certain sites and in a few cases incorrect information. The final set of sites visited and inspected still included 16 sites, even through the evolution of the list. The full database of pipe repairs, as well as the final list of potential sites can be found in Appendix C.

3.3 Task 3 – Conduct Field Research at the Acceptable Project Review Sites

3.3.1 Task 3a – Obtain Data Using CCTV and Laser Profiling Technologies

After Larry Ritchie approved the UF research team's list of potential sites, the research team began contacting the District Maintenance Engineers for each district that had potential sites to determine the amount of assistance each district would be able to provide.

Due to the fact that District 2 is the only district with their own CCTV equipment, first contact was made with them. Cindy Tramel, Field Operations Engineer, put the research team in contact with Lawrence Rentz, who was in charge of the Pipe Inspection Video crews. District 2 was able to provide full service to the UF research team with proper notice. The Pipe Inspection

Video Crew had a trailer with all the necessary equipment to complete the CCTV video recording (see Figure 3-1). The District 2 Inspection Crew was always very thorough and helpful at each of the 8 sites completed in Duval, Clay, Alachua and Putnam counties. All necessary data were acquired.

Figure 3-1. District 2 trailer equipped with CCTV video – Pipe inspection crew inspecting a pipe connected to a curb and gutter inlet in Duval County.

The next sites visited were located in Districts 1 and 5. Both Districts were efficient and ensured that the sites would be accessible. The UF research team was advised to use WW Engineering to complete the 5 sites in Orange and Polk counties. The WW Engineering crew that met with the research team at these sites was very effective and innovative in completing sites that were in high-traffic situations (see Figure 3-2).

Figure 3-2. Pipe inspection crew from WW Engineering preparing to inspect a pipe connected to a curb and gutter system in an extremely urban area in Orange County.

There was some difficulty in District 1 with getting the site visit underway, but eventually Cleo Marsh, District Maintenance Engineer, was able to use an existing contract to get the site visit completed. Shenandoah Construction was hired to complete the site in Indian River County. They cleaned and dewatered the pipe that was inspected prior to the CCTV video recording. FDOT supplied a crew to bore through the pavement of SR 60 to obtain an accurate soil sample directly above the pipe (see Figure 3-3).

Figure 3-3. The crew from District 1 boring through roadway pavement to obtain a soil sample on top of the pipe in Indian River County.

3.3.2 Task 3b – Obtain Soil Sample Data at Acceptable Project Review Sites

Soil analysis – Soils were sampled at the inspection sites with the objectives of obtaining samples as close to the pipe as possible and assessing local natural soil conditions that could influence the physicochemical environment of the pipe. There were constraints limiting our ability to accomplish these objectives to varying degrees from site-to-site. These constraints were related to the specific location of the pipe (e.g., accessibility, whether there was soil contact, etc.) and to the extent to which disturbance from the construction itself had obliterated morphological cues of the natural soils.

Samples were air-dried, weighed, and sieved for thorough mixing and to quantitatively remove > 2-mm rock fragments (gravel-size). All subsequent analyses were performed on the < 2-mm fraction.

Electrical conductivity (Rhoades 1996) and pH measurements (Thomas 1996) were made using a standard conductivity/pH meter (Pinnacle model M545P). A combination electrode with silver/silver chloride reference was used for the pH measurements. The pH measurements were performed after equilibrating soil samples with double-deionized (DI) water (pH_{water}) or 0.02 M $CaCl_2$ (pH_{salt}), in 1:1 (mass:mass) soil-to-solution ratios. Electrical conductivity was determined after equilibration with DI water in 1:2 (mass:mass) soil-to-solution ratios. Duplicate measurements were performed on every tenth sample. Mean relative standard deviations for duplicates were 0.3, 0.9, and 17.2 for pH_{water}, pH_{salt}, and EC, respectively.

Geographic information pertinent to soil distribution and pipe setting was compiled for each site using Arc-GIS. Images were prepared for this document and can be found in Appendix D.

<u>*Corrosion analysis*</u> – Field data was analyzed for fifteen reinforced concrete pipes varying in diameter from 15″ in diameter to 60″ in diameter. The pipes tested were located in FDOT Districts 1, 2, 4, and 5, and the types of repairs included chemical grouts, pipe liners, fiberglass liner, joint seals, band seal and a repair sleeve. The pipes were analyzed using a CCTV camera that was not fitted with a laser profiling device. As stated before, the laser profiler tool allows one to not only observe the pipe condition, pipe joints and repair, but also determine ovality, corrosion, material loss, current diameter, build-up, sediment depth and project life expectancy of the pipe repair system.

Nevertheless, the CCTV camera inspections revealed some interesting aspects of the pipe joints and repairs investigated. A summary of the observations from the video footage of each of the fifteen pipes is given in Section 4.4 on corrosion analysis (page 47).

3.4 Task 4 – Analyze the Field Data

The research team used the following criteria to analyze the field data:

1. Infiltration of water or sediment
2. Corrosion of pipe or the repair
3. Staining associated with infiltration
4. Defects in the installation and quality of repair
5. General appearance of the repair/host pipe
6. Any cracking associated with the repair
7. Presence of debris at repair locations

The reports for each repair/site visit can be found in Section 3 along with screenshots from the pipe inspection CCTV videos.

3.5 Materials and Procedure

While conducting the field research, the UF research team used the following materials:

1) CCTV video inspection rover
2) Inspection Trailer
3) Extension arm
4) Computer
5) As-Built forms provided by FDOT
6) Vehicle
7) Soil bore
8) Gutter
9) Pipe Cleaning Truck
10) Boring Truck

After determining to visit a site for field research, the UF research team would contact a contract or FDOT inspection team to conduct the inspection. An appointment was met between the two parties. The UF research team would provide the inspector with the appropriate details of where to meet the team using As-Build forms. The UF research team would meet the inspector at the site of the piping project. The inspection team would use the extension arm to lower the rover into the manhole where the piping project extended from. Using the video equipment on the rover, the team would record the inspection seen on the computer inside the inspection trailer. After recording the pipe inspection the UF research team would collect soil samples using a soil bore extending 4 feet into the existing ground surrounding the project. After analyzing the soil, samples were select, bagged, and labeled. After restoring the site to the original condition both parties would depart from the site.

On select sites, the UF research team determined it was necessary to clean the pipe prior to inspection. When this was determined, a cleaning crew would arrive at the site to clean the pipe utilizing the pipe cleaning truck prior to inspection. At one site where boring was completed, the UF research team arranged maintenance of traffic and closed a lane of traffic to allow for a boring truck to bore through the pavement surface that allowed the UF research team to obtain a soil sample directly above the pipe being inspected. Once again the site was returned to original condition and all parties departed.

CHAPTER 4
SITE VISIT REVIEWS

4.1 Chemical Grout

4.1.1 Duval County Site #000, 10 Years Old

This site is located in Duval County off of SR 115 (see Figure 4-1). The drainage system utilized a curb and gutter system and a 15″-diameter pipe running along the roadway. Soil samples were obtained near the pipe location. The repair utilized at this location was chemical grouting. There was a small amount of standing water in the pipes, probably 1″ to 2″. All joints along the pipes were supposed to be grouted, but the grout was not apparent (see Figures 4-2 through 4-4). We could not determine with complete accuracy whether the grout was completely eroded or never actually installed, however there were certain joints that may have shown some minute remnants of grout, leading us to believe the grouting was completed and the repair had failed at this point. The appearance of the host pipe was good, with no signs of cracking caused by the installation of the repair. All of the standing water could not be attributed to infiltration, but the repairs showed slight infiltration in certain joints. Some joints were holding up better than others.

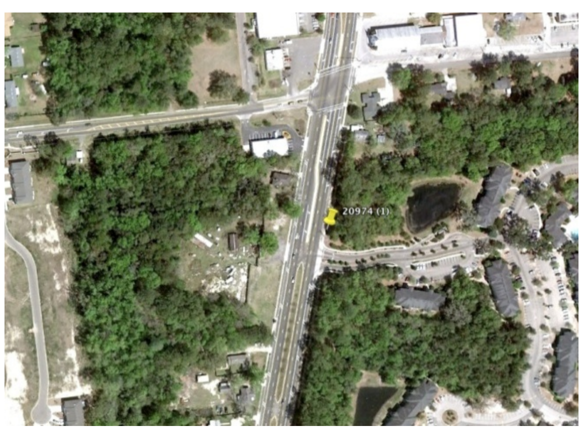


Figure 4-1. Google earth image showing location of Site #000 in Duval County.

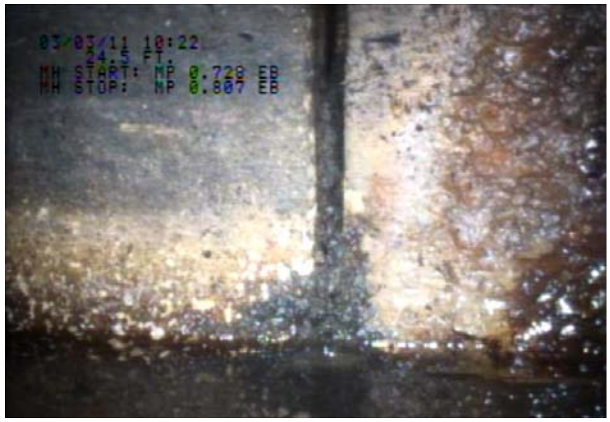


Figure 4-2. Screenshot from pipe inspection video of Site #000, showing a joint which was supposed to have been repaired with chemical grout but shows no evidence of grout.

Figure 4-3. Screenshot from pipe inspection video of Site #000, showing inside of the pipe.

Figure 4-4. Screenshot from pipe inspection video of Site #000, showing a joint which was supposed to have been repaired with chemical grout. The orange spots may be remnants of grout.

4.1.2 Duval County Site #001, 10 Years Old

This site is located in Duval County off of SR 115 (see Figure 4-5). The drainage system utilized a curb and gutter system and a 15″-diameter pipe running along the roadway. Soil samples were obtained near the pipe location. The repair utilized at this location was chemical grouting. There was only a small amount of infiltration of sediment despite the poor quality of the repair. Corrosion was so bad in some areas of the repair that it had completely failed, while in other areas it appeared to be effective. The apparent inconsistency in the effectiveness of the repair between various locations throughout the pipe suggests faulty repair installation (see Figures 4-6 through 4-8). The host pipe was in good shape. There was no cracking in any of the repairs. There was some debris at a few locations in the repair, probably the results of repair failure which led to a small amount of infiltration.

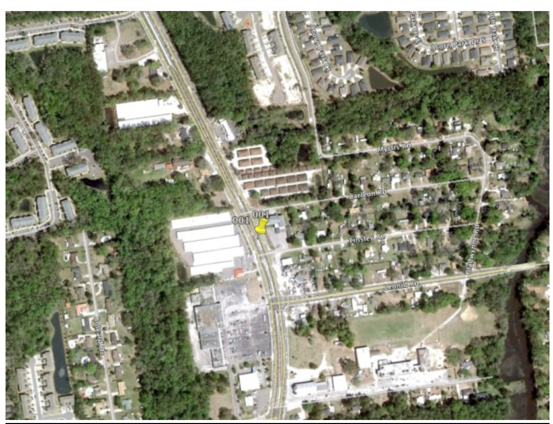


Figure 4-5. Google earth image showing location of Site #001 located in Duval County.

Figure 4-6. Screenshot from pipe inspection video of Site #001, showing a close up of a joint which has been repaired with chemical grout. Some remnants of the grout can be seen.

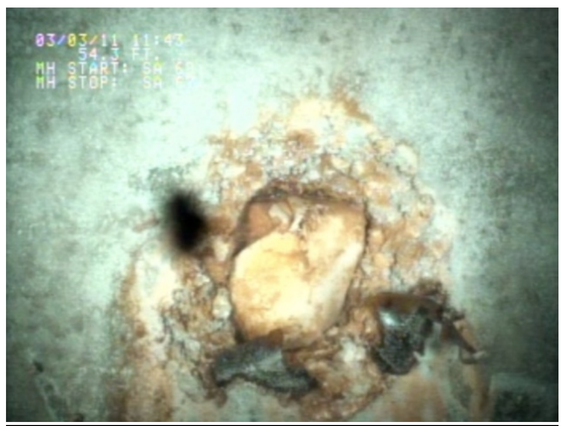


Figure 4-7. Screenshot from pipe inspection video of Site #001, showing a close up of a damaged point on the pipe which has been repaired with chemical grout.

Figure 4-8. Screenshot from pipe inspection video of Site #001, showing a close up of a joint which did not show any separation and was not repaired with grout.

4.1.3 Duval County Site #002, 10 Years Old

This site is located in Duval County off of SR 115 (see Figure 4-9). The drainage system utilized a curb and gutter system and a 36″-diameter pipe running along the roadway. Soil samples were obtained near the pipe location. The repair utilized at this location was chemical grouting due to infiltration in the joints repaired. There was no staining, water, or sediment due to infiltration as the repair showed no infiltration. However, there was mild staining at the bottom of the host pipe due to the chemical grouting (see Figure 4-10). Only the joints that had separation or other causes of infiltration were grouted. The appearance of both the host pipe and the repairs was very good and the host pipes showed no cracking caused by the installation of the repair. The repair installation had no apparent defects. Chemical grouting appears to be a good solution to small gaps and slight infiltrations at joints of the host pipe, such as shown in Figure 4-11 from Site #000.

Figure 4-9. Google earth image showing location of Site #002 located in Duval County.

Figure 4-10. Screenshot from pipe inspection video of Site #002, showing the inside of the pipe.

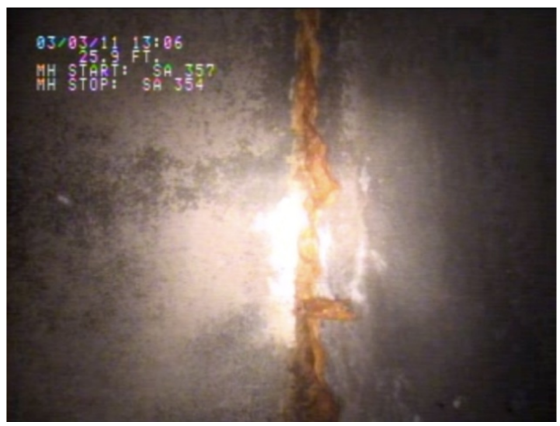


Figure 4-11. Screenshot from pipe inspection video of Site #000, showing a joint which has been repaired with chemical grout. Some remnants of the grout can be seen.

4.1.4 Orange County Sites #003 and #004, 11 Years Old

These sites are located in Orange County off of SR 50 (see Figure 4-12). The drainage system utilized a curb and gutter system and 60″-diameter pipes running along the roadway in an extremely urban area (downtown Orlando). No relevant soil samples were obtained due to the urban location and the volume of traffic on the roadway. The repair utilized at this location was chemical grouting (see Figures 4-13 through 4-17). There was a large amount of standing water in the pipes, probably 3′. Due to the large amount of standing water, it was not possible to get the rover through the pipe, so the contractor walked the camera through the pipe. All joints along the pipes were grouted, but the grout seemed to be fading and slightly deteriorating. The appearance of the host pipe was good and the host pipes showed no cracking caused by the installation of the repair. All of the standing water could not be attributed to infiltration, but a small number of the repaired joints showed very light infiltration, according to the contractor. Some joints were holding up better than others. These failures appeared to be caused by the effect of time rather than by poor installation or implementation.

Figure 4-12. Google earth image showing locations of Site #003 and Site #004 located in Orange County.

Figure 4-13. Screenshot from pipe inspection video of Site #003, showing a joint which has been repaired with chemical grout. The joint is completely sealed with grout.

Figure 4-14. Screenshot from pipe inspection video of Site #003, showing the inside of the pipe.

Figure 4-15. Screenshot from pipe inspection video of Site #004, showing the inside of the pipe.

Figure 4-16. Screenshot from pipe inspection video of Site #004, showing a close up of a joint which has been repaired with chemical grout. The joint is completely sealed with grout.

Figure 4-17. Screenshot from pipe inspection video of Site #004, showing a joint which has been repaired with chemical grout. The joint is completely sealed with grout.

4.2 Pipe Liner

4.2.1 Clay County Site #005, 9 Years Old

This site is located in Clay County off of SR 224 (see Figure 4-18). The drainage system utilized a curb and gutter system and a 15″-diameter pipe running across the roadway. Soil samples were obtained near the pipe location. The repair utilized at this location was a pipe liner (see Figure 4-19). There was no staining or water or sediment due to infiltration as the repair showed no infiltration. The liner was placed in the entire run of the pipe. The appearance of the repair was very good; it showed no cracking caused by the installation of the repair. The repair installation had no apparent defects. See Figures 4-20 and 4-21.

Figure 4-18. Google earth image showing location of Site #005 located in Clay County.

Figure 4-19. Screenshot from pipe inspection video of Site #005, showing a joint of the pipe liner.

Figure 4-20. Screenshot from pipe inspection video of Site #005, showing the inside of the pipe.

Figure 4-21. Screenshot from pipe inspection video of Site #005, showing a joint of the pipe liner.

4.2.2 Duval County Site #006, 9 Years Old

This site is located in Duval County off of SR 128 (see Figure 4-22). The drainage system utilized a curb and gutter system and a 48″-diameter pipe running across the roadway. Soil samples were obtained near the pipe location and directly on top of the pipe. The repair utilized at this location was a pipe liner to seal a large portion of the pipe (see Figures 4-23 through 4-25). There was no staining or water or sediment due to infiltration as the repair showed no infiltration. The liner was placed in the entire run of the pipe. The appearance of both the host pipe and the repairs was very good and the host pipes showed no cracking caused by the installation of the repair. There was a small section of the liner which showed a wrinkle in the felt tube, but it appeared this was done for a purpose unknown to us, rather than due to poor installation.

Figure 4-22. Google earth image showing location of Site #006 located in Duval County.

Figure 4-23. Screenshot from pipe inspection video of Site #005, showing the pipe liner.

Figure 4-24. Screenshot from pipe inspection video of Site #006, showing the inside of the pipe.

Figure 4-25. Screenshot from pipe inspection video of Site #005, showing the pipe liner and the wrinkle.

4.2.3 Orange County Site #008, 10 Years Old

This site is located in Orange County off of SR 482 (see Figure 4-26). The drainage system was directly off the highway and utilized dual 13″ × 24″ elliptical pipe running across the highway. Soil samples were obtained directly on top of the pipe. The repair utilized at this location was a pipe liner (see Figure 4-27). There was a small amount of standing water, probably 1″ to 2″; however, there did not appear to be much, if any, infiltration. The repair installation appeared to be proper; however, it did show a large amount of erosion. The liner was placed along the entire run of the pipe where there appeared to have been cracking, and separation of the host pipe. The appearance of the repair was not great and the host pipe was in poor shape; however, this appeared to have been the reason for the repair not a result of it. There was a small amount of debris in the pipe which possibly restricted drainage, resulting in the small amount of standing water observed.

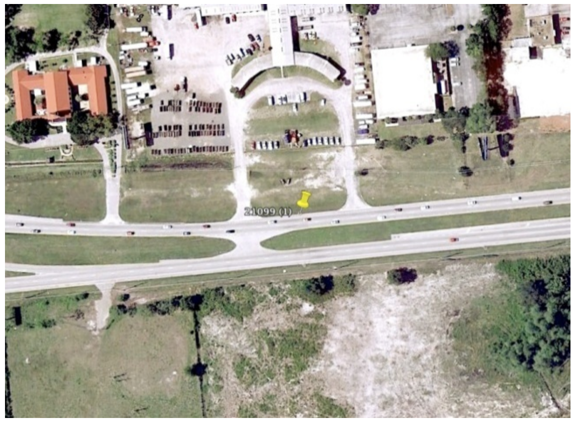


Figure 4-26. Google earth image showing location of Site #008 located in Orange County.

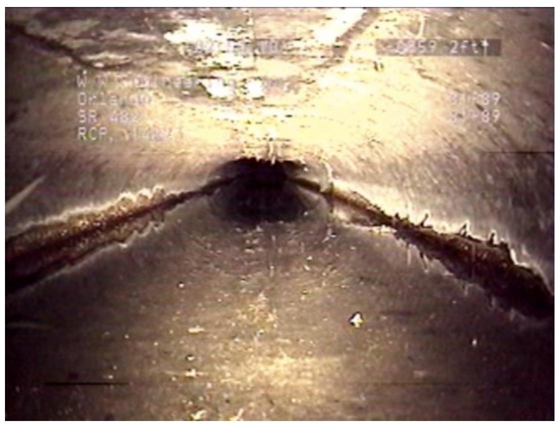


Figure 4-27. Screenshot from pipe inspection video of Site #008, showing the inside of the pipe and the pipe liner.

4.2.4 Alachua County Site #009, Installation Unknown (Older than 15 Years)

This site is located in Alachua County off of SR 24 (see Figure 4-28). The drainage system utilized a curb and gutter system connecting to a pipe running across the roadway. Soil samples were obtained near the pipe location. The repair utilized at this location was a cured in place impermeable fiberglass pipe liner to seal the entire run of the pipe (see Figure 4-29). There was no staining or water or sediment due to infiltration since the repair showed no infiltration. The liner was placed in the entire run of the pipe. The appearance of both the host pipe and the repair was very good and the host pipes showed no cracking caused by the installation of the repair.

Figure 4-28. Google earth image showing location of Site #009 located in Alachua County.

Figure 4-29. Screenshot from pipe inspection video of Site #009, showing the inside of the pipe and the pipe liner placed along the entire run of the pipe.

4.2.5 Orange County Site #007, 11 Years Old

This site is located in Orange County off of SR 50 (see Figure 4-30). The drainage system utilized a curb and gutter system and a 24″-diameter pipe, which connected to the pipes in Sites #003 and #004, in an extremely urban area (downtown Orlando). No relevant soil samples were obtained due to the urban location and the volume of traffic on the roadway. The repair utilized at this location was a sectional liner that ran the length of the pipe (see Figure 4-31). There was no staining or sediment due to infiltration; however, water was present and the repair showed signs of infiltration. At this location, it was impossible to get the rover into the pipe because the connecting pipes had too much standing water. Due to these conditions, a full run of the pipe was impossible, however, the contractor was able to observe a large amount of infiltration and get a look into the pipe. All the sectional liners were placed from joint-to-joint for the entire length of the pipe and the installation appeared to be proper. The appearance of the host pipe was good and the host pipe showed no cracking caused by the installation of the repair. The joints seemed to be showing a slight recurrence of separation, causing the infiltration, which can probably be attributed to age.

Figure 4-30. Google earth image showing location of Site #007 located in Orange County.

Figure 4-31. Screenshot from pipe inspection video of Site #007, showing the inside of the pipe and the sectional liner placed from joint to joint.

4.3 Point Repairs

4.3.1 Putnam County Sites #010, #011 and #012, 6 Years Old

These sites are located in Putnam County off of SR 20 (see Figures 4-32 and 4-33). The drainage systems utilized a curb and gutter system connecting to 18″ and 24″-pipes running along the roadway and across the roadway. Soil samples were obtained near the pipe location. We were informed and assured that the repair utilized at these sites were internal joint seals, however this did not appear to be the case. In some places it appeared that grouting may have been used. These seals were supposed to have been placed only at joints which required them, as some of the joints were still in good shape. There was a significant amount of standing water in the pipes, nearly 1′ at some points, but it did not appear that all of this water could be attributed to infiltration. The host pipe appeared to be in good shape; there was no cracking caused by the installation of the repair. See various screenshots in Figures 4-34 through 4-41. In Site #011, the rover was unable to complete the run of the pipe due to a large amount of debris.

Figure 4-32. Google earth image showing locations of Site #010 and Site #011 located in Putnam County.

Figure 4-33. Google earth image showing location of Site #012 located in Putnam County.

Figure 4-34. Screenshot from pipe inspection video of Site #010, showing the inside of the pipe.

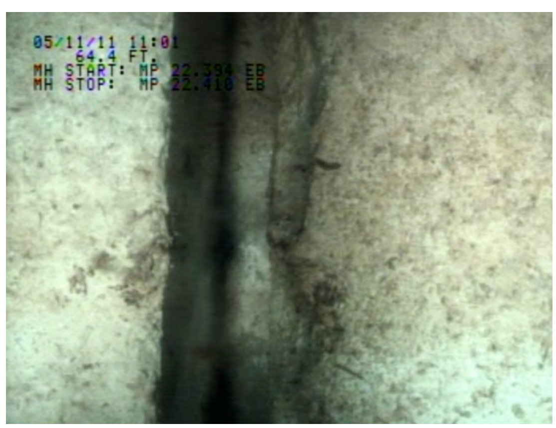


Figure 4-35. Screenshot from pipe inspection video of Site #010, showing a joint which was not repaired.

Figure 4-36. Screenshot from pipe inspection video of Site #010, showing a joint which was supposed to be repaired using an internal joint seal.

Figure 4-37. Screenshot from pipe inspection video of Site #011, showing the inside of the pipe.

Figure 4-38. Screenshot from pipe inspection video of Site #011, showing a joint which was supposed to be repaired using an internal joint seal.

Figure 4-39. Screenshot from pipe inspection video of Site #011, showing a joint which was supposed to be repaired using an internal joint seal.

Figure 4-40. Screenshot from pipe inspection video of Site #012, showing the inside of the pipe.

Figure 4-41. Screenshot from pipe inspection video of Site #012, showing a joint which was supposed to be repaired using an internal joint seal

4.3.2 Polk County Site #015, 3 Years Old

This site is located in Polk County off of SR 25 and US 27 (see Figure 4-42). The drainage system utilized a curb and gutter system and a 24″-pipe running along the highway. Soil samples were obtained near the pipe location. The repair utilized at this location was a repair sleeve (see Figures 4-43 and 4-44). There was no staining or water or sediment due to infiltration as the repair showed no infiltration. The repair installation appeared to have no defects and to be of high quality. The sleeve was placed along the middle section of the pipe where the host pipe showed some cracking; other joints which showed no such issues were not included in the sleeve. The appearance of both the repairs and the host pipe was good and the host pipe showed no cracking caused by the installation of the repair. There was no debris in the host pipe.

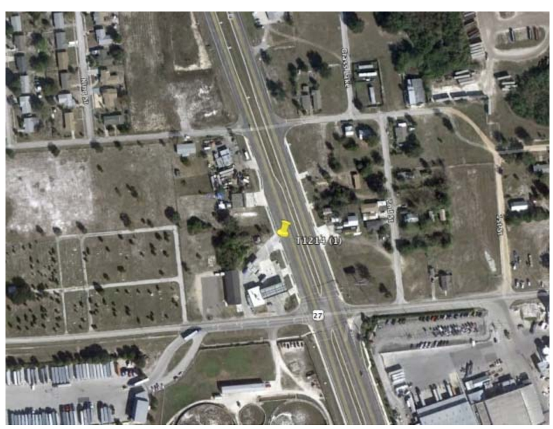


Figure 4-42. Google earth image showing location of Site #015 located in Polk County.

Figure 4-43. Screenshot from pipe inspection video of Site #015, showing the repair sleeve over the damaged section of pipe.

Figure 4-44. Screenshot from pipe inspection video of Site #015, showing the inside of the pipe.

4.4 Band Seals

4.4.1 Okeechobee Site #013, 9 Years Old

This site is located in Okeechobee County off of SR 700 and US 98 (see Figure 4-45). The drainage system was directly off the highway and utilized dual 24″-pipe running across the highway. Soil samples were obtained directly on top of the pipes. The repair utilized at this location was NPC internal joint seals (see Figure 4-46). There was no staining or water or sediment due to infiltration as the repair showed no infiltration. The repair installation appeared to have no defects and to be of high quality. The seals were placed only at joints that had significant separation; other joints which had acceptable separation were not repaired. The appearance of both the repairs and the host pipes was good, and the host pipes showed no cracking caused by the installation of the repair (see Figure 4-47). There was minimal debris in the host pipes; the small amount of debris was probably due to the location of the pipes (the pipes were directly exposed to the outside environment).

Figure 4-45. Google earth image showing location of Site #013 located in Putnam County.

Figure 4-46. Screenshot from pipe inspection video of Site #005, showing a joint which has been repaired using an NPC Internal Joint Seal.

Figure 4-47. Screenshot from pipe inspection video of Site #013, showing the inside of the pipe.

4.4.2 Indian River County Site #014, 3 Years Old

This site is located in Indian River County off of SR 60 (see Figure 4-48). The drainage system utilized a curb and gutter system and a 36″-pipe which ran along the roadway. Soil samples were obtained directly on top of the pipes via boring through the pavement. The repair utilized at this location was a set of band seals (see Figure 4-49). There was no staining or water or sediment due to infiltration as the repair showed no infiltration. The repair installation appeared to have no defects and to be of high quality. The seals were placed on all joints along the run of the pipe. The appearance of both the repairs and the host pipes was good and the host pipes showed no cracking caused by the installation of the repair (see Figure 4-50). There was minimal debris in the host pipes.

Figure 4-48. Google earth image showing location of Site #014 located in Indian River County.

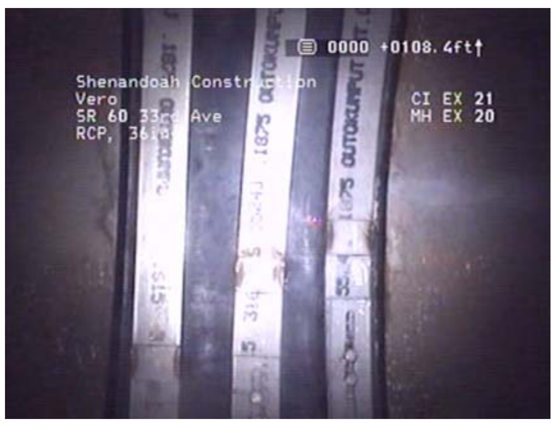


Figure 4-49. Screenshot from pipe inspection video of Site #005, showing a joint which has been repaired using a set of band seals.

Figure 4-50. Screenshot from pipe inspection video of Site #014, showing the inside of the pipe.

4.5 Summary of Site Visits

After visiting the sites, the UF research team created a rating system shown in Table 4-1. The rating system is based on the functionality, durability and overall effectiveness of the existing pipe repair observed. Also, contained in Table 4-1 are the ranges in pH (H_20) and Electrical Conductivity (EC) from the soil samples gathered at each site.

Table 4-1. Age and Rating of the Existing Pipe Repairs at Each Site

Pipe Repair Ratings 1-Failing, 2-Poor, 3-Fair, 4-Good, 5-Excellent						
Site	**County**	**Size (in)**	**Age (yr)**	**Rating**	**Range in pH (H_2O)***	**Range in EC***
000	DUVAL	15	10	1	3.8-4.4	0.01-0.03
001	DUVAL	15	10	3	7.8 - 8.0	0.07 - 0.13
002	DUVAL	36	10	3	7.1 - 8.2	0.02 - 0.05
003[1]	ORANGE	60	11	3	7.7 - 7.9	0.06 - 0.20
004[1]	ORANGE	60	11	3	7.7 - 7.9	0.06 - 0.20
005	CLAY	15	9	4	7.7 - 8.0	0.02 - 0.05
006	DUVAL	48	9	3	7.2 - 8.2	0.02 - 0.07
007[1]	ORANGE	24	?	1	7.7 - 7.9	0.06 - 0.20
008	ORANGE	14 X 23	10	3	6.9 - 8.1	0.02 - 0.05
009	ALACHUA	36	11	5	8.0 - 8.1	0.04 - 0.06
010[2]	PUTNAM	18	6	1	8.0 - 8.2	0.07 - 0.12
011[2]	PUTNAM	18	6	1	8.0 - 8.2	0.07 - 0.12
012[2]	PUTNAM	24	6	1	8.0 - 8.2	0.07 - 0.12
013	OKEECHOBEE	24	9	5	8.0 - 8.3	0.07 - 0.10
014	INDIAN RIVER	36	3	5	7.4 - 8.5	0.07 - 0.15
015	POLK	24	3	4	7.1 - 8.2	0.02 - 0.07

1Represented by same soils data 2Represented by same soils data
*For complete pH and EC data see Table 5-1

CHAPTER 5
SOIL AND CORROSION ANALYSIS

5.1 Physical Soil Properties

For most samples analyzed on the 16 FDOT sites, Munsell color values were low (i.e., dark-colored; see Table 5-1). The consistently dark color of fill material identified as ^C1, ^C2, and other is presented in Table 5-1. Dark color generally arises from organic matter (not particularly favorable engineering construction material). Exceptions to the dark color were Eg and Btg horizons of natural soils sampled on the periphery of Duval (Jacksonville) pipe repair sites (#000 and #002). These horizons were light-colored due to having experienced sufficient water saturation to chemically reduce and deplete iron (Vepraskas and Faulkner 2003; Morgan and Stolt 2006), resulting in color being controlled by sand surfaces. The soil survey maps along the strip of road where Duval sites #000, #001, and #002 (Appendix D) were located, indicate a predominance of poorly-drained soils over which the highway was constructed. The morphology of natural soils described at all 3 Duval sites was consistent with seasonal high water table conditions prior to road construction, including a truncated soil overlain with fill material sampled from a median near the pipe repair location at Site #001. Imperfect natural drainage was also indicated at most of the other sites, as discussed in Section 5.3. Hydrologic controls implemented with urbanization may well have altered drainage conditions that produced the soil morphology.

Soil textures were coarse at all sites. The textural classes as estimated by an experienced technician were confined to sand or loamy sand, with variable gravel (> 2-mm material) content as determined gravimetrically (shown in Table 5-1). Coarse textures were expected given the

Table 5-1. Summary of Soils Data for Sites Investigated. Fill material was identified, when recognized, as ^C1, ^C2, etc. Other horizon designations conform to conventions of the *USDA-NRCS Soil Survey Manual* (Soil Survey Division Staff 1993).

Pipe Durability Field Identity #	Horizon*	Lower Depth (cm)	Munsell Color	Textural Class Estimate**	Comments	Coarse Fragments (%)	pH (CaCl2)	pH (H_2O)	EC (mS/cm)
000	Ap	17	10YR 3/2	S		0.04	3.8	4.8	0.03
	EA	62	10YR 4/1	S		0.00	4.4	5.3	0.01
	Eg	132	10YR 7/1	S	Saturation @ 130cm	0.00	4.4	5.1	0.03
	Btg	145+	2.5Y 6/2	LS		0.00	4.0	4.6	0.02
001	^C1	25	2.5Y 3/1	S		6.37	7.1	7.8	0.13
	^C2	50	10YR 3/1	S		7.07	7.2	7.9	0.10
	^C3	75	2.5Y 3/1	S		8.39	7.3	8.0	0.07
	E	102	10YR 4/1	S		0.03	6.8	6.9	0.05
	Bh1	109	10YR 2/2	SL		0.00	7.0	7.2	0.07
	Bh2	115	10YR 3/2	SL		0.00	6.8	7.6	0.01
	Bw	130+	10YR 4/3	S		0.00	6.9	7.7	0.06
002-1	Ap1	25	10YR 2/1	S		0.00	5.0	5.9	0.03
	Ap2	45	10YR 3/1	S		0.00	4.8	5.9	0.02
	AE	65	10YR 4/1	S		0.00	4.5	5.5	0.01
	Eg	85	10YR 6/1	S		0.00	4.7	5.5	0.07
	Btg &Bh	118+	10YR 5/2	SL		0.00	4.3	4.9	0.14
002-2	^C1	25	10YR 2/1	LS	^C1-^C5 dug directly above pipe	17.49	7.1	7.1	0.05
	^C2	54	10YR 3/1	LS		9.99	7.0	7.6	0.04
	^C3	80	2.5Y 4/2	LS		3.17	7.2	8.0	0.03
	^C4	105	2.5Y 4/1	LS	"+ 2.5Y 4/2	6.03	7.1	8.2	0.02
	^C5	120+	10YR 4/2	LS	"+10YR 5/4, 2.5Y 2.5/1	7.70	7.2	8.1	0.03
006	^C1	30	2.5Y 2.5/1	S		4.11	7.1	7.8	0.03
	^C2	38	10YR 2/1	S		2.55	7.2	7.9	0.02
	^C3	69	2.5Y 3/1	S		8.40	7.4	8.1	0.03
	^C4	94	10YR 3/1	S		9.77	7.3	8.2	0.07

Table 5-1. Summary of Soils Data for Sites Investigated, continued.

Pipe Durability Field Identity #	Horizon*	Lower Depth (cm)	Munsell Color	Textural Class Estimate**	Comments	Coarse Fragments (%)	pH (CaCl2)	pH (H_2O)	EC (mS/cm)
	^C5	104+	2.5Y 2.5/1	S		1.13	7.3	7.2	0.06
005		16	10YR 2/1	LS		0.69	7.1	7.4	0.03
		41	10YR 3/1	LS		3.72	7.3	8.0	0.05
		57+	10YR 3/1	LS		7.03	7.5	7.9	0.02
009		28	10YR 3/1	LS	hydrophobic	3.72	7.2	8.1	0.04
		61	10YR 3/1	LS		1.96	7.2	8.0	0.06
		84	10YR 3/1	LS		1.65	7.3	8.0	0.05
		112	10YR 3/1	LS		1.05	7.3	8.0	0.05
		112+	10YR 2/1	LS		1.43	7.3	8.1	0.06
0015	^C1	25	10YR 3/2	S		12.30	7.3	7.1	0.05
	^C2	50	10YR 3/2	S		5.03	7.4	8.2	0.04
	^C3	75	10YR 3/2	S		9.35	7.5	7.4	0.02
	^C4	100	2.5 Y 3/1	S		7.04	7.5	8.0	0.06
	^C5	100+	2.5 Y 3/2	S		5.91	7.5	8.2	0.07
008		25	10YR 3/1	S		2.10	7.5	8.0	0.04
		40	10YR 2/1	S		0.35	7.4	8.1	0.03
		50	10YR 2/1	S		1.18	7.3	8.0	0.04
		75	10YR 2/2	S		0.00	7.2	7.8	0.05
		100	10YR 2/2	S		0.00	6.1	7.3	0.02
		100+	10YR 2/2	S		0.00	5.9	6.9	0.02
003, 004, 007		25	10YR 2/1	S	hydrophobic	11.16	7.3	7.7	0.20
		50	10YR 2/1	S	hydrophobic	7.80	7.4	7.8	0.06
		50+	10YR 2/1	S	hydrophobic	4.76	7.4	7.9	0.16
013		20	2.5Y3/2	S		14.12	6.9	8.0	0.08
		41	2.5Y 3/2	S		18.43	7.1	8.2	0.10
		60	2.5Y 4/2	S		10.12	7.3	8.3	0.07
		60+	2.5Y 3/1	S		6.28	7.3	8.3	0.08

Table 5-1. Summary of Soils Data for Sites Investigated, continued.

Pipe Durability Field Identity #	Horizon*	Lower Depth (cm)	Munsell Color	Textural Class Estimate**	Comments	Coarse Fragments (%)	pH (CaCl2)	pH (H_2O)	EC (mS/cm)
014		71	10YR 3/2	S		0.69	7.3	8.5	0.07
		96	10YR 3/2	S		0.62	7.2	8.2	0.15
		96+	10YR 2/2	S		0.00	6.6	7.4	0.15
010, 011, 012		18	10YR 2/1	S		8.25	7.3	8.1	0.07
		43	10YR 3/2	S		20.34	7.4	8.2	0.11
		60	10YR 3/2	S		4.39	7.3	8.0	0.09
		85	10YR 2/2	S		6.39	7.4	8.1	0.11
		85+	10YR 2/2	S		2.70	7.4	8.0	0.12

* Horizon explanation:

Ap = Disturbed surface (e.g., tilled)
E = Depleted via leaching of clay, metals, etc.
EA = Transitional between A and E.
Btg = Accumulation of clay translocated from above; “g” conveys iron depletion via chemical reduction (as also with Eg).
Bh = Accumulation of organic matter and metals translocated from above.
Bw = Some in-situ weathering
^C = Human-transported material (e.g., fill with gravel)

** Experienced soil scientist or technicians can make reasonably accurate estimations of textural classes by hand using guidelines reflecting plasticity, grittiness, etc. These estimations were made by a worker experienced with Florida soils on the < 2-mm material (after removal of gravel by sieving). Textural classes include: S = sand; LS = loamy sand; SL = sandy loam. Sand-sized particles (2.00 – 0.05 mm) dominated all samples after gravel removal. Clay content in most cases would be < 10%, but SL samples could have as much as 20%. Percentages of fine particles (< 0.05 mm) would generally be in the order S < LS < SL.

sandy nature of the indigenous soils and the advantage of sandy or gravelly materials in construction.

5.2 Chemical Soil Properties

The pH values of natural soils (Sites #000 and #002-1) were in the typical acidic range (Table 5-1) for common Florida sandy soils (http://soils.ifas.ufl.edu/flsoils/). An exception was the truncated soil overlain by fill material (Site #001), which had an alkaline reaction which likely is attributable to a leaching effect from the limestone gravel in the fill. The pH of fill material sampled as close to the pipe as possible was consistently in the neutral to alkaline range and much higher than that of typical natural soil of the area. Materials selected for fill, therefore, contained an alkaline buffer, which in most or all cases was likely a form of calcium carbonate (e.g., lime or limestone gravel; most fill samples contained at least some gravel). It seems unlikely that the pH of fill material would be detrimental to the concrete pipes being assessed given that the pipes were also composed in part of calcium carbonate. The pH_{water} was slightly higher than that determined in $CaCl_2$, which is a typical tendency for soils with relatively low electrical conductivity (EC) (and high resistivity).

The variation of EC values for samples analyzed was not large and no sample was exceptionally high. Even fill-material samples fell within the range typical of Florida soils (http://soils.ifas.ufl.edu/flsoils/); values of native soils and fill materials of this study were comparable. The relatively low magnitude of EC values is consistent with the observed lowering of pH with salt ($CaCl_2$) addition; the $CaCl_2$ effect would have been muted had EC been high in the original soil and fill materials. The highest EC value measured (0.20 mS/cm) among the samples analyzed is only 1/20 the value needed to qualify as saline soil material under USDA criteria (Soil Survey Staff 1999).

In summary, neither pH nor EC of soils or fill materials in the vicinity of the pipe repairs suggests a chemically hostile external environment to pipes. It is possible that the internal pipe environment could have conditions (e.g., sulfidic materials or production of hydrogen sulfide gas from sulfate-reducing bacteria) that could induce corrosion.

5.3 Implications Derived from Soil Maps and Field Assessments (see Table 5-1 and Appendix D)

General comments – Acid soils were dominant at all sites except Site 13 in Okeechobee County, where there were significant areas of Ft. Drum and Riviera soils that have alkaline subsurface horizons. However, most samples collected in the vicinity of pipes were neutral to mildly alkaline as reported above. Hence, the chemical environment has been altered, most likely by the influence of fill material with limestone. Soil maps provided cues as to the precon-struction hydrology; most sites are surrounded by poorly- to somewhat-poorly-drained soils, with a few exceptions that are noted below. The post-construction alteration of hydrology likely varies among the sites; the influence of surrounding soil water tables and consequent effects of chemical oxidation and reduction on pipes is uncertain but would be a pertinent issue to pursue.

Duval County Sites #000-#002 – Four soil excavations were performed by auger at these sites (two at Site #002). Horizon morphologies (color and texture) were consistent with the prevalence of poorly- (e.g., Albany, Sapelo, and Pelham Series) to very-poorly-drained (e.g., Surrency Series) soils as was conveyed on the soil maps in the vicinity of construction disturbance (disturbance designated by "Urban Land").

Orange County Sites #003, #004, and #007) – This area was highly urbanized and designated as "Urban Land." The closest identifiable natural soil in the vicinity as indicated by the soil survey was the Millhopper series, a moderately-well-drained soil. However, the natural (original) hydrology of this area has been altered profoundly by urban features (impervious surfaces, artificial drainage, etc.).

Clay County Site #005 – This site is in an area that in its original state represented extremes in natural drainage, from excessively-well (Penney Fine Sand, 0-5% Slopes) to very-poorly (Surrency Fine Sand, Depressional). The excessively-well-drained landscape is restricted to an area about 0.1 miles to the west of the site. The remainder of the area is dominated by relatively wet soils, mostly complexed with "Urban Land." It is likely that significant urbanization has occurred since the soil map was made, given the abundance of impervious surfaces in an area mapped as Scranton Fine Sand (a poorly-drained soil). The specific pipe site is located in an Urban Land map unit, but its context suggests that it was originally a relatively wet site prior to construction.

Duval County Site #006 – This site is in an "Urban Land" map unit and surrounded by poorly-drained soils (Leon and Boulogne) mapped in complex with a predominant urban land component.

Orange County Site #008 – This site is in an "Urban Land" map unit but in close proximity to a non-urbanized area of wet soils to the south, including Smyrna Fine Sand (poorly drained) and Basinger Fine Sand, Depessional (very-poorly drained). A Smyrna-Urban Land Complex is mapped in the area to the north of the "Urban Land" map unit, indicating that this area had relatively poor natural drainage prior to construction.

Alachua County Site #009 – The soils map indicated that this site is in an area of soil that is prevalently poorly drained (Wauchula) but with moderately-well (Millhopper) to well-drained (Arredondo) soils on the periphery. All map units are complexes that include an “Urban Land” component.

Putnam County Sites #010 and #011 – These sites are located within a somewhat-poorly-drained map unit (Electra Fine Sand) (seasonal high water tables shallower that one meter). Wetter soils (Pomona and Ona) occur in close proximity to the south of the sites, and drier soils (Tavares Fine Sand, 0-5% Slopes; moderately well-drained) are mapped to the northeast and northwest. This site is not intensely urbanized and natural drainage may not have been extremely altered.

Putnam County Site #012 – This site is located within a somewhat-poorly-drained map unit (Zolfo Fine Sand) having seasonal high water tables shallower that one meter. It is near the edge of a better drained area (Tavares Fine Sand, 0-5% Slopes; moderately well-drained) directly to the north. However, most of the area is somewhat poorly-drained or wetter. Poorly- (Ona Fine Sand) to very-poorly-drained (Pomona Fine Sand, Depressional; Placid Fine Sand, Depressional) occur within approximately 0.05 to 0.1 miles. No urban land map units occur nearby, but the aerial photo indicates significant construction and impervious surface near the site.

Okeechobee County Site #013 – This site occurs within, and is completely surrounded by (to a distance of > 0.1 miles), poorly-drained soils as indicated by the soils map. The aerial photo shows moderate levels of construction and impervious surfaces but map unit names do not reflect urban land influence. Some construction could have occurred after the soil map was created.

Indian River County Site #014 – This site occurs within what was originally a poorly-drained, nearly-level landscape that has been heavily modified by drainage necessities of urbanization.

Polk County Site #015 – This site is in an “Urban Land” map unit. The landscape context suggests a former drainage of moderately-well- (Tavares Fine Sand, 0-5% Slopes) to excessively-well-drained (St. Lucie Fine Sand, 0-5% Slopes) soils. A lot of land disturbance is indicated in the area. The map unit “Arents, 0-5% Slopes” designates an area with highly disrupted soil horizons.

5.4 Corrosion Analysis

Duval County Site #000 –There were several joints with a large amount of separation throughout the project. Due to standing water within the pipe, the bottom of the pipe was not visible. However, it is apparent that there was some corrosion along the side of the pipe, visible by discoloration from three o’clock to nine o’clock. Despite the mild corrosion, the host pipe remained efficient.

Duval County Site #001 – Within the entire piping project, there were no visible structural issues. There appeared to be zero corrosion showing on the surface of the host pipe.

Duval County Site #002 – Throughout this piping project, there were no visible structural issues. There was a small amount of running water throughout the pipe and the pipe appeared to have some mild corrosion along the water line seen from discoloration of the host pipe. Despite the mild corrosion, the host pipe remained efficient.

Orange County Site #003 – Throughout this piping project, there were no visible structural issues. Due to the large amount of standing water within the pipe from three o'clock to nine o'clock, no corrosion could be seen.

Orange County Site #004 – Throughout this piping project, there were no visible structural issues. Due to the large amount of standing water within the pipe from three o'clock to nine o'clock, no corrosion could be seen.

Clay County Site #005 – Within the host pipe there was zero noticeable structural issues. There was a small amount of running water along the bottom of the pipe where there appeared to be some mild corrosion seen by discoloration along the water line of the host pipe. Despite the mild corrosion, the host pipe remained efficient.

Duval County Site #006 – Separation had occurred at one joint where the alignment of the bottom portion of the pipe was not level. There was a small amount of running water along the bottom of the pipe where there appeared to be some mild corrosion seen by discoloration along the water line of the host pipe. Despite the small separation and mild corrosion, the host pipe remained efficient.

Orange County Site #007 – Within the entire piping project, there were no visible structural issues. There appeared to be zero corrosion showing on the surface of the host pipe.

Orange County Site #008 – The pipe had standing water from five o'clock to seven o'clock and there appeared to be some light corrosion below the water line. Along the left side of the pipe, there was a wrinkle in the felt tube, however this did not seem to cause any issues.

Alachua County Site #009 – The pipe had a small amount of water but showed no visible structural issues and zero corrosion on the surface of the pipe.

Putnam County Site #010 – The pipe had no standing water and there were no visible structural issues. There appeared to be a very light amount of corrosion along some of the joints.

Putnam County Site #011 –The pipe had some debris along the bottom of the pipe, but had no visible structural issues. There appeared to be some corrosion along some of the joints.

Putnam County Site #012 – The pipe had standing water from five o'clock to seven o'clock. There were no visible structural issues and there appeared to be some corrosion along some of the joints.

Okeechobee County Site #013 – The pipe had no standing water and no visible structural issues. There appeared to be some corrosion along the joints which had not been banded.

Indian River County Site #014 – The pipe had standing water along the bottom of the pipe. There were no visible structural issues, but the pipe appeared to have some light corrosion along the length of the pipe from 3 o'clock to 6 o'clock.

Polk County Site #015 – The pipe had no standing water and no visible structural issues. There appeared to be some light corrosion along the very bottom of the pipe and along some of the joints.

CHAPTER 6
RECOMMENDATIONS

Guidelines should be developed and implemented to systematically track and assess the condition of pipes over time. The data collected during these assessments should be maintained in a comprehensive pipe management system to enable scheduling of maintenance activities, justification of funding needs, prioritization of pipe work, and methods of repair. The existence of a prescriptive system of pipe management will enable FDOT to determine long-term durability of various pipe repair methods over the service life of the pipes. As was detailed in earlier sections, information on pipe repair projects throughout the Districts was unorganized and in many places unrecorded. The research team recommends some type of organizational structure be implemented for these types of projects.

Due to the fact that the research team was limited by time and funding, this research is not completely comprehensive, as only 16 repair sites could be visited and inspected. However, the legwork has been completed and a database of sites compiled. Several important connections were made, and it is recommended that FDOT utilize this work to build on. An extension or secondary project similar to this one, to include more site visits and laser profiling, would provide FDOT with a much more conclusive analysis. The post-construction alteration of hydrology likely varies among the sites; the influence of surrounding soil water tables and consequent effects of chemical oxidation and reduction on pipes is uncertain but would be a pertinent issue to pursue. The research team would like to acknowledge a few important items based on each repair type.

6.1 Chemical Grout

The UF research team analyzed 5 chemical grout repairs that included point repairs and joint repairs throughout the pipe project. The overall durability of this repair appears to be weak. The longevity seems to be shorter than many other repairs. Seen in Site #000, there is little to no chemical grouting evident throughout the entire pipe project. Chemical grouting is most commonly used for leaking problems but can be helpful in structural and corrosion problems as well (Section 2.4.2.11, Chapter 2). In the case of leakages, chemical grouting seems to be the only cost-effective method of solving the problem. However, despite the initially low cost of chemical grouting, its limited durability may reduce its ultimate cost-effectiveness. Chemical grouting appears to be more effective in smaller diameter pipes. Application of structural adhesives, chemical grouting, and sealing are appropriate methods of repair for cracked joints. Open joints may be sealed with similar methods unless the opening is wide. Wide openings can be repaired by installing steel bands and covering with shotcrete (Section 2.1.1).

6.2 Pipe Liner

The UF research team analyzed five pipe liner repairs that included shorter repairs (under 20′) and liners that extended a much further distance. The durability of pipe liners appears to be very strong. Increased wall thickness yields higher strength, but also higher weight which can cause the liner to buckle (Section 2.4.3.1, Chapter 2). All pipe liners that the UF research team analyzed are still extremely effective. As seen in Site #008 from Appendix D, despite the bad overall appearance of the pipe, the liner remains effective in allowing flow throughout the project. Pipe liners are a more expensive initial cost; however, they make up for the steep initial cost with the longevity they provide. However, Site #007 which utilized a joint-to-joint liner, was extremely ineffective Cured in-place pipe (CIPP) liner can provide structural (or nonstructural) rehabilitation of existing pipe, depending on the thickness of the liner (Section 2.4.3.1, Chapter 2). Pipe liners are extremely effective in all pipe diameters.

6.3 Point Repair

The UF research team analyzed four point repairs, three joint seals, and one repair sleeve that was applied to only a portion of the pipe. The joint seals did not appear to be completed or there appeared to have been a different repair type utilized, however the UF research team was assured joint seals were used at these locations. There appeared to be a lot of infiltration in the joint seals, so the durability is weak. Site #007 which utilized a sectional liner, as seen in Appendix D, was extremely ineffective. Sites #010, #011, and #012, which utilized internal joint seals, were more effective but were inconsistently installed. The large initial cost and ineffective/inconsistent performance makes this repair type unattractive. Also, analyzed was a repair sleeve which extended over a few joints in the middle of the pipe. The durability of the repair sleeve is extremely strong. This repair type is very similar to a pipe liner except that repair sleeves are always applied only to an affected area rather than the entire project. Repair sleeves are a more expensive initial cost; however, they make up for the steep initial cost with the longevity they provide. Repair sleeves are extremely effective in all pipe diameters.

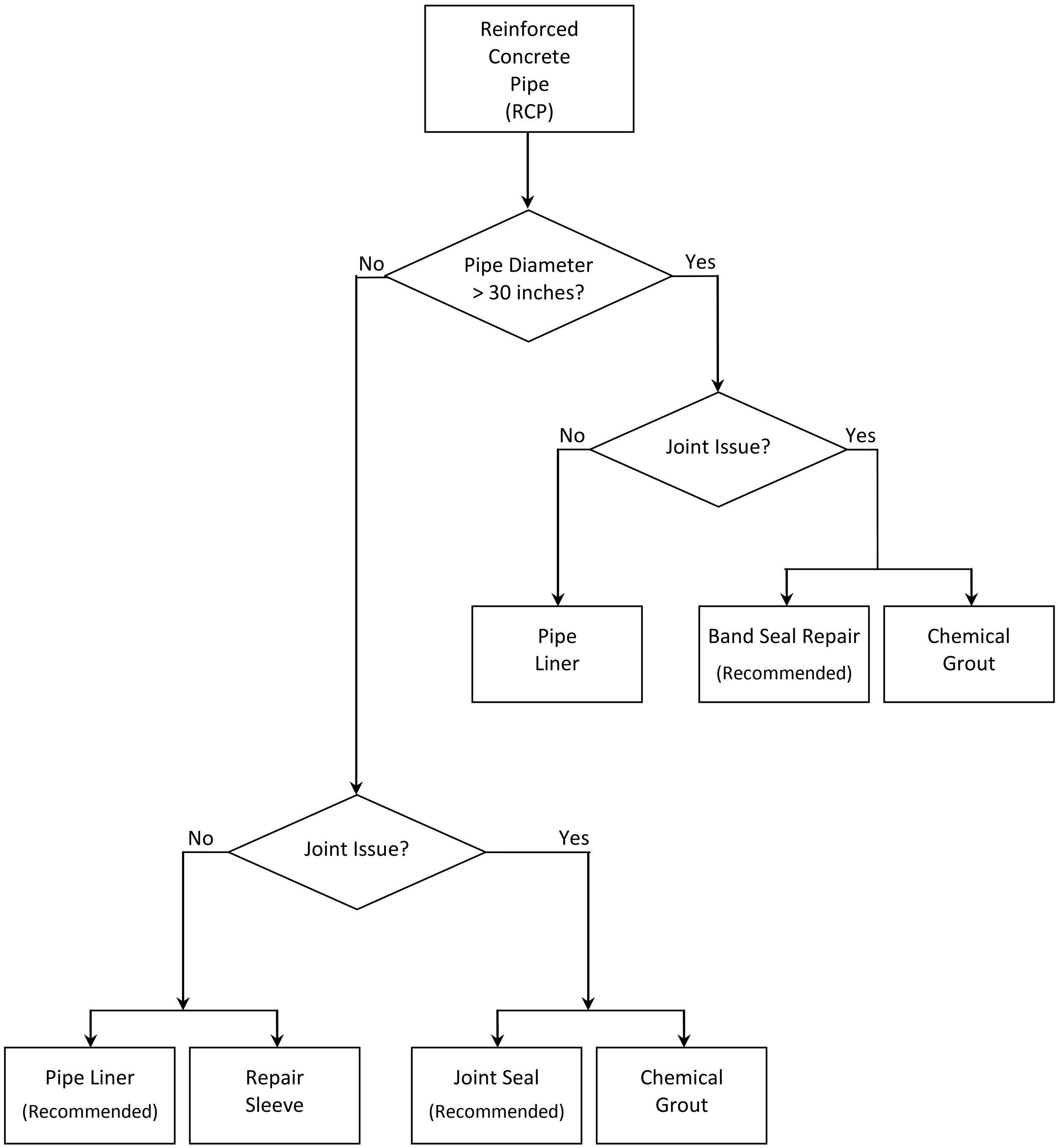
6.4 Band Seal

The UF research team analyzed two band seal repairs that were applied to separated joints throughout the repair. The durability of the repair was strong. The longevity of this repair type is extremely good. Each joint with a band seal repair remained extremely effective and sealed. The band seals appear to be an excellent choice for joint issues. Band seals are effective in all pipe diameters. Due to the greater initial cost for band seals than other joint repairs, band seals are recommended for use in larger diameter pipes.

6.5 Overview of Recommendations for Joint Issues

Figure 6-1 presents a pipe repair flow chart based on the analysis of 16 sites. For RCP greater than 30″ in diameter, joint issues are best repaired using band seals or chemical grout; however, band seals are more effective. For non-joint issues, pipe liner is recommended.

For RCP less than 30″ in diameter, joint issues are best repaired using internal joint seals or chemical grout; however, internal joint seals are more effective. Non joint issues can be repaired using pipe liners or repair sleeves; however, pipe liners are more effective.



NOTE: Sectional liner is not suggested for use.

Figure 6-1. Proposed Pipe Repair Flowchart

REFERENCES

AASHTO. 1991). *Model Drainage Manual*. American Association of State Highway and Transportation Officials, Washington, D.C.

Adams, D. N., Muindi, Y., and Selig, E. T. (1989). Polyethylene Pipe Under High Fill. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1231, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 88-95.

AK Steel. Aluminized Steel Type 2 Corrugated Steel Pipe. AK Steel. www.lane-enterprises.com/downloads/Aluminized_Steel_Folder.pdf. Accessed Aug. 18, 2010.

Alamilla J. L., Espinosa-Medina, M. A., and Sosa, E. (2009). Modelling Steel Corrosion Damage in Soil Environment. *Corrosion Sci*., Vol. 51, pp. 2628-2638.

Alcorn, S. R., Coons, W. E. and Gardiner, M. A. (1990). Estimation of Longevity of Portland Cement Grout Based on Chemical Modeling Techniques. *Materials Research Society Symposium Proceedings*, Vol. 176, Materials Research Society.

All American Trenchless Technologies. (2010). *Trenchless Pipe Bursting*. All American Trenchless Technologies. www.allamericantrenchless.com/services/trenchless-pipe-bursting.html. Accessed Aug. 15, 2010.

American Concrete Pipe Association. Why Concrete Pipe? American Concrete Pipe Association. www.concrete-pipe.org/why.htm?cp_Session=8ed8723def8251379f8fd09f3a6f9fb8. Accessed Aug. 12, 2010.

Anis W. R., and Alfons, H. A. (1994). Photovoltaic Powered Regulated Cathodic Protection System. *Sol. Energy*, Vol. 53, pp. 211-214.

Arnoult, J. D. (1986). *FHWA Culvert Inspection Manual: Supplement to the Bridge Inspector's Training Manual*. Report No. FHWA-IP-86-2, Byrd, Tallamy, MacDonald and Lewis group, Federal Highway Administration, U.S. Department of Transportation, July.

ASTM. (2003). *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)*. Report No. ASTM F 1743–96, American Society for Testing and Materials, Washington, D.C.

Atlas Inspection Technologies, Inc. (2010). Laser Profiling. www.atlas-inspection.com/laser-profiling.html. Accessed August 2010.

Ault, J. P., and Ellor, J. A. (2000). Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe. Publication FHWA-RD-97-140, Federal Highway Administration, U.S. Department of Transportation, January, 106 pp. www.fhwa.dot.gov/engineering/hydraulics/pubs/97140/97140.pdf. Accessed Aug. 20, 2010.

Ballinger, C. A., and Drake, P. G. (1995a). *FHWA Culvert Repair Practices Manual: Volume I*. Publication FHWA-RD-94-096. Federal Highway Administration, U.S. Department of Transportation, May.

Ballinger, C.A., and Drake, P. G. (1995b). *FHWA Culvert Repair Practices Manual: Volume II (Appendices)*. Publication No. FHWA-RD-95-089, Federal Highway Administration, U.S. Department of Transportation, May.

Bellair, P. J., and Ewing, J. P. (1984). Metal-Loss Rates of Uncoated Steel and Aluminum Culverts in New York. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1001, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 60-69.

Benedict R. L., Ott, J. G., Marshall, D. H., and White, D. (1997). Cathodic Protection of Prestressed Concrete Cylinder Pipe Utilizing Zinc Anodes. *Mater. Perform*., Vol. 36, pp. 12-16.

Benmoussa, A., Hadjel, M., and Traisnel, M. (2006). Corrosion Behavior of api 5l x-60 Pipeline Steel Exposed to Near-neutral pH Soil Simulating Solution. *Mater. Corros*., Vol. 57, pp. 771-777.

Benson, R. C. (2002). A Review of Soil Resistivity Measurements for Grounding, Corrosion Assessment, and Cathodic Protection. *Mater. Perform*., Vol. 41, pp. 28-34.

Beucler, B., Pipe Rehabilitation on Skyline Drive—Shenandoah National Park, Report FHWA EP-85-004, Federal Highway Administration, Washington, D.C., 1985.

Bhardwaj, A., Isor, A., Chugh, S. K., Kapoor, I. R., and Sonawane, A. K. (2004). Rehabilitating the Coating and CP Systems of In-plant Parallel Pipelines. *Corrosion Prev. Control*, Vol. 51, pp. 83– .

Bohn, H. L., McNeal, B. L., and O'Connor, G. A. (2001). *Soil Chemistry*. Third edition. John Wiley and Sons, New York.

Caltrans. (2003a). Culvert Structures. *Design Information Bulletin No. 83-01: Caltrans Supplement to FHWA Culvert Repair Practices Manual, DIB 83-01*. California Department of Transportation (Caltrans), June 30. www.dot.ca.gov/hq/oppd/dib/dib83-01-2.htm. Accessed Aug. 17, 2010.

Caltrans. (2003b). General Culvert Barrel Rehabilitation Techniques. *Design Information Bulletin No. 83-01: Caltrans Supplement to FHWA Culvert Repair Practices Manual, DIB 83-01*. Caltrans, June 30. www.dot.ca.gov/hq/oppd/dib/dib83-01-6.htm. Accessed Aug. 17, 2010.

Caltrans. (2003c). Problem Identification and Associated Repair for Culvert Barrels. *Design Information Bulletin No. 83: Caltrans Supplement to FHWA Culvert Repair Practices Manual, DIB 83*. Caltrans, June 30. www.dot.ca/gov/hq/oppd/dib/dib83-5.htm. Accessed Aug. 29, 2010.

Charalambous, C., and Cotton, I. (2007). Influence of Soil Structures on Corrosion Performance of Floating-DC Transit Systems. *IET Electr. Power Appl*., Vol. 1, pp. 9-16.

Chin, D. T., and Sabde, G. M. (2000). Modeling Transport Process and Current Distribution in a Cathodically Protected Crevice. *Corrosion* , Vol. 56, pp. 783-793.

Choi, Y. S., Kim, J. G., and Yang, S. J. (2006). A galvanic sensor for monitoring the corrosion damage of buried pipelines: Part 2 - correlation of sensor output to actual corrosion damage of pipeline in soil and tap water environments. *Corrosion*, Vol. 62, pp. 522-532.

Corwin, D. L., and Lesch, S. M. (2003). Application of Soil Electrical Conductivity to Precision Agriculture: Theory, Principles, and Guidelines. *Agronomy J*., Vol. 95, pp. 455-471.

Cues, Inc. Laser Profiler System. *Laser Profiler Brochure*. www.cuesinc.com/pdf%20docs/Laser%20Profiler%20Brochure.pdf. Accessed August 2010.

DelDOT. (2009). *Storm Sewer CCTV Manual for Storm Sewer Assessment and Acceptance*. Delaware Department of Transportation (DelDOT), January 1, 93 pp.

Donner, H. E., and Grossl, P. R. (2002). Carbonates and Evaporites. In: J. B. Dixon and D. G. Schultz (Eds.), *Soil Mineralogy with Environmental Applications*, Soil Science Society of America, Madison, pp. 199-228.

Doyle, G., Seica, M. V., and Grabinsky, M. W. F. (2003). The Role of Soil in the External Corrosion of Cast Iron Water Mains in Toronto, Canada. *Can. Geotech. J.*, Vol. 40, pp. 225-236.

Durability of Building Materials and Components. (1999). *Proceedings 8th International Conference, National Research Council of Canada*, M.A. Lacasse and D.J. Vanier (Eds.), Vancouver, Canada, May 30-June 3.

Essington, M. E. (2004). *Soil and Water Chemistry: An Integrative Approach*. CRC Press, Boca Raton.

Fanning, D. S., Rabenhorst, M. C., Burch, S. N., Islam, K. R., and Tangren, S. A. (2002). Sulfides and Sulfates. In: J. B. Dixon and D. G. Schultz (Eds.), *Soil Mineralogy with Environmental Applications*, Soil Science Society of America, Madison, pp. 229-260.

FDOT. (2010a). *Pipe Repair Matrix*. Florida Department of Transportation, Office of Construction. www.dot.state.fl.us/construction/ContractorIssues/PipeMatrix/MatrixMain.shtm. Accessed July 9, 2010.

FDOT. (2010b). *Standard Specifications for Road and Bridge Construction 2010*, Florida Department of Transportation. ftp://ftp.dot.state.fl.us/LTS/CO/Specifications/SpecBook/2010Book/2010Master.pdf. Accessed August 6, 2010.

FEMA. (2005). *Technical Manual: Conduits through Embankment Dams – Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair*. Publication No. FEMA 484, Federal Emergency Management Agency, September, 614 pp.

Gabriel, L. H. Chapter 7: Durability and Service Life. *The Complete Corrugated Polyethylene Pipe Design Manual and Installation Guide*. Plastic Pipe Institute. http://plasticpipe.org/pdf/chapter-7_durability_service_life.pdf. Accessed May 20, 2010.

Gabriel, L.H. and Moran, E.T., 1998, "Service Life of Drainage Pipe," NCHRP Synthesis of Highway Practice 254.

GalvInfo Center. (2010). Metallic-Coated Products and Specifications: 55% Aluminum-Zinc Alloy-Coated Steel Sheet. *GalvInfo Note 1.4*, GalvInfo Center, Revision 1.0, Feb. http://galvinfo.com/ginotes/GalvInfoNote_1_4.pdf. Accessed Aug. 20, 2010.

Gan, F., Sun, Z. W., Sabde, G., and Chin, D. T. (1994). Cathodic Protection to Mitigate External Corrosion of Underground Steel Pipe Beneath Disbonded Coating. *Corrosion*, Vol. 50, pp. 804-816.

Gassman, S. L., Schroeder, A. J., and Ray, R. P. (2002). Performance Evaluation of High Density Polyethylene Culvert Pipe. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1814, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 171-178.

Guan, S. W. (2000). The Selection, Application and Inspection of 100% Solids Polyurethane Coatings for Corrosion Protection. *Proceedings of SSPC 2000*, Tennessee, Nashville, Madison Chemical Industries Inc., Canada, Nov. 12-16. www.madisonchemical.com/pdf_tech_papers/sspc2000_Selection_Application_Inspection.pdf. Accessed Aug. 12, 2010.

Guan, S. W. (2001). Corrosion Protection by Coatings for Water and Wastewater Pipelines. *46th Proceedings of AUCSC*, Appalachian Underground Corrosion Short Course, Water and Wastewater Program, West Virginia University PA, May 15. www.madisonchemical.com/pdf_tech_papers/AUCSC2001_The_Corrosion_Protection.pdf. Accessed Aug. 13, 2010.

Guan, S. W. (2003). Advanced 100% Solids Rigid Polyurethane Coatings Technology for Pipeline Field Joints and Rehabilitation. *Proceedings of Corrosion NACExpo*, Madison Chemical Industries Inc., Canada. http://madisonchemical.com/madison_resources/downloads/tech_nace2003.pdf. Accessed Aug. 13, 2010.

Heger, F. J., and Selig, E. T. (1994). Rigid Pipe Distress in High Embankments over Soft Soil, Strata. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1431, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 46-52.

Hirsch, C. L. (1984). Durability of Polymer-Coated Steel Pipe. In: *Symposium on Durability of Culverts and Storm Drains, Transportation Research Record: Journal of the Transportation Research Board*, No. 1001, Sponsored by Committees on Corrosion; Hydrology, Hydraulics, and Water Quality; and Culvert and Hydraulic Structures, Transportation Research Board of the National Academies, National Research Council, Washington, D.C.

Hollingshead, T., and Tullis, B. P. (2009). *In-Situ Culvert Rehabilitation: Synthesis Study and Field Evaluation*. Utah Department of Transportation Research Division, June. www.udot.utah.gov/main/uconowner.gf?n=9732720543913757. Accessed Aug. 27, 2010.

Hurd, J. O. (1984). Field Performance of Protective Linings for Concrete and Corrugated Steel Pipe Culverts. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1001, Sponsored by Committees on Corrosion; Hydrology, Hydraulics, and Water Quality; and Culvert and Hydraulic Structures, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 35-40.

ILDOT. (2010). *Acceptable, Unacceptable, and Unacceptably Repaired Precast Concrete Products–A visual aid for Bureau of Materials and Physical Research's Policy Memorandum,* "*Quality Control/Quality Assurance Program for Precast Concrete Products*." Illinois Department of Transportation (ILDOT), February 1, 61 pp.

Iowa DOT. (2006). *Pipe Rehabilitation*. Iowa Department of Transportation, October. www.iowadot.gov/erl/archives/Oct_2006/US/content/4030.htm. Accessed August 27, 2010.

IPS. (2010). *Swagelining Projects.* Innovative Pipeline Solutions, Aug. 19. www.innovativepipes.com/InnovativeSolutions/Swagelining/Projects.aspx. Accessed Aug. 19, 2010.

ISTT. (2005). *Insitu Applied Coatings*. International Society for Trenchless Technology, August. www.astt.com.au/05%20INSITU%20APPLIED%20COATINGS.pdf. Accessed Aug. 10, 2010.

Jarvis, M. G., and Hedges, M. R. (1994). Use of Soil Maps to Predict the Incidence of Corrosion and the Need for Iron Mains Renewal. *Journal of the Institution of Water and Environmental Management*, Vol. 8, pp. 68-75.

Jenny, H. (1994). *Factors of Soil Formation: A System of Quantitative Pedology*. Dover Press, New York.

Johnson, D., and Zollars, J. (1992). Culvert Renewal. Report No. MN/RD-92/02, Minnesota Department of Transportation (Mn/DOT).

Kajiyama, F., and Okamura, K. (1999). Evaluating Cathodic Protection Reliability on Steel Pipe in Microbially Active Soils. *Corrosion*, Vol. 55, pp. 74-80.

Karathanasis, A. D. (2002). Mineral Equilibria in Environmental Soil Systems. In: J. B. Dixon and D. G. Schultz (Eds.), *Soil Mineralogy with Environmental Applications*, Soil Science Society of America, Madison, pp. 109-152.

Khan, N. A. (2004). Using Electrical Resistance Soil Corrosion Probes to Determine Cathodic Protection Effectiveness in High-Resistivity Soils. *Mater. Perform.*, Vol. 43, pp. 20-25.

Khare, M., and Nahar, S. N. (1997). Soil Aggressiveness Towards Buried Water Pipelines. *Environ. Technol.*, Vol. 18, pp. 187-194.

Li, M. C., Han, Z., Lin, H. C., and Cao, C. N. (2001a). A New Probe for the Investigation of Soil Corrosivity. *Corrosion*, Vol. 57, pp. 913-917.

Li, S., Jung, S., Park, K. W., Lee, S. M,. and Kim, Y. G. (2007). Kinetic Study on Corrosion of Steel in Soil Environments Using Electrical Resistance Sensor Technique. *Mater. Chem. Phys.*, Vol. 103, pp. 9-13.

Li, S.Y., Kim, Y. G., Jeon, K. S., Kho, Y. T., and Kang, T. (2001b). Microbiologically Influenced Corrosion of Carbon Steel Exposed to Anaerobic Soil. *Corrosion*, Vol. 57, pp. 815-828.

Liu, T. M., Wu, Y. H., Luo, S. X., and Sun, C. (2010a). Effect of Soil Compositions on the Electrochemical Corrosion Behavior of Carbon Steel in Simulated Soil Solution. *Materialwiss. Werkstofftech.*, Vol. 41, pp. 228-233.

Liu, Z., Sadiq, R., Rajani, B., and Najjaran, H. (2010b). Exploring the Relationship Between Soil Properties and Deterioration of Metallic Pipes Using Predictive Data Mining Methods. *J. Comput. Civil. Eng.*, Vol. 24, pp. 289-301.

Lynn, W. C., Ahrens, R. I., and Smith, A. I. (2002). Soil Minerals, Their Geographic Distribution, and Soil Taxonomy. In: J. B. Dixon and D. G. Schultz (Eds.), *Soil*

Mineralogy with Environmental Implications, Soil Science Society of America, Madison, pp. 691-710.

Maverick Inspection Ltd. (2009). Laser Profiler System: What Is It? www.maverickinspection.com/Services/LaserProfiling/tabid/135/Default.aspx. Accessed August 2010.

McBride, M. (1994). *Environmental Chemistry of Soils*. Oxford University Press, New York.

McCullouch, B. G. (1992). *Repair/Rehabilitation of Deteriorated Drainage Pipe*. Report No. C-36-62H. Purdue University, April 30. http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1763&context=jtrp. Accessed Aug. 27, 2010.

MDWS. (2008). *Pipe Lining*. Mitchell Drainage and Waste Services. www.mdws.org.uk/services/pipelining.html. Accessed Aug. 15, 2010.

Meegoda, P. E., Thomas, M., and Juliano, P. E. (2009). *Corrugated Steel Culvert Pipe Deterioration*. New Jersey Department of Transportation. Final Report, August.

Mirshahi, M. (2008). *Pipe Rehabilitation: Methods and Selection Process*. Virginia Department of Transportation, March 21. www.extranet.vdot.state.va.us/locdes/electronic%20pubs/iim/IIM244.pdf. Accessed Aug. 27, 2010.

Morgan, C. P., and Stolt, M. H. (2006). Soil Morphology-Water Table Cumulative Duration Relationships in Southern New England. *Soil Sci. Soc. Am. J.*, Vol. 70, pp. 816-824.

Najafi, M. (2004). *Trenchless Technology*. McGraw-Hill.

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

Najafi, M., Salem, S., Bhattachar, D., Salman, B., and Patil, R. (2008). An Asset Management Approach for Drainage Infrastructure and Culverts. *Project 06-08*, Midwest Regional University Transportation Center (UTC), College of Engineering, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, Wisconsin, Madison, June, 271 pp.

NCHRP. (1978). Current Specification for Drainage Pipe. *National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 50*, Durability of Drainage Pipe, Transportation Research Board, Washington, D.C.

NCI. 2010. Acrylamide in Food and Cancer Risk. *National Cancer Institute Fact Sheet*. National Cancer Institute, U.S. National Institutes of Health. www.cancer.gov/cancertopics/factsheet/risk/acrylamide-in-food. Accessed July 30, 2010.

NYSDOT. (2006). *Standard Specifications*. New York State Department of Transportation, May 4. https://www.nysdot.gov/portal/page/portal/main/business-center/engineering/specifications/specs-repository/section600.pdf. Accessed August 27, 2010.

Oberdorfer AG. *Pipe Inspection*. Oberdorfer AG Service Division. www.oberdorfer-ag.de/html/pipe_inspection.html. Accessed Aug. 17, 2010.

ODOT. (2005). *Hydraulics Manual Chapter 16 Trenchless Technology*. Oregon Department of Transportation. ftp://ftp.odot.state.or.us/techserv/Geo-

Environmental/Hydraulics/Hydraulics%20Manual/Chapter_16/Chapter_16.pdf. Accessed August 28, 2010.

Oetting, D. (2005). The Economics of Chemical Grouting. *Proceedings of No-Dig Conference,* North American Society for Trenchless Technology (NASTT), April 24-27, 11 pp. www.nastt.org/store/technical_papersPDF/460.pdf. Accessed July 30, 2010.

Okpala, D., and Anderson, W. (1997). Culvert Pipe Rehabilitation Using Slipliners. Wisconsin DOT (WisDOT), Madison, Wisconsin, February, 9 pp.

Osella, A., and Favetto, A. (2000). Effects of Soil Resistivity on Currents Induced on Pipelines. *J. Appl. Geophys*., Vol. 44, pp. 303-312.

Palmer, J. D. (1989). Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping. In: V. Chakar and D. Palmer (Eds.), *Effects of Soil Characteristics on Corrosion*, ASTM, Philadelphia. pp. 5-17.

Perma-Liner Industries. *Perma-Liner Systems and Products*. www.perma-liner.com/. Accessed Aug. 16, 2010.

Piehl, R. (2005). *Summary of Trenchless Technology for Use with USDA Forest Service Culverts*. U. S. Department of Agriculture Forest Service, Technology and Development Program, 7700–Transportation Management, 0577 1201–SDTDC, September.

Potter, J.C., Life-Cycle Cost for Drainage Structures, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi (1988).

Potter, J.C. and L. Schindler, "Life-Cycle Cost for Design of Army Drainage Structures," Transportation Research Record 1191, Transportation Research Board, National Research Council, Washington, D.C., 1988. pp. 106-112.

Rabenhorst, M. C., and Castenson, K. L. (2005). Temperature Effects on Iron Reduction in a Hydric Soil. *Soil Sci*., Vol. 170, pp. 734-742.

Redaelli, E., Bertolini, L., Peelen, W., and Polder, R. (2006). Fem-Models for the Propagation Period of Chloride Induced Reinforcement Corrosion. *Mater. Corros.* Vol. 57, pp. 628-635.

Rhoades, J.D. 1996. Salinity: electrical conductivity and total dissolved solids. p. 417-436. *In* Sparks et al. (eds.) Methods of soil analysis: part 3 – chemical methods. Soil Sci. Soc. Am. Madison, WI.

Ring, G. W. (1984). Culvert Durability: Where Are We? In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1001, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 1-9.

Sagues, A. A., Scott, R., Rossi, J., Pena, J. A., and Powers, R. (2000). Corrosion of Galvanized Strips in Florida Reinforced Earth Walls. *J. Mater. Civ. Eng*., Vol. 12, pp. 220-227.

Salem, S., Najafi, M., Salman, B., Calderon, D., Patil, R., and Bhattachar, D. (2008). Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures. *Project 07–15*, Midwest Regional UTC, College of Engineering, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, August.

Schwerdt, W. (1965). Soil Resistivity as Related to Underground Corrosion and Cathodic Protection. *Journal of Research of the National Bureau of Standards Section C-Engineering and Instrumentation*, Section C, Vol. 69, pp. 71–.

Scully, J. R., and Bundy, K. J. (1985). Electrochemical Methods for Measurement of Steel Pipe Corrosion Rates in Soil. *Mater. Perform*., Vol. 24, pp. 18-25.

Seica, M. V., Packer, J. A., Grabinsky, M. W. F., and Adams, B. J. (2002). Evaluation of the properties of toronto iron water mains and surrounding soil. *Can. J. Civ. Eng*., Vol. 29, pp. 222-237.

Soil Survey Division Staff. 1993. Soil survey manual,USDA handbook no.18 U.S. Gov. Print. Office, Washington,DC.

Soil-Survey-Staff. (1999). *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. U.S. Government Printing Office, Washington, D.C.

Sparks, D. L. (2003). *Environmental Soil Chemistry*. Second ed. Elsevier, San Diego.

Sposito, G. (2008). *The Chemistry of Soils*. Second ed. Oxford University Press, New York.

Stains, J. *Supplemental Specification 802: Constructing and Inspecting Pipe Culverts, Sewers, Drains and Drainage Structures*. Ohio Department of Transportation. www.dot.state.oh.us/Divisions/HighwayOps/Structures/Hydraulic/PDF_DOC%20File/SS802%20Presentation.pptx. Accessed August 27, 2010.

Summerson, T. J. (1984). *Corrosion Resistance of Aluminum Drainage Products: The First 25 Years.* In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1001, Sponsored by Committees on Corrosion; Hydrology, Hydraulics, and Water Quality; and Culvert and Hydraulic Structures, Transportation Research Board of the National Academies, National Research Council, Washington, D.C.

Sukley, R. and B. St. John, Evaluation of INSITUFORM Pipe Rehabilitation, PA-94-002-84-103, Pennsylvania Department of Transportation, Harrisburg, October 1994.

Thomas, G.W. 1996. Soil pH and soil acidity. p. 475-490. *In* Sparks et al. (eds.) Methods of soil analysis: part 3 – chemical methods. Soil Sci. Soc. Am. Madison, WI.

TI. (2009). *Sliplining Strasbourg's Sewers*. Trenchless International, Nov. 20. http://trenchlessinternational.com/news/sliplining_strasbourgs_sewers/008770/. Accessed August 16, 2010.

Transportation Research Board, 2002, "Assessment and Rehabilitation of Existing Culverts," NCHRP Synthesis 303.

Trelleborg AB. (2010). *epros® Drain Internal Joint Seal*. (2010). Trelleborg AB Pipe Seals, May 11. www.trelleborg.com/en/Epros/Product-Range/DRAIN-INternal-Joint-Seal/. Accessed August 14, 2010.

Uni-Bell PVC Pipe Association. (2007). PVC Pipe. Uni-Bell Technical Publication UNI-PUB-11-07, Uni-Bell PVC Pipe Association. www.uni-bell.org/pubs/uni-pub-11.pdf. Accessed May 16, 2010.

USACE. (1999). Application of Trenchless Technology at Army Installations. Public Works Technical Bulletin 420-49-10. U.S. Army Corps of Engineers, Washington, D.C., February 28. www.wbdg.org/ccb/ARMYCOE/PWTB/pwtb_420_49_10.pdf. Accessed August 20, 2010.

Velazquez, J. C., Caleyo, F., Valor, A., and Hallen, J. M. (2009). Predictive Model for Pitting Corrosion in Buried Oil and Gas Pipelines. *Corrosion*, Vol. 65, pp. 332-342.

Vepraskas, M. J., and Faulkner, S. P. (2001). Redox Chemistry of Hydric Soils. In: J. L. Richardson and M. J. Vepraskas (Eds.), *Wetland Soils: Genesis, Hydrology, Landscapes, and Classification*, CRC Press, Boca Raton, pp. 85-106.

WERF. (2000). New Pipes for Old: A Study of Recent Advances in Sewer Pipe Materials and Technology. Final Report, Project 97-CTS-3, Water Environment Research Foundation, Alexandria, Virginia.

Zhao, J. Q. (1998). Durability and Performance of Gravity Pipes: A State-of-the-Art Literature Review. Institute for Research in Construction National Research Council of Canada, Ottawa, Canada.

SUPPLEMENTAL BIBLIOGRAPHY

ACI Manual of Concrete Practice, Part I, American Concrete International, "Chapter 2: Aggressive Chemical Exposure," American Concrete Institute (January 1996).

Alberta Infrastructure and Transportation. May 2002, "Section 7 – Geotechnical Considerations," Engineering Consultant Guidelines for Highway and Bridge Projects.

Alexander, J.A., Sandford, T.C., and Seshadri, A., "Rehabilitation of Large Diameter Steel Culverts," Maine Department of Transportation, Technical Services Division, Augusta, Maine, December 1994.

Aluminum Association, The, "Aluminum Drainage Products Manual," The Aluminum Association, Washington, D.C. (1983)

American Association of State Highway and Transportation Officials (AASHTO), "AASHTO Highway Drainage Guidelines: Volume 14—Culvert Inspection, Material Selection and Rehabilitation," AASHTO, Washington, D.C., August 1999, 60 pp.

American Association of State Highway and Transportation Officials (AASHTO), Bridge Design Specification, Section 18, paragraph 18.4.3.1.1., Washington, D.C.

American Iron and Steel Institute, 1983, Handbook of Steel Drainage and Highway Construction Products, Chapters 5 and 6.

American Iron & Steel Institute, 1994, "Steel Drainage and Highway Construction Products," American Iron & Steel Institute Handbook, 5th Edition.

American Society for Metals, Corrosion Resistance of Aluminum and Aluminum Alloys, Metal Handbook, Desk Edition, Materials Park, Ohio.

American Waterworks Association, Fiberglass Pipe Design Manual M-45, manual of Water Supply Practices, Denver, Colorado (1996).

American Waterworks Association, "Glass-Fiber-Reinforced Thermosetting-Resin Pressure Pipe," C 950-81. (1981).

Arnoult, J.D., Culvert Inspection Manual: Supplement to the Bridge Inspector's Training Manual, Report FHWA-IP-86-002, Federal Highway Administration, McLean, Va., July 1986, 215 pp.

Aryani, C. and Al-Kazily, J. , Culvert Restoration Techniques, FHWA/CA/93-14, California State University, Sacramento (1993).

Attewell, P.B., and Fry, R.H., "The Effects of Explosive Detonations and Mechanical Impacts upon Adjacent Buried Pipelines," Europipe '83 Conference, Basle, Switzerland, Paper 16, (1983).

Azar, D.G., "Drainage Pipe Study." Research Rep. No. 57, Louisiana Dept. of Hwys. (May 1971).

Ballinger, C.A. and Drake, P.G., Culvert Repair Practices Manual, Vols. 1 and 2, Reports FHWARD-94-096 and FHWA-RD-95-089, Federal Highway Administration, McLean, Va., May 1995, (Vol. 1) 265 pp. and (Vol. 2) 354 pp.

Bauman, E.E., and Lewis, D.W., “Five-Year Field Corrosion Study of Steel Pipe to Determine Effects of Backfill materials.” Hwy. Res. Record No. 140 (1966) pp. 1-8.

Bealey, M., “Precast Concrete Pipe Durability: State of the Art,” Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C., 1984, pp. 88- 94.

Bearg, E.A. et al., “Durability Design Method for Galvanized Steel Pipe in Nebraska.” Armco Steel Corp. (1966-67).

Beaton, J.L., and Stratfull, R.F., “Corrosion of Corrugated Metal Culverts in California.” HRB Bull. 223 (1959) pp. 1-13.

Beaton, J.L., and Stratfull, R.F., “Field Test for Estimating Service Life of Corrugated Metal Pipe Culverts.” Proc., HRB, Vol. 41 (1962) pp. 255-272.

Bednar, L., “The Durability of Galvanized Highway Culverts,” Seminar on Performance of Galvanized Product5s, American Hot Dip Galvanizers Association, Chicago, Il. (1980).

Bednar, L., “Plain Galvanized Steel Drainage Durability Estimation with a Modified California Chart,” in Transportation Research Record 1231, Transportation Research Board, National Research Council, Washington, D.C. (1989) pp. 70-79

Bednar, L., Aluminized Steel T2 Pipe, Industrial Report, Armco, Inc. (December 1991).

Bednar, L., Resistivity and pH Limits for the Use of Aluminized Steel Type 2 Drainage Pipe, Armco Research and Technology (1989).

Bellport, B.P., “Combating Sulfate Attack on Concrete on Bureau of Reclamation Projects.” U.S. Bureau of Reclamation, presented at symposium sponsored by Div. of Bldg. Res., Natl. Res. Council of Canada & ACI, Toronto (Apr. 7, 1967) 24 pp.

Bearg, E.A. et al., Durability Design Method for Galvanized Steel Pipe in Nebraska, ARMCO Steel Corporation (1966-67)

Berg, V.E., “A Culvert Material Performance Evaluation in the State of Washington.” Res. Proj. no. HPR-1-2, Washington State Hwy. Comm. (Apr. 1965) 44 pp.

“Beth-Cu-Loy,” PC Sales Brochure No. 3434, Bethlehem Steel Corporation, Bethlehem, P.A. (Sep. 1981) 2 pp.

Bland, C.E.G., Bayley, E.V., and Thomas, E.V., “Accumulation of Slime in Drainage Pipes and Their Effect of Flow Resistance,” Journal of Water Pollution Control Federation, (Jan. 1978).

Bloodgood, D.E., and Bell, J.M., “Study of Flow Coefficients,” Journal of Water Pollution Control Federation, (Feb. 1961).

Borgard, B. et al., Mechanism of Corrosion of Steel in Concrete, ATMP STP 1065, American Society for Testing materials, Philadelphia 91990) pp. 174-188

Bortz, S.A., “Durability of Clay Pipe,” Proceedings of the International Conference on Advances in Underground Pipelines Engineering, American Society of Civil Engineering, New York (1985).

Brasunas, A. deS., et al., “NACE Basic Corrosion Course.” Natl. Assn. of Corrosion Eng., Houston (Apr. 1971).

Brasunas, A. deS., et al. editor, "NACE Basic Corrosion Course," National Association of Corrosion Engineers, Houston, 2nd printing (April 1971)

Brown, F.A., and Lytton, R.L., "Design Criteria for Buried Flexible Pipe," Pipeline Materials and Design, American Society of Civil Engineers National Convention, San Francisco, Calif. (Oct. 1984). pp 36-47.

Brown, R.F., and Kessler, R.J., "Performance Evaluation of Corrugated Metal Culverts in Florida," Florida Department of Transportation, Tallahassee, FL (April 1976).

Brown, R. "Pipe Evaluation Study – 1964," Southern Association of State Highway Officials, Annual Meeting, New Orleans, La. (1964).

Brown, R. "Mississippi pipe Evaluation Study-1964," Mississippi State Highway Department, Jackson, Miss. (Nov. 1964).

Bureau of Reclamation, Concrete Manual, 8th Ed., U.S. Government Printing Office, Washington, D.C. (1975).

Butler, B.E., "Structural Design Practice of Pipe Culverts." Hwy. Res. Record No. 413 (1972) pp. 57-66

California Department of Transportation Division of Engineering Services, 2003, Corrosion Guidelines Version 1.0.

California Test 643, Method for Estimation the Service Life of Steel Culverts, State of California DOT, Division of New Technology and Material Research, Sacramento (1993).

Cassidy, M., Review Specifications and Performance Requirements for Plastic Pipe Systems, Battelle, Columbus, Ohio (1994).

Cerlanek W.D. and Powers, R.G., Drainage Culvert Service Life Performance and Estimation, Report No. 93-4a, State of Florida, Department of Transportation, State Materials Office, Corrosion Research Laboratory, Tallahassee, Florida (1993).

Chambers, R.E., McGrath, T.J., and Heger, F.J., NCHRP Report 225: Plastic Pipe for Subsurface Drainage of Transportation Facilities, Transportation Research Board, National Research Council, Washington, D.C., October 1980, 153 pp.

Chua, K.M., and Lytton, R.L., "Design Equations for Buried Flexible Piping Systems," 1986 American Gas Association Distribution/ Transmission Conference, Chicago, Ill. (1986).

Chua, K.M., and Petroff, L.J., "Soil-Pipe Interaction of Large Diameter Profile Wall-HDPE Pipe," 1985 Plastics Symposium: Managing Corrosion with Plastics, October 12-17, St. Louis, Mo. (1985).

Cleary, H.J. "The Microstructure and Corrosion Resistance of Aluminum-Zinc Coatings on Sheet Steel," Microstructural Science Vol. 12, New York (1985).

Clifton, J.R., Oltikar, B.C., and Johnson, S.K. "Development of Durcon, An Expert System for Durable Concrete: Part 1," U.S. Department of Commerce, National Bureau of Standards, Gaithersburg, Md. (Jul 1985).

Coated Steel Products, Standards Vol. 01.06, American Society for Testing and Materials, West Conshohocken Pa., 2001.

Colorado Department of Transportation, 1998, Pontis Bridge Inspection Coding Guide.

Colorado Department of Transportation, 2003, “Summary of I-70 Culvert Inspections.”

Colorado Department of Transportation, 2004, Pipe Material Selection Guidelines.

Colorado Department of Transportation, 2005, “SIA Report.”

Connecticut Department of Transportation, 2002, “4.4 Culvert Materials,” Connecticut Department of Transportation Drainage Manual.

Corrugated Polyethylene Pipe Association, 1997, Chemical & Abrasion Resistance of Corrugated Polyethylene Pipe.

Corps of Engineers, 1998, “Engineering and Design - Conduits, Culverts, and Pipes,” EM 1110-2- 2902, Change 1.

Cross Reference for Drainage Pipe Specifications for Waterways, Airports, Railroads, Transit and Highways, AASHTO-AGC-ARTBA Joint Committee Subcommittee on New Highway Materials, Task Force 22 Report, Washington, D.C.

Crum, R.W., “Report on Culvert Investigation.” Proc., HRB, Vol. II, Part I (1932) pp. 338-363.

Curtice, D.K., and Funnell, J.E., “Comparative Study of Coatings on Corrugated Metal Culvert Pipe.” Southwest Research Institute, San Antonio (Mar. 1971) 50 pp.

Dana, J.S., “Corrosion of Highway Metal Structures and Cathodic Protection.” Final Prep., Arizona Hwy. Dept. (Nov. 1973) 60pp.

Degler, D.H., D.C. Cowherd, and J.O. Hurd, “An Analysis Of Visual Inspection Data of 900 Pipe- Arch Structures,” in Transportation Research Record 1191, Transportation Research Board, National Research Council, Washington, D.C. (1988).

Design Guidance on Alternative Pipe Selection, Federal Lands, Highway Project Development, electronically published www.bts.gov/NTL/frames/smart facilities @ BTS.Gove.htm (1996).

Design of Spiral Rib Pipe System for Control of External Corrosion, Farwest Corrosion Control Company, Cardena, California (1984).

Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading, ASTM D2412, American Society for Testing and Materials, Philadelphia (1993).

Downs, W.S. “A Survey of Culverts in West Virginia,” The West Virginia University in Cooperation with The State Road Commission of West Virginia, Morgantown, W. Va. (Dec. 1934).

Drainage Condition Survey Field Manual, Publ. 73, Pennsylvania Department of Transportation, Harrisburg, April 1999.

Duncan, C.R., “Innovated Repair of a Large Failing Structural Steel Plate Pipe Arch Culvert,” Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C., 1984, pp. 98-101

“Durability of Concrete in Service.” Proc., ACL, Vol. 59, No. 12, ACI (Dec. 1962) pp. 1771-1820.

“Durability of Metal Pipe Culverts.” Idaho Dept. of Hwys., Res. Proj. No. 16 (Apr. 1965).

Durability of Special Coatings for Corrugated Steel Pipe, FHWA, Washington, D.C. (1991).

"Duracoat, National Steel's Pre-Coated Culvert Sheet," Sales Brochure No. C-679-1M, National Steel Corporation, Pittsburgh, PA.

Economic Studies for Military Construction Design Applications, TM 5-802-1, Department of the Army, Headquarters, Alexandria, Virginia (December 1986).

Ellis, J.G., "Corrosion Performance of Aluminum Culverts." Second progress rep., Res. Rep. R-679, Michigan Dept. of State Hwys. (Dec. 1968) 25 pp,; Final progress rep., Rees. Rep. R-976 (Nov. 1975) 22 pp.

Esparza, E.D., Westine, P.S., and Wenzel, A.B., "Pipeline Response to Buried Explosive Detonations," Vol. 1 –Summary Report; Vol. 2-Technical Report. Final Report to the American Gas Association, Project PR-15-109, Southwest Research Institute Project 02-5567 (1981).

Eubank, D., and Thomas H.D., "1964 Pipe Evaluation Study Supplement." Mississippi State Hwy. Dept. (1964) 14 pp.

Evaluation Methodology for Corrugated Steel Pipe Coating/Invert Treatments, Prepared for National Corrugated Steel Pipe Association, Ocean City Research Corporation, Washington, D.C. (March 1996).

Federal Highway Administration, 1991, Durability of Special Coatings for Corrugated Steel Pipe.

Federal Highway Administration, 1995, Recording and Coding for the Structure Inventory and Appraisal of the Nation's Bridges.

Federal Highway Administration, 1995, "Errata Sheet," Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges.

Federal Highway Administration, 2005, Culvert Pipe Liners Guide and Specifications.

Federal Highway Administration, Culvert Inspection Manual, FHWA-IP-86-2, U.S. Department of Transportation, Washington, D.C. (1986)

Federal Highway Administration, "Corrugated Metal Pipe Durability Guidelines," Technical Advisory T5040.12, Washington D.C. (1979).

Florida Department of Transportation, 1999, Drainage Handbook: Optional Pipe Materials.

Florida Department of Transportation, 2003, FDOT Drainage Manual.

Florida Department of Transportation, 2003, "FDOT Drainage Manual Revisions," FDOT Drainage Manual.

Florida Department of Transportation, 2004, "FDOT Drainage Manual Revisions," FDOT Drainage Manual.

Garber, J.D. and J.H. Lin, Accelerated Corrosion Test for Metal Drainage Pipes, Louisiana Transportation Research Center, Baton Rouge (June 1987).

Garber, J.D., J.H. Lin and L.G. Smith, Feasibility of Applying Cathodic Protection to Underground Culverts, Report No. FHWA/LA-94/289, University of Southwestern Louisiana, Lafayette (1995).

Gaube, E., "HDPE Sewage Pipes: Results of Tests to Determine Time Dependence of Soil Pressure and Deformation," Kunstsoff, Vol. 61, (Oct. 1971) pp 765-769.

Gaube, E., and Muller, W., "Thirteen Years of Deformation Measurements on HDPE-(Hostalen GM 5010) Sewer Pipe," Plastic Pipes V, 5th International Conference, University of York, London (1982).

Gietz R.H., Metal Culvert Performance, Washington State Department of Transportation, Material Office, Tumwater (1981).

Gift, A. and B. Smith, Culvert Study Repot, Research Investigation 91-11, Missouri Department of Transportation, Jefferson City, August 2000.

Goble, G., NCHRP Synthesis of Highway Practice 176: Geotechnical Related Development and Implementation of Load and Resistance Factor Design (LRFD) Methods, Transportation Research Board, National Research Council, Washington, D.C., 1999 69 pp.

Gray, A., and Frye, C.J., "Measurement of Toughness in Pipe Materials," Plastic Pipes V, 5th International Conference, university of York, London (1982)

Guidelines for Culvert Relining, Lane Enterprises, Inc., Camp Hill, Pa., Revised May 1999.

Hadipriono, F.C., "Durability of Concrete Pipe Culverts: Service Life Assessment," The Ohio State University, Columbus, Ohio. (1986).

Hadipriono, F.C., "Analysis of Events in Recent Structural Failures," Journal of Structural Engineering, Vol. 111, no. 7, Jul. 1985, pp 1468-1481.

Hadipriono, F.C., and Lai, J.Y., "Assessment of Urgency Measure to Prevent Further Damage of Concrete Components," Structural Safety, Elsevier Science Publishers, B.V., Amsterdam. (1986).

Hadipriono, F.C., Toh, H.S., "Approximate Reasoning Models for Consequences on Structural Component Due to Failure Events," Journal of Civil Engineering for Practicing and Design Engineers. (May 1986).

Hadipriono, F.C., and Wang, H.K., "Analysis of Causes of Falsework Failures in Concrete Structures," Journal of Construction Engineering and Management, Vol. 112, No 1, pp 112-121 (Mar. 1985).

Hadipriono, F.C., Wong, H.K., and Lim, C.L., "Use of Micro-Computers in Assessing Failures of Concrete Box Girder Bridges," Journal of Civil Engineering for Practicing and Design Engineers. (Apr. 1986).

Hadipriono, F.C., and Wong, H.K., "Cumulative Damage Study Based on Subjective Ratings of Bridge Conditions," Quality Assurance and Structural Safety, American Society of Civil Engineers Structures Congress 86, Committee on Safety of Buildings, New Orleans, La. (Sep. 1986).

Handbook of Street Drainage and Highway Construction Products, Fifth edition, American Iron and Steel Institute (1994)

Hansson C.M. and B. Sorensen, The Threshold Concentration of Chloride in Concrete for the Initiation of Reinforcement Corrosion, ASTM STP 1065, American Society for Testing Materials, Philadelphia (1990) pp. 3-16.

Harris, J.O., "Microbiological Studies Reveal Significant Factors in Oil and Gas Pipeline Back-Filled Ditches." Kansas Agric. Exper. Sta. (1963) 47 pp.

Havens, J.H., “Considerations Regarding Type of Culverts; Pennyrile (Pennyroyal) Parkway.” Kentucky Dept. of Hwys. (June 1966).

Havens, J.H., “durability of Culvert Pipe.” Kentucky Dept of Hwys. (Aug. 1968) 13 pp.

Havens, J.H., Young, J.L., and Field, H.J., “A Survey of Acidity in Drainage Waters and the Condition of Highway Drainage Installations,” Progress Report No. 1, Commonwealth of Kentucky Department of Highways, Highway Materials Research Laboratory, Lexington, Ky. (Dec. 1950).

Havens, J.H., Young, J.L., and Field, H.J., “A Survey of Acidity in Drainage Waters and the Condition of Highway Drainage Installations,” Progress Report No. 2, Commonwealth of Kentucky Department of Highways, Highway Materials Research Laboratory, Lexington, Ky. (Dec. 1952).

Haviland J.E. Et Al., “Durability of Corrugated Metal Culverts.” Hwy. Res. Record No. 242 (1968) pp. 41-66 (Also published by New York State DOT as Res. Rep 66-5, Nov. 1, 1967)

Hayes, C.J., “A Study of the Durability of Corrugated Steel Culverts in Oklahoma.” Oklahoma Dept. of Hwys. (1971) 39 pp.

Hayes, C.J., “A Study of the at Test Sites in Colorado (1962-1968).” Res. Rep. No. 68-8, Colorado Div. of Hwys. (Aug 1968) 15 pp.

Haynes H.R., O’Neill and P.A. Mehta, “Concrete Deterioration from Physical Attack by Salts,” Concrete International, American Concrete Institute, Farmington Mills, Michigan (January 1996).

Headquarters, Department of the Army, “Engineering and Design – Conduits, Culverts, and Pipes,” Engineer Manual 1110-2-2902, Washington, D.C. (1969)

Hirsch, C. “NYDOT Proposed Recommendations,” NCSPA Memorandum, Washington, D.C. (1985).

Hixon, C.D., Performance of Polyethylene Pipe in Oklahoma, Oklahoma Department of Transportation, Oklahoma City, June, 1992.

Hoeg, K., “Stresses Against Underground Structural Cylinders,” Journal of Soil Mechanics and Foundations Divisions, American Society of Civil Engineers, No. SM1, (Jul 1986) pp 833-858.

Horton, J.B., “Adhesion of Asphalt to Beth-Cu-Loy PC Vinyl Plastisol Coated Sheet,” Unpublished Report, Homer Research Laboratory, Bethlehem Steel Corporation, Bethlehem, P.A. (Oct. 1977) 4 pp.

Housz, A.J.I., “Dynamic Testing of GRP Pipe,” Plastic Pipes V, 5th International Conference, University of York, London (1982).

Howard, A.K., “Modulus of Soil Reaction Values for Buried Flexible Pipe,” Journal of the Geotechnical Engineering Division, Proceedings Paper 12700, 103, no. GTI, American Society of Civil Engineers, (Jan. 1977) pp 33-43.

Howard, A.K., “The USBR Equation for Predicting Flexible Pipe Deflection,” Proceeding International Conference on Underground Plastic Pipe, American Society of Civil Engineers, New Orleans, La. (1981) pp 37-55.

Hurd, J.O., “Field Performance of Concrete and Corrugated Steel Pipe Culvert and Bituminous Protection of Corrugated Steel Pipe Culverts,” in Transportation Research Record 1001, Transportation Research Board, national Research Council, Washington, D.C. (1984).

Hurd, J.O. and S. Sargand, “Field Performance of Corrugated Metal Box Culverts,” in Transportation Research Record 1191, Transportation Research Board, National Research Council, Washington, D.C. (198).

Hyde, L.W., Et Al., “Detrimental Effects of Natural Soil and Water Elements on Drainage Pipe Structures in Alabama.” Geological Survey of Alabama for Alabama Hwy. Dept. (Aug. 1969).

Ikerd, S.R., “Invert Replacement of Corrugated Metal Structural Plate Pipe,” Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C., 1984, pp. 102-103.

Inland Steel, “Blac-Klad 10.10 Performance Report,” Chicago, Ill. (1983).

Inventory Managed Assets—Data Collection Manual, Maine Department of Transportation, Maintenance and Operations, Augusta, August 1999, 59 pp.

“Investigation of the Long-Term Creep Modulus for Buried Polyethylene Pipes Subjected to Constant Deflection,” 2nd International Conference: Underground Pipeline Engineering, Wis., (1985) pp 253-262.

Jackson, G.W. and M. Subramanian, A Literature Review for a Study of an Accelerated Laboratory Test to Determine Durability of Pipe Culvert Material, Ohio Department of Transportation (ODOT) Contract 5813, ODOT, Columbus, November 1990.

Jacob, K.M., “Aluminum Culvert Corrosion,” Materials and Research Division Technical Paper 76-5, Maine Department of Transportation, Bangor, Maine (1976).

Jacobs, K.M., “Culvert Life Study.” Tech. Paper 74-1, Main DOT (Jan. 1974) 24 pp.

Jacobs, K.M., “Zinc Content of Streams with Corrugated Metal Pipes.” Tech. Paper 74-2, Maine DOT (Jan. 1974) 11 pp.

James, L.M., “Unexpected Corrosion of Galvanized Corrugated Metal Culverts.” Proc., Australian Road Res. Board, Vol. 4, Part 2, Paper No. 437 (1968) 6pp.

Janson, L.E., “Plastic Gravity Sewer Pipes Subjected to Strain by Deflection,” Proceeding International Conference on Underground Plastic Pipes, American Society of Civil Engineers, New Orleans, La., (1981) pp 104-116

Jenkins, S.V., J.L. Leatham and S.E. Goodwin, Pipe Culvert Durability, Utah State Department of Transportation, Salt Lake City (1989).

Jeyapalan, J.K., and Abdelmagid, A.M., “Importance of Pipe Soil Stiffness Ratio in Plastic Pipe Design,” Pipeline Materials and Design, American Society of Civil Engineers National Convention, San Francisco, Calif. (Oct. 1984) pp 49-66.

Jiang Y. and R.S. McDaniel, Evaluation of Galvanume and Aramid Fiber Bonded Bituminous Coated Pipes, Indiana Department of Transportation, Indianapolis (1990).

Johansen, D., Copstead, R., Moll, J., 1997, Relief Culverts. U.S. Forest Service.

Jonas, S. et al., Corrugated Metal Pipe Study—Final Report, Alberta Agriculture Irrigation Branch, Alberta, Canada (March 1988).

Kalb, M., “Statewide Survey of Bituminous-Coated Only, and Bituminous Coated and Paved Corrugated Metal Pipe.” Final rep., Maryland State Roads Comm. (Apr. 1971).

Kessler, R.J., R.G. Powers and R.M. Langley, Two Years Evaluation of Corrugated Metal Pipe Alternate Materials, Florida Department of Transportation, Materials Office, Corrosion Research Laboratory, Gainesville (1989).

Kill, D.L. “Serviceability of Corrugated Metal Culverts.” Investigation No. 116, final rep., Minnesota Dept. of Hwys. (1969) 22 pp.

Koepf, A.H., “The mechanisms of Abrasion of Aluminum Alloy Culvert, Related Field Experiences, and a Method to Predict Culvert Performance.” Hwy. Res. Record No. 262 (1969) pp. 44-45.

Koepf, A.H, and Ryan, P.H., “Abrasion Resistance of Aluminum Culvert Based on Long-Term Field Performance,” Transportation Research Board, 65th annual meeting, Session 195, Washington, D.C. (1986).

Koscelny J.A., Polymer Coated and Paved Culverts in Southeastern Oklahoma, Oklahoma Department of Transportation, Oklahoma City (1992).

Krizek, R.J., Et Al., “Structural Analysis and Design of Pipe Culverts.” NCHRP Report 116 (1971) 155 pp.

Kurdziel, J.M., “Culvert Durability Rating Systems,” Transportation Research Record 1191, Transportation Research Board, National Research Council, Washington, D.C., 1988, pp. 132-140

Kurdiziel, J.M., “Least Cost (Life Cycle) Analysis Microcomputer program,” Transportation Research Record 1191, Transportation Research Board, National Research Council, Washington, D.C., 1988, pp. 141-154.

Kurt, C.E., and G.W. McNichol, “Microcomputer-Based Culvert Ranking System,” Transportation Research Record 1315, Transportation Research Board, National Research Council, Washington, D.C., 1991, pp. 21-27.

Lang, D.C., and Howard, A.K., “Buried Fiberglass Pipe Responses to Field Installation Methods,” 2nd International Conference American Society of Civil Engineers: Underground Pipeline Engineering, Wis. (1985) pp. 341-353.

Lawson, H.H., “Data on Aluminized Steel Type 2 Corrugated Steel Pipe – CALTRANS,” Memorandum, ARMCO Research and Technology, Middletown, Ohio.

Lea, F.M., The Chemistry of Cement and Concrete, First American Edition, Chemical Publishing Company, New York (1971).

Leeds, J.M., “Parameters That Determine the Need for External Pipeline Refurbishment,” Pipeline Risk Assessment, Rehabilitation and repair Conference, Houston, Texas (1991).

Life Expectancy Determination of Zinc-Coated Corrugated Steel and Reinforced Concrete Pipe Used in Missouri, MR 91-1, Missouri Highway and Transportation Department, Division of Materials and Research, Jefferson City, Missouri (1990).

Lindberg, R.I., “Method of Estimating Corrosion of Highway Culverts by Means of Polarization Curves.” Hwy. Res. Record No. 204 (1967) pp. 1-10.

Little, H.P., Boedecker, K.J., and Brawner, J.B., “Performance Evaluation of Corrugated Metal Culverts in Georgia,” Southern Corrugated Steel Pipe Association, Washington, D.C. (April 1977)120 pp.

Loving, M.W., “Autogenous Healing of Concrete,” American Concrete Pipe Association, Bulletin 13. (1936).

Lowe, T.A., and Koepf, A.H., “Corrosion Performance of Aluminum Culvert.” Hwy. Res. Record No. 56 (1964) pp. 98-115.

Lowe, T.A. Et Al., “Corrosion Evaluation of Aluminum Culvert Based on Field Performance.” Hwy. Res. Record No. 262 (1969) pp 56-68.

MacDougall, C.A., Culvert Inventory and Inspection manual, New York State Department of Transportation, Albany, December 1991, 146 pp.

MacDowell, R.F., “Engineering Design Manual for Sanitary Sewerage and Drainage Facilities,” Regional Planning Commission, Cuyahoga County, Ohio (Feb. 1952).

Malcolm, H.R., Forecasting Service Life of Culverts in North Carolina, Center of Transportation Engineering Studies, North Carolina State University, Raleigh (1993).

Malcom, W.J., “Durability Design Method for Galvanized Steel Pipe in Iowa.’ Corrugated Metal Pipe Assn. of Iowa& Nebraska (Spring 1968) 24 pp.

Marbut, Soils of the U.S., Atlas of American Agriculture, Part III, U.S. Government Printing Office, Washington, D.C. (1935).

Marshall, G.P., and Birch, M.W., “Criteria for High Toughness in UPVC Pressure Pipes,” Plastic Pipes V, 5th International Conference, University of York, London (1982).

Marshal, G.P., Taylor, M.D., and Dickinson, A.J., “Assessment of the Influence of Processing on Medium-High Density PE Pressure Pipes,” Plastic Pipes V, 5th International Conference, University of York, London. (1982).

Mather, B., “Field and Laboratory Studies of Sulfate Resistant Concrete, Performance of Concrete-Resistance of Concrete to Sulfate and Other Environmental Conditions”, Throvaldson Symposium, University of Toronto Press, Toronto, Canada (1968) pp. 66-76.

Mathioudakis, M. and A. Agarwal, “Re-Evaluation of Design Procedures for non-Bridge-Size Culverts”, Client Report 74, New York State Department of Transportation, Albany, May 1996, 30 pp.

McGrath, T.J., and V.E. Sagan, NCHRP Report 438: Recommended LRFD Specifications for Plastic Pipe and Culverts, Transportation Research Board, National Research Council, Washington, D.C., 2000, 69 pp.

McKeel, W.T., Jr., “A Comparative Study of Aluminum and Steel Culverts.” Culvert Studies Rep. No. 3, Virginia Hwy. Res. Council (Feb 1965).

McKeel, W.T., Jr., “A Comparative Study of Aluminum and Steel Culverts.” Culvert Studies Progress Rep. No. 4, Virginia Hwy. Res. Council (May 1971).

McNichol, G.W., Development of a Microcomputer Based Culvert Management System, Department of Civil Engineering, University of Kansas, Lawrence, 1989.

Meacham, D.G., "Culvert Durability Study: An Interim Report." Ohio DOT (Dec. 1972) 14 pp.

Mehta, P.K., "Discussion of Combating Sulfate Attack in Corps Engineers Concrete Construction," ACI journal, Vol.73, No. 4 (April 1976) pp. 237-238.

Mendenhall, W., and NcClave, J.T., "A Second Course in Business Statistics: Regression Analysis," Dellen Publishing Co., San Francisco and Santa Clara Calif. (1981).

Modern Sewer Design Fifth Ed., American Iron and Steel Institute, Washington, D.C. (1995).

Molin, J., "Long-Term Deflection of Buried Plastic Sewer Pipes," 2nd International Conference: Underground Pipeline Engineering, Wis. (1985) pp 263-277.

Montana Department of Transportation, 2003, Culvert Service Life Guidelines.

Moore, D.R., Stephenson, R.C., and Whale, M., "Some Factors Affecting Toughness in UPVC Pipe Materials," Plastic Pipes V, 5th International Conference, University of York, London (1982).

Morris, G.E. and L. Bednar, "Comprehensive Evaluation of Aluminized Type 2 Pipe Field Performance," in Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C. (1984).

Moser, A.P., "Strain as a Design Basis for PVC Pipes," Proceeding International Conference on Underground Plastic Pipe, American Society of Civil Engineers, New Orleans, La. (1981) pp 89-103.

Moser, A.P., Bishop, R.R., Shupe, O.K., and Bair, D.R., "Deflections and Strains in Buried FRP Pipes Subjected to Various Installation Conditions," Presented at the Transportation Research Board, 64th Annual Meeting (Jan. 1985).

Najafi M., Trenchless Pipeline Rehabilitation, Missouri Western State College, St. Joseph (1994).

National Association of Sewer Service Companies (NASSCO), Manual of Practices, NASSCO, Maitland, Fla., August 1996.

"National Corrugated Steel Pipe Association- Coating Selection Guide For Corrugated Pipe," National Corrugated Steel Pipe Association, Washington, D.C. (1983).

National Clay Pipe Institute, "Abrasion Rating of Sewer Pipe Materials," Crystal Lake, Ill. (1985).

"NCHRP Synthesis of Highway Practice 50: Durability of Drainage Pipe," Transportation Research Board, National Research Council, Washington, D.C., 1978, 37 pp.

NCHRP Report 222: Bridges on Secondary Highways and Local Roads—Rehabilitation and Replacement, Transportation Research Board, National Research Council, Washington, D.C., 1980, 132 pp.

NCHRP Report 243: Rehabilitation and Replacement of Bridges on Secondary Highways and Local Roads, Transportation Research Board, National Research Council, Washington, D.C., December 1981, 46 pp.

Neter, J., and Wasserman, W., "Applied Linear Statistical Models," Irwin Press (1974).

"Nebraska Soil Resistivity and pH Investigation as Related to Metal Culvert Life." Nebraska Dept. of Roads (Apr. 1969)

New York Department of Transportation, 2001, Design Guidelines for Rehabilitation of Culvert and Storm Drain Pipe.

New York Department of Transportation, "Durability of Corrugated metal Culverts," Research Report 66-5, New York (1966).

"N.Y. DOT Culvert Durability Study," Letter Report for ARMCO Construction Products Division, ARMCO Research and Technology, Middletown, Ohio (1985).

Nordlin, E.F., and Stratfull, R.F., "A Preliminary Study of Aluminum as a Culvert Material." Hwy. Res. Record No. 95 (1965) pp. 1-70

Ocean City Research Corporation, Evaluation Methodology for Corrugated Steel Pipe, Coating/Invert Treatments, National Corrugated Steel Pipe Association, Washington D.C. (March 1996).

"Ohio DOT Report on Culvert Pipe Durability," Letter Report for ARMCO Construction Products Division, ARMCO Research and Technology, Middletown, Ohio (1985).

O'Leary, P.M., and Datta, S.K., "Dynamics of Buried Pipelines," 2nd International Conference, American Society of Civil Engineers: Underground Pipeline Engineering, Madison, Wis. (1985). pp 285-290.

Oliver, J.C., and Palmore, R.D., "Iso-pH Maps Identify Areas Detrimental to Drainage Structure Performance Life." Hwy. Res. Record No. 56 (1964) pp. 116-123.

O'Reilly, M.P., Crabb, G.I., and Trott, J.J., "Loading Tests on Buried Plastic Pipes to Validate a New Design Method, Plastic Pipes V, 5th International Conference, University of York, London, (1982).

Ovunc, B.A., "Dynamic Responses of Buried Pipelines," Proceedings of the International Conference on advances in Underground Pipeline Engineering, American Society of Civil Engineers, New York, (1985).

Patenaude, Robert, 2003, Experimental Culvert Pipe, STH 80 Juneau and Wood Counties, Wisconsin, Wisconsin Department of Transportation.

Peabody, A.W., "Control of Pipeline Corrosion." Natl. Assn. of Corrosion Eng., Houston (Dec. 1967).

Pennsylvania Department of Highways, "Culvert Pipe Study," (Nov. 1950).

Peterson, D.E., "Evaluation of Aluminum Alloy Pipe for Use in Utah's Highways." Utah State Hwy. Dept. (June 1973) 43 pp.

Petroff, L.J., "Performance of Low Stiffness Plastic Pipe in Stiff Soils," Pipeline Materials and Design, American Society of Civil Engineers National convention, San Francisco, Calif. (Oct. 1984) pp 24-35.

Peyer, J.H., et al., "Final Report on a Study of the Durability of Asbestos Bonded Metal Pipe in Sewer Service to ARMCO Steel Corporation," Battelle Columbus Laboratories, Columbus, OH, (July 1976) 202 pp.

Pipe Selection for Corrosion Resistance, Implementation Package UDOT-IMP-76-1, Utah Department of Transportation, Research and Development Unit, Salt Lake City.

Pipe Selection Guidelines and Procedures, Arizona Department of Transportation, Phoenix (February 1, 1996).

"Pipeline Risk Assessment, Rehabilitation and Repair," in When to Renew a Pipeline, Gulf Publishing Company and Scientific Surveys Ltd., Houston, Texas (1991).

Potter, J.C., Lewandowsky, L., and White, D.W. Jr., Durability of Special Coatings for Corrugated Steel Pipe, FHWA-91-FLP-006, U.S. Army Waterways Experiment Station, Geotechnical Laboratory, Vicksburg, Mississippi (1991).

Potter, J.C., "Aluminum Coated Corrugated Steel Pipe Field Performance," Journal of Transportation Engineering ASCE, Vol. 116, No. 2 (March/April 1990).

Progress on Durability Study of Corrugated Aluminum Drainage Pipe, Sponsored by the Aluminum Association, Committee A2C06, Report to Transportation Research Board, National Research Council, Washington, D.C. (January 1987).

Puterman, M., "Natural and Accelerated Weathering of PVC and Polyethylene Wastewater pipes," Materials and Construction, Vol. 22, No. 129 (1989) pp. 170-175.

Pyskaldo, R.M., Experimental Culvert Test Plates, Engineering Research and Development Bureau, New York Department of Transportation, Albany (1988).

Pyskaldo, R.M., "Polymer Coatings for Corrugated Steel," Special Report #64 FHWA/NY/SR-79/64, NYSDOT, Engineering Research & Development Bureau, NYSDOT State Campus, Albany, N.Y. (Oct. 1979) 17 pp.

Rao, P. and Miller, R.L., "Applied Econometrics," Wadsworth Publishing Co., Belmout, Calif. (1971).

Ray, A.A., "SAS User's Guide: Basics," 1982 Edition, SAS Institute Inc., Cary, N.C.

Ray, D., and Croteaun, J., "Corrosion of Corrugated Metal Pipe." Final rep., New Jersey DOT, unpublished (Feb. 1974) 30 pp.

Renfrew, W.W. and R.M. Pyskadio, National Survey of State Culvert Use and Policies, Special Report 68, New York State Department of Transportation, Albany (May 1980).

"Republic PolyCote Polymer Coated Galvanized Corrugated Steel Pipe," G-180, Republic Steel Corporation, Drainage Products Division, Canton, OH (1982) 4 pp.

Ring, G.W., "Culvert Durability: Where Are We?" in Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C. (1984).

Roadway Engineering Group Design Section, 1996, Appendix A: Pipe Selection Guidelines and Procedures.

Romanoff, M., "Underground Corrosion." Circ. 579, Natl. Bur. Of Standards, U.S. Govt. Printing Ofc. Washington, D.C. (Apr. 1957) 227 pp.

Romanoff, M., "Performance of Ductile Iron in Soils," Journal of the American Water Works Association, Vol. 60, No. 6 (June 1968) pp. 645-655.

Ropke, J.C., "Concrete Problems Causes and Cures," McGraw-Hill, Inc. (1982).

Sagues, A.A., 2001, Corrosion Resistance and Service Life of Drainage Culverts. Florida Department of Transportation.

Sagues, A.A., Kranc, S.C., Presuel-Moreno, F., Rey, D. Torres-Acosta, A., Yao, L., 2001, Corrosion Forecasting for 75-Year Durability Design of Reinforced Concrete. Florida Department of Transportation.

Sagues, A.A., Corrosion Measurement of Aluminum Alloys and Reinforced Concrete for Determination of Culvert Service Life, University of South Florida, Tampa (1989).

Schrock, B.J., "Plastic Pipe Overview- 1983," Europipe '83 Conference, Basle, Switzerland, Paper No. 12. (1983).

Schwerdtfeger, W.J., "Soil Resistivity as Related to Underground Corrosion and Cathodic Protection." Hwy. Res. Record No. 110 (1966) pp. 20-21.

Sears, E.C., "Comparison of the Soil Corrosion Resistance of Ductile Iron pipe and Gray Cast Iron Pip," Materials Protection. Vol. 7, No. 10 (1968) pp. 33-36.

Seed, R.B., and Duncan, J.M., "Earth Pressure and Surface Load Effects on Buried Pipelines," 2nd International Conference: Advances in Underground Pipeline Engineering, Madison, Wis., (Aug. 1985) pp 21-329.

Sewer Manual for Corrugated Steel Pipe, National Corrugated Steel Pipe Association, Washington, D.C. (1949).

Sheppard, D. M. and Renna, R., 2003, "Florida Bridge Scour Research," AASHTO proceedings, Cody, WY.

Sikora, E., "Predicted Vs. Actual Field Measured Deflections of PVC Sewer Pipe," N.C.P.I, Crystal Lake, Ill. (Nov. 1977).

Singhal, A.C., and Veliz, V., "Experimental and Field Observation of Dynamic Behavior of Buried Pipelines," 2nd International Conference American Society of Civil Engineers: Underground Pipeline Engineering, Madison, Wis. (1985).

Slack, S.B., and Abercrombie, W.F., "Report on Study of Culvert Durability," State Highway Board, Georgia State Highway Department Bureau of Investigations. (1928).

Spangler, M.G., "Structural Design of Flexible Pipe Culverts," Bulletin 153, Engineering Experiment Station, Iowa State University, Iowa. (1941).

Statement Attributed to California Legislative Analyst Elizabeth G. Hill, Sacramento Bee, Forum 3, Sacramento, California (December 3, 1975).

Stephens, J.W., and Gill, B.W., "Service Failure Experience of UPVC Pressure Pipes in the Water Industry," Plastic Pipes V, 5th International Conference, University of York, London (1982) pp 33.1-33.15.

Stratfull, R.F., "Report one the Experimental Placing of a Cement Mortar Coating in Corrugated Metal Culverts in District 1." California Div. of Hwys. Memo. Unpublished (May 1954) 14 pp.

Stratfull, R.F., "A New Test for Estimating Soil Corrosivity Based on Investigation of Metal Highway Culverts." Corrosion, Vol. 17, No. 10 (Oct. 1961).

Stratfull, R.F., "Highway Corrosion Problems, Metal Culverts and Reinforced Concrete Bridges." Western Region Conf. Natl. Assn. of Corrosion Eng. (Oct. 1962) 20 pp.

Stratfull. R.F., "Field Method of Detecting Corrosive Soil Conditions." Proc., 15th Ann. Street and Hwy. Conf., ITTE and Univ. Extension, Univ. of California at Los Angeles (Jan. 1963).

Stratton, F.W., J.A. Frantzen and J.A. Meggers, Cause of Deterioration of Corrugated Metal Pipe Installed After 1974, Kansas Department of Transportation, Topeka, Kansas (1990).

Stroud, T.F., Control Measures for Ductile Iron Pipe, Corrosion/89, National Association of Corrosion Engineers, Houston, Texas (1989).

Stroud, T.F., "Polyethylene Encasement versus Cathodic Protection," Ductile Iron Pipe News (Spring/Summer 1968).

Sudol, J.J., Pipe Coating Study, Indiana Department of Highways, Indianapolis, Indiana (1982).

Summerson, T.J., "1981 Survey of Type II Aluminized Steel Riveted Culvert Test Sites," Kaiser Aluminum and Chemical Corporation – Center for Technology, Report ZCFT-82-35-TJS, Pleasanton, Calif. (1982).

Swan, J.D., "The Field Service Performance of USS Nexon Culverts," United States Steel Bulletin, Unite States Steel Corp., Pittsburgh PA (Nov. 1975).

Swan, J.D., "Steel Products for Culvert Applications." Paper presented at 51st Ann. Meet. Of HRB unpublished (Jan. 1972).

Swanson, H.N., and Donnelly, D.E., "Performance of Culvert Materials in Various Colorado Environments," Colorado Department of Highways Report No. CDOH-P&R-R-77-7, Denver, CO, (1977).

Symposium on Durability of Culverts and Storm Drains," Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C., 1984, 114 pp.

"Symposium on Effects of Aggressive Fluids on Concrete." Hwy. Rees. Record No. 113, 6 reps. (1966) 117 pp.

Table 6-1, Culvert Material Application and Design Services Life (DSL) Drainage Manual, Vol. I Standards, Florida Department of Transportation, Tallahassee (1993).

Temple, W.H., S.L. Cumbaa and B.J. Gueho, "Evaluation of Drainage Pipe by Field Experimentation and Supplementary Laboratory Experimentation," FHWA/LA-85/174, Louisiana Department of Transportation, Baton Rouge (1985).

Temple, W., Rasoulian, M., and Gueho, B.J., "Louisiana Highway Research Evaluation of Drainage Pipe by Field Experimentation and Supplemental Laboratory Experimentation," Interim Report No. 3 (Nov. 1981) 52 pp.

Thompson, R.E., Culvert Management System (CMS) for Local Governments, Federal Highway Administration, McLean, Va., 2000.

"Time Dependant Properties of Embedment Soils Back-Calculated from Deflections of Buried Pipes," Specialty Geomechanics Symposium: Interpretation of Field Testing for Design Parameters, Adelaide, Australia. (1986).

Tymkowicz, S., Pipe Rehabilitation with Polyethylene Pipe Liners—Construction Report, Iowa Department of Transportation, Ames, March 1996, 59 pp.

Uhlig, H.H., Corrosion and Corrosion Control: an Introduction to Corrosion Science and Engineering, 2nd ed., Wiley (June 1971) 419 pp.

"U.S.S Nexon-Precoated Culvert Sheets," Brochure no. ADUSS 30-5201-99, U.S. Steel Corporation, Pittsburgh, PA, (May 1975) 24 pp.

Vancrombrugge, R., "Fracture Propagation in Plastic Pipes," Plastic Pipes V, 5th International Conference, University of York, London (1982).

Velasquez, Larry, 2002, "Design Insight," vol. 1, edition IV.

Ward, I.M., "Mechanical Properties of Solid Polymers," Wiley (Inter-science), New York, (1971).

Washington State Highway Commission, "Culvert Performance Evaluation," Olympia, Wash. (1965).

Watkins, R.K., Reeve, R.C., and Goddard, J.B., "Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe," Transportation Research Record no. 903.

Welborn, J.Y., and Olsen, R.E., "Report on Inspection of Bituminous Coated and Uncoated Galvanized Metal Culvert Pipe." Bur. of Pub. Roads, Ofc. of Res. & Dev. (Oct. 1964) 11pp. + tables.

Welch, B.H., "Pipe Corrosion and Protective Coatings." Utah State Hwy. Dept. (Nov. 1974) 72 pp. (Also published in Transp. Res. Record 604, 1976, pp. 20-24)

West Virginia Department of Transportation, 2003, DD-503: Design of Alternative Pipe Materials.

Wheeling Corrugation Company, "Wheeling Plasticote Corrugated Steel Pipe Case Histories for NCSPA Service Life Manual," Letter Report for NCSPA, Wheeling, W. Va. (1983).

Wheeling Corrugation Company, "Corrosion Performance of Metallic Coated Steel Culvert," Test Report No. 20-663, Wheeling, W. Va. (1980).

Wilson, C.L., and Oates, J.A., Corrosion and the Maintenance Engineer, 2nd ed., Hart (1968) 196 pp.

Wolfe, V.D., and Macnab, S.H., "Corrugated Metal Pipe Comparison Study," Oregon Department of Transportation Official Publication 76-3, Salem, Oreg. (1976).

Woods, H., "Durability of Concrete Construction." Monograph No. 4, ACI (1968) 187 pp.

Worley, H. E., "Effectiveness of Bituminous Coatings on Corrugated Metal Pipe." State Hwy. Comm. Of Kansas (1970) 9 pp.

Worley, H.E., and Curbpton, C.F., "Corrosion and Service Life of Corrugated Metal Pipe in Kansas." Hwy. Res. Record No. 412 (1972) pp. 35-40.

APPENDIX A
GLOSSARY

A

Ablation The process by which ice and snow waste away from melting and evaporation or by which land wears away by the action of surface water.

Abrasion Wearing or grinding of material by water laden with sand, gravel or stones.

Absorption The assimilation or taking up of water or other solutions by soil or other material, the entrance of water into the soil or rocks by all natural processes. It includes the infiltration of precipitation or snowmelt; gravity flow of streams into the valley alluvium (see storage, bank), sinks, or other large openings; and the movement of atmospheric moisture.

Abstraction That portion of rainfall that does not become runoff. It includes interception, infiltration, and storage in depressions. It is affected by land use, land treatment and condition, and antecedent soil moisture.

Abutment The superstructure support at either end of a bridge or similar type structure, usually classified as spill through or vertical. Considered part of the bridge substructure.

Acidic The substances with a pH less than 7.0 which may react with or corrode certain metals. Soils or water may be acidic and react with metal culverts.

Aggradation It is the process of general and progressive rising of the streambed by deposition of sediment.

Afflux Backwater or height by which water levels are raised at a stated point, owing to presence of a constriction or obstruction, such as a bridge.

Algae Any of various primitive, chiefly aquatic, one-celled or multi-cellular plants that lack true stems, roots, and leaves but usually contain chlorophyll.

Alkaline Substances having pH greater than 7.0 such substances are caustic or able to corrode.

Allowable Headwater Difference in elevation between the flowline of the culvert and the lowest point in which the water surface at upstream would either flood the highway or jeopardize the property.

Alluvial Referring to deposits of silts, sands, gravels, or similar detritus material that has been transported by running water.

Anode A metallic surface on which oxidation occurs, giving up electrons with metal ion going into solution or forming an insoluble compound of the metal.

Amphibian Any of the various cold-blooded, smooth-skinned vertebrate (with backbone) organisms such as toads, frogs, and salamanders, characteristically hatching as an aquatic larvae that breathe by means of gills and metamorphosing to an adult form having air-breathing lungs.

Angle of Flare Angle between direction of wingwall and the centerline of a culvert barrel.

Angle of repose The maximum angle, as measured from the horizontal, at which granular particles can stand.

Angularity The acute angle between the plane of the highway centerline along the bridge, and a line normal to the thread of the stream, i.e., the acute angle between the thread of the stream and a line normal to the centerline along bridge.

Antidune A particular type of bed form caused by water flowing over a mobile material such as sand.

Apex The highest point, the vertex.

Approach Channel The reach of channel upstream from a dam, bridge constriction, culvert, or other drainage structure.

Apron Protective material laid on a streambed to prevent scour commonly caused by some drainage facility or a floor lining of such things as concrete, timber, and riprap, to protect a surface from erosion.

Aqueduct An open or closed channel used to convey water, or an open conduit of things such as wood, concrete, or metal on a prepared grade, trestle, or bridge.

Area Rainfall Average rainfall of the area.

Arid Geographic areas that are dry, lacking moisture. Compare with desert and semi-arid.

Armoring A natural process whereby an erosion-resistant layer of relatively large particles is formed on a channel bank and/or channel bed due to the removal of finer particles by stream flow, i.e., the concentration of a layer of stones on the bed of the stream that are of a size larger than the transport capability of the recently experienced flow—the winnowing out of smaller material capable of being transported while leaving the larger sizes as armor that, for discharges up to that point in time, cannot be transported.

Augmented Flow The increased volume of water entering a channel, or allowed to run overland as waste waters from the diversion of surface flow or as water from another stream or watershed; or from waters withdrawn or collected upstream and released after use.

Autogeneous Healing A process where small cracks are healed by exposure to moisture, forming calcium carbonate crystals that accumulate along the crack edges, inter twining and building until the crack is filled.

B

Backfill The material used to refill the trench or the embankment placed over the top of the bedding and culvert.

Backwater The water upstream from an obstruction in which the free surface is elevated above the normal water surface profile.

Baffle A structure constructed on the bed of a stream or drainage facility to deflect or disturb the flow. Vanes or guides, a grid, grating, or similar device placed in a conduit to check eddy currents below them, and effect a more uniform distribution of velocities. Also a device used in a culvert or similar structure to facilitate fish passage.

Bank The side slopes or margins of a channel between which the stream or river is normally confined. More formally, the lateral boundaries of a channel or stream, as indicated by a scarp, or on the inside of bends, by the stream ward edge of permanent vegetal growth.

Bar It is an elongated deposit of alluvium, not permanently vegetated, within or along the side of a channel.

Barrage See Check Dam.

Barrel Width Commonly the inside, horizontal extent of a drainage facility.

Base The layers of specified material placed on the sub base or sub grade to support the pavement, surface course, or a drainage facility.

Base Flow In the U.S. Geological Survey's annual reports on surface-water supply, the discharge above which peak discharge data are published. The base discharge at each station is selected so that an average of approximately three peaks a year will be presented.

Basic Hydrologic Data Includes inventories of land and water features that vary only from place to place (topographic and geologic maps are examples) and records of processes that vary with both place and time (records of precipitation, stream flow, groundwater, and quality-of-water analyses are examples).

Basin, Detention A basin or reservoir incorporated into the watershed whereby runoff is temporarily stored, thus attenuating the peak of the runoff hydrograph.

Bedding The soil used to support the load on the pipe. For, rigid pipe, the bedding distributes the load over the foundation. It does the same thing for the flexible pipe except that it is not as important a design factor.

Bedload The sediment that is transported in a stream by rolling, sliding, or skipping along the bed or very close to it; considered to be within the bed layer.

Bed The bottom of a channel. The part of a channel not permanently vegetated which is bounded by banks and over which water normally flows.

Bed Layer A flow layer, several grain diameters thick (usually two) immediately above the bed.

Bed Material The sediment mixture of which a streambed, lake, pond, reservoir, or estuary bottom is composed.

Bedrock The scour-resistant material underlying erodible soils and overlying the mantle rock, ranging from surface exposure to depths of several hundred miles.

Bed Slope The longitudinal inclination of a channel bottom

Bench-Flume A conduit on a topographical bench, cut into sloping ground. Compare with flume.

Best Management Practices (BMPs) Erosion and pollution control practices employed during construction to avoid or mitigate damage or potential damage from the contamination or pollution of surface waters or wetlands from a highway action.

Bituminous Mattress An impermeable rock-, mesh-, or metal-reinforced layer of asphalt or other bituminous material placed on a channel bank to prevent erosion.

Blanket Material covering all or a portion of a channel bank to prevent erosion. Stream bank surface covering, usually impermeable, designed to serve as protection against erosion. Common pavements used on channel banks are concrete, compacted asphalt, and soil-cement.

Bore Hydraulic A wave of water having a nearly vertical front, such as a tidal wave, advancing upstream as a result of high tides in certain estuaries; a similar wave advancing downstream as the result of a "cloudburst," or the sudden release of a large volume of water from a reservoir, as in the Johnstown (PA) flood.

Bottom Contraction Channel contraction resulting from some protrusion across the bottom of a channel.

Boulder A rounded or angular fragment of rock, the diameter of which is in the size range of 250 mm to 4000 mm (10 in. to 160 in.) according to FHWA Highways in the River Environment Manual.

Box Section A concrete or corrugated pipe with a rectangular or nearly rectangular cross section.

Braid A subordinate channel of a braided stream. See stream, braided. Compare with anabranch.

Breakers It is the surface discontinuities of waves as they breakup. They may take different shapes (spilling, plunging, surging). Zone of break-up is called the surf zone.

Bridge A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a tract or passageway for carrying traffic or moving loads, and, for definition purposes (AASHTO), having an opening measured along the center of the roadway equal to or more than 6.1 m (20′) between under copings of abutments or spring lines of arches, or extreme outside ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening.

Bridge Opening The total cross section area beneath a bridge superstructure that is available for the conveyance of water. Compare with bridge waterway.

Bridge Waterway The area of a bridge opening available for flow as measured below a specified stage and normal to the principal direction of flow. Compare with bridge opening.

Buckling Failure by an inelastic change in alignment.

Buried Pipe A structure that incorporates both the properties of the pipe and properties of the soil surrounding it.

Buoyancy The upward force exerted by a fluid on a body in it.

C

Canal A constructed open conduit or channel for the conveyance of irrigation water that is distinguished from a ditch or lateral by its larger size. It is usually excavated in natural ground, although lined canals on berms are not uncommon.

Capacity The maximum flow rate that a channel, conduit or structure is hydraulically capable of carrying. The units are usually CFS or GPM.

Catch Basin The structure, sometimes with a sump, for inletting drainage from such places as a gutter or median and discharging the water through a conduit. In common usage it is a grated inlet, curb opening, or combination inlet with or without a sump.

Cathode The surface that accepts electrons and does not corrode.

Cathodic Protection Preventing metal from eroding. This is done by making the metal a cathode through the use of impressed direct current or by attaching a sacrificial anode.

Cavitation A phenomenon associated with the vaporization of the flowing liquid at high velocities in a zone of low pressure, wherein cavities filled with liquid alternatively develops and collapse; surface pitting of a culvert may arise.

Cement Mortar Lining Cement mortar grout centrifugally applied to the interior of existing culverts. Grout is applied after cleaning the existing pipe to protect the pipe and maintain capacity.

CFS Rate of flow in cubic feet per second.

Channel The bed and banks that confine the flow of surface water in a natural stream or artificial channel; also see river and stream or the course where a stream of water runs or the closed course or conduit through which water runs, such as a pipe.

Channelization Straightening and/or deepening of a channel by such things as artificial cutoffs, grading, flow-control measures, river training, or diversion of flow into an artificial channel.

Chlorides Binary chemical compounds containing chlorine which can corrode concrete reinforcing steel.

Check Dam A relatively low dam or weir across a channel for the diversion of irrigation flows from a small channel, canal, ditch, or lateral. A check dam can also be a low structure, dam, or weir, across a channel for such things as the control of water stage or velocity or the control of channel bank erosion and channel bed scour from such things as head cutting.

Chemical Stabilization It is the process of applying of chemical substances to increase particle cohesiveness and to shift the size distribution toward the coarser fraction. The net effect is to improve the erosion resistance of the material.

Chute An open or closed channel used to convey water, usually situated on the ground surface.

Cladding It is aluminum culvert sheet sandwich with aluminum magnesium – manganese alloy 3004 between two layers of aluminum – zinc alloy 7072 cladding for corrosion protection.

Class The grade or quality of pipe.

Coating Any material used to protect the integrity of the structural elements of a pipe from the environment and add service life to culvert.

Coefficient of Contraction The ratio of smallest cross sectional area of the flow after passing the constriction to the nominal cross section area of the constriction.

Coefficient of Discharge Ratio of observed to theoretical discharge. Also the coefficient used for orifice or other flow processes to estimate the discharge past a point or through a reach.

Compaction The process by which a sufficient amount of energy is applied to soil to achieve a specific density.

Conductivity Is a measure of the corrosive potential of soils, which is expressed in milli-mhos per centimeter. It is the reciprocal of resistivity.

Conductor Is a metallic connection that permits electrical current flow by completing the circuit.

Conduit Usually a pipe, designed to flow according to open flow equations.

Conveyance A measure of the ability of a stream, channel, or conduit to convey water or a comparative measure of the water-carrying capacity of a channel; that portion of the Manning discharge formula that accounts for the physical elements of the channel.

Corrosion Deterioration or dissolution of a material by a chemical or electrochemical reaction with its environment.

Cover The depth of backfill over the top of the pipe.

Crack A fissure in an installed precast concrete culvert.

Critical Depth Critical depth is the depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross – section geometry, there is only one critical depth.

Critical Flow The flow in open channels or conduits at which the energy content of the fluid is at a minimum.

Critical Velocity Mean velocity (Vc) of flow at critical depth (dc); in open channels the velocity head equals one-half the mean depth.

Cross Drainage It is the runoff from contributing drainage areas both inside and outside the highway right-of-way and the transmission thereof from the upstream side of the highway facility to the downstream side.

Crown The top side of the culvert.

Culvert Is a structure that is usually designed hydraulically to take advantage of submergence to increase hydraulic capacity; a structure used to convey surface runoff through embankment.

D

Dam A barrier to confine or raise water for storage or diversion, or to create a hydraulic head.

Debris Any material including floating woody materials and other trash, suspended sediment, or bed load moved by a flowing stream.

Deflection Change in the original or specified inside diameter of pipe.

Degradation Process of general progressive lowering of the stream channel by erosion.

Depletion Is the progressive withdrawal of water from surface or groundwater reservoirs at a rate greater than that of replenishment.

Deposition Settling of material from the stream flow onto the bed.

Design Discharge The maximum rate of flow (or discharge) for which a drainage facility is designed and thus expected to accommodate without exceeding the adopted design constraints.

Detour A temporary change in the roadway alignment. It may be localized at a structure or may be along an alternative route.

Discharge (Q) Flow from a culvert, sewer or channel in CFS.

Drainage The interception and removal of ground water or surface water by artificial or natural means.

Drainage Area The catchment area for rainfall and other forms of precipitation that is delineated as the drainage area producing runoff, i.e., contributing drainage area. Usually it is assumed that base flow in a stream also comes from the same drainage area.

Drainage Basin A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water

Drop Inlet Type of inlet structure that conveys water from higher elevation to a lower outlet elevation smoothly without a free fall at the discharge.

Durability The ability to withstand corrosion and abrasion over time or service life.

E

Embankment A bank of earth, rock or material constructed above the natural ground surface over a culvert.

End Section A concrete or steel appurtenance attached to the end of a culvert for the purpose of hydraulic efficiency and anchorage.

Energy Dissipator Device to decrease hydraulic energy placed in ditches or culvert outfalls to reduce streambed scour.

Energy Gradient The increase or decrease in total energy of flow with respect to distance along the channel.

Energy Grade Line The line which represents the total energy gradient along the channel. It is established by adding together the potential energy expressed as the water surface elevation referenced to a datum and the kinetic energy at points along the stream bed or channel floor.

Environmental Effects Pertaining to the effects of highway engineering works on their surroundings and on nature.

EPA Environmental Protection Agency.

Erosion (Culvert) Wearing o grinding away of culvert material by water laden with sand, gravel or stones; generally referred to as abrasion.

Erosion (Stream) The process of the wearing of the streambed by flowing water.

Exfiltration The process by which storm water leaks or flows to the surrounding soil through such things as openings in a conduit, channel banks, or lake shores.

F

FHWA Federal Highway Administration.

Filtration The process of passing water through a filtering medium consisting of either granular material or filter geo textiles for the removal of suspended or colloidal matter.

Fish Passage Ability of fish to pass through bridge and culvert structure.

Flexible Pipe A pipe with relatively little resistance to bending i.e. as the load increases the vertical diameter decreases and the horizontal diameter increases, which is resisted by the soil around the pipe.

Flood In common usage, an event that overflows the normal flow banks or runoff that has escaped from a channel or other surface waters.

Flood Frequency The number of years, on the average, within which a given discharge will be equaled or exceeded.

Flow A stream of water; movement of such things as water, silt and/or sand; discharge; total quantity carried by a stream.

Flow Line A line formed by the invert of pipe.

Flow Regime The system or order characteristic of stream flow with respect to velocity, depth, and specific energy.

Flow Steady A flow in which the flow rate or quantity of fluid passing a given point per unit of time remains constant or a constant discharge with respect to time.

Flow Subcritical In this state, gravity forces are dominant so that the flow has a relatively low velocity and is often described as tranquil or streaming and the flow that has a Froude number less than unity.

Flow Supercritical In this state, inertia forces are dominant so that flow has a high velocity and is usually described as rapid or shooting and the flow that has a Froude number greater than unity.

Flow Turbulent The flow condition in which inertial forces predominate over viscous forces and in which head loss is not linearly related to velocity.

Flow Uniform Flow of constant cross section and average velocity through a reach of channel during an interval of time. It is also a constant flow of discharge, the mean velocity of which is also constant.

Foundation It is the material beneath the pipe.

Freeboard It is the vertical clearance between the lowest structural member of the bridge superstructure, the top culvert invert, or the point of escape in a canal or channel to the water surface elevation of a flood.

Free Flow A condition of flow through or over a structure not affected by submergence.

Free Outlet A free outlet has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

Froude Number A dimensionless number (expressed as F = V/(gy)1/2) that represents the ratio of inertial to gravitational forces, i.e., at a Froude number of unity the flow velocity and wave celerity are equal

G

Galvanizing It is the process of applying of a thin layer of zinc to steel by hot dipping.

Gauge Thickness of sheet metal used in corrugated metal pipe.

Grade The longitudinal slope of the channel as a ratio of the drop in elevation to the distance.

Gradient See Grade.

Gravel The particles, usually of rock, whose diameter is between 2 mm and 100 mm (0.08 in. and 4.0 in.).

Groundwater Water contained in the subsoil, which is free to move either vertically or horizontally.

Groundwater runoff That part of the runoff that has passed into the ground, has become groundwater, and has been discharged into a stream channel as spring or seepage water.

Grout A fluid mixture of cement and water or of cement, sand, and water used to fill joints and voids.

H

Hairline Cracks Very small cracks that form in the surface of the concrete pipe due to tension caused by loading.

Head The height of water above any point, plane, or datum of reference. Used also in various computations, such as energy head, entrance head, friction head, static head, pressure head, lost head, etc.

Headloss The loss of energy reported in feet of head.

Head Velocity The distance a body must fall freely under the force of gravity to acquire the velocity it possesses; the kinetic energy, in meters [feet] of head, possessed by a given velocity.

Headwall A concrete structure placed at the inlet and outlet of a culvert to protect the embankment slopes, anchor the culvert and prevent undercutting.

Headwater It is the distance between the flowline elevation at the inlet of a culvert and the water surface at the inlet.

Holidays Defect in protective coating on metal surface.

Hydraulics The mechanics of fluids, mainly water.

Hydraulic Gradeline An imaginary line, representing the total energy and paralleling the free water surface if the flows were at atmospheric pressure.

Hydraulic Friction A force resisting flow that is exerted on contact surface between a stream and its containing channel.

Hydraulic Jump An abrupt rise in the water surface in the direction of flow when the type of flow changes from supercritical to subcritical.

Hydraulic Radius The cross-sectional area of flow divided by the length of that part of its periphery in contact with its containing conduit; the ratio of area to wetted perimeter.

Hydrology The science of water related to its properties and distribution in the atmosphere, on the land surface, and beneath the surface of the land.

I

Improved Inlet An improved inlet has an entrance geometry that decreases the flow constriction at the inlet and thus increases the capacity of the culverts.

Impermeable Strata It is a stratum in which texture is such that water cannot move perceptibly through it under pressures ordinarily found in subsurface water.

Impervious It is impermeable to the movement of water.

Impingement Suspended solid particles or gas bubbles in water striking the surface or turbulence along breaking down the protective layer of a metal or a concrete surface.

Infiltration The flow of a fluid into a substance through pores or small openings. It connotes flow into a substance in contradistinction to the word percolation, which connotes flow through a porous substance.

Inflow The rate of discharge arriving at a point (in a stream, structure, or reservoir).

Inundate To cover or fill as with a flood.

Inversion Lining Process of inverting pliable tube into existing pipe with hydrostatic or air pressure to reline existing pipe. The tube is forced against the existing pipe and thermosetting resins to provide structural strength and improved smoothness.

Invert The invert is the flowline of a culvert (inside bottom) or the flow line in a channel cross section, pipe, or culvert or the lowest point in the channel cross section or at flow-control devices such as weirs or dams.

J

Joint A connection between two pipe sections made either with or without the use of additional parts.

L

Lateral A conduit, ditch, canal, or channel conveying water diverted from a main conduit, canal, or channel for delivery to distributaries; sometimes considered a secondary ditch.

Launching Release of undercut material (stone riprap, rubble, slag, etc.) down slope; if sufficient material accumulates on the stream bank face, the slope can become effectively armored.

Link Pipe Lining Method of pulling a short, pipe line segment to the damaged point in an existing pipe and jacking the segment into place.

Load (or sediment load) The amount of sediment being moved by a stream.

Long Span Culverts These culverts are designed on structural aspects rather than hydraulic considerations. Usually constructed of structural plates, which exceed defined sizes for pipes, pipe arches, arches or special shape that involve a long radius or curvature in the crown or side plates.

M

Manning's Equation An equation for the empirical relationship used to calculate the barrel friction loss in culvert design.

Meander The winding of a stream channel. Any reverse or letter-S channel pattern fashioned in alluvial materials by erosion of the concave bank, which is free to shift its location and adjust its shape as part of a stage in the migratory movement of the channel as a whole down an erodible, alluvial valley.

Metal Corrosion It is an electrical process involving an electrolyte (moisture), an anode (the metallic surface where oxidation occurs), a cathode (the metallic surface that accepts electrons and does not corrode), and a conductor (the metal pipe itself).

Minor Head Losses Head lost through transitions such as entrances, outlets, obstructions, and bends.

Moisture Water diffused in the atmosphere or the ground.

N

Nonworker-entry: Size of pipe, duct, or bore less than that for worker-entry.

Normal Flow Normal flow occurs in a channel reach when the discharge, velocity and depth of flow do not change throughout the reach. The water surface profile and channel bottom slope will be parallel. This type of flow will exist in a culvert operating on a steep slope provided the culvert is sufficiently long.

O

Outfall The discharge end of drains or sewers.

Outlet Control A condition where the relation between headwater elevation and discharge is controlled by the conduit, outlet, or downstream conditions of any structure through which water may flow.

P

Parameter A characteristic descriptor, such as a mean or standard deviation or sometimes considered as a variable comprised of the product of two or more variables.

Peak Discharge The highest value of the stage or discharge attained by a flood; thus, peak stage or peak discharge.

Permeability The property of a material that permits appreciable movement of water through it when it is saturated and movement is actuated by hydrostatic pressure of the magnitude normally encountered in natural subsurface water.

Perforation Complete penetration of metal culvert that generally occurs in the invert.

pH Value The log of the reciprocal of the hydrogen ion concentration of a solution. The pH value of 7.0 is neutral; values of less than 7.0 are acid; values of more than 7.0 are basic.

Pipe A tube or conduit.

Pipe Diameter The inside diameter of a pipe.

Piping Action A process of subsurface erosion in which surface runoff flows along the outside of a culvert and with sufficient hydraulic gradient erodes and carries away soil around or beneath the culvert.

Polyethylene Pipe Plastic pipe manufactured from polymerized ethylene in corrugated or smooth configurations of various dimensions.

Polymer Coating A protective coating of plastic polymer resins with other materials.

Ponding Water back up in a channel or ditch as the result of a culvert of inadequate capacity or design to permit the water to flow unrestricted.

R

Reinforced Concrete Pipe A concrete pipe designed with reinforcement as a composite structure.

Rigid Pipe A pipe with high resistance to bending.

Riprap Rough stones of various sizes placed compactly or irregularly to prevent scour by water or debris.

Roughness Coefficient (n) A factor in the Kutter, Manning, and other flow formulas representing the effect of channel roughness upon energy losses in flowing water.

Resistivity (Soil) An electrical measurement in ohm-cm, which is one of the factors for estimating the corrosiveness of a given soil to metal.

Runoff That part of precipitation carried off from the area upon which it falls.

S

Sacrificial Coating A coating over the base material to provide protection to the base material. Examples include galvanizing on steel and cladding on aluminum.

Sacrificial Thickness Additional pipe thickness provided for extra service life of the culvert in an aggressive environment.

Scour (outlet) The process of degradation of the channel at the culvert outlet as a result of erosive velocities.

Seepage It is the process of escaping of water through the soil, or water flowing from a fairly large area of the soil instead of from one spot, as in the case of a spring.

Shotcrete Lining Application of pneumatically applied cement plaster or concrete to an in place structure to increase structural strength and improve the surface smoothness.

Skew The acute angle formed by the intersection of the line normal to the centerline of the road with the centerline of a culvert or other structure.

Slabbing The radial tension failure of concrete pipe resulting from the tendency of curved reinforcing steel or cage to straighten out under the load.

Slide Movement of a part of the earth under the force of gravity.

Sliplining The process of placing a smaller diameter pipe in a larger diameter existing pipe to improve the culvert structure and repair leaks. The annular space between the pipes is usually filled with grout.

Slope Steep slopes occur where the critical depth is greater than the normal depth.

Spelter Zinc slabs or plates.

Spalling (Culvert) The separation of surface concrete due to fractures in the concrete parallel or slightly inclined to the surface of the concrete.

Springline The points on the internal surface of the transverse cross section of a pipe intersected by the line of maximum horizontal dimension; or in box sections, the mid height of the internal vertical wall.

Structural Plate Plates of structural steel used to fabricate large culvert structures such as arches or boxes.

Submerged Inlet A submerged inlet occurs where the headwater is greater than 1.2D.

Submerged Outlet A submerged outlet occurs where the tailwater elevation is higher than the crown of the culvert.

Sulfates Chemical compounds containing SO4 found in alkaline soils that cause concrete deterioration.

T

Tailwater Depth The depth of water just downstream from a structure.

Trenchless Renewal It is the process of Upgrading to a new design life by forming a new pipe within the existing pipe with minimum or no excavation.

Trenchless Replacement Upgrading to a new design life by destroying the existing pipe and installing a new pipe with minimum or no excavation.

V

Velocity Head For water moving at a given velocity, the equivalent head through which it would have to fall by gravity to acquire the same velocity.

W

Wrapped casing: A coating on pipe for protection from corrosion usually composed of asphalt and asphalt-coated paper. Some coatings may contain plastic, fiberglass, coal tar, or other materials.

Watercourse A channel in which a flow of water occurs, either continuously or intermittently, with some degree of regularity.

Weir A man made barrier in an open channel over which water flows. It is used to measure the quantity of flow.

Wetted Perimeter The length of the wetted contact between the water and the containing conduit measured at right angles to the conduit.

APPENDIX B
PROJECT LETTER AND SAMPLE DATA COLLECTION FORM

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Dear Sir/Madam,

The Florida Department of Transportation is currently funding a research project titled: "Durability of In-situ Pipe Repair, Contract: BDK 75-977-38" at the University of Florida. As part of the project, the FDOT would like us to collect data from the past 15 years of pipe repair projects from every district in the state. We have completed a rough draft of the spreadsheet we will use for data collection (see attached Microsoft Excel file). Please, review the spreadsheet and send back any input for the final data collection spreadsheet.

Once the form is approved, a project team member will travel to your district to collect the information. If your pipe repair data is electronically available, or if there are videos of the pipe repair projects, please let us know as this will save us time in the data collection phase of our project. Hopefully, your records will allow my team and me to fill in the necessary information so that we can accurately report our findings to FDOT Project Manager, Mr. Larry Ritchie. Any additional information or assistance that you could give would be greatly appreciated. We need your response on this matter as soon as possible. I appreciate your time and effort on this important matter.

Thanks,
Best regards,
Sincerely,

Dr. Fazil T. Najafi
Professor

The Foundation for The Gator Nation

An Equal Opportunity Institution

Figure B-1. Copy of the Project Letter announcing the project to the Districts.

Table B-1. Copy of the Sample Data Collection Spreadsheet sent to the Districts with the Project Letter.

DURABILITY OF IN-SITU PIPE REPAIRS | ***SAMPLE DATA COLLECTION FORM*** | 27 JULY 2010

DATA PERTINENT TO REPAIR DURABILITY AT EACH SITE

LOCATION IDENTIFIERS								HOST PIPE CHARACTERIZATION			
Site ID (assigned by UF)	State Road Number	US Hwy Number (if applicable)	County	FDOT District Number	Nearest Town or City	Milepost of Repair Point	Function of Host Pipe	Original In-service Date of Host Pipe	Host Optional Pipe Type	Diameter or WxD Dimension of Host Pipe (inches)	Original Installation Method of Host Pipe
301	63	27	Leon	3	Tallahassee	12.5	SD	1989	CSP	24	OT
302	10	90	Gadsden	3	Havana	2.1	CD	1996	HECP	72 x 44	BJ
303	30-A	98	Santa Rosa	3	Seaside	6.2	STD	1948	RCP	48	OT
304	61	319	Wakulla	3	Woodville	5.8	STD	1977	CAP	60	OT

POINT OF REPAIR DETAILS (CONSTRUCTION OR MAINTENANCE)									
	(If attributed to a construction project)								
Date of Point Repair	FPID No.	Stationing of Point Repair	Nearest Downsteam Structure Number	Contractor	Point Repair Type	CCTV Video Available to Review	Laser Profile Available to Review	Pipe Defect Corrected by the Repair	Cost of Repair ($ US at date of repair)
1999	219843	150+21	S-89	Sandco	SL	Y	Y	Corr	2,000
2005	409525	25+39	S-50	Anderson	CG	Y	N	Spall	1,000
2003	281599	69+85	S-101	Peavy	CCOL	Y	Y	Crack	5,500
1998	419258	1120+75	S-60	Roberts	JS	N	N	Abras	1,000

IN-SITU SOIL BACKFILL CHACTERIZATION						
Date of Observations	Cover (ft.)	Cohesive (C) or Non-cohesive (NC) Soil	In-situ Resistivity (ohm-cm)	In-situ Soil pH	Sulfates (ppm)	Chlorides (ppm)
2010	5	C	1500	7.8	5423	1988
2010	15	C	700	6.9	4877	2100
2010	8	NC	650	8.9	6500	2300
2010	8	NC	2000	9.6	5871	1500

WATER COURSE CHARACTERIZATION							
Date of Observations	Water Surface Profile Observed Above Pipe Invert (ft.)	Evidence of Abrasion	Depth of Sediment Deposition Depth Observed (ft.)	Water Resistivity (ohm-cm)	Water pH	Sulfates (ppm)	Chlorides (ppm)
2010	0.2	N	0.5	1000	7.7	5300	2000
2010	1.0	N	0.3	850	6.8	4900	2584
2010	0.3	Y	0.1	250	8.5	6423	2387
2010	0.8	N	0.2	2500	9.4	5774	1600

ABBREVIATIONS	
CSP corrugated steel pipe	N no
CAP corrugated aluminum pipe	Y yes
RCP round concrete pipe	
HECP horizontal elliptical pipe	Corr corrosion
....and so on, using the abbrevations in the FDOT Optional Pipe Handbook	Abras abrasion
	Spall spalling
CD cross drain	Crack cracking
SD side drain	
STD storm drain	SL slip lining
	CG chemical grouting
OT open trench	CCOL concrete collar
BJ bore and jack	JS joint seal

Note: There are many more pipe repair types than given in this example. The abbreviations for pipe repair types can be created from those described in the FDOT Pipe Repair Matrix with some "creative" acronymns or using code numbers.

APPENDIX C
SPREADSHEET DATABASE

C.1 Pipe Repair Database

Through the investigation, the UF Research team found many pipe repair sites which could potentially be inspected for useful data. However, due to time constraints on the project only 16 sites were selected from over 150 potential sites. The full database of potential sites can be found in Table C-1.

Table C-1. Database of potential pipe repair inspection sites.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Host Pipe Diameter (in)	Ty
2			20974	9/28/2001	DUVAL	SR115	I-95, I-295	SR115/LEM TURNER RD,I-95, I-295	RCP	15	C (I
2			20974	9/28/2001	DUVAL	SR115	I-95, I-295	SR115/LEM TURNER RD,I-95, I-295	RCP	15	C (I
2			20974	9/28/2001	DUVAL	SR115	I-95, I-295	SR115/LEM TURNER RD,I-95, I-295	RCP	36	C (I
5			20853	9/26/2000	ORANGE	SR 50	-	SR 50,FROM MILLS AVE, TO FASHION SQUARE	RCP	60	C
5			20853	9/26/2000	ORANGE	SR 50	-	SR 50,FROM MILLS AVE, TO FASHION SQUARE	RCP	60	C (I
2			21374	9/3/2002	CLAY	SR 224	-	SR 224/KINGSLEY AVE,BLANDING BLVD, US17	RCP	15	P M
2			21390	9/14/2002	DUVAL	SR 128	*	SR 128,CASSAT AVE, HERCHELL ST	RCP	48	P M
2			?	?	ALACHUA	SR 331	-	0.25 MILES NORTH OF E UNIVERSITY AVE INTERSECTION	RCP		In
5			21099	11/6/2001	ORANGE	SR 482	-	SR 482,FROM PC E OF INTRNAT'L DR, TO 0.1MI W OF CROWN POINT	RCP	14 X 23	P
5			20853	9/26/2000	ORANGE	SR 50	-	SR 50,FROM MILLS AVE, TO FASHION SQUARE	RCP	24	S
2			21583	7/1/2005	PUTNAM	SR 20		S 328 to S 325	RCP	18	J
2			21583	7/1/2005	PUTNAM	SR 20		S 312 to S 314	RCP	18	J
2			21583	7/1/2005	PUTNAM	SR 20		S 437 to S 438	RCP	24	J
1			T1287	9/17/2009	OKEECHOBEE	700	98	S-1 STA. 95+63.70 LT and S-2 STA. 95+63.70 RT	RCP	24	N
4			E4D31	12/16/2002	INDIAN RIVER	60	?	EX 21	RCP	36	B
1			T1214	8/28/2008	POLK	25	27	Between S-583 and S-582	RCP	24	R
2			E2J31	2006/2007	St. John's				RCP		In
2			E2K58	2007/2008	Putnam				RCP		P
2			E2L64	2008/2009	Madison	SR 53		Between milepost 6.358-6.430	RCP		S
2			E2M18	2008/2009	Duval	SR 9	I-95	420+00-428+00	RCP		D
2			E2M87	2008/2009	Duval	SR 5		44+90	RCP		P
2			E2M88	2008/2009	Levy	SR 24		Between milepost 23.817	RCP		P
2			E2M20	2008/2009	St. John's				RCP		P
2			E2L80	2009/2010	Putnam & St. John's				RCP		P
2			E2N95	2009/2010	Duval				RCP		D
2			E2O74	2010/2011	St. John's				RCP		S
2			E2O16	2010/2011	St. John's				RCP		P

Table C-1. Database of potential pipe repair inspection sites, continued.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Host Pipe Diameter (in)
2			E2O18	2010/2011	St. John's				RCP	
2			E2O30	2010/2011	Taylor, Madison & Lafayette	SR 55/SR 51	US 19		RCP	
4		413795			Broward	816		Sta. 443+80	RCP	15
4		230428			Broward	A1A		Milepost 2.0 to 3.0	RCP	18" to 30"
4		228803-1			Indian River	SR-5	US-1		RCP	
4		228820-1			Indian River	SR-60	-		RCP	
4		230262-4			St Lucie	SR-70	-		RCP	
4		230262-5			St Lucie	SR-70	-		RCP	
4		230288-2			St Lucie	SR-5	US-1		RCP	
4		230428-2			Mart/St Luc/IRC	DW Drainage	-		RCP	
4		230428			St. Lucie	713		Milepost 0.2 to 1.8	CSP	18" to 48"
4					Indian River	60		Milepost 29.5 to 30.4	RCP	15" to 42"
4					Indian River	5	US-1	Milepost 19.1 to 19.5	RCP	18" to 36"
4		230428			Martin	5	US-1	Milepost 13.96	RCP	48"
5	75190			3/16/2003	Orange	423	-	WB from Firestone to Adanson	RCP	36
5	75060			3/30/2003	Orange	50	-	Huboap Heavan Crossdrain	RCP	18
5	77010			8/23/2003	Seminole	15/600	17/92	Sta 412+18 to 414+04	RCP	24
5	77120			6/7/2003	Seminole	434	-	MP 8.285	RCP	15
5	77120			3/15/2003	Seminole	434	-	Timberlane	RCP	24
5	77010			3/16/2003	Seminole	15/600	17/92	Raven to Gen. Huchenson	RCP	18
5	77120			2/8/2003	Seminole	434	-	Mingo Trail	RCP	15
5	75200			3/16/2003	Orange	551	-	SB 2nd inlet north of SR 408	RCP	18
5	75060			4/28/2003	Orange	50	-	Walmart - Oooooe Project	RCP	36
5	77010				Seminole	15/600	17/92	MP 11.675	RCP	15
5	77010				Seminole	15/600	17/92	MP 11.675	RCP	15
5	77010				Seminole	15/600	17/92	MP 11.675	RCP	18
5	75200			12/14/2002	Orange	551	-	MP 8.558 to MP 8.610	RCP	30

Table C-1. Database of potential pipe repair inspection sites, continued.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Host Pipe Diameter (in)
5	75008			11/17/2004	Orange	426	-	WB @ Harold Ave.	RCP	38
5	75030			8/1/2004	Orange	15/600	17/92	MP 3.750	RCP	24
5	77160			7/13/2004	Seminole	400	I-4	MP 10.300	RCP	30
5	77010			4/24/2004	Seminole	15/600	17/92	MP 9.057	RCP	24
5	77170			4/24/2004	Seminole	434	-	MP 3.783	RCP	18
5	75020			11/18/2003	Orange	500	441	RR S of Maitland Blvd.	RCP	18
5	75050			11/18/2003	Orange	50	-	Texas Ave. and Tampa Ave.	RCP	24
5	75030			8/17/2005	Orange	15/600	17/92	Rollins Street	RCP	15
5	77040			9/21/2005	Seminole	426	-	MP 11.200	RCP	24
5	77040			9/19/2005	Seminole	46	-	MP 7.550	RCP	24
5	75030			1/28/2005	Orange	15/600	17/92	MP 3.750	RCP	24
5	75090			12/3/2004	Orange	426	-	MP 4.191	RCP	38
5	75040			3/28/2005	Orange	527	-	MP 14.950	RCP	15
5	75090			12/3/2004	Orange	426	-	MP 4.125	RCP	18
5	75090			12/3/2004	Orange	426	-	MP 4.060 - MP 4.125	RCP	54
5	75090			12/3/2004	Orange	426	-	MP 4.258	RCP	38
5	75090			12/3/2004	Orange	426	-	MP 3.978 - MP 4.060	RCP	54
5	77040			3/8/2006	Seminole	46	-	MP 11.578	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 11.658	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 11.984	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 12.207	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 12.257	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 13.417	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 13.882	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 7.243	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 8.903	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 9.291	RCP	24

Table C-1. Database of potential pipe repair inspection sites, continued.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Ho[st] Pipe Diame[ter] (in)
5	77040			3/8/2006	Seminole	46	-	MP 8.903	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 8.903	RCP	24
5	77040			3/8/2006	Seminole	46	-	MP 8.903	RCP	18
5	77010			3/20/2007	Seminole	15/600	17/92	MP 11.648 - MP 13.370	RCP	30
5	77010			3/20/2007	Seminole	15/600	17/92	MP 11.648 - MP 13.370	RCP	15
5	77010			3/20/2007	Seminole	15/600	17/92	MP 11.648 - MP 13.370	RCP	18
5	77010			3/20/2007	Seminole	15/600	17/92	MP 11.648 - MP 13.370	RCP	24
5	75280			11/22/2008	Orange	637	-	SR 438 - SR 50	RCP	15
5	75280			11/22/2008	Orange	637	-	SR 438 - SR 50	RCP	18
5	75280			11/22/2008	Orange	637	-	SR 438 - SR 50	RCP	24
5	75280			11/22/2008	Orange	637	-	SR 438 - SR 50	RCP	30
5	77010			8/28/2008	Seminole	15/600	17/92	Melody - Concord	RCP	18
5	75030			7/16/2008	Orange	526	-	State Rd. - N. Gertrude Ave.	RCP	15
5	75030			6/11/2008	Orange	527	-	Magnolia - Marks	RCP	15
5	75030			6/11/2008	Orange	527	-	Magnolia - Marks	RCP	15
5	75008			7/16/2008	Orange	426	-	Ohio	RCP	18
5	75008			7/16/2008	Orange	426	-	Harold Ave. - Blue Heron Dr.	RCP	36
5	77160			12/18/2009	Seminole	400	I-4	W of SR 46 Bridge, Ramp # 035	RCP	0 - 24
5	75260			6/20/2010	Orange	424	-	MP 3.451 - 3.883	RCP	54
5	75260			6/20/2010	Orange	424	-	MP 3.451 - 3.883	RCP	60
5	75200			Fall 2003	Orange	551	-	MP 8.728 - 8.793	RCP	30
5		241543			Marion	CR 484		Sta. 512+25, S-1	RCP	18
5		241543			Marion	CR 484		Sta. 520+50, S-9	Hardee	18
5		241543			Marion	CR 484		Sta. 530+65, S-17 to S-18	Hardee	18
5		241543			Marion	CR 484		Sta. 624+20, S-47 to S-48	Hardee	24
5		241543			Marion	CR 484		Sta. 685+20, S-65	RCP	18

Table C-1. Database of potential pipe repair inspection sites, continued.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Host Pipe Diamete (in)
4			T4263	-	PALM BEACH	SR-809		SR-809/MILITARY TRL FR OXFORD STREET TO SR-704/OKEECHOBEE BL,FROM OXFORD ST TO SR 704 (OKEECHOBEE BLVD),		
5			T5228	11/24/2008	VOLUSIA	SR-5A		SR-5A (NOVA RD) (STA) Resurfacing,FROM SR 600 (INTERNATIONAL SPEEDWAY BLVD) TO BRENTWOOD DR,		
5			T5228	11/24/2008	VOLUSIA	SR-5A		SR-5A (NOVA RD) (STA) Resurfacing,FROM SR 600 (INTERNATIONAL SPEEDWAY BLVD) TO BRENTWOOD DR,		
7			E7E51	11/4/2008	PINELLAS	SR 699		SR 699 (GULF BLVD) RESURFACING,FROM SR 688 TO COLONY CIRCLE,		
7			E7E51	11/4/2008	PINELLAS	SR 699		SR 699 (GULF BLVD) RESURFACING,FROM SR 688 TO COLONY CIRCLE,		
7			E7D91	4/2/2008	HILLSBOROUGH	SR 573		SR 573 (DALE MABRY),FROM W PINEWOOD ST TO W BALLAST POINTE BLVD,		
7			E7D91	4/2/2008	HILLSBOROUGH	SR 573		SR 573 (DALE MABRY),FROM W PINEWOOD ST TO W BALLAST POINTE BLVD,		
1			21262	9/21/2001	DESOTO	SR 35	US 17	US 17 (SR 35),FROM HEARD STREET, TO MAGNOLIA STREET		8
1			T1038	9/24/2003	COLLIER	SR 45	US 41	SR 45 (US 41),FROM A PT E OF 10TH ST TO 22ND AVE,		38
1			T1038	9/24/2003	COLLIER	SR 45	US 41	SR 45 (US 41),FROM A PT E OF 10TH ST TO 22ND AVE,		48
1			T1044	12/3/2003	COLLIER	SR 45	US 41	SR 45 (US 41),S.R. 45 (US 41) from pt S of 22nd Avenue N to pt S of, Old Trail Drive in Naples, Collier Cnty		60
1			T1044	12/3/2003	COLLIER	SR 45	US 41	SR 45 (US 41),S.R. 45 (US 41) from pt S of 22nd Avenue N to pt S of, Old Trail Drive in Naples, Collier Cnty		18
2			21374	1/28/2002	CLAY	SR 224	-	SR 224/KINGSLEY AVE,BLANDING BLVD, US17		15
2			E2K40	10/1/2007	COLUMBIA	SR 10	US 90	SR 10 (US 90),AT MP 8.85 NORTH SIDE NEAR HESS GAS STATION,		48-60*
2			T2236	7/10/2009	DUVAL	SR 10	-	SR 10 (ATLANTIC BLVD),FROM SR 9 TO SR 109,		25-38*
2			T2257	9/29/2008	ALACHUA	SR 26	-	SR 26,AT SR 222 AND CR 234,		0-24*
3			T3041	6/21/2004	GULF	SR 71	-	SR 71 (5TH ST),FROM SR 30 (US 98) TO A PT E OF PARK AVE,		12
3			T3041	6/21/2004	GULF	SR 71	-	SR 71 (5TH ST),FROM SR 30 (US 98) TO A PT E OF PARK AVE,		24
3			T3172	1/18/2008	FRANKLIN	SR 30	US 98	SR 30 (US 98),FROM SR 30A/CR 67 TO SR 377 (US 319),		37-48*
3			T3172	1/18/2008	FRANKLIN	SR 30	US 98	SR 30 (US 98),FROM SR 30A/CR 67 TO SR 377 (US 319),		0-24*

Table C-1. Database of potential pipe repair inspection sites, continued.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Host Pipe Diameter (in)
4			19387	5/17/2010	PALM BEACH	SR-809	-	SR-809/MILITARY TRL FR OXFORD STREET TO SR-704/OKEECHOBEE BL,FROM OXFORD ST TO SR 704 (OKEECHOBEE BLVD),		?
4			19720	5/5/1997	PALM BEACH	SR-5	US-1	SR-5 (US-1),N. OF CR-806A, BOYNTON CANAL		?
4			20946	1/3/2001	PALM BEACH	SR-5	-	SR-5/BROADWAY AVE,FROM NORTHWOOD RD, TO 59 STREET		?
4			21521	3/3/2003	PALM BEACH	SR-5	-	SR-5/FEDERAL HWY,FROM SILVER BEACH ROAD, TO S OF PARKER BRIDGE		?
4			T4016	1/5/2004	PALM BEACH	I-95	-	I-95 Project 3 from 10th Ave North to South of SR 80,FROM MP 21.610 TO MP 24.596,		?
4			T4039	7/8/2004	PALM BEACH	I-95	*	I-95 Project 2 from 12th Ave South to 10th Ave North,FROM 12TH AVE SOUTH TO 10TH AVE NORTH,		?
4			T4124		*	*	*	*		?
4			T4239	1/19/2010	PALM BEACH	SR-5	-	SR-5 FEDERAL HY FROM C-16 CANAL TO HYPOLUXO RD,FROM BOYNTON CANAL TO HYPOLUXO RD,		37-48
4			T4253	5/17/2010	PALM BEACH	SR-809	-	SR-809/MILITARY TRL FR OXFORD STREET TO SR-704/OKEECHOBEE BL,FROM OXFORD ST TO SR 704 (OKEECHOBEE BLVD),		37-48
5			19414	6/3/1996	ORANGE	I-4,SR 500	US 441	I-4,SR 500 US 441, LEE ROAD		?
5			19652	2/8/1997	ORANGE	SR 500	US 441	SR 500 US 441 0BT,34TH STREET, COLUMBIA STREET		?
5			21686	3/17/2003	ORANGE	SR 438	-	SR 438,FROM SR 416, TO SR 500 US 441 OBT		24
5			T5087	6/8/2005	FLAGLER	SR 100	-	SR 100 (STA) Add 2 lanes to existing 2,FROM SR 5 (US 1) TO A PT W OF BELLE TERRE BLVD,		38
5			T5087	6/8/2005	FLAGLER	SR 100	-	SR 100 (STA) Add 2 lanes to existing 2,FROM SR 5 (US 1) TO A PT W OF BELLE TERRE BLVD,		15
5			T5173	7/23/2007	MARION	SR-93 (I-75) SR-464 & SR 500	*	SR-93 (I-75) SR-464 & SR 500 (EXN) Mill/Resurface,FROM SUMTER CO LINE TO SR 200,		25-36
6			T6190	1/0/1900	MIAMI-DADE	SR 5	US 1	SR 5 (US 1) (BRICKELL AVE),FROM A PT S OF SE 25TH RD TO SE 5TH ST,		37-48
7			E7B25	6/1/2004	PINELLAS	SR 699	-	SR 699 (GULF BLVD),FROM 97TH AVE TO 105TH AVE,		15
7			E7B25	6/1/2004	PINELLAS	SR 699	-	SR 699 (GULF BLVD),FROM 97TH AVE TO 105TH AVE,		24
7			E7E45	12/3/2007	PINELLAS	SR 651,& 688,	-	DRAINAGE IMPROVEMENT,ON SR 651,& 688,		25-36
7			E7E51	5/8/2008	PINELLAS	SR 699	-	SR 699 (GULF BLVD) RESURFACING,FROM SR 688 TO COLONY CIRCLE,		0-24

Table C-1. Database of potential pipe repair inspection sites, continued.

FDOT District Number	Section Number	FPID Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Hos Pipe Diamet (in)
7			E7E61	5/8/2008	PINELLAS	SR 699	-	SR 699 (GULF BLVD) RESURFACING,FROM SR 666 TO COLONY CIRCLE,		37-48
7			T7044	1/4/2005	PINELLAS	I-275 (SR 93	-	I-275 (SR 93),FROM 13TH AVE N TO 62ND AVE N,		60
7			T7044	1/4/2005	PINELLAS	I-275 (SR 93	-	I-275 (SR 93),FROM 13TH AVE N TO 62ND AVE N,		48
7			T7148	6/11/2007	HILLSBOROUGH	US 41	-	US 41 (NEBRASKA AVE) RESURFACING,FROM KENNEDY BLVD TO HILLSBOROUGH AVE,		25-36

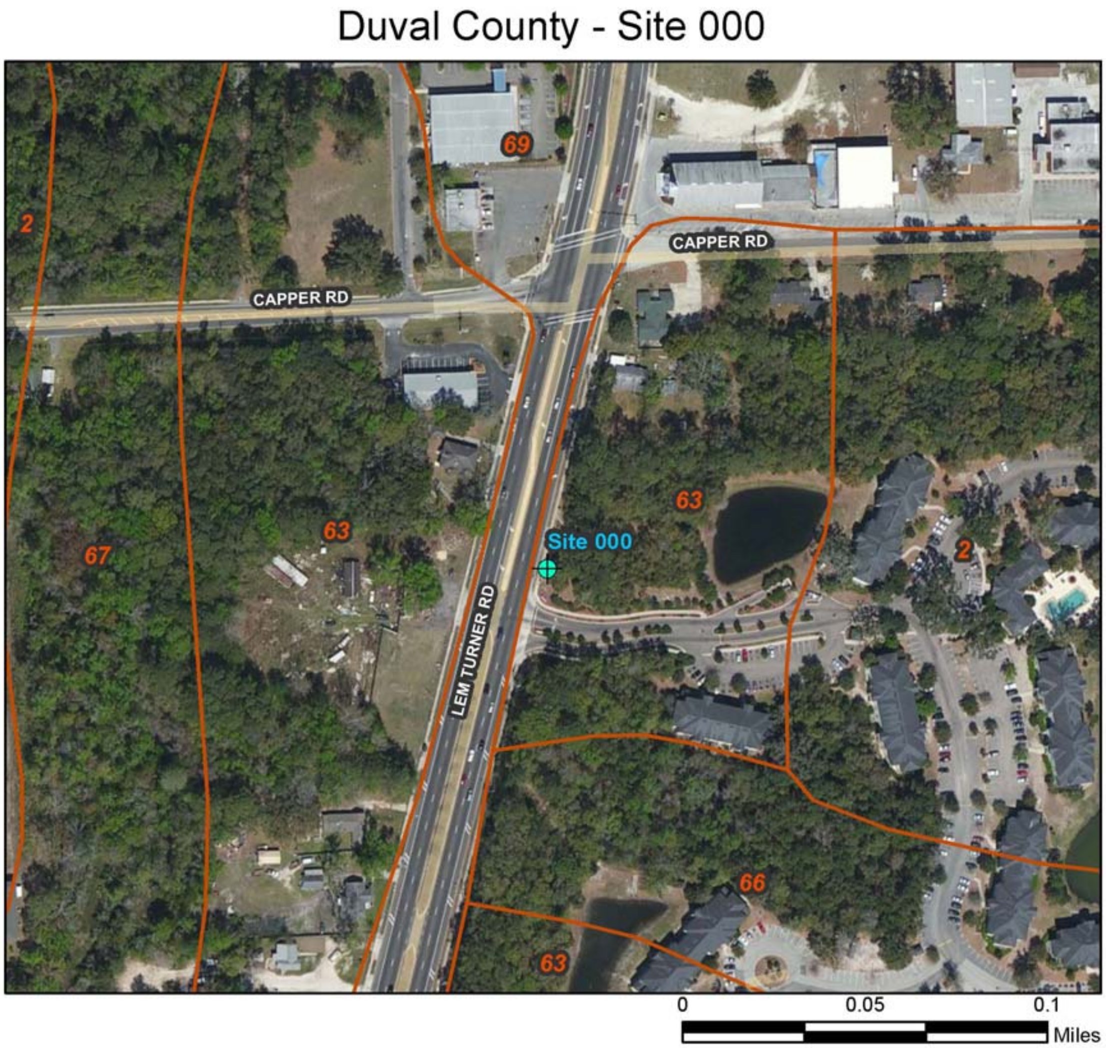
From the database, the potential sites were narrowed down by type of repair, date of repair, and pipe diameter. The final list of sites included sites from Districts 1, 2, 4, and 5. The counties visited included Duval, Orange, Clay, Alachua, Putnam, Polk, and Okeechobee. The final spreadsheet of sites visited can be found in Table C-2.

Table C-2. Spreadsheet showing sites chosen for inspection.

FDOT District Number	Contract No.	Final Acceptance Date	County	State Road Number	US Road Number	Location	Original Host Pipe Type	Original Host Pipe Diameter (in)	Type of Repair/ Pay Item Description
2	20974	9/28/2001	DUVAL	SR115	I-95, I-295	SR115/LEM TURNER RD,I-95, I-295	RCP	15	CHEM GROUT REPAIR (PIPE)(NON-TEST) (15")
2	20974	9/28/2001	DUVAL	SR115	I-95, I-295	SR115/LEM TURNER RD,I-95, I-295	RCP	15	CHEM GROUT REPAIR (PIPE)(NON-TEST) (15")
2	20974	9/28/2001	DUVAL	SR115	I-95, I-295	SR115/LEM TURNER RD,I-95, I-295	RCP	36	CHEM GROUT REPAIR (PIPE)(NON-TEST) (36")
5	20853	9/25/2000	ORANGE	SR 50	-	SR 50,FROM MILLS AVE, TO FASHION SQUARE	RCP	60	CHEM GROUT REPAIR (PIPE)
5	20853	9/25/2000	ORANGE	SR 50	-	SR 50,FROM MILLS AVE, TO FASHION SQUARE	RCP	60	CHEMICAL GROUT REPAIR (PIPE)
2	21374	8/3/2002	CLAY	SR 224	-	SR 224/KINGSLEY AVE,BLANDING BLVD, US17	RCP	15	PIPE LINER(OPTIONAL MATERIAL)(15")
2	21390	9/14/2002	DUVAL	SR 128	*	SR 128,CASSAT AVE, HERCHELL ST	RCP	48	PIPE LINER(OPTIONAL MATERIAL)(48")
2	?	?	ALACHUA	SR 331	-	0.25 MILES NORTH OF E UNIVERSITY AVE INTERSECTION	RCP	36	Impermeable Fiberglass Liner
5	21099	11/5/2001	ORANGE	SR 482	-	SR 482,FROM PC E OF INTRNAT'L DR, TO 0.1MI W OF CROWN POINT	RCP	14 X 23	PIPE LINER (14" X 23" SS)
5	20853	9/25/2000	ORANGE	SR 50	-	SR 50,FROM MILLS AVE, TO FASHION SQUARE	RCP	24	Sectional Liner
2	21583	7/1/2005	PUTNAM	SR 20		S 326 to S 325	RCP	18	Joint Seal
2	21583	7/1/2005	PUTNAM	SR 20		S 312 to S 314	RCP	18	Joint Seal
2	21583	7/1/2005	PUTNAM	SR 20		S 437 to S 436	RCP	24	Joint Seal
1	T1214	8/28/2008	POLK	25	27	Between S-563 and S-562	RCP	24	Repair sleeve
1	T1267	6/17/2009	OKEECHOBEE	700	98	S-1 STA. 95+53.70 LT and S-2 STA. 95+53.70 RT	RCP	24	NPC Internal Joint Seal
4	E4D31	12/15/2002	INDIAN RIVER	60	?	EX 21	RCP	36	Band Seal

APPENDIX D
SOIL MAPPING

D.1 Soil Site Maps



Duval Soils

Symbol	Name
2	Albany Fine Sand, 0 To 5 Percent Slopes
63	Sapelo Fine Sand, 0 To 2 Percent Slopes
66	Surrency Loamy Fine Sand, Depressional, 0 To 2 Percent Slopes
67	Surrency Loamy Fine Sand, 0 To 2 Percent Slopes, Frequently Flooded
69	Urban Land

Figure D-1. Soil mapping for the Duval County Site 000.

Duval County - Site 001

Duval Soils

Symbol	Name
2	Albany Fine Sand, 0 To 5 Percent Slopes
51	Pelham Fine Sand, 0 To 2 Percent Slopes
63	Sapelo Fine Sand, 0 To 2 Percent Slopes
66	Surrency Loamy Fine Sand, Depressional, 0 To 2 Percent Slopes
67	Surrency Loamy Fine Sand, 0 To 2 Percent Slopes, Frequently Flooded
68	Tisonia Mucky Peat, 0 To 1 Percent Slopes, Very Frequently Flooded
69	Urban Land
74	Pelham-Urban Land Complex, 0 To 2 Percent Slopes

Figure D-2. Soil mapping for the Duval County Site 001.

Duval County - Site 002

Duval Soils

Symbol	Name
38	Mascotte Fine Sand, 0 To 2 Percent Slopes
51	Pelham Fine Sand, 0 To 2 Percent Slopes
63	Sapelo Fine Sand, 0 To 2 Percent Slopes
66	Surrency Loamy Fine Sand, Depressional, 0 To 2 Percent Slopes
69	Urban Land

Figure D-3. Soil mapping for the Duval County Site 002.

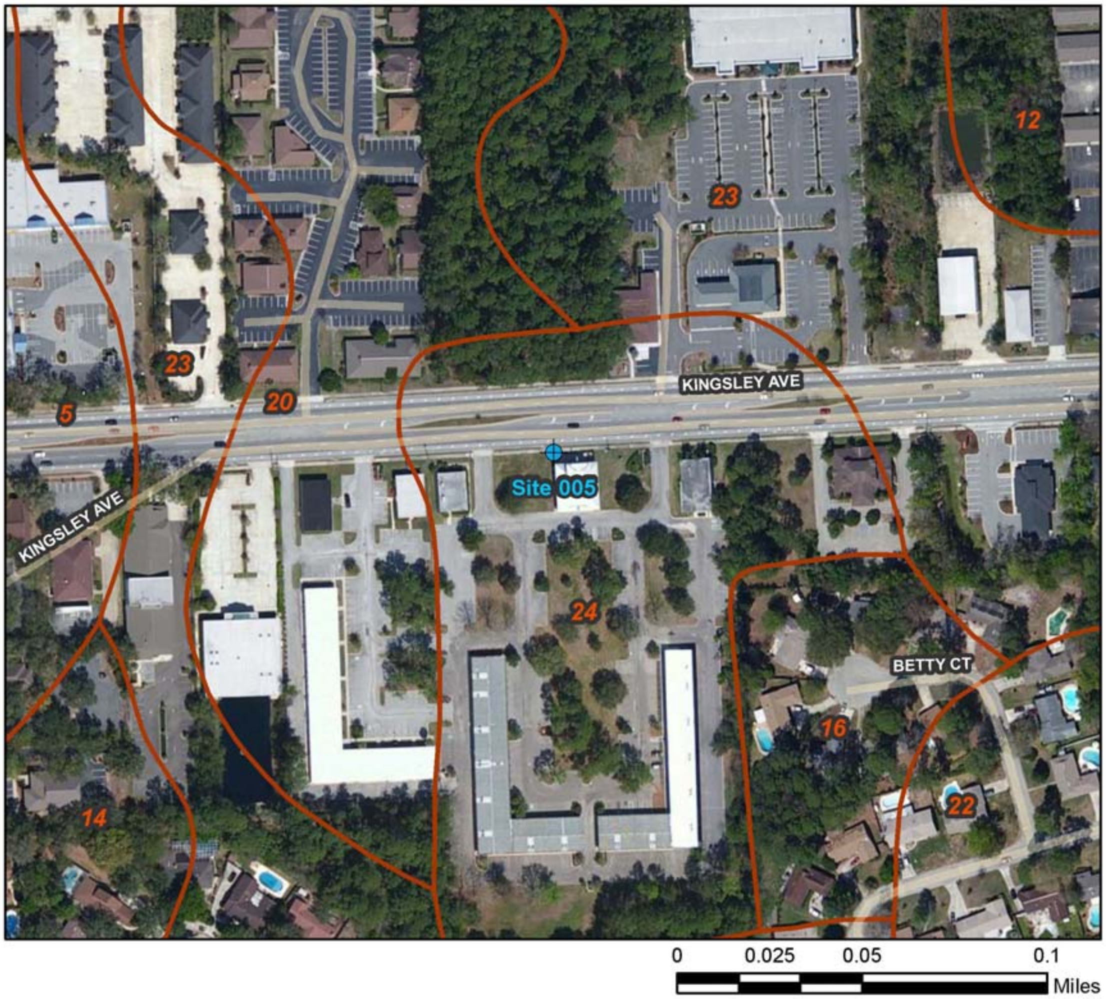
Orange County - Site 003, Site 004, and Site 007

Orange Soils

Symbol	Name
24	Millhopper-Urban Land Complex, 0 To 5 Percent Slopes
50	Urban Land

Figure D-4. Soil mapping for the Orange County Sites 003, 004, and 007.

Clay County - Site 005



Clay Soils

Symbol	Name
5	Penney Fine Sand, 0 To 5 Percent Slopes
8	Sapelo Fine Sand
12	Surrency Fine Sand, Depressional
14	Ortega-Urban Land Complex, 0 To 5 Percent Slopes
16	Hurricane-Urban Land Complex, 0 To 5 Percent Slopes
20	Scranton Fine Sand
22	Pelham Fine Sand
23	Sapelo-Urban Land Complex
24	Urban Land

Figure D-5. Soil mapping for the Clay County Site 005.

Duval County - Site 006

Duval Soils

Symbol	Name
69	Urban Land
71	Urban Land-Leon-Boulogne Complex, 0 To 2 Percent Slopes

Figure D-6. Soil mapping for the Duval County Site 006.

Orange County - Site 008

Orange Soils

Symbol	Name
3	Basinger Fine Sand, Depressional
44	Smyrna Fine Sand
45	Smyrna-Urban Land Complex
50	Urban Land

Figure D-7. Soil mapping for the Orange County Site 008.

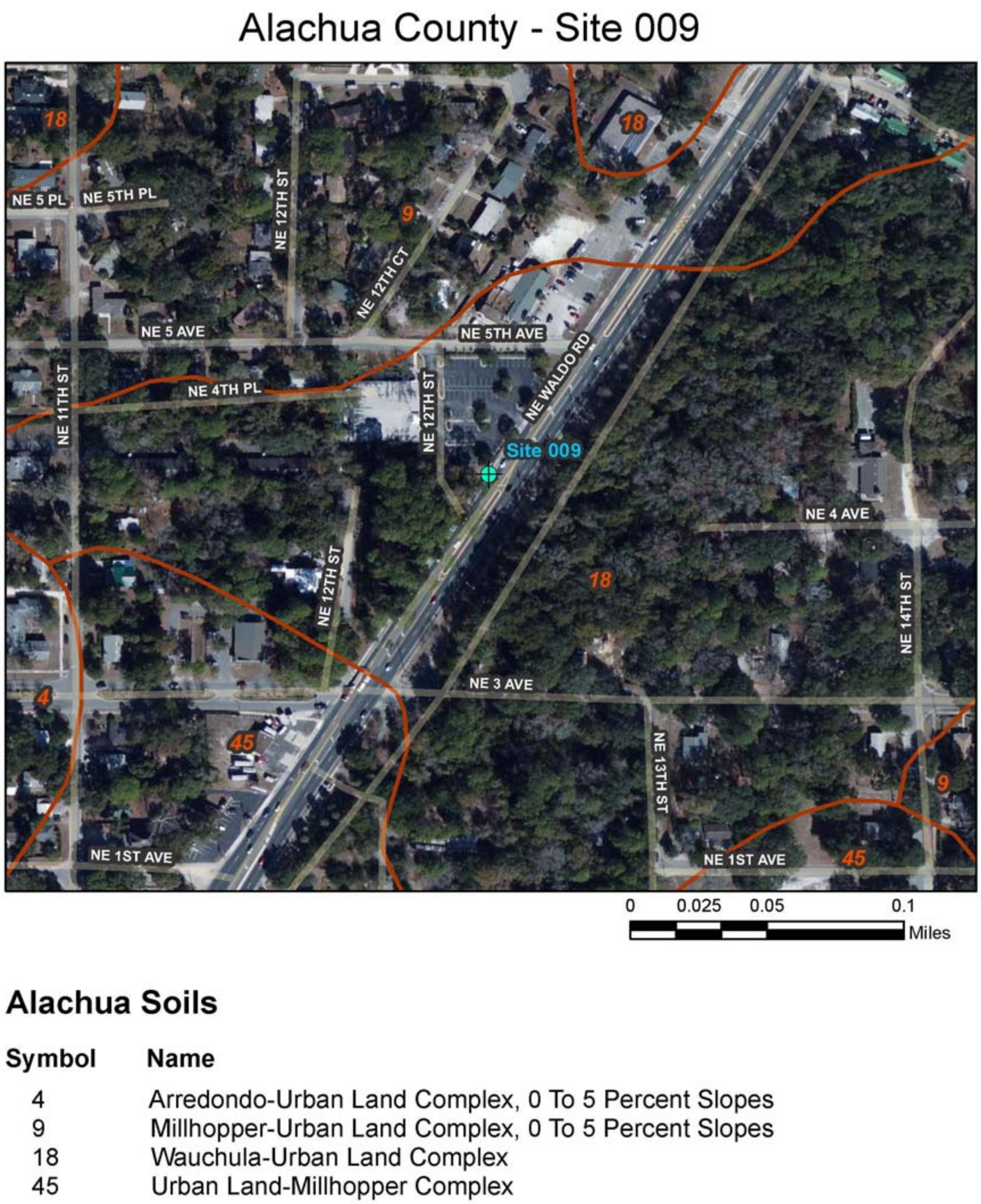
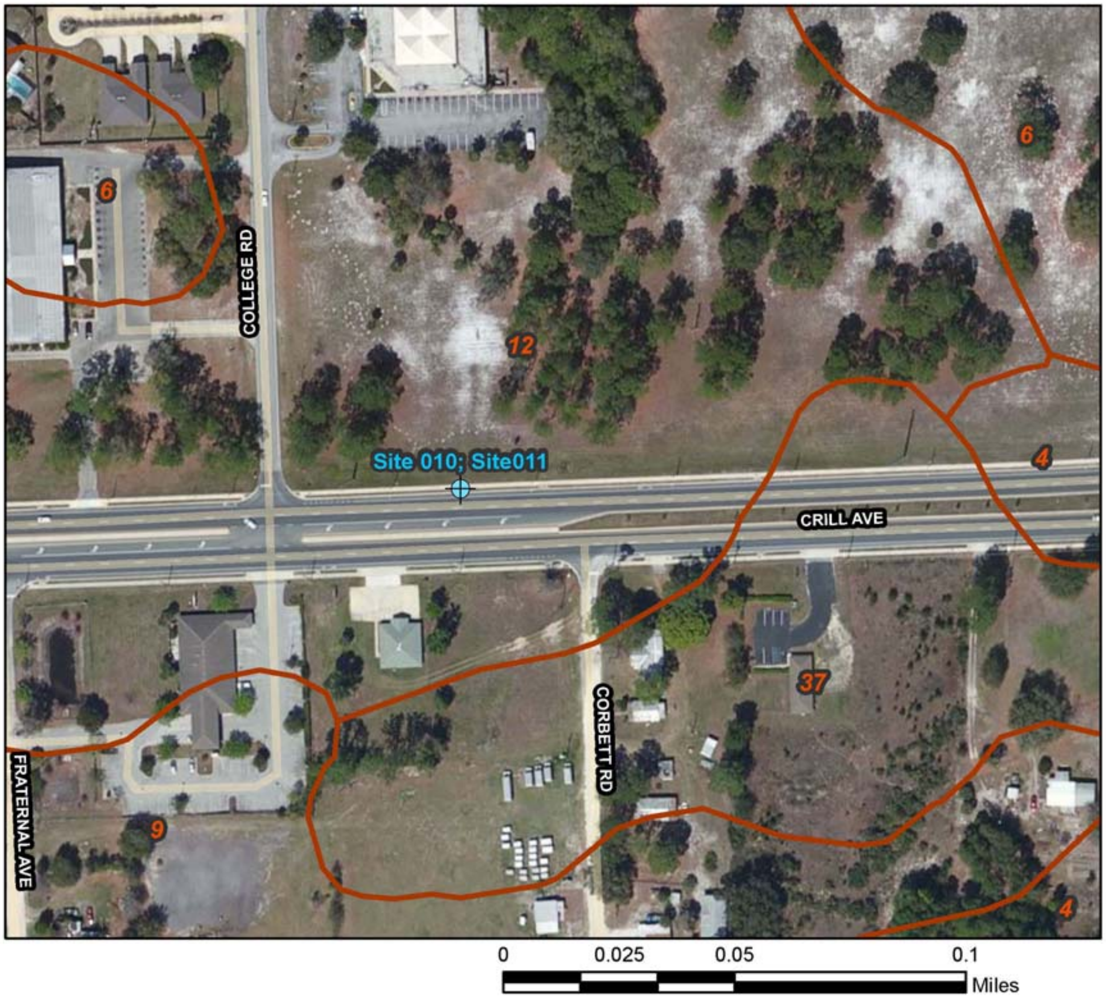


Figure D-8. Soil mapping for the Alachua County Site 009.

Putnam County - Site 010, Site 011



Putnam Soils

Symbol	Name
4	Zolfo Fine Sand
6	Tavares Fine Sand, 0 To 5 Percent Slopes
9	Pomona Fine Sand
12	Electra Fine Sand
37	Ona Fine Sand

Figure D-9. Soil mapping for the Putnam County Site 010 and 011.

Putnam County - Site 012

Putnam Soils

Symbol	Name
4	Zolfo Fine Sand
5	Placid Fine Sand, Depressional
6	Tavares Fine Sand, 0 To 5 Percent Slopes
19	Pomona Fine Sand, Depressional
37	Ona Fine Sand
99	Water

Figure D-10. Soil mapping for the Putnam County Site 012.

Okeechobee County - Site 013

Okeechobee Soils

Symbol	Name
9	Riviera Fine Sand
10	Ft. Drum Fine Sand
14	Myakka Fine Sand
25	Wabasso Fine Sand

Figure D-11. Soil mapping for the Okeechobee County Site 013.

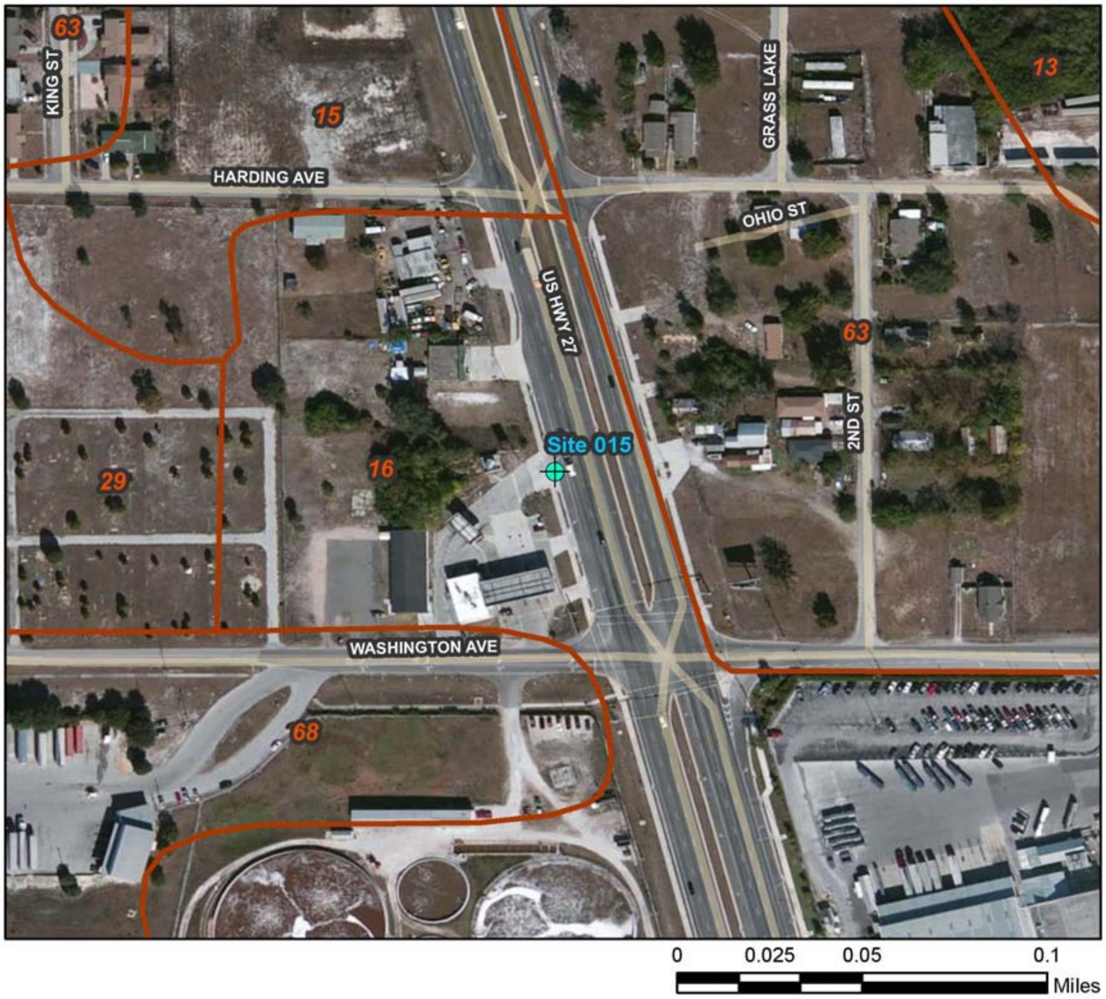
Indian River - Site 014

Indian River Soils

Symbol	Name
17	Quartzipsamments, 0 To 5 Percent Slopes
28	Eaugallie-Urban Land Complex
100	Waters Of The Atlantic Ocean

Figure D-12. Soil mapping for the Indian River County Site 014.

Polk County - Site 015



Polk Soils

Symbol	Name
13	Samsula Muck
15	Tavares Fine Sand, 0 To 5 Percent Slopes
16	Urban Land
29	St. Lucie Fine Sand, 0 To 5 Percent Slopes
63	Tavares-Urban Land Complex
68	Arents, 0 To 5 Percent Slopes

Figure D-13. Soil mapping for the Polk County Site 015.