The Development of a Decision Algorithm to Aid in the Selection of Pipe Material for Cross-Drainage Application

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science of Civil Engineering

Auburn, Alabama
May 07, 2016

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Abstract

The Code of Federal Regulations effectively limited allowable culvert materials to reinforced concrete pipe and corrugated steel pipe on Federal-aided projects. Angered by the exclusion, the plastics industry lobbied congress demanding equal consideration be given to plastic pipe. In 2012, the Moving Ahead for Progress in the 21st Century Act was signed into law. The Act granted states the authority to designate which culvert materials could be used on Federal-aided projects. Input or approval from the Federal Highway Administration would not be necessary.

The field performance of plastic pipes has not been thoroughly established. Yet, State departments are required to comply with Federal Regulations regarding plastic pipe. This thesis serves as a guideline to the Alabama Department of Transportation in the selection of culvert materials for cross-drainage application. The material properties, serviceability, and durability of the following culvert materials are critically analyzed: reinforced concrete, aluminized steel, galvanized steel, high density polyethylene, and polypropylene.

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List of Abbreviations

AASHTO	American Association of State Highway Transportation Officials
ACI	American Concrete Institute
ACPA	American Concrete Pipe Association
ADOT	Arizona Department of Transportation
ADS, Inc.	Advanced Drainage Systems, Incorporated
ALDOT	Alabama Department of Transportation
AOP	Aquatic Organism Passage
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BLM	Bureau of Land Management
CALTRANS	California Department of Transportation
CDOT	Colorado Department of Transportation
ConnDOT	Connecticut Department of Transportation
EPA	Environmental Protection Agency
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
GAO	General Accounting Office

GDOT	Georgia Department of Transportation
HALS	Hindered Amine Light Stabilizer
HDPE	High Density Polyethylene
LaDOTD	Louisiana Department of Transportation & Development
LRFD	Load Resistance Factor Design
MaineDOT	Maine Department of Transportation
MDOT	Maryland Department of Transportation
MnDOT	Minnesota Department of Transportation
MAP-21	Moving Ahead for Progress in the 21st Century Act
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCSPA	National Corrugated Steel Pipe Association
NYSDOT	New York Department of Transportation
ODOT	Oregon Department of Transportation
PCA	Portland Cement Association
pH	Hydrogen Ion Concentration
PPI	Plastics Pipe Institute
PPM	Parts Per Million
SCDOT	South Carolina Department of Transportation
VDOT	Virginia Department of Transportation
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation

Chapter 1: Introduction

1.1 Policy History

Appendix A to Subpart D of Part 635 of the Code of Federal Regulations effectively excluded plastic pipe as an allowable culvert material on Federal-aided projects. According to the Federal Highway Administration (FHWA), "When Appendix A was codified in 1974, the universe of available culvert materials was very limited and the state DOTs' experience with new culvert materials was equally limited" (CEnews 2006). Appendix A is shown in Table 1-1.

Subpart D General Material Requirements of Part 635 Construction and Maintenance sets forth conditions for the product and material selection on a Federal-aided highway project. As stated in the Subpart:

> Appendix A sets forth the FHWA requirements regarding (1) the specification of alternative types of culvert pipes, and (2) the number and types of such alternatives which must be set forth in the specifications for various types of drainage installations (2000).

Table 1-1: Appendix A to Subpart D of Part 635 (GPO 2004)

APPENDIX A TO SUBPART D OF PART 635—SUMMARY OF ACCEPTABLE CRITERIA FOR SPECIFYING TYPES OF CULVERT PIPES

Type of drainage installation	Alternatives required			AASHTO designations to be included with alternatives	Application	Remarks
	Yes	No	Number			
Cross drains under high-type pavement.[1]	....	X	....	....	Statewide	Any AASHTO-approved material.[2]
Other cross-drain installations.	X	....	3 minimum	M–170 and M–190.	......do	Do.[2]
Side-drain installations	X	....	......do	M–36	......do	Do.[2]
Special installation conditions.	....	X	....	....	Individual installation.	Specified to meet special conditions.
Special drainage systems (storm sewers, inverted siphons, etc.).	....	X	....	....	......do	Specified to meet site requirements.

[1] High-type pavement is generally described as FHWA construction type codes I, J, K, L, and plant mix and penetration macadam segments, respectively shown in the right-hand columns of type codes G and H having a combined thickness of surface and base of 7 in or more (or equivalent) or that are constructed on rigid bases.
[2] Types not included in currently approved AASHTO specifications may be specified if recommended by the State with adequate justification and approved by FHWA.

The plastics industry lobbied congress, and in 2005, The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users was signed into law by President George W. Bush. The Act guaranteed $244.1 billion in funding for highways, highway safety and public transportation, which made it the largest surface transportation investment in our Nation's history. Heavily favored by the plastics industry, the Act modified the former regulation and required equal consideration of alternative pipe material.

Section 5514 Competition for Specification of Alternative Types of Culvert Pipes now certified that "… the Secretary shall ensure that States provide for competition with respect to the specification of alternative types of culvert pipes through requirements that are commensurate with competition requirements for other construction materials" (Federal Register 2013). None of the 23 commenters, which included members of the American Concrete Pipe Association and the National Corrugated Steel Pipe Association, objected to the proposed changes after reviewing the Notice of Proposed Rulemaking.

The FHWA offered the following comment in reaction to the signing of The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users:

> With the deletion of Appendix A, contracting agencies will no longer be able to cite Appendix A as their basis for not considering other culvert alternatives. The FHWA does not have a specific policy requiring the specification, number, and types of alternative materials for any other highway construction material. ... Thus, it is important to treat culvert materials the same as other materials by removing Appendix A (CEnews 2006).

After expiring in 2009, the Act was extended ten times until it was finally replaced by the Moving Ahead for Progress in the 21st Century Act (MAP-21). This Act was signed into law by President Barack Obama in 2012 and guaranteed more than $105 billion in funding for surface transportation programs. MAP-21 granted States the autonomy or sole authority to choose which culvert materials to use on a Federal-aided highway project. The significance of the word autonomy is defined by the FHWA as follows:

> The use of the word "autonomy" in this section gives the State Departments of Transportation (State DOTs) and other direct recipients the sole authority and discretion to make a decision regarding culvert and storm sewer material types without any input or approval from the FHWA (Federal Register 2013).

Although State Departments of Transportation were no longer required to give equal consideration of alternative pipe material, the plastic pipe industry thrived. An increasing number of plastic pipes were now being chosen for transportation projects over the traditional concrete pipes and galvanized steel pipes. Thermoplastic pipe offers considerable advantages including a greater ease of transportation and handling and a greater resistance to corrosion and abrasion. However, most State departments have little experience with thermoplastic pipe and are hesitant to revise conventional selection policies.

Concrete pipe and galvanized steel pipe are tried-and-true culvert materials. Numerous laboratory tests and infield case studies have been performed. Furthermore, concrete pipes and galvanized steel pipes have successfully withstood the test of time. Unlike thermoplastic pipes, concrete pipes have a longer expected service life and a greater structural capacity. According to Robert French's report *Cross-Drain Pipe Material Selection Algorithm*, concrete pipe is "still recommended for the majority of applications under routes classified as arterials and highways by State agencies" (French 2013). At the county level, small-diameter thermoplastic pipes are primarily used for drainage beneath driveways in suburban neighborhoods.

1.2 Plastic Pipe for Highway Construction Project

In 2008, the Alabama Department of Transportation (ALDOT) contracted with Auburn University to investigate the field performance of plastic pipes in cross-drainage application. The Plastic Pipe for Highway Construction Project was assigned to former Auburn University students Robert French and Doug Abernathy. The project addressed three distinct research components: literature review, finite element modeling, and a field study.

According to Robert French's report *Cross-Drain Pipe Material Selection Algorithm,*

> Approximately 1,000 feet of thermoplastic pipes that were installed in an actual construction project in Auburn, Alabama were monitored for their structural performance and deflection measurements recorded through March 2013. In an effort to save time and money, a more time-efficient test method for testing future cross-drainage products under in-situ conditions was also developed as part of a separate project effort (French 2013).

The project was completed in 2011. Robert French completed the detailed report *Cross-Drain Pipe Material Selection Algorithm.* The report investigated the durability and structural limitations of different pipe material and concluded with final recommendations. "The primary objective of this research project was completed by investigating research results in conjunction with other State department policies to determine adequate performance limits for the most common cross-drainage pipe materials as well as thermoplastics" (French 2013).

ALDOT reviewed *Cross-Drain Pipe Material Selection Algorithm* and recommended that additional tasks and research be performed. As a result, Phase Two of The Plastic Pipe for Highway Construction Project was initiated with three key components on the agenda. ALDOT requested the continuation of monitoring the long-term plastic pipe performance at Beehive Road, the evaluation of real-world construction effects, and the development of a comprehensive specification or "decision tree" to aid in the selection of pipe material.

1.3 Research Objectives

The primary objective of this thesis research was to develop a practical selection algorithm that can be used by State and county highway engineers. The algorithm will determine the optimum type and class of pipe for cross-drainage application.

1.4 Scope and Methodology

The primary objective of this thesis research was achieved by integrating all of the research findings from the initial Plastic Pipe for Highway Construction Project and critically analyzing the material properties, serviceability, durability, and installation requirements, as well as case studies and reports for the following culvert material:

- Class II, III, IV, and V Precast Reinforced Concrete
- Corrugated High Density Polyethylene
- Corrugated Polypropylene
- Corrugated Aluminum
- Corrugated Aluminized Steel
- Corrugated Galvanized Steel

This critical analysis laid the groundwork for weighing the considerations between plastic pipe, concrete pipe, and metal pipe for a specific highway construction project. *The Specification for Culvert Material Selection* was developed from the conclusions reached by this comparison and by the initial input parameters defined in *Cross-Drain Pipe Material Selection Algorithm.* The purpose of *The Specification for Culvert Material Selection* was not only to assist highway engineers with choosing the optimum solution but to make and defend contract decisions. *The Specification for Culvert Material Selection* may be found in Appendix B.

1.5 Report Organization

Chapter 2 provides a thorough literature review. The review is a compilation of information collected from countless sources including: State Departments of Transportation, the Transportation Research Board, the University of South Carolina, Colorado, and South Florida, the Plastics Pipe Institute, the National Corrugated Steel Pipe Association, the American Concrete Pipe Association, the American Society for Testing and Materials, and the American Association of State Highway and Transportation Officials. The literature review focused on a detailed evaluation of each culvert material type based on durability concerns, service life expectations, and installation requirements. A summarized tabulated comparison of each culvert material concludes the chapter.

Chapter 3 provides the decision process and pertinent information that was used to create *The Specification for Culvert Material Selection.* Chapter 4 provides several demonstrations proving the effectiveness of *The Specification for Culvert Material Selection*. The demonstrations represent culvert installation projects throughout the United States. Chapter 5 provides a final summary and conclusions formulated from this thesis research. Final recommendations of suitable culvert material for cross-drainage application conclude the chapter. Appendix A provides 13 specific design parameters recommended by the American Society of Civil Engineers Task Force on Hydraulics of Culvert as "Attributes of a Good Highway Culvert". Appendix B provides *The Specification for Culvert Material Selection*.

Chapter 2: Literature Review

2.1 Definition of a Culvert

Culverts function similarly to bridges, but rarely receive the same level of attention. Culverts allow the passage of water beneath a roadway, protect against erosion and flooding, enhance the safety of pedestrian traffic, and allow the passage of farm animals. According to the National Oceanic and Atmospheric Administration, culverts are especially popular for small streams or where building a bridge would be too expensive or impractical. An example of a double box culvert is shown in Figure 2-1.

Culverts exceeding a 20-foot span width are classified as bridges in the National Bridge Inspection Standards and must receive routine inspections in accordance with National Bridge Inspection Standards requirements. As stated in the FHWA *Hydraulic Design of Highway Culverts,* "Maintenance costs for culverts may result from channel erosion at the inlet and outlet, erosion and deterioration of the culvert invert, sedimentation, ice and debris building, and embankment repair in case of overtopping" (2012).

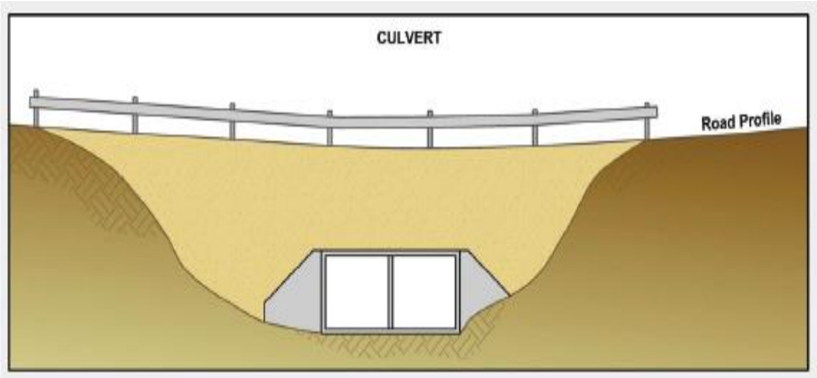


Figure 2-1: Example of a Culvert (FHWA 2012)

Culverts used for cross-drainage application were the sole focus of this thesis. The primary function of a cross-drain is to convey the flow of surface water across a highway. A culvert used for cross-drainage application must support construction traffic, highway traffic, and earth loads. Therefore, the design of a culvert must include both hydraulic and structural design. The ideal placement for a cross drain culvert is on a straight alignment with constant slope. Variations in alignment should only be used to accommodate unusual conditions as abrupt changes in direction or slope may negatively affect the hydraulic efficiency and lead to unforeseen maintenance issues. Figure 2-2 illustrates proper and improper culvert alignment.

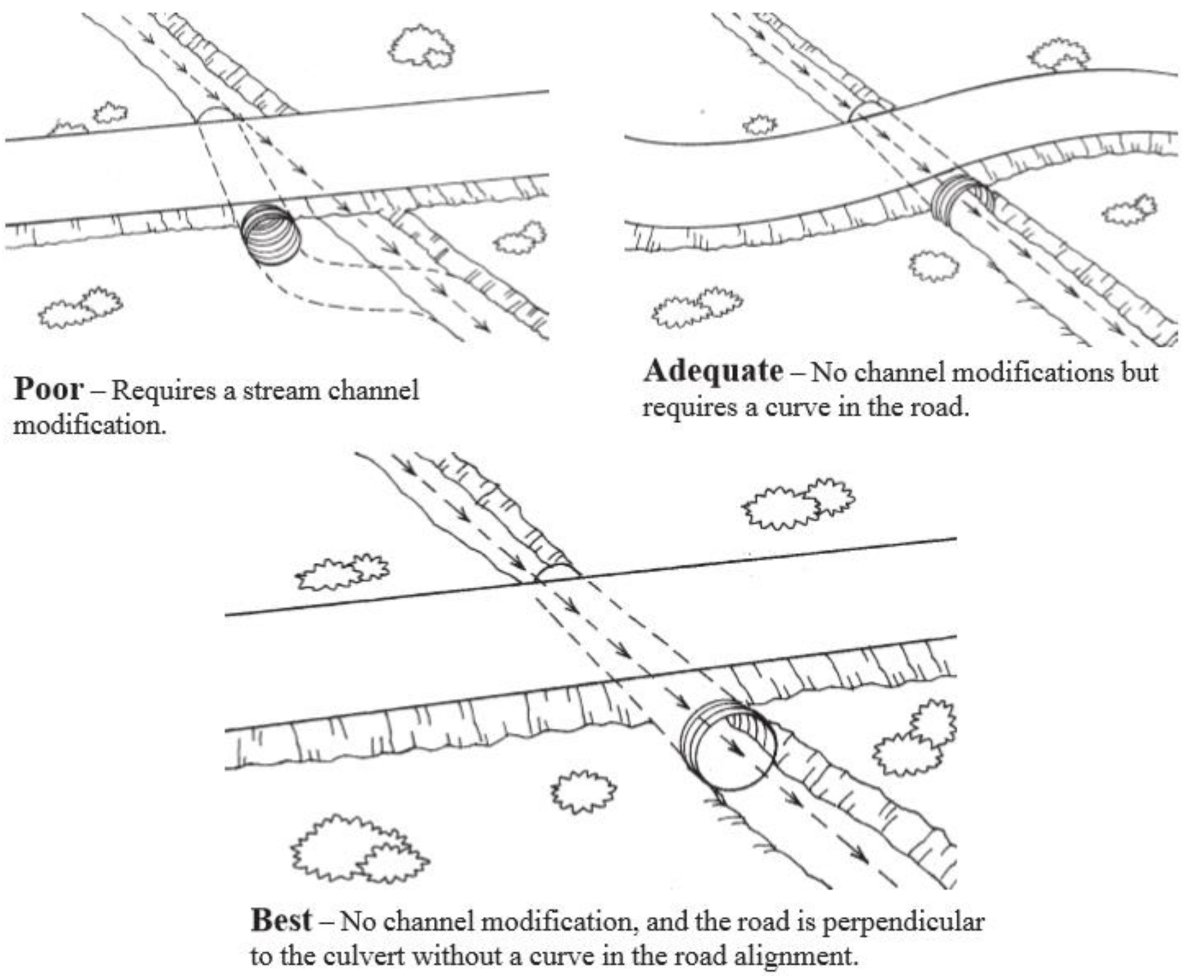


Figure 2-2: Culvert Alignment beneath a Roadway (Keller 2003)

2.1.1 Typical Culvert Shapes

Culverts are available in a wide range of shapes and configurations. The most common culvert shape is circular, but other typical shapes include pipe arch, elliptical, box, frame, and multiple barrel. Culvert selection factors include roadway profiles, channel characteristics, flood damage elevations, construction and maintenance costs, and estimates of service life (FHWA 2012).

As described in the Wisconsin Department of Transportation (WisDOT) *Structure Inspection Manual*, typical culvert shapes are defined below (2011).

- Circular – This is the most common culvert shape. Although hydraulically and structurally efficient, circular culverts can reduce a stream's width and circular culverts are more prone to clogging than any other shape.

- Pipe Arch – The pipe arch culvert is used when the distance from the stream bottom to the roadway is limited. The culvert is arched on top and flattened on the bottom. Pipe arch culverts are prone to clogging.

- Elliptical – Elliptical culverts have the same advantages and disadvantages as pipe arch culverts.

- Box – Box culverts are adaptable for many site conditions. Square or rectangular in shape, box culverts always have a floor ensuring the natural stream bed is covered.

- Frame – Similar to box culverts, but frame culverts do not have a floor allowing the natural stream bed to be exposed.

- Multiple Barrel – Multiple barrel or cell culverts are a series of pipes, arches, or boxes placed side by side. Multiple barrel culverts are commonly used when the distance from the stream bottom to the roadway is limited. The major disadvantage to using multiple barrel culverts is that waterway debris is easily snagged by the cell walls or soil between the openings.

2.1.2 Culvert Material

Section 12 of the American Association of State Highway and Transportation Official's (AASHTO) *Load and Resistance Factor Design* (*LRFD) Bridge Design Specifications* identifies four materials approved for use as circular pipe for buried structures.

- Aluminum Pipe (ASTM B745)
- Precast Concrete Pipe (ASTM C76)
- Steel Pipe (ASTM A760)
- Thermoplastic Pipe (AASHTO M294)

In 2014, The National Cooperative Highway Research Program (NCHRP) surveyed transportation agencies across North America. One of the questions asked was, "Which of the following pipe material types does your agency currently use or is considering for use?" Based on the responses shown in Figure 2-3, concrete is the most commonly used culvert material in North America with galvanized steel and high density polyethylene following closely behind.

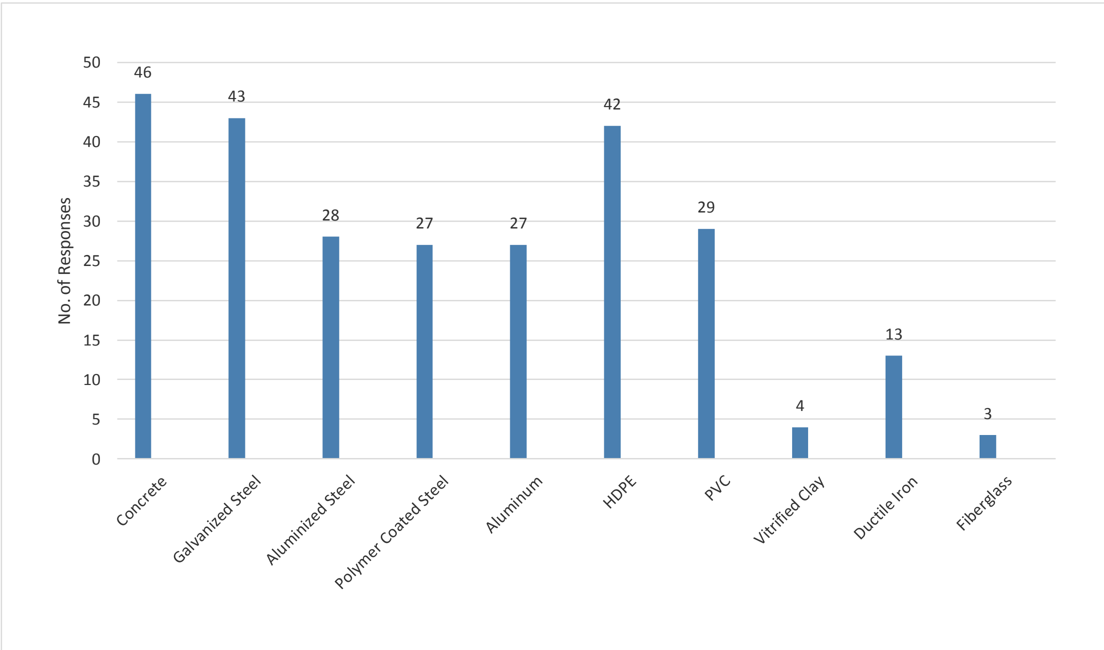


Figure 2-3: Pipe Material Types in Use or Being Considered for Use (NCHRP 2015)

2.1.2.1 Reinforced Concrete

According to the American Concrete Pipe Association (ACPA), concrete pipe has been used in the United States for over a century. The article, “Century Concrete Pipe Does Exist” written by A. Grant Lee of the Canadian Concrete Pipe Association, claims that the earliest recorded use of concrete pipe in the United States was constructed between 1840 and 1842 in Mohawk, New York, at the home of General Francis Elias Spinner. The concrete pipes were used to convey domestic sewage to the Erie Canal.

> In 1982 (140 years after installation), the pipeline was exhumed and found to be in excellent condition, and still functioning. Details about America’s earliest sewers are rare, but it is known that concrete pipe was used for sanitary sewers to control outbreaks of Yellow Fever in the mid-1800s (Lee 2011).

It was not until 1867 that the idea for reinforced concrete was patented by a French gardener named Joseph Monier. Frustrated with the brittleness of clay, Monier began strengthening his cement flower pots with wire mesh. Figure 2-4 illustrates Monier’s initial design for a reinforced flower pot. He patented the idea in 1867 and debuted his invention that same year at the Paris Exposition. According to Britannica, Monier extended the application to other engineering structures, such as railway ties (sleepers), pipes, floors, arches, and bridges.

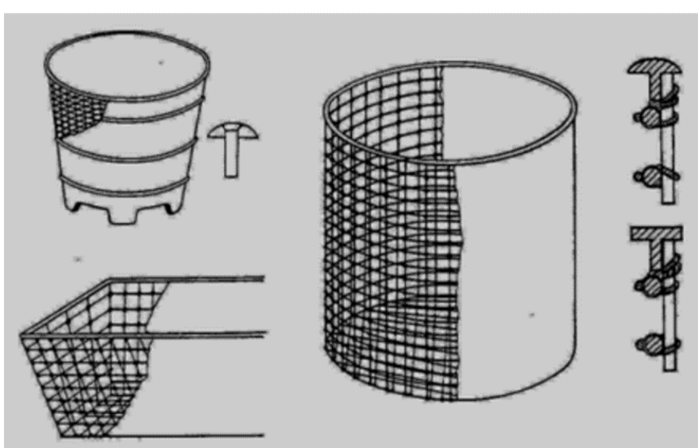


Figure 2-4: Monier’s Design for a Reinforced Flower Pot (Barbisan 2005)

The basic materials that are used to create concrete are Portland cement, aggregates, and water. As the Portland cement mixes with water, a paste begins to form that coats the aggregates. The paste then hardens and gains strength through a chemical reaction known as hydration. This paste will eventually form what is known as concrete. However, the process is not as simple as mixing several materials together. Improper proportioning can lead to an inferior product. According to the Portland Cement Association's (PCA) article, "How Concrete is Made",

> A mixture that does not have enough paste to fill all the voids between the aggregates will be difficult to place and will produce rough surfaces and porous concrete. A mixture with an excess of cement paste will be easy to place and will produce a smooth surface; however, the resulting concrete is not cost-effective and can more easily crack (n.d.).

There are five basic methods for producing concrete pipe and these methods are differentiated based on the concrete mix. Wet casting is the most common method used to manufacture large diameter pipe. Wet casting uses a high-slump concrete mix with a slump typically less than four inches. The other four methods include: centrifugal/ spinning, dry cast, packerhead, and tamp-entail. These methods use a dry concrete mix.

Concrete may be precast or cast-in-place. Precast concrete is manufactured in a plant then transported to the construction site. Cast-in-place concrete is manufactured directly at the construction site. Precast concrete is typically more efficient and timesaving because weather will not delay the manufacturing process. "Precast concrete is more popular for smaller, cross-drain pipe applications because it can be manufactured in a controlled environment and save significant installation time" (PCA 2013). Therefore, cast-in-place concrete shall not be considered in this thesis.

Reinforced concrete culverts must meet the requirements of American Society for Testing and Materials (ASTM) C76 (or AASHTO M170) *Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe*. Concrete pipe is specified according to strength class and inside diameter. The five strength classes are identified as Class I, Class II, Class III, Class IV, and Class V and correspond to varying D-loads. This correlation is shown in Table 2-1.

Table 2-1: Required D-Load Capacity per Strength Class (ASTM C76 2015)

Class	0.01-Inch Crack D-Load (lbs/ft/ft)	Ultimate D-Load (lbs/ft/ft)
I	800	1200
II	1000	1500
III	1350	2000
IV	2000	3000
V	3000	3750

Reinforced concrete culverts must also meet the requirements of ASTM C655 *Standard Specification for Reinforced Concrete D-Load Culvert, Storm Drain, and Sewer Pipe* when the culvert is designed for specific D-loads. According to ASTM C655, strength of a reinforced concrete culvert is designated as follows:

> The design strength designation of the pipe shall be the D-load to produce the 0.01-in. crack. The relationship of ultimate strength D-load to the design strength D-load shall be determined using a factor of 1.5 for design strength designations up to 2000 lbf/ft·ft of diameter, a factor varying in linear proportions from 1.5 to 1.25 for design strength designations from 2000 through 3000, and a factor of 1.25 for design strength designations in excess of 3000 (2015).

Table 2-2: Standard Designated Inside Diameter, in. (ASTM C655 2015)

12	24	36	60	84	108	132
15	27	42	66	90	114	138
18	30	48	72	96	120	144
21	33	54	78	102	126	

2.1.2.2 Corrugated Steel

In 1895, two residents of Indiana, E. Stanley Simpson and James Watson, sent a patent application to Washington, D.C. for their invention of a corrugated metal culvert. Watson wanted to create a corrugated sheet-metal pipe to replace the existing vitrified tile that was currently being used as a culvert material. Vitrified tile was very heavy, which required the material to be manufactured in short lengths for ease of transportation. As horse drawn wagons were the sole transportation of that time, vitrified tile culverts were never manufactured longer than 20 feet.

As stated in the article "There are Interesting Inventions," the two inventors had difficulty finding investors despite the widespread consensus that the product was strong, durable and had a long life expectancy. Several of the engineers in Crawfordsville doubted the new invention so strength tests were performed. "Steam tractors and even an elephant from a visiting circus tested the strength of the Simpson-Watson invention" (Baldwin 2014). The installation of Simpson's and Watson's culvert is shown in Figure 2-5.

Figure 2-5: Installation of Corrugated Metal Culvert (Baldwin 2014)

Corrugated steel culverts must meet the requirements of ASTM A760 (or AASHTO M36) *Standard Specification for Corrugated Steel Pipe, Metallic-Coated, for Sewers and Drains*. Corrugated steel pipe is classified based on the pipe's cross-sectional geometry and type of corrugations. An example of corrugated steel pipe sizes is shown in Table 2-3. The classifications considered in this thesis include: Type I, Type IA, Type IR, and Type IS. According to ASTM A760, Type I, Type IA, Type IR, and Type IS are applicable to pipe having a full circular cross section.

Type I is fabricated with annular (circumferential) or helical corrugations with a single thickness of corrugated sheet. Type IA is fabricated with helical corrugations and lock seams with an outer shell of corrugated sheet and an inner liner of smooth sheet. Type IR is fabricated with helical ribs projecting outwardly with a single thickness of smooth sheet. Type IS is fabricated with helical ribs projecting outwardly with metallic coated steel inserts.

Table 2-3: Corrugated Steel Pipe Sizes (ASTM A760 2015)

Nominal Inside Diameter		Corrugation Sizes[A]				Ribbed Pipe			Minimum Outside Circumference[B]	
in.	mm	1½ by ¼ in. [38 by 6.5 mm]	2⅔ by ½ in. [68 by 13 mm]	3 by 1 in. [75 by 25 mm]	5 by 1 in. [125 by 25 mm]	¾ by ¾ by 7½ in. [19 by 19 by 190 mm]	¾ by 1 by 11½ in. [19 by 25 by 292 mm]	¾ by 1 by 8½ in. [19 by 25 by 216 mm]	in.	mm
4	100	X							11.4	264
6	150	X							17.7	441
8	200	X							24.0	598
10	250	X							30.2	755
12	300	X	X						36.5	912
15	375	X	X			X[C]			46.0	1148
18	450	X	X			X	X	X	55.4	1383
21	500		X			X	X	X	64.8	1620
24	600		X			X	X	X	74.2	1854
27	675		X			X	X	X	83.6	2091
30	750		X			X	X	X	93.1	2483
33	825		X			X	X	X	102.5	2561
36	900		X	X	X	X	X	X	111.9	2797
42	1050		X	X	X	X	X	X	130.8	3269
48	1200		X	X	X	X	X	X	149.6	3739
54	1350		X	X	X	X	X	X	168.4	4209
60	1500		X	X	X	X	X	X	187.0	4675
66	1650		X	X	X	X	X	X	205.7	5142
72	1800		X	X	X	X	X	X	224.3	5609
78	1950		X	X	X	X	X	X	243.0	6075
84	2100		X	X	X	X	X	X	261.7	6542
90	2250			X	X	X	X	X	280.3	7008
96	2400			X	X	X	X	X	299.0	7475
102	2550			X	X	X	X	X	317.6	7941
108	2700			X	X	X	X	X	336.3	8408
114	2850			X	X	X		X	355.0	8874
120	3000			X	X	X		X	373.6	9341
126	3150			X	X			X	392.3	9807
132	3300			X	X			X	410.9	10274
138	3450			X	X			X	429.6	10740
144	3600			X	X			X	448.3	11207

[A]An" X" indicates standard corrugation sizes for each nominal diameter of pipe.
[B]Measured in valley of annular corrugations. Not applicable to helically corrugated pipe.
[C]Additional size for Type IS pipe.

2.1.2.3 Corrugated Aluminum

Aluminum was not identified as an elemental metal until 1807. Copper, bronze, iron, and steel have been in use for thousands of years. Compared to these metals, aluminum is relatively young. First refined in 1825, aluminum was considered a luxurious metal more expensive than gold. According to The Aluminum Association's article *History of Aluminum*, "Napoleon III, the first President of the French Republic, served his state dinners on aluminum plates. Rank-and-file guests were served on dishes made with gold or silver". It was not until the late 1800s that the development of commercial production of aluminum became affordable.

In 1965, Purdue University published the report *Aluminum Pipe Culverts* at the request of the Indiana State Highway Department. The purpose of the report was to provide general practices and policies regarding the use of corrugated aluminum culvert pipe. "Although aluminum has been used extensively in the construction industry for several decades," the report states, "its advent into the culvert pipe market is relatively new." This fact remains true as little research is available for aluminum culverts compared to the vast amount of documented studies available on reinforced concrete culverts and corrugated steel culverts.

According to Figure 2-3, the top five most widely used culvert materials in North America include: concrete, galvanized steel, high density polyethylene, polyvinyl chloride, and aluminized steel. Aluminum is considered the sixth most widely used culvert material by transportation agencies along with polymer coated steel. The only culvert materials that were used less than aluminum are vitrified clay, ductile iron, and fiber glass. The results shown in Figure 2-3 were obtained from a survey conducted in 2014.

Corrugated aluminum culverts must meet the requirements of ASTM B745 (or AASHTO M196) *Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains*. Corrugated aluminum pipe is classified similar to corrugated steel pipe. An example of corrugated aluminum pipe sizes is shown in Table 2-4. The classifications considered in this thesis include: Type I, Type IA, and Type IR. According to ASTM B745, Type I, Type IA, and Type IR are applicable to pipe having a full circular cross section. However, each Type has different corrugations. Type I is fabricated with annular or helical corrugations. Type I has only a single thickness of corrugated sheet. Type IA pipe has an outer shell of corrugated sheet and an inner liner of uncorrugated sheet. Type IR is fabricated with helical ribs projecting outwardly. Type IR pipe has only a single thickness of un-corrugated sheet.

Table 2-4: Corrugated Aluminum Pipe Sizes (ASTM B745 2015)

Nominal Inside Diameter		Corrugation Sizes[A]					Minimum Outside Circumference[B]	
in.	mm	1½ by ¼ in. 38 by 6.5 mm	2⅔ (by ½ in. 68 by 13 mm	3 by 1 in. 75 by 25 mm	6 by 1 in. 150 by 25 mm	Ribbed Pipe[C]	in.	mm
4	100	X					11.4	284
6	150	X					17.7	441
8	200	X					24.0	598
10	250	X					30.2	755
12	300		X				36.5	912
15	375		X			X	46.0	1148
18	450		X			X	55.4	1383
21	525		X			X	64.8	1620
24	600		X			X	74.2	1854
27	675		X			X	83.6	2091
30	750		X	X		X	93.1	2325
33	825		X	X		X	102.5	2561
36	900		X	X		X	111.9	2797
42	1050		X	X		X	130.8	3269
48	1200		X	X	X	X	149.6	3739
54	1350		X	X	X	X	168.4	4209
60	1500		X	X	X	X	187.0	4675
66	1650		X	X	X	X	205.7	5142
72	1800		X	X	X	X	224.3	5609
78	1950			X	X	X	243.0	6075
84	2100			X	X	X	261.7	6542
90	2250			X	X		280.3	7008
96	2400			X	X		299.0	7475
102	2550			X	X		317.6	7941
108	2700			X	X		336.3	8408
114	2850			X	X		355.0	8874
120	3000			X			373.6	9341

[A] An "X" indicates standard corrugation sizes for each nominal diameter of pipe.
[B] Measured in valley of annular corrugations. Not applicable to helically corrugated pipe.
[C] Rib sizes ¾ by ¾ by 7½ in. [19 by 19 by 190 mm] and ¾ by 1 by 11½ in. [19 by 25 by 292 mm].

2.1.2.4 High Density Polyethylene

The discovery of polyethylene was purely accidental. In 1933, two British chemists, Eric Fawcett and Reginald Gibson, were working with ethylene at high pressures when they created a solid form of polyethylene. According to the British Broadcasting Company article *History of the World: The First Piece of Polyethylene*, polyethylene proved to be a timely breakthrough.

> By the start of World War II, large plants were busy producing large quantities of this new substance which proved invaluable to the war effort. Polyethylene was used as an insulating material for radar cables during World War II, and the substance was a closely guarded secret. Its availability gave Britain an advantage in long-distance air warfare, most significantly in the Battle of the Atlanta against the German submarines which threatened to starve Britain of food (2012).

In 1953, German chemists Karl Ziegler and Erhard Holzkamp invented high density polyethylene. In 1954, the Phillips Petroleum Company introduced high density polyethylene under the brand name Marlex® polyethylene. Marlex® polyethylene was used by Wham-O, an American toy manufacturer, to develop a large ring of plastic tubing that would eventually be inducted into the National Toy Hall of Fame.

> The first Hula-Hoops were made from a patented plastic called Marlex and sold for $1.98. Amazingly, twenty million hoops were sold in the very first 6 months of production which ignited the Hula-Hoop craze of the 1950's. And in the first two years, we sold over a staggering 100 million of them! (Wham-O, n.d.)

According to the Plastics Technology article *No. 3 - HDPE*, "It was this fad that led to large-volume manufacturing of extruded HDPE pipe for high-performance applications such as natural-gas distribution, handling mine tailings, and sewer lines" (2005). In time, Marlex® also became the preferred plastic for baby bottles and for safe, shatterproof food containers (ACS 1999).

In 1967, the first corrugated polyethylene pipe was commercially produced in the United States. The pipe was 4-inches in diameter. According to the article, "A Brief History of the Development and Growth of the Corrugated Polyethylene Pipe Industry in North America" written by James B. Goddard, "The intended market was agricultural drainage to increase crop yields, replacing clay tile, which dominated the market at that time, but was cumbersome and costly to install" (Goddard 2011).

In the early 1970s, polyethylene pipes were installed as highway underdrains by the Iowa Department of Transportation and the Georgia Department of Transportation. Georgia was the first department of Transportation to include corrugated polyethylene in their standard specifications. "In September of 1981, the Ohio Department of Transportation installed the first known corrugated polyethylene cross-drain culvert under a state highway" (Goddard 2011). "Since then, more high density polyethylene pipes have been used for drainage applications than all other types of plastic pipe combined" (Gabriel 2008).

High density polyethylene is a thermoplastic material composed of carbon and hydrogen atoms. Polyethylene is formed when methane gas is converted into ethylene. Common polyethylene materials include high density polyethylene, medium density polyethylene, and low density polyethylene. Medium density polyethylene is typical for low-pressure gas pipelines. Low density polyethylene is mainly used for small-diameter water-distribution pipes. High density polyethylene has greater density and strength than medium density polyethylene and low density polyethylene due to the branching of its molecular chain. A comparison of the three common polyethylene materials is shown in Table 2-5.

Table 2-5: Density of Polyethylene Materials (Gabriel n.d.)

Polyethylene Material	Density
High Density Polyethylene	0.941 g/cm^3 $\leq$ density $\leq$ 0.965 g/cm^3
Medium Density Polyethylene	0.926 g/cm^3 $\leq$ density $\leq$ 0.940 g/cm^3
Low Density Polyethylene	0.910 g/cm^3 $\leq$ density $\leq$ 0.925 g/cm^3

According to the article *History and Physical Chemistry of HDPE*, "The property characteristics of polyethylene depend upon the arrangement of the molecular chains".

> The number, size and type of these side chains determine, in large part, the properties of density, stiffness, tensile strength, flexibility, hardness, brittleness, elongation, creep characteristics, and melt viscosity that are the results of the manufacturing effort and can occur during service performance of polyethylene pipe (Gabriel n.d.).

According to *History and Physical Chemistry of HDPE*, "Density, molecular weight, and molecular weight distribution dominate the resin properties that influence the manufacture of the polyethylene pipe and the subsequent performance of the pipe". The effects of density, melt index, and molecular weight distribution are shown in Table 2-6.

High density polyethylene is a viscoelastic material. Viscoelastic materials exhibit a nonlinear stress-strain relationship and are dependent on time. Steel and concrete, on the other hand, are both elastic materials. Elastic materials have a linear stress-strain relationship and will return to their original shape after unloading. A perfect example of viscoelastic behavior can be seen by Silly Putty. According to the article *The Nature of Polyethylene Pipe Failure*,

> If this material is pulled apart quickly, it breaks in a brittle manner. If, however, it is pulled slowly apart the material behaves in a ductile manner and can be stretched almost indefinitely. Decreasing the temperature of Silly Putty decreases the stretching rate at which it becomes brittle. Plastic designers are well aware that, in the short term, many polymers can endure strain levels of 300% or more. However, for long-term performance, the window for design strain is massively smaller (O'Connor 2011).

Table 2-6: Effects of Density, Melt Index, and Molecular Weight Distribution (Gabriel n.d.)

EFFECTS OF CHANGES IN DENSITY, MELT INDEX AND MOLECULAR WEIGHT DISTRIBUTION			
Property	**As Density Increases, Property:**	**As Melt Index Increases, Property:**	**As Molecular Weight Distribution Broadens, Property:**
Tensile Strength (At Yield)	Increases	Decreases	
Stiffness	Increases	Decreases Slightly	Decreases Slightly
Impact Strength	Decreases	Decreases	Decreases
Low Temperature Brittleness	Increases	Increases	Decreases
Abrasion Resistance	Increases	Decreases	
Hardness	Increases	Decreases Slightly	
Softening Point	Increases		Increases
Stress Crack Resistance	Decreases	Decreases	Increases
Permeability	Decreases	Increases Slightly	
Chemical Resistance	Increases	Decreases	
Melt Strength		Decreases	Increases
Gloss	Increases	Increases	Decreases
Haze	Decreases	Decreases	
Shrinkage	Decreases	Decreases	Increases

Polyethylene is prone to slow crack growth through the pipe wall. According to the report *Plastic Pipe Failure, Risk, and Threat Analysis*, “Slow crack growth failures occur over long periods of time at relatively low loads below the yield point of the material and are characterized by brittle fractures which exhibit very little material flow or deformation” (2009). ASTM F2136 *Standard Test Method for Notched, Constant Ligament-Stress (NCLS) Test to Determine Slow-Crack-Growth Resistance of HDPE Resins or HDPE Corrugated Pipe* may be used to determine the susceptibility of high density polyethylene pipe. Figure 2-6 shows an optical micrograph of the slow crack growth failure process in polyethylene.

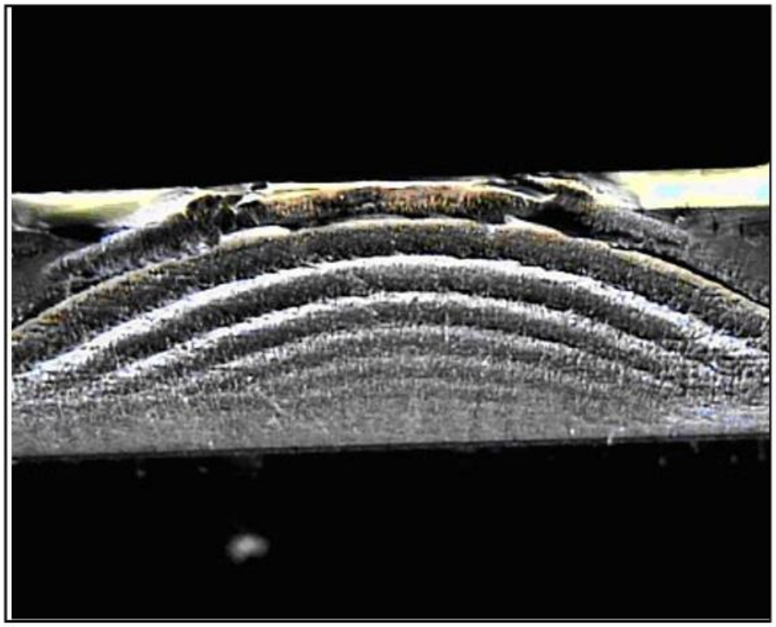


Figure 2-6: Slow Crack Growth Failure Morphology (Gas Technology Institute 2009)

As described in *The Nature of Polyethylene Pipe Failure*,

> These cracks can initiate at microscopic stress-raising flaws, inherent in the basic pipe product or, more likely, from defects. These brittle mechanical failures are typically slit-type fractures that lie parallel to the pipe's extrusion direction. Circumferential hoop stress in the pipe wall is the driving force for crack opening (O'Connor 2011).

In 2006, The University of South Carolina published the report *Specifications for Culvert Pipe used in SCDOT Highway Applications*. The purpose of the report was to improve the field performance of reinforced concrete pipe, corrugated aluminum pipe, and high density polyethylene pipe used in roadway applications. In an effort to determine the field performance of high density polyethylene pipe, 45 high density polyethylene pipes were installed and monitored in sideline and driveway applications. Results concluded that high density polyethylene is a suitable pipe material. However, several of the pipes had cracks, localized bulges, and excess deformations. As noted in the report,

> Installation problems such as poor preparation of bedding soils, inappropriate backfill material, and inadequate backfill cover contributed to the excessive deflection and observed internal cracking in pipes with noted damage. Appropriate installation procedures are essential to achieving high quality performance (Gassman 2006).

Field investigations proved that the performance of flexible, high density polyethylene pipe is significantly dependent on installation technique. Recommendations to improve the performance of high density polyethylene pipe in South Carolina include:

1. Training maintenance crews in the laying of plastic pipe
2. Following ASTM and AASHTO installation procedures
3. Inspecting the pipes after installation
4. Developing guidelines for pipe product approval

In 2009, the Texas Parks and Wildlife Department was forced to replace two miles of high density polyethylene pipe after two sections of 60-inch and 48-inch diameter pipe had collapsed under 10-to-17 feet of earth fill. The repair cost $3.3 million and delayed the project by more than a year. Investigators found that 11,000 feet of pipe had questionable structural integrity. The high density polyethylene pipe was replaced with reinforced concrete pipe. Dr. Patricia D. Galloway, CEO of Pegasus Global Holdings Inc., released the following statement in the article *HDPE Pipe Failure at Texas Fish Hatchery offers Costly Lessons*:

> Because corrugated HDPE pipe is a flexible material, not an independent structure like RCP, up to 90 percent of its successful installation is driven by the soil envelope surrounding it. It's imperative that the design firm and the installing engineers account for a wide range of pipe-soil variables when dealing with HDPE, ranging from material properties to installation conditions to external loads, any of which can lead to catastrophic failure (2010).

High density polyethylene culverts must meet the requirements of AASHTO M252 *Standard Specification for Corrugated Polyethylene Drainage Pipe* or AASHTO M294 *Standard Specification for Corrugated Polyethylene Pipe, 300- to 1500-mm Diameter*. Section 7.4 of AASHTO M294 2008 requires high density polyethylene pipe to have a minimum pipe stiffness as shown in Table 2-7 at five percent deflections.

According to AASHTO M294, corrugated polyethylene pipe is classified as follows:

- Type C – This pipe shall have a full circular cross section, with a corrugated surface both inside and outside. Corrugations shall be annular.
- Type CP – This pipe shall be Type C with perforations.
- Type S – This pipe shall have a full circular cross section, with an outer corrugated pipe wall and a smooth inner linear. Corrugations shall be annular.
- Type SP – This pipe shall be Type S with perforations.
- Type D – This pipe shall consist of an essentially smooth inner wall/liner braced circumferentially or spirally with projections or ribs joined to an essentially smooth outer wall.
- Type DP – This pipe shall be Type D with perforations.

Table 2-7: Pipe Stiffness per Diameter (AASHTO M294 2008)

Diameter		Pipe Stiffness	
mm	in	kPa	psi
300	12	345	50
375	15	290	42
450	18	275	40
525	21	260	38
600	24	235	34
675	27	205	30
750	30	195	28
900	36	150	22
1050	42	140	20
1200	48	125	18
1350	54	110	16
1500	60	95	14

AASHTO M294 requires testing for stress crack resistance in accordance with ASTM F2136 with one modification. According to Section 9.5.1, "The applied stress for the NCLS test shall be 4100 kPa (600 psi)" (2008). AASHTO M294 also requires testing for pipe stiffness in accordance with ASTM D2412 *Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading*. The Parallel-Plate Loading Test determines the load-deflection characteristics of plastic pipe. As defined in the Standard, pipe stiffness is "the value obtained by dividing the force per unit length of specimen by the resulting deflection in the same units at the prescribed percentage deflection" (2011).

The pipe stiffness can be used to calculate approximate deflection under earth loads. The modified Spangler equation shown below can be used to approximate deflections. "Pipe stiffness also relates to handling and installation characteristics of a pipe during the very early stages of soil consolidation around the pipe" (2011).

$$x = \frac{D_e * K * W_c}{0.149 * PS + 0.061 * E'}$$

Where,

x = Deflection of Pipe, in.
K= Bedding Constant
W_c = Vertical Load per Unit of Pipe Length, lbf/in.
PS = Pipe Stiffness, lbf/in./in.
D_e = Deflection Lag Factor
E' = Modulus of Soil Reaction, psi

In addition, the measured value of pipe stiffness can be related to the true EI of the pipe provided the pipe remains elliptical. As stated in Appendix X2 of ASTM D2412,

> The EI of a pipe is a function of the material's flexural modulus (E) and the wall thickness (t) of the pipe. However, the quantities pipes stiffness (PS) and stiffness factor (SF) are computed values determined from the test resistance at a particular deflection. These values are highly dependent on the degree of deflection, for as the pipe deflects the radius of curvature changes. The greater the deflection at which PS or SF are determined, the greater the magnitude of the deviation from the true EI value (2011).

Figure 2-7: Type C HDPE Pipe Interior and Exterior Corrugations (Bennett n.d.)

Figure 2-8: Type S HDPE Pipe Corrugated Exterior and Smooth Interior (Bennett n.d.)

2.1.2.5 Polypropylene

The discovery of polypropylene occurred almost simultaneously in the United States and in Europe. As World War II ground to a halt, the Phillips Petroleum Company looked for different ways to expand its product line as the wartime demand for oil diminished. J. Paul Hogan and Robert L. Banks, two researchers working for the Phillips Petroleum Company, were asked to find ways to convert propylene and ethylene into gasoline. Instead, they discovered crystalline polypropylene. The American Chemical Society credits J. Paul Hogan and Robert L. Banks with the discovery of polypropylene. Both researchers were posthumously inducted into the Plastics Hall of Fame.

Despite being used for underground drainage and sewage applications in Europe for approximately 30 years, polypropylene is relatively new to North America. According to Borealis, a European polyolefin product manufactuer, “It [polypropylene] began being specified for the production of sewerage pipes from the 1970’s. Since 1950, there has been an average global increase of 9% per year in the production and consumption of plastics” (Borealis 2010). The demand for plastic gravity pipe systems in Europe is shown in Figure 2-9.

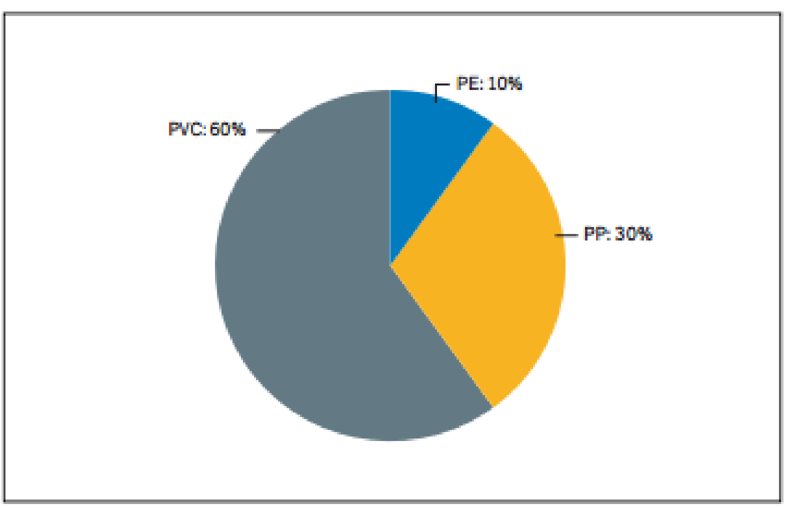


Figure 2-9: Demand for Plastic Gravity Pipe Systems in Europe (Borealis 2010)

Polypropylene is also a viscoelastic material and has properties between that of high density polyethylene and low density polyethylene. According to the report *Evaluation of Polypropylene Drainage Pipe,* "In general, polypropylene exhibits excellent mechanical and chemical characteristics, including high strength, high stiffness, high resistance to stress crack propagation, and high chemical resistance. Because of its relatively high strength to weight ratio, it is more rigid than other polyolefin" (Hoppe 2011). Table 2-8 illustrates some of the mechanical properties for polyethylene pipe and polypropylene pipe.

Table 2-8: Mechanical Properties for Thermoplastic Pipe (ADS, Inc. 2015)

Product	Material	Allowable Strain, %	Initial		75-Year	
			F_u psi	E psi	F_u psi	E psi
N-12 ST IB, WT IB, Plain End, SaniTite, Low Head	Polyethylene	5	3,000	110,000	900	21,000
NP-12 HP Storm and SaniTite HP Sanitary	Polypropylene	4	3,500	175,000	1,000	28,000

Section 12 of the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing* requires the material properties shown in Table 2-9 for the design of thermoplastic pipe. According to Section 12.12.3.3, it is the responsibility of the Engineer to choose between the initial and the 50-year mechanical property requirements. However, buckling must be based on the 50-year value for modulus of elasticity. As stated in the Commentary,

> The PE and PVC materials described herein have stress/strain relationships that are nonlinear and time-dependent. The 50-year design tensile strength requirements are derived from hydrostatic design models and indicate a minimum 50-year life expectancy under continuous application of that stress. The 50-year moduli of elasticity do not indicate a softening of the pipe material but the time-dependent relation between stress and strain (AASHTO 2008).

Table 2-9: Mechanical Properties of Thermoplastic Pipe (AASHTO 2008)

Type of Pipe	Minimum Cell Class	Service Long-Term Tension Strain Limit, ε_{yt} (%)	Factored Compr. Strain Limit, ε_{yc} (%)	Initial F_u min (ksi)	Initial E min (ksi)	50-yr F_u min (ksi)	50-yr E min (ksi)	75-yr F_u min (ksi)	75-yr E min (ksi)
Solid Wall PE Pipe – ASTM F714	ASTM D3350, 335434C	5.0	4.1	3.0	110.0	1.44	22	1.40	21
Corrugated PE Pipe – AASHTO M 294	ASTM D3350, 435400C	5.0	4.1	3.0	110.0	0.90	22	0.90	21
Profile PE Pipe – ASTM F894	ASTM D3350, 334433C	5.0	4.1	3.0	80.0	1.12	20	1.10	19
	ASTM D3350, 335434C	5.0	4.1	3.0	110.0	1.44	22	1.40	21
Solid Wall PVC Pipe – AASHTO M 278, ASTM F679	ASTM D1784, 12454C	5.0	2.6	7.0	400.0	3.70	140	3.60	137
	ASTM D1784, 12364C	3.5	2.6	6.0	440.0	2.60	158	2.50	156
Profile PVC Pipe – AASHTO M 304	ASTM D1784, 12454C	5.0	2.6	7.0	400.0	3.70	140	3.60	137
	ASTM D1784, 12364C	3.5	2.6	6.0	440.0	2.60	158	2.50	156

According to *Evaluation of Polypropylene Drainage Pipe*, “Polypropylenes exhibit higher tensile, flexural, and compressive strength and higher moduli than polyethylene” (Hoppe 2011). Table 2-10 provides typical uses for polypropylene and high density polyethylene.

Table 2-10: Uses for Polypropylene and High Density Polyethylene (ACS 1999)

Industry	Polypropylene	High Density Polyethylene
Automotive	Battery Cases and Trays Bumpers Fender Liners Interior Trim Reservoirs	Fuel Tanks Motor Oil Containers Portable Gas Cans Under-hood Reservoirs Wire Insulation
Education	Binders Transparent Sleeves Writing Instruments	Classroom/ Stadium Seating Notebook Binders
Environment	Geotextiles for Erosion Pavement Under-liners	Chemical Toilets Erosion Barriers Landfill Liners Pond and Canal Liners
Home	Appliance Housings Bottles and Containers Food Packaging Microwave Cookware	Food and Drink Containers Household Product Bottles Outdoor Furniture Toys Trash and Lawn Bags
Industry	Carpeting Crates and Trays Filters Office Furniture Tapes Woven Bags	Cable Jacketing Oil and Gas Lines Packaging Films Tank and Drums Wire Insulation
Medical	Medical Implements Packaging Syringes	Biomedical Waste Containers Pharmaceutical Bottles Tubing and Catheters
Municipal	Ropes and Twine	Highway Barriers Slip-lining for Sewers Trash Containers Utility Pipes
Recreation	Safety Equipment Sporting Goods Sportswear	Basketball Backboards Water Bottles and Coolers Watercraft Components

The Virginia Center for Transportation Innovation and Research published the report *Evaluation of Polypropylene Drainage Pipe* for the Virginia Department of Transportation (VDOT). The purpose of the report was to conduct a field evaluation to assess the potential suitability of polypropylene pipe for drainage applications. The VDOT selected five test locations on low-volume rural roads. Average daily traffic counts were obtained from the 2007 VDOT traffic survey and indicated that there were: 910 vehicles per day on Route 684, 60 vehicles per day on Route 736, 570 vehicles per day on Route 635, and 90 vehicles per day on Route 698. A summary of the pipe installations is shown in Table 2-11. Polypropylene pipes replaced the existing corrugated metal pipes and concrete pipes that had reached the end of their service life.

American Drainage Systems (ADS, Inc.) supplied the dual- and triple-wall plastic pipes with nominal diameters of 30 and 48 inches (Figure 2-10). The pipes manufactured by ADS, Inc. were part of ADS' N-12 High Performance product line that was specifically designed for gravity flow and sanitary sewer applications. The stiffness of the pipe was 46 psi at 5 percent deflection, Manning's n value was 0.012, and the cover height was approximately 2 feet. The results concluded that after one year of service, the maximum deformations of all pipes were less than 5 percent. This satisfied current VDOT post-installation inspection requirements. The report noted that no signs of crushing, buckling, or material degradation were detected.

Table 2-11: Summary of Pipe Installation at Test Sites

Route	Diameter	Pipe Wall	Length	Vehicle per Day
684	48-inch	Triple	55.0 ft	910
736	30-inch	Dual	50.0 ft	60
635	30-inch	Dual	30.0 ft	570
635	48-inch	Triple	33.5 ft	
698	48-inch	Triple	31.2 ft	90

Figure 2-10: Dual-Wall and Triple-Wall Profiles of ADS Pipes (Hoppe 2011)

Weather conditions were severe during the field evaluations. This resulted in substantial precipitation and unusually low ambient air temperatures. Based on visual observations and cross-sectional measurements, the report concluded that all polypropylene pipes performed satisfactory in the first year of service and were found to be fully functional. Other observations made by the report include:

1. Polypropylene is lightweight and easy to handle, assemble and install.
2. It does not require any specialized equipment or methods during construction.
3. When tested at Route 698, the pipe showed no evidence of wear and erosion from a relatively high water flow combined with the substantial presence of large rock particles.
4. Its double seal design reduced the risk of a joint leakage.

2.2 Flexible and Rigid Culverts

Culverts are separated into two distinct categories: flexible and rigid. According to the ACPA, flexible pipe is at least 95% dependent on soil support and the installation expertise of the contractor. As stated in the Plastics Pipe Institute's (PPI) *Design Methodology*, "When flexible pipe deflects against the backfill, the load is transferred to and carried by the backfill. When loads are applied to rigid pipe, on the other hand, the load is transferred through the pipe wall into the bedding" (n.d.). Backfill quality and compaction are the most important factors in ensuring satisfactory performance of flexible pipe (Zhao 1988).

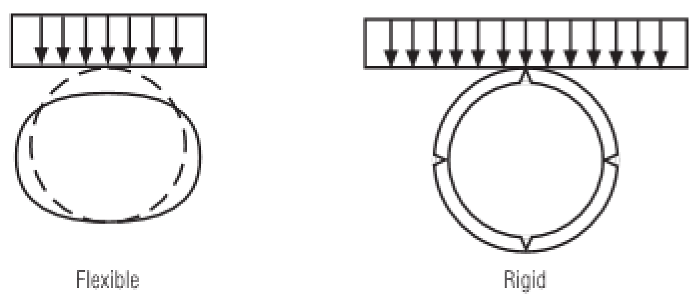


Figure 2-11: Flexible and Rigid Pipe Response to Loading (PPI n.d.)

As Robert French stated in *Cross-Drain Pipe Material Selection Algorithm*, "A flexible pipe's ability to deflect under loads without any structural damage when installed properly is often beneficial in deep installations" (French 2013). Figure 2-11 illustrates a flexible pipes' and rigid pipes' response to loading. A flexible pipe can deflect at least two percent without cracking, rupture, or any other sign of structural distress. However, "due to loss of lateral support, partial excavation and exposure of flexible pipe is likely to result in excessive deformation, and may lead to collapse" (Zhao 1998). Examples of flexible culverts include corrugated steel, corrugated aluminum, high density polyethylene and polypropylene.

Rigid culverts include non-reinforced concrete, reinforced concrete, and clay. According to the ACPA, concrete pipe is a rigid pipe system that is over 85% dependent on the pipe strength and only 15% dependent on the strength derived from the soil envelope. Rigid pipe is sometimes classified as pipe that cannot deflect more than 2% without significant structural distress such as cracking (PPI n.d.). "Existing buried, rigid pipe is less sensitive to re-excavation and backfilling, because of its inherent strength" (Zhao 1998). Figure 2-12 illustrates the difference in backfill interaction between a flexible pipe and a rigid pipe. The installation parameters of various pipes are shown in Table 2-12.

The Connecticut Department of Transportation (ConnDOT) *Drainage Manual* differentiates between flexible and rigid culvert behavior (2000):

> Flexible pipe has relatively little bending stiffness or bending strength of its own. As loads are applied to the culvert, the culvert attempts to deflect. In the case of a round pipe, the vertical diameter decreases and the horizontal diameter increases.
>
> The load carrying capacity of rigid culverts is essentially provided by the structural strength of the pipe and little benefit from the surrounding earth is required. When vertical loads are applied to a rigid pipe, zones of tension and compression are created.

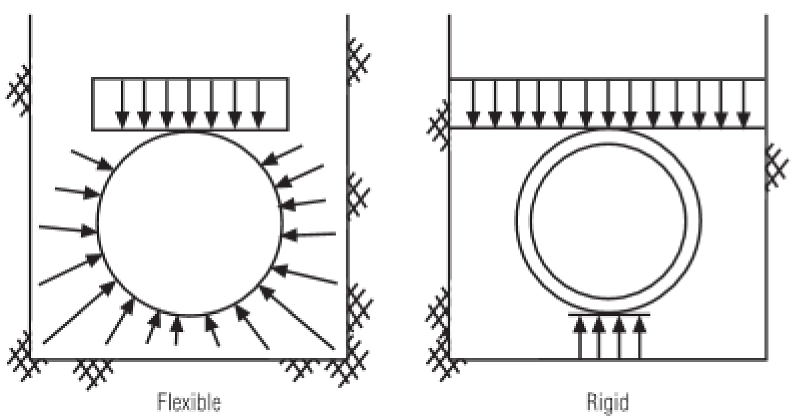


Figure 2-12: Flexible and Rigid Pipe Backfill Interaction (PPI n.d.)

Table 2-12: Installation Parameters of Various Pipes (Zhao 1998)

Installation Parameter	Rigid Pipe	Flexible Pipe
Trench Width	As narrow as possible. Earth load increases as the trench width increases, until transition width. Less width required for work space.	Earth load does not increase with width beyond the prism limits. Sufficient width is required to carry out careful compaction.
Joints	Bell-spigot joints with gaskets. More joints due to short sections.	Plastic Pipe: Elastomeric seal or solvent cement. Easy cutting for length adjustment/ fewer joints. Corrugated Steel Pipe: Steel coupling bands with neoprene gaskets or bitumen sealants. Welding.
Minimum Cover	900 mm required before use of a heavy compactor. Damage due to compaction not reported.	Plastic Pipe: 900 mm required before use of a heavy compactor. Over compaction may cause excessive deflection. CSP: Minimum cover ranging from 700 to 1400 mm.
Operation	May require additional equipment and manpower to handle heavier pipe sections. Requires less compaction effort.	Requires adequate on-site inspection. Requires maximum effort for effective compaction. Ease of transportation and handling.
Temperature Effects	Strength increases as temperature decreases in the range of -20 to -30°C. Impact strength also increases with decrease in temperature.	HDPE: Minimum installation temperature is -34°C. Impact strength is not affected significantly by low temperature. PVC: Minimum installation temperature is -18°C. Impact strength is reduced by up to 30% when temperature decreases from 23 to 0°C.
UV Degradation	UV degradation is negligible.	Plastic Pipe: Susceptible to UV degradation in long-term exposure.
Adjacent Excavation	Less sensitive to re-excavation and backfilling. Depending on the location, partial exposure usually does not cause significant distress to pipes.	Once exposed, flexible pipe must be backfilled and compacted with great care, according to the original specifications to restore its strength. Partial excavation and exposure is likely to result in excessive deformation.

Dr. Anson Marston, Dean of Engineering at Iowa State University and Chairman of the Iowa State Highway Commission, conducted a 21-year study to analyze soil pressures on buried culverts. He claimed that the "load on a rigid pipe would always be higher than the load on a flexible pipe due to the differences in interaction between each type of pipe with surrounding soils." He began his study by applying measured loads to concrete, cast iron, and corrugated steel pipes buried under an embankment of 15 feet.

His results indicated that the load on the concrete pipe was consistently 50% greater than the load on the corrugated steel pipe of approximately the same diameter (Figure 2-13). According to the study, "This load difference can be attributed to the difference in vertical deflection of the pipes that influenced the settlement ratios, and the magnitude of the shear stress components, as correctly theorized for flexible and rigid pipe materials" (Rahman 2010).

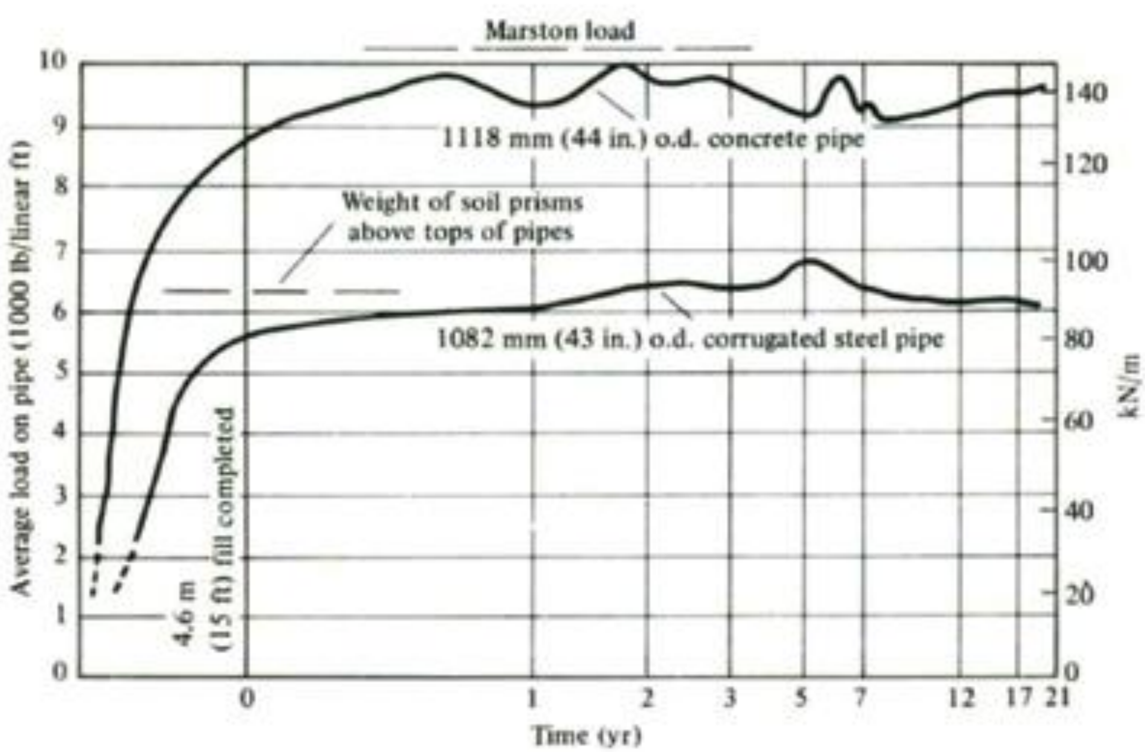


Figure 2-13: Soil Land Differences in Rigid and Flexible Pipe (Rahman 2010)

2.3 Service Life

America's aging infrastructure increases the risk of structural failures. Bridge corrosion and roadway degradation are extremely serious and increasing concerns. Culvert failures are no exception. Culvert failures have resulted in considerable damage to roadways causing widespread flooding and sinkholes throughout the United States. These failures are not only expensive but can be difficult to repair. Failures can occur without warning threatening the safety of American citizens. As a consequence, the FHWA and every State Department of Transportation stress the importance of considering the service life of the culvert in the selection process.

The Minnesota Department of Transportation's (MnDOT) Drainage Manual defines service life as "the period of service without a need for major repairs." "It is important to recognize that culverts are not assumed to be at or near the point of collapse at the end of their design service life. Rather, it is the period of little to no rehabilitative maintenance" (2000). Important factors that affect the service life of a culvert include:

- Corrosion
  - Soil Resistivity, Chloride, and Sulfate Concentration in Soil
  - Hydrogen Ion Concentration (pH) of the Surrounding Soil and Water
- Abrasion
  - Size, Shape, Hardness, and Volume of Bedload
  - Volume, Velocity, and Frequency of Streamflow
- Ultraviolet Radiation Exposure
- Flammability

2.3.1 Reinforced Concrete

The service life of a reinforced concrete culvert ends when the reinforcing steel has been exposed or significant cracks begin to form. The most critical factor affecting the service life of concrete pipe is chemical corrosion. Concrete can corrode when exposed to high concentrations of chloride and sulfate, as well as low pH and resistivity levels. Due to all of these varying components, many studies have been performed to evaluate the service life of concrete pipe including a study performed by the NCHRP entitled *Synthesis 474: Service Life of Culverts*.

This study came at the request of the AASHTO subcommittee on culverts. The study collected the predication methods developed by various agencies and researchers to determine the expected service life of concrete pipe. Examples of a few of the prediction methods include the following:

- Utah DOT tests soil and water for resistivity, pH, soluble salts, and sulfate content, then uses charts to estimate the expected service life for various types of pipe. The expected service life of Portland cement concrete can be up to approximately 120 years.
- Arizona DOT assigns concrete pipe a service life of 100 years for installations where the pH is 5 or greater
- The U.S. Forest Service has defined acceptable conditions for concrete pipe to resist corrosion. If the pH of the water or soil surrounding the pipe is between 4.5 and 10 and the resistivity of the soil is greater than 1,500 ohm-cm, then the expected corrosion service life of concrete pipe is 75 years or greater.
- A study commissioned by the Ohio Department of Transportation found from a survey of 40 DOTs that service life of concrete culverts appeared to be limited to 70 to 80 years.
- A literature review by the National Research Council of Canada predicted the service life of concrete pipe varies from 50 to more than 100 years, depending on the environmental conditions to which the pipe is subjected.

The Army Corp of Engineers recommends a design life of 70 to 100 years.

2.3.2 Corrugated Steel

The service life of a corrugated metal culvert ends when deterioration reaches the point of perforation. The most critical factors affecting the service life of steel pipe are corrosion, abrasion, and wall thickness. The most commonly used method to predict the durability of galvanized steel culverts is The California Method 643 published by the California Department of Transportation (CALTRANS). The California Method 643 considers two environmental factors when estimating the service life of steel culverts: the pH and electrical resistivity of the site and backfill materials. Applying these factors, CALTRANS developed a chart to estimate the maintenance-free service life of a galvanized steel culvert at any location. This chart is shown in Figure 2-14.

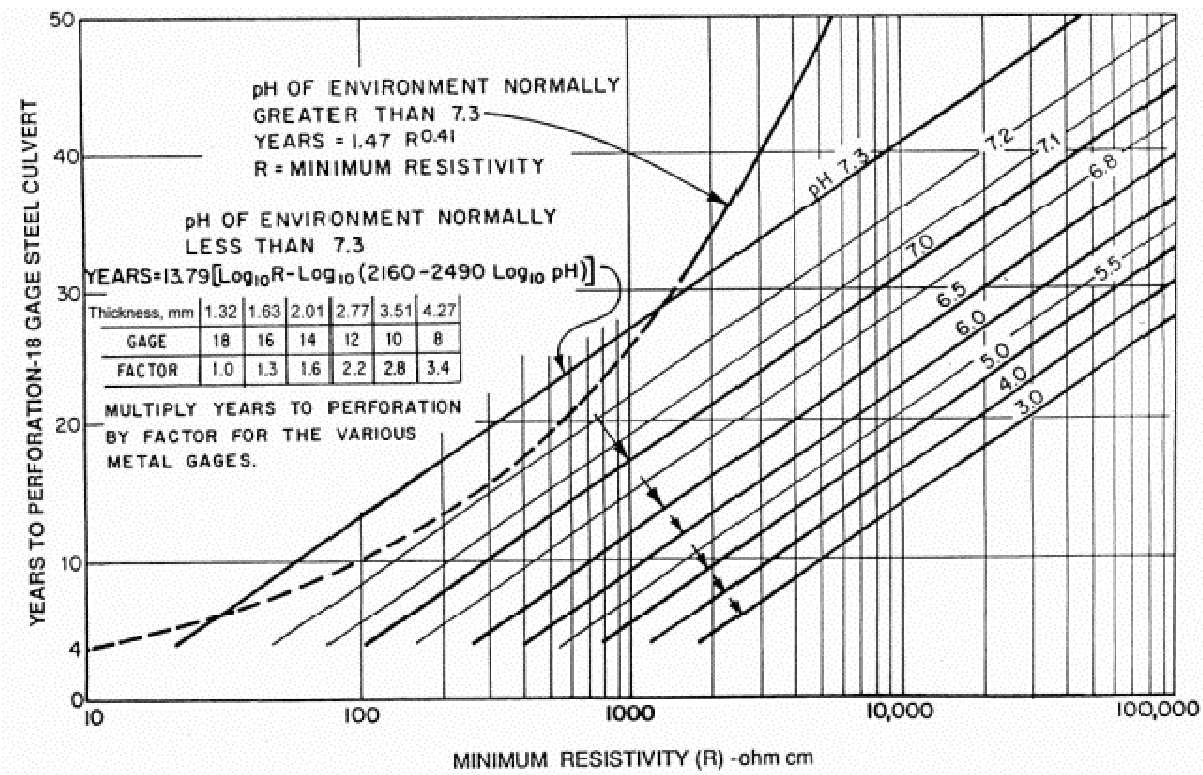


Figure 2-14: Estimating Years to Perforation of Steel Culverts (CALTRANS 1999)

Aluminized steel is more resistant to corrosion than galvanized steel. The University of Minnesota's report *Minnesota Steel Culvert Pipe Service-Life Map* concluded that "aluminized pipe overall provides a greater potential for higher service life than galvanized pipe" (2015). According to NCHRP's Synthesis 474,

> CALTRANS recommends using aluminized steel culverts instead of using other coatings or increasing the steel thickness in nonabrasive conditions with 5.5 < pH < 8.5 and minimum resistivity of at least 1,500 ohm-cm. With 5.5 < pH < 8.5 and resistivity less than 1,500 ohm-cm, CALTRANS does not recommend the use of aluminized type 2 steel culvert (2015).

Recent testing has shown that polymer coated steel provides the most abrasion resistance, as it can withstand Abrasion Level 3 conditions. The National Corrugated Steel Pipe Association (NCSPA) guarantees a 100-year service life for polymer coated steel pipe if the environmental conditions shown in Table 2-13 are met.

Table 2-13: Estimated Material Service Life for Corrugated Steel (NCSPA 2010)

Estimated Material Service Life for Corrugated Steel Pipe			
Estimated Service Life	Site Environmental Conditions	Maximum FHWA Abrasion Level	Material
Minimum 100 Years	5.0 < pH < 9.0 r > 1500 ohm-cm	Level 3	Polymer Coated
		Level 2	Aluminized Type 2*
Minimum 75 Years	4.0 < pH < 9.0 r > 750 ohm-cm	Level 3	Polymer Coated
	5.0 < pH < 9.0 r > 1500 ohm-cm	Level 2	Aluminized Type 2
Minimum 50 Years	3.0 < pH < 12.0 r > 250 ohm-cm	Level 3	Polymer Coated
Average 50 Years	6.0 < pH < 10.0 2000 < r < 10,000 ohm-cm > 50 ppm $CaCo_3$	Level 2	Galvanized

*14 gauge minimum

2.3.3 Corrugated Aluminum

The most critical factors affecting the service life of aluminum pipe are corrosion, abrasion, and wall thickness. These factors are dependent on the pH and resistivity of the soil, as well as the velocity of the water flowing through the culvert. Therefore, the service life of aluminum varies by state and is typically deduced from a chart. The Maryland Department of Transportation (MDOT) published the chart shown below to estimate the service life of aluminum pipe. This chart is shown in Figure 2-15.

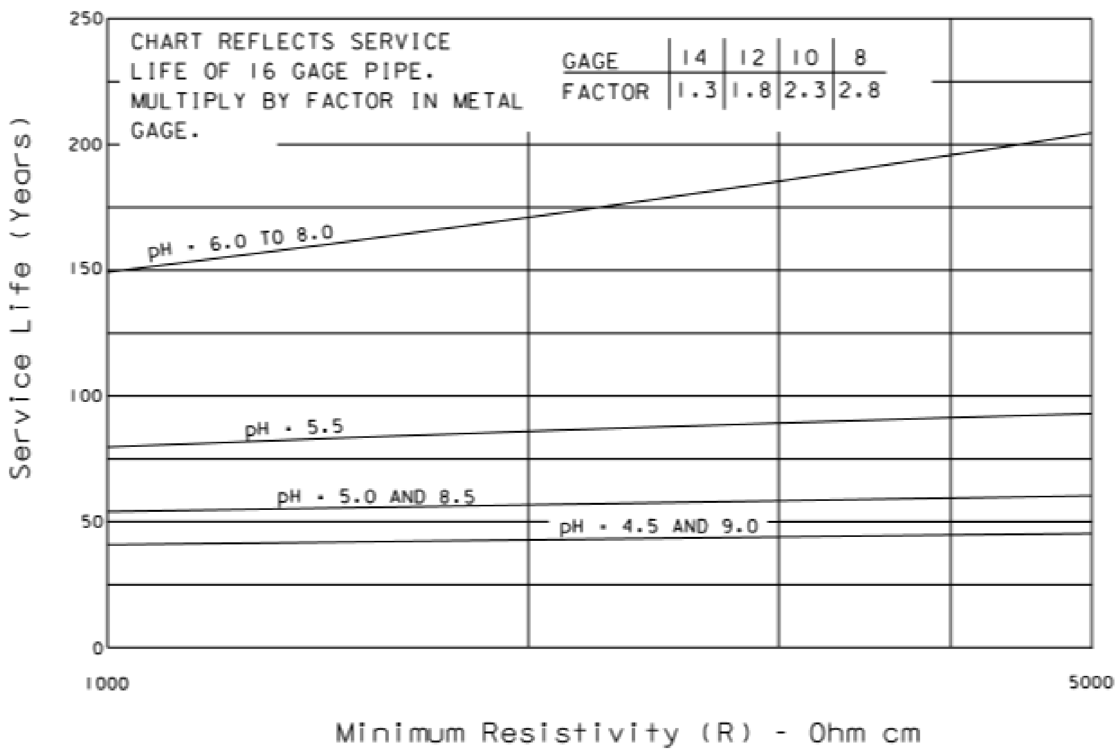


Figure 2-15: Estimated Service Life vs. pH and Resistivity for Aluminum (MDOT 2005)

The New York Department of Transportation (NYSDOT) anticipates a 70-year service life for aluminum pipe, unless high velocities, potentially abrasive bed loads, or high concentrations of industrial waste are present. CALTRANS recommends a 50-year maintenance-free service life if the pH and resistivity of the soil, backfill, and drainage water meet the requirements stipulated in the Highway Design Manual.

As stated, the service life of metal pipe is dependent on wall thickness. The Oregon Department of Transportation's *Hydraulic Manual* specifies corrugated metal pipe wall thickness to the nearest 0.001 inch. Standard wall thicknesses and gage values used by the Oregon Department of Transportation are shown in Table 2-14. Most departments of Transportation specify one standard service life for a pipe material. However, some departments of Transportation will increase the service life by a factor based on material type and wall thickness (Table 2-15).

Table 2-14: Wall Thicknesses (ODOT 2014)

Galvanized Iron and Steel		Aluminum	
Wall Thickness (inches)	Gage	Wall Thickness (inches)	Gage
0.064	16	0.060	16
0.079	14	0.075	14
0.109	12	0.105	12
0.138	10	0.135	10
0.168	8	0.164	8

Note: Dimensions applicable to uncoated or metallic coated pipes.

Table 2-15: Increase in Service Life per Wall Thickness (ODOT 2014)

Material	Wall Thickness (inches)	Material	Wall Thickness (inches)	Factor
Aluminum	0.075	Steel	0.079	1.3
Aluminum	0.105	Steel	0.109	1.7
Aluminum	0.135	Steel	0.138	2.2
Aluminum	0.164	Steel	0.168	2.9

2.3.4 High Density Polyethylene

The most critical factors affecting the service life of high density polyethylene pipe are oxidation, ultraviolet radiation, and flammability. There is an extensive amount of research claiming that the service life of high density polyethylene pipe is well in excess of 100 years, even at deflections greater than 5%. The PPI references three published papers from independent studies on their website as proof of this claim. The papers were presented at Plastics Pipes XIII in Washington, DC and at the American Society of Civil Engineers Pipelines Conference in Chicago. The three published papers are as follows:

1. "Establishing 100-Year Service Life for Corrugated HDPE Drainage Pipe" by Michael Pluimer, Technical and Engineering Manager at Plastics Pipe Institute

2. "Evaluate the Long-Term Stress Crack Resistance of Corrugated HDPE Pipes" by Y. Grace Hsuan, J-Y Zhang, and W-K Wong, of the Department of Civil, Architectural, and Environmental Engineering at Drexel University in Philadelphia, Pennsylvania

3. "New Test Method to Determine Effect of Recycled Materials on Corrugated HDPE Pipe Performance as Projected by the Rate Process Method" by Dr. Gene Palermo, Palermo Plastics Pipe Consulting

With the exception of Florida and Pennsylvania, State Departments of Transportation are hesitant to approve a 100-year service life for high density polyethylene pipe despite many of these case studies. MDOT assumes a 75-year service life for corrugated polyethylene pipe. NYSDOT anticipates a 70-year service life for polyethylene pipe. According to *A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota,*

> HDPE pipe has the durability and corrosive resistance to have a service life of over 100 years and is not significantly susceptible to freeze/thaw damage. We recommend adopting testing methods similar to the Florida testing methods for determining service life to identify HDPE pipes capable of yielding a 100-year service life (Marr 2012).

In the paper “Establishing 100-Year Service Life for Corrugated HDPE Drainage Pipe”, Michael Pluimer discusses the three failure modes of high density polyethylene. Pluimer begins the discussion by a brief abstract explaining the process to predict a long-term service life. First, Pluimer explains, the anticipated service conditions such as the environmental conditions, soil loads, traffic loads, and long-term stresses and strains must be assessed. Secondly, the capacity of the material must be assessed. The service conditions will vary by geographic location. “While deep installations may result in large compressive stresses on the pipe, shallow installations are more subject to bending and tensile stresses” (Pluimer 2006). Pluimer calculates the maximum demand placed on the pipe by the stress equation shown below.

$$\sigma = \frac{P}{A} \pm \frac{Mc}{I}$$

Where:

σ = Stress in Pipe Wall, psi
P = Hoop Thrust in Pipe Wall, lb/in
A = Wall Area, in^2/in
M = Moment in Pipe Wall, lb-in/in
c = Distance from Extreme Fiber in Pipe Wall to Centroidal Axis, in
I – Moment of Inertia of Pipe Wall, in^4/in

The hoop stress is always compressive and increases as the cover height increases. Because high density polyethylene is more prone to tensile failure than compressive failure, the hoop stress should be minimized and the bending stress maximized to determine the maximum tensile stress. According to Pluimer, the worst-case condition for a high density polyethylene pipe is to have a shallow installation with high deflections, or to have a low hoop thrust with large bending stresses. “It is interesting to note that if the pipe is properly installed, this type of condition should be rare as high deflections are typically not observed in shallow burials; such a condition is generally the result of poor installation practices" (Pluimer 2006).

Dr. Timothy McGrath for the Florida Department of Transportation determined the long-term stress and strain induced on the pipe wall using Finite Element Analysis and theoretical AASHTO design calculations. Based on a total vertical deflection of 5% with minimum thrust, a long-term modulus of elasticity of 20,000 psi, and a factor of safety of 1.5, McGrath calculated a long-term stress of 450 psi and a long-term strain of 2.25%. However, McGrath's calculations only considered the circumferential stresses in the pipe. Citing two papers by Dr. Ian Moore, McGrath determined that the longitudinal stresses are of the same order of magnitude as the circumferential stresses. "Therefore, in order to ensure 100-year service life, the capacity of the material must be able to withstand this demand" (Pluimer 2006).

As mentioned previously, Pluimer discusses three failure modes of high density polyethylene crucial to the evaluation of the material's long-term performance.

- Stage I – Failures are ductile in nature, and occur at very high stress levels.
- Stage II – Failures are brittle types of fractures and occur at moderate stress levels. This is one of the primary failures modes and is associated with slow crack growth.
- Stage III – Failures occur as a result of chemical degradation.

Defined earlier, slow crack growth is a phenomenon characterized by crack propagation at low stress levels. ASTM F2136 *Standard Test Method for Notched, Constant Ligament-Stress (NCLS) Test to Determine Slow-Crack-Growth Resistance to HDPE Resins or HDPE Corrugated Pipe* compares the slow crack growth resistance for a limited set of resins. This test helps prevent Stage II failures. Pluimer also recommends utilizing the Rate Process Method to determine the 100-year service life of high density polyethylene.

The Rate Process Method "takes advantage of the Arrhenius principle of time-temperature superposition to accelerate the test and extrapolate data to predict service life at the anticipated service temperature" (Pluimer 2006). The Rate Process Method is included in ASTM D2837 *Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products*. The Rate Process equation shown below relates time and hoop stress as a function of absolute temperature. A pipe's brittle failure performance is determined by the three coefficients. "Once the three coefficients are determined, the Rate Process equation is used to determine if the time to failure at the required service conditions is greater than 100 years" (Pluimer 2006).

$$\log_t = A + \frac{B}{T} + \frac{C \log S}{T}$$

Where:

t = Time, hr
S = Hoop Stress, psi
T = Absolute Temperature, °K
A, B, C = Constants

Another test method to evaluate high density polyethylene's resistance to Stage II failures was proposed by Dr. Grace Hsuan for the Florida Department of Transportation. Hsuan's test focused on the junction between the corrugation and liner. A diagram of the junction specimen is shown in Figure 2-16. This junction was chosen based on Hsuan and McGrath's prior work on NCHRP Report 429 *HDPE Pipe: Recommended Material Specifications and Design Requirements*. A field sample of high density polyethylene pipe with noted slow crack growth failures is shown in Figure 2-17. "By the nature of the geometry of this junction, it will act as a stress concentration point where slow crack growth failure is most likely to occur. This proposed junction test consists of a tensile load applied to the test specimen while immersed in a water bath" (Pluimer 2006).

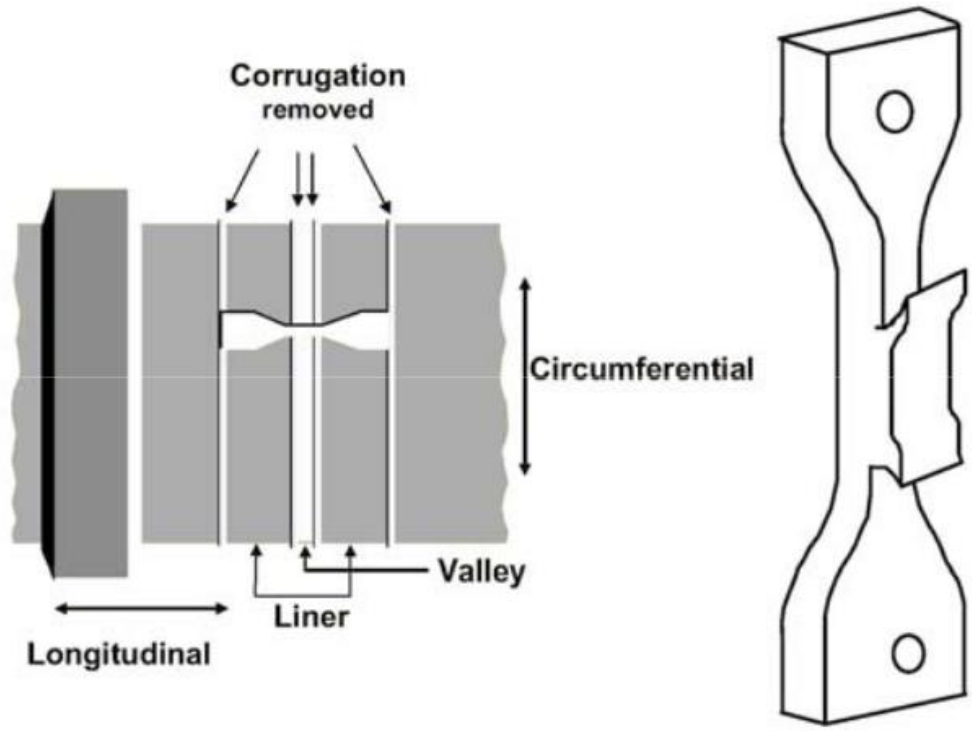


Figure 2-16: Diagram of Junction Specimen (Hsuan and McGrath 2005)

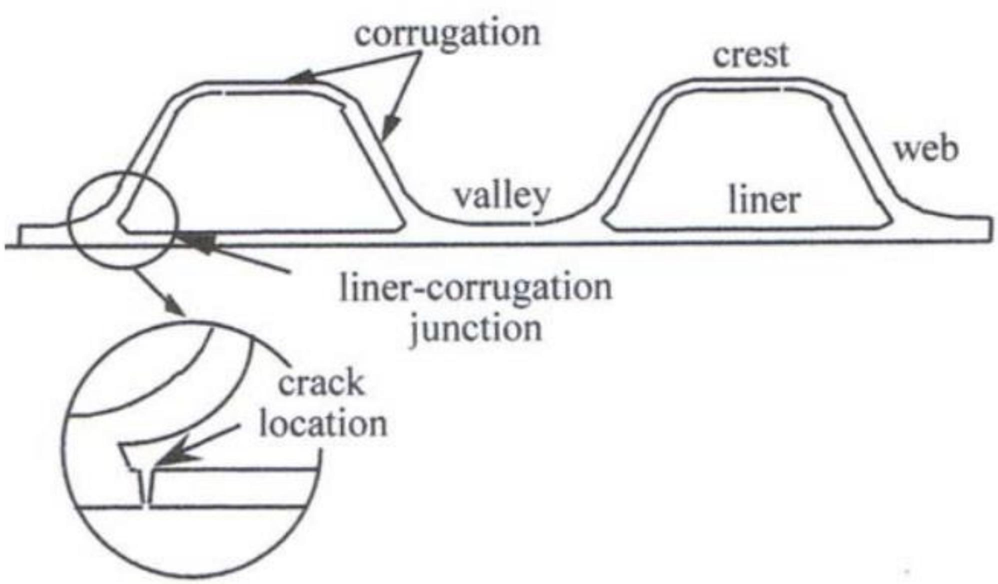


Figure 2-17: Location of Linear-Corrugation Junction (Hsuan and McGrath 2005)

Stage III failures are prevented by the addition of antioxidants to the material formulation. Antioxidants protect the resin from oxidative degradation. "Thus, if it can be shown that there will be some antioxidant present in the material over the 100 year service life, one can be assured that the pipe will not experience Stage III failures in this time period" (Pluimer 2006). Figure 2-18 illustrates how poor oxidation stabilizers can affect the service life of the pipe. A lack of antioxidants shift the Stage III failure curve to the left. If the Stage III failure curve is shifted far enough, the service life will be detrimentally impacted.

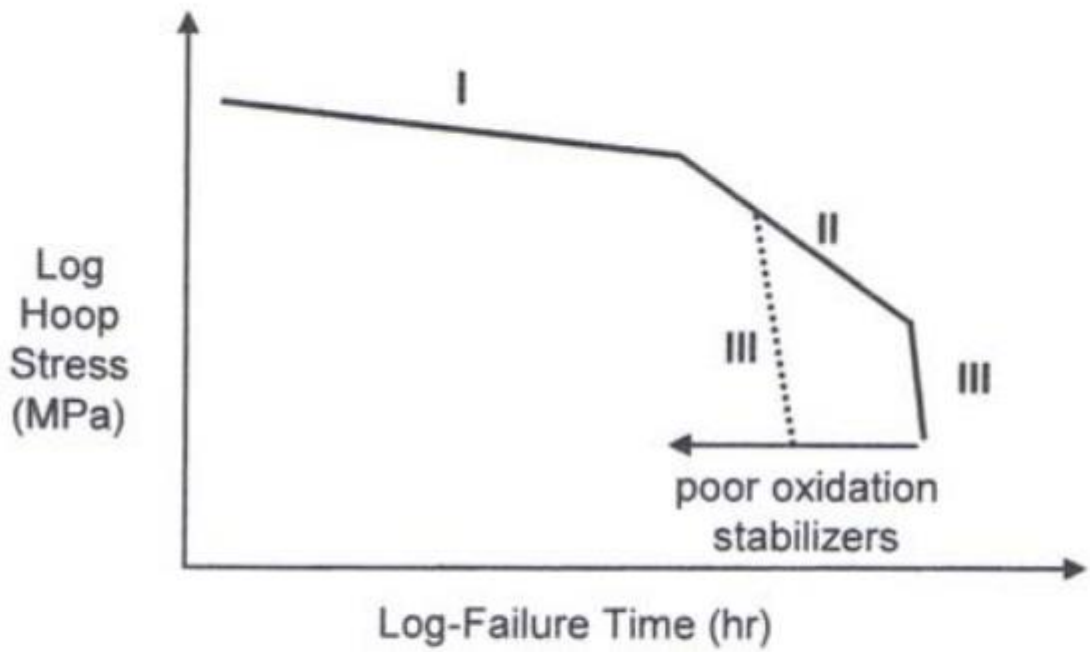


Figure 2-18: Antioxidants Effect on Service Life (Hsuan and McGrath 2005)

Pluimer recognizes two tests to determine the antioxidant activity in a polyethylene formulation. The first test is known as the induction temperature test or the thermal stability test. This test is performed "by heating a test specimen at a constant rate and recording the temperature at which oxidation initiates". The second test is known as the oxidation induction time test. This test is performed by "measuring the time to achieve oxidation at a given test temperature".

In conclusion, Pluimer reaffirms that the 100-year service life is dependent on the installation conditions to determine the demand placed on the pipe and the material properties of the pipe. McGrath determined that the maximum factored tensile stress and strain in a pipe was 450 psi and 2.25%, respectively, based on a total vertical deflection of 5%, a long-term modulus of elasticity of 20,000 psi, and a factor of safety of 1.5. In order to determine the material's capability to meet these predetermined demands, Hsuan applied the Rate Process Method to predict Stage II performance. He performed an oxidation induction time test to check the antioxidant performance. This ensured Stage III failures would not occur. Based on these calculations and tests, Pluimer concludes that high density polyethylene corrugated pipe can be evaluated for a 100 year service life.

2.3.5 Polypropylene

The most critical factors affecting the service life of polypropylene pipe are oxidation, ultraviolet radiation, and flammability. In 2014, ADS, Inc. released the news article "ADS HP Polypropylene Pipe Meets Specification for 100-Year Design Life in Side Drain, Cross Drain and Storm Sewer Applications." The article announced that the Florida Department of Transportation (FDOT) approved the use of ADS' High Performance polypropylene pipes ranging from 12-inch to 60-inch in diameter for 100-year service life applications. According to FDOT documents,

> Polypropylene pipe has passed the needed testing to be accepted for 100-year side drain, cross drain and storm sewer applications. Until project plans and specifications reflect this update, PP pipe may be selected by the contractor for any project where high-density polyethylene (HDPE) pipe is allowed (2014).

While polypropylene has recently emerged as a culvert material in North America, it has been used in Europe for the past 40 years. In 2015, The European Plastic Pipes and Fittings Association published a technical report on the service life of non-pressure polyethylene and polypropylene pipes. According to *100 Year Service Life of Polypropylene and Polyethylene Gravity Sewer Pipes,* polyolefin products are expected to have a service life of at least 100 years. The report was published because "no scientific study on service life expectancy had been done on pipes that operate with a constant strain in sewage and drainage applications" (2014). As stated in the news article *Study: Service Life for PE, PP Sewer Pipes at least 100 Years,*

> The findings were based on a two-year study of pipes excavated from five sites in Finland, Norway, Denmark and Germany. One pipe made of first-generation high density PE had been in the ground 38 years and the PP pipes had been in operation 10-23 years. The tests found no excessive deterioration or degradation and the results demonstrate the long-term performance of solid wall and structured wall sewer pipes using long-term, real-time data (Kavanaugh 2015).

2.4 Durability

Durability is crucial to a culvert's serviceability. As defined by the PPI, "durability is the property to resist erosion, material degradation and subsequent loss of function due to environmental or other service conditions" (Gabrial n.d.). Material degradation can occur by cracking, tearing, spalling, abrading, or corroding. It can also occur due to joint separation, excessive buckling, and deflection.

2.4.1 Chemical Corrosion

Each day, 850 water mains break in the United States and Canada. One in four of those breaks are caused by corrosion. As mandated by the United States Congress, the FHWA released a study in 2002 on the direct costs associated with corrosion. According to the study "Corrosion Costs and Preventative Strategies in the United States", corrosion costs the United States' water and wastewater systems over $50.7 billion annually. The American Society for Civil Engineers estimated that 2.6 trillion gallons of potable water are lost every year through leaking pipes or 17% of all water pumped in the United States.

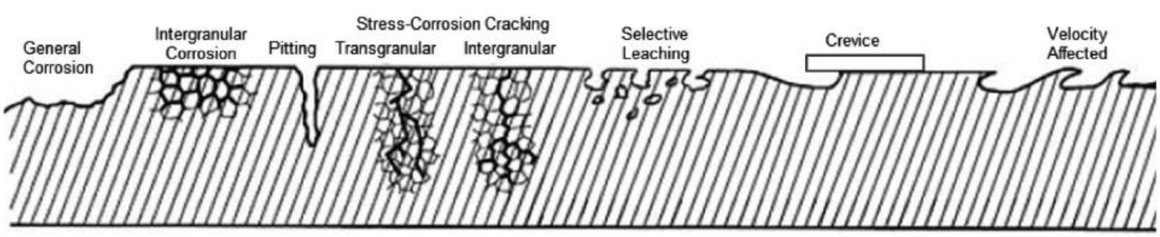


Figure 2-19: Schematic of Common Corrosion Mechanisms (NCHRP 2015)

The most common reason for a culvert to fail is due to a gradual weakening caused by corrosion (Figure 2-19). Corrosion can occur on both the inside and outside of the culvert. According to Victor Chaker's *Effects of Soil Characteristics on Corrosion: Issue 1013*, the rate of deterioration is a function of many factors. This includes properties of the pipe and its protective coatings, the nature of the soil, and the chemicals in solution in the soil water. The presence of soils and waters in the pipes containing acids, alkalis, dissolved salts and organic industrial wastes is a likely indicator of corrosion. Many factors carry these contaminants including surface water, ground water, sanitary effluent, acid rain, marine environments and mine drainage.

Corrosion most commonly attacks unprotected metal culverts and the reinforcement in concrete pipes. Corrosion of the reinforcing steel or other embedded metals is the leading cause of deterioration in concrete. When the reinforcing steel corrodes, the resulting rust occupies a greater volume than the reinforcing steel. An example of this expansion is shown in Figure 2-20. According to the article *Types and Causes of Concrete Deterioration*, "This expansion creates tensile stresses in the concrete, which can eventually cause cracking, delamination, and spalling" (2002). The article goes on to state:

> Steel corrodes because it is not a naturally occurring material. Steel, like most metals except gold and platinum, is thermodynamically unstable under normal atmospheric conditions and will release energy and revert back to its natural state – iron oxide, or rust. This process is called corrosion (2002).

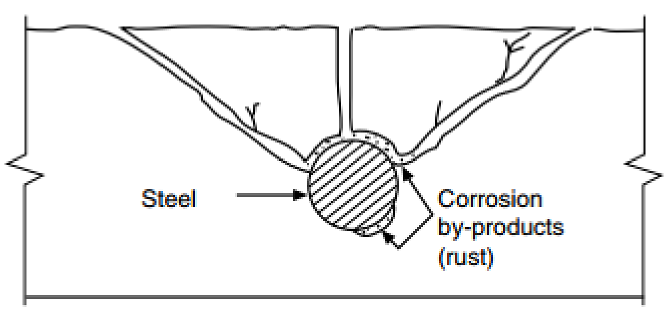


Figure 2-20: Expansion of Corroding Steel in Concrete (PCA 2002)

An example of a corroded concrete box culvert is shown in Figure 2-21. The box culvert was installed north of Walsenburg in Colorado. Soil samples were taken from the site which indicated an extremely high sulfate concentration. Three samples had a sulfate concentration of 16,800 ppm, 11,200 ppm, and 20,800 ppm. An example of a corroded corrugated metal culvert is shown in Figure 2-22. The metal culvert had corroded so severely that the bottom of the culvert had completely disintegrated.

Figure 2-21: Corrosion of Reinforced Concrete Culvert (Molinas 2009)

Figure 2-22: Corrosion of Corrugated Metal Culvert (Kestler 2012)

The alkaline environment of concrete provides steel with corrosion protection. According to the article *Types and Causes of Concrete Deterioration*, “At the high pH, a thin oxide layer forms on the steel and prevents metal atoms from dissolving. Without the passive film, the steel would corrode at rates at least 1,000 times higher” (2002). Despite concrete’s inherent protection, corrosion can occur when the passivating layer is destroyed. While this thin oxide layer will not stop corrosion, it will reduce the corrosion rate to an insignificant level. The destruction of the passivating layer occurs “when the alkalinity of the concrete is reduced or when the chloride concentration in concrete is increased to a certain level” (2002). A list of chemicals known to deteriorate concrete is shown in Table 2-16. Table 2-17 lists likely causes of culvert deterioration.

Table 2-16: Chemicals that Deteriorate Concrete (PCA 2002)

Chemicals That Deteriorate Concrete

Promote rapid deterioration of concrete:

Aluminum Chloride
Calcium Bisulfite
Hydrochloric Acid (all concentrations)*
Hydrofluoric Acid (all concentrations)
Nitric Acid (all concentrations)
Sulfuric Acid, 10-80 percent*
Sulfurous Acid

Promote moderate deterioration of concrete:

Aluminum Sulfate*	Mustard Oil*
Ammonium Bisulfate	Perchloric Acid, 10%
Ammonium Nitrate	Potassium Dichromate
Ammonium Sulfate*	Potassium Hydroxide (>25%)
Ammonium Sulfide	Rapeseed Oil*
Ammonium Sulfite	Slaughterhouse Waste[2]
Ammonium Superphosphate	Sodium Bisulfate
Ammonium Thiosulfate	Sodium Bisulfite
Castor Oil	Sodium Hydroxide (>20%)
Cocoa Bean Oil*	Sulfite Liquor
Cocoa Butter*	Sulfuric Acid, 80% Oleum*
Coconut Oil*	Tanning Liquor (if acid)
Cottonseed Oil*	Zinc Refining Solutions[3]
Fish Liquor[1]	

* Sometimes used in food processing or as food or beverage ingredient. Ask for advisory opinion of Food and Drug Administration regarding coatings for use with food ingredients.

[1] Contains carbonic acid, fish oils, hydrogen sulfide, methyl amine, brine, other potentially active materials

[2] May contain various mixtures of blood, fats and oils, bile and other digestive juices, partially digested vegetable matter, urine, and manure, with varying amounts of water.

[3] Usually contains zinc sulfate in sulfuric acid. Sulfuric acid concentration may be low (about 6 percent in "low current density" process) or higher (about 22-28% in "high current density" process).

Table 2-17: Likely Causes of Culvert Deterioration (Wagener 2014)

Observed Condition	Likely Cause
Invert and crown cracking width in excess of 0.10” in RCP culverts	• Dead and live loading on culvert exceeding design capacity • Increased loading on culvert due to increased soil or groundwater elevations
Slabbing (slabs of concrete “peeling” away from the sides of the pipe and a straightening of the reinforcement due to excessive deflection or shear cracks) in RCP culverts	• Dead and live loading on culvert exceeding culvert design capacity • Increased loading on culvert due to increased soil or groundwater excavations • Improper bedding of culvert
Deflections exceeding 7% in flexible culverts	• Dead and live loading on culvert exceeding culvert design capacity • Increased loading on culvert due to increased soil or groundwater excavations • Improper installation or selection of haunching materials or insufficient compaction • Loss of soil through pipe wall or joints • Piping of materials on exterior of culvert • Excessive construction equipment loading with insufficient cover
Loss/erosion of invert	• Erosion of culvert material due to stream bed loading (all pipe materials) • Corrosion or deterioration of culvert material due to pH of water, resistivity of soil, chemical attack, etc. (all pipe materials) • Corrosion of reinforcement and resulting expansive forces resulting in delaminations of concrete (RCP) • Freeze-thaw deterioration (RCP)
Joint separation and infiltration of soil	• Improperly seating of joint during installation • Movement of pipe due to slope erosion, free-thaw or settlement • Movement of pipe due to excessive deflection or structural deterioration • Buoyancy of culvert with insufficient cover

High density polyethylene pipes and polypropylene pipes are unaffected by most inorganic acids, alkalis, and aqueous solutions. Dow Chemical released a case-study praising the superiority of plastics used in nuclear power plants. The case-study, The Power of Plastic, cited that one of the main advantages to replacing carbon steel in safety-related pipe systems with high density polyethylene was the plastic's inability to corrode. "Polyethylene material does not corrode, rust, rot, pit, tuberculate or support biological growth, and it has an outstanding field performance record (for more than half a century) in water piping systems" (2009). Prior to the installation at Callaway Nuclear Power Plant, high density polyethylene pipes had never been used for a safety-related American Society of Mechanical Engineers Class 3 water pipe application at a nuclear power plant in North America.

AmerenUE, a subsidiary of Ameren Corporation and owner of Callaway Nuclear Power Plant cited several advantages to using high density polyethylene for safety-related pipe at nuclear power plants. The advantages are listed below.

1. HDPE pipe is leak-free when produced and installed properly, even at joints, which can be as strong and leak-free as the pipe itself through use of the heat fusion joining technique.

2. It offers seismic resistance, in that it can safely accommodate repetitive pressure surges above its static pressure rating and is well-suited for seismic loading due to its natural flexibility.

3. HDPE is easier and more cost-efficient to install than carbon steel

However, the high density polyethylene pipes studied by Dow Company were installed in a pristine environment that was free of soil and water contamination and climatic influence. Though unlikely, some concentrated acids and oxidizing agents can pose a threat to plastic pipe at extremely elevated temperatures.

2.4.1.1 Chloride Concentration

Chloride ions are the most extensively documented contaminant that cause corrosion of the embedded steel in concrete. The embedded steel is more susceptible to corrosion if the concrete cover is inadequate, cracked, or highly permeable. As stated in the Portland Cement Association's (PCA) article *Types and Causes of Concrete Deterioration*,

> When the chloride content at the surface of the steel exceeds a certain limit, called the threshold value, corrosion will occur if water and oxygen are also available. Federal Highway Administration studies found that a threshold limit of 0.20% total chloride by weight of cement could induce corrosion of reinforcing steel in bridge decks (2002).

Table 2-18: Maximum Chloride Ion Content of Concrete (ACI 318 2002)

Type of Member	Maximum Cl^-*
Prestressed concrete	0.06
Reinforced concrete exposed to chloride in service	0.15
Reinforced concrete that will be dry or protected from moisture in service	1.00
Other reinforced concrete construction	0.30

*Water-soluble chloride, percent by weight of cement

Table 2-18 presents the maximum chloride ion content associated with various types of concrete members. Chloride ions are present in deicing salts and seawater. The degradation is often accelerated in regions where successive freeze-thaw cycles occur. Figure 2-23 illustrates the frequency of freeze-thaw exposure in the United States. Based on the figure, the majority of Alabama rarely experiences freeze-thaw exposure. Only the northern part of the state may experience an occasional freeze-thaw exposure. However, higher elevations receive a greater frequency of exposure.

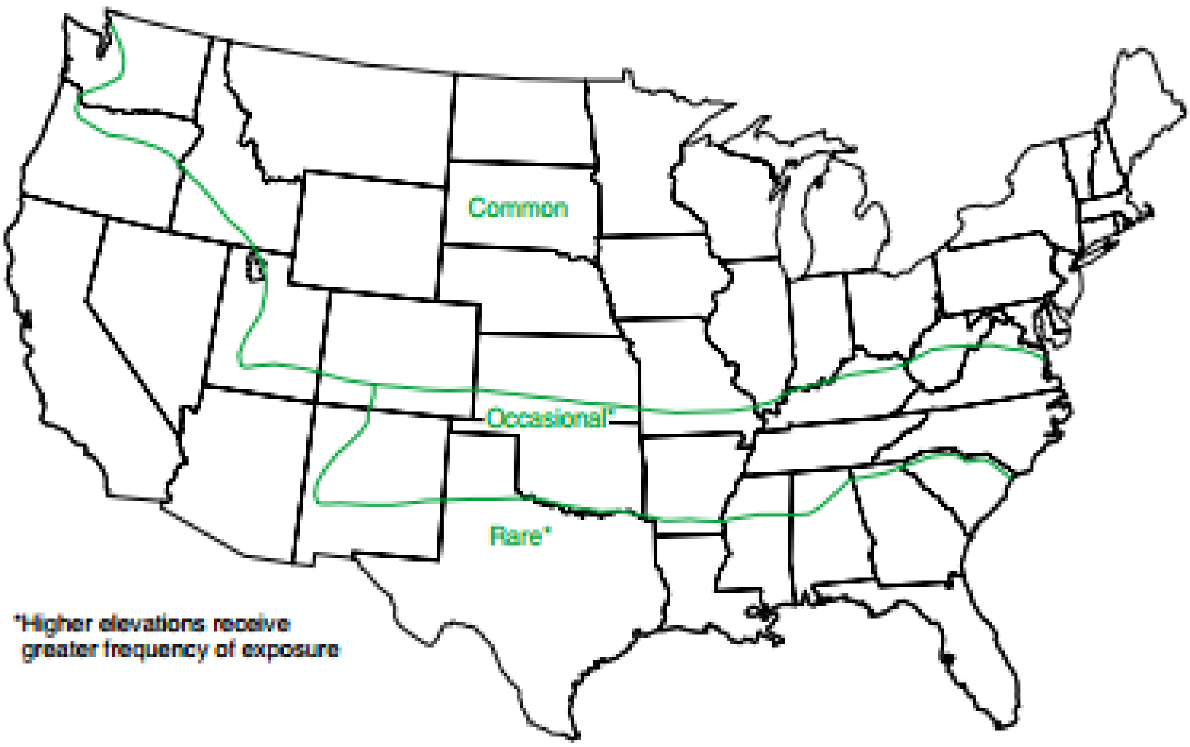


Figure 2-23: Frequency of Freeze-Thaw Exposure in the United States (PCA 2002)

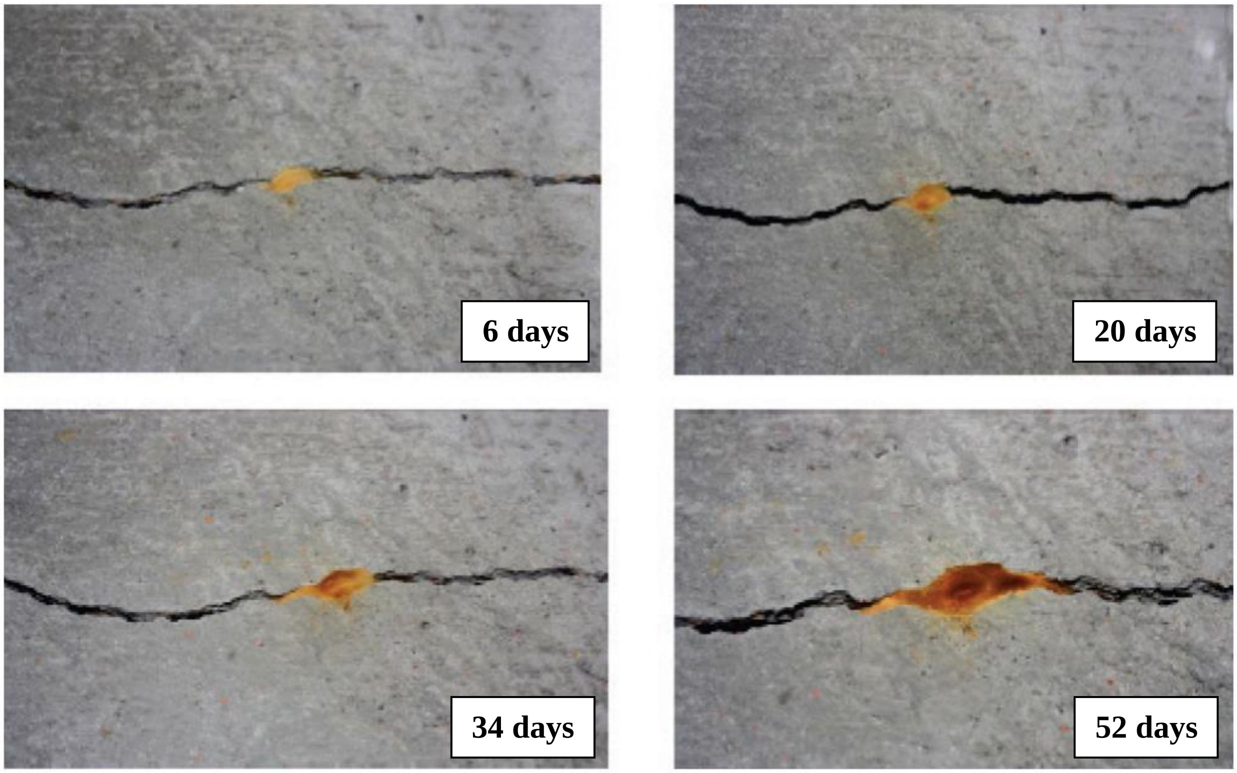


Figure 2-24: Chloride Attack on Reinforced Concrete Pipe (NCHRP 2015)

The LRFD Bridge Construction Specifications specifies a maximum in-place width of 0.100-inch for noncorrosive conditions and 0.010-inch for corrosive conditions. According to NCHRP's *Synthesis 474*, "The general view was that in the case of very narrow cracks, the process of concrete leachate interacting with atmospheric or waterborne CO_2 would cause calcite and other carbonate deposits that would seal such cracks" (2015). This process known as autogenous healing prompted FDOT to initiate a study at South Florida University (Figure 2-24). Results of the study determined that:

> Significant autogenous healing was not detected in cracks as narrow as 0.020 in. Corrosion tests showed that significant reinforcement corrosion took place in a short period of time with 0.100-in.-wide cracks, but that corrosion damage was much slower with cracks 0.020 in. wide. Allowable crack width limits above 0.100 in. are not acceptable under any circumstances (2015).

2.4.1.2 Sulfate Concentration

While a high concentration of sulfates may corrode metal culverts, they are typically more damaging to concrete. According to *Types and Causes of Concrete Deterioration*, “Sulfates can attack concrete by reacting with hydrated compounds in the hardened cement. These reactions can induce sufficient pressure to disrupt the cement paste, resulting in loss of cohesion and strength” (2002). A sulfate attack is greatly influenced by environmental conditions. An attack is more common in dry areas such as the Northern Great Plains and parts of the Western United States.

The Colorado Department of Transportation (CDOT) sponsored Colorado State University to research the relationship between the service life of a culvert and various parameters including the pH level and chloride and sulfate concentrations levels in the surrounding soil and water. The report *Development of New Corrosion/ Abrasion Guidelines for Selection of Culvert Pipe Materials* indicated that problems arise for concrete pipes when the sulfate concentration exceeds 1,000 parts per million (ppm).

The South Carolina Department of Transportation (SCDOT) and MnDOT both stipulate that concrete pipes are sufficient to withstand sulfate concentrations of 1,000 ppm or less. CALTRANS considers a site corrosive if the sulfate concentration exceeds 2,000 ppm. FDOT does not consider concrete vulnerable to accelerated deterioration unless the sulfate concentration exceeds 5,000 ppm. However, chloride ions are considered a larger threat in Florida as sulfate concentrations rarely exceed 1,500 ppm.

The most efficient way to protect against a sulfate attack is to choose a cement with a limited amount of tricalcium aluminate. ASTM C150, *Standard Specification for Portland Cement*, covers ten types of Portland cement: Type I, Type IA, Type II, Type IIA, Type II (MH), Type II (MH)A, Type III, Type IIIA, Type IV, and Type V. Type II or Type V cement is recommended when sulfate resistance is desired (Table 2-19). Other resistance factors may include reducing the water-to-cement ratio, using a higher strength concrete, or applying special coatings.

Table 2-19: Optional Composition Requirements (ASTM C150 2015)

Cement Type	Applicable Test Method	I and IA	II and IIA	II(MH) and II(MH)A	III and IIIA	IV	V	Remarks
Tricalcium aluminate (C_3A)[B], max, %	See Annex A1	...	...	...	8	...	...	for moderate sulfate resistance
Tricalcium aluminate (C_3A)[B], max, %	See Annex A1	...	...	...	5	...	...	for high sulfate resistance
Equivalent alkalies (Na_2O + 0.658K_2O), max, %	C114	0.60[C]	0.60[C]	0.60[C]	0.60[C]	0.60[C]	0.60[C]	low-alkali cement

[A] These optional requirements apply only when specifically requested. Verify availability before ordering. See Note 2.
[B] See Annex A1 for calculation.
[C] Specify this limit when the cement is to be used in concrete with aggregates that are potentially reactive and no other provisions have been made to protect the concrete from deleteriously reactive aggregates. Refer to Specification C33 for information on potential reactivity of aggregates.

In 2003, the Montana Department of Transportation sponsored a nationwide survey to determine the service life guidelines developed by other State Departments of Transportation. All 50 States were encouraged to participate, however only 20 States responded. According to the responses, "Two of the twenty states limit the use of reinforced concrete pipe based on sulfates. Eighteen states do not" (Molinas 2009). Table 2-20 depicts various sulfate exposures and the recommended cement type.

Table 2-20: Various Sulfate Concentrations (PCA 2002)

Sulfate exposure	Water-soluble sulfate (SO_4)in soil, percent by mass	Sulfate (SO_4) in water, ppm	Cement type[2]	Maximum water-cementitious material ratio, by mass	Minimum design compressive strength, MPa (psi)
Negligible	Less than 0.10	Less than 150	No special type required	—	—
Moderate[1]	0.10 to 0.20	150 to 1500	II, MS, IP(MS), IS(MS), P(MS) I(PM)(MS), I(SM)(MS)	0.50	28 (4000)
Severe	0.20 to 2.00	1500 to 10,000	V, HS	0.45	31 (4500)
Very severe	Over 2.00	Over 10,000	V, HS	0.40	35 (5000)

[1] Seawater.
[2] Pozzolans or slags that have been determined by test or service record to improve sulfate resistance may also be used.
Test method: *Method for Determining the Quantity of Soluble Sulfate in Solid (Soil or Rock) and Water Samples*, Bureau of Reclamation, 1977.
Source: Adapted from Bureau of Reclamation 1981 and ACI 318.

2.4.1.3 Electrochemical Corrosion

Resistivity is a measure of the soil's ability to conduct electrical current. Resistivity is measured in units of ohm-centimeters and, it greatly affects metal culverts. "Unlike zinc that acts as a sacrificial barrier, an aluminum coating serves as a long-lasting barrier. Aluminum reduces the potential differences between cathodes and anodes and therefore decreases the rate of the electrochemical process" (French 2013). According to MnDOT's *Drainage Manual*, "The greater the resistivity of the soil, the less capable the soil is of conducting electricity and the lower the corrosive potential" (2000). As stated in the *Drainage Manual,*

> Resistivity values in excess of about 5,000 ohm-cm are considered to present limited corrosion potential. Resistivities below the range of 1,000 to 3,000 ohm-cm will usually require some level of pipe protection, depending on the corresponding pH level (2000).

According to FDOT'S *Drainage Handbook Optional Pipe Material*s, resistivity values greater than 3,000 ohm-cm are considered high and will impede corrosion. Resistivity values less than 1,000 ohm-cm will accelerate corrosion. Typical soil corrosion potential resistivity values are shown in Table 2-21 and Table 2-22. Table 2-23 lists typical resistivity values associated with soil and water.

Table 2-21: Typical Soil Corrosion Potential Resistivity Values (NCHRP 2015)

Soil Corrosion Potential	Resistivity (Ohm-Centimeter)
Normal	R > 2,000
Mildly Corrosive	2,000 > R > 1,5000
Corrosive	1,500 > R

Table 2-22: Typical Soil Corrosion Potential Resistivity Values (NCHRP 2015)

Soil Corrosion Potential	Resistivity (Ohm-Centimeter)
Negligible	R > 10,000
Very Low	10,000 > R > 6,000
Low	6,000 > R > 4,500
Moderate	4,500 > R > 2,000
Severe	2,000 > R

Table 2-23: Typical Resistivity Values (Molinas 2009)

Soil		Water	
Classification	Ohm-Centimeter	Source	Ohm-Centimeter
Clay	750 – 2,000	Seawater	25
Loam	3,000 – 10,000	Brackish	2,000
Gravel	10,000 – 30,000	Drinking Water	4,000 +
Sand	30,000 – 50,000	Surface Water	5,000 +
Rock	50,000 – Infinity	Distilled Water	Infinity

The type of soil in which a culvert is buried is critical as granular soil exhibits a higher resistivity than non-granular soil. This soil-resistivity relationship is shown in Table 2-24. Agronomy and Soils Professor Charles C. Mitchell, Junior of Auburn University issued the report *Soils of Alabama* in furtherance for the United States Department of Agriculture. In the report, Professor Mitchell classifies Alabama's soil into seven major areas around the state. Figure 2-25 presents Professor Mitchell's seven classifications.

Table 2-24: Typical Corrosion Potential of Various Soil Conditions (NCHRP 2015)

Soil Type	Description of Soil	Aeration or Drainage	Water Table
Lightly Corrosive	- Sands or sandy loams - Light-textured silt loams - Porous loams or clay loams thoroughly oxidized to great depths	Good	Very low
Moderately Corrosive	- Sandy loams - Silt loams - Clay loams	Fair	Low
Badly Corrosive	- Clay loams - Clays	Poor	2 to 3-ft below surface
Unusually Corrosive	- Muck - Peat - Tidal marsh - Clays and organic soils	Very Poor	At surface or extreme impermeability

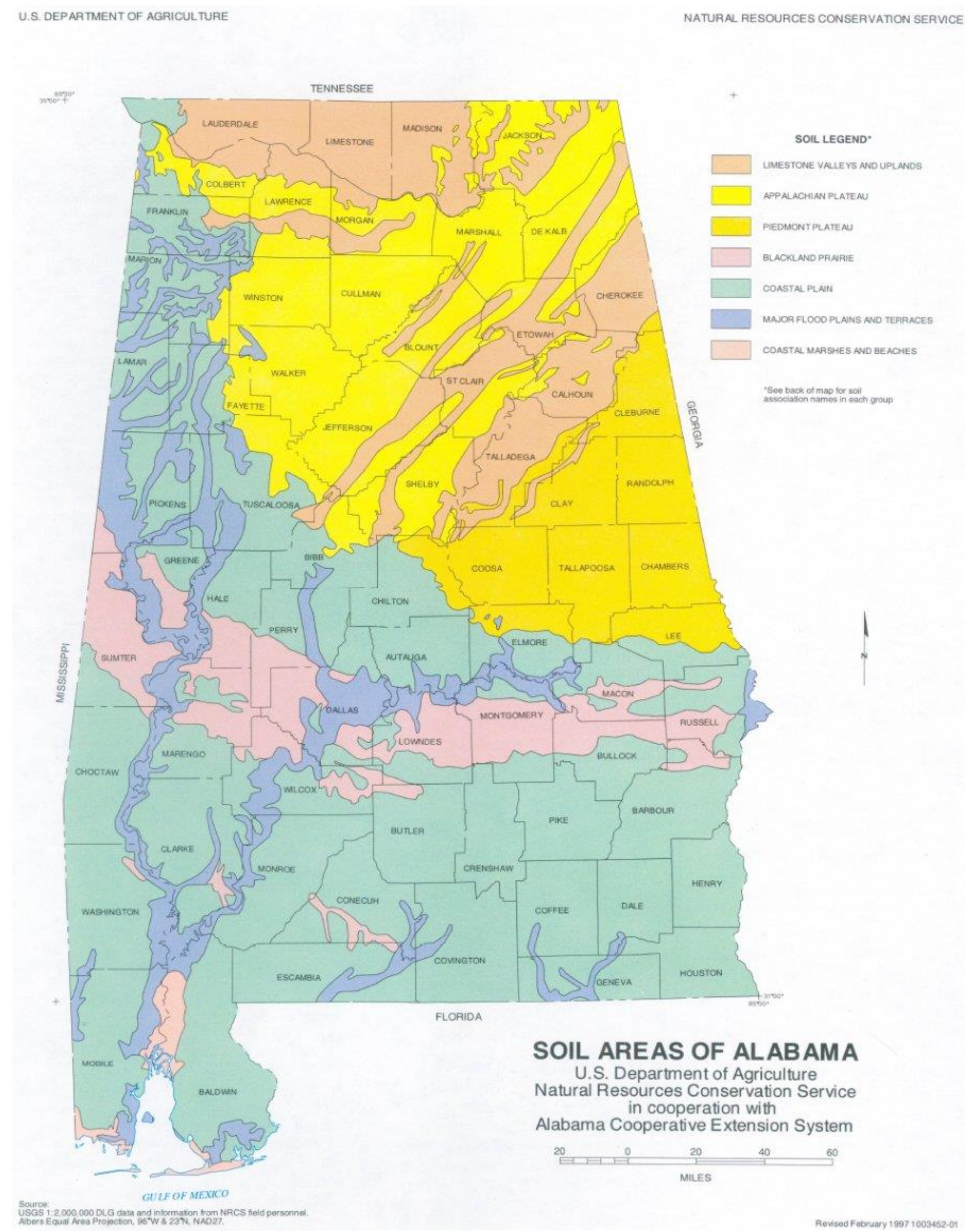


Figure 2-25: Soil Areas of Alabama (Mitchell 2008)

2.4.1.4 Hydrogen Ion Concentration

As defined by the United States Environmental Protection Agency,

> pH is an expression of hydrogen ion concentration in water. Specifically, pH is the negative logarithm of hydrogen ion (H^+) concentration in an aqueous solution:
>
> $$pH = -log_{10}(H^+)$$
>
> The term is used to indicate the degree of basicity or acidity of a solution ranked on a scale of 0 to 14, with pH 7 being neutral. As the concentration of H^+ ions in solution increases, acidity increases and pH gets lower, below 7. When pH is above 7, the solution is basic.

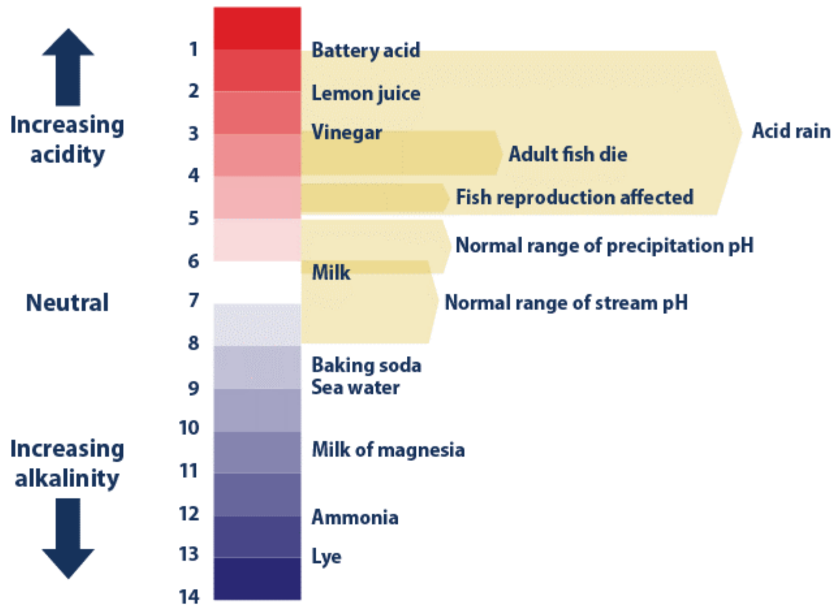


Figure 2-26: Hydrogen Ion Scale (EPA 2012)

The hydrogen ion scale shown in Figure 2-26 distinguishes between a basic and acidic solution. According to FDOT's *Drainage Handbook Optional Pipe Materials*, "When a culvert is placed in an environment in which the pH is too low (≤ 5.0) or too high (≥ 9.0), the protective layers of the culvert (concrete, galvanizing, aluminizing, etc.) can weaken, leaving the metal vulnerable to early corrosion" (2014). It is extremely important that the appropriate culvert material is chosen for the specific environmental conditions of the site. One of the most common preventative measures is to apply a protective coating.

The NCSPA published the *CSP Durability Guide* to provide environmental ranges for corrugated steel pipe products. An excerpt from this guide is shown in Figure 2-27. Accorrding to the *CSP Durability Guide*, in natural enviroments galvanized steel corrodes slower than steel. Galvanized steel should not be used where the pH is outside the range of 6.0 to 12.5. Aluminumized steel is quite stable in neutral solutions, as well as many acid solutions. However, aluminized steel is vulnerable to alkalies and should not be used where the pH is greater 9.0. Based on the pH levels, aluminumized steel has an advantage over galvanized steel in lower pH environments.

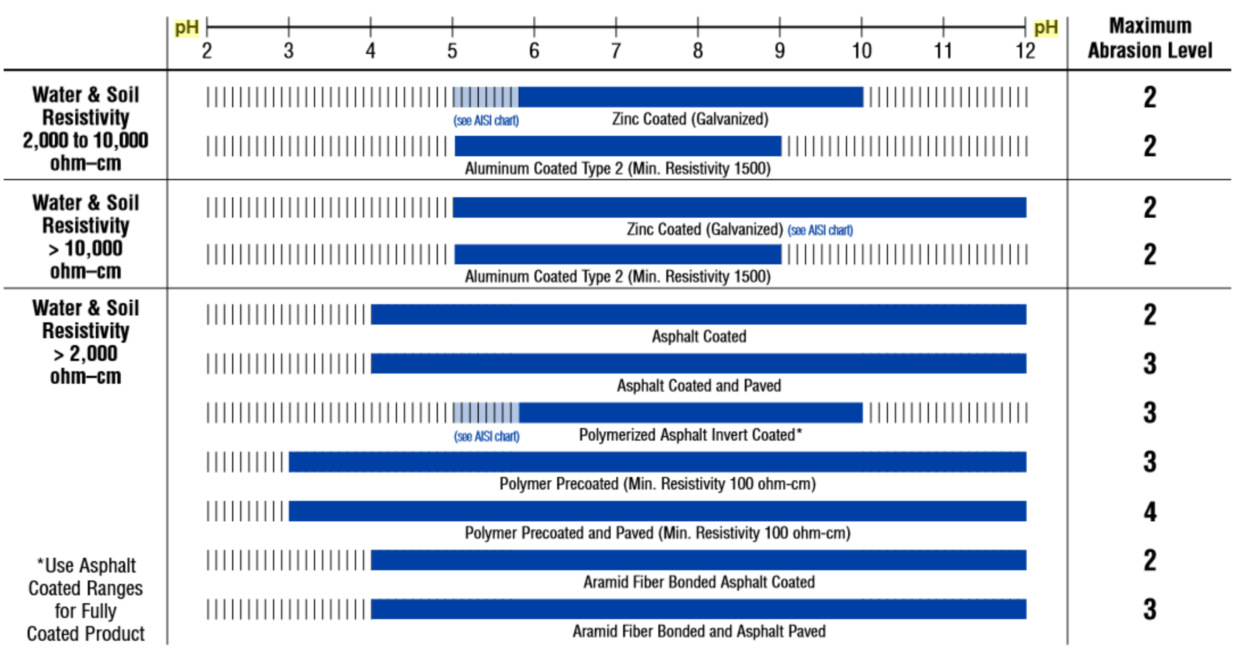


Figure 2-27: Environmental Guidelines for Corrugated Steel Pipe (NCSPA 2000)

Table 2-25: Environmental Ranges (NCSPA 2000)

Environmental Ranges	pH	Resistivity
Normal Conditions	5.8 – 8.0	> 2,000 ohm-cm
Mildly Corrosive	5.0 – 5.8	1,500 – 2,000 ohm-cm
Corrosive	< 5.0	< 1,500 ohm-cm

The FHWA allows high density polyethylene culverts to be used without regard to the resistivity and pH of the soil. Table 2-25 depicts various environmental ranges based on pH and resistivity. However, the same liberties cannot be applied to metal culverts or concrete culverts. According to the FHWA's *Hydraulic Design of Highway Culverts*, "Metal culverts are adversely affected by acidic and alkaline conditions in the soil and water, and by high electrical conductivity of the soil. Concrete culverts are sensitive to saltwater environments and to soils containing sulfates and carbonates" (2012). The hydrogen ion range for various culvert materials is shown in Table 2-26. Table 2-27 illustrates the Corps of Engineers' environmental range for metal pipes.

Table 2-26: Hydrogen Ion Range (FHWA 2012)

Galvanized Steel	6.0 < pH < 10
Aluminum	4.0 < pH < 9.0
Reinforced Concrete	< 5.0
High Density Polyethylene	1.5 < pH < 14

Table 2-27: Corps of Engineers' Range for Metal Pipe (French 2013)

Type of Material Used to Make Pipe	Soil and Water pH	Minimum Soil Resistivity (ohm-cm)
Galvanized Steel	6.0 – 8.0	≥ 2,500
Aluminized Steel, Type 2	5.0 – 9.0	≥ 1,500
Aluminum	5.0 – 9.0	≥ 1,500
Stainless Steel, Type AISI 409	5.0 – 9.0	≥ 1,500

2.4.2 Abrasion

As defined by the NCHRP, "Abrasion is the progressive loss of section or coating of a culvert by the continuous, rapid movement of turbulent water containing a bedload of particulate matter" (2015). Abrasion often accelerates corrosion by stripping away the surface material or protective coating of a culvert. Once the protective coating has been removed, the culvert's main defense against corrosion has been destroyed (Figure 2-28). The combined effects of corrosion and abrasion are well documented in NCHRP's *Synthesis 474*:

> The abrasive properties of bedload that is traveling at high velocities and is harder than the exposed pipe invert or coating will erode metal, concrete, and thermoplastic pipes. When corrosion and abrasion operate together in this manner, they can produce a larger detrimental effect than either would if applied in isolation. Abrasion accelerates corrosion by removing protective coatings, and corrosion can produce products less resistant to abrasion (2015).

Figure 2-28: Corrosion Accelerated by Abrasion of Metal Culvert (NCHRP 2015)

Steel pipe is the most susceptible to abrasion. However, aluminum pipe offers no improvement. According to *Synthesis 474*, “Although aluminum culverts are occasionally specified to combat corrosion, plain aluminum is typically not recommended for abrasive environments since tests indicate that aluminum can abrade as much as three times faster than the rate of steel” (2015). While the California Design Information Bulletin 83-2003 considers aluminized steel equivalent to galvanized steel in abrasive resistance, the NCSPA recommends using non-metallic coatings over metallic coatings for increased abrasion resistance (Figure 2-29).

● Shaded Circles Indicate Applicable Coatings

★ See AISI Chart

COATING	WATERSIDE: Normal Conditions	Mildly Corrosive	Corrosive	Non-Abrasive/Low Abrasion (Lvl. 1 & 2)	Moderate Abrasion (Level 3)	High Abrasion (Level 4)	Provides Additional Soil Side Protection
Zinc Coated (Galvanized)	●★	●★	○	●	○	○	○
Aluminum Coated Type 2	●	●	○	●	○	○	○
Asphalt Coated	●	●	●	●	○	○	●
Asphalt Coated and Paved	●	●	●	●	●	○	●
Polymerized Asphalt Invert Coated*	●	●	○	●	●	○	○
Polymer Precoated	●	●	●	●	●	○	●
Polymer Precoated and Paved	●	●	●	●	●	●	●
Polymer Precoated w/ Polymerized Asphalt	●	●	●	●	●	●	●
Aramid Fiber Bonded Asphalt Coated	●	●	●	●	○	○	●
Aramid Fiber Bonded and Asphalt Paved	●	●	●	●	●	○	●
High Strength Concrete Lined	●	●	○	●	●	○	○
Concrete Paved Invert (75mm (3”) Cover)	●	●	○	●	●	●	○

* Use Asphalt Coated Environmental Ranges for Fully Coated Product

Note: Coatings listed under additional soil side protection are generally considered to provide 100 years service life from a soil side perspective within appropriate environmental conditions.[1]

Figure 2-29: Product Usage Guidelines for Corrugated Steel Pipe (NCSPA 2000)

Abrasion is dependent on the velocity of water. As the velocity increases, the sand, gravel or stones carried by the water more forcefully attack the inside of a culvert. The Federal Lands Highway Division of the FHWA developed four levels of abrasion to help characterize the abrasion potential of a site (Table 2-28). According to *Synthesis 474*, "Generally, flow velocities less than 5 feet per second (ft./s) are not considered to be abrasive, even if bedload material is present. Velocities that exceed 15 ft./s and carry a bedload are considered to be very abrasive" (2015).

Table 2-28: Abrasion Levels (FLH 2012)

Non-Abrasive	Level 1	Non-abrasive conditions exist in areas of no bed load and very low velocities. This is the condition assumed for the soil side of drainage pipes
Low Abrasion	Level 2	Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 ft./sec. or less
Moderate Abrasion	Level 3	Moderate abrasive conditions exists in areas of moderate bed loads of sand and gravel and velocities between 5 ft./sec. and 15 ft./sec.
Severe Abrasion	Level 4	Severe abrasive conditions exist in areas of heavy bed loads of sand, gravel and rock and velocities exceeding 15 ft./sec.

Plastic pipe exhibits good abrasion resistance and will likely not experience the dual action of corrosion and abrasion. "Multiple tests and field evaluations prove that it takes significantly longer to abrade through high density polyethylene pipe walls than through concrete and metal" (French 2013). However, this claim was based on tests using small aggregate sizes flowing at low velocities. The effects of large bedload particles or high velocity flows are not well documented. In addition, rehabilitative strategies have not been specifically developed for plastic pipe due to their more recent emergence as a culvert material. While invert paving is a very common strategy for metal culverts, it would be "ineffective with plastic pipes because of their smooth surface and inability to achieve a satisfactory bond" (NCHRP 2015). Corrosion and abrasion guidelines followed by the New Mexico Department of Transportation are shown in Table 2-29.

Table 2-29: New Mexico DOT Corrosion and Abrasion Guidelines (Molinas 2009)

Material	Recommended Adjustments for Abrasion			
	Low Abrasion Level 1	Mild Abrasion Level 2	Moderate Abrasion Level 3	Severe Abrasion Level 4
Concrete Pipe	No Addition	No Addition	No Addition	Modify Mix Design
Aluminized Steel Type II	No Addition	No Addition	Add One Gage	Add One Gage and Pave Invert
Galvanized Steel (2 & 3 oz. Coating)	No Addition	Add One Gage*	Add Two Gages*	N/A
Polymer Pre-coated Galvanized Steel	No Addition	No Addition	Add One Gage	Add One Gage and Pave Invert
Aramid Fiber Bonded Galvanized Steel	No Addition	No Addition	No Addition	Add One Gage
Aluminum Alloy	No Addition	No Addition	Add One Gage	Add One Gage and Pave Invert
Thermoplastic Pipe (PVC & HDPE)	No Addition	No Addition	No Addition	N/A

*A field applied concrete paved invert per ASTM A849 may be substituted for one (1) gage thickness

2.4.3 Ultraviolet Radiation

Plastic pipes are affected by oxidation and ultraviolet radiation. According to the report *Evaluation of Polypropylene Drainage Pipe* published by the Virginia Center for Transportation Innovation and Research, "Polypropylene is highly susceptible to oxidation and undergoes oxidation more readily than polyethylene. Polypropylene can begin to disintegrate to an oxidized powder right after formation if no antioxidants are added during manufacturing" (Hoppe 2011).

Ultraviolet stabilizers and antioxidant packages are used to protect plastic pipes against this form of degradation. ASTM D 3350-14 *Standard Specification for Polyethylene Plastics Pipes and Fittings Materials* requires a minimum carbon black content of 2.0% be used for all polyethylene compounds. According to ADS Inc.'s *Drainage Handbook*:

> With the UV stabilizers incorporated into polyethylene and polypropylene, the radiation can only penetrate a thin layer into the pipe wall over the service life of the pipe. It is important to understand that once the outer layer has been faded by the sun, it functions as a shield to protect the rest of the pipe from further degradation. A high percentage of the pipe's original strength properties remain intact because the majority of the wall remains unharmed (2015).

The NCHRP published the report *HDPE Pipe: Recommended Material Specifications and Design Requirements* which describes the use of carbon black as a combatant to ultraviolet radiation. The report states, "Carbon black is added to the resin formulation to provide ultraviolet resistance. The pipe is only vulnerable to ultraviolet resistance light during the storage period and before backfilling. Once the pipe is covered by soil, it is not subjected to ultraviolet light" (1999).

While polyethylene pipes are black due to the carbon black resin, polyethylene pipes are grey. Carbon black is not used on polypropylene. Instead, ADS, Inc. incorporates an outdoor, weather-able pigment system plus a Hindered Amine Light Stabilizer (HALS) on polypropylene products. BASF, the North American affiliate of BASF SE, is a producer of HALS and discusses its use in the article *Get a Grip on Light with Uvinul®!*. According to the article,

> In contrast to the physically active UV absorbers, the various HALS react chemically. They interrupt the propagation of polymer degradation by scavenging the radicals created at chain breaks, thus rendering them harmless. Their high level of protection is due to the fact that each stabilizer molecule is not only able to react once but may react many times. This sustainably decelerates the chain reaction of degradation (BASF n.d.).

M. S. Jones of the Building Research Association of New Zealand published the paper *Effects of UV Radiation on Building Materials*. The paper examined the effects of ultraviolet radiation on polymer-based products as well as the use of accelerated weathering techniques. *Effects of UV Radiation on Building Materials* warns of the serious effects of photo-degradation including discoloration, micro-cracking and embrittlement of substrates (Figure 2-30). “These effects [micro-cracking and embrittlement] are often accompanied by extensive deterioration in the mechanical properties of the materials, such as tensile strength, impact strength and elongation” (Jones 2002).

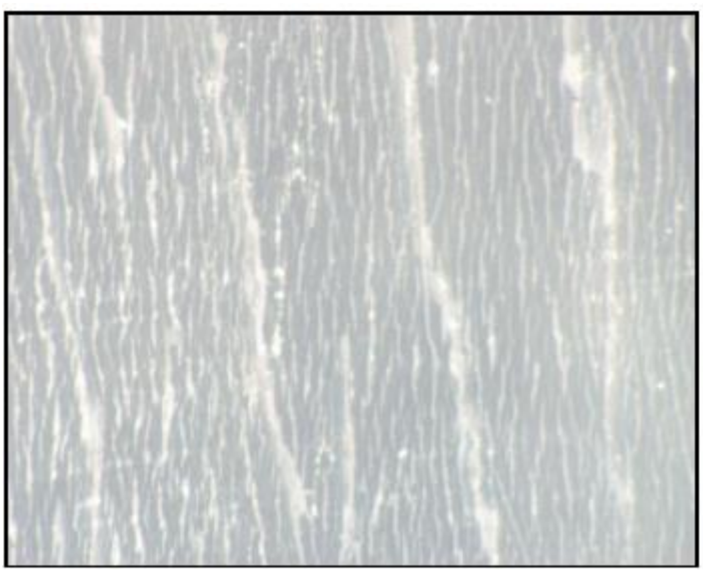


Figure 2-30: Micro-cracking of UV Exposed Polypropylene (Jones 2002)

The Building Research Association of New Zealand established four identical exposure sites across the country to determine whether climatic variations, including ultraviolet radiation, have a significant effect on plastics. The plastic samples that were chosen include polyvinyl chloride, low density polyethylene, and polypropylene. The exposure sites were located at Kaitaia, Paraparaumu, the Building Research Association of New Zealand at Judgeford, and Invercargil. According to the results, "There are noticeable trends developing with the tensile strengths of the polyolefins" (Jones 2002). The results of the study are shown in Figure 2-31.

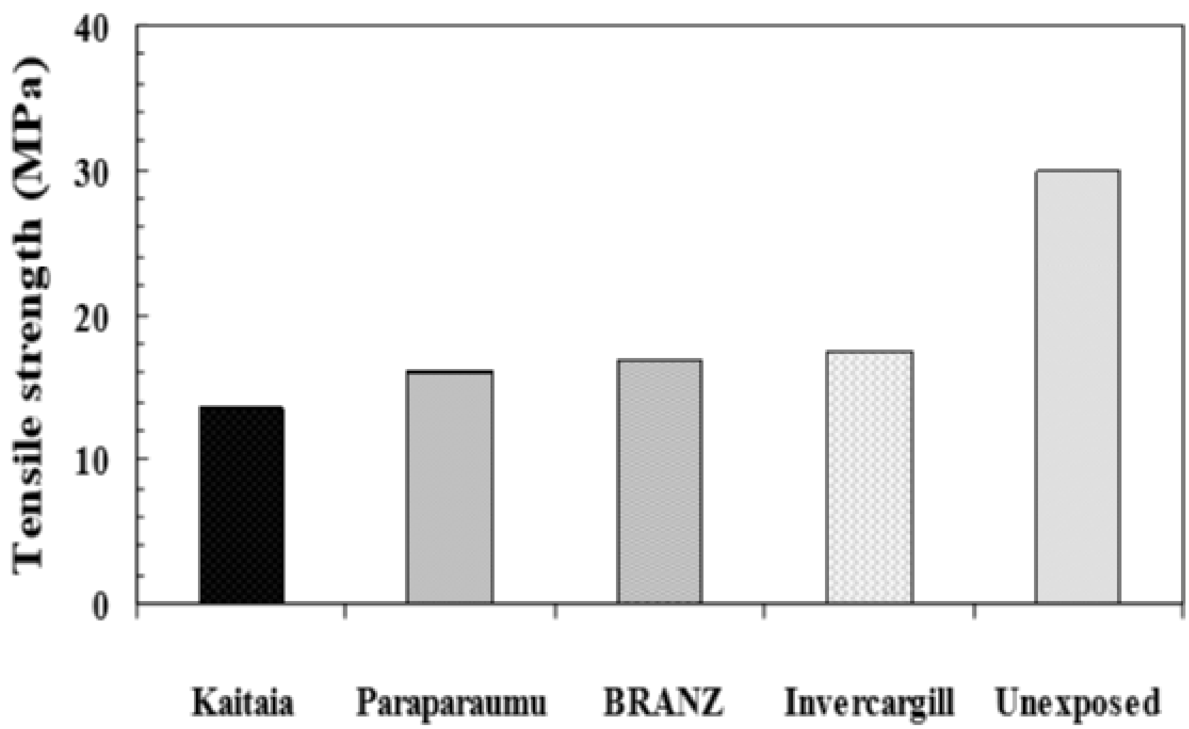


Figure 2-31: Tensile Strengths of Exposed Polypropylene (Jones 2002)

2.4.4 Flammability

All culvert materials are affected by fire and extremely high temperatures. According to the *Buried Facts* article "Fires in Sewers and Culverts" published by the ACPA,

> Fires in concrete pipe generally do not affect structural strength, flow capacity, or corrosion and abrasion resistance. Metal pipe is usually lined and coated to forestall electrolytic and galvanic corrosion of the pipe wall and to improve hydraulic characteristics. These coatings will burn when exposed to fire. The intense heat can also alter the properties of the metal and result in deflection and loss of structural integrity. Plastic pipe will suffer the same fate as metal, or worse, if the pipe melts and collapses (1982).

Hancock Concrete Products, a precast concrete manufacturing company in the United States, and the ACPA claim that concrete will not burn. However, extremely high temperatures can affect the compressive strength, flexural strength, and modulus of elasticity of the concrete. The modulus of elasticity is the most sensitive to elevated temperatures of those three. The effects of elevated temperatures are shown in Figure 2-32.

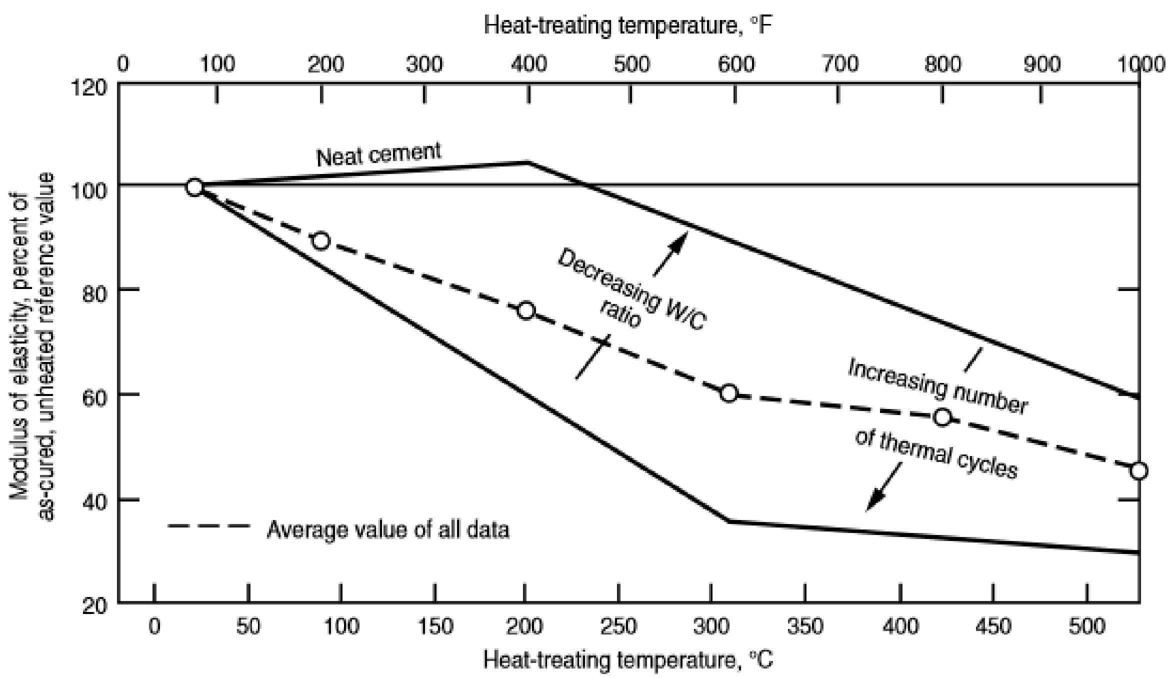


Figure 2-32: Effects of Elevated Temperatures on Modulus of Elasticity (PCA 2002)

Mounting concerns regarding the flammability of high density polyethylene prompted the FDOT to conduct a study to determine the actual risk of fire in typical pipe installations. The results of the study indicate that "high-density polyethylene pipe is not at significant risk of fire when installed to present standards and exposed to fire such as that which may be encountered in roadside grass fires." This claim is further supported by *Synthesis 474* which states,

> In forest fires, all pipe material types can sustain damage from exposure to extremely high temperatures. While thermoplastic pipes would be the most vulnerable, the National Fire Protection Association (NFPA 2012) has given both polyethylene and polypropylene a rating of 1 (Slow Burning) on a scale of 0 to 4, where higher ratings indicate a greater vulnerability (2015).

Figure 2-33: Plastic Culvert on Fire in Santa Barbara, California (Scully 2015)

Despite these assurances, several departments of Transportation have reported that the pipe ends and the flared end sections of polyethylene pipe have caught on fire as a result of crop, leaf, or controlled burning in roadside ditches. Figure 2-33 illustrates a plastic culvert on fire in Santa Barbara, California. The Michigan Department of Transportation updated their "Culvert and Storm Sewer Pipe Material Policy on Federally Funded Local Agency Projects" in March 2013 to warn of the flammability of polyethylene pipe. As stated in the policy, "In project locations where controlled burning is a common occurrence, concrete or metal culverts may be specified. It may be possible to specify polyethylene culverts as long as a metal or concrete flared end section is also installed" (2013).

The United States Department of Agriculture examined slip-lining as a possible rehabilitative measure for corrugated metal culverts in the report *Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement using Trenchless Technology*. The report listed polyethylene as a possible material for slip-lining, but noted cases of the liner catching on fire. According to *Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement using Trenchless Technology*,

> North Dakota Department of Transportation incurred severe damage to some polyethylene liners installed in corrugated metal pipes due to ditch fires. In 2007, the Cascade Complex fires in the Payette National Forest in Idaho resulted in the destruction of 142 high-density polyethylene culverts ranging in diameter from 18 to 36 inches, 41 wood culvert inlet headwalls, and 50 high-density polyethylene culvert downspouts (Kestler 2012).

As a result, the North Dakota Department of Transportation researched alternative liners in the report *Cost Effective Non-Flammable Pipe Liners*. The fiberglass composites pipes revealed to have the most fire resistance. However, polyethylene liners are more economical. Therefore, the report recommended using high density polyethylene liners with concrete end caps. As a result of the Cascade Complex fires in Idaho, “the Forest Service and the FHWA recommend concrete or masonry headwalls for flammable plastic culverts and liners in forest environments where fire is a possibility” (Kestler 2012). Figure 2-34 depicts one of the burned high density polyethylene culvert inlets at the Cascade Complex in Idaho.

Figure 2-34: Burned High Density Polyethylene Inlet (Kestler 2012)

In addition to the lessons learned by Michigan, North Dakota, and Iowa, AASHTO M294 2008 warns that, “When polyethylene pipe is to be used in locations where the ends may be exposed, consideration should be given to protection of the exposed portions due to combustibility of the polyethylene and the deteriorating effects of prolonged exposure to ultraviolet radiation” (2008).

2.5 Hydraulic Design

Before the hydraulic design of a culvert can begin, the design discharge must be estimated. According to CALTRAN's *Highway Design Manual*, "The most important step is to establish the appropriate design storm or flood frequency for the specific site and prevailing conditions" (2006). The types of flow and control used in the design of highway culverts are: Inlet Control and Outlet Control. Different factors and formulas are used to compute the hydraulic capacity of a culvert based on the type of control. The FHWA's *Hydraulic Design of Highway Culverts* presents the primary design factors associated with each type of control. These design factors are shown in Table 2-30.

Table 2-30: Factors Influencing Culvert Design (FHWA 2012)

Factor	Inlet Control	Outlet Control
Headwater	X	X
Area	X	X
Shape	X	X
Inlet Configuration	X	X
Barrel Roughness	–	X
Barrel Length	–	X
Barrel Slope	X	X
Tailwater	–	X

Note: For inlet control the area and shape factors relate to the inlet area and shape. For outlet control they relate to the barrel area and shape.

Headwater and tailwater refer to specific depths of water measured from the culvert. An example of headwater and tailwater is shown in Figure 2-35 and Figure 2-36, respectively. As stated in Chapter 1 of the FHWA's *Hydraulic Design of Highway Culverts*,

> The depth of the upstream water surface measured from the invert at the culvert entrance is generally referred to as headwater depth. Tailwater is defined as the depth of water downstream of the culvert measured from the outlet invert. It is an important factor in determining culvert capacity under outlet control conditions (2012).

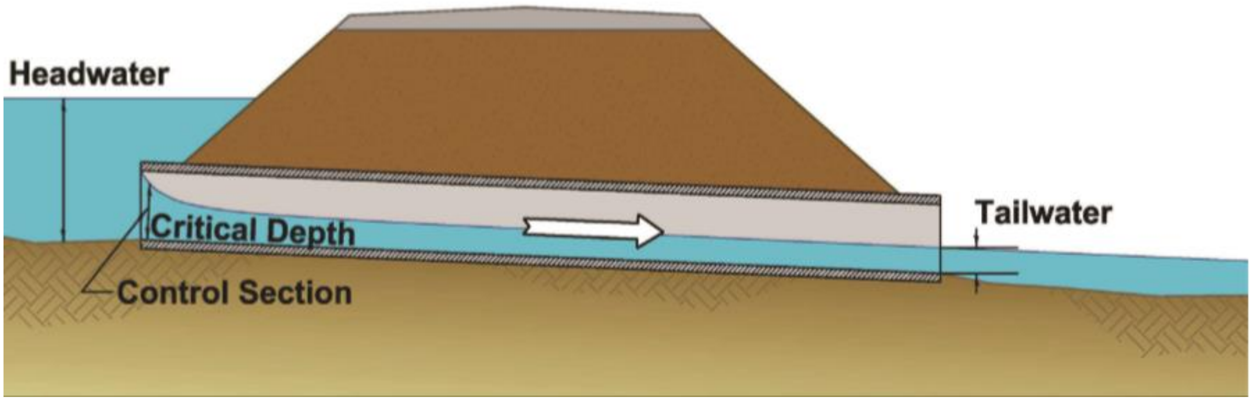


Figure 2-35: Typical Inlet Flow Control Section (FHWA 2012)

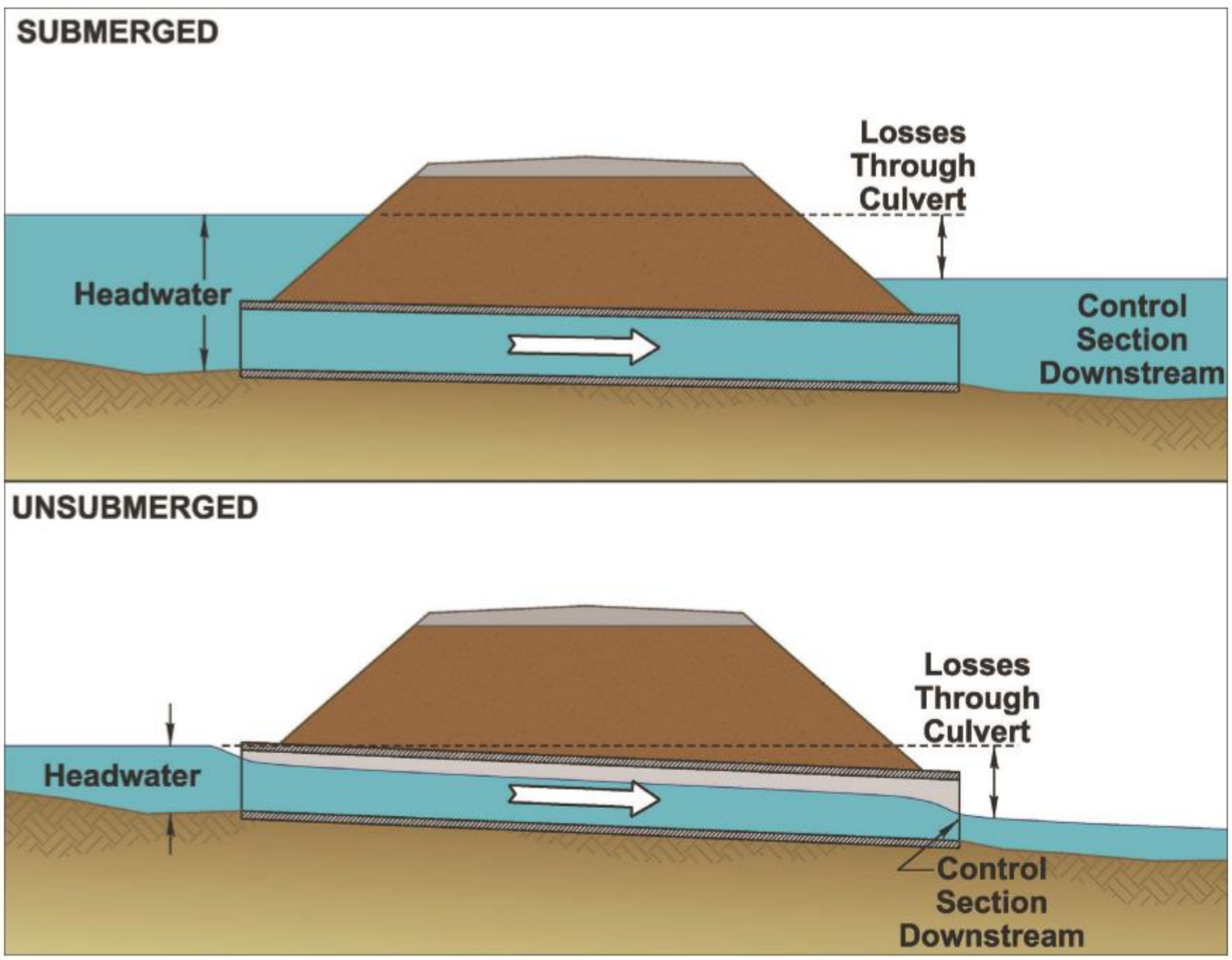


Figure 2-36: Typical Outlet Control Flow Conditions (FHWA 2012)

2.5.1 Roughness Coefficient

Selecting the correct coefficient of roughness is essential in evaluating the flow and determining the adequate pipe diameter. An excessive coefficient of roughness leads to an uneconomical design and oversizing of the pipe. However, an insufficient coefficient of roughness leads to a hydraulically inadequate pipe. An inadequate hydraulic design leaves culverts susceptible to debris and sediment buildup. This buildup will slowly reduce the capacity of the culvert leading to expensive, time-consuming maintenance and will begin to prohibit the passage of aquatic organisms.

One way to determine the capacity of flow is by the use of Manning's Equation shown below. As stated in ADS, Inc.'s *Drainage Handbook*, "Manning's Equation is the most widely recognized means of determining pipe capacity for gravity flow installations" (2015). The equation was developed by Irish engineer Robert Manning as an alternative to the Chezy Equation. Manning's Equation assumes uniform flow conditions. While the coefficient of roughness or Manning's n can be calculated, it is often selected from tables.

$$Q = \frac{1.486}{n} AR^{2/3} S^{1/2}$$

Where:

Q = Pipe Capacity
A = Cross-sectional Flow Area
R = Hydraulic Radius
S = Slope of Pipe
N = Coefficient of Roughness

The coefficient of roughness has been the focus of extensive research, and recommended values vary by State Departments of Transportation (Table 2-31, Table 2-32, and Table 2-33). However, the values generally fall within the same range. The most significant variances have been found between laboratory tests and accepted design values. According to the article *Hydraulic Efficiency*, laboratory results have been obtained utilizing clean water and straight pipe sections. This leads to wide discrepancies between the coefficient of roughness for smooth wall and rough wall pipes. According to *Manning's n Values History of Research*,

> Rough wall, such as unlined corrugated metal pipe have relatively high values which are approximately 2.5 to 3 times those of smooth wall pipe. Smooth wall pipes were found to have values ranging between 0.009 and 0.010 but, historically, engineers familiar with sewers have used 0.012 or 0.013. This "design factor" of 20-30 percent takes into account the difference between laboratory testing and actual installed conditions (2012).

Table 2-31: Coefficient of Roughness (FDOT 2016)

Concrete	Metal		Polyethylene		Polypropylene	
	Helical	Spiral Rib	Single Wall	Double Wall	Single Wall	Double Wall
0.012	0.020 – 0.024	0.012	0.024	0.012	0.024	0.012

Table 2-32: Recommended Values for Manning's Coefficient of Roughness

American Concrete Pipe Association (ACPA)	National Corrugated Steel Association (NCSA)	Advanced Drainage Systems (ADS, Inc.)
Precast Concrete	Corrugated Metal	High Density Polyethylene
0.011 – 0.012	0.011 – 0.021	0.009 – 0.012

Table 2-33: Manning's n Value for Metal Culverts (FHWA 2012)

Type of Metal Culvert	Roughness or Corrugation	Manning's n
Spiral Rib	Smooth	0.012 – 0.013
Helical Corrugations	2-2/3 x ½ inch	0.011 – 0.023
Helical Corrugations	6 x 1inch	0.022 – 0.025
Annular Corrugations	2-2/3 x ½ inch	0.022 – 0.027
Annular Corrugations	5 x 1 inch	0.025 – 0.026
Annular Corrugations	3 x 1 inch	0.027 – 0.028

2.5.2 Aquatic Organism Passage

Culverts have only recently been designed to consider fish passageways. The desire for hydraulic efficiency often controlled the design. This caused engineers to overlook how the structure might impact the aquatic environment. Figure 2-37 illustrates a culvert design that prevents fish passage while Figure 2-38 illustrates a culvert design that allows fish passage. According to a study performed by North Carolina State University, "Alteration of streams by constructing of road crossing structures can degrade stream habitat leading to a loss of fish spawning sites and an overall reduction of species richness and diversity" (Bogan 2007). The report *A Comparison of the Impacts of Culverts versus Bridges on Stream Habitat and Aquatic Fauna* assessed the impacts of culverts and bridges on stream habitat and stream fauna for the North Carolina Department of Transportation.

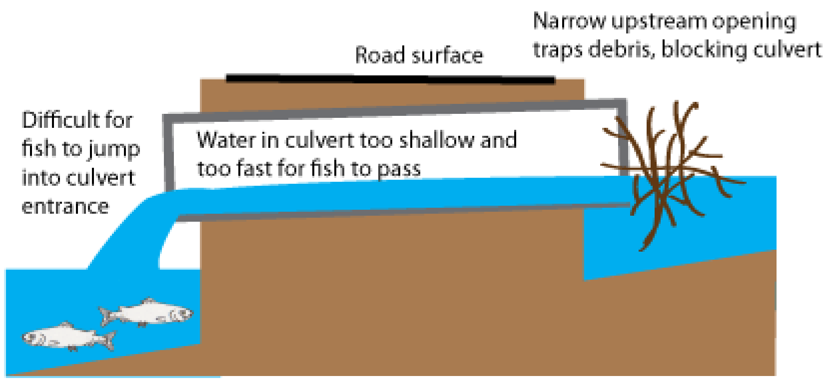


Figure 2-37: Culvert Design that Prevents Aquatic Organism Passage (NOAA n.d.)

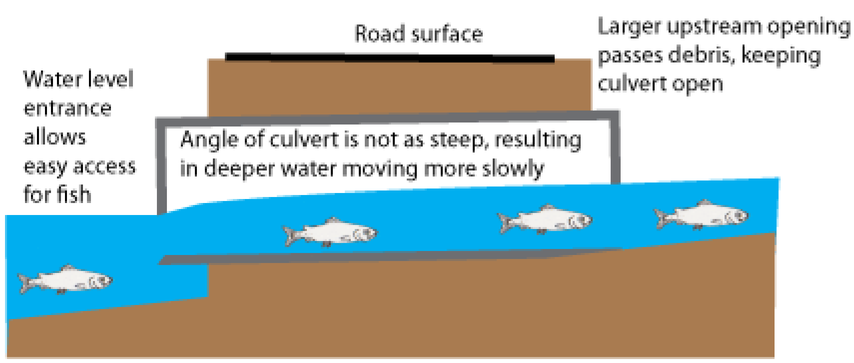


Figure 2-38: Culvert Design that Allows Aquatic Organism Passage (NOAA n.d.)

According to *A Comparison of the Impacts of Culverts versus Bridges on Stream Habitat and Aquatic Fauna*, "Culverts are typically the most economically feasible road crossing and potentially the most damaging to biota, stream morphology, and hydraulics" (Bogan 2007). The United States General Accounting Office published the report *Restoring Fish Passage through Culverts and Forest Service and BLM Lands in Oregon and Washington could Take Decades.* The report determined that over half of the 10,000 culverts surveyed on Bureau of Land Management and Forest Service lands in Oregon and Washington are considered barriers to the passage of juvenile salmon.

> Agency inventory and assessment efforts have already identified nearly 2,600 barrier culverts, but agency officials estimate that more than twice that number may exist. Based on current assessments, the agencies estimate that efforts to restore fish passage may ultimately cost over $375 million and take decades (2001).

The FHWA published two documents to serve as a design aid to facilitate aquatic organism passage in culverts. These documents include: *Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report* and *Culvert Design for Aquatic Organism Passage*. The *Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report* is a compilation of design options, case histories, and assessment techniques to provide an array of appropriate design methods to facilitate fish passage. The document serves only as a reference. The *Culvert Design for Aquatic Organism Passage* presents a stream simulation design procedure as well as methods and best practices for designing culverts to facilitate fish passage. Table 2-34 lists seven types of barriers that have the potential to act as a barrier of fish passage. Figure 2-39 is an example of a metal culvert that prevents fish passage. Figure 2-40 and Figure 2-41 illustrate bottomless culverts designed for aquatic organism passage.

Table 2-34: Why Culverts are a Barrier of Fish Passage (FHWA 2007)

Barrier Type	Impact
Drop	Fish cannot enter structure, can be injured, or will expend too much energy entering the structure to transverse other obstacles
Velocity	High velocity exceeds fish swimming causing fish to tire before passing the crossing
Turbulence	Fire do not enter culvert or are unable to successfully navigate the waterway
Length	Fish may not enter structure due to darkness and fish may fatigue before traversing the structure
Depth	Low flow depth causes fish not to be fully submerged causing fish to be unable to swim efficiently or unable to pass the structure
Debris	Fish may not be able to pass by debris or constricted flow may create a velocity or turbulence barrier within the culvert
Cumulative	Group of culverts, each marginally passable, may be a combined barrier which stresses fish during passage

Figure 2-39: Culvert Barrier to Fish Passageway (USDA 2005)

Figure 2-40: Bottomless Culvert for Aquatic Organism Passage (GDOT 2014)

Figure 2-41: Embedded Box Culvert for Aquatic Organism Passage (GDOT 2014)

2.7 Minimum and Maximum Diameter

Culverts must be sized appropriately to meet the maximum anticipated site conditions. If a culvert is too small, debris may prevent the flow of water or the passage of aquatic organisms. Other possible failures that could result from incorrect sizing can include flooding, road washouts, blowouts, and erosion. The culvert shown in Figure 2-42 is inadequately sized to pass the large debris moving through the drainage. In addition to rainfall, some culverts must be designed for sudden snowmelt in areas subjected to snow accumulation. The effects of a hurricane may also be considered in the design. These conditions could greatly exceed the pipe's designed capacity if not taken into account.

Figure 2-42: Inadequately Designed Culvert (Keller 2003)

According to the Department of the Interior Bureau of Land Management, culverts are typically designed for a minimum 20-year storm event. However, local regulations may require a more conservative design. The double box culvert shown in Figure 2-43 may appear overdesigned. However, it was strategically designed to safely pass the anticipated design flow based upon a hydrological analysis of a 20 year to 50 year storm recurrence event.

Figure 2-43: Reinforced Concrete Box Culvert (Keller 2003)

In 2004, the WisDOT published the bulletin *Culverts – Proper Use and Installation*. According to the bulletin, "Small increases in diameter can significantly increase culvert capacity. For example, a 30" culvert can handle 50% more water than a 24" culvert" (2004). The Office of Federal Lands and Highway established the following minimum pipe size criteria to limit maintenance problems due to debris or sedimentation:

- 24-inch or equivalent for cross-road culverts
- 18-inch or equivalent for parallel culverts in roadside ditches and channels

Culvert pipes are available in 6-inch increments. Table 2-35 shows the maximum culvert pipe diameters specified by the ConnDOT.

Table 2-35: Specified Maximum Pipe Diameters (ConnDOT 2000)

Pipe Material	Maximum Diameter
Reinforced Concrete	180 inches
Corrugated Steel	144 inches
Corrugated Aluminum	120 inches
Polyethylene	96 inches

The following State Departments of Transportation specify a minimum 18-inch pipe diameter for cross drain application: Florida, Kentucky, Pennsylvania, Massachusetts, Maine, Georgia, Tennessee, and California. The South Dakota Department of Transportation specifies a 24-inch minimum pipe diameter for cross drain application to avoid construction, maintenance and clogging problems. Table 2-36 shows the minimum size culvert used for cross drain application by the Louisiana Department of Transportation (LaDOTD). Circular and arch cross drain pipes are given the same minimum size. According to LaDOTD's *Hydraulic Manual*,

> In general, plastic pipes are the same size as concrete pipes, whereas metal pipes are at least one size larger in order to achieve the same hydraulic performance. That is, for diameters up to 60″ in diameter, metal pipes will be 6″ larger and for diameters 60″ and greater, metal pipes will be 12″ larger (2011).

Table 2-36: LaDOTD Minimum Culvert Size (LaDOTD 2011)

Location	Structure	Minimum Size
Cross Drains	Cross Drain Pipe (Arch)	24″ diameter or round equivalent arch
	Reinforced Concrete Box	4′ x 4′

2.8 Minimum and Maximum Soil Cover

"Buried structures shall be designed for force effects resulting from horizontal and vertical earth pressure, pavement load, live load, and vehicular dynamic load allowable" (AASHTO 2007). The amount of load exerted on a culvert is dependent on many factors. According to ConnDOT's *Drainage Manual*,

> The amount of both dead and live load that is actually exerted on a culvert depends upon whether it is a rigid or flexible material, the height of the embankment above the culvert, the type of material surrounding the culvert, the degree of compaction of the material, and whether special types of structural members are built around the culvert to resist and distribute soil pressures (2000).

Examples of dead loads include the weight of embankment or fill covering the culvert. Examples of live loads include vehicular or pedestrian traffic plus an impact factor. "Wind, temperature, vehicle braking, and centrifugal forces typically have little effect due to earth protection. Structure dead load, pedestrian live load, and ice loads are insignificant in comparison with force effects due to earth fill loading" (AASHTO 2007). The impact factor equation shown below accounts for the rolling motion of the vehicle over a relatively shallow buried pipe. The stationary vehicular load is then multiplied by the impact factor to incorporate additional forces into the design.

$$\mathrm{IM} = 33(1.0 - 0.125\mathrm{H}) \geq 0\%$$

Where:

IM = Impact Factor, %
H = Burial Depth, ft.

Standard vehicular live loads have been established by AASHTO. These loads are not representative of actual vehicles, but serve as a good approximation based on analysis. The most common vehicular loading for design and analysis include the H and HS standard trucks. Figure 2-44 illustrates typical AASHTO highway loads and Table 2-37 shows the load carried by wheel set. According to CALTRANS' *Bridge Design Specifications*, culverts shall be designed for only HS-20 live loads.

According to the Ohio Department of Transportation's *Bridge Mechanics*, the H and HS standard trucks are defined as follows:

- H Loading – H20-44 indicates a 20 ton vehicle with a front axle weighing 4 tons and a rear axle weighing 16 tons. The two axles are spaced 14 feet apart.
- HS Loading – A two unit, three axle vehicle comprised of a highway tractor with a semi-trailer. Spacing from the rear tractor axle can vary from 14 to 30 feet.

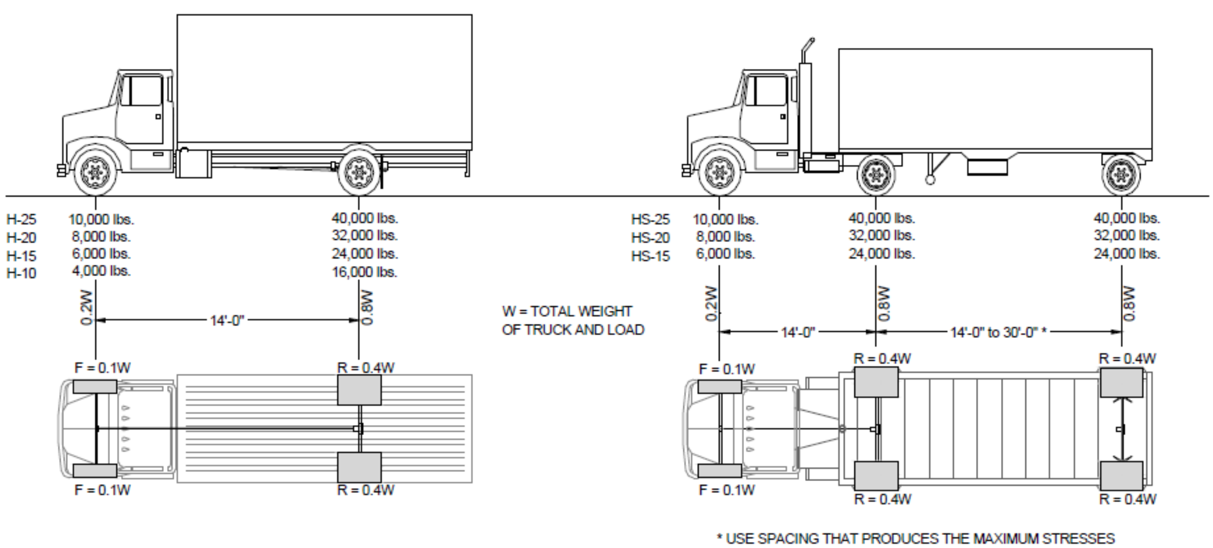


Figure 2-44: AASHTO Highway Loads (ADS, Inc. 2015)

Table 2-37: AASHTO Highway Loads Carried by Wheel Set (ADS, Inc. 2015)

Wheel Set	H-10 lbs. (kN)	H-15 or HS-15 lbs. (kN)	H-20 or HS-20 lbs. (kN)	H-25 or HS-25 lbs. (kN)
W	20,000 (89.0)	30,000 (133.4)	40,000 (178.0)	50,000 (222.4)
F	2,000 (8.9)	3,000 (13.3)	4,000 (17.8)	5,000 (22.2)
R	8,000 (35.6)	12,000 (53.4)	16,000 (71.2)	20,000 (89.0)
R_{AXEL}	16,000 (71.1)	24,000 (106.7)	32,000 (142.3)	40,000 (177.9)

The amount of cover height required is dependent on the pipe material and varies by Departments of Transportation. The Department of the Interior Bureau of Land Management illustrates proper culvert backfill and compaction in Figure 2-45 and recommends the following:

- Metal and plastic culvert pipes have a minimum fill depth of 1 foot
- Concrete culvert pipes have a minimum fill depth of 2 feet

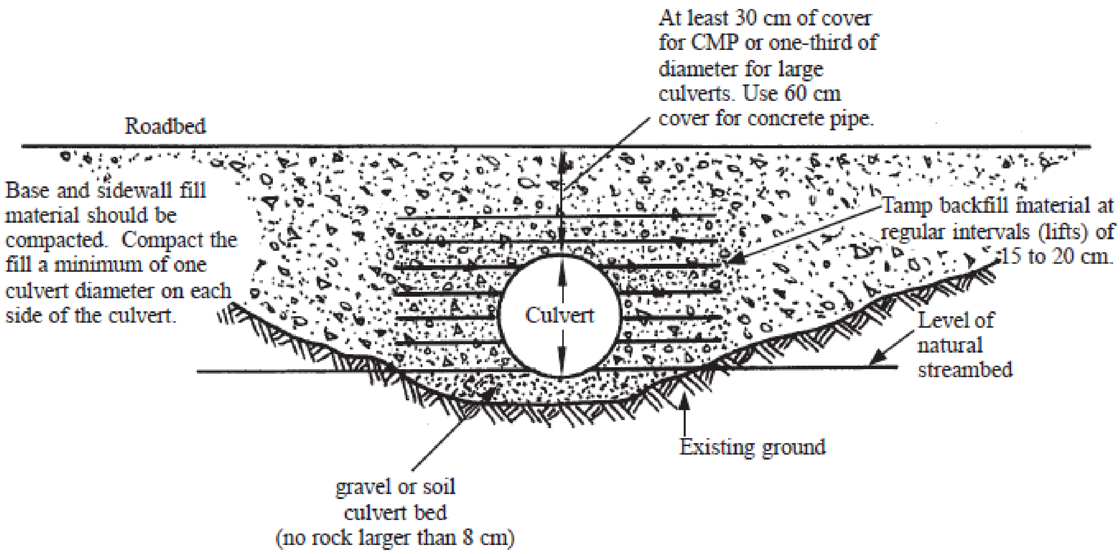


Figure 2-45: Culvert Backfill and Compaction (Keller 2003)

The cover height may be temporarily increased during construction to protect the culvert against heavy equipment. If the weight of the equipment exceeds the design load of the pipe, serious structural problems may occur. "Field tests and analyses prove that the use of heavy construction equipment for compacting or other construction purposes can cause significant stresses and deformations in pipes" (Zhao 1998). According to the report *High Density Polyethylene Pipe Fill Height Table*, three State Departments of Transportation specified an increase in minimum cover during construction: Alaska, Colorado, and South Carolina. These minimum covers may be found in Table 2-38. Figure 2-46 illustrates the use of a temporary cover to protect the pipe against construction equipment traffic.

Table 2-38: Minimum Fill Height during Construction (Ardani 2006)

State Department of Transportation	Minimum Fill Height during Construction
Alaska	4 ft.
Colorado	3-4 ft.
South Carolina	3-4 ft.

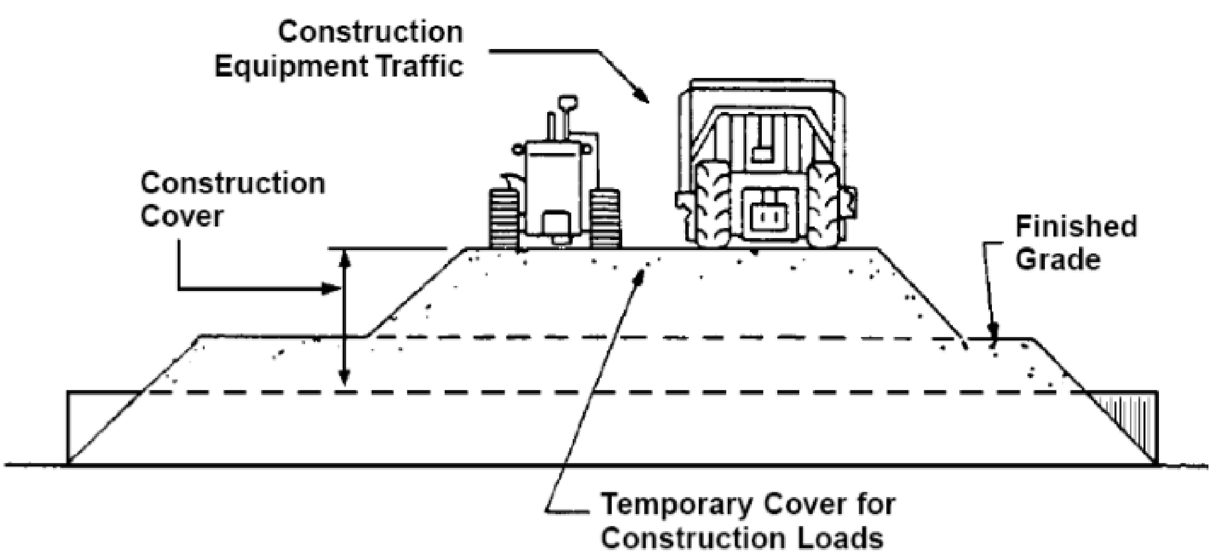


Figure 2-46: Temporary Cover for Construction Loads (UDOT 2008)

According to the NYDOT's *Geotechnical Design Manual*, "Use of extra strong pipe, placement of timbers as bridging to spread the load, or increasing the fill height above the pipe at crossings are precautions which can be taken" (2013). Appendix C to ConnDOT's *Drainage Manual* requires the engineer to determine the minimum cover for plastic pipe be based on an evaluation of specific site conditions. However, the minimum cover above the pipe shall be at least 3 feet or one pipe diameter in the absence of pipe strength calculations. "The minimum cover should be maintained before allowing vehicles or heavy construction equipment to traverse the pipe trench" (2002).

The NCDOT's *Drainage User Manual* permits an increase in minimum cover if the Contractor's equipment would cause damage to the completed pipe culvert. As stated in the *Drainage User Manual*,

> The Specifications require that no heavy equipment shall be allowed to operate over any pipe culvert until the backfill is completed to at least three feet above the top of the pipe. This minimum cover must be maintained until heavy equipment usage is discontinued and the Contractor is prepared to set the final grade (2003).

The Corrugated Polyethylene Pipe Association published the guide *Recommended Installation Practices for Corrugated Polyethylene Pipe and Fittings*. According to the guide, the surest solution to protect plastic pipe from unanticipated equipment loads is to reroute construction traffic around the pipe. However, if construction traffic cannot be rerouted, the guide recommends adding at least 3 feet of additional compacted soil over the pipe crown. "This mound can then be graded at the end of construction when heavy traffic is no longer present" (2000). Temporary cover for construction loads shall not be considered in Appendix B.

Section 12 of the *AASHTO LRFD Bridge Design Specifications* specifies the minimum soil cover for buried structures and tunnel liners. According to Section 12.6.6.3, "The cover of a well-compacted granular subbase, taken from the top of rigid pavement or the bottom of flexible pavement, shall not be less than that specified in Table 6-5" (2007). AASHTO Table 6-5 is represented by Table 2-39 shown below. These minimum values match the majority of minimum covers specified by the State departments. "Additional cover requirements during construction shall be taken as specified in Article 30.5.5 of the *AASHTO LRFD Bridge Construction Specifications*" (2007).

Table 2-39: Minimum Soil Cover (AASHTO 2007)

Type	Condition	Minimum Cover
Corrugated Metal Pipe	–	$S/8 \geq 12.0$ in.
Spiral Rib Metal Pipe	Steel Conduit	$S/4 \geq 12.0$ in.
	Aluminum Conduit	$S/2 \geq 12.0$ in.
	Aluminum Conduit	$S/2.75 \geq 24.0$ in.
Structural Plate Pipe Structures	–	$S/8 \geq 12.0$ in.
Long-Span Structural Plate Pipe Structures	–	Refer to Table 12.8.3.1.1-1
Structural Plate Box Structures	–	1.4 ft. as specified in Article 12.9.1
Reinforced Concrete Pipe	Unpaved areas and under flexible pavement	$B_c/8$ or $B'_c/8$, whichever is greater, ≥ 12.0 in.
	Compacted granular fill under rigid pavement	9.0 in.
Thermoplastic Pipe	–	$ID/8 \geq 12.0$ in.

Where,

S = Diameter of Pipe (in.)
B_c = Outside Diameter or Width of the Structure (ft.)
B'_c = Out-to-out Vertical Rise of Pipe (ft.)
ID = Inside Diameter (in.)

2.8.1 Reinforced Concrete

Concrete pipe must meet the requirements of the *AASHTO LRFD Bridge Construction Specifications* or ASTM C1479 *Standard Practice for Installation of Precast Concrete Sewer, Storm Drain, and Culvert Pipe using Standard Installations*. There are four types of Standard Installations for concrete pipe. These types of standard installation are shown in Table 2-40. Each type differs in soil and compaction requirements. According to *LRFD for Fill Height Tables*, "Type 1 bedding provides the most support using highly compacted granular material, while Type 4 provides for less support allowing the use of silts and clay soils with little or no compaction" (2013).

Table 2-40: Installation Soils and Minimum Compaction Requirements (ACPA 2013)

Installation Type	Bedding Thickness	Haunch and Outer Bedding	Lower Side
Type 1	D_0/24 minimum, not less than 3". If rock foundation, use D_0/12 minimum, not less than 6"	95% Category I	90% Category I, 95% Category II, or 100% Category III
Type 2	D_0/24 minimum, not less than 3". If rock foundation, use D_0/12 minimum, not less than 6"	90% Category I or 95% Category II	85% Category I, 90% Category II, or 95% Category III
Type 3	D_0/24 minimum, not less than 3". If rock foundation, use D_0/12 minimum, not less than 6"	85% Category I, 90% Category II, or 95% Category III	85% Category I, 90% Category II, or 95% Category III
Type 4	No bedding required except if rock foundation, use D_0/12 minimum, not less than 6"	No compaction required, except if Category III, use 85%	No compaction required, except if Category III, use 85%

The minimum and maximum fill height varies with each department of Transportation. The minimum cover is measured from the top of the pipe to either the bottom of the flexible pavement or to the top of the rigid pavement. As explained in the *Corrugated Steel Pipe Manual*,

> While asphalt does at least as good a job of distributing wheel loads as soil, it is not counted in the minimum cover. The asphalt layer is often very thick and must be placed and compacted in lifts with heavy equipment which would then be on the pipe with inadequate cover. Considering the asphalt thickness as part of the minimum cover could lead to construction problems (2008).

The ACPA published *LRFD for Fill Height Tables* using the indirect design method in accordance with Section 12.10.4.3 of the *AASHTO LRFD Bridge Design Specification*, 6th Edition. The Fill Height Tables were based on the following conditions:

1. Soil Density, $\Upsilon_s = 120$ lb/ft^3
2. AASHTO HL-93 live load
3. Positive Projecting Embankment Condition. This gives conservative results in comparison to trench conditions.
4. A Type 1 installation requires greater soil stiffness from the surrounding soils than the Type 2, 3, and 4 installations, and is thus harder to achieve.

In recent years, precast concrete manufacturers are seeing contract documents that require AASHTO HL-93 truckloads. However, a comparison between the old HS-20 wheel loads and the new HL-93 wheel loads indicates that the difference is very small. According to the National Precast Concrete Association, “The small increases in wheel loads will not affect designs that have excess capacity” (Munkelt 2010).

Table 2-41: D-Load (lb/ft/ft) for Type 1 Bedding (ACPA 2013)

	Fill Height in Feet													
Pipe Size (in)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
12	1612	1399	888	695	633	620	635	661	544	603	662	721	780	839
15	1546	1344	856	673	614	602	617	644	532	589	646	704	761	818
18	1462	1307	836	660	604	593	608	634	526	583	639	696	752	809
21	1309	1281	823	653	598	588	604	630	525	581	637	693	749	805
24	1287	1262	814	648	595	587	603	629	527	583	638	694	750	805
27	1230	1217	789	636	587	582	600	627	530	586	642	697	753	809
30	1581	1272	819	660	605	598	615	640	535	591	646	702	758	814
33	1443	1222	798	651	599	596	615	641	541	597	653	709	765	821
36	1329	1187	780	643	595	595	616	643	547	603	660	716	772	829
42	1151	1099	745	627	587	591	613	641	553	609	665	721	778	834
48	1019	961	713	614	582	589	612	641	560	616	673	729	785	841
54	969	919	689	604	578	589	613	643	569	625	681	737	794	850
60	994	890	670	596	577	590	615	646	578	634	691	747	804	860
66	946	865	657	589	576	592	618	651	588	644	701	758	814	871
72	881	844	647	584	578	595	622	656	598	655	712	769	826	883
78	827	823	637	582	579	597	625	659	606	663	720	777	834	892
84	782	805	629	580	580	600	628	664	615	672	729	786	843	901
90	744	789	622	580	582	603	632	668	712	681	738	795	853	910
96	712	749	616	580	585	606	637	673	718	690	747	805	862	920
102	685	723	623	587	592	614	645	682	727	774	757	814	872	929
108	662	711	629	595	600	623	654	691	736	783	766	824	882	940
114	642	715	636	603	609	631	663	700	745	793	842	834	892	950
120	625	720	642	609	617	640	672	709	755	802	852	844	903	961
126	611	726	649	617	625	649	681	719	764	812	862	913	913	971
132	599	731	651	625	634	658	690	728	774	822	872	924	976	983
138	589	736	645	633	643	667	699	738	784	832	883	934	987	994
144	580	742	651	642	652	676	709	747	794	843	893	945	998	1052

Class I
Class II
Class III
Class IV
Class V
Special Design

Table 2-41 illustrates the D-load for Type 1 bedding. The ACPA provides three additional Fill Height Tables for Type 1 Bedding. A maximum fill height of 54 feet is permitted for specially designed concrete pipes. Class V concrete pipes are used for deep installations with a maximum fill height ranging from 31 feet to 53 feet. The burial depth increases as the pipe diameter increases. Therefore, large diameter concrete culverts are used for deep installation.

Table 2-42: D-Load (lb/ft/ft) for Type 2 Bedding (ACPA 2013)

	Fill Height in Feet													
Pipe Size (in)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
12	1492	1322	880	727	694	705	741	788	704	781	858	934	1011	1087
15	1434	1272	851	707	676	688	724	771	691	843	841	915	990	1065
18	1358	1240	834	697	668	680	717	763	688	837	835	909	983	1056
21	1220	1218	824	692	665	678	715	762	689	839	836	909	983	1056
24	1202	1203	818	690	665	680	717	764	694	844	841	915	988	1062
27	1151	1162	796	679	657	675	714	762	696	846	842	915	989	1062
30	1471	1213	823	701	674	690	727	773	699	850	845	919	992	1065
33	1347	1168	805	693	669	688	727	773	704	855	850	923	996	1069
36	1244	1137	789	687	665	687	728	775	710	861	856	929	1003	1076
42	1084	1059	759	673	659	685	726	773	715	867	861	933	1006	1079
48	966	935	732	663	655	684	726	774	722	874	867	940	1013	1085
54	923	899	712	655	654	685	728	777	731	884	876	948	1021	1094
60	948	875	696	650	654	688	731	781	740	894	885	958	1031	1103
66	906	855	687	646	655	691	736	787	750	906	896	969	1041	1114
72	850	837	679	643	658	696	741	793	761	918	907	980	1053	1126
78	802	820	672	642	660	697	744	796	768	925	913	986	1059	1131
84	763	805	665	641	661	700	747	799	775	932	920	993	1065	1138
90	730	791	660	641	664	703	750	803	863	940	927	999	1072	1144
96	703	756	655	642	666	706	754	807	867	948	934	1006	1078	1151
102	679	734	662	649	674	714	761	814	875	1019	941	1013	1086	1158
108	660	723	668	657	681	721	769	822	882	1027	949	1021	1093	1165
114	643	729	675	665	689	729	776	830	890	1036	1016	1028	1100	1172
120	629	734	682	670	697	737	784	837	898	1044	1024	1036	1108	1180
126	617	740	689	678	705	744	792	845	905	1053	1032	1097	1115	1187
132	607	745	691	686	712	752	800	853	913	1061	1039	1105	1171	1195
138	599	751	686	694	720	760	808	861	921	1070	1047	1112	1178	1203
144	592	757	692	701	728	768	816	869	929	1079	1055	1120	1186	1253

Class I
Class II
Class III
Class IV
Class V
Special Design

Table 2-42 illustrates the D-load for Type 2 bedding. The ACPA provides two additional Fill Height Tables for Type 2 Bedding. A maximum fill height of 42 feet is permitted for specially designed concrete pipes. Class V concrete pipes are used for deep installations with a maximum fill height ranging from 26 feet to 40 feet.

Table 2-43: D-Load (lb/ft/ft) for Type 3 Bedding (ACPA 2013)

Pipe Size (in)	Fill Height in Feet													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
12	1490	1588	1686	1784	1882	1980	2078	2176	2274	2372	2470	2568	2666	2764
15	1450	1545	1640	1735	1830	1925	2020	2115	2210	2305	2401	2496	2591	2686
18	1430	1523	1617	1710	1803	1897	1990	2083	2177	2270	2363	2457	2550	2643
21	1421	1513	1606	1698	1790	1883	1975	2068	2160	2252	2345	2437	2529	2622
24	1419	1511	1603	1695	1786	1878	1970	2062	2154	2246	2338	2430	2521	2613
27	1422	1514	1605	1697	1789	1880	1972	2064	2155	2247	2339	2431	2522	2614
30	1428	1520	1612	1704	1795	1887	1979	2071	2162	2254	2346	2437	2529	2621
33	1437	1529	1621	1713	1805	1897	1989	2081	2173	2265	2357	2449	2541	2633
36	1449	1541	1633	1726	1818	1910	2003	2095	2187	2280	2372	2464	2557	2649
42	1455	1547	1639	1731	1823	1915	2007	2098	2190	2282	2374	2466	2558	2650
48	1465	1556	1648	1740	1832	1924	2016	2108	2200	2291	2383	2475	2567	2659
54	1477	1569	1661	1753	1845	1937	2029	2121	2213	2305	2397	2489	2581	2673
60	1492	1584	1676	1768	1861	1953	2045	2137	2229	2321	2413	2506	2598	2690
66	1508	1601	1693	1786	1878	1970	2063	2155	2248	2340	2433	2525	2617	2710
72	1526	1619	1711	1804	1897	1990	2083	2175	2268	2361	2454	2547	2639	2732
78	1533	1625	1718	1810	1903	1995	2088	2180	2273	2365	2458	2550	2643	2735
84	1540	1632	1725	1817	1909	2001	2094	2186	2278	2370	2463	2555	2647	2740
90	1548	1640	1732	1824	1916	2008	2100	2192	2284	2377	2469	2561	2653	2745
96	1556	1648	1740	1832	1924	2016	2108	2199	2291	2383	2475	2567	2659	2751
102	1565	1657	1748	1840	1932	2024	2115	2207	2299	2390	2482	2574	2666	2757
108	1574	1666	1757	1849	1940	2032	2123	2215	2307	2398	2490	2581	2673	2764
114	1583	1675	1766	1857	1949	2040	2132	2223	2315	2406	2498	2589	2680	2772
120	1593	1684	1775	1866	1958	2049	2140	2232	2323	2414	2506	2597	2688	2780
126	1602	1693	1785	1876	1967	2058	2149	2241	2332	2423	2514	2605	2697	2788
132	1612	1703	1794	1885	1976	2067	2158	2250	2341	2432	2523	2614	2705	2796
138	1622	1713	1804	1895	1986	2077	2168	2259	2350	2441	2532	2623	2714	2805
144	1632	1722	1813	1904	1995	2086	2177	2268	2359	2450	2541	2632	2723	2814

Class I
Class II
Class III
Class IV
Class V
Special Design

Table 2-43 illustrates the D-load for Type 3 bedding. The ACPA provides two additional Fill Height Tables for Type 3 Bedding. A maximum fill height of 35 feet is permitted for specially designed concrete pipes. Class V concrete pipes are used for deep installations with a maximum fill height ranging from 20 feet to 32 feet.

Table 2-44: D-Load (lb/ft/ft) for Type 4 Bedding (ACPA 2013)

Pipe Size (in)	Fill Height in Feet													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
12	1579	1481	1111	1032	1071	1154	1264	1383	1372	1521	1671	1820	1969	2119
15	1519	1426	1073	998	1036	1116	1221	1336	1326	1616	1612	1756	1899	2042
18	1443	1391	1050	978	1015	1093	1195	1307	1297	1580	1576	1715	1854	1994
21	1306	1366	1035	966	1002	1079	1179	1288	1279	1557	1552	1688	1825	1961
24	1288	1349	1025	959	994	1070	1168	1276	1267	1541	1535	1670	1804	1938
27	1238	1309	1002	945	982	1060	1158	1265	1259	1531	1524	1657	1790	1922
30	1560	1360	1029	965	995	1070	1166	1270	1254	1524	1517	1648	1780	1911
33	1437	1316	1010	955	988	1064	1160	1264	1252	1520	1512	1642	1773	1903
36	1336	1285	993	947	982	1060	1157	1260	1251	1518	1509	1639	1768	1898
42	1181	1211	966	935	976	1057	1153	1256	1252	1518	1508	1636	1764	1892
48	1068	1090	941	927	973	1056	1152	1255	1257	1522	1511	1638	1765	1892
54	1029	1058	925	921	973	1058	1154	1257	1264	1529	1516	1642	1768	1894
60	1059	1038	912	918	975	1062	1158	1261	1273	1538	1523	1649	1774	1899
66	1021	1022	906	917	978	1066	1163	1266	1282	1548	1532	1657	1781	1906
72	969	1008	902	917	984	1072	1169	1272	1292	1559	1541	1666	1790	1914
78	927	996	899	920	990	1079	1176	1280	1303	1570	1551	1675	1799	1923
84	893	986	898	925	997	1086	1184	1288	1315	1582	1562	1686	1810	1933
90	866	978	898	931	1004	1094	1192	1296	1408	1595	1574	1697	1820	1944
96	844	948	899	936	1012	1102	1201	1305	1417	1608	1585	1708	1831	1955
102	826	932	911	949	1024	1115	1214	1318	1429	1685	1597	1720	1843	1966
108	812	927	923	962	1037	1128	1226	1330	1441	1698	1609	1732	1855	1978
114	801	938	935	975	1050	1141	1239	1343	1454	1712	1682	1745	1867	1990
120	793	949	947	986	1063	1154	1252	1356	1467	1726	1694	1757	1879	2002
126	786	960	959	999	1076	1167	1265	1369	1480	1740	1707	1823	1892	2014
132	782	971	967	1013	1090	1180	1278	1382	1493	1754	1720	1836	1952	2027
138	779	982	968	1026	1103	1194	1292	1395	1506	1769	1733	1848	1965	2040
144	778	994	980	1039	1116	1207	1305	1409	1519	1783	1746	1861	1978	2095

Class I
Class II
Class III
Class IV
Class V
Special Design

Table 2-44 illustrates the D-load for Type 4 bedding. The ACPA provides one additional Fill Height Tables for Type 4 Bedding. A maximum fill height of 25 feet is permitted for specially designed concrete pipes. Class V concrete pipes are used for deep installations with a maximum fill height ranging from 14 feet to 22 feet.

Table 2-45, Table 2-46, Table 2-47, Table 2-48, Table 2-49, Table 2-50, and Table 2-51 present the required fill height for concrete pipe specified by various State Departments of Transportation and the FHWA.

Table 2-45: WisDOT's Fill Height for Concrete Pipe (WisDOT 2012)

Type/ Class of Pipe	AASHTO Materials Designation	Pipe Size I.D. (inches)	Maximum Height of Cover over Top of Pipe (feet)
Reinforced Concrete Class I	M 170	60 – 108	9
Reinforced Concrete Class II	M 170	12 – 108	11
Reinforced Concrete Class III	M 170	12 – 108	15
Reinforced Concrete Class IV	M 170	12 – 84	25
Reinforced Concrete Class V	M 170	12 – 72	35

Table 2-46: FDOT's Fill Height for Concrete Pipe (FDOT 2016)

Type I Installation					
Pipe Diameter	Maximum Cover (ft)				
	Class I	Class II	Class III	Class IV	Class V
12"	11	16	22	34	45
15"	12	16	23	34	45
18"	12	16	23	35	45
24"	11	16	22	34	45
30"	11	15	22	34	45
36"	11	15	21	33	45
42"	10	15	21	33	45
48	10	14	21	32	45
54	10	14	21	32	45
60	9	14	20	32	45
66	9	13	20	31	45
72	7	12	18	29	45
78	7	12	18	29	45
84	7	12	18	29	45
90	6	11	18	29	45
96	5	11	18	29	45
102	–	11	17	28	45
108	—	11	17	28	45
114	–	11	17	28	45
120	–	10	17	28	44

Table 2-47: FHWA's Fill Height for Concrete Pipe (FHWA 2007)

Pipe Size Diameter Inches	Embankment					Trench			
	Min Cover Inches	Class II	Class III	Class IV	Class V	Class II	Class III	Class IV	Class V
		Maximum Fill Height above Top of Pipe in Feet							
12	12	11	11	16	23	18	18	26	37
18	12	10	10	25	39	14	14	31	45
24	12	11	11	15	31	15	15	22	40
30	12	9	13	16	35	13	17	20	46
36	12	9	9	20	41	11	14	26	56
48	12	12	14	26	44	16	17	31	50
60	12	15	17	28	44	15	20	32	50
72	12	13	17	31	41	16	20	35	49
84	12	13	19	31		15	23	37	
96	12	13	20			16	24		
108	12	16	20			19	26		

Table 2-48: WSDOT's Fill Height for Concrete Pipe (WSDOT 2008)

Pipe Diameter in.	Maximum Cover in Feet				
	Plain AASHTO M 86	Class II AASHTO M 170	Class III AASHTO M 170	Class IV AASHTO M 170	Class V AASHTO M 170
12	18	10	14	21	26
18	18	11	14	22	28
24	16	11	15	22	28
30		11	15	23	29
36		11	15	23	29
48		12	15	23	29
60		12	16	24	30
72		12	16	24	30
84		12	16	24	30

Minimum Cover: 2 feet

Table 2-49: NCDOT's Fill Height for Reinforced Concrete Pipe (NCDOT 2003)

Pipe Diameter (in)	Maximum Fill Height (ft)		
	Class III	Class IV	Class V
All Sizes	23	32 60*	90*

*Use Method "B" Installation under fills greater than 32 feet.

Table 2-50: SCDOT's Fill Height for Reinforced Concrete Pipe (Gassman 2016)

Installation Type[1]	Pipe Diameter (in)	Maximum Height of Fill[2] (ft)			Minimum Allowable Cover Height (ft)	
		Class III	Class IV	Class V	HS-20 Vehicle Loading[3]	Construction Vehicle Loading
Type I	12 – 36	27	40	60	1	3
	42 – 66	26	39	58	1	3
	72 – 96	25	38	57	1	3
Type II	12 – 30	19	28	42	1	3
	36 – 96	18	27	41	1	3
Type III	12 – 42	14	22	33	1	3
	48 – 96	13	21	32	1	3
Type IV	12 – 21	9	14	21	1	3
	24 – 96	9	15	23	1	3

Notes:
[1]Installation Type is per ASTM C1479 and AASHTO Section 27, Standard Specification for Highway Bridges, Division II: Construction, American Association of State Highway and Transportation Officials, Washington D.C., 2002
[2]Maximum fill heights based on American Concrete Pipe Association (ACPA) Charts
[3]A minimum height of cover is 9 in. is acceptable if pipe is constructed under a rigid pavement and granular backfill is used.

Table 2-51: ODOT's Fill Height for Reinforced Concrete (ODOT 2015)

Pipe Diameter (inches)	Reinforced Concrete Pipe					
	Class III		Class IV		Class V	
	Minimum Cover (feet)	Maximum Cover (feet)	Minimum Cover (feet)	Maximum Cover (feet)	Minimum Cover (feet)	Maximum Cover (feet)
12	1.5	17	1.0	27	0.5	41
15	1.5	18	1.0	27	0.5	42
18	1.5	18	1.0	27	0.5	42
21	1.5	17	1.0	27	0.5	42
24	1.5	1	1.0	27	0.5	42
27	1.5	17	1.0	27	0.5	41
30	1.5	17	1.0	27	0.5	41
33	1.5	17	1.0	27	0.5	41
36	1.5	17	1.0	26	0.5	41
42	1.5	17	1.0	26	0.5	41
48	1.5	16	1.0	26	0.5	41
54	1.5	16	1.0	26		
60	1.5	16	1.0	26		
66	1.5	16	1.0	26		
72	1.5	16	1.0	25		

2.8.2 Corrugated Metal

According to the NCSPA's *Corrugated Steel Pipe Design Manual*, "Minimum covers for H20 and H25 highway loads are taken as the greater of span/8 or 12 inches for all corrugated steel pipe except spiral rib pipe" (2008). The NCSPA provides height of cover tables for standard corrugated steel pipe based on the American Iron and Steel Institute method (Table 2-52). The tables are dependent on pipe shape, wall thickness, and corrugations.

Table 2-52: NCSPA's Fill Height for Steel Pipe (NCSPA 2008)

Height of Cover Limits for Steel Pipe H20 or H25 Live Load · 2-⅔ x ½ Corrugation						
Diameter or Span, in.	Min.* Cover, in.	Maximum Cover (ft.) for Specified Thickness (in.)				
		0.064	0.079	0.109	0.138	0.168
12	12	248	310			
15	12	198	248			
18	12	165	206			
21	12	141	177	248		
24	12	124	155	217		
30	12	99	124	173		
36	12	83	103	145	186	
42	12	71	88	124	159	195
48	12	62	77	108	139	171
54	12	(53)	67	94	122	150
60	12		(57)	80	104	128
66	12			68	88	109
72	12			(57)	75	93
78	12			(48)	63	79
84	12			(40)	52	66
90	12			(32)	43	54
96	12				35	45

Notes:

1. Fill heights in parentheses require standard trench installation; all others may be embankment or trench.
2. 12. in. through 36 in. diameter, heavier gages may be available.

* Minimum covers are measured from top of pipe to bottom of flexible pavement or top of pipe to top of rigid pavement. Minimum covers must be maintained in unpaved traffic areas.

Table 2-53, Table 2-54, Table 2-55, Table 2-56, Table 2-57, and Table 2-58 present the required fill heights for corrugated steel pipe and corrugated aluminum pipe specified by various departments of Transportation. State Departments of Transportation include Maine, Florida, Washington, Oregon, and New York.

Table 2-53: MaineDOT's Fill Height for Corrugated Steel (MaineDOT 2005)

Round Pipe – 2-⅔" x ½" Corrugations				
Pipe Diameter (in)	Standard Thick (in)/ Height of Fill (ft)	Non-Standard Thick./Height of Fill	Non-Standard Thick./Height of Fill	Non-Standard Thick./Height of Fill
12 & 15	0.064/1.5 – 45			
18	0.064/1.5 – 35	0.079/35 – 55		
21	0.064/1.5 – 35	0.079/35 – 50	0.109/50 – 55	
24	0.064/1.5 – 20	0.079/20 – 40	0.109/40 – 50	0.138/50 – 60
30	0.079/1.5 – 25	0.109/25 – 40	0.138/25 – 45	0.168/55 – 60
36	0.079/1.5 – 15	0.109/15 – 25	0.138/25 – 45	0.168/45 – 60
42	0.109/1.5 – 20	0.138/20 – 35	0.168/35 – 60	
48	0.109/1.5 – 25	0.138/20 – 50	0.168/50 – 60	
54	0.109/1.5 – 20	0.138/20 – 40	0.168/40 – 50	
60	0.138/1.5 – 25	0.168/25 – 45		
66	0.138/1.5 – 20	0.168/20 – 40		
72	0.168/1.5 – 30			

Table 2-54: FDOT's Fill Height for Corrugated Aluminum (FDOT 2016)

Round Pipe – 2-⅔" x ½" Corrugations											
D (in.)	Area (sq. ft.)	Minimum Cover (in.)					Maximum Cover (ft.)				
		Sheet Thickness in Inches (Gage)					Sheet Thickness in Inches (Gage)				
		0.06	0.075	0.105	0.135	0.164	0.06	0.075	0.105	0.135	0.164
		(16)	(14)	(12)	(10)	(8)	(16)	(14)	(12)	(10)	(8)
12	0.8	12	12	NA	NA	NA	100+	100+	NA	NA	NA
15	1.2	12	12	NA	NA	NA	100+	100+	NA	NA	NA
18	1.8	12	12	12	NA	NA	83	100+	100+	NA	NA
21	2.4	12	12	12	NA	NA	71	89	100+	NA	NA
24	3.1	12	12	12	NA	NA	62	78	100+	NA	NA
30	4.9	12	12	12	NA	NA	50	62	87	NA	NA
36	7.1	NS	12	12	12	NA	NS	52	73	94	NA
42	9.6	NS	NS	12	12	NA	NS	NS	62	80	NA
48	12.6	NS	NS	12	12	12	NS	NS	54	70	86
54	15.9	NS	NS	NS	12	12	NS	NS	NS	62	76
60	19.6	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
66	23.8	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
72	28.3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NA – Not Available
NS – Not Suitable (For Highway LRFD HL-93 Live Loadings)

Table 2-55: WSDOT's Fill Height for Corrugated Steel (WSDOT 2008)

Round Pipe – 2-⅔" x ½" Corrugations					
Pipe Diameter in.	Maximum Cover in Feet				
	0.064 in.	0.079 in.	0.109 in.	0.138 in.	0.168 in.
12	100	100	100	100	
18	100	100	100	100	
24	98	100	100	100	100
30	78	98	100	100	100
36*	65	81	100	100	100
42*	56	70	98	100	100
48*	49	61	86	100	100
54*		54	76	98	100
60*			68	88	100
66*				80	98
72*				73	90
78*					80
84*					69

* Designers should consider the most efficient corrugation for the pipe diameter.
Minimum Cover: 2 feet

Table 2-56: WSDOT's Fill Height for Corrugated Aluminum (WSDOT 2008)

Round Pipe – 2-⅔" x ½" Corrugations					
Pipe Diameter in.	Maximum Cover in Feet				
	0.060 in.	0.075 in.	0.105 in.	0.135 in.	0.164 in.
12	100	100			
18	75	94	100		
24	56	71	99		
30		56	79		
36		47	66	85	
42			56	73	
48			49	63	78
54			43	56	69
60				50	62
66					56
72					45

Minimum Cover: 2 feet

Table 2-57: ODOT's Fill Height for Aluminum (ODOT 2015)

Helical · 2-⅔" x ½"							
Pipe Diameter (in.)	Minimum Cover (ft.)	Lock Seam					Minimum Cover (ft.)
		Specified Thickness (in.)					
		0.060	0.075	0.105	0.135	0.164	
		Maximum Cover (ft.)					
12	1.0	100	100	100			1.0
15	1.0	100	100	100			1.0
18	1.0	84	100	100			1.0
21	1.0	72	90	100			1.0
24	1.0	63	78	100	100	100	1.0
30	1.0		63	88	100	100	1.0
36	1.0		52	73	94	100	1.0
42	1.5			63	81	99	1.0
48	1.5			55	71	86	1.0
54	1.5			48	63	77	1.0
60	1.5				52	65	1.0
66	1.5					53	1.5
72	1.5					43	1.5

Table 2-58: NYDOT's Fill Height for Aluminum (NYDOT 2014)

Corrugated Aluminum Pipe[1,2]					
Pipe Diameter (in.)	Minimum Fill Height to Subgrade Surface (ft.)	Maximum Allowable Height of Cover[3] (ft)			
		Gauge for 2-½ x ½ Corrugation			
		16	14	12	10
12	1	50	50	86	Not Recommended[4]
15		40	40	69	
18		33	33	57	
21		28	28	49	
24		25	25	43	
27		22	22	38	40
30		–	20	34	36

Notes:
[1] Gauge, diameter, and corrugation combinations not included in this table shall not be specified.
[2] HS-25 Live Loading.
[3] Maximum vertical distance between the top of the pipe and finished or surcharge grade.
[4] Gauge, diameter, and corrugation combinations do not meet structural criteria, or are not manufactured.

2.8.3 Plastic

Thermoplastic pipe must meet the requirements of the *AASHTO LRFD Bridge Construction Specifications* or ASTM D2321 *Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications*. According to the guideline "Design Methodology" published by the PPI, "Pipe in traffic areas should have at least 1 ft. of cover over the pipe crown for 4" – 48" diameter pipe and 1.5 ft. of cover for 54" and 60" diameter pipe" (n.d.). Table 2-59 presents the maximum fill heights for high density polyethylene pipe specified by the PPI. Table 2-60, Table 2-61, Table 2-62, Table 2-63, Table 2-64, Table 2-65, Table 2-66, Table 2-67 present the required fill height for high density polyethylene and polypropylene specified by various State Departments of Transportation.

Table 2-59: Maximum Cover Heights (PPI)

	Class I		Class II				Class III		
Pipe Dia.	Uncompacted	Compacted	85%	90%	95%	100%	85%	90%	95%
4	17(ft)*	59(ft)	17(ft)	24(ft)	37(ft)	59(ft)	15(ft)	18(ft)	24(ft)
6	16	57	16	24	36	57	15	17	24
8	14	51	14	21	32	51	13	15	22
10	13	50	13	20	31	50	12	14	21
12	13	49	13	20	31	49	12	14	21
15	13	49	13	20	31	49	12	14	21
18	13	49	13	20	31	49	12	14	21
24	13	51	13	21	32	51	12	14	21
30	13	51	13	21	32	51	12	14	21
36	13	50	13	20	31	50	12	14	21
42	11	47	11	19	29	47	10	13	19
48	11	46	11	18	29	46	10	12	19
54	11	44	11	18	28	44	10	12	18
60	11	45	11	18	28	45	10	12	19

Note: Alternate backfill materials and compaction levels not shown in the table may also be acceptable. This is a general guideline. Contact the manufacturer for further detail. *All cover heights measured in feet.

Table 2-60: NCDOT's Fill Height for Corrugated Double Wall Pipe (NCDOT 2003)

Pipe Size (inches)	Minimum Cover (inches)	Maximum Cover (feet)
12	12	20
15	12	20
18	12	20
24	12	20
30	12	20
36	12	20
42	12	20
48	12	20

Table 2-61: WisDOT's Fill Height for Corrugated Plastic (WisDOT 2012)

		Maximum Cover	
Pipe Diameter	Minimum Cover	Corrugated Polyethylene	Corrugated Polypropylene
12 in	2 ft	11 ft	15 ft
15 in	2 ft	11 ft	15 ft
18 in	2 ft	11 ft	15 ft
21 in	2 ft	11 ft	15 ft
24 in	2 ft	11 ft	15 ft
30 in	2 ft	11 ft	15 ft
36 in	2 ft	11 ft	15 ft

Table 2-62: WSDOT's Fill Height Table for Plastic (WSDOT 2008)

Solid Wall PVC	Profile Wall PVC	Corrugated Polyethylene
ASTM D 3034 SDR 35 3 in. to 15 in. dia. ASTM F 679 Type 1 18 in. to 48 in. dia.	AASHTO M 304 Or ASTM F 794 Series 46 4 in. to 48 in. dia.	AASHTO M 294 Type S 12 in. to 60 in. dia.
25 feet All diameters	25 feet All diameters	25 feet All diameters

Note: Minimum Cover: 2 feet

Table 2-63: FDOT's Minimum Cover for Plastic Pipe (FDOT 2016)

Pipe Material	Pipe Diameter	Minimum Cover
	Inch	Inch
Corrugated Polyethylene	12 – 48	24
	60	30
Corrugated Polypropylene	12 – 48	24
	60	30

Table 2-64: FDOT's Maximum Cover for Corrugated Polyethylene (FDOT 2016)

Diameter (in.)	Maximum Cover (ft.)
12	19
15	20
18	17
24	13
30	13
36	14
42	13
48	12
60	13

Table 2-65: FDOT's Maximum Cover for Corrugated Polypropylene (FDOT 2016)

Diameter (in.)	Maximum Cover (ft.)
12	21
15	22
18	19
24	16
30	19
36	16
42	15
48	15
60	16

Table 2-66: NYDOT's Fill Height for Corrugated Polyethylene (NYDOT 2014)

Smooth Interior Corrugated Polyethylene Pipe[1]		
Diameter (in.)	Minimum Fill Height to Subgrade Surface (ft.)	Maximum Allowable Height of Cover[2] (ft.)
12	1	15
15		
18		
24		
30		
36		
42		
48		
60		

Notes:
[1] HS-25 Live Loading
[2] Maximum vertical distance between the top of the pipe and the finished or surcharge grade

Table 2-67: NYDOT's Fill Height for Polypropylene (NYDOT 2014)

Polypropylene[1,3]		
Diameter (in.)	Minimum Fill Height to Subgrade Surface (ft)	Maximum Allowable Height of Cover (ft)[2]
12	1	24
15	1	28
18	1	21
24	1	18
30	1	19
36	1	18
42	1	20
48	1	18
60	2	20

Notes:
[1] HL-93 Live Loading
[2] Maximum vertical distance between the top of the pipe and the finished or surcharge grade
3 This table is applicable to Type S and Type D pipe

In 2006, the Arizona Department of Transportation (ADOT) sponsored a nationwide survey to determine the recommended use of high density polyethylene pipe for roadway application. The survey requested pipe diameter, minimum and maximum fill heights, and backfill material. According to the report *High Density Polyethylene Pipe Fill Height*,

1. The most prevalent sizes of pipes ranged from 12 inches to 48 inches
2. 54 inch to 60 inch diameters have only recently been approved by AASHTO

Table 2-68: Collected Data from ADOT Survey (Ardani 2006)

State	HDPE Pipe Diameter		State	HDPE Pipe Diameter	
	Minimum	Maximum		Minimum	Maximum
	Inch	Inch		Inch	Inch
Alabama	12	48	Missouri	12	60
Alaska	12	48	Montana	Only Allow 18	
Arkansas	No Standard Criteria		Nebraska	12	36
California		60	Nevada	No Standard Criteria	
Colorado	12	48	New Jersey	No Standard Criteria	
Connecticut	12	48	New Mexico	12	60
Delaware	8	48	New York	12	48
District of Columbia	HDPE Pipes Not Used		North Carolina	12	48
Florida	15	48	Ohio	12	60
Georgia	12	36	Oklahoma	18	60
Hawaii	18	60	Oregon	12	60
Idaho	12	48	Rhode Island	12	48
Illinois		36	South Carolina	12	60
Indiana	12	36	South Dakota	18	
Iowa	24	48	Tennessee	12	48
Kansas	No Standard Criteria		Texas	18	48
Kentucky	12	48	Utah	18	60
Louisiana	12	48	Vermont	12	48
Maine	12	48	Virginia	12	48
Massachusetts	6	36	Washington	12	60
Michigan	12	36	West Virginia	12	48
Minnesota	12	36	Wisconsin		36
Mississippi	12	36	Wyoming	No Standard Criteria	

All 50 State Departments of Transportation were asked to participate in the survey. However, only 47 State Departments of Transportation responded. Table 2-68 shows the minimum and maximum pipe diameter used by each State Department of Transportation. The maximum fill heights varied between departments. Fill heights ranged from a few feet to over 50 feet. The most commonly used fill heights reported were 10 feet and 20 feet. Of the 47 departments of Transportation that responded, 11 had no specified maximum fill height. The maximum fill heights specified by each State Department of Transportation are shown in Figure 2-47.

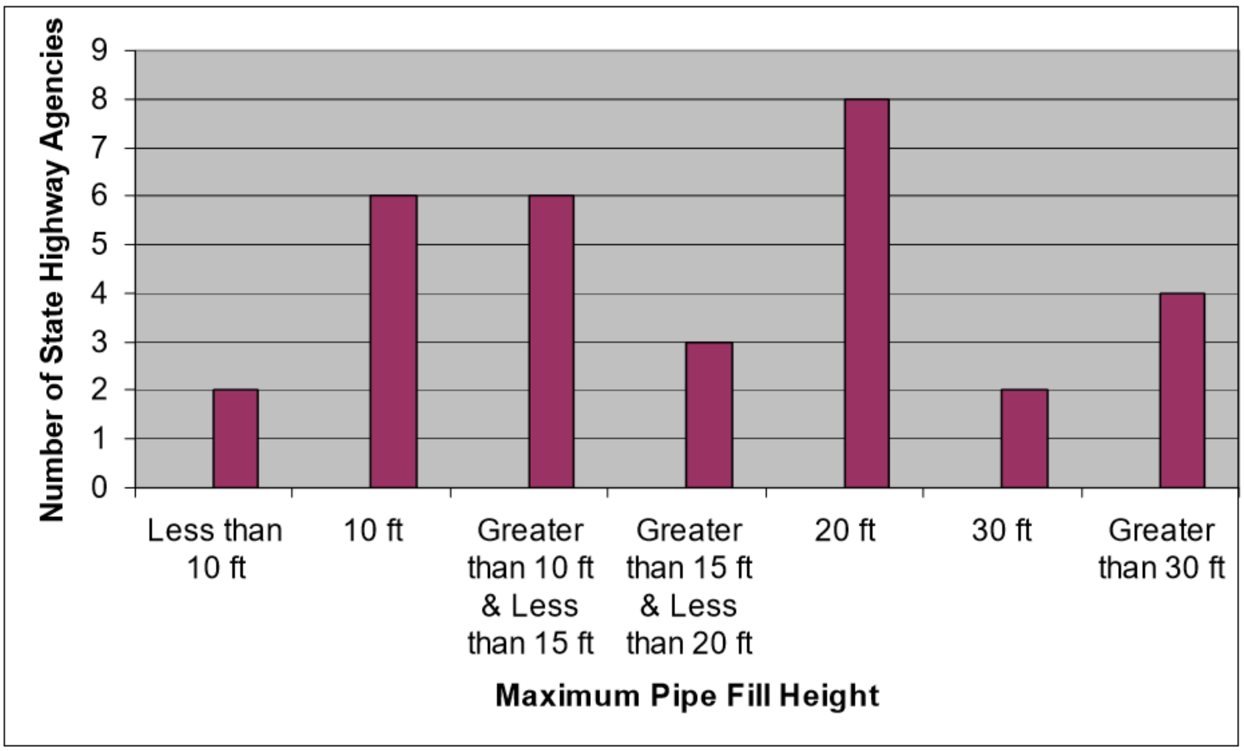


Figure 2-47: Surveyed Maximum Fill Heights (Ardani 2006)

2.9 Literature Review Summary

The Commentary to Section 12 of the *AASHTO LRFD Bridge Design Specifications* recommends the following items as useful information for the design of buried structures and tunnel liners. The literature review was developed from these recommendations.

- Strength and compressibility of foundation materials
- Chemical characteristics of soil and surface waters, e.g., pH, resistivity, and chloride content of soil and pH, resistivity, and sulfate content of surface water
- Stream hydrology, e.g., flow rate and velocity, maximum width, allowable headwater depth, and scour potential
- Performance and condition survey of culverts in the vicinity

Reinforced concrete pipes are the oldest and most commonly used culvert material in North America. Reinforced concrete pipes have the longest expected service life over all other culvert materials. The service life of a reinforced concrete culvert ends when the reinforcing steel has been exposed or significant cracks begin to form. The most critical factor affecting the service life of a concrete pipe is chemical corrosion.

The service life of a corrugated metal culvert ends when the deterioration reaches the point of perforation. The most critical factors affecting the service life of steel pipe and aluminum pipe are corrosion, abrasion, and gage thickness. Aluminized steel is more resistant to corrosion than galvanized steel. The most critical factors affecting the service life of high density polyethylene culverts and polypropylene culverts are oxidation, ultraviolet radiation, and flammability. High density polyethylene culverts and polypropylene culverts are not affected by chemical or electrochemical corrosion.

The most common reason for a culvert to fail is due to a gradual weakening caused by corrosion. Corrosion can occur on both the inside and outside of the culvert. Corrosion most commonly attacks unprotected metal culverts and the reinforcement in concrete pipes. High density polyethylene pipes and polypropylene pipes are unaffected by most inorganic acids, alkalis, and aqueous solutions.

Chloride ions are the most extensively documented contaminant that cause corrosion of the embedded steel in concrete. The embedded steel is more susceptible to corrosion if the concrete cover is inadequate, cracked, or highly permeable. Chloride ions are present in deicing salts and seawater. The degradation is often accelerated in regions where successive freeze-thaw cycles occur.

While a high concentration of sulfates may corrode metal culverts, they are typically more damaging to concrete. Concrete pipes are sufficient to withstand sulfate concentrations of 1,000 ppm or less. The most efficient way to protect against a sulfate attack is to choose a cement with a limited amount of tricalcium aluminate. Resistivity is a measure of the soil's ability to conduct electrical current and, it greatly affects metal culverts. Resistivity values greater than 3,000 ohm-cm are considered high and will impede corrosion.

The pH is an expression of the hydrogen ion concentration in water or soil. It is extremely important that the appropriate culvert material is chosen for the specific site conditions. The FHWA allows high density polyethylene culverts to be used without regard to the resistivity and pH of the soil. However, the same liberties cannot be applied to metal or concrete culverts.

Abrasion often accelerates corrosion by stripping away the surface material or protective coating of a culvert. Once the protective coating has been removed, the culvert's main defense against corrosion has been destroyed. Steel pipe is the most susceptible to corrosion. However, aluminum pipe offers no improvement.

Plastic pipe exhibits good abrasion resistance and will likely not experience the dual action of corrosion and abrasion. However, this claim was based on tests using small aggregate sizes flowing at low velocities. The effects of large bedload particles or high velocity flows are not well documented. In addition, rehabilitative strategies have not been specifically developed for plastic pipe due to their more recent emergence as a culvert material.

Plastic pipes are affected by oxidation and ultraviolet radiation. Ultraviolet stabilizers and antioxidant packages are used to protect plastic pipes from this form of degradation. All culvert materials are affected by fire and extremely high temperatures. While it is highly unlikely for concrete to burn, extremely high temperatures can affect the compressive strength, flexural strength, and modulus of elasticity of concrete. Several State Departments of Transportation have reported that the pipe ends and the flared end sections of polyethylene pipe have caught on fire as a result of crop, leaf, or controlled burning in roadside ditches.

The minimum and maximum fill heights for culverts vary with each department of Transportation. The fill height for reinforced concrete pipe is dependent on the D-load, installation type, and pipe diameter. The fill height for standard corrugated metal pipe is dependent on pipe diameter, wall thickness, and corrugations. The fill height for plastic pipe is dependent on pipe material and pipe diameter. Plastic pipe requires a minimum 2 ft. of cover.

Table 2-69: Summarized Comparison of Culvert Material Types

	Precast Reinforced Concrete	Steel		Aluminum	Plastic	
		Galvanized	Aluminized		High Density Polyethylene	Polypropylene
Sulfate Concentration	Susceptible to degradation if the sulfate is ≥ 1,000 ppm	Susceptible to degradation if the sulfate is ≥ 1,000 ppm	Susceptible to degradation if the sulfate is ≥ 1,000 ppm	Susceptible to degradation if the sulfate is ≥ 1,000 ppm	Not Applicable	Not Applicable
Resistivity	May require additional cover over embedded reinforcing steel	Susceptible to degradation if the resistivity is ≤ 3,000 ohm-cm	Susceptible to degradation if the resistivity is ≤ 3,000 ohm-cm	Susceptible to degradation if the resistivity is ≤ 3,000 ohm-cm	Not Applicable	Not Applicable
pH Concentration	pH < 5	6.0 < pH < 10	5.0 < pH < 9.0	5.0 < pH < 9.0	Not Applicable	Not Applicable
Abrasion	Modify mix design for severe abrasion	Not recommended for moderate or severe abrasion	Not recommended for moderate or severe abrasion	Not recommended for moderate or severe abrasion	Not recommended for severe abrasion	Not recommended for severe abrasion
Ultraviolet Radiation	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Most susceptible to degradation	Most susceptible to degradation
Flammability/ Heat	Least susceptible	Protective coatings may burn	Protective coatings may burn	Protective coatings may burn	Most susceptible	Most susceptible
Maximum Pipe Diameter	96 in.	72 in.	72 in.	72 in.	48 in.	48 in.
Minimum Fill Height	1 – 2 ft.	1 – 2 ft.	1 – 2 ft.	1 – 2 ft.	2 ft.	2 ft.
Maximum Fill Height	Not as limited	Not as limited	Not as limited	Not as limited	20 ft.	20 ft.
Quality-Controlled Installation	Not as critical	Important	Important	Important	Required	Required

Chapter 3: Decision Algorithm

3.1 Introduction

The Specification for Culvert Material Selection found in Appendix B will provide guidance and the latest research to ALDOT to aid in the selection of culvert material for cross-drainage application. *The Specification for Culvert Material Selection* is comprised of checklists and a condensed summary of the material contained within this thesis. The checklists will allow for the quick selection or elimination of culvert material based upon predetermined site conditions. The accompanying condensed summary will serve as an on-the-go literature guide and represent fundamental information that has been extracted from this thesis.

The checklists were created from crucial durability concerns and installation requirements. The checklists may be completed either by hand or by electronic methods. Crucial durability concerns include: sulfate content, resistivity, pH levels, abrasion, flammability, and ultraviolet radiation. Installation requirements include: minimum soil cover, maximum soil cover, culvert diameter, and presence of Quality Control personnel.

The flowcharts illustrate the decision process and pertinent information that was used to create *The Specification for Culvert Material Selection*. *The Specification for Culvert Material Selection* was developed from these flowcharts and by the initial input parameters defined in *Cross-Drain Pipe Material Selection Algorithm*.

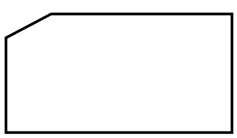
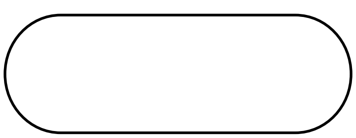
3.2 Flowchart Key

Table 3-1 depicts the abbreviations that have been used to create the flowcharts. Table 3-2 depicts the three shapes have been chosen to create the flowcharts. These three shapes will be used throughout each flowchart to maintain consistency. The colors were only chosen to visually assist the user. Therefore, any of the material may be printed in black and white without the concern of losing vital information.

Table 3-1: Flowchart Abbreviations

RCP	Reinforced Concrete Pipe
CSP	Corrugated Steel Pipe
CAP	Corrugated Aluminum Pipe
HDPE	High Density Polyethylene
PP	Polypropylene

Table 3-2: Flow Chart Key

	Decision – This shape will pose a question to the user.
	Answer – This shape will show the recommended culvert material.
	Reroute – This shape may direct the user to a different flowchart.

3.3 Selection Process

The selection process begins by determining the required service life of the culvert. Reinforced concrete culverts have the longest expected service life over all other culvert materials. Therefore, reinforced concrete culverts are recommended when the required service life exceeds 75 years. If the service life of the culvert is not expected to exceed 75 years, then reinforced concrete, corrugated steel, corrugated aluminum, high density polyethylene, and polypropylene are all acceptable culvert materials.

If the required service life exceeds 75 years, a checklist is provided to ensure environmental and site conditions are suitable for a reinforced concrete pipe. If the service life of the culvert is not expected to exceed 75 years, the next deciding factor is the pipe diameter.

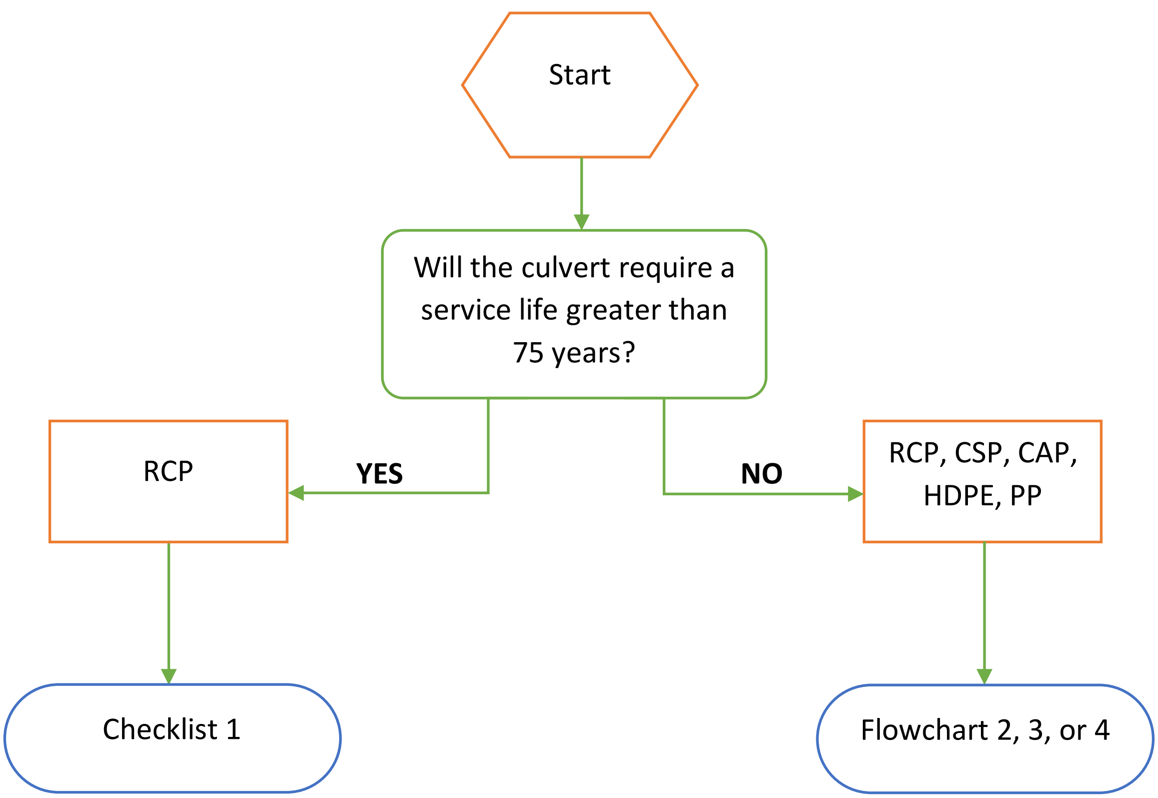


Figure 3-1: Flow Chart 1

While plastic pipe can be manufactured up to 60-inch in diameter, most State Departments of Transportation are hesitant to choose a plastic pipe that large. Therefore, the largest plastic pipe diameter that shall be considered is 48 inches. If the design requires a pipe diameter larger than 48 inches, high density polyethylene pipe and polypropylene pipe are no longer considered acceptable culvert materials. Reinforced concrete, corrugated steel, and corrugated aluminum are recommended when the pipe diameter exceeds 48 inches. A checklist is provided to ensure environmental and site conditions are suitable for a corrugated metal pipe.

After the required service life and the required pipe diameter have been established, the acceptable culvert materials are narrowed down based on environmental and site conditions.

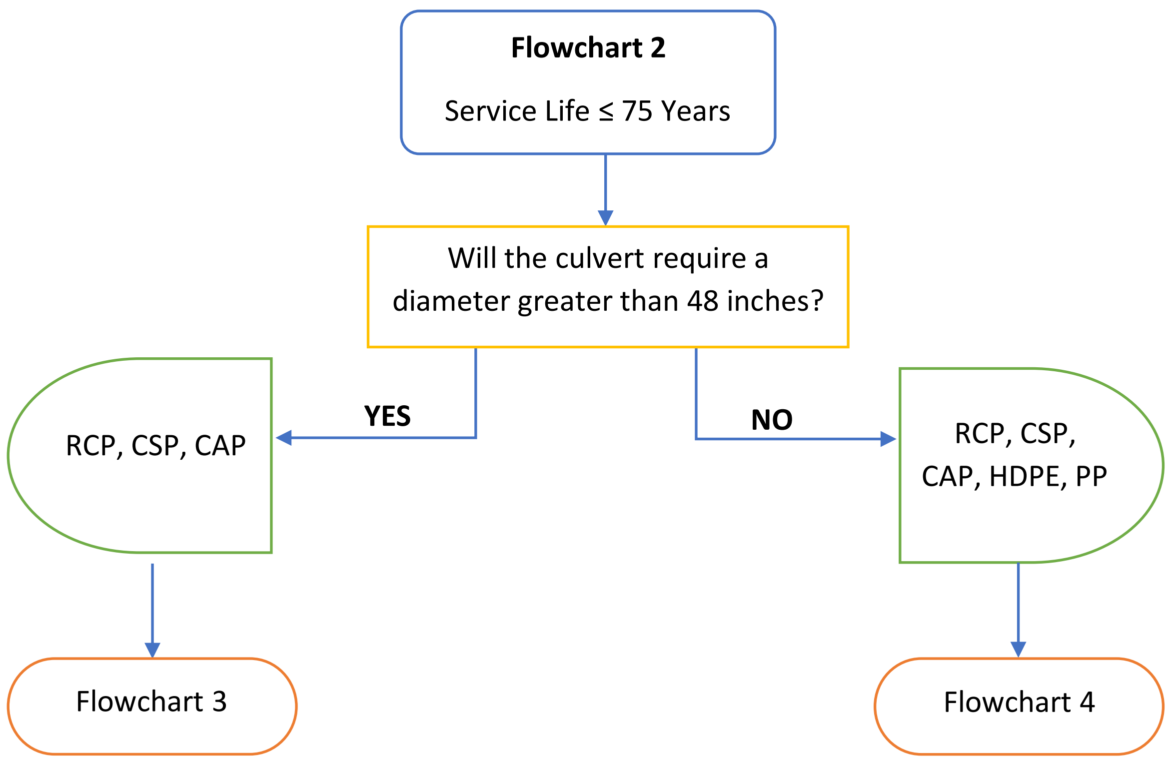


Figure 3-2: Flow Chart 2

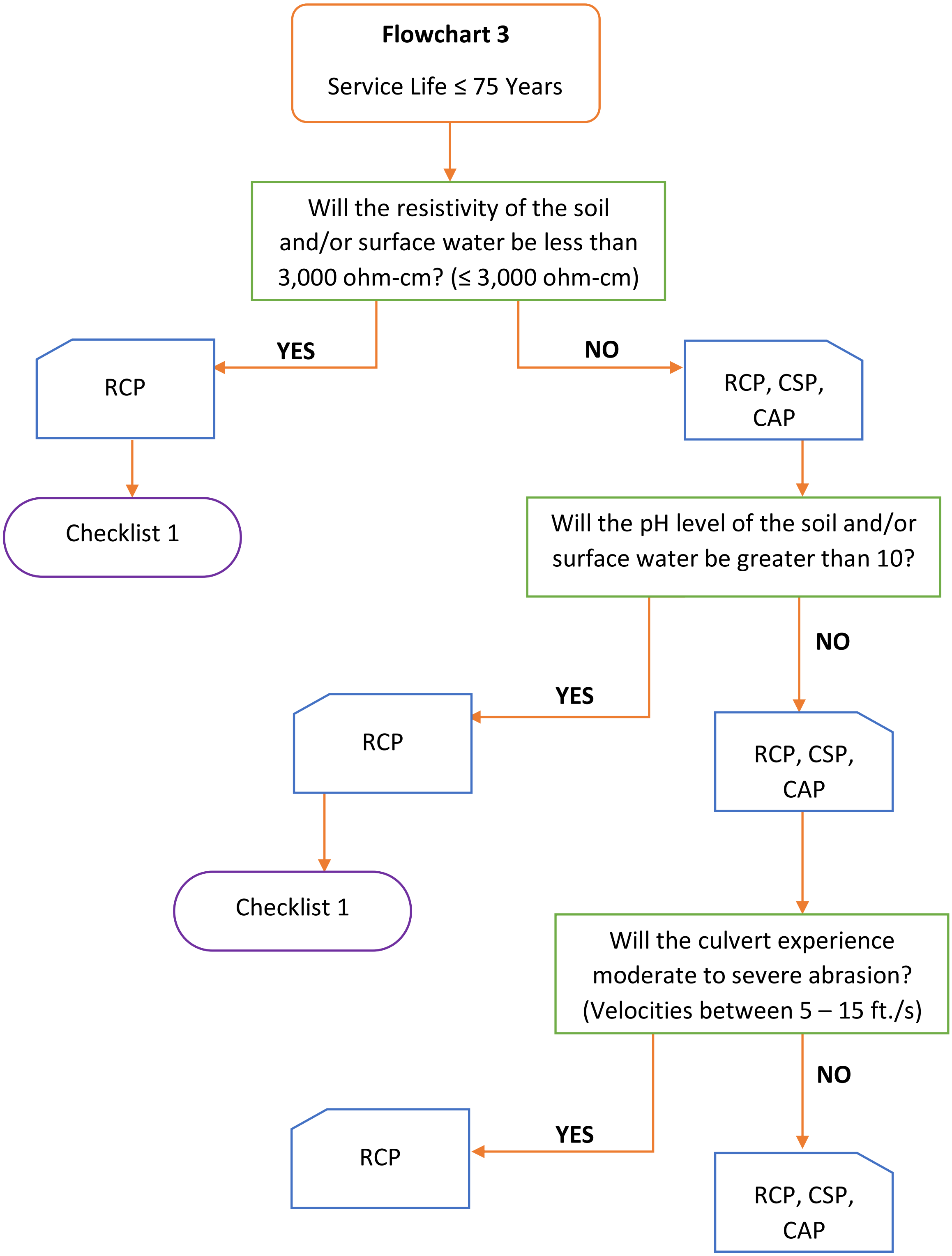


Figure 3-3: Flow Chart 3

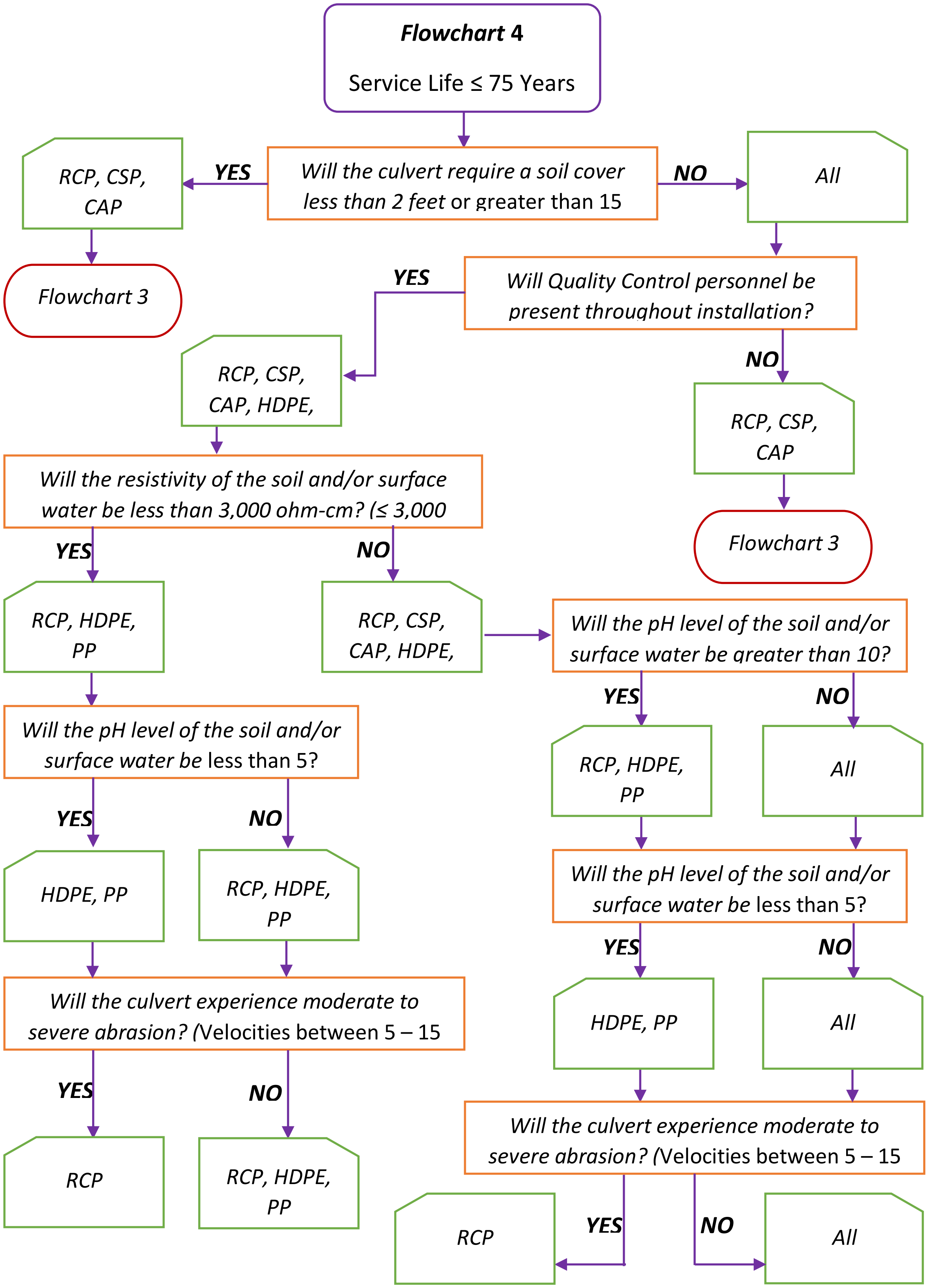


Figure 3-4: Flow Chart 4

Checklist 1: Concrete Culverts

Directions:

Place a check in the box if the condition is true. Note if additional protection is required. A reinforced concrete culvert shall only be used if the provisions of Checklist 1 are satisfied.

Sulfate Content			
Will the sulfate content of the surface water be less than 1,000 ppm? (<1,000 ppm)		☐	No additional protection required.
Will the sulfate content of the surface water exceed 1,000 ppm? (≥1,000 ppm)		☐	Additional protection required.
Resistivity			
Will the resistivity of the soil and/or surface water be less than 3,000 ohm-cm? (≤ 3,000 ohm-cm)		☐	Ensure adequate cover over reinforcing steel.
Will the resistivity of the soil and/or surface water exceed 3,000 ohm-cm? (> 3,000 ohm-cm)		☐	No additional protection required.
pH Level			
Will the pH of the soil and/or surface water be less than 5?		☐	Reinforced concrete should not be used.
Will the pH of the soil and/or surface water exceed 5?		☐	No additional protection required.
Abrasion			
Level 1	Non-abrasive conditions exist in areas of no bed load and very low velocities.	☐	No additional protection required.
Level 2	Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 ft./sec. or less	☐	No additional protection required.
Level 3	Moderate abrasive conditions exists in areas of moderate bed loads of sand and gravel and velocities between 5 ft./sec. and 15 ft./sec.	☐	No additional protection required.
Level 4	Severe abrasive conditions exist in areas of heavy bed loads of sand, gravel and rock and velocities exceeding 15 ft./sec.	☐	Additional protection required.

Checklist 2: Metal Culverts

Directions:

Place a check in the box if the condition is true. Note if additional protection is required. A metal culvert shall only be used if the provisions of Checklist 2 are satisfied.

Service Life			
Will the service life of the culvert exceed 75 years?		☐	Metal culverts shall not be used.
Sulfate Content			
Will the sulfate content of the surface water be less than 1,000 ppm? (<1,000 ppm)		☐	No additional protection required.
Will the sulfate content of the surface water exceed 1,000 ppm? (≥1,000 ppm)		☐	Additional protection required.
Resistivity			
Will the resistivity of the soil and/or surface water be less than 3,000 ohm-cm? (≤ 3,000 ohm-cm)		☐	Metal culverts shall not be used.
Will the resistivity of the soil and/or surface water exceed 3,000 ohm-cm? (> 3,000 ohm-cm)		☐	No additional protection required.
pH Level			
$6.0 < pH < 10$		☐	Galvanized steel culverts.
$5.0 < pH < 9.0$		☐	Aluminum culverts.
Abrasion			
Level 1	Non-abrasive conditions exist in areas of no bed load and very low velocities.	☐	No additional protection required.
Level 2	Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 ft./sec. or less	☐	No additional protection required.
Level 3	Moderate abrasive conditions exists in areas of moderate bed loads of sand and gravel and velocities between 5 ft./sec. and 15 ft./sec.	☐	Metal culverts shall not be used.
Level 4	Severe abrasive conditions exist in areas of heavy bed loads of sand, gravel and rock and velocities exceeding 15 ft./sec.	☐	Metal culverts shall not be used.

Checklist 3: Plastic Culverts

Directions:

Place a check in the box if the condition is true. Note if additional protection is required. A plastic culvert shall only be used if the provisions of Checklist 4 are satisfied.

Service Life			
Will the service life of the culvert exceed 75 years?		☐	Plastic culverts shall not be used.
Installation			
Will the culvert require a diameter greater than 48 inches?		☐	Plastic culverts shall not be used.
Will the culvert require a minimum fill height less than 2 feet?		☐	Plastic culverts shall not be used.
Will the culvert require a maximum fill height greater than 15 feet?		☐	Plastic culverts shall not be used.
Quality Control			
Will Quality Control personnel be present throughout installation?		☐	If not, plastic culverts should not be used.
Ultraviolet Radiation			
Will the culvert be exposed to prolonged sunlight/ ultraviolet radiation?		☐	Additional protection required.
Flammability			
Will the culvert be installed at a location prone to fires?		☐	Additional protection required.
Sulfate Content			
No limitation.			
Resistivity			
No limitation.			
pH Level			
No limitation.			
Abrasion			
Level 1	Non-abrasive conditions exist in areas of no bed load and very low velocities.	☐	No additional protection required.
Level 2	Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 ft./sec. or less	☐	No additional protection required.
Level 3	Moderate abrasive conditions exists in areas of moderate bed loads of sand and gravel and velocities between 5 ft./sec. and 15 ft./sec.	☐	No additional protection required.
Level 4	Severe abrasive conditions exist in areas of heavy bed loads of sand, gravel and rock and velocities exceeding 15 ft./sec.	☐	Plastic culverts shall not be used.

Chapter 4: Demonstration

4.1 Demonstration

The following culvert installation projects have been fabricated to illustrate the usefulness and accuracy of *The Specification for Culvert Material Selection*. Project information was fabricated due to time constraints and a reluctance of several State Departments of Transportation to divulge project-specific information. However, the demonstrations proved immensely valuable. Four demonstrations were created to represent culvert installation projects throughout the United States. Installation consisted of a brand new circular culvert. Rehabilitation projects were not considered.

4.2 Interstate 81 Culvert Project

The Pennsylvania Department of Transportation has agreed to the installation of a new culvert beneath Interstate 81 in Carlisle. According to design calculations, the culvert will be 24-inches in diameter, and require a minimum fill height of 1 foot and a maximum burial depth of 12 feet. The culvert is expected to last 50 years. The area is prone to heavy snowfall and does not experience severely high temperatures. Extensive environmental testing has been performed and the results are shown below. Representatives of the Pennsylvania Department of Transportation have confirmed that Quality Control personnel will be present throughout installation. The likelihood of fire is highly unlikely as well as long-term ultraviolet radiation exposure.

Table 4-1: Environmental Testing Results for Interstate 81

Sulfate Content	pH Concentration	Resistivity	Velocity
570 ppm	6	6,000 ohm-cm	5 – 10 ft./sec.

Figure 4-1: Location of Proposed Culvert Installation beneath Interstate 81

Based on the chart shown on the following page, the Pennsylvania Department of Transportation can choose from three possible culvert material types. A reinforced concrete culvert will meet all of the project criteria and not require additional protection. A corrugated aluminized steel culvert and a corrugated aluminum culvert will also meet all of the project criteria. However, these culverts will require additional protection (i.e., increased gage thickness) to protect against abrasion. A plastic culvert was eliminated due to minimum fill height requirements.

Directions: Input the predetermined site/project specific conditions into the blank column shown. Compare the inputted data to the data shown to the right of the bolded black line. Note if additional protection is required.

	Site Conditions	Reinforced Concrete	Galvanized Steel	Aluminized Steel	Aluminum	High Density Polyethylene	Polypropylene
Service Life (Years)	50	+ 75	75	75	75	75	75
Sulfate Content (ppm)	570	≤ 1,000 (1)	≤ 1,000(1)	≤ 1,000(1)	≤ 1,000(1)	N/A	N/A
Resistivity (ohm-cm)	6,000	> 3,000(2)	> 3,000(2)	> 3,000(2)	> 3,000(2)	N/A	N/A
pH Levels	6	pH < 5	6 < pH < 10	5 < pH < 9	5 < pH < 9	N/A	N/A
Abrasion (Level)	3	1, 2, 3	1, 2, 3(3)	1, 2, 3(3)	1, 2, 3(3)	1, 2, 3	1, 2, 3
Ultraviolet Radiation	No	N/A	N/A	N/A	N/A	Highly Sensitive	Highly Sensitive
Flammability/ Heat	No	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive
Max. Pipe Diameter (in.)	24	96	72	72	72	48	48
Min. Fill Height (ft.)	1	1 – 2	1 – 2	1 – 2	1 – 2	2	2
Max. Fill Height (ft.)	12	N/A	N/A	N/A	N/A	20	20
Quality Controlled Installation	Yes	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive

Note:
(1) Additional protection required if the sulfate content exceeds 1,000 ppm.
(2) Additional protection required if the resistivity is less than 3,000 ohm-cm. Metal culverts not recommended.
(3) Additional protection required for moderate abrasion conditions.

4.3 Interstate 520 Culvert Project

The Georgia Department of Transportation has begun the design of a new culvert beneath Interstate 520 in Augusta. According to preliminary calculations, the culvert will be 30-inches in diameter, and require a minimum fill height of 2 feet and a maximum burial depth of 20 feet. The culvert is expected to last 70 years. The area is not prone to heavy snowfall and experiences relatively high temperatures. Extensive environmental testing has been performed and the results are shown below. Representatives of the Georgia Department of Transportation have confirmed that Quality Control personnel will be present throughout installation. The likelihood of fire is unlikely as well as long-term ultraviolet radiation exposure.

Table 4-2: Environmental Testing Results for Interstate 520

Sulfate Content	pH Concentration	Resistivity	Velocity
850 ppm	9	10,000 ohm-cm	5 ft./sec.

Figure 4-2: Location of Proposed Culvert Installation beneath Interstate 520

Based on the chart shown on the following page, the Georgia Department of Transportation can choose from four possible culvert material types. A reinforced concrete culvert, a corrugated galvanized steel culvert, a high density polyethylene culvert, and a polypropylene culvert will meet all of the project criteria and not require additional protection.

Directions: Input the predetermined site/project specific conditions into the blank column shown. Compare the inputted data to the data shown to the right of the bolded black line. Note if additional protection is required.

	Site Conditions	Reinforced Concrete	Galvanized Steel	Aluminized Steel	Aluminum	High Density Polyethylene	Polypropylene
Service Life (Years)	70	+ 75	75	75	75	75	75
Sulfate Content (ppm)	850	≤ 1,000 [1]	≤ 1,000[1]	≤ 1,000[1]	≤ 1,000[1]	N/A	N/A
Resistivity (ohm-cm)	10,000	> 3,000[2]	> 3,000[2]	> 3,000[2]	> 3,000[2]	N/A	N/A
pH Levels	9	pH < 5	6 < pH < 10	5 < pH < 9	5 < pH < 9	N/A	N/A
Abrasion (Level)	2	1, 2, 3	1, 2, 3[3]	1, 2, 3[3]	1, 2, 3[3]	1, 2, 3	1, 2, 3
Ultraviolet Radiation	No	N/A	N/A	N/A	N/A	Highly Sensitive	Highly Sensitive
Flammability/ Heat	No	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive
Max. Pipe Diameter (in.)	30	96	72	72	72	48	48
Min. Fill Height (ft.)	2	1 – 2	1 – 2	1 – 2	1 – 2	2	2
Max. Fill Height (ft.)	20	N/A	N/A	N/A	N/A	20	20
Quality Controlled Installation	Yes	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive

Note:
(1) Additional protection required if the sulfate content exceeds 1,000 ppm.
(2) Additional protection required if the resistivity is less than 3,000 ohm-cm. Metal culverts not recommended.
(3) Additional protection required for moderate abrasion conditions.

4.4 Route 25 Culvert Project

The South Carolina Department of Transportation has agreed to the installation of a new culvert beneath Route 25 in Greenville. According to design calculations, the culvert will be 18-inches in diameter, and require a minimum fill height of 2 feet and a maximum burial depth of 40 feet. The culvert is expected to last 75 years. The area is not prone to heavy snowfall and experiences relatively high temperatures. Extensive environmental testing has been performed and the results are shown below. Representatives of the South Carolina Department of Transportation have confirmed that Quality Control personnel will be present throughout installation. The likelihood of fire is probable.

Table 4-3: Environmental Testing Results for Route 25

Sulfate Content	pH Concentration	Resistivity	Velocity
1,200 ppm	8	4,000 ohm-cm	5 ft./sec.

Figure 4-3: Location of Proposed Culvert Installation beneath Route 25

Based on the chart shown on the following page, the South Carolina Department of Transportation will either need to provide additional protection or modify the design calculations. A high density polyethylene culvert and a polypropylene culvert satisfy all of the requirements with the exception of the maximum fill height. A plastic culvert is limited to a maximum fill height of 20 feet. Reinforced concrete culverts, corrugated steel culverts, and corrugated aluminum culverts are susceptible to degradation when the sulfate content is greater than 1,000 ppm. Therefore, if the maximum fill height cannot be modified, a reinforced concrete culvert, a corrugated steel culvert, and a corrugated aluminum culvert are all acceptable material types on the condition that additional protection is provided.

Directions: Input the predetermined site/project specific conditions into the blank column shown. Compare the inputted data to the data shown to the right of the bolded black line. Note if additional protection is required.

	Site Conditions	Reinforced Concrete	Galvanized Steel	Aluminized Steel	Aluminum	High Density Polyethylene	Polypropylene
Service Life (Years)	75	+ 75	75	75	75	75	75
Sulfate Content (ppm)	1,200	≤ 1,000 [(1)]	≤ 1,000[(1)]	≤ 1,000[(1)]	≤ 1,000[(1)]	N/A	N/A
Resistivity (ohm-cm)	4,000	> 3,000[(2)]	> 3,000[(2)]	> 3,000[(2)]	> 3,000[(2)]	N/A	N/A
pH Levels	8	pH < 5	6 < pH < 10	5 < pH < 9	5 < pH < 9	N/A	N/A
Abrasion (Level)	2	1, 2, 3	1, 2, 3[(3)]	1, 2, 3[(3)]	1, 2, 3[(3)]	1, 2, 3	1, 2, 3
Ultraviolet Radiation	No	N/A	N/A	N/A	N/A	Highly Sensitive	Highly Sensitive
Flammability/ Heat	No	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive
Max. Pipe Diameter (in.)	18	96	72	72	72	48	48
Min. Fill Height (ft.)	2	1 – 2	1 – 2	1 – 2	1 – 2	2	2
Max. Fill Height (ft.)	40	N/A	N/A	N/A	N/A	20	20
Quality Controlled Installation	Yes	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive

Note:
(1) Additional protection required if the sulfate content exceeds 1,000 ppm.
(2) Additional protection required if the resistivity is less than 3,000 ohm-cm. Metal culverts not recommended.
(3) Additional protection required for moderate abrasion conditions.

4.5 Culvert Project

The Mississippi Department of Transportation has begun the design of a new culvert beneath Robinson Road in Jackson. According to preliminary calculations, the culvert will be 36-inches in diameter, and require a minimum fill height of 2 feet and a maximum burial depth of 15 feet. The culvert is expected to last 70 years. The area is not prone to snowfall and experiences relatively high temperatures. Extensive environmental testing has been performed and the results are shown below. Representatives of the Mississippi Department of Transportation have confirmed that Quality Control personnel will not be present during installation. The likelihood of fire is unlikely.

Table 4-4: Environmental Testing Results for Robinson Road

Sulfate Content	pH Concentration	Resistivity	Velocity
700 ppm	5	3,500 ohm-cm	5 – 15 ft./sec.

Figure 4-4: Location of Proposed Culvert Installation beneath Robinson Road

Based on the chart shown on the following page, the Mississippi Department of Transportation can only choose a reinforced concrete culvert. A corrugated aluminized steel culvert, a corrugated galvanized steel culvert, and a corrugated aluminum culvert were eliminated due to pH levels. A plastic culvert was eliminated due to the lack of presence of Quality Control personnel.

Directions: Input the predetermined site/project specific conditions into the blank column shown. Compare the inputted data to the data shown to the right of the bolded black line. Note if additional protection is required.

	Site Conditions	Reinforced Concrete	Galvanized Steel	Aluminized Steel	Aluminum	High Density Polyethylene	Polypropylene
Service Life (Years)	65	+ 75	75	75	75	75	75
Sulfate Content (ppm)	700	≤ 1,000 [1]	≤ 1,000[1]	≤ 1,000[1]	≤ 1,000[1]	N/A	N/A
Resistivity (ohm-cm)	3,500	> 3,000[2]	> 3,000[2]	> 3,000[2]	> 3,000[2]	N/A	N/A
pH Levels	5	pH < 5	6 < pH < 10	5 < pH < 9	5 < pH < 9	N/A	N/A
Abrasion (Level)	3	1, 2, 3	1, 2, 3[3]	1, 2, 3[3]	1, 2, 3[3]	1, 2, 3	1, 2, 3
Ultraviolet Radiation	No	N/A	N/A	N/A	N/A	Highly Sensitive	Highly Sensitive
Flammability/ Heat	No	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive
Max. Pipe Diameter (in.)	36	96	72	72	72	48	48
Min. Fill Height (ft.)	2	1 – 2	1 – 2	1 – 2	1 – 2	2	2
Max. Fill Height (ft.)	15	N/A	N/A	N/A	N/A	20	20
Quality Controlled Installation	No	N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive

Note:
[1] Additional protection required if the sulfate content exceeds 1,000 ppm.
[2] Additional protection required if the resistivity is less than 3,000 ohm-cm. Metal culverts not recommended.
[3] Additional protection required for moderate abrasion conditions.

Chapter 5: Conclusions and Recommendations

5.1 Research Summary and Conclusions

Changes in Federal legislation led to an increasing number of plastic pipes chosen for transportation projects. Thermoplastic pipe offers considerable advantages over the conventional reinforced concrete pipe and the corrugated steel pipe. However, most State Departments have little experience with thermoplastic pipe and are hesitant to revise conventional selection policies. In 2008, ALDOT contracted with Auburn University to investigate the field performance of plastic pipe in cross-drainage application. This marked Phase One of The Plastic Pipe for Highway Construction Project. Completed in 2011, the project addressed three distinct research components: a literature review, finite element modeling, and a field study.

In 2015, Phase Two of The Plastic Pipe for Highway Construction Project was initiated with three key components on the agenda. In this phase, ALDOT requested the continuation of monitoring the long-term plastic pipe performance at Beehive Road, the evaluation of real-world construction effects, and the development of a comprehensive specification or “decision tree” to aid in the selection of pipe material.

The primary objective of this thesis research was to develop a practical selection algorithm that can be used by State and county highway engineers. The algorithm determines the optimum type and class of pipe for cross-drainage application. This thesis research accomplishes one of the three key components on the agenda.

The Specification for Culvert Material Selection is comprised of checklists and a condensed summary of the material contained within this thesis. The checklists will allow for the quick selection or elimination of culvert material based upon predetermined site conditions. The accompanying condensed summary will serve as an on-the-go literature guide and represent fundamental information that has been extracted from this thesis. The checklists were created from crucial durability concerns and installation requirements most commonly involved in the selection process. Crucial durability concerns include: sulfate content, resistivity, pH levels, abrasion, flammability, and ultraviolet radiation. Installation requirements include: minimum soil cover, maximum soil cover, culvert diameter, and presence of Quality Control personnel.

High density polyethylene and polypropylene are viscoelastic materials. Viscoelastic materials exhibit a nonlinear stress-strain relationship and are dependent on time. According to *Evaluation of Polypropylene Drainage Pipe*, “Polypropylenes exhibit higher tensile, flexural, and compressive strength and higher moduli than polyethylene” (Hoppe 2011). Steel and concrete, on the other hand, are both elastic materials. Elastic materials have a linear stress-strain relationship and will return to their original shape after unloading. Thermoplastic pipe is prone to slow crack growth through the pipe wall.

Thermoplastic pipes have excellent resistance to most durability issues. Plastic pipes are unaffected by the sulfate content, the chloride content, and the resistivity in the soil. Plastic pipes are also unaffected by the hydrogen ion concentration of the surrounding soil and water. Reinforced concrete culverts, corrugated steel culverts, and corrugated aluminum culverts are all susceptible to these common forms of degradation. Plastic pipe exhibits good abrasion resistance and will likely not experience the dual action of corrosion and abrasion. However, abrasion tests were based on using small aggregate sizes flowing at low velocities. Steel pipe is the most susceptible to abrasion. However, aluminum pipe offers no improvement. The NCSPA recommends using non-metallic coatings over metallic coatings for increased abrasion resistance.

Plastic pipe is susceptible to extremely high temperatures and ultraviolet radiation. According to the report *Evaluation of Polypropylene Drainage Pipe* published by the Virginia Center for Transportation Innovation and Research, "Polypropylene is highly susceptible to oxidation and undergoes oxidation more readily than polyethylene" (Hoppe 2011). All culvert materials are affected by fire and extremely high temperatures. The National Fire Protection Association has given both polyethylene and polypropylene a rating of 1 (Slow Burning) on a scale of 0 to 4. The higher the rating, the more vulnerable the material to combustion. However, several departments of Transportation have reported cases of the pipe ends catching on fire. AASHTO M294 2008 even recommends protecting the exposed portions of polyethylene pipe to protect against combustion and ultraviolet radiation.

Very few State Departments of Transportation recommend a fill height greater than 25 feet for high density polyethylene or polypropylene. However, thermoplastic agencies like the Plastics Pipe Institute permit a fill height up to 50 feet for a certain diameter of pipe. The cover height may be temporarily increased during construction to protect the culvert against heavy equipment. Culvert pipes are available in 6-inch increments. State Departments like New York and Florida have only recently begun to update selection policies and allow 60-inch diameter plastic pipe. Most State Departments of Transportation limit the diameter of a plastic pipe to 48 inches. Polyvinyl chloride pipe was not included in this thesis research. However, polyvinyl chloride pipe will be considered as an allowable material type in the final project report submitted to ALDOT.

5.2 Recommendations

Thermoplastic pipe offers considerable advantages. However, thermoplastic pipe is so new that most State Departments of Transportation are reluctant to install large-diameter thermoplastic pipes beneath major roadways with high volumes of heavy traffic. In an effort to counteract the hesitancy, the following recommendations are presented.

1. Perform a comparative economic analysis of the following culvert material for cross-drainage application: reinforced concrete, corrugated steel, corrugated aluminum, high density polyethylene, and polypropylene.
2. Continue monitoring the field performance of high density polyethylene culverts and polypropylene culverts installed in Alabama and the Southeastern United States.
3. Continue field testing to determine the maximum allowable fill height of high density polyethylene culverts and polypropylene culverts. Field testing should include standard highway construction equipment traffic.
4. Continue field testing to determine the maximum allowable pipe diameter of high density polyethylene culverts and polypropylene culverts.
5. Determine the effects of large bedload particles and high velocity flows on the inside of high density polyethylene culverts and polypropylene culverts. Current abrasion tests have used small aggregate sizes flowing at low velocities.
6. Research and test rehabilitative strategies specifically developed for high density polyethylene culverts and polypropylene culverts.

References

AASHTO LRFD Bridge Design Specifications Errata. Washington, DC: American Association of State Highway and Transportation Officials, 2012. Electronic.

AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing. Washington, DC: American Association of State Highway and Transportation Officials, 2008. Print.

Advanced Drainage Systems, Incorporated. *Drainage Handbook*. 2014. Electronic.

Ardani, Ahmad, Mallela, Jagannath, and Wyatt, Tim. *High Density Polyethylene Pipe Fill Height Table in Arizona*. 2006. Electronic.

ASTM Standard A760, 2015. “Standard Specification for Corrugated Steel Pipe, Metallic-Coated, for Sewers and Drains.” ASTM International, West Conshohocken, PA.

ASTM Standard B745, 2015. “Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains.” ASTM International, West Conshohocken, PA.

ASTM Standard C76, 2015. “Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe.” ASTM International, West Conshohocken, PA.

ASTM Standard C150, 2015. “Standard Specification for Portland Cement.” ASTM International, West Conshohocken, PA.

ASTM Standard C655, 2015. “Standard Specification for Reinforced Concrete D-Load Culvert, Storm Drain, and Sewer Pipe.” ASTM International, West Conshohocken, PA.

ASTM Standard C1479, 2015. “Standard Practice for Installation of Precast Concrete Sewer, Storm Drain, and Culvert Pipe using Standard Installations.” ASTM International, West Conshohocken, PA.

ASTM Standard D2321, 2015. “Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications.” ASTM International, West Conshohocken, PA.

ASTM Standard D3350, 2014. “Standard Specification for Polyethylene Plastics Pipes and Fittings Materials.” ASTM International, West Conshohocken, PA.

ASTM Standard F2136, 2015. “Standard Test Method for Notched, Constant Ligament-Stress (NCLS) Test to Determine Slow-Crack-Growth Resistance of HDPE Resins or HDPE Corrugated Pipe.” ASTM International, West Conshohocken, PA.

Baldwin, Suzie. “There are Interesting Inventions.” *Montgomery Memories*. Oct. 2014. Electronic. 4 Jan. 2016.

Barbisan, Umberto and Guardini, Matteo. “Short History of Concrete.” *McGill School of Architecture*. 2005. Web. 2 Jan. 2016. <http://www.arch.mcgill.ca/prof/sijpkes/abc-structures-2005/concrete/history-of-concrete_files/concrete.html>.

Bergendahl, Bart S., Hotchkiss, Rollin H., and Kilgore, Roger T. *Culvert Design for Aquatic Organism Passage*. 2010. Electronic. 3 Jan. 2016.

Bogan, Arthur E., et al. *A Comparison of the Impacts of Culverts versus Bridges on Steam Habitat and Aquatic Fauna*. Jan. 2007. Electronic. 7 March 2016.

“Brand Story of Hula-Hoop.” *Wham-O*. Wham-O, n.d. Web. 7 March 2016. <http://www.wham-o.com/brands/Hula_Hoop.html>.

Brown, R. H. *Aluminum Pipe Culverts*. Sep. 1965. Electronic. 2015.

California Department of Transportation. *Bridge Design Specifications*. 2000. Electronic. 2016.

California Department of Transportation. *Highway Design Manual*. Mar. 2014. Electronic. 2016.

Chaker, Victor. *Effects of Soil Characteristics on Corrosion*. 1989. Electronic. 2015.

“Concrete Pipe.” *Portland Cement Association*. Portland Cement Association, n.d. Web. 2015. <http://www.cement.org/cement-concrete-basics/products/concrete-pipe>.

Connecticut Department of Transportation. *Drainage Manual*. 2000. Electronic. 2015.

"Culverts." *National Oceanic and Atmospheric Administration*. National Oceanic and Atmospheric Administration, n.d. Web. 2015. <http://www.westcoast.fisheries.noaa.gov/fish_passage/solutions/Culverts.html>.

"Culvert Language in Map-21 Highway Bill." *American Concrete Pipe Association*. American Concrete Pipe Association, n.d. Web. 2015. <http://www.concretepipe.org/engineerdecision.html>.

"Culverts – Proper Use and Installation." *Wisconsin Department of Transportation*. 2004. Electronic. 2016.

"Design Methodology." *Plastics Pipe Institute*. Electronic. 2015.

"Discovery of Polypropylene and High-Density Polyethylene." *American Chemical Society*. 12 Nov. 1999. Web. 2015. <http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/polypropylene.html>.

Dreiling, Gunter, et al. *100 Year Service Life of Polypropylene and Polyethylene Gravity Sewer Pipes*. Dec. 2014. Electronic. 2015.

"Fill Height Table for Circular Concrete Pipe." *Oregon Standard Drawings*. 2015. Electronic. 2016.

Gabriel, Lester H. "Durability and Service Life." *Plastics Pipe Institute*. Plastics Pipe Institute, n.d. Electronic. 2015.

Gabriel, Lester H. "History and Physical Chemistry of HDPE." *Plastics Pipe Institute*. Plastics Pipe Institute, n.d. Electronic. 2015.

"HDPE Pipe Failure at Texas Fish Hatchery Offers Costly Lessons." *PR Newswire*. 2010. Web. 2016. < http://www.prnewswire.com/news-releases/hdpe-pipe-failure-at-texas-fish-hatchery-offers-costly-lessons-104309423.html>.

"High-Density Polyethylene Pipe Systems." *Plastics Pipe Institute*. Plastics Pipe Institute, n.d. Electronic. 2016.

"History of Aluminum." *The Aluminum Association*. The Aluminum Association, n.d. Web. 5 Jan. 2016. < http://www.aluminum.org/aluminum-advantage/history-aluminum>.

“History of Aluminum Extrusion.” *Spectra Aluminum Products*. 2010. Web. 5 Jan. 2016. <http://www.spectraaluminum.com/article-history-of-aluminum-extrusion>.

“History of the World: The First Piece of Polythene.” *British Broadcasting Company*. 29 Sep. 2010. Web. 2015. <http://news.bbc.co.uk/local/manchester/hi/people_and_places/ history/newsid_9042000/9042044.stm>.

Hollands, Bruce. “PVC Piping is the Future.” *The Hill*. 2 May 2011. Web. 5 Jan. 2016. < http://thehill.com/opinion/letters/158815-pvc-piping-is-the-future>.

Hoppe, Edward J. *Evaluation of Polypropylene Drainage Pipe.* 2011. Electronic. 2015.

Hsuan, Y. Grace and McGrath, Timothy. *Protocol for Predicting Long-term Service of Corrugated High Density Polyethylene Pipes*. 29 July 2005. Electronic. 10 March 2016.

“Hydraulic Efficiency.” *American Concrete Pipe Association*. 2010. Electronic. 2015.

Katti, Kalpana, et al. *Cost Effective Non-Flammable Pipe Liners*. 2003. Electronic. 2016.

Kavanaugh, Catherine. “Study: Service Life for PE, PP Sewer Pipes at least 100 Years.” *Plastic News*. 14 Dec. 2015. Web. 18 Dec. 2015. < http://www.plasticsnews.com/article/ 20151214/NEWS/151219923/ study-service-life-for-pe-pp-sewer-pipes-at-least-100-years>.

Keller, Gordon and Sherar, James. *Best Management Practices Field Guide*. 2003. Electronic. 2016.

Kentucky Department of Transportation. *Drainage Manual*. 1993. Electronic. 2015.

Kestler, Maureen A, et al. *Decision Analysis for Corrugated Metal Culvert Rehabilitation using Trenchless Technology*. December 2012. Electronic. 2016.

Kilgore, Roger T, et al. *Hydraulic Design of Highway Culverts*. 3rd ed. 2012. Electronic. 2015.

“FHWA Broadens Allowable Pipe Choices.” *Civil + Structural Engineer*. 2006. Web. 11 June 2015. < http://cenews.com/post/110/fhwa_broadens_allowable_pipe_choices>.

“Fires in Sewers and Culverts.” *American Concrete Pipe Association*. 1982. Electronic. 2015.

Florida Department of Transportation. *Drainage Handbook Optional Pipe Materials*. 2014. Electronic. 2016.

Florida Department of Transportation. *Drainage Manual*. Tallahassee: 2016. Electronic. 2016.

"Florida Department of Transportation Report No. 94-7A High Density Polyethylene Pipe Fire Risk Evaluation." *Advanced Drainage Systems, Inc*. 15 July 1994. Electronic. 2015.

"Florida DOT Approves use of Polypropylene Pipe." *Advanced Drainage Systems, Inc.* 10 Mar. 2014. Web. 18 Dec. 2015. < http://www.ads-pipe.com/en/article.asp?articleID=292>.

Frei, Christopher M. and Hotchkiss, Rollin H. *Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report*. 2007. Electronic. 2015.

French, Robert Chandler. *Cross-Drain Pipe Material Selection Algorithm*. 2013. Print. 2015.

Gassman, Sarah L. *Specifications for Culvert Pipe used in SCDOT Highway Applications*. Columbia: 2006. Electronic. 2015.

Gas Technology Institute. *Plastic Pipe Failure, Risk, and Threat Analysis*. 2009. Electronic. 2015.

General Accounting Office. *Restoring Fish Passage through Culverts on Forest Service and BLM Lands in Oregon and Washington could Take Decades*. 23 Nov. 2001. Electronic. 2015.

"Get a Grip with Uvinul®!" *BASF The Chemical Company*. BASF, n.d. Web. 2016.

Goddard, James B. "A Brief History of the Development and Growth of the Corrugated Polyethylene Pipe Industry in North America." *Journal of ASTM International*. Jan. 2011. Electronic. 2016.

Golder Associates, Inc. *NCHRP 10-86, Bidding of Alternative Drainage Pipe Systems*. 2011. Electronic. 2016.

Jones, M.S. "Effects of UV Radiation on Building Materials." *Building Research Association of New Zealand*. Jan. 2002. Electronic. 2016.

"Joseph Monier." *Encyclopedia Britannica*. Encyclopedia Britannica, n.d. Web. 2015. <http://www.britannica.com/biography/Joseph-Monier>.

Kestler, Maureen A., et al. *Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology*. 2012. Electronic. 2016.

Lee, A. Grant. “Century Concrete Pipe Does Exist.” *Canadian Concrete Pipe Association*. Canadian Concrete Pipe Association, n.d. Electronic. 2015.

Louisiana Department of Transportation. *Hydraulics Manual*. 2011. Electronic. 2016.

“LRFD Fill Height Tables for Concrete Pipe.” *American Concrete Pipe Association*. 2013. Electronic. 2016.

Maine Department of Transportation. *Urban & Arterial Highway Design Guide*. 2005. Electronic. 2016.

“MAP-21 – Moving ahead for Progress in the 21st Century.” *Federal Highway Administration*. 11 May 2015. Web. 17 June 2015. < https://www.fhwa.dot.gov/map21/>.

“Manning’s *n* Values History of Research.” *American Concrete Pipe Association*. 2012. Electronic. 2015.

Marr, Jeff and Taylor, Craig A. *A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota*. 2012. Electronic. 2015.

Maryland Department of Transportation. *Highway Drainage Manual Design Guidelines*. 2009. Electronic. 2016.

Massachusetts Department of Transportation. *Project Development & Design Guide*. 2006. Electronic. 2016.

Michigan Department of Transportation. *Culvert and Storm Sewer Pipe Material Policy on Federally Funded Local Agency Projects*. 2013. Electronic. 2015.

Minnesota Department of Transportation. *Drainage Manual*. 2000. Electronic. 2015.

Mitchell Jr, Charles C. “Soils of Alabama.” 2008. Electronic. 2015.

Molinas, Albert and Mohmand, Amanullah. *Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Material*. 2009. Electronic. 2015.

National Corrugated Steel Pipe Association. *Corrugated Steel Pipe Design Manual.* Dallas: 2008. Electronic. 2015.

National Corrugated Steel Pipe Association. “CSP Durability Guide.” May 2000. Electronic. 2016.

National Corrugated Steel Pipe Association. “Steel: Proven 100-Years Strong.” The National Corrugated Steel Pipe Association, n.d. Electronic. 2015.

New York Department of Transportation. *Highway Design Manual*. 2 Dec. 2014. Electronic. 2016.

Nicol, David. “Re: Information: Map-21 Section 1525 Interim Policy Guidance.” Message to Division Administrators. 9 Oct. 2012. E-mail. 17 June 2015.

North Carolina Department of Transportation. *Drainage Users Manual*. 1 Jan. 2003. Electronic. 2016.

North Carolina Department of Transportation. *Drainage Users Manual Appendices.* 18 Jan. 2016. Electronic. 2016.

O’Connor, Chris. “The Nature of Polyethylene Pipe Failure.” *Pipeline & Gas Journal* 239.12 (2012). Electronic. 2016.

Ohio Department of Transportation. *Bridge Mechanics*. 2014. Electronic. 2016.

Oregon Department of Transportation. *Hydraulics Manual*. 2014. Electronic. 2016.

Pennsylvania Department of Transportation. *Maintenance Manual*. 2012. Electronic. 2016.

“pH: Introduction.” *Environmental Protection Agency*. Environmental Protection Agency, n.d. Web. 2015. < http://www3.epa.gov/caddis/ssr_ph_int.html>.

Rahman, Shah. “An Objective Understanding of Pipe-Soil Interaction, Design and Installation.” *Trenchless Technology*. Nov. 2010. Electronic. 2015.

Scully, Janene. “Crews Gain Upper Hand with Fire Burning along Highway 101 near Nojoqui Summit.” *Noozhawk*. 16 Aug. 2015. Web. 2015. < http://www.noozhawk.com/article/fire_burning_nojoqui_grade_summit_south_of_buellton>.

“Service Life of HDPE Corrugated Pipe.” *Plastics Pipe Institute*. Plastics Pipe Institute, n.d. Electronic. 2015.

“Solution to Corrosion.” *PVC Pipe Association*. 2011. Web. 5 Jan. 2016. < http://www.uni-bell.org/corrosion.html>.

South Dakota Department of Transportation. *Drainage Manual*. 2011. Electronic. 2015.

"Title 23 – Highways." *Code of Federal Regulations*. 1 Apr. 2011. Electronic. 2015.

"The Difference between Elastic Materials and Viscoelastic Materials." *Sorbothane*. Sorbothane, n.d. Web. 2015. < http://www.sorbothane.com/the-difference-between-elastic-materials-and-viscoelastic-materials.aspx>.

"The Power of Plastic." *Dow Chemical Company*. Oct. 2009. Electronic. 2016.

Transportation Research Board. *NCHRP Report 429 HDPE Pipe: Recommended Material Specifications and Design Requirements*. 1999. Electronic. 2016.

Transportation Research Board. *NCHRP Synthesis 474 Service Life of Culverts*. 2015. Electronic. 2015.

"Types and Causes of Concrete Deterioration." *Portland Cement Association*. 2002. Electronic. Dec. 2015.

Utah Department of Transportation. "Commentary to Aid Inspection of PVC & HDPE Pipe Conforming to Section 02610 of the UDOT Specifications." *Pipe, Pipe-arch, Structural Plate Pipe, and Structural Pipe Arch.* 2008. Electronic. 2016.

Washington State Department of Transportation. *Hydraulics Manual*. 2008. Electronic. 2016.

"Watershed and Fisheries Ecological Restoration on the Six Rivers National Forest". *United States Department of Agriculture*. 2005. Electronic. 12 March 2016.

Wisconsin Department of Transportation. *Structure Inspection Manual*. 2011. Electronic. 2015.

Zhao, Jack Q, et al. *Durability and Performance of Gravity Pipes: A State-of-the-Art Literature Review.* 1998. Electronic. 2016.

"14 Reasons to Choose Concrete." *American Concrete Pipe Association*. American Concrete Pipe Association, n.d. Web. 2016. <http://www.concretepipe.org/ pipe-box-resources/design/14-reasons/>.

"23 CFR Appendix A to Subpart D of Part 635 – Summary of Acceptable Criteria for Specifying Types of Culvert Pipes." *United States Government Publishing Office*. 1 April 2004. Web. Dec. 2015. <https://www.gpo.gov/fdsys/granule/CFR-2004-title23-vol1/

CFR-2004-title23-vol1-part635-subpartD-appA>.

Appendix A: Attributes of a Good Highway Culvert

According to the American Society for Civil Engineers Task Force on Hydraulics of Culverts, 13 specific design parameters are recommended as "Attributes of a Good Highway Culvert."

1. The culvert, appurtenant entrance and outlet structures should properly take care of water, bed load, and floating debris at all stages of flow.
2. It should cause no unnecessary or excessive property damage.
3. Normally, it should provide for transportation of material without detrimental change in flow pattern above and below the structure.
4. It should be designed so that future channel and highway improvement can be made without too much loss or difficulty.
5. It should be designed to function properly after fill has caused settlement.
6. It should not cause objectionable stagnant pools in which mosquitoes may breed.
7. It should be designed to accommodate increased runoff occasioned by anticipated land development.
8. It should be economical to build, hydraulically adequate to handle design discharge, structurally durable and easy to maintain.
9. It should be designed to avoid excessive ponding at the entrance which may cause property damage, accumulation of drift, culvert clogging, saturation of fills, or detrimental upstream deposits of debris.
10. Entrance structures should be designed to screen out material which will not pass through the culvert, reduce entrance losses to a minimum, make use of the velocity of approach in so far as practicable, and by use of transitions and increased slopes, as necessary, facilitate channel flow entering the culvert.
11. The design of the culvert outlet should be effective in re-establishing tolerable non-erosive channel flow within the right-of-way or within a reasonably short distance below the culvert.
12. The outlet should be designed to resist undermining and washout.
13. Energy dissipaters, if used, should be simple, easy to build, economical and reasonably self-cleaning during periods of easy flow.

Appendix B: The Specification for Culvert Material Selection

Directions: Input the predetermined site/project specific conditions into the blank column shown. Compare the inputted data to the data shown to the right of the bolded black line. Note if additional protection is required.

	Site Conditions	Reinforced Concrete	Galvanized Steel	Aluminized Steel	Aluminum	High Density Polyethylene	Polypropylene
Service Life (Years)		+ 75	75	75	75	75	75
Sulfate Content (ppm)		≤ 1,000 (1)	≤ 1,000(1)	≤ 1,000(1)	≤ 1,000(1)	N/A	N/A
Resistivity (ohm-cm)		> 3,000(2)	> 3,000(2)	> 3,000(2)	> 3,000(2)	N/A	N/A
pH Levels		pH < 5	6 < pH < 10	5 < pH < 9	5 < pH < 9	N/A	N/A
Abrasion (Level)		1, 2, 3	1, 2, 3(3)	1, 2, 3(3)	1, 2, 3(3)	1, 2, 3	1, 2, 3
Ultraviolet Radiation		N/A	N/A	N/A	N/A	Highly Sensitive	Highly Sensitive
Flammability/ Heat		N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive
Max. Pipe Diameter (in.)		96	72	72	72	48	48
Min. Fill Height (ft.)		1 – 2	1 – 2	1 – 2	1 – 2	2	2
Max. Fill Height (ft.)		N/A	N/A	N/A	N/A	20	20
Quality Controlled Installation		N/A	Sensitive	Sensitive	Sensitive	Highly Sensitive	Highly Sensitive

Note:
(1) Additional protection required if the sulfate content exceeds 1,000 ppm.
(2) Additional protection required if the resistivity is less than 3,000 ohm-cm. Metal culverts not recommended.
(3) Additional protection required for moderate abrasion conditions.

	Reinforced Concrete	Galvanized Steel	Galvanized Aluminum	Aluminum	High Density Polyethylene	Polypropylene
Sulfate Concentration						
≤ 1,000 ppm	X	X	X	X	X	X
> 1,000 ppm	X(1)	X(1)	X(1)	X(1)	X	X
Resistivity						
< 3,000 ohm-cm	X(2)				X	X
> 3,000 ohm-cm	X	X	X	X	X	X
pH						
pH < 5					X	X
5 < pH < 9	X		X	X	X	X
6 < pH < 10	X	X			X	X
Abrasion						
Level 1 Non-Abrasive	X	X	X	X	X	X
Level 2 Low Abrasion	X	X	X	X	X	X
Level 3 Moderate Abrasion	X	X(3)	X(3)	X(3)	X	X
Level 4 Severe Abrasion	X(4)					
Ultraviolet Radiation						
Susceptible to degradation?					X	X
Flammability/ Heat						
Susceptible to degradation?		X(5)	X(5)	X(5)	X	X
Maximum Pipe Diameter						
6 in. – 48 in.	X	X	X	X	X	X
54 in. – 72 in.	X	X	X	X		
78 in. – 94 in.	X					
Minimum Fill Height						
1 ft.	X	X	X	X		
≥ 2 ft.	X	X	X	X	X	X
Maximum Fill Height						
≤ 20 ft.	X	X	X	X	X	X
> 20 ft.	X	X	X	X		
Quality Control						
Will installation be monitored?		X	X	X	X	X

Environmental/ Site/ Project Parameters

	Reinforced Concrete	Galvanized Steel	Galvanized Aluminum	Aluminum	High Density Polyethylene	Polypropylene
Service Life						
≤ 75 years	X	X	X	X	X	X
> 75 years	X					
Sulfate Concentration						
≤ 1,000 ppm	X	X	X	X	X	X
> 1,000 ppm	X(1)	X(1)	X(1)	X(1)	X	X
Resistivity						
< 3,000 ohm-cm	X(2)				X	X
> 3,000 ohm-cm	X	X	X	X	X	X
pH						
pH < 5					X	X
5 < pH < 9	X		X	X	X	X
6 < pH < 10	X	X			X	X
Abrasion						
Level 1 Non-Abrasive	X	X	X	X	X	X
Level 2 Low Abrasion	X	X	X	X	X	X
Level 3 Moderate Abrasion	X				X	X
Level 4 Severe Abrasion	X(3)					
Ultraviolet Radiation						
Susceptible to degradation?					X	X
Flammability/ Heat						
Susceptible to degradation?		X(4)	X(4)	X(4)	X	X

Notes:

(1) Additional protection required if the sulfate content exceeds 1,000 ppm.

(2) Additional protection required if the resistivity is less than 3,000 ohm-cm. Metal culverts not recommended.

(3) Additional protection required for moderate abrasion conditions.

(4) Additional protection required for severe abrasion conditions.

(5) Protective coatings may be flammable.

Site/ Project Installation Parameters

	Reinforced Concrete	Galvanized Steel	Galvanized Aluminum	Aluminum	High Density Polyethylene	Polypropylene
Maximum Pipe Diameter						
6 in. – 48 in.	X	X	X	X	X	X
54 in. – 72 in.	X	X	X	X		
78 in. – 94 in.	X					
Minimum Fill Height						
1 ft.	X	X	X	X		
≥ 2 ft.	X	X	X	X	X	X
Maximum Fill Height						
≤ 20 ft.	X	X	X	X	X	X
> 20 ft.	X	X	X	X		
Quality Control						
Will installation be monitored?		X	X	X	X	X

Reference Information

This section provides a brief description of the key decision factors affecting the selection of culvert materials for cross-drainage application. This section shall be used in conjunction with the checklists.

I. Sulfate Concentration

While a high concentration of sulfates may corrode metal culverts, sulfates are typically more damaging to concrete culverts. A site shall be considered corrosive if it contains ≥ 1,000 ppm.

- If the sulfate concentration is < 1,000 ppm, concrete, metal, and plastic are all acceptable culvert materials.
- If the sulfate concentration is ≥ 1,000 ppm, concrete and metal culvert materials are the most susceptible to degradation and will require additional protection.

<u>Protective Measures</u>

The most efficient way to protect against a high concentration of sulfates is to choose a cement with a limited amount of tricalcium aluminate. Other resistance factors may include reducing the water-to-cement ratio, using a higher strength concrete, or applying special coatings.

II. Resistivity

Low resistivity values are typically more damaging to metal culverts. A site shall be considered corrosive if it contains ≤ 3,000 ohm-cm.

- If the resistivity value is > 3,000 ohm-cm, concrete, metal, and plastic are all acceptable culvert materials.
- If the resistivity value is ≤ 3,000 ohm-cm, metal culvert materials are the most susceptible to degradation and will require additional protection.

Metal culverts are not recommended if the resistivity value is ≤ 3,000 ohm-cm. Special coatings and/or internal and external cathodic protection is required.

III. Hydrogen Ion Concentration (pH)

Concrete culverts and metal culverts are the most affected by pH levels. Protective coatings may be applied. However, choosing an alternative culvert material more suited for site pH levels may be more desirable.

Concrete Culverts – Concrete should not be used where the pH is less than 5. Concrete culverts are sensitive to saltwater.

Metal Culverts – Galvanized steel should not be used where the pH is outside the range of 6.0 to 10. Aluminized steel is vulnerable to alkalis and should not be used where the pH is greater than 9. Aluminized steel has an advantage over galvanized steel in lower pH environments

Plastic Culverts – High density polyethylene and polypropylene are not affected by pH.

IV. Abrasion

Abrasion is typically more damaging to concrete culverts and metal culverts. Abrasion is dependent on the velocity of water. Table B-2 provides four abrasion levels characterized by the Federal Lands Highway Division.

Concrete Culverts

- Concrete is recommended for abrasive conditions.
- Protective measures shall be taken for severe abrasive conditions.

Metal Culverts

- Steel and plain aluminum are not recommended for abrasive conditions.
- Non-metallic coatings should be chosen over metallic coatings for increased abrasion resistance.

Plastic Culverts

- High density polyethylene is not recommended for severe abrasive conditions.
- Polypropylene is not recommended for severe abrasive conditions.

V. Ultraviolent Radiation

Prolonged exposure to ultraviolet radiation is typically more damaging to high density polyethylene culverts and polypropylene culverts. Extra care shall be taken during the storage period. Extra care shall be taken before backfilling.

VI. Flammability

All culvert materials are affected by fire and extremely high temperatures.

VII. Minimum Fill Height

Concrete culverts and metal culverts typically have a minimum fill height of 12 inches to 24 inches. High density polyethylene culverts and polypropylene culverts shall have a minimum fill height of 24 inches.

VIII. Maximum Burial Depth

Concrete Culverts

The burial depth of concrete culverts is dependent upon the class of pipe and the pipe diameter. Class V requires the greatest amount of cover. The burial depth increases as the pipe diameter increases. Therefore, large diameter concrete culverts are used for deep installation.

Metal Culverts

The burial depth for steel culverts and aluminum culverts is dependent upon pipe diameter, specified sheet thickness, and corrugations.

The burial depth increases as the specified thickness increases, but decreases the pipe diameter increases. Therefore, thicker steel and aluminum culverts with a smaller diameter are used for deep installation.

Plastic Culverts

The burial depth for high density polyethylene culverts and polypropylene culverts is dependent upon pipe material and pipe diameter. The burial depth decreases as the pipe diameter increases. Therefore, small diameter plastic culverts are used for deep installation. Plastic culverts shall not be used in deep installations where the burial depth exceeds 20 feet.