RESEARCH & DEVELOPMENT

Durability of Pipe Materials in Soils

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16. Abstract

A large number of culvert pipes are installed every year in North Carolina. In general, these pipes are mainly selected based on structural requirements with less of an emphasis placed on the subsurface environmental parameters and their impact on the pipe's material durability. Therefore, an improved selection criteria with a focus on durability and service life are proposed herein. As a part of developing such criteria, relevant environmental subsurface exposure conditions including pH, resistivity, chloride and sulfate are cataloged by using GIS database offered by the United States Department of Agriculture (USDA) and the National Atmospheric Deposition Program (NADP). Exposure conditions compatible with various pipe materials are identified based on material science and corrosion principles in published literatures and utilizing existing specifications by departments of transportation across the US. A software, referred to as Pipe Assessment and Selection Software (PASS), is developed in support of implementing the research findings. PASS is programmed in a form of a spreadsheet with readily accessible interfaces and interactive menu. The development of PASS benefited from several meetings with our NCDOT colleagues during which valuable comments and suggestions were received. PASS provides rapid assessment of pipe options for a given project's subsurface environmental conditions and therefore facilitates the estimation of the pipe service life. A training video is developed for the use of PASS. Furthermore, as the service life of galvanized and aluminized steel pipes is directly related to the thickness of their coating, a proposed approach for estimating discount rate as a function of coating thickness is proposed. This aspect addresses the potential of manufacturing processes leading to the coating on the pipes being thinner than specified by standards (e.g., ASTM or AASHTO), and therefore resulting in reduced galvanized and aluminized steel pipes service life. The influence of coating thickness on the service life is quantified using data from a set of corrosion testing. A "discount rate" approach is proposed such that the cost of the pipes can be adjusted based on the estimated reduction in their service life. The discount rate is also programmed in spreadsheet to facilitate its implementation in practice.

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Executive Summary:

A considerable number of culvert pipes are installed yearly in North Carolina. While the loads and structural requirements for these pipes are considered throughout the selection process, the impact of the environmental exposure conditions on the culverts' service life has received less consideration. Selecting the proper pipe for a given exposure condition is a time-consuming process and requires a significant effort. The existing NCDOT selection method provides guidance, but the consensus is it often leads to overly conservative selections, and therefore an increased cost of project.

In this project, the exposure conditions that affect the service life of culverts (e.g., chloride exposure, soil pH and resistivity) were studied and characterized through data in literature and experimental measurements from laboratory testing program. The synthesized information was cross-referenced with the exposure conditions in North Carolina (NC) and the data were programmed onto software tool referred to as Pipe Assessment and Selection Software (PASS). PASS provides service life estimations for a wide range of pipes including Reinforced Concrete Pipe (RCP), galvanized and aluminized Corrugated Steel Pipe (CSP), corrugated aluminum, steel, cast iron, High Density Polyethylene (HDPE), Polypropylene, and Polyvinyl chloride (PVC) pipes. PASS is programmed to automatically retrieve soil pH, resistivity, and chloride data using GPS coordinates of the project. While PASS can retrieve soil properties using GPS coordinates, it also allows the user to input such data if field measurements are available. In addition, and through location triangulation, physicochemical properties of the fill material from nearby quarries of a given project in NC can be uploaded into PASS. PASS then uses these data to provide estimates of service life for different types of pipe if the backfill were to be replaced with materials from a selected quarry. Monte Carlo simulations were used to establish uncertainty in service life estimations through quantifying the environmental condition as random variables.

An additional aspect of pipe durability addressed herein is the effect of coating thickness on the durability of galvanized and aluminized CSPs. If the coating thickness is less than that specified by the relevant standards, the anticipated service life of the coated CSP will be negatively impacted. Pipes with substandard coating thickness however may provide enough service life for certain areas or can be used for short term projects. It is therefore practical to have a reduced (or discount) cost for pipes with reduced coating. To facilitate the development of such discount rate protocol, corrosion experiments were performed on galvanized and aluminized steel with different coating thicknesses in simulated exposure conditions. Results from these experiments were used to quantify the effect of coating thickness on the service life of pipes. The findings indicate that the corrosion rate was independent of coating thicknesses; that is the increase of coating thickness has a linear correlation with increase in the service life. Therefore, a linear model was developed which suggests a "discount rate" for galvanized and aluminized pipes based on the reduced coating thickness. The discount rate model is programmed as well in an Excel spreadsheet.

The products of this research can be used to realize cost and time saving for NCDOT. The developed PASS software enables selection of pipes based on their exposure condition and estimated service life. PASS is also automated to utilize a given project GPS coordinates to retrieve exposure data in North Carolina and provide an estimate of expected service life of a verity of pipe types. Having such feature reduces the effort needed for gathering data and evaluating the suitability of different pipe types at a given project location. In addition, the discount rate model provides data on appropriate related cost index for pipes with reduced coating thickness which are still suitable for use in a project with a reduced demand for service life.

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1. INTRODUCTION

1.1. Background

A large number of culvert pipes are installed every year in North Carolina. While these culverts are selected largely based the required structural performance, their environmental exposure conditions have received less attention in the current selection criteria. A lack of guidelines regarding choosing the appropriate pipe material for a given in situ exposure conditions often leads to a conservative material selection, and therefore higher costs of the project. At the same time, choosing a pipe material type on the un-conservative side with regards to service life can lead to costly re-work and expensive loss of performance.

In addition to selecting the most appropriate pipe's material type given in situ environmental exposure conditions, the coating thickness used in metal pipes for the purpose of corrosion protection needs to be considered in assessing pipes' service life. Galvanized and aluminized steel pipes are prevalent, but so are variations in their coating thicknesses. Such variation in metallic coating thickness have been observed by NCDOT personnel, and it is unclear as how these variations impact the service life. It is also unclear whether NCDOT should reject pipes having coating that is thinner-than-specified, or whether it is acceptable in some cases to pay a reduced price for pipe with reduced-thickness coatings (and use them in areas where the anticipated shorter service life they provide is adequate.) Quantifying the relationship between coating thickness and pipe service life for both galvanized and aluminized pipes will contribute to refining specifications and will provide key data for improving pipes' selection and acceptance criteria. Furthermore, having an estimate of the service life of different pipes enables lifecycle assessment and comparison of cost over service life.

1.2. Research Objectives and Tasks

The specific objectives of the research project included the following:

(i) Catalog the relevant pipes' exposure conditions including (but not limited to) soil pH, soil type, salt exposure across North Carolina, and identify the pipe types appropriate for each exposure condition based on available data in literature. Other data from pipe manufacturers are available and are used to enhance the pipe selection guide.

(ii) Implement the developed pipe selection guide in the form of an automated software to facilitate its use.

(iii) Perform quantitative corrosion rate measurements on galvanized and aluminized steel pipe materials having different thickness coatings to quantify the effect of coating thickness on the service life of the pipe. Use such data to develop guidelines for the financial value in terms of service life given reduced coating thicknesses.

(iv) Provide an estimate of the service life of different pipes so that this information can be used for estimating the life cycle cost of the pipes and used in decision making.

2. Literature Review

2.1. Pipe materials selection guidelines of other Department of Transportations (DOTs)

The literature review included surveying selection methods/criteria used by the Departments of Transportations (DOTs) across the US. Figure 1 shows the DOTs across the country that have pipe material selection procedure specifically based on in situ environmental parameters. Out of the 50 States, 26 States have pipe selection criteria in their drainage manual or pipe material selection guide. Out of these 26 States, 25 states utilize soil pH and soil resistivity for their pipe selection procedure. States highlighted in red use both pH and resistivity as well as other factors such as abrasion, sulfate, moisture content, chloride, bacteria and/or average daily traffic (ADT). States highlighted in light brown only consider pH but do not consider soil resistivity (other factors such as abrasion may be considered). The New York State uses geographic-based exposure parameters and includes guidelines based on two geographic regions; the geographic regions do not seem to rely on pH or resistivity and other consideration may have been used (e.g., prior experience). Figure 2 presents the environmental factors and the number of each which are utilized by the various States in selecting pipe material.

Appendix B provides a detailed review of the selection criteria used by the different States. Appendix B is organized based on the specific criteria used by States; that is States that use pH and resistivity, States that use pH only and State that categorize selection based on geographical regions.

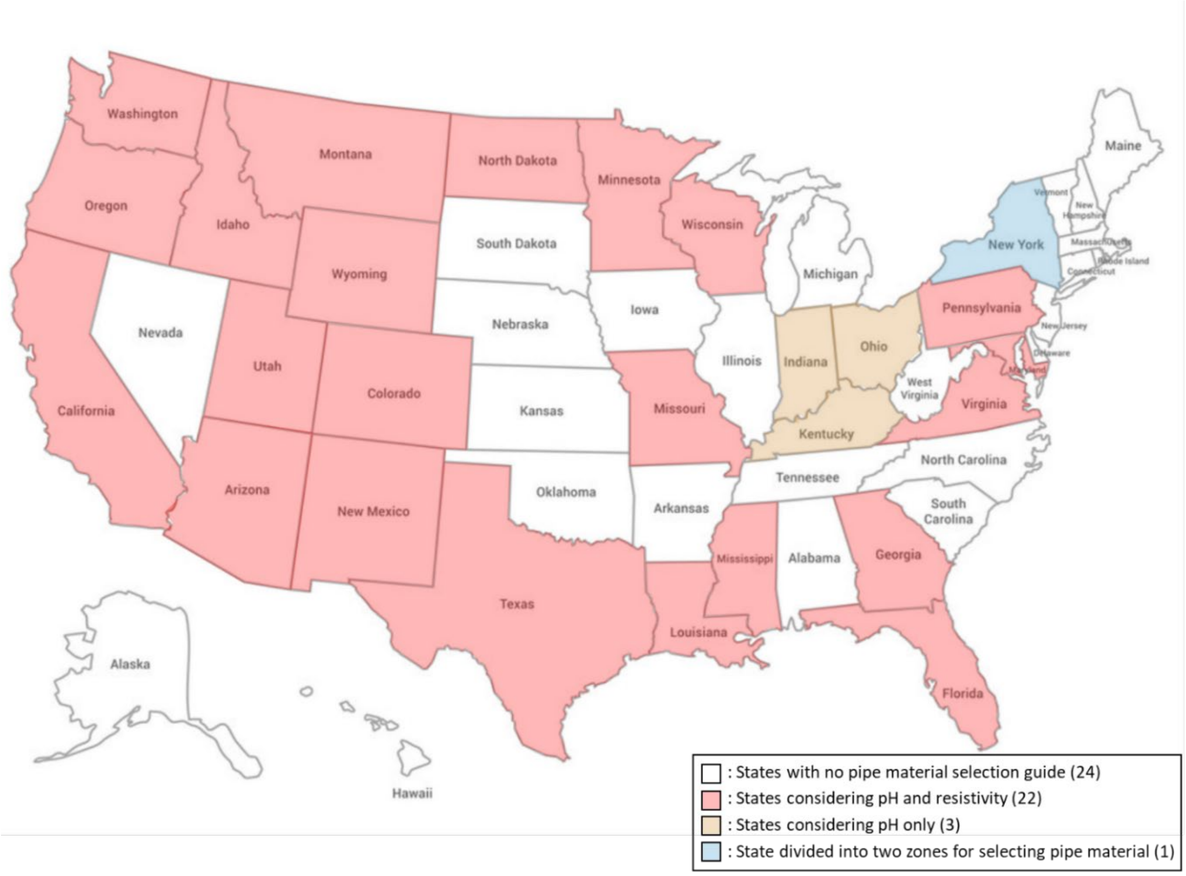


Figure 1. DOTs having pipe material selection guide (The numbers in the parentheses of the legend are the number of states)

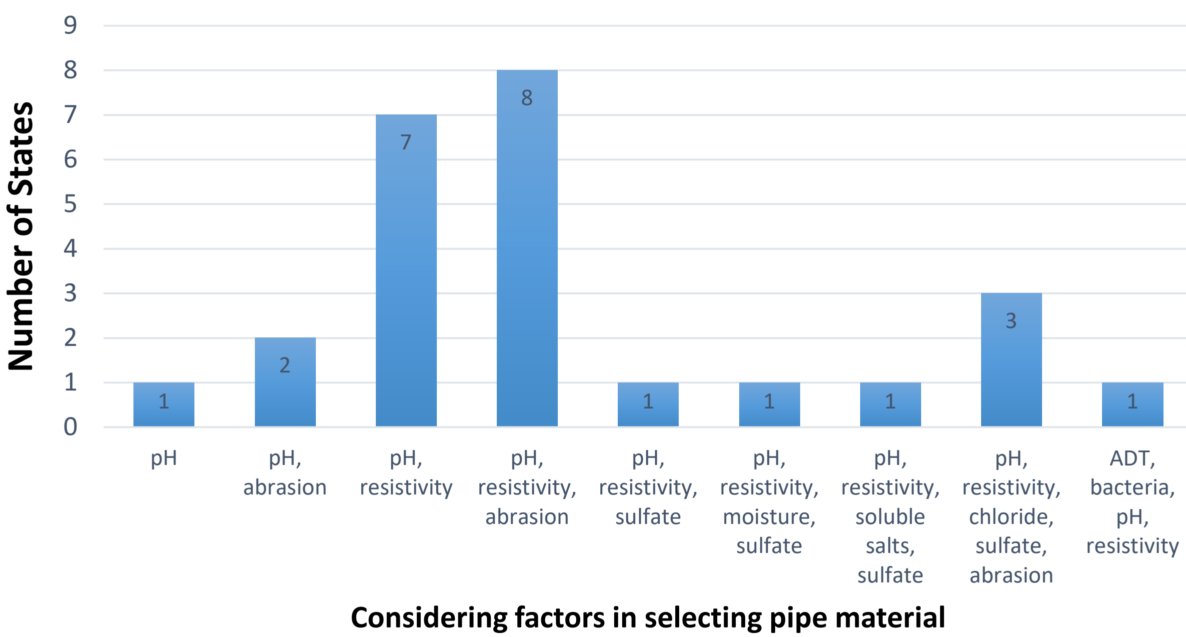


Figure 2. Factors considered by State DOTs in selecting pipe material

2.2. Equations to predict the service life of various pipe materials

While a large number of DOTs have their own guidelines, the majority use some variation of methods used by the California DOT (CALTRANS), AISI, and/or Florida DOT (FDOT). Accordingly, a review of these three methods is presented herein; a detailed literature review of criteria used by other DOTs is provided in Appendix B.

2.2.1. CALTRANS Method

The *Highway Design Manual* of the California Department of Transportation (CALTRANS) provides standards for material selection of drainage pipes. Caltrans has different definitions for the "maintenance-free service life" for metal pipes versus reinforced concrete pipe (RCP). For all metal pipes utilized by Caltrans, the service life is the number of years from installation until the deterioration reaches the point of perforation at any location on the pipe. For RCP, it is the number of years from installation until the deterioration reaches the point of exposure of reinforcement rebars along any point on the pipe.

According to this manual, the anticipated maintenance-free service life of corrugated steel pipe (CSP) installations is primarily a function of the corrosivity and abrasiveness of the environment into which the pipe is placed. The risk of corrosion must be determined from the pH and minimum resistivity tests, as covered in California Test 643. Abrasive potential must be estimated from the grain size of the bed material and the anticipated flow velocities.

Figure 3, "Chart for Estimating Years to Perforation of Steel Culverts" is widely known as the "California Method," and is a part of the *Highway Design Manual* developed based on investigating more than 12,000 corrugated metal highway pipes throughout the California highway system. However, by itself, it is not sufficient for determining service life because it does not consider the effects of abrasion or overfill. In Figure 3, the estimated years-to-perforation is based on both soil pH and soil resistivity for pH values at or below 7.3. For pH values above 7.3 only soil resistivity is used. When pH is greater than 7.3, soil-side corrosion is the controlling mechanism and service life is estimated based on resistivity. However, when pH is less than 7.3, the interior invert corrosion generally controls the rate of corrosion and both resistivity and pH are important.

Caltrans recommends using Figure 4 to determine the minimum thickness of metal pipes for 50-year maintenance-free service life and to impose limitations on the use of corrugated steel and spiral rib pipes for various levels of pH with minimum resistivity. In Figure 4, "curved lines" are used when pH is below 7.30 and straight lines are used for pH values above 7.30. The ranges of pH and minimum resistivity for galvanized steel are not limited; however, for aluminized steel (Type 2) and aluminum, pH is limited to the range from 5.5 to 8.5 and the minimum resistivity is 1,500 ohm-cm. Thickness of galvanized metal pipe is determined by the gage shown in the region between two lines. However, the thickness of aluminized or aluminum pipe is fixed at 16 gage.

To clarify further, some examples were provided by Caltrans as follows:
Given a soil environment with pH and minimum resistivity levels of 6.5 and 15,000 ohm-cm, respectively, the minimum thickness for the various metal pipes is as follows:

i. 0.019 inch (12 gage) galvanized steel,
ii. 0.064 inch (16 gage) aluminized steel (Type 2), and,
iii. 0.060 inch (16 gage) aluminum.

Because the minimum thickness of metal pipe obtained from Figure 4 only satisfies corrosion requirements, overfill requirements for minimum metal thickness must also be checked, and both requirements should be used to determine the minimum metal thickness. In NCDOT pipe selection guide, minimum metal thickness along with the overfill height are provided.

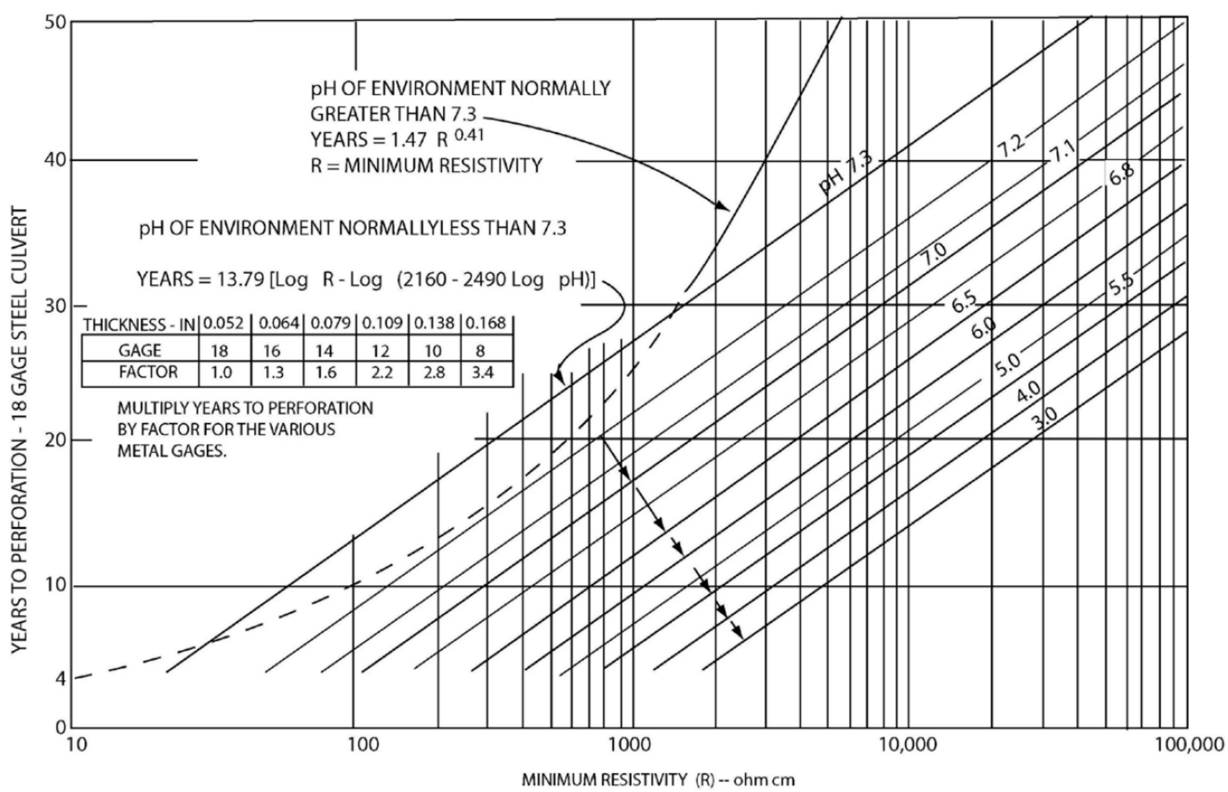


Figure 3. Chart for Estimating Years to Perforation of Steel Culverts (Courtesy of CALTRANS)

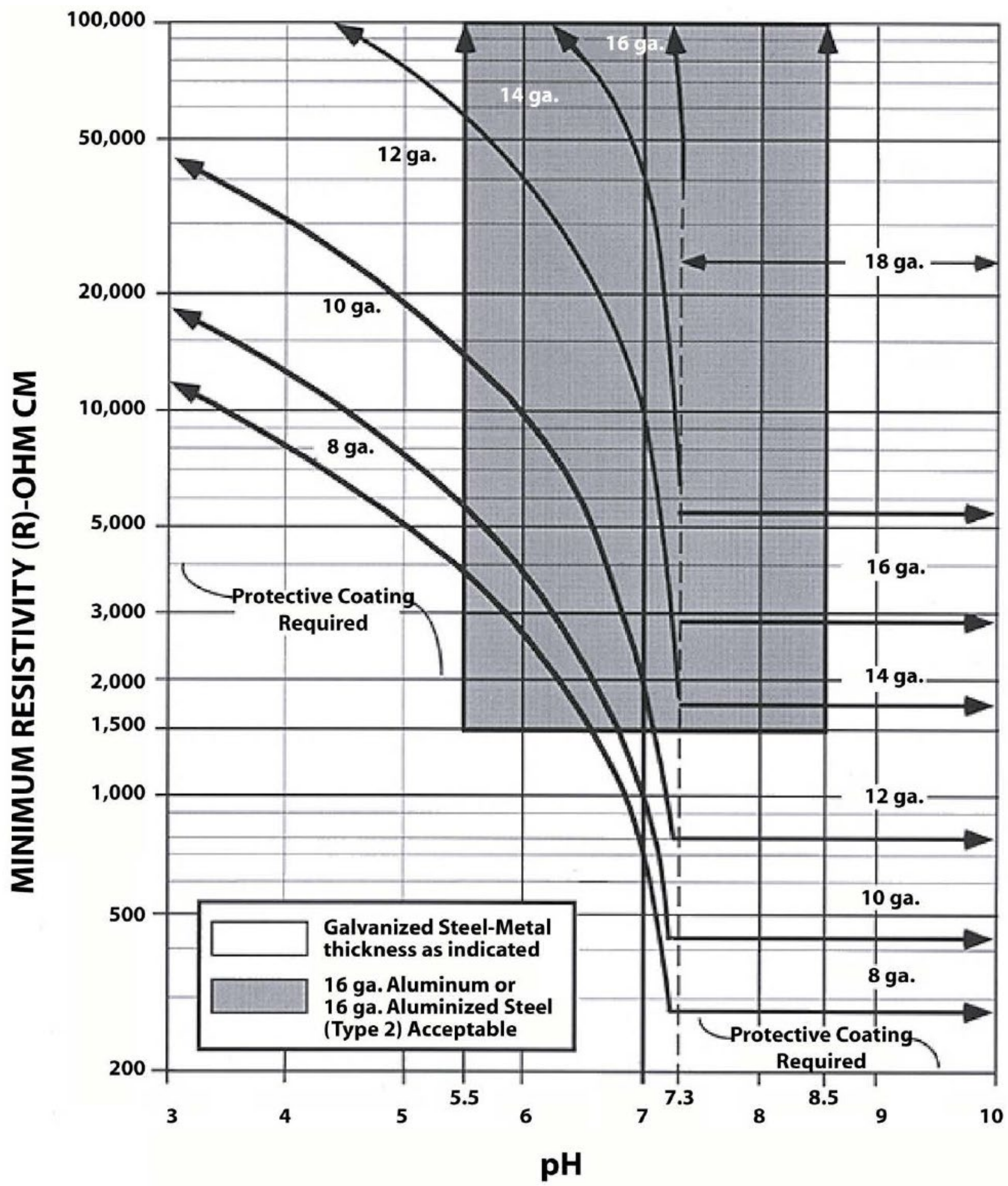


Figure 4. Minimum thickness of metal pipe for 50-year maintenance-free service life (Courtesy of CALTRANS)

Several States have evaluated the Caltrans Method for its suitability for estimating the service life of galvanized corrugated steel pipe and have arrived at differing conclusions. Table 1 summarizes the conclusions reached by the different States. The States of Florida, Idaho and Louisiana are in favor of using the California method, while Georgia and Oklahoma concluded that the method was not suitable for correlation with their local environmental conditions.

Table 1. Selected research conclusions about the California method

Reference	Conclusions about the California Method on the basis of data and/or observations
Florida	Accepts the California Method as suitable for the performance of galvanized steel in the Florida environment but develops new equations to predict durability for aluminized Type 2, aluminum alloy, and concrete.
Idaho	"The test developed by the California Division of Highways and their service life chart appears to be satisfactory. It appears the test method estimates the service life conservatively in all but a few installations."
Louisiana	"Under the environmental conditions (moderately to very corrosive) encountered during this study, the California Chart overestimates predicted pipe life. The chart does, however, combine pH and resistivities to correctly predict life in a relative sense for the mildly, moderately, and very corrosive environments."
Georgia	On the basis of a survey of 251 culverts (140 plain galvanized) in Georgia, it was concluded that expected service life was 50 percent greater than that predicted by the California Method. The AISI method is consistent to conservative in Georgia.
Oklahoma	The California Method generally does not correlate with the observed culvert conditions in the State. The method predicts a shorter lifetime than observed in the western two-third of the State, with the exception of the high plains area of the panhandle where it was quite accurate.

In addition to considering pH and resistivity, Caltrans adapted abrasion levels to select pipe materials. Table 2 shows the considered abrasion levels to vary on a scale of 1 to 5. The level of abrasion is estimated by the amount of bedload, its type, and flow velocity. Generally, coated steel pipes and reinforced concrete pipes are influenced by abrasion, while plastic pipes are normally impacted by the abrasion.

Table 2. Abrasion levels and materials (Courtesy of CALTRANS)

Abrasion level	General site characteristics	Allowable pipe materials and lining alternatives
Level 1	• Bedloads of silts and clays or clear water with virtually no abrasive bed load. No velocity limitation	• All pipe materials listed in Table 857.2 allowable for this level. • No abrasive resistant protective coatings listed in Table 855.2C needed for metal pipe.
Level 2	• Moderate bed loads of sand or gravel • Velocities ≥ 1 ft/s and ≤ 5 ft/s	All allowable pipe materials listed in Table 857.2 with the following considerations: • Generally, no abrasive resistant protective coatings needed for steel pipe. • Polymeric, or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential.
Level 3	• Moderate bed load volumes of sands, gravels and small cobbles. • Velocities ≥ 5 ft/s and ≤ 8 ft/s	All allowable pipe materials listed in Table 857.2 with the following considerations: • Steel pipe may need one of the abrasive resistant protective coatings listed in Table 855.2C or additional gauge thickness if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential. • Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential. • Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (equivalent to galv. Steel) where pH < 6.5 and resistivity < 20,000. Lining alternatives: • PVC, • Corrugated or Solid Wall HDPE, • CIPP
Level 4	• Moderate bed load volumes of angular sands, gravels, and/or small cobbles/rocks.	All allowable pipe materials listed in Table 857.2 with the following considerations: • Steel pipe will typically need one of the abrasive resistant protective coatings listed in Table 855.2C or may need additional gauge thickness if

	• Velocities > 8 ft/s and ≤ 12 ft/s	thickness for structural requirements is inadequate for abrasion potential. • Aluminum pipe not recommended. • Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. • Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended. • Corrugated HDPE (Type S) limited to ≥ 48" min. diameter. • Corrugated HDPE Type C not recommended. • Corrugated PVC limited to ≥ 18" min. diameter Lining alternatives: • Closed profile or SDR 35 PVC (corrugated and ribbed PVC limited to ≥ 18" min. diameter. • SDR HDPE • CIPP (min. thickness for abrasion specified) • Concrete and authorized cementitious pipeliners and invert paving. See Table 855.2F.
Level 5	• Moderate bed load volumes of angular sands and gravel or rock. • Velocities > 12 ft/s and ≤ 15 ft/s	• Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. • For steel pipe invert lining additional gauge thickness is recommended if thickness for structural requirements is inadequate for abrasion potential. See lining alternatives below. • Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended. • Lining alternatives: • Closed profile (≥ 42 in) or SDR 35 PVC (PVC liners not recommended when freezing conditions are often encountered and cobbles or rocks are present) • SDR HDPE • CIPP (with min. thickness for abrasion specified) • Concrete and authorized cementitious pipeliners and invert paving. See Table 855.2F.

2.2.2. Methods utilizing information from the California approach

American Iron and Steel Institution (AISI) method is based on modification of the California approach. The AISI chart, which specifies service life in terms of resistivity and pH, was developed from a chart originally prepared by Caltrans (Figure 5). The Caltrans study of durability was based on life to first perforation in culverts that have not received any special maintenance treatment. However, AISI defines the end of useful service life as the time when an average metal loss of 25% occurs in the invert of the pipe. Therefore, AISI predicts a service life that is approximately twice as long as that of the California method. The National Corrugated Steel Pipe Association (NCSPA) also published a corrugated steel pipe (CSP) durability guide that includes the AISI chart to predict service life of corrugated steel pipe and provides a Table with additional service life durations for different coatings.

The chart included the combined effects of soil-side and interior corrosion, as well as the average effects of abrasion. For pipes in environment with pH greater than 7.3, soil-side corrosion is the controlling mechanism, and service life could be predicted by resistivity. For pipes where the pH was less than 7.3, the interior invert corrosion generally controls the deterioration and both resistivity and pH are important.

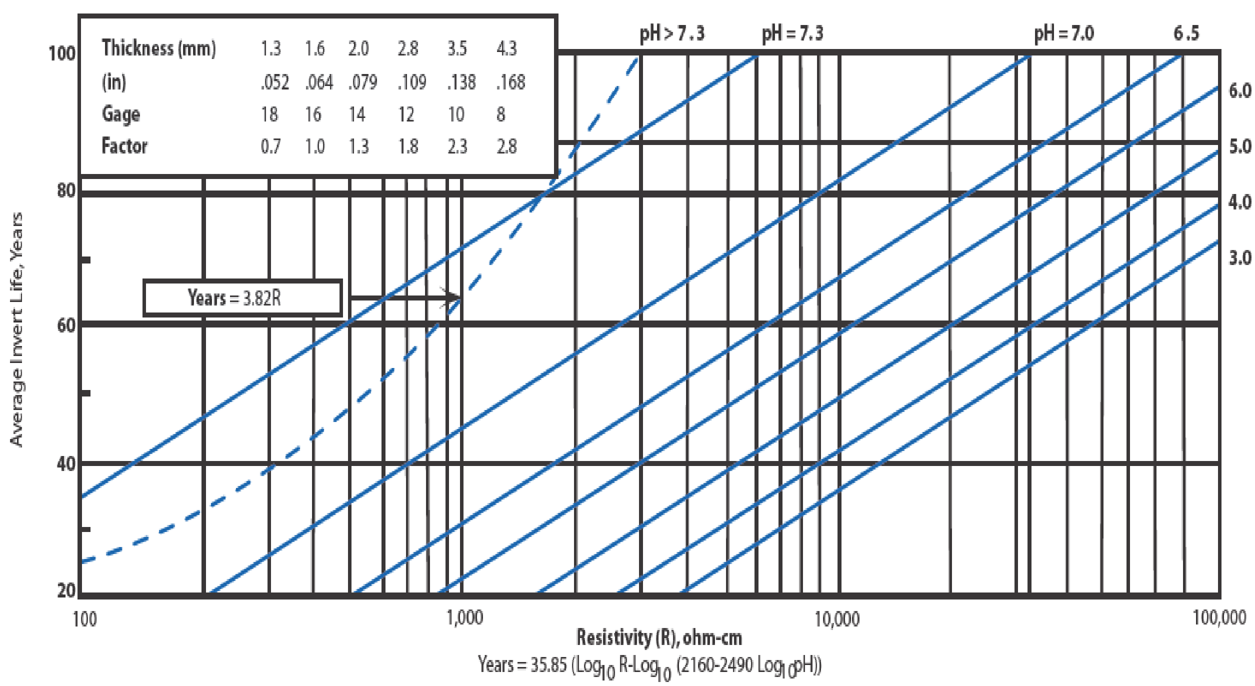


Figure 5. AISI chart for estimating average invert life for galvanized CSP (Courtesy of AISI)

Along with the chart in Figure 5, the National corrugated steel pipe association (NCSPA) provides estimated material service life for CSP which is shown in Table 3. Based on pH, resistivity and FHWA abrasion level (defined in Table 4) an estimated service life and each material is specified.

Table 3. Estimated material service life for CSP (Courtesy of NCSPA)

Estimated Service life	Site environmental conditions	Maximum FHWA abrasion level	Material
Minimum 100 Years	5.0 < pH < 9.0 R > 1,500 ohm-cm	Level 3	Polymer coated
		Level 2	Aluminized Type 2 (14 gauge minimum)
Minimum 75 Years	4.0 < pH < 9.0 R > 750 ohm-cm	Level 3	Polymer coated
	5.0 < pH < 9.0 R > 1,500 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 2,000 < R < 10,000 ohm-cm > 50 ppm CaCO3	Level 2	Galvanized

Table 4. FHWA abrasion levels (Courtesy of FHWA)

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

2.2.3. Florida DOT

Florida DOT (FDOT) recognizes four driving environmental factors that have direct effect on the service life and durability of pipes. These factors are pH, resistivity, chloride, and sulfate ion concentrations. The FDOT approach calls for conducting tests to measure these parameters before selecting the most suitable type of pipe. Figure 6 shows estimated service life versus pH and resistivity for 16 gage aluminized Type 2 pipe. Modification factors are also specified for 14, 12, 10, and 8 gage pipes. Figures 7 and 8 present estimated service life versus pH and resistivity for 16 gage aluminum pipe. There are also modification factors for 14, 12, 10, and 8 gage pipes.

Florida DOT has developed a computerized culvert service life estimator software to help with the selection of pipe material for a given design service life. Figure 9 provides a screenshot of such software. The first “through thickness penetration” is considered to be the end of service life of metal culvert pipes. Fill height requirements for any pipe materials are also provided to aid in pipe material selection.

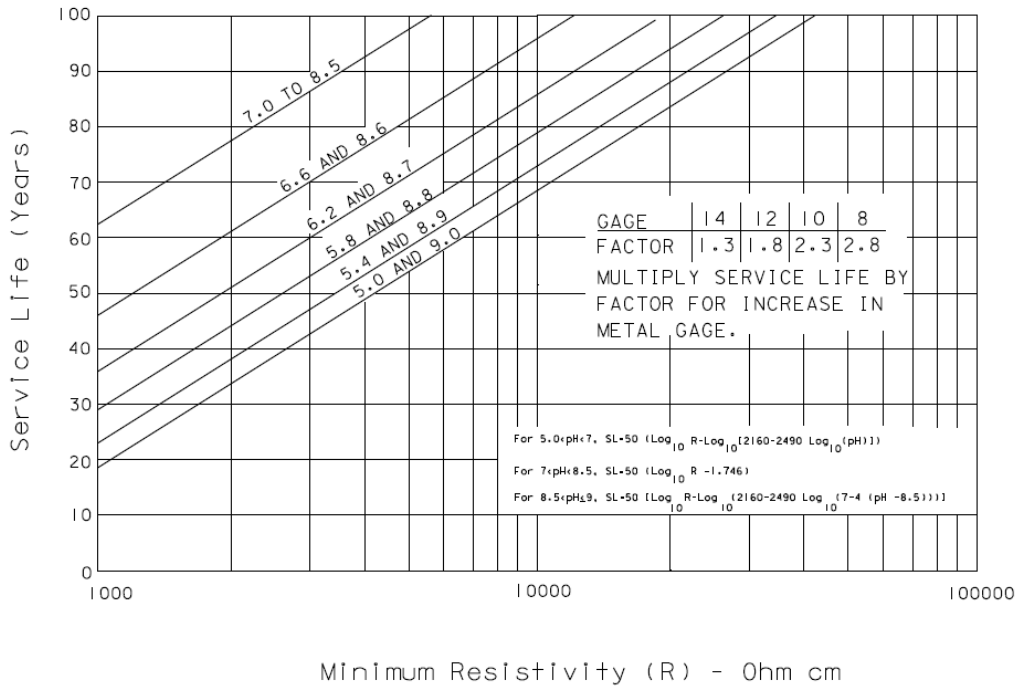


Figure 6. Estimated service life versus pH and resistivity for aluminized Type 2 pipe using FDOT method (courtesy of FDOT)

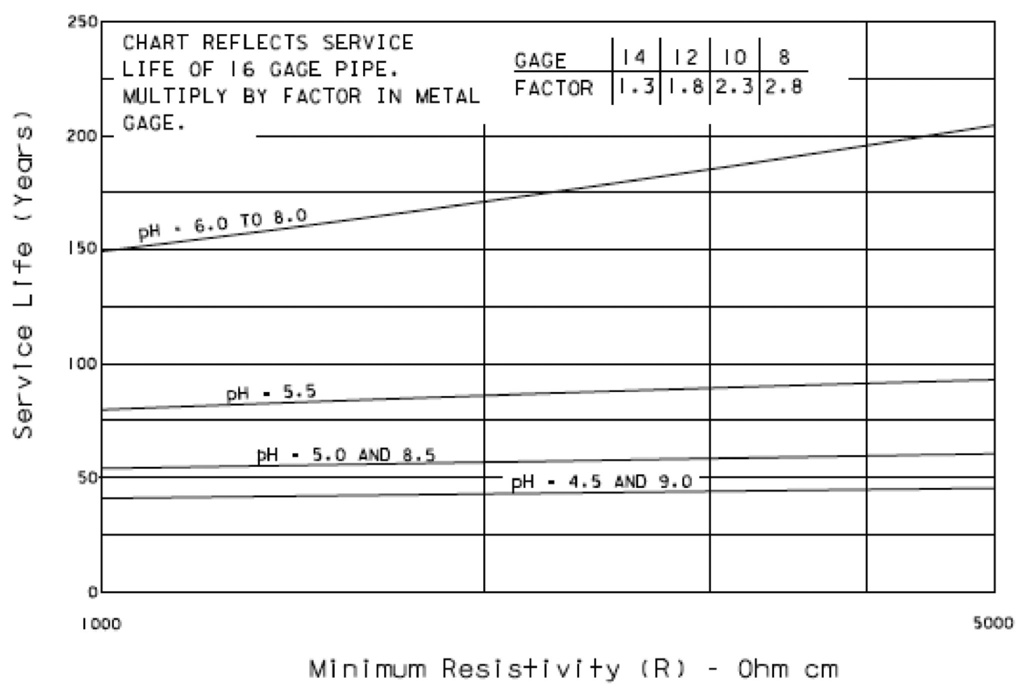


Figure 7. Estimated service life versus pH and resistivity for aluminum pipe using FDOT method (courtesy of FDOT)

pH	Resistivity ≥200	400	600	800	1000	1200	1400	1600	1800	2000	2300	2700	3200	3800	4500	≤5000
4.5 & 9.0	36	39	40	41	41	42	42	42	43	43	43	43	44	44	44	45
4.6 & 8.9	38	41	42	43	43	44	44	45	45	45	45	46	46	47	47	48
4.7 & 8.8	40	43	44	45	46	46	47	47	47	48	48	48	49	49	50	51
4.8 & 8.7	42	45	46	48	48	49	49	50	50	50	51	51	52	52	53	54
4.9 & 8.6	44	48	49	50	51	52	52	53	53	54	54	55	55	56	56	57
5.0 & 8.5	46	50	52	53	54	55	56	56	57	57	58	58	59	59	60	61
5.1	49	53	56	57	58	59	60	60	61	61	62	62	63	64	65	66
5.2 & 8.4	52	57	59	61	62	63	64	65	65	66	67	67	68	69	70	71
5.3	55	61	64	66	67	68	69	70	71	71	72	73	74	75	76	77
5.4 & 8.3	59	66	69	71	73	74	75	76	77	78	79	80	81	82	83	84
5.5	63	71	75	78	80	81	83	84	85	86	87	88	90	91	92	93
5.6 & 8.2	68	78	82	85	88	90	91	93	94	95	97	98	100	102	104	105
5.7	74	85	91	95	98	100	102	104	106	107	109	111	113	116	118	119
5.8 & 8.1	81	95	102	107	110	114	116	119	121	122	125	128	131	134	137	138
5.9	89	107	115	122	127	131	134	138	140	143	146	150	154	158	163	165
≥6.0 & ≤8.0	100	122	133	142	149	154	159	164	168	171	176	182	188	194	200	204

Service Life (SL) = $T_p / (R_{pH} + R_r)$

Where:
SL = Years to first perforation
T_p = Thickness of pipe (inches)
R_{pH} = Corrosion rate for pH (inches/year)
R_r = Corrosion rate for resistivity (inches/year)

Figure 8. Design service life versus pH and resistivity for 16-gage aluminum culvert pipe using FDOT method (courtesy of FDOT)

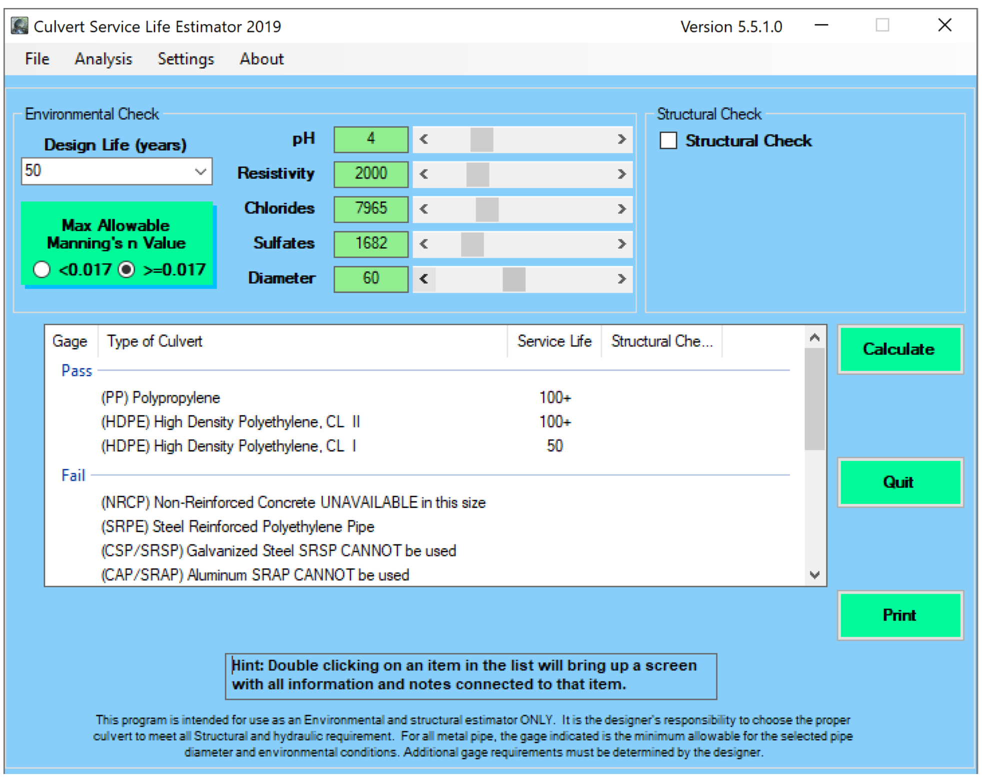


Figure 9. FDOT culvert service life estimator 2019 (Courtesy of FDOT)

3. Pipe material Assessment and Selection Software (PASS)

This section describes the software developed in this research project for NCDOT. Since Pipe Assessment and Selection Software (PASS) is programmed to automatically retrieve soil pH, resistivity, and chloride content using GPS coordinates of a given project, background information on the methods used to retrieve this information is provided.

3.1. Soil pH, resistivity and chloride concentration of North Carolina

The research team utilized the GSSURGO (Gridded Soil Survey Geographic) data for North Carolina from the USDA (United States Department of Agriculture) database in developing PASS. The metadata are rasterized as shown in Figures 10 and 11. In order to use coordinates of a specific site, the research team converted the rasterized data to point data by using ArcGIS PRO software; an example of point data is shown in Figure 12. ArcGIS PRO enables each point to have XY coordinates. The distance between two neighboring points herein are 90 m.

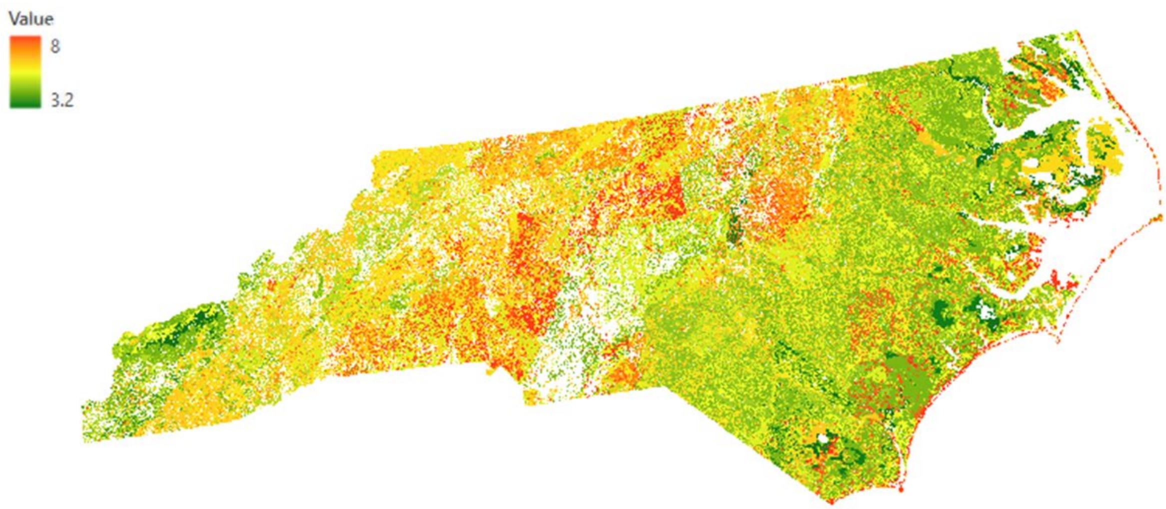


Figure 10. Soil pH of North Carolina

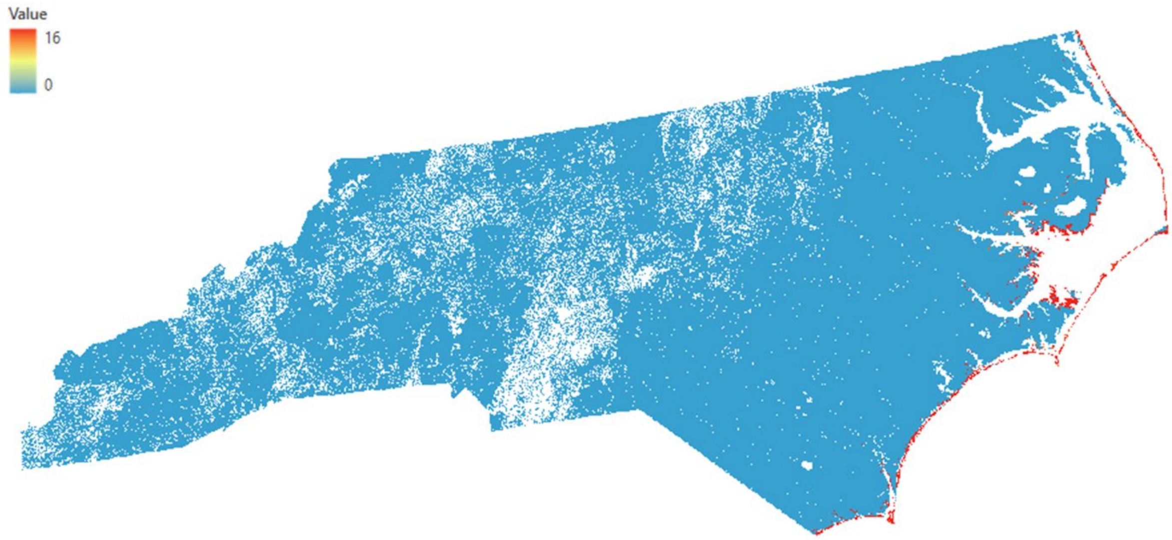


Figure 11. Soil electrical conductivity of North Carolina

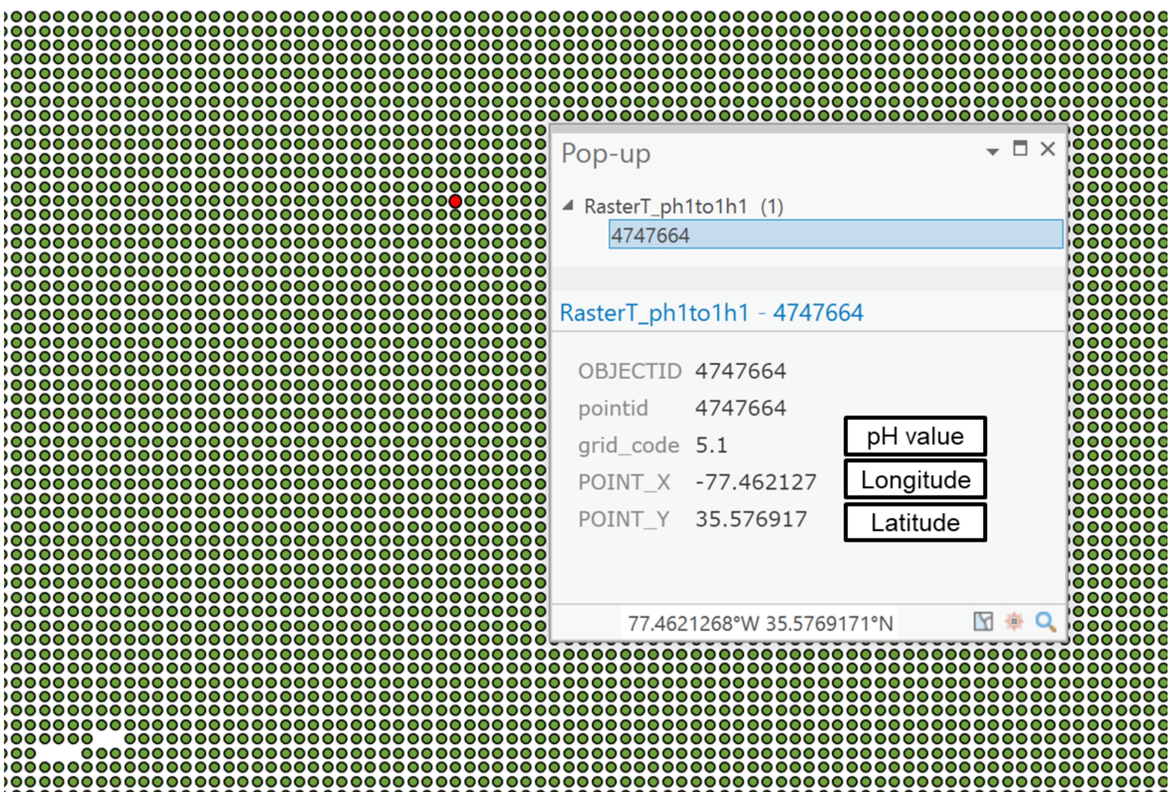


Figure 12. Identification of point data using ArcGIS

In addition, data of chloride concentration in soils have been obtained from the NADP (National Atmospheric Deposition Program) and are used as a part of the algorithm to compute the service life of reinforced concrete pipe (RCP). The approach used herein utilized the NADP data to develop soil chloride concentration; in this approach, correlation of the average 19 years deposition with soil concentration was used as shown in Figure 13. This correlation was then programmed in PASS using the corresponding GPS coordinates.

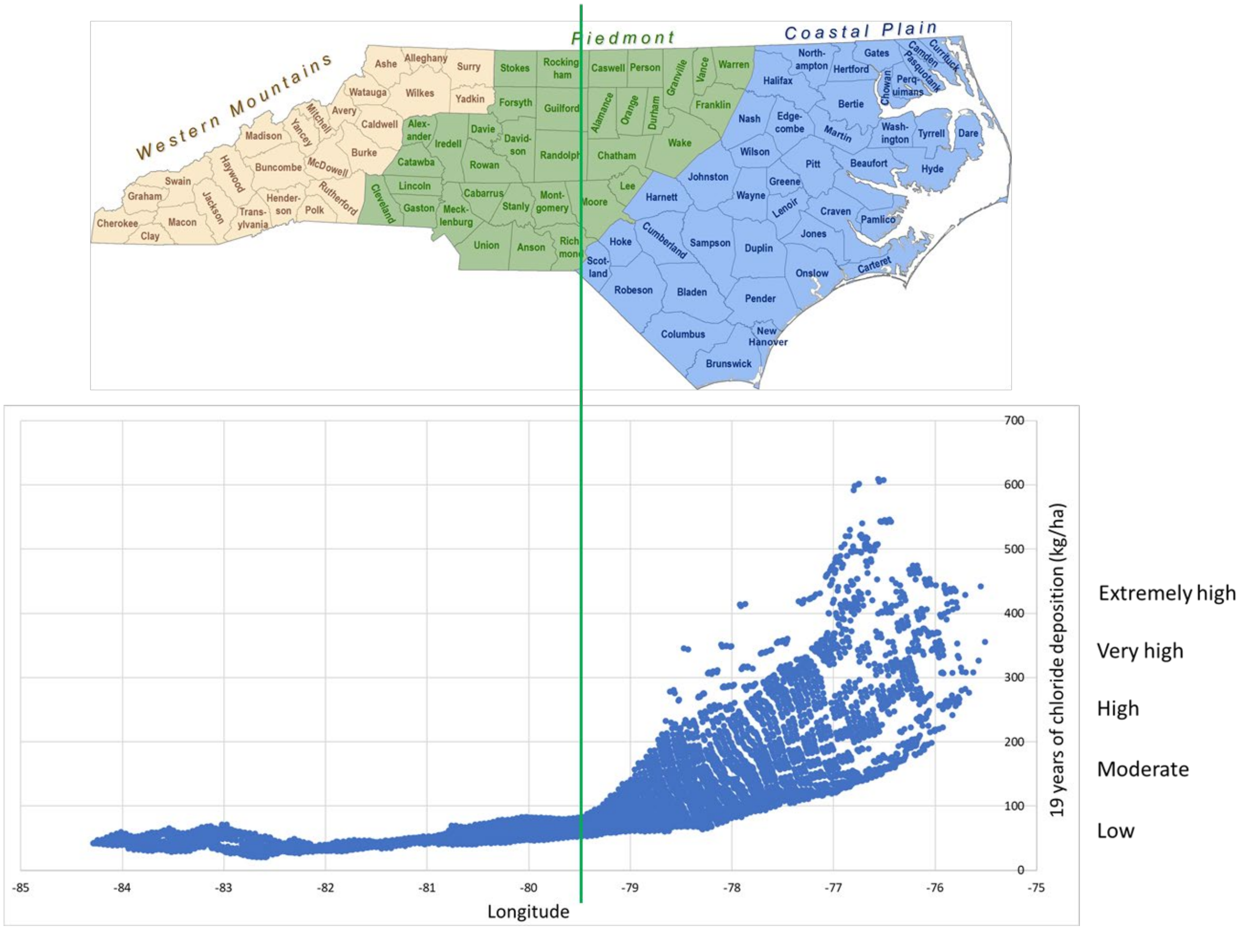


Figure 13. Chloride concentration of North Carolina for estimating the service life of RCP

3.2. Service life estimation: pipes used in North Carolina

According to the current NCDOT pipe selection guide, there are nine types of pipe materials that are used. These include RCP (class ll to V, AASHTO M170), CSP (corrugated steel, AASHTO M36), CAAP (corrugated aluminum, AASHTO M196), HDPE (AASHTO M294), PP (ASTM F2764 or AASHTO M330), and PVC (ASTM F949 or AASHTO M304). Cast iron pipes and galvanized pipes were also included in the PASS as per the comments from our NCDOT colleagues. From extensive literature review and by considering the mechanisms of deteriorations, the research team established acceptable ranges for different pipe materials, as shown in Table 5.

Table 5. Acceptable ranges for different pipe materials

Material	pH (soil)	Resistivity (ohm-cm)	Chloride (%, in soil)	Abrasion level
RCP	5.5 < pH < 12.0	All	< 0.5	< 3
Galvanized CSP	6.0 < pH < 10.0	R > 2,000	< 0.2	< 2
Aluminized Type 2 CSP	5.0 < pH < 9.0	R > 1,500	< 0.2	< 2
Aluminum	4.5 < pH < 9.0	R > 1,500	< 0.5	< 2
Steel pipe	6.0 < pH < 8.5	R > 2,200	< 0.05	< 2
Cast iron pipe	5.0 < pH < 9.0	R > 2,000	< 0.05	< 2
Plastic (PVC, PP, and HDPE)	1.25 < pH < 15.0	All	-	< 3

3.2.1. Reinforced concrete pipe (RCP)

The service life of RCP was calculated using the Life-365 program that considers the onset of corrosion of rebar plus six year (corrosion propagation) as the end of the service life; it should be noted that this “end of service life” does not correspond to structural deficiency but rather it is the time that some intervention may be required (e.g., repair). Based on the amount of chloride deposition encountered in North Carolina, chloride concentration was estimated and the service life of RCP was determined as shown in Table 6.

Table 6. Chloride concentration

Concentration	Chloride (kg/ha)	Default Exposure*	Service life (year)**
Low	0 < cl ≤ 100	Rural highway bridges	33.4
Moderate	100 < cl ≤ 200	Urban highway bridges	28.5
High	200 < cl ≤ 300	Parking garages	26.5
Very High	300 < cl ≤ 400	Marine spray	9.5
Extremely High	cl > 400	Marine tidal	7.2

*: Default exposure condition shown in Life-365 program

**: Service life of RCP based on the concentration of chloride calculated from Life-365 program

3.2.2. Galvanized pipe

The American Iron and Steel Institute (AISI) model was adopted to estimate the service life of 16-gage galvanized pipes; this method applies to cases with pH values greater than 7.3 where the resistivity of soil governs the service life; the method uses Equation (1). For pH values of 7.3 or less, resistivity and pH govern the service life and Equation (2) is used.

AISI defines the estimated service life as 25% reduction in the thickness of the culvert wall at the invert, where most damage usually occurs. For other gage thicknesses, modification factors are applied as shown in Table 7.

For pH values greater than 7.3:

$$Service\ life = 3.82R^{0.41} \tag{1}$$

For pH values less than 7.3:

$$Service\ life = 35.85(logR - \log(2160 - (2490\ logpH))) \tag{2}$$

Where:
pH = pH of soil
R = minimum resistivity of soil.

Table 7. Multiplying factors for different size of galvanized pipes (courtesy of AISI)

Gage	18	14	12	10	8
Factor	0.7	1.3	1.8	2.3	2.8

3.2.3. Aluminized CSP Type 2 Pipe

The service life of aluminized Type 2 pipe is calculated using FDOT method. For 16-gage aluminized steel pipe, equations (3) - (5) are used for different pH values. Modification factors are applied for other gage thicknesses of aluminized Type 2 pipes as shown in Table 8.

For 5.0 ≤ pH < 7:

$$Service\ life = 50(logR - \log(2160 - (2490\ logpH))) \tag{3}$$

For 7 ≤ pH ≤ 8.5:

$$Service\ life = 50(logR - 1.746) \tag{4}$$

For 8.5 < pH ≤ 9:

$$Service\ life = 50(logR - \log(2160 - (2490\log(7 - 4(pH - 8.5))))) \tag{5}$$

Where:
pH = pH of soil
R = minimum resistivity of soil.

Table 8. Multiplying factors for different size of aluminized Type 2 pipes (courtesy of FDOT)

Gage	14	12	10	8
Factor	1.3	1.8	2.3	2.8

3.2.4. Aluminum pipe

While FDOT provides the service life of aluminum pipes based on the pH and resistivity of soil, the equations used for these estimations are not provided. Therefore, the research team plotted the numerical values as shown in Figure 14 (the numerical values are shown in Figure

8); lines in Figure 14 present service life equations for different pH values. Table 9 shows the equations on the Figure 14. Table 10 shows modification factors for gage thickness of aluminum pipes.

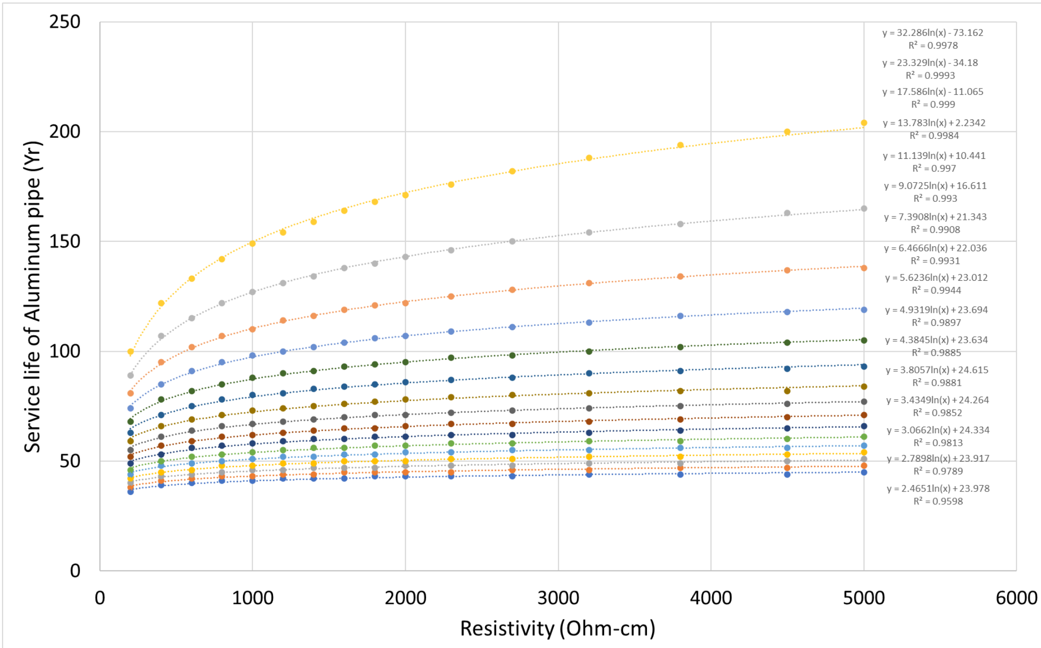


Figure 14. Plotted design service life versus pH and resistivity for 16-gage aluminum culvert pipe using FDOT method (data from FDOT)

Table 9. Equations to calculate the service life of 16-gage aluminum culvert pipe based on pH and resistivity (data from FDOT)

pH range	Equation	R^2
4.5 & 9.0	$y = 32.286\ln(x) - 73.162$	0.9978
4.6 & 8.9	$y = 23.329\ln(x) - 34.18$	0.9993
4.7 & 8.8	$y = 17.586\ln(x) - 11.065$	0.999
4.8 & 8.7	$y = 13.783\ln(x) + 2.2342$	0.9984
4.9 & 8.6	$y = 11.139\ln(x) + 10.441$	0.997
5.0 & 8.5	$y = 9.0725\ln(x) + 16.611$	0.993
5.1	$y = 7.3908\ln(x) + 21.343$	0.9908
5.2 & 8.4	$y = 6.4666\ln(x) + 22.036$	0.9931
5.3	$y = 5.6236\ln(x) + 23.012$	0.9944
5.4 & 8.3	$y = 4.9319\ln(x) + 23.694$	0.9897
5.5	$y = 4.3845\ln(x) + 23.634$	0.9885
5.6 & 8.2	$y = 3.8057\ln(x) + 24.615$	0.9881
5.7	$y = 3.4349\ln(x) + 24.264$	0.9852
5.8 & 8.1	$y = 3.0662\ln(x) + 24.334$	0.9813
5.9	$y = 2.7898\ln(x) + 23.917$	0.9789
≥6.0 & ≤8.0	$y = 2.4651\ln(x) + 23.978$	0.9598

Table 10. Multiplying factors for different size of aluminum pipes (courtesy of FDOT)

Gage	14	12	10	8
Factor	1.3	1.8	2.3	2.8

3.2.5. Steel pipe

In PASS, the service life of steel pipes is computed by using CALTRANS method. For 18-gage steel pipe, equations (6) and (7) are used depending on the pH value. Modification factors are applied for different gage thicknesses of steel pipes as shown in Table 11.

For pH values greater than 7.3:

$$Service\ life = 1.47R^{0.41} \tag{6}$$

For pH values less than 7.3:

$$Service\ life = 13.79\{logR - log[2160 - (2490\ logpH)]\} \tag{7}$$

Where:
pH = pH of soil
R = minimum resistivity of soil.

Table 11. Multiplying factors for different size of steel pipes (courtesy of CALTRANS)

Gage	16	14	12	10	8
Factor	1.3	1.6	2.2	2.8	3.4

3.2.6. Cast iron pipe

Romanoff (1968) stated that gray iron and ductile iron corrode at nearly the same rate under the same environmental parameters. In addition, according to Ductile Iron Pipe Research Association (DIPRA), the projected service life for modern ductile iron pipe is at least 105 years. Table 12 shows a list of cast iron pipes that have been in-service for over 100 years in North Carolina. Based on observations in Table 12, the estimate of a minimum of 105 years suggested by DIPRA seems reasonable.

Table 12. Cast iron pipe century club (courtesy of DIPRA)

Location	State	Utility	Year inducted	Oldest pipe
Asheville	North Carolina	City of Asheville Water Resources	2008	1903
Greensboro	North Carolina	City of Greensboro	1987	1887
Salisbury	North Carolina	City of Salisbury	1994	1887
Winston-Salem	North Carolina	Winston-Salem-Forsyth County Utilities	1951	1842

Rajani et al. (2000) proposed a model for the pitting corrosion of gray cast iron:

$$P_{avg} = at + b(1 - e^{-ct})$$

$$P_{max} = 3P$$

Where:

a, b, and c = constants (refer to Table 13)

t = time in years.

Table 13. Constants for the pitting corrosion of gray cast iron

Metric	a (mm/year)	b (mm)	c (mm/year)	Corrosion rate (mm/year)
	0.0042	1.95	0.058	Average
	0.0125	5.85		Maximum
Imperial	a (mils/year)	b (mils)	c (mils /year)	Corrosion rate (mils/year)
	0.165	76.77	2.283	Average
	0.492	230.31		Maximum

ASTM A716 specifies standard wall thickness of ductile iron culvert pipe. Each nominal diameter (inside diameter) of pipe has nominal thickness; by using the nominal thickness, the research team computed the service life of cast iron pipe from Figure 15 with the results reported in Table 14. These service life estimations were conducted using the maximum value of the parameter values provided in Table 13. The minimum estimate provided in Table 14 is approximately equal to the minimum service life suggested by DIPRA.

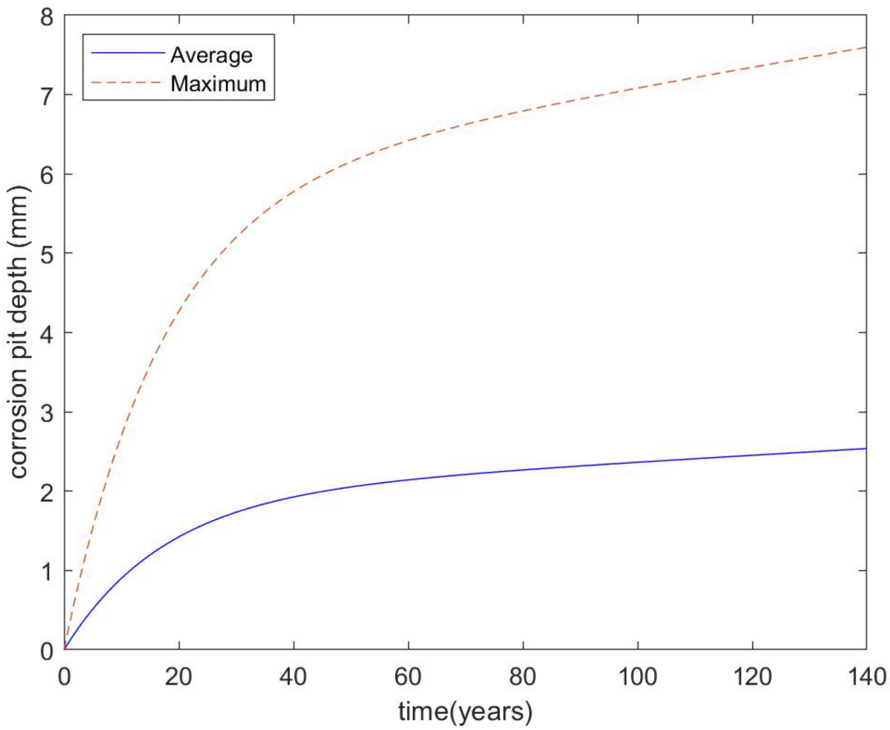


Figure 15. Corrosion pit depth of cast iron

Table 14. Service life of cast iron pipe computed using Rajani model (2000)

Nominal diameter (in)	Nominal thickness (mm)	Service life (years)
14	7.1	101.3
16	7.6	140.1
18	7.9	164
20	8.4	204
24	8.4	204
30	8.6	220
36	9.7	308
42	10.4	364
48	12.4	524
54	13	527
60	13.7	628
64	14.2	668

3.2.7. Plastic pipes (HDPE, PP, and PVC)

The research team conducted a comprehensive literature review on the deterioration of plastic pipes including HDPE, PP, and PVC. The detailed literature review is provided in Appendices C and E.

In general, chemical degradation of polymeric pipe is shown to be minimal. Rather, stress cracking (also known as slow crack growth or environmental stress cracking), UV radiation, and oxidation are primary factors that govern the service life of plastic pipes According to Plastic Pipe Institute (PPI). The durability of plastic pipes is a function of the type of resin (HDPE versus PPE or PVC) the installation conditions, and the loads applied. While some of the resins are mainly susceptible to creep (such as HDPE), other are susceptible to hydrolysis and dissolution (such as PVC.) The service life of corrugated HDPE pipes manufactured with virgin materials can range between 50 years to more than 100 years per the PPI. NCHRP Report 631: *Test and Design Methods for Thermoplastic Drainage Pipe* recommended design guidance for a 50-, 75-, and 100-year service life of plastic pipes.

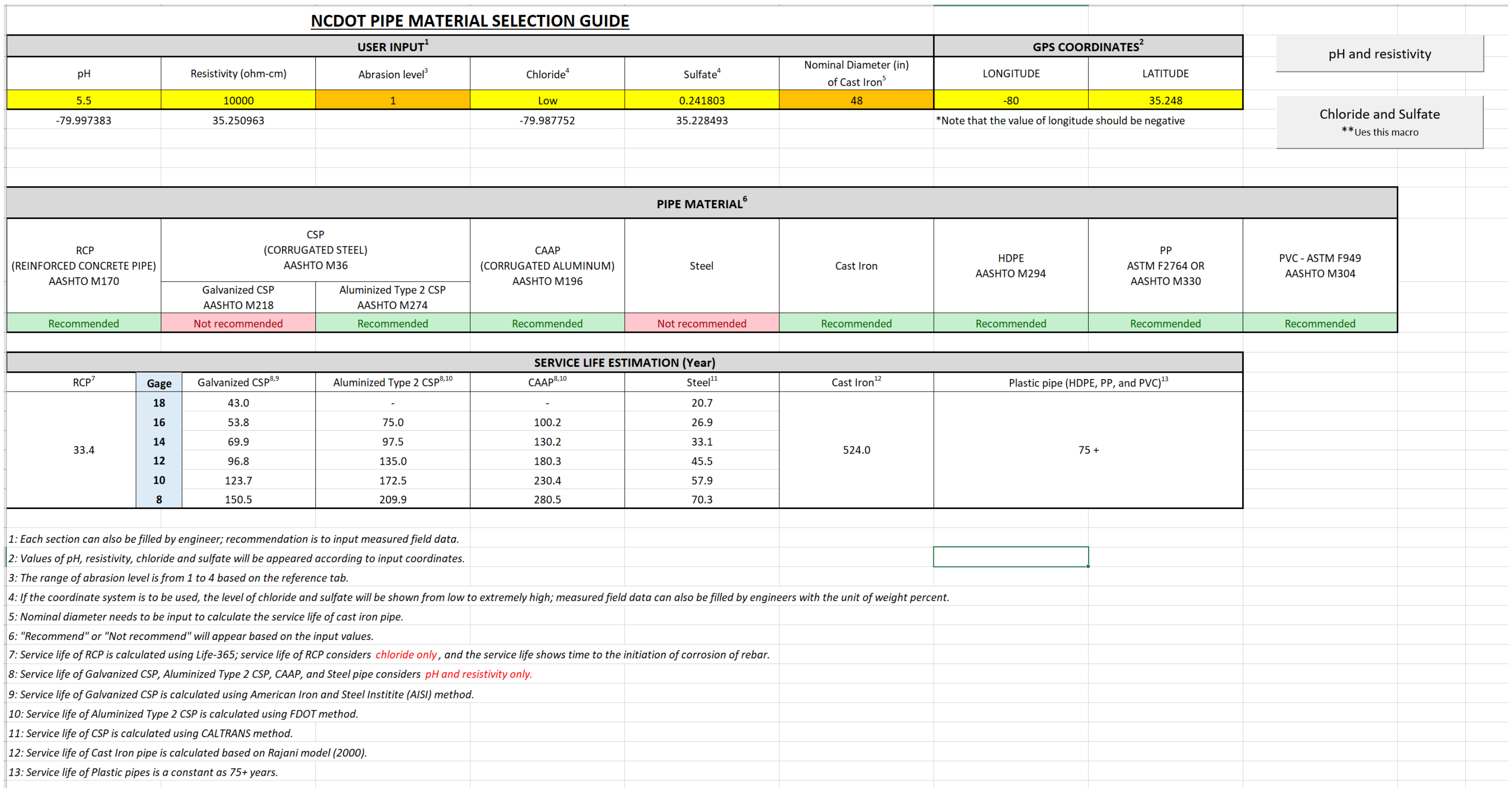
3.3. Integration of different pipe materials and exposure conditions into PASS

3.3.1. Overview of PASS

Figure 16 shows the initial version of PASS, developed within the framework of EXCEL spreadsheet. The required data for the specification of each material are shown in the reference tab of PASS. These requirements are pH, resistivity, and chloride of soil, abrasion level, and nominal diameter (inside diameter) in the case of the cast iron pipe. As stated in the section *3.2 Service life estimation of different pipe materials that are used in North Carolina*, the service life of each material is computed based on these input parameters. The calculations in PASS are performed using five different Visual Basic (VBA) modules; The code details are provided in Appendix F.

Users can either manually input pH, resistivity, and chloride concentration of soil for a given project or retrieve such data by specifying the GPS coordinates of the project. Abrasion level and nominal diameter (inside diameter) of cast iron pipe should always be input manually since they cannot be retrieved by GPS coordinates.

In addition, and based on feedback received through the project, the following features are implemented in PASS: i. providing estimate of service life for each pipe material (as opposed to the use of the binary system of “Yes and No” or “suitable and unsuitable,” respectively) and ii. including a triangulation approach such that physiochemical data of aggregates from different quarries near a given project in North Carolina are dynamically obtained. These features were implemented in PASS, and Figure 17 shows the current version of PASS. This current version of PASS provides estimated service life of each pipe material and accounts for the physiochemical backfill properties based on data from different quarries in North Carolina if a backfill different from the native soil were to be used.



NCDOT PIPE MATERIAL SELECTION GUIDE

USER INPUT[1]						GPS COORDINATES[2]	
pH	Resistivity (ohm-cm)	Abrasion level[3]	Chloride[4]	Sulfate[4]	Nominal Diameter (in) of Cast Iron[5]	LONGITUDE	LATITUDE
5.5	10000	1	Low	0.241803	48	-80	35.248
-79.997383	35.250963		-79.987752	35.228493		*Note that the value of longitude should be negative	

pH and resistivity

Chloride and Sulfate
**Ues this macro

PIPE MATERIAL[6]								
RCP (REINFORCED CONCRETE PIPE) AASHTO M170	CSP (CORRUGATED STEEL) AASHTO M36		CAAP (CORRUGATED ALUMINUM) AASHTO M196	Steel	Cast Iron	HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC - ASTM F949 AASHTO M304
	Galvanized CSP AASHTO M218	Aluminized Type 2 CSP AASHTO M274						
Recommended	Not recommended	Recommended	Recommended	Not recommended	Recommended	Recommended	Recommended	Recommended

SERVICE LIFE ESTIMATION (Year)							
RCP[7]	Gage	Galvanized CSP[8,9]	Aluminized Type 2 CSP[8,10]	CAAP[8,10]	Steel[11]	Cast Iron[12]	Plastic pipe (HDPE, PP, and PVC)[13]
33.4	18	43.0	-	-	20.7	524.0	75 +
	16	53.8	75.0	100.2	26.9		
	14	69.9	97.5	130.2	33.1		
	12	96.8	135.0	180.3	45.5		
	10	123.7	172.5	230.4	57.9		
	8	150.5	209.9	280.5	70.3		

1: Each section can also be filled by engineer; recommendation is to input measured field data.
2: Values of pH, resistivity, chloride and sulfate will be appeared according to input coordinates.
3: The range of abrasion level is from 1 to 4 based on the reference tab.
4: If the coordinate system is to be used, the level of chloride and sulfate will be shown from low to extremely high; measured field data can also be filled by engineers with the unit of weight percent.
5: Nominal diameter needs to be input to calculate the service life of cast iron pipe.
6: "Recommend" or "Not recommend" will appear based on the input values.
7: Service life of RCP is calculated using Life-365; service life of RCP considers chloride only, and the service life shows time to the initiation of corrosion of rebar.
8: Service life of Galvanized CSP, Aluminized Type 2 CSP, CAAP, and Steel pipe considers pH and resistivity only.
9: Service life of Galvanized CSP is calculated using American Iron and Steel Institite (AISI) method.
10: Service life of Aluminized Type 2 CSP is calculated using FDOT method.
11: Service life of CSP is calculated using CALTRANS method.
12: Service life of Cast Iron pipe is calculated based on Rajani model (2000).
13: Service life of Plastic pipes is a constant as 75+ years.

Figure 16. Initial version of PASS

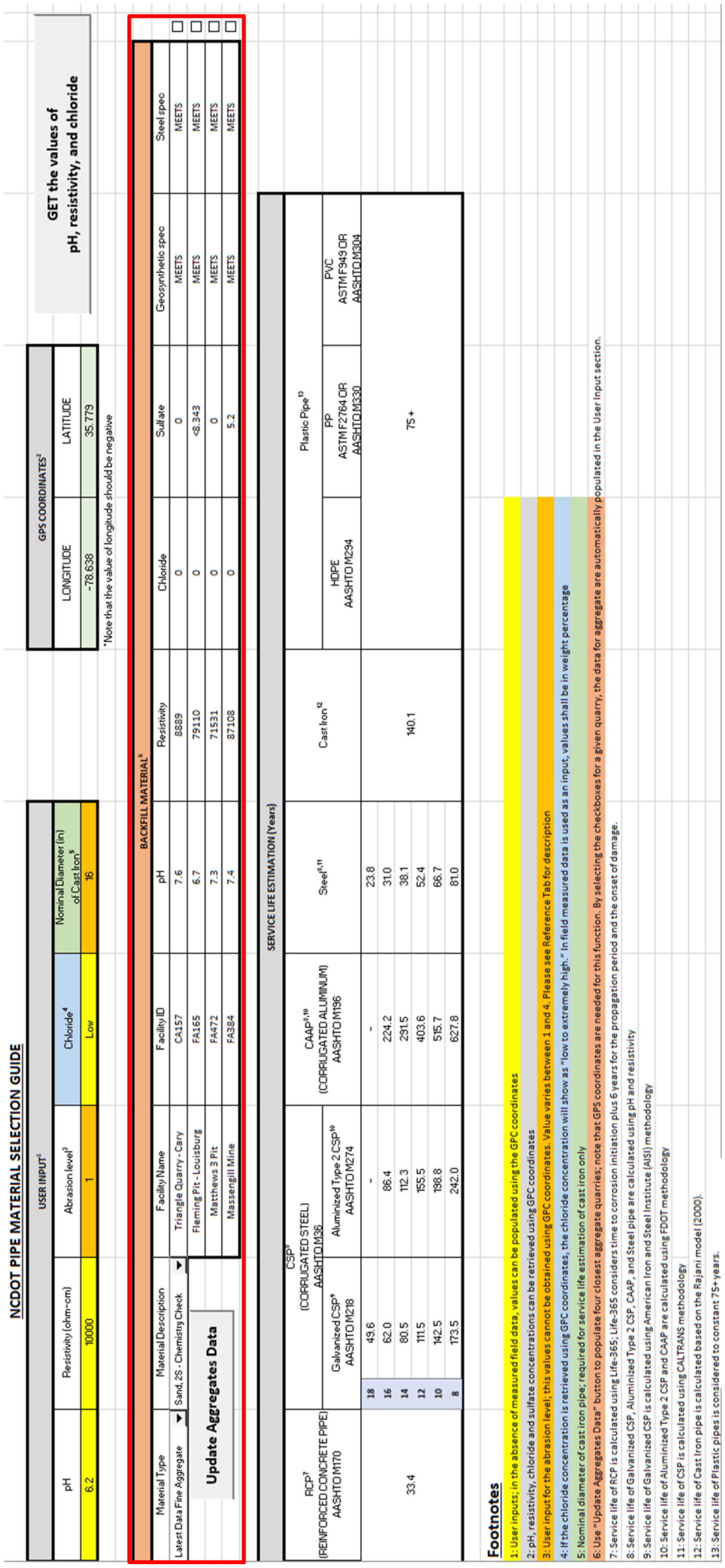


Figure 17. Final version of PASS

3.3.2 PASS – Users' manual

In this section, guidance on using PASS is presented. A detailed users' manual is provided in Appendix G. A training video is also included on YouTube to facilitate the training on using PASS.

A shown in Figure 18, the GPS coordinates of the project, where the installation of pipe is being considered, are entered (highlighted in a red box). Pressing the "GET the values of pH, resistivity, and chloride" retrieves these values using the specified GPS coordinates. For example, inputting a coordinate corresponding to a location in Raleigh (-78.638, 35.779) will result in pH of 6.2, resistivity of 10,000 ohm-cm, and low chloride concentration as shown in Figure 18. To consider abrasion, the abrasion level needs to be manually provided. To consider cast iron pipes, the nominal diameter (inner diameter) of the pipe needs to be provided (as shown in Figure 19). Once the input parameters are provided, estimated service life of different pipe materials with different gages is presented in years (in the service life estimation) section as shown in Figure 20.

GPS COORDINATES[2]	
LONGITUDE	LATITUDE
-78.638	35.779

*Note that the value of longitude should be negative

GET the values of pH, resistivity, and chloride

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

Figure 18. PASS example – inputting GPS coordinates and pushing the button

Raleigh coordinates

GPS COORDINATES[2]	
LONGITUDE	LATITUDE
-78.638	35.779

*Note that the value of longitude should be negative

GET the values of
pH, resistivity, and chloride

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

Figure 19. PASS example – getting parameters and inputting abrasion level and nominal diameter (inside diameter) of cast iron pipe

RCP[7] (REINFORCED CONCRETE PIPE) AASHTO M170	CSP[8] (CORRUGATED STEEL) AASHTO M36			CAAP[8,10] (CORRUGATED ALUMINUM) AASHTO M196
		Galvanized CSP[9] AASHTO M218	Aluminized Type 2 CSP[10] AASHTO M274	
33.4	**18**	49.6	-	-
	16	62.0	86.4	224.2
	14	80.5	112.3	291.5
	12	111.5	155.5	403.6
	10	142.5	198.8	515.7
	8	173.5	242.0	627.8

SERVICE LIFE ESTIMATION (Years)				
Steel[8,11]	Cast Iron[12]	Plastic Pipe[13]		
		HDPE AASHTO M294	PP ASTM F2764 OR AASHTO M330	PVC ASTM F949 OR AASHTO M304
23.8	140.1	75 +		
31.0				
38.1				
52.4				
66.7				
81.0				

Figure 20. PASS example – Service life estimation

3.3.3 PASS – Retrieving quarries information

PASS also enables assessing the service life of pipes when the native soil is not used as backfill materials and aggregate sources are imported for backfilling. Several quarries exist in North Carolina. Since the physiochemical data of aggregates can be continually updated, PASS was programmed to recall the physiochemical information from a database that can be continuously updated by NCDOT. The data are populated in two separate tabs: Latest data on fine aggregate, and Latest data on coarse aggregate, as shown in Figure 21.

After inputting the GPS coordinates of the project and pressing the “Update Aggregate Data” designated by the “red box “in Figure 22, different material types can be selected (depending on the project objectives).

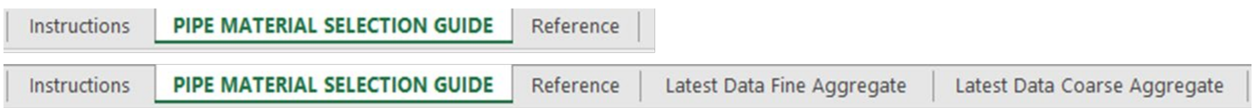


Figure 21. PASS example – tabs before and after recalling physiochemical data of aggregates

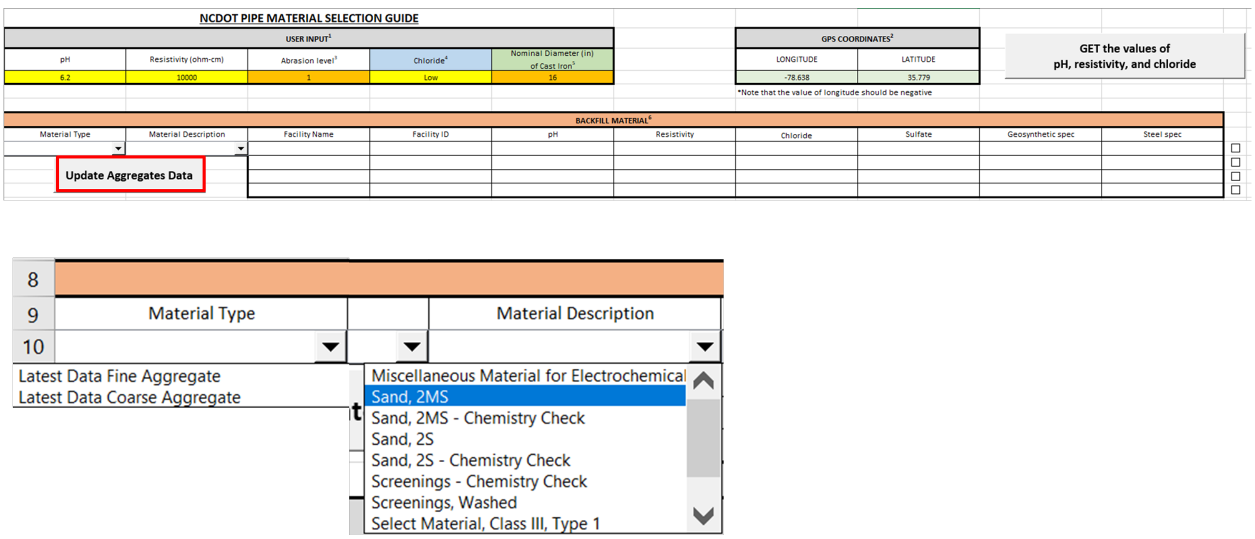


Figure 22. PASS example – recalling physiochemical data of aggregate and selecting material type and material description

Furthermore, PASS is programmed to automatically determine the four closest quarries to a given project location using the GPS coordinates of the project, selected Material Type, and Material Description as shown in Figure 23. Next to each identified quarry, there is a check box; by checking one of the boxes, physiochemical parameters (pH, resistivity, and chloride concentration) of the backfill will be automatically populated in the input section of PASS, and the service life estimation section will be updated to reflect the effect of changing the type of backfill as shown in Figure 24.

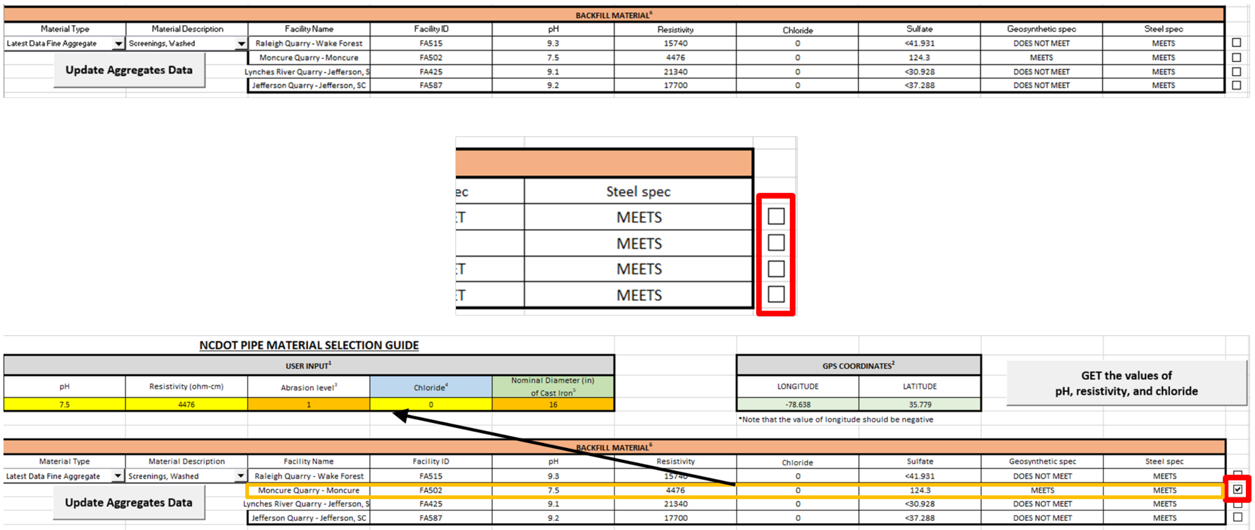
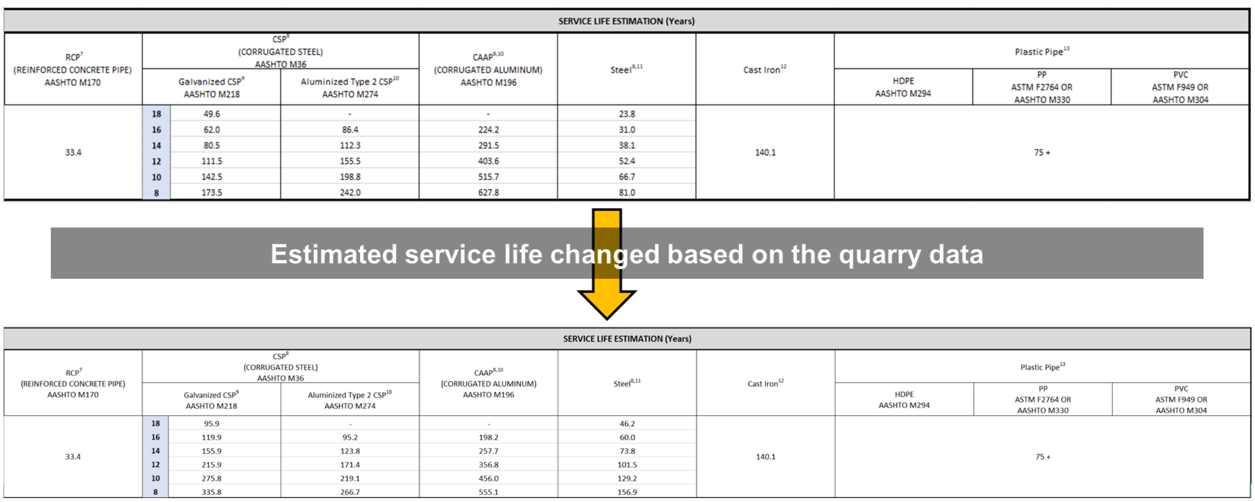


Figure 23. PASS example – identified four closest quarries and recalling the condition of selected quarry



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

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

Figure 24. PASS example – service life estimation before and after checking quarry data

Examples for selecting pipe materials and quarries are shown in Table 15 with regards to three assumed sites (A, B, and C). Each site was run through the pipe selection criteria of three States (Virginia, Georgia, and Arizona) and PASS for North Carolina. Site parameters are assumed as follows:

- Site "A" - pH of 7.0 and a resistivity of 8,000 ohm-cm.
- Site "B" - pH of 7.0, a resistivity of 1,000 ohm-cm and anticipated chloride attack (over 100 ppm).

- Site “C” – pH of 4.0, a resistivity of 5,500 ohm-cm and anticipated high velocity of bed loads (FHWA abrasion level 3).

Table 15. Pipe material selection for different DOTs

Site	Virginia	Georgia	Arizona	North Carolina
A	G, A2, A, P, C	G, A2, A, P, C	G, A2, A, P, C	G, A2, A, P, C
B	P, C	P, C	A, P, C	P, C
C	P, C	P, C	P, C	P
Abbreviations: Galvanized (G), Aluminized Type 2 (A2), Concrete (C), Plastic (PVC, PP, HDPE) (P), and Aluminum (A).				

Table 15 shows that PASS is rather consistent with criteria used by other States but is slightly more restrictive given the exposure conditions in North Carolina.

4. Corrosion testing on galvanized and aluminized Type 2 pipe

To better understand and quantify the effect of coating thickness on the rate of corrosion of galvanized and aluminized CSP, laboratory corrosion rate measurements were performed. The experimental program included open circuit potential (OCP) and corrosion rate measurement using galvanostatic testing. “Discount rate index” based on tradeoff between pipe cost and coating thickness is proposed.

In order to perform the experimental program, pipe samples were collected from three different manufacturers:

1. Southeastern Pipe & Drain Systems, Inc., SC: aluminum, aluminized, and galvanized pipes (16 Ga.)
2. Smith Setzer & Sons, NC: aluminized pipes with 3 different gauges (16, 14, and 12 Ga.)
3. Contech Engineered Solutions, NC: galvanized and aluminized pipes (16 Ga.)

As a part of the effort to collect pipe samples, the Research team visited The Contech Engineered Solutions LLC in Raleigh as documented in Figure 25.

(a) (b) (c) (d)

Figure 25. Visiting Contech Engineered Solutions

4.1. Coating thickness measurement

At Contech Engineered Solutions, the measurements of coating thickness are performed on the coil (before manufacturing pipes) as shown in Figure 25 (a). Coating thickness measurements are performed on the outer part and the inner part for three times respectively, before making corrugations.

During the laboratory experimental program, coating thickness measurements were performed with DeFelsko PosiTector 6000 FNS1 device, shown in Figure 26. Since coated pipe samples have variation in coating thickness from point to point, 1 ft × 1 ft pipe samples from three vendors were obtained and cleaned with acetone. For the corrosion testing area of 2.85 cm^2, as shown in Figure 27 (a), grids consisting of approximately 60 segments were drawn on the surface of each pipe piece, as shown in Figure 27 (b). Coating thickness measurements were performed before cutting pipe samples into small segments to avoid the edge effect leading to abrupt surface changes; this effect usually extends 3 to 13 mm (1⁄8 to 1/2 in.) from the discontinuity.

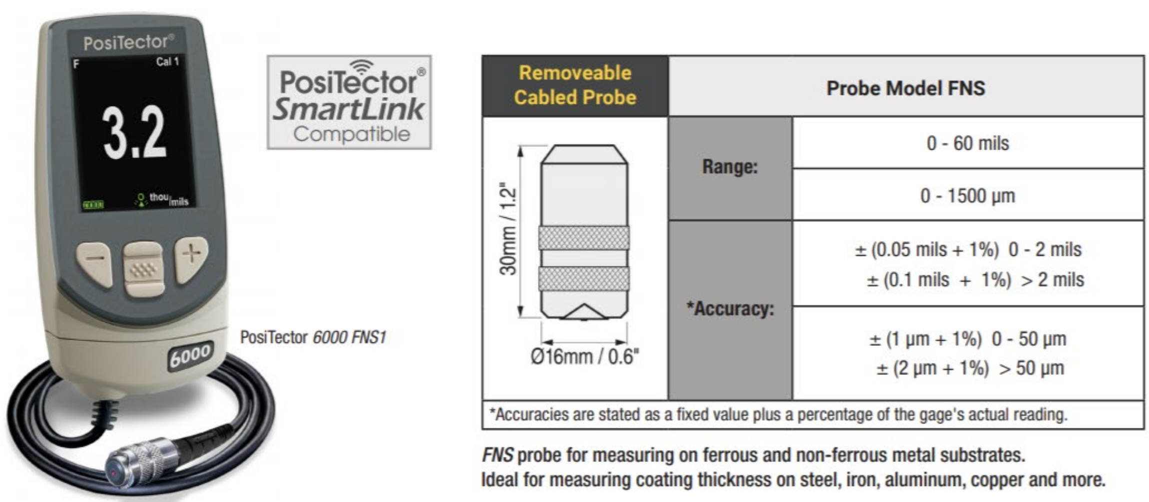
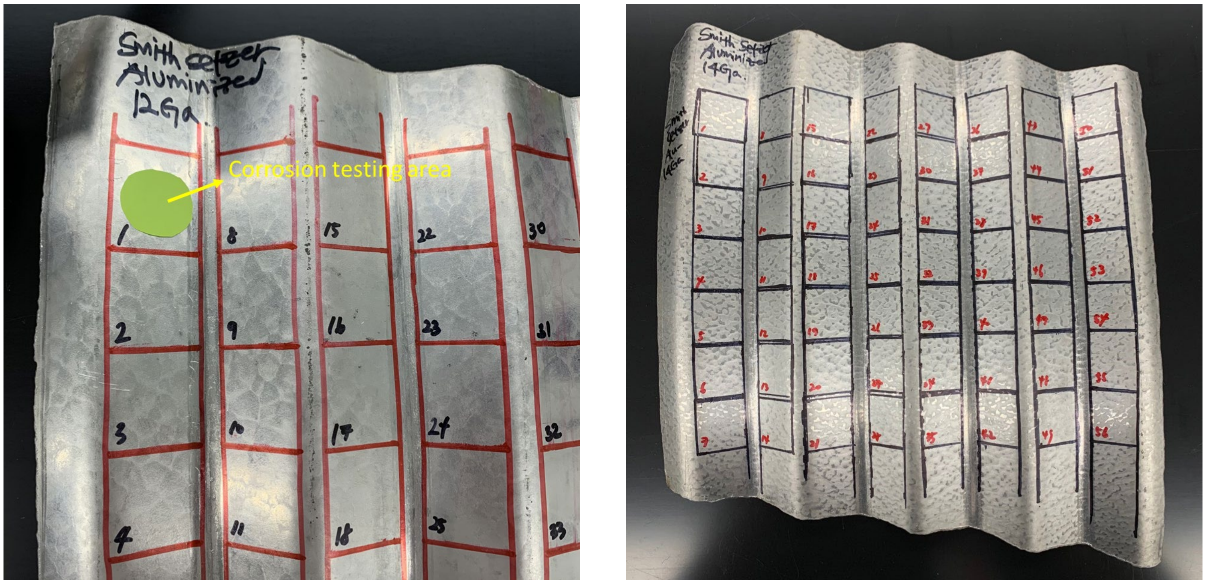


Figure 26. Coating thickness measurement device



(a) (b)

Figure 27. Grids on the surface of a pipe sample

Statistical analyses were performed for to discern the minimum number of measurements needed at a given location to provide precise thickness data. A various number of thickness measurements (3, 6, 10, and 15 measurements) was performed on each segment, and the variation in the coating thickness measurement was compared as a function of the number of measurements.

The mean coating thickness values obtained using 3, 6, 10, and 15 measurements were statistically compared using Analyses of Variance (ANOVA) and Tukey's HSD analysis with R studio. The statistical analyses seek to discern if the mean coating thickness is dependent on the number of measurements per pipe segment and assess the minimum number of measurements to eliminate such dependency per the electromagnetic measuring device. Table 16 compares the average values obtained using different number of coating thickness measurements. In Table 16, "O" means that the mean values of each of the groups (number of measurement) are not significantly different (P-value > 0.05) and "X" means that the means of the compared groups are significantly different (P-value < 0.05).

The results from vendor 1 show high variability in 12- and 16-gauge aluminized pipe except for the comparison of 10 and 15 times. However, the results from the vendor 2 indicate quite consistent coating thickness given the different number of measurements. Since the measuring approach cannot be different from vendor to vendor (e.g., 10 times for vendor 1 and 3 times for vendor 2), we suggest that a minimum of 10 measurements are required to properly represent the coating thickness at a given pipe location, regardless of the vendor. Detailed results of coating thickness measurements are provided in appendix H.

Table 16. Comparison of the coating thickness measurement results

	3-6**	3-10**	3-15**	6-10**	6-15**	10-15**
12-V1-Al*	X	O	O	X	X	O
14-V1-Al*	O	O	O	O	O	O
16-V1-Al*	X	X	X	X	X	O
16-V2-Al*	O	O	O	O	O	O
16-V2-Ga*	O	O	O	O	O	O

*: gauge (12, 14, and 16) - vendor (1 or 2) – material (aluminized or galvanized)

**: comparison in different number of measurements

4.2. Preparation of corrosion specimens

Pipe samples were cut into small segments along the grid lines; samples were cleaned using acetone and then were stored in a container with silica gel to avoid moisture as shown in Figure 28. Contamination of the sample surfaces were avoided during the handling and installation in the corrosion test setup.

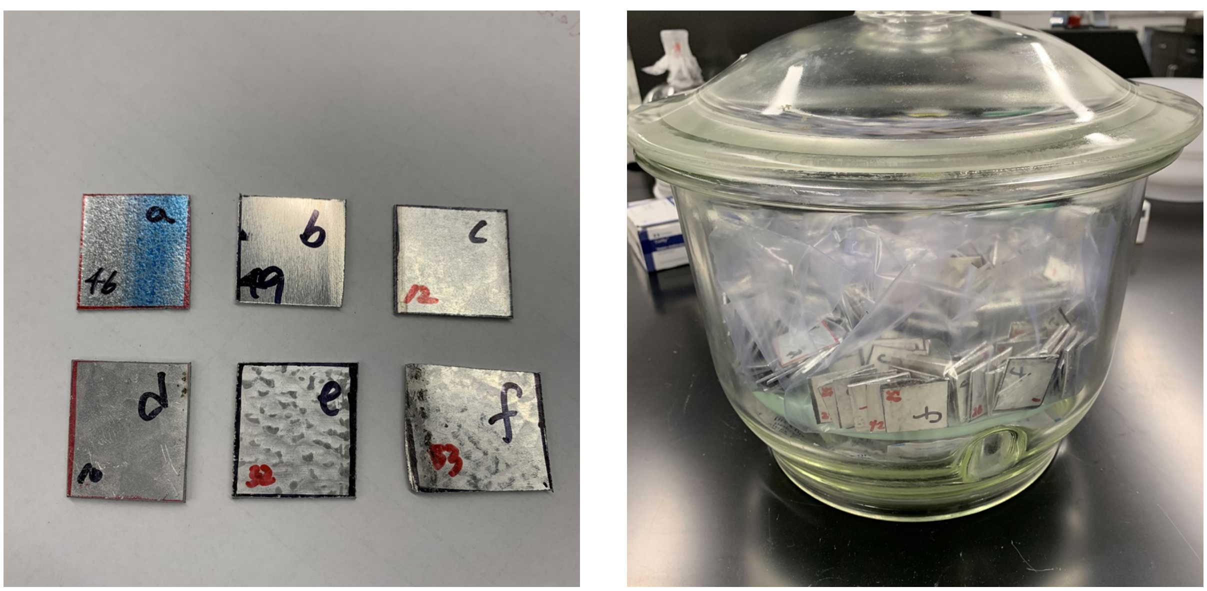


Figure 28. Samples for corrosion test

4.3. Corrosion testing setup

All samples were cleaned with acetone and deionized water and dried prior to being exposed to the electrochemical testing solution. Gamry Paracell was used as a corrosion cell and Solartron

ModuLab XM ECS was used as a potentiostat. Potentiodynamic polarization testing (PDP) was carried out from 0.25 V below the open-circuit potential (OCP) up to 1.0 V above the OCP. The test setup is shown in Figure 29.

Saturated calomel electrode (SCE) was used as a reference electrode at room temperature (25±2°C). The bridge tube was filled with saturated KCl solution. A graphite block was used as a counter electrode. The scan rate was set to 0.166 mV/s as ascribed in ASTM G5. Once the sample was mounted and the solution was filled, the setup was held at the OCP for 1 hour to reach a steady state prior to the electrochemical experiment.

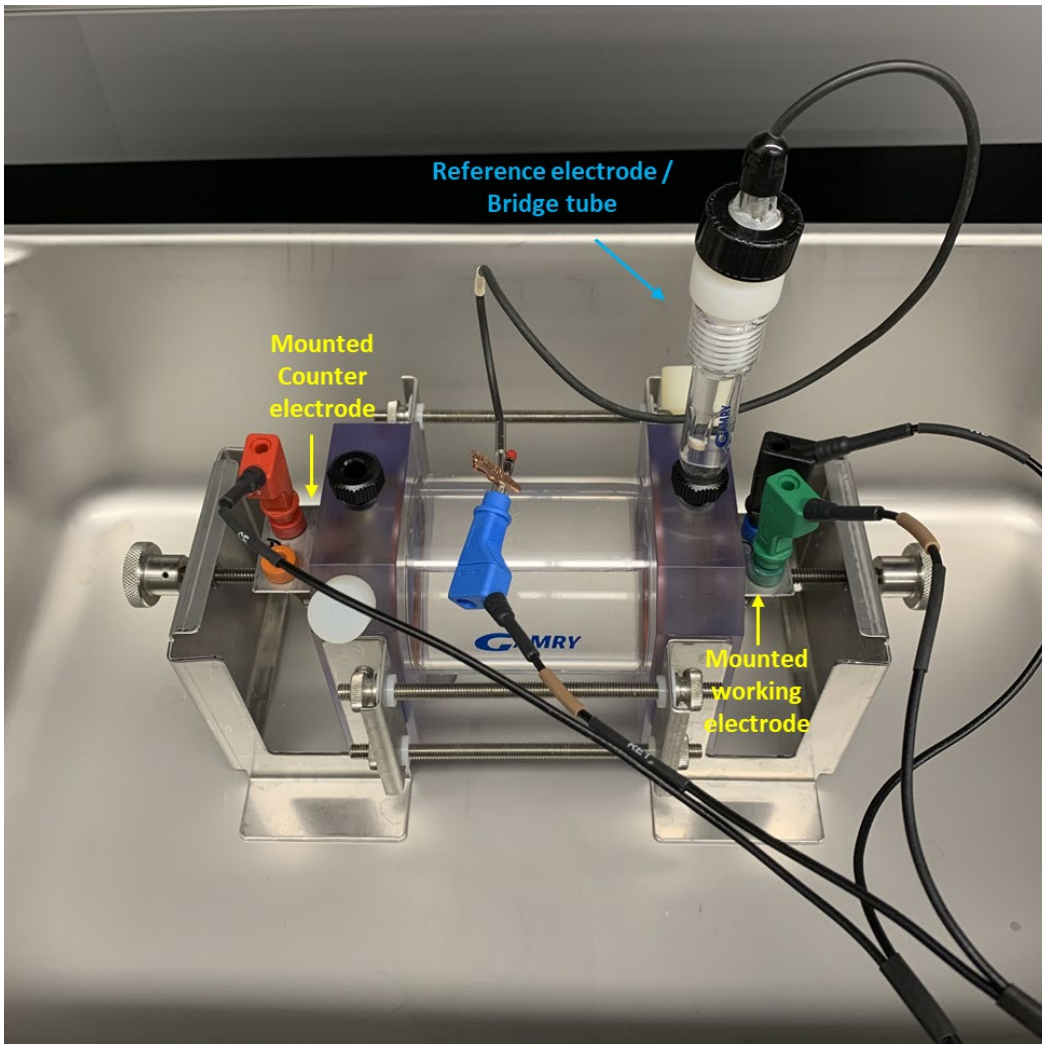


Figure 29. PDP testing set up

4.3.1. Electrolyte Solution 1 – simulating corrosive soil

According to Uhlig and Revie (1985), the relative rate of corrosion peaks at 3.5 % of sodium chloride (NaCl) solution concentration which is close to the concentration in seawater. The solution was prepared with dissolving 3.5 wt.% sodium chloride (NaCl) and 1 wt.% sodium sulfate (Na_2SO_4); the initial pH of the solution was 5.65. Corrosion rates were calculated using Tafel extrapolation method for various coating thicknesses of the materials.

Figures 30 and 31 show the corrosion rate results of galvanized and aluminized pipe samples, respectively. The scatter in the data indicates that the corrosion rates are independent of the coating thickness for the galvanized and aluminized pipe samples. The mean corrosion rate is calculated using bootstrap method by R studio for both materials. The bootstrap enables resampling with replacement with the same number of populations and calculating the mean of the resampled means. The bootstrap was iterated for 10,000 times and the results are shown in Figures 32 and 33.

Results show that in the electrolyte simulating a corrosive soil the corrosion rate of galvanized pipe is 267 µm/year and the corrosion rate of aluminized pipe is 5.37 µm/year. According to Padilla et al. (2013) the corrosion rate of galvanized steel in the same solution at 25°C was 444 µm/year (while the results are at the same order of magnitude the difference is mainly due to the rate of measurements and polarization).

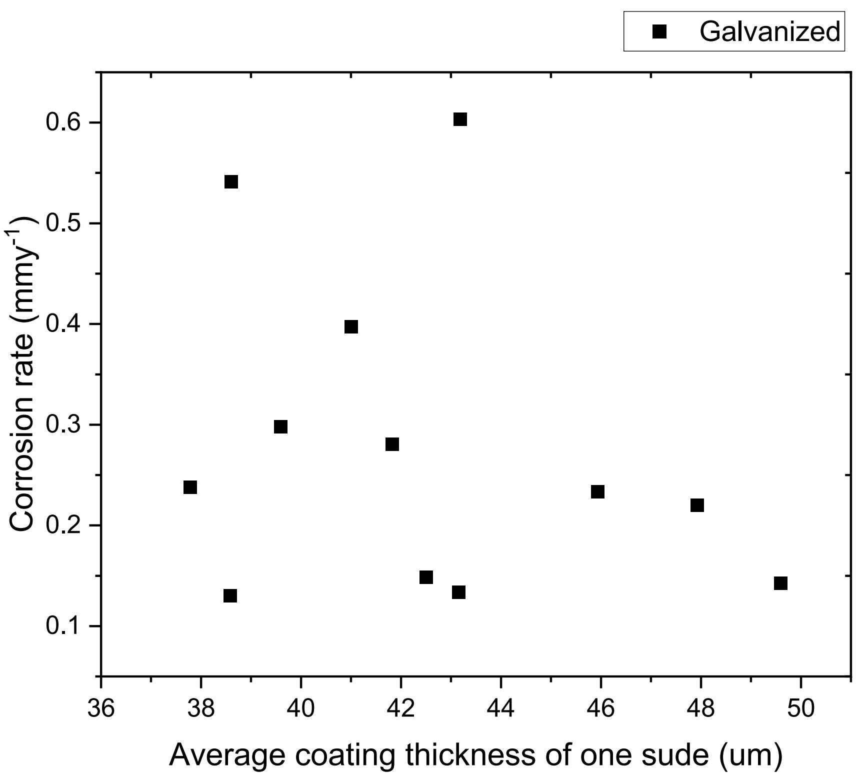


Figure 30. Corrosion rate result of galvanized pipe

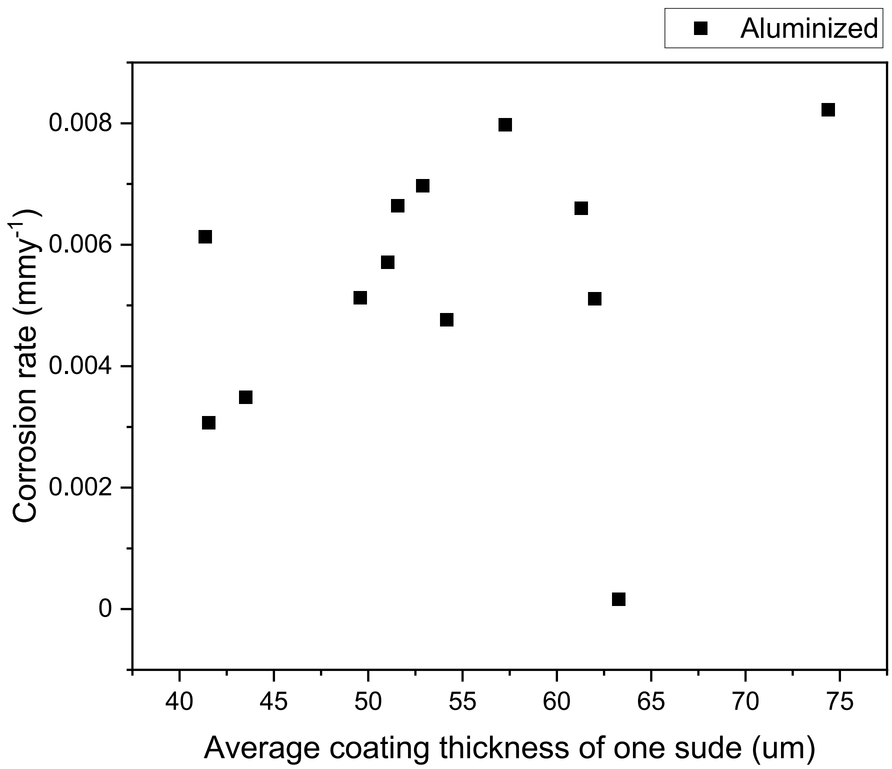


Figure 31. Corrosion rate result of aluminized pipe

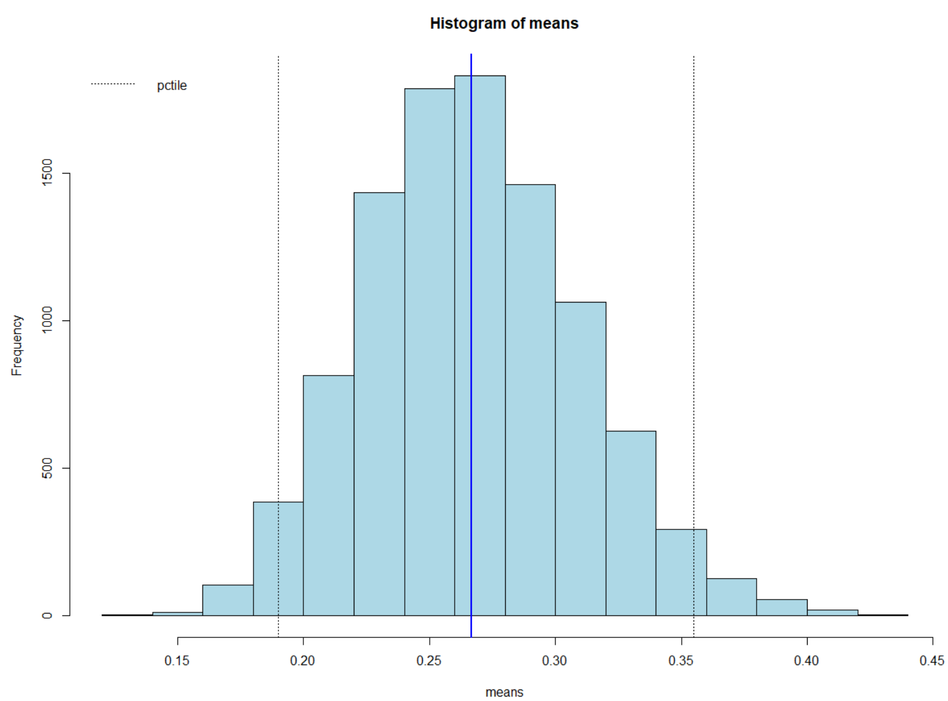


Figure 32. Bootstrap result of the corrosion rate of galvanized pipe samples

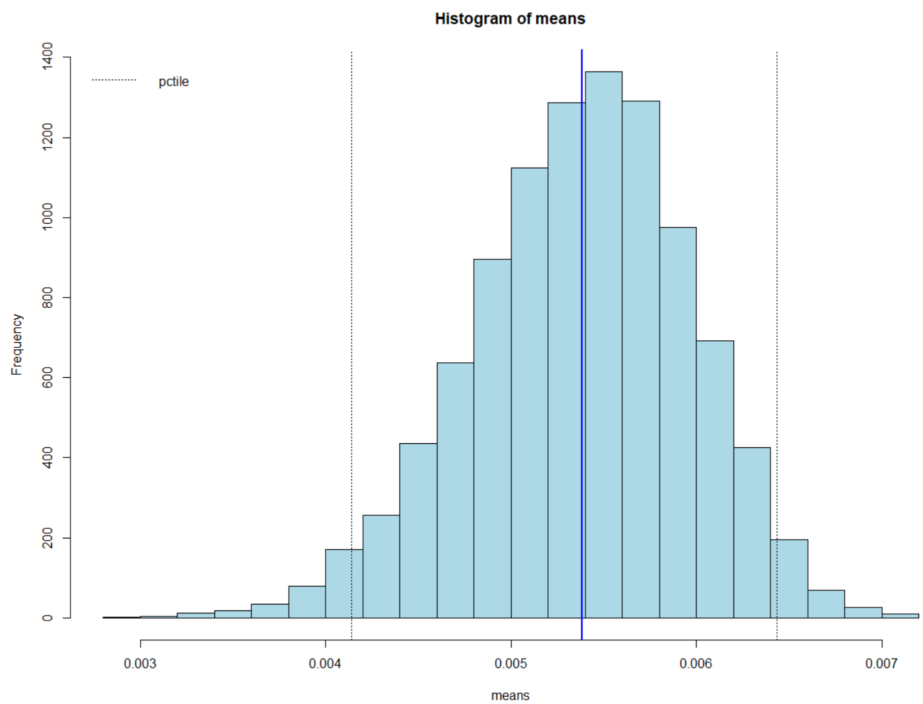


Figure 33. Bootstrap result of the corrosion rate of aluminized pipe samples

4.3.2. Electrolyte Solution 2 – simulated soil solution NS4

As galvanized pipes are not used in coastal area, simulated soil solution NS4 was considered as an alternative electrolytic solution representing a moderate exposure. The composition of NS4 solution is presented in Table 17 (Parkins et al., 1994). The NS4 solution has been widely used as soil simulating solution with its aggressiveness in corrosion study of pipeline steel, especially stress cracking corrosion (SCC) area.

Table 17. Composition of simulated soil solutions (Parkins et al. (1994))

	Composition (g/L)			
Reagents	NS1	NS2	NS3	NS4
KCl	0.149	0.142	0.037	0.122
$NaHCO_3$	0.504	1.031	0.559	0.483
$CaCl_2 \cdot 2H_2O$	0.159	0.073	0.008	0.181
$MgSO_4 \cdot 7H_2O$	0.106	0.254	0.089	0.131

As it was concluded that corrosion rates are independent of coating thicknesses from the corrosion tests in 3.5wt% NaCl + 1.0wt% Na_2SO_4 solution, more corrosion tests were done in NS4 solution for both galvanized and aluminized pipe samples. The results are shown in Table 18.

Table 18. Corrosion test results in both solutions for aluminized and galvanized pipe samples

Material	Aluminized	Galvanized	Aluminized	Galvanized
Solution	3.5wt% NaCl + 1.0wt% Na_2SO_4		NS4 solution	
Corrosion rate (µm/yr)	5.37	267	2.5	49

4.3.3. Discussion

According to Padilla et al. (2011), there are three stages for the corrosion of galvanized pipe inside soil. In stage 1, anodic process is accelerated mainly due to the dissolution of the oxide layer (ZnO) which was formed in the air. In stage 2, the corrosion rate rapidly decreases as the underlying steel begins to corrode and the coating acts as a sacrificial anode. In stage 3, the galvanized steel shows almost the same corrosion potential as that of steel, even though the zinc coating is still covering a few parts of the reinforcement. The zinc coating no longer acts as a sacrificial anode as the underlying steel corrosion progresses by dissolution of iron as schematically shown in Figure 34. Akhoondan and Sagüés (2013) studied the corrosion mechanism of aluminized steel and stated that it follows the same stages that are shown in Figure 35.

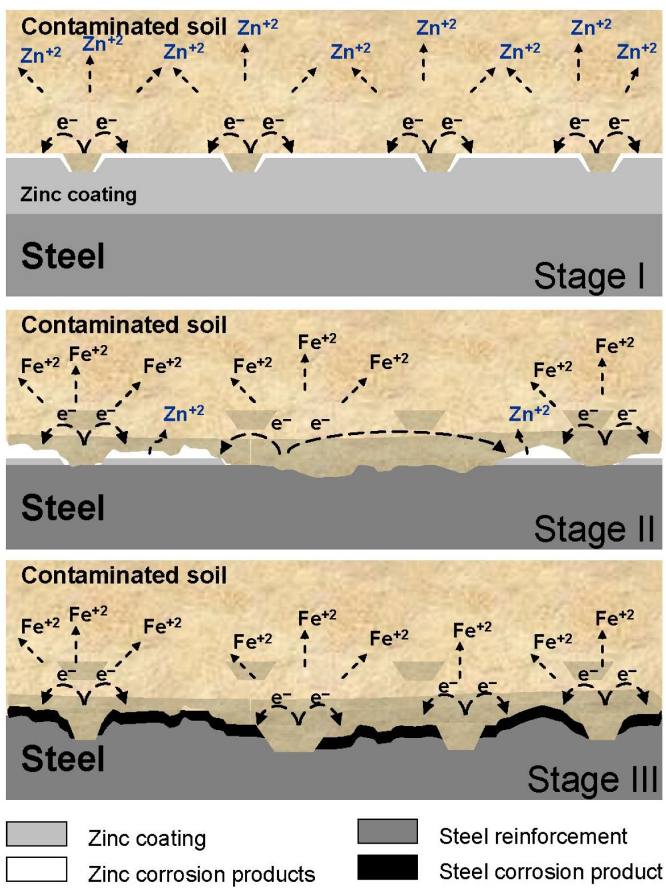


Figure 34. Three stages of galvanized steel corrosion (Padilla et al. 2013)

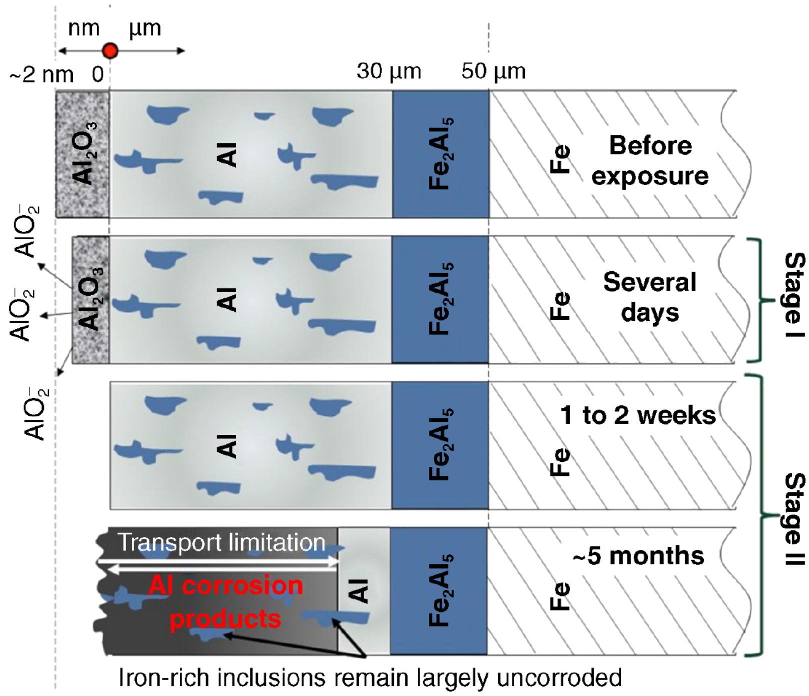


Figure 35. Mechanism of aluminized Type 2 steel corrosion in limestone-saturated flowing water condition (Akhoondan and Sagüés, 2013)

The results of extensive field testing on metal pipes and buried sheet steel by the US National Bureau of Standards (NBS), dating back to 1910, provide the most comprehensive data on underground corrosion currently available (Romanoff, 1957). As shown in Table 19, generally the rate of corrosion is highest in the first few years following burial, and then gradually reduces to a stable but greatly reduced pace.

Table 19. Loss in weight and corrosion rate of galvanized steel buried in 1937 (Romanoff, 1957)

Types of soil	Weight loss (oz/ft^2)	Time (yr)	Corrosion rate (µm/yr)
Cecli clay loam	0.3	2.1	6.11
	1.4	4	14.96
	0.6	8.9	2.88
	1	11.2	3.82
	0.6	12.7	2.02
Hagers town loam	0.3	1.9	6.75
	1.2	3.9	13.15
	0.7	9	3.32
	1	11	3.89
	0.6	12.6	2.04
Susquehanna clay	1	2.1	20.36

	2.3	4	24.58
	0.9	8.9	4.32
	1.1	11.2	4.20
	0.8	12.7	2.69
Chino silt loam	1.1	2.1	22.39
	2.3	4	24.58
	1.6	9	7.60
	1.7	11.2	6.49
	1.1	12.7	3.70
Mohave fine graveliy loam	1.6	2.1	32.57
	3.3	4	35.27
	1.1	9	5.22
	2.7	11.2	10.31
	1.1	12.7	3.70
Sharkey clay	0.6	2.1	12.21
	1.5	4	16.03
	0.7	8.9	3.36
	2.2	11.2	8.40
	1.1	12.7	3.70
Acadia clay	3.3	2.1	67.18
	4.8	9	22.80
Docas clay	3.2	2.1	65.14
	1.6	4	17.10
	1.6	9	7.60
	2.4	11.2	9.16
	1.6	12.8	5.34
Merced silt loam	2.1	2.1	42.75
	4.5	4	48.09
	0.1	9	0.47
	2.6	11.2	9.92
	1.3	12.8	4.34
Lake Charles clay	3.7	2.1	75.32
	3.9	4	41.68
	5.5	8.9	26.42
	14.3	11.1	55.07
	13.8	12.7	46.45

AASHTO specifies the corrosion rate of galvanized steel reinforcement when the soluble chlorides and sulfates of soil fills are not exceeding 100 PPM and 200 PPM respectively as follows:

- Zinc corrosion rate first 2 years - 15 µm/year/side
- Zinc corrosion to depletion - 4 µm/year/side
- Carbon steel rate – 12 µm/year/side

The Stuttgart model for corrosive conditions are 17 µm/year, 2 µm/year, and 12 µm/year for stages 1, 2, and 3, respectively.

According to Uhlig's Corrosion Handbook (2011,) rates of pitting of aluminum alloys in seawater usually ranges from 3 to 6 µm/year during the first year and from 0.8 to 1.5 µm/year averaged over a 10-year period. In 1978, Legault and Pearson conducted five-year investigation on atmospheric corrosion of aluminized Type 2 steel. The corrosion rate in industrial environment was ~0.2 µm/year and in marine environment was ~0.45 µm/year. Akhoondan and Sagüés in 2013 conducted an experiment with aluminized Type 2 steel in a near neutral environment for saturated and moist sand, which resulted in extremely low corrosion rates of ~1 µm/year.

From the corrosion test and data reported in literature, the research team conclude the following:

- Corrosion rate is not dependent on the coating thickness
- Reduction in coating thickness is related to two stages of corrosion

These two findings and the corrosion rates are used in developing a proposed discount rate model.

5. Discount rate

For the development of a discount rate model, we adopted the corrosion rate of galvanized and aluminized steel in a non-corrosive soil from the literatures considering the stages of corrosion shown in Table 20. Also, the corrosion rate of steel was adopted from literature as 21.5 µm/yr as indicated in Table 21.

Table 20. Corrosion rate of aluminized and galvanized steel from the experiment versus literatures

Material	Aluminized	Galvanized	Aluminized	Galvanized
Solution	3.5wt% NaCl + 1.0wt% Na_2SO_4 (marine simulated)		NS4 solution (soil simulated)	
Corrosion rate (µm/yr)*	5.37	267	2.5	49
Corrosion rate (µm/yr)**	3-6 (first year) 0.8-1.5 (over 10 yrs)	444	4.5 (stage 1) 1 (stage 2)	16 (stage 1) 3 (stage 2)

*: corrosion rate results from the experiments

**: corrosion rate of both materials in literatures

Table 21. Corrosion rate of different steel after 12-years of exposure in 44 soils (Romanoff, 1957)

	Open Hearth Iron	Wrought Iron	Bessemer Steel
Corrosion rate (µm/yr)	21	22	21

To develop a discount rate of both pipe materials, we assumed no pitting corrosion since this type of corrosion cannot be easily considered and does not impose significant risk on the performance of culverts. In addition, duration of stage 1 corrosion is considered as 2 years which corresponds to 32 µm (16 µm x 2 years) for galvanized and 9 µm (4.5 µm x 2 years) for aluminized Type 2 pipe.

Then, the service life of galvanized and aluminized steel can be estimated, respectively, as follows:

- $Year\ (galvanized) = \frac{zinc\ (\mu m) - 32}{3} + \frac{steel\ (\mu m)}{21.5}$
- $Year\ (aluminized) = \frac{aluminum\ (\mu m) - 9}{1} + \frac{steel\ (\mu m)}{21.5}$

According to AASHTO M218 and M274, specified coating thickness for galvanized and aluminized pipes are 43 µm and 47.5 µm for one side, respectively. The service life of both coatings will be varied depends on the gage of steel as shown in Table 22.

Table 22. Default service life (DSL) of different size of both pipes for the calculation of discount rate

Gage	Steel part	Galvanized	Aluminized	DSL of galvanized	DSL of aluminized
	Year				
18	55.81	3.67	38.5	59.48	94.31
16	74.42			78.09	112.92
14	93.02			96.69	131.52
12	120.93			124.6	159.43
10	148.84			152.51	187.34

The discount rates for different sizes of pipes are then proposed as follows:

$$Discount\ rate = \frac{\left(DSL - \left(steel\ part + \frac{measured\ coating\ thickness\ (\mu m) - k}{corrosion\ rate\ (\mu m/yr)}\right)\right)}{DSL} \times 100$$

Where,
DSL = default service life as shown in Table 22;
k = constant for stage 1 corrosion; 32 for galvanized pipe and 9 for aluminized Type 2 pipe;
corrosion rate in μm/yr = 3 for galvanized pipe and 1 for aluminized Type 2 pipe.

For example, when the measured coating thicknesses for both galvanized and aluminized coatings are half of the default coating thicknesses (21.5 µm and 23.75 µm for galvanized and aluminized pipes, respectively), the percent discount rates for both materials are shown in Table 23.

Table 23. Discount rate example

Gage	Discount rate (galvanized)	Discount rate (aluminized)
	%	
18	12.0	25.2
16	9.2	21
14	7.4	18.1
12	5.8	14.9
10	4.7	12.7

6. Findings and Conclusions

Pipe Assessment and Selection Software (PASS) was developed and programmed in an Excel Spreadsheet to facilitate pipe material selection process with information on expected service life. Discount rate models to provide reduced coast index for subpar coating thicknesses for both galvanized and aluminized pipes were developed and programmed in an Excel spreadsheet.

The exposure conditions that affect the service life of culvert pipes (e.g., chloride exposure, soil pH and resistivity) were studied and characterized through literature review and the performance of an experimental program. The synthesized information was cross-referenced with the exposure conditions in North Carolina (NC) and the data were programmed onto software tool PASS. PASS provides service life estimation for a wide range of pipes including Reinforced Concrete Pipe (RCP), galvanized and aluminized Corrugated Steel Pipe (CSP), corrugated aluminum, steel, cast iron, High Density Polyethylene (HDPE), Polypropylene, and Polyvinyl chloride (PVC) pipes. PASS is also programmed to automatically retrieve soil pH, resistivity, and chloride data using GPS coordinates of a given project. While PASS can retrieve soil properties using GPS coordinates, it also allows the user to manually input such data if field measurements are available. In addition, and through location triangulation, physicochemical properties of fill material from quarries near a given project location in NC can be automatically uploaded into PASS. PASS then uses these data to provide estimates of service life for different types of pipes if the backfill were to be replaced with materials from the nearby quarries. Monte Carlo simulations were used to establish uncertainty in service life estimations through quantifying the environmental condition as random variables.

Through an experimental program, the variation of coating thickness of galvanized and aluminized pipes was measured, and statistical analysis were performed to characterize the minimum number of coating thickness measurements to provide representative data. The results indicate that a minimum of 10 measurements are needed to obtain reliable measurements of coating thickness. While the coating thickness less than that specified by the relevant standards will lead to reduced service life, pipes with substandard coating thickness may however be adequate for certain areas where short term installations is acceptable. It is therefore practical to have guidelines for a reduced (or discount) cost for pipes with reduced coating. To facilitate the development of such discount rate protocol, corrosion experiments were performed on galvanized and aluminized steel with different coating thicknesses in simulated exposure conditions. Results from these experiments were used in quantifying the effect of coating thickness on the service life of pipes. The findings indicate that the corrosion rate was independent of coating thicknesses; that is the increase in coating thickness has a linear correlation with increase in the service life. Therefore, a linear model was developed in which a “discount rate” for galvanized and aluminized pipes based on the reduced coating thickness is proposed. The discount rate model is programmed as well in an Excel spreadsheet.

The products of this research can be used to realize cost and time saving for NCDOT. The developed PASS software enables selection of pipes based on their exposure condition and estimated service life. PASS is also automated to utilize a given project GPS coordinates to retrieve exposure data in North Carolina and provide an estimate of expected service life of a verity of pipe types. Having such feature reduces the effort needed for gathering data and evaluating the suitability of different pipe types at a given project location. In addition, the discount rate model provides data on appropriate related cost index for pipes with reduced coating thickness which are still suitable for use in a project with a reduced demand for service life.

7. Recommendations

We recommend:

- The use of Pipe Assessment and Selection Software (PASS) that was developed in consultation with NCDOT. This software provides an estimate the service life of different pipes in a given exposure condition
- The use of PASS with actual measured data in the field (pH, resistivity, and chloride content). In the absence of such measurements, the use of GPS coordinates provides an alternative method to retrieve input parameters
- In circumstances that a given project covers a wide area, we recommended using PASS with 3 different coordinates (e.g., the east, the west, and the middle) to provide more representative information on pipe material selection options as PASS requires a specific geo coordinate
- The use of physiochemical quarry data that was included in PASS. The included data will be kept updated by NCDOT and provide 4 closest quarries from a specific job site
- The use of discount rate model and program for determining a reduced price for galvanized and aluminized Type 2 CSP with substandard coating thickness
- Measuring coating thickness a minimum of 10 times (as opposed to 3 times) and taking an average of the data to increase the reliability of the results

8. Implementation and Technology Transfer Plan

The major outcomes of the present project are two programs: (i) Pipe Assessment and Selection Software (PASS) and (ii) discount rate models and programs. During the development, PASS was shared during meetings with the Steering Committee and NCDOT colleagues; all the received comments within the scope of the project were implemented.

These outcomes are implementation ready; both are programmed in an Excel spreadsheet and are ready for use by NCDOT. A training video accompanies PASS to accelerate training and implementation.

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APPENDIX A:

Meeting Notes

MEETING NOTES FOR MAY 21ST

Research Project No. 2020-077

Contract Start Date: *August 1, 2019* Contract Expiration Date *July 31, 2021*

Project Title: *Durability of Pipe Materials in Soils*

Participants:

Research Team:

Mohammad Pour-Ghaz	Principal Investigator
Gregory Lucier	Other Investigator
Mo Gabr	Other Investigator
Hyun-Jun Choi	Graduate Student
Faria Ahmed	Graduate Student

NCDOT:

Cabell Garbee (Chair)	Emily McGraw
John W. Kriby	Ray Lovinggood
Stephen Morgan	Brian Skeens
Brian Hunter	Ryan Mullins
Joshua Law	John Pilipchuk
Wiley Jones	
Ashley Cox	

- *The use of "Yes and No" in the Pipe Selection Excel Worksheet was discussed and suggestions were provided to change the "binary "yes/no" outcome. In addition, the use of some strict statement such as "Do not use in highly corrosive environments" was suggested as there may be occasions that service life of less than 5 or 10 year life may be appropriate (e.g., temporary structures)*
  The research team believe that if the output of the Program is provided in "Years" of service life," then this issue will be addressed.

- *What if a project covers a lot of territory' do we pick just one coordinates for longitude and latitude as part of the input parameters?*
  At present, the solution is to select multiple points along the pipe corridor and using the program to assess the suitable pipe material. In the future, the plan is to extend and enhance the Excel work sheet where such input is facilitated. Additionally, the possibility of producing contour map for the Project will be explored.

- *It was suggested that this program needs to be evaluated by end users to know their thoughts on how this program can be effectively used.*
  It was also suggested that NCDOT colleagues will discuss this later after receiving the revised program and will share their thoughts with the research team.

- *It was suggested that service life be a user-specified input since depending on the project such expected service life can vary (e.g., in case of detour anything that provide 18 months of service life can be used; however, in the case of interstate one may need 75 years).*
  The research team believe that this issue will be addressed when the output of the program is in “Years” of service life.

- *Scientific evaluation of the work was discussed.*
  The research team is planning to publish this work as a peer reviewed journal paper, once permission from NCDOT is granted.

- *Questions were asked about the accuracy of the service life estimations.*
  The service life estimations are based on models and fundamental sciences per published literature. Many simplifying assumptions are used in such modeling and therefore there are uncertainties in such estimation. More accurate modeling can be done but requires significant collections of input data and computational resources. As such there is always a trade-off between accuracy and practicality of a model.

- The definition of the velocity with regard to the abrasion level and its relevance to storms (10-year, 25-year or 50-year) was discussed.
  Different storm can induce different velocities depending on the waterways; abrasion levels 1 through 4 are categories; the site velocity as a function of the storm level needs to be assessed, and compared to the 1-4 categories to decide upon the abrasion level.

- Definition of the service life of pipe materials was discussed and a question was asked whether it corresponds to fully deteriorated condition or when first hole appears?
  The AISI method that is used to calculate the service life of galvanized pipe defines the end of the useful service life of the pipe as the time when an average metal loss of 25% occurs in the invert. There are other approaches, such as the Caltrans (California DOT) approach of durability, which was not used in the excel sheet, is based on life to first perforation in culverts that had not received any special maintenance treatment. According to FDOT (Florida DOT) drainage manual, for metal pipe including aluminized type 2 pipe, the time of first perforation (complete penetration) is the service life end point.

- How much does the temperature play into the calculation?
  The temperature certainly affects the corrosion rate. The service life estimation is based on an average yearly temperature. Daily or monthly temperature variations can be programed but at the end, once will need to design for an average value given the number of years of service life.

- Does the guide take into account the NCDOT design criteria on the limits of how much fill or cover can be placed on the pipe? How a certain pipe material can vary based on loading?
  At this point, the program only considers exposure condition; this program currently does not account for any structural requirements. The NCDOT guide can be integrated into the program. The research team need to first enhance the program before adding another components that may complicate its usability. There was a discussion regarding the limited time and resources within the current project to accomplish this task.

- Questions were asked about the potential evaluation of mitigation measures such as clay fill around the pipe or lining strategies such as grouting using the program.
  The effect of changing backfill materials can be evaluated using the program by changing the input parameters (such as pH and resistivity) to match those of the backfill materials. The evaluation of the duration for which the backfill material remains effective (i.e., maintains the resistivity and pH) requires simulations and is out of the scope of the current research project.
  Evaluation of repair methods such as lining is challenging and perhaps this is an idea for the next project (which by the way Neil asked for these ideas by July 10th.)

- Inclusion of steel pipe and cast iron with different thicknesses in the program was requested.
  The research team will include steel pipe in the program; cast iron pipe requires more investigation. I models are available or can be developed quickly the research will include cast iron in the program as well.

- Potential field verifications in collaboration with NCDOT colleagues was discussed.
  The research team had proposed (as a part of the research program) to perform limited site visits for verifications. The current plan is do so potentially early 2021. The research team will work with Mr. Cabell Garbee to identify potential sites. Mr. Drew Cox is also interested to be involved in site visit and the research team will coordinate with him as well.
  It was also proposed that the recent pipe inspection report can be used for verification.
  It was proposed that verification can be collaborative, and some can be performed by NCDOT colleagues.

Requested information by the research team from NCDOT:

- Pipe inspection report

- Sampling of pipes
- Any information about variation of coating thickness for galvanized and aluminized steel pipes
  Sulfate and chloride content data of soils if available in a database that is used by NCDOT

MEETING NOTES FOR NOVEMBER 24TH

Research Project No. 2020-22

Contract Start Date: *August 1, 2019* Contract Expiration Date *July 31, 2021*

Project Title: *Durability of Pipe Materials in Soils*

Participants:

Research Team:

Mohammad Pour-Ghaz	Principal Investigator
Mo Gabr	Other Investigator
Hyun-Jun Choi	Graduate Student

NCDOT:

Cabell Garbee (Chair)	Ethan J. Caldwell
John W. Kriby	Neil Mastin
Stephen R. Morgan	Brian C. Skeens
Brian J. Hunter	Ryan M. Mullins
Wiley W. Jones	
John L. Pilipchuk	
Andrew H. McDaniel	

- *Pipe Assessment and Selection Software (PASS) was demonstrated, and valuable comments were received.*
- *When the input values were out of the range of the models used, PASS provided negative values for the service life.*
- *The research team has updated PASS to provide* "N/A" instead of a negative value; this means the equations used is not applicable for the conditions entered. Detailed descriptions of service life models used of each material will be provided in the users' manual.

- *Next steps that can be expected at this point were discussed.*
At present, the next step is to correct the value outputs; all the descriptions about the models that are used will be reviewed in greater detail. In the future, the plan is to write a users' manual for PASS as a part of a delivery and a short training video. During the remaining part of the project, the research team will focus on understanding and measuring the effect of coating thickness on the time to the start of corrosion for galvanized and aluminized steel pipes. A model will be developed that provides the effect of coating thickness on the service life of it to calculate discount rate.

- *Linking the quarry excel data on PASS was requested.*
The research team received physio-chemical data for aggregates from multiple quarries; these aggregates may be used as backfill materials.

- *It was suggested that the service life estimates provided by PASS should be very transparent and clear to make sure that the users are fully informed since the definition of service life varies with the materials.*
  The research team is planning to provide a short definition of the service life used for different materials types in PASS and write a user manual that include detailed information. The work done is also can be published as a peer reviewed journal paper, once permission from NCDOT is granted.

- *Statistical background of the estimates was discussed.*
  The models themselves do not have uncertainties built into them. One option is to use a Monte Carlo Simulations and generate some uncertainty using the models. It can be done by looking at the variation of the input parameters and how those uncertainty propagates in these models and provide a range.

MEETING NOTES FOR SEPTEMBER 16TH

Research Project No. 2020-22

Contract Start Date: *August 1, 2019* Contract Expiration Date: *December 31, 2021*

Project Title: *Durability of Pipe Materials in Soils*

Participants:

Research Team:

Moe Pour-Ghaz	Principal Investigator
Gregory W. Lucier	Other Investigator
Mo Gabr	Other Investigator
Faria Ahmed	Graduate Student
Hyunjun Choi	Graduate Student

NCDOT:

Cabell W. Garbee (Chair)	Joshua A. Law
Andrew H. McDaniel	Matthew J. York
Ashley B. Cox	Paul Atkinson
Brian J. Hunter	Paul A. Jordan
Charles S. Miller	Ray D. Lovinggood
Ethan J. Caldwell	Ryan M. Mullins
Helen Corley	Stephanie C. Bolyard
John L. Pilipchuk	Stephen R. Morgan
John W. Kriby	

- *Pipe Assessment and Selection Software (PASS) was demonstrated, and valuable comments were received. These comments are summarized as follows:*

- *Including detailed definitions of the service life of each material on PASS itself was requested.*
  The research team is planning to provide a detailed definition on the service life of different material types in PASS and develop a user's manual that includes detailed information. For example, the service life of RCP represents the onset of the corrosion of steel, which in this case means the start of corrosion plus 6 years; by experience this criterion corresponds to spalling and cracking. Moreover, the research team will provide footnotes that can be used to interpret the estimated service life properly (e.g., replacement needed, or repair needed).

- *Service life of different types of RCP and its definition was discussed.*
  At present, the research team considered the average cover thickness for pipes across different classes to simplify the estimate process; it is envisioned that accounting for the variation in those cover thickness and the reinforcement arrangement will better serve our colleagues at NCDOT when selecting proper materials.

- *It was suggested that the term "**Nominal** diameter of cast iron pipe" needs to be changed to "**Inside** diameter of cast iron pipe" to make it transparent and clear to the users.*

- *It was suggested a range for service life of each material is more realistic since estimation is based on the worst-case scenario (i.e., margin of safety).*
  Current PASS itself does not account for a range for service life of each material. The research team is planning to use Monte Carlo Simulations and generate a margin of safety using such analysis.

- *Coordinate range of a project was discussed.*
  As PASS requires a specific geo coordinate, it will be for projects with long corridors to have to a wide range of input coordinates. One possible option is to input 3 different coordinates (e.g., the east, the west, and the middle) to provide more representative information on pipe material selection options.

APPENDIX B:

Literature Review: methodology of other DOTs

1. Literature Review

This literature review document presents a summary of a number of published documents on the subject of pipe material selection for drainage pipes. The information in this document is organized under the following categories:

- Departments of Transportation (DOTs) in the US that have guidelines for selecting pipe materials;
- Methodology of selecting pipe materials used by different DOTs;
- Background on corrosion of pipe materials in soil; and,
- Background on the abrasion of pipe materials in soil.

1.1 Departments of Transportation (DOTs) in the US that have guidelines for selecting pipe materials

In Figure 1, the state DOTs that have pipe material selection procedure are highlighted. Out of the 50 states, 26 states have selection criteria in their drainage manual or pipe material selection guide. Out of these 26 states, 25 states include both soil pH and soil resistivity for their pipe selection procedure, as indicated on Figure 1. States highlighted in red use both pH and resistivity as well as other factors such as abrasion, sulfate, moisture content, chloride, bacteria or average daily traffic (ADT). States highlighted in yellow consider only pH but do not consider soil resistivity (other factors such as abrasion are considered). The New York State DOT has a guideline based on two geographic regions; the division of state however does not rely on pH or resistivity. Figure 2 presents number of states that consider various factors for selecting pipe material in each DOT. The orders of chapter “1.2 Methodology of selecting pipe materials used by different DOTs” follow the legend of Figure 1: 1. States considering pH and resistivity; 2. States considering pH only; 3. State divided into two zones for selecting pipe material.

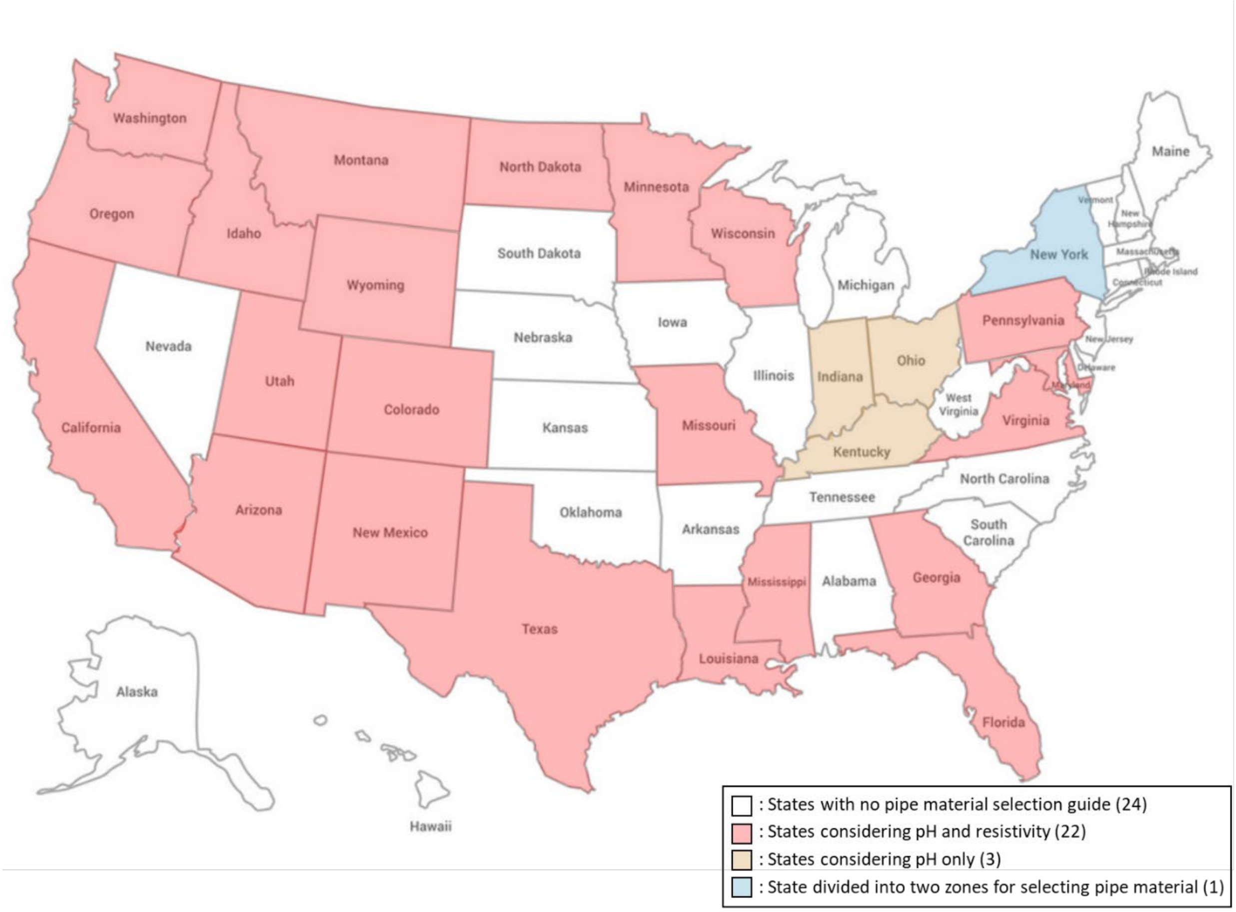


Figure 1. DOTs having pipe material selection guide (The numbers in the parentheses of the legend is the number of states)

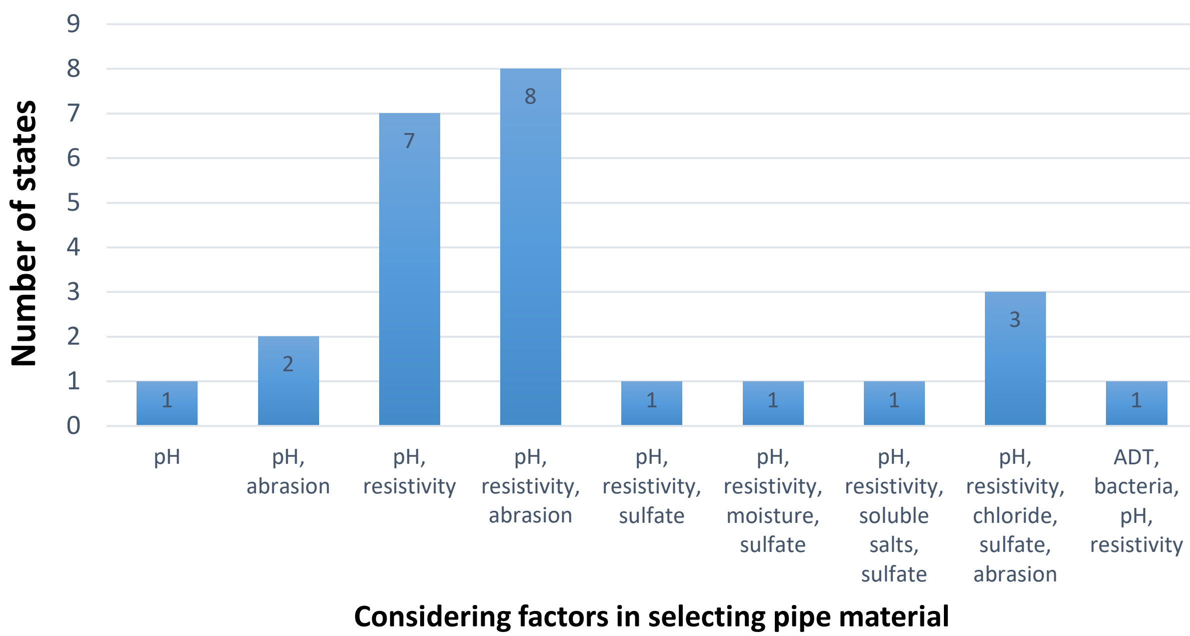


Figure 2. Factors considered by State DOTs in selecting pipe material

1.2 Methodology of selecting pipe materials used by different DOTs

1.2.1 Arizona DOT

Arizona DOT uses the AISI method for selecting proper coating (galvanized or aluminized) on steel pipe. Table 1 shows the allowable pH and resistivity value for each pipe types. If bituminous coating is required to be to achieve the design service life, this coating is assumed to extend the service life an additional 20 years. However, they recommend only using the bituminous coating if the pipe under consideration is not available in the gage needed to obtain required service life. After determining the location of the new pipe, the minimum pipe wall thickness or class of pipe is determined based on the maximum height of fill over a given pipe section. A storm drain system is also considered in the pipe selection procedure [1,2].

Table 1. Acceptable pH and resistivity value for each pipe types (Courtesy of Arizona DOT)

Types of pipe	pH	Resistivity (Ohm-cm)	Other
Galvanized steel pipe	6 < pH < 9	R > 2,000	-
Aluminized steel pipe	5 < pH < 9	R > 1,500	-
	7.2 < pH < 9.0	1,000 < R < 1,500	
Aluminum pipe	5< pH < 9	R > 500	No design procedure outside these pH and/or resistivity ranges
Concrete pipe	pH > 5	-	For high sulfates levels, Type Ⅴ cement shall be required
Plastic pipe	1.25 < pH < 15	All ranges of R	Service life of 75 years

1.2.2 California DOT

The *Highway Design Manual* of the California Department of Transportation (Caltrans) provides physical standards for material selection of drainage pipes. Caltrans has different definitions for the "maintenance-free service life" for metal pipes versus reinforced concrete pipe (RCP). For all metal pipes utilized by Caltrans, the service life is the number of years from installation until the deterioration reaches the point of perforation at any location on the pipe. For RCP, it is the number of years from installation until the deterioration reaches the point of exposure of reinforcement at any point on the pipe. According to the manual, the anticipated maintenance-free service life of corrugated steel pipe (CSP) installations is primarily a function of the corrosivity and abrasiveness of the environment into which the pipe is placed. The risk of corrosion must be determined from the pH and minimum resistivity tests, as covered in California Test 643. Abrasive potential must be estimated from bed material that is present and anticipated flow velocities [3].

Figure 3, "Chart for Estimating Years to Perforation of Steel Culverts" is widely known as the "California Method," and is a part of the *Highway Design Manual* developed based on the investigation of more than 12,000 corrugated metal highway pipes throughout the California highway system [4]. However, it alone is not used for determining service life because it does not consider the effects of abrasion or overfill. In Figure 3, the estimated years-to-perforation is based on both soil pH and soil resistivity for pH values at or below 7.3. For pH values above 7.3 only soil resistivity is used. When pH is greater than 7.3, soil-side corrosion is the controlling mechanism of corrosion and service life is estimated based on resistivity. However, when pH is less than 7.3, the interior invert corrosion generally controls the rate of corrosion and both resistivity and pH are important.

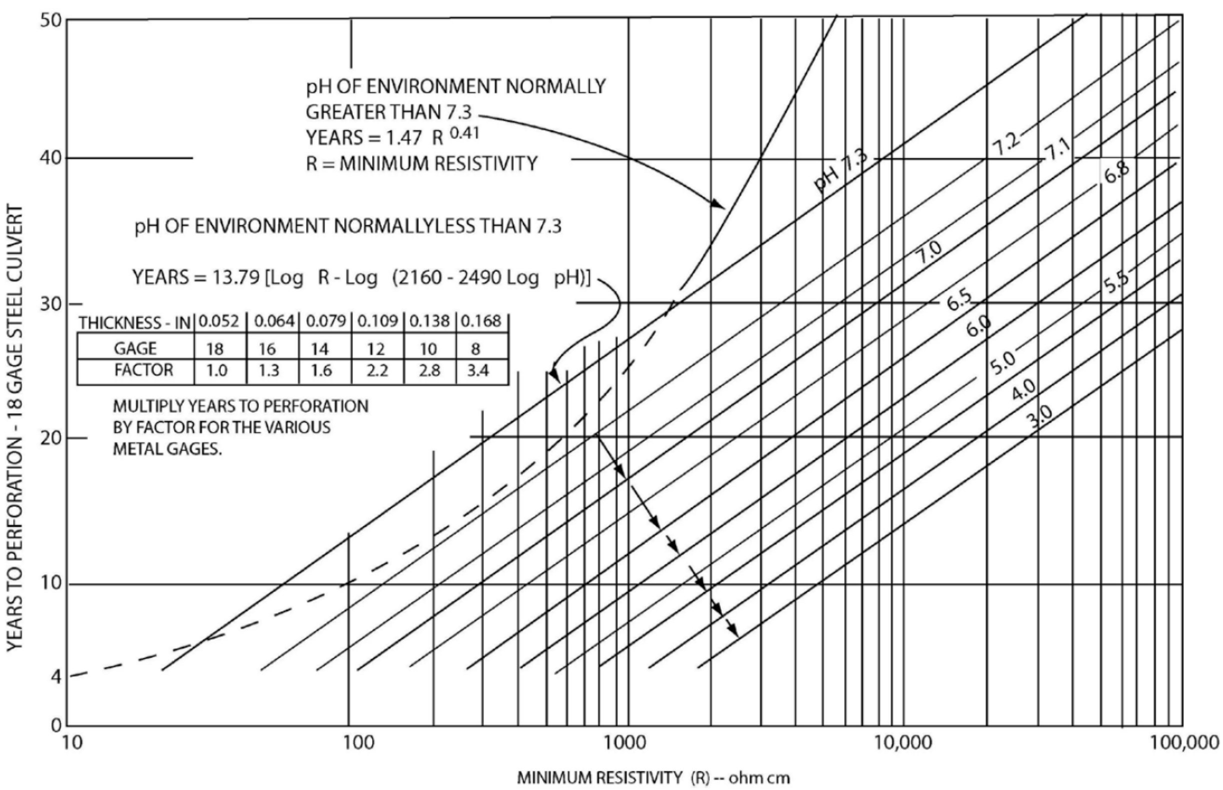


Figure 3. Chart for Estimating Years to Perforation of Steel Culverts
(Courtesy of California DOT)

Caltrans recommends using Figure 4 to determine the minimum thickness and impose limitations on the use of corrugated steel and spiral rib pipe for various levels of pH and minimum resistivity. In Figure 4, curved lines are used below pH of 7.30 and straight lines are used above pH of 7.30. The ranges of pH and minimum resistivity for galvanized steel are not limited in extent, however, for aluminized steel (type 2) and aluminum, pH is limited to the range from 5.5 to 8.5 and the range of minimum resistivity should be more than 1,500 ohm-cm. Thickness of galvanized metal pipe is determined by the gage shown in the region between two lines. However, the thickness of aluminized or aluminum pipe is fixed to 16 gage. Here are some examples that were provided by Caltrans: Given a soil environment with pH and minimum resistivity levels of 6.5 and 15,000 ohm-cm, respectively, the minimum thickness for the various metal pipes are:

1) 0.019 inch (12 gage) galvanized steel,
2) 0.064 inch (16 gage) aluminized steel (type 2), and
3) 0.060 inch (16 gage) aluminum.

Because the minimum thickness of metal pipe obtained from Figure 4 only satisfies corrosion requirements, overfill requirements for minimum metal thickness must also be satisfied, and both requirements should be used to determine the minimum metal thickness. Minimum metal thickness along with the overfill height are provided as stated in NCDOT pipe selection guide [5].

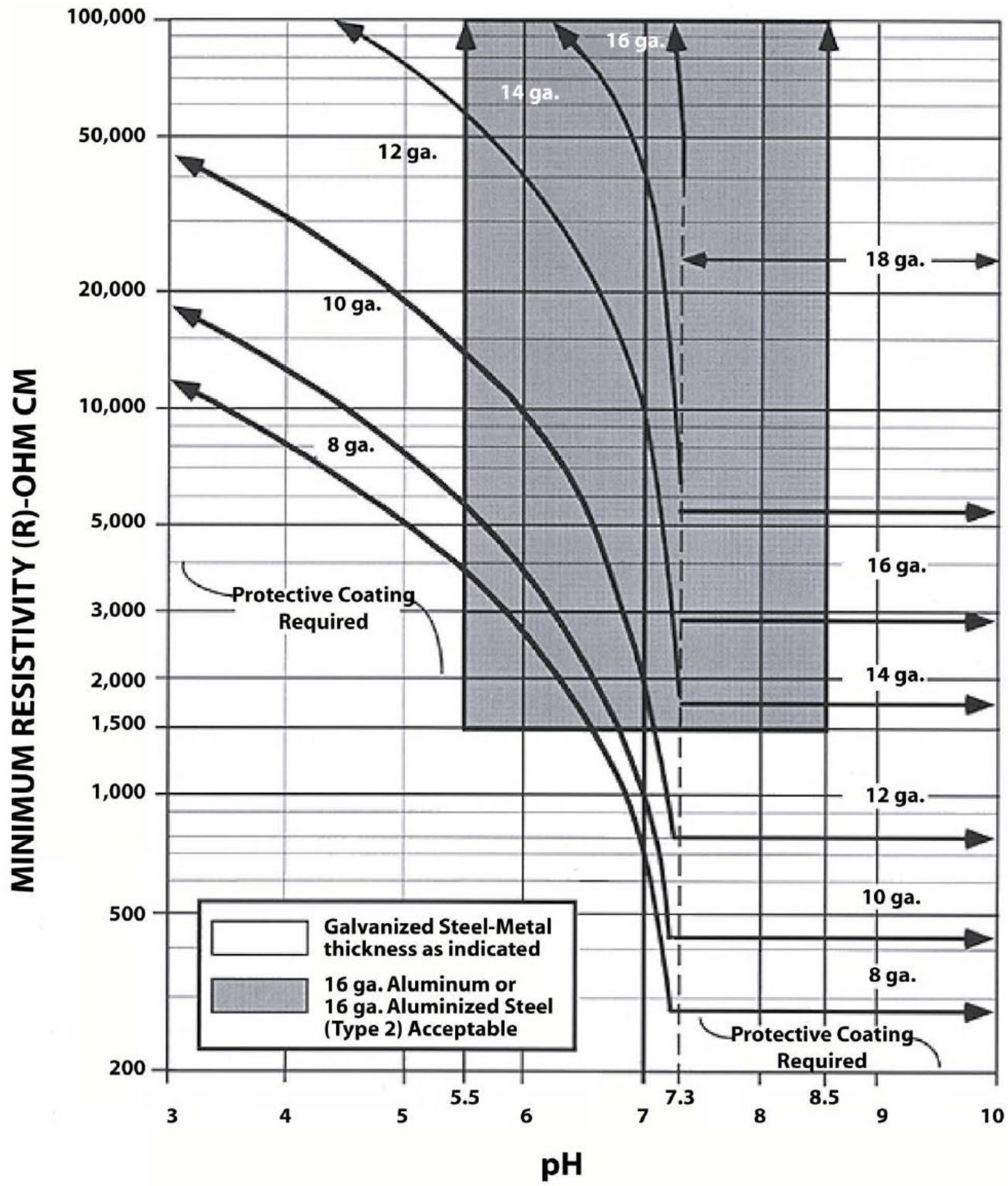


Figure 4. Minimum thickness of metal pipe for 50-year maintenance-free service life (Courtesy of California DOT)

Several states have evaluated the California Method, shown in Figure 4, for suitability to estimate the service life of galvanized corrugated steel pipe for their region and have arrived at differing conclusions. Table 2 summarizes the conclusions of different states. The states of Florida, Idaho and Louisiana are in favor of using the California method, while Georgia and Oklahoma concluded that the method was not suitable for correlation with their local environment [6].

Table 2. Selected research conclusions about the California method [6]

Reference	Conclusions about the California Method on the basis of data and/or observations
Florida	Accepts the California Method as suitable for the performance of galvanized in the Florida environment but develops new equations to predict durability for Aluminized Type 2, aluminum alloy, and concrete.
Idaho	"The test developed by the California Division of Highways and their service life chart appears to be satisfactory. It appears the test method estimates the service life conservatively in all but a few installations."
Louisiana	"Under the environmental conditions (moderately to very corrosive) encountered during this study, the California Chart overestimates predicted pipe life. The chart does, however, combine pH and resistivities to correctly predict life in a relative sense for the mildly, moderately, and very corrosive environments."
Georgia	On the basis of a survey of 251 culverts (140 plain galvanized) in Georgia, it was concluded that expected service life was 50 percent greater than that predicted by the California Method. The AISI method is consistent to conservative in Georgia.
Oklahoma	The California Method generally does not correlate with the observed culvert conditions in the State. The method predicts a shorter lifetime than observed in the western two-third of the State, with the exception of the high plains area of the panhandle where it was quite accurate.

In addition to considering pH and resistivity, Caltrans adapted abrasion levels to select pipe materials. Table 3 shows the abrasion levels are considered to vary on a scale of 1 to 5. The level of abrasion is, estimated by the amount of bedloads, its type and flow velocity. Generally, coated steel pipes and reinforced concrete pipes are influenced by abrasion, while plastic pipes are not relatively impacted by the abrasion [3].

Table 3. Abrasion levels and materials (Courtesy of California DOT)

Abrasion level	General site characteristics	Allowable pipe materials and lining alternatives
Level 1	• Bedloads of silts and clays or clear water with virtually no abrasive bed load. No velocity limitation	• All pipe materials listed in Table 857.2 allowable for this level. • No abrasive resistant protective coatings listed in Table 855.2C needed for metal pipe.
Level 2	• Moderate bed loads of sand or gravel	All allowable pipe materials listed in Table 857.2 with the following considerations:

	• Velocities ≥ 1 ft/s and ≤ 5 ft/s	• Generally, no abrasive resistant protective coatings needed for steel pipe. • Polymeric, or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential.
Level 3	• Moderate bed load volumes of sands, gravels and small cobbles. • Velocities ≥ 5 ft/s and ≤ 8 ft/s	All allowable pipe materials listed in Table 857.2 with the following considerations: • Steel pipe may need one of the abrasive resistant protective coatings listed in Table 855.2C or additional gauge thickness if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential. • Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential. • Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (equivalent to galv. Steel) where pH < 6.5 and resistivity < 20,000. Lining alternatives: • PVC, • Corrugated or Solid Wall HDPE, • CIPP
Level 4	• Moderate bed load volumes of angular sands, gravels, and/or small cobbles/rocks. • Velocities > 8 ft/s and ≤ 12 ft/s	All allowable pipe materials listed in Table 857.2 with the following considerations: • Steel pipe will typically need one of the abrasive resistant protective coatings listed in Table 855.2C or may need additional gauge thickness if thickness for structural requirements is inadequate for abrasion potential. • Aluminum pipe not recommended. • Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if

		thickness for structural requirements is inadequate for abrasion potential. • Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended. • Corrugated HDPE (Type S) limited to ≥ 48" min. diameter. • Corrugated HDPE Type C not recommended. • Corrugated PVC limited to ≥ 18" min. diameter Lining alternatives: • Closed profile or SDR 35 PVC (corrugated and ribbed PVC limited to ≥ 18" min. diameter. • SDR HDPE • CIPP (min. thickness for abrasion specified) • Concrete and authorized cementitious pipeliners and invert paving. See Table 855.2F.
Level 5	• Moderate bed load volumes of angular sands and gravel or rock. • Velocities > 12 ft/s and ≤ 15 ft/s	• Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. • For steel pipe invert lining additional gauge thickness is recommended if thickness for structural requirements is inadequate for abrasion potential. See lining alternatives below. • Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended. • Lining alternatives: • Closed profile (≥ 42 in) or SDR 35 PVC (PVC liners not recommended when freezing conditions are often encountered and cobbles or rocks are present) • SDR HDPE • CIPP (with min. thickness for abrasion specified) • Concrete and authorized cementitious pipeliners and invert paving. See Table 855.2F.

1.2.3 Methods based on the California Method

American Iron and Steel Institution (AISI) method is based on modification of the California method. The AISI chart, which specifies service life in terms of resistivity and pH, was developed from a chart originally prepared by Caltrans (Figure 5.) The Caltrans study of durability was based on life to first perforation in culverts that had not received any special maintenance treatment. However, AISI defines the end of the useful service life of the pipe as the time when an average metal loss of 25% occurs in the invert. Therefore, AISI predicts a service life that is approximately twice as long as that of the California method. The National Corrugated Steel Pipe Association (NCSPA) also published a corrugated steel pipe (CSP) durability guide that includes the AISI chart to predict service life of corrugated steel pipe and provides a table with additional service life durations for different coatings [7,8].

The chart included the combined effects of soil-side and interior corrosion, as well as the average effects of abrasion. For pipes where the pH was greater than 7.3, soil-side corrosion is the controlling mechanism, and life could be predicted by resistivity. For pipes where the pH was less than 7.3, the interior invert corrosion generally controls the deterioration and both resistivity and pH are important [7,8].

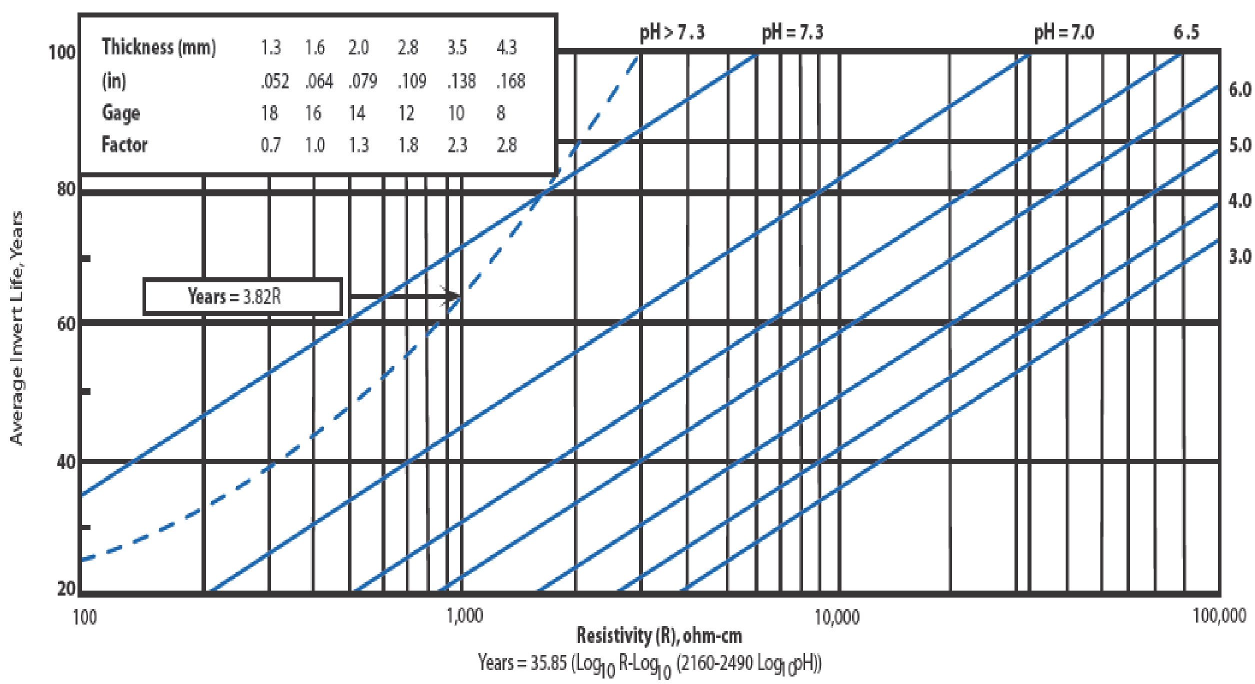


Figure 5. AISI chart for estimating average invert life for galvanized CSP (Courtesy of AISI)

Along with the chart, the National corrugated steel pipe association (NCSPA) provides estimated material service life for CSP which is shown in Table 4. Based on pH, resistivity and FHWA abrasion level (defined in Table 5,) estimated service life and each material is specified [7,8].

Table 4. Estimated material service life for CSP (Courtesy of NCSPA)

Estimated Service life	Site environmental conditions	Maximum FHWA abrasion level	Material
Minimum 100 Years	5.0 < pH < 9.0 R > 1,500 ohm-cm	Level 3	Polymer coated
		Level 2	Aluminized Type 2 (14 gauge minimum)
Minimum 75 Years	4.0 < pH < 9.0 R > 750 ohm-cm	Level 3	Polymer coated
	5.0 < pH < 9.0 R > 1,500 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 2,000 < R < 10,000 ohm-cm > 50 ppm CaCO3	Level 2	Galvanized

Table 5. FHWA abrasion levels (Courtesy of FHWA)

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

1.2.4 Colorado DOT

Figure 6 summarizes the procedure for selecting pipe types. Colorado DOT's current guidelines for selecting the type of pipe are based on the abrasion level and Corrosion Resistance (CR) which are shown in Table 6 and Table 7, respectively. Table 6 shows the descriptions for each abrasion level. The guidelines given in Table 7 use primarily the pH and the concentrations of chloride and sulfate to determine the corrosion resistance levels, rated from 0 to 6. These levels, in turn, are associated with various acceptable pipe materials. For testing those factors, following test methods are used: Sulfate levels (CPL 2103); Chloride levels (CPL 2104); Resistivity (ASTM G 57);

pH (ASTM G 51). Table 8 shows the allowed class of materials for each exposure; Table 8 is reproduction of Table 624-1 in the section of the CDOT construction specification book. Table 9 is used if there are additional requirements for metal pipes. According to CDOT's guidelines, any pipe culvert operating within the acceptable range of pH and falling within the soil and water environment with allowable levels of sulfate and chloride is assumed to have a service life of 50 years or more [9,10].

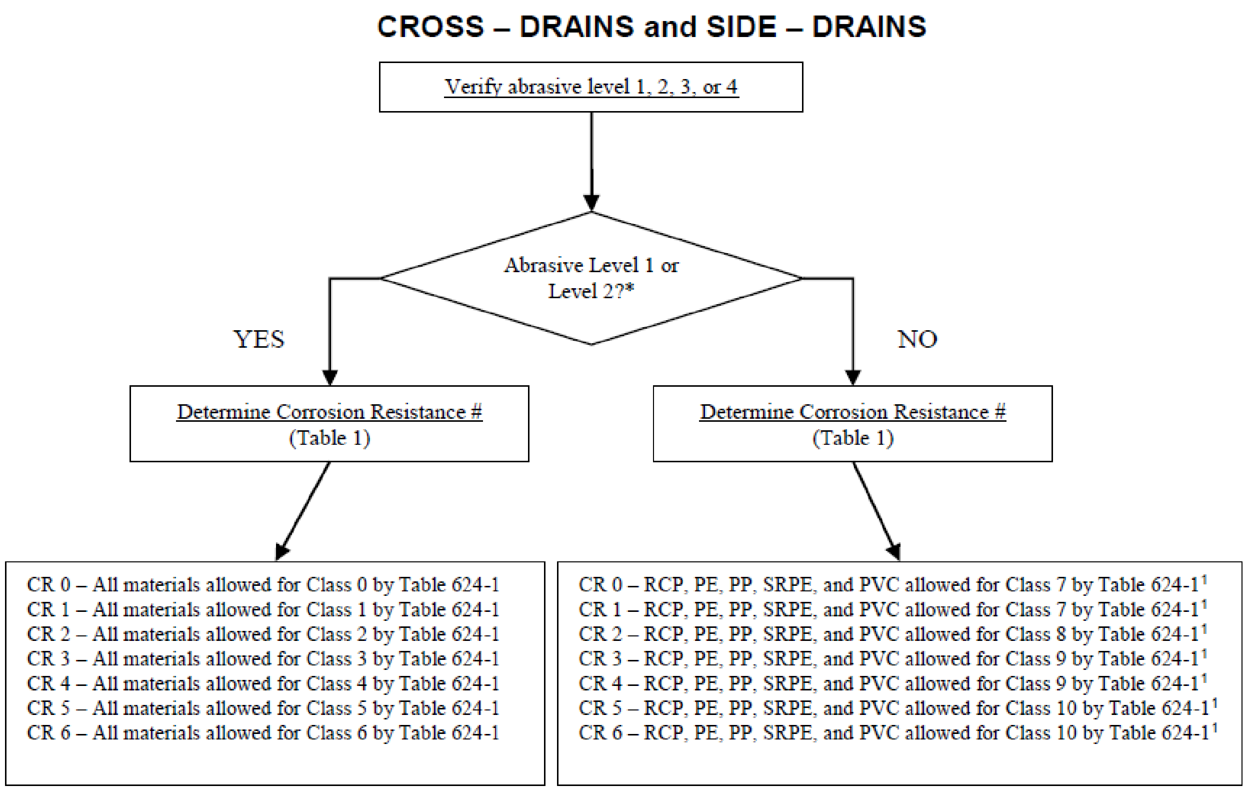


Figure 6. Diagram for selecting pipe materials (Courtesy of Colorado DOT)

In summary, the Colorado DOT suggests the pipe selection process:

1. Determine application
2. Determine abrasion level
3. Determine corrosion level
4. Selection of pipe material type
5. Verify fill height
6. Address exceptions to CDOT pipe materials selection guide
7. Documentation[9,10]

Table 6. Guidelines for the selection of abrasion levels (Courtesy of Colorado DOT)

Abrasion level	Description
1	This level applies where the conditions are nonabrasive. Nonabrasive conditions exist in areas of no bed load and very low velocities. This is the level assumed for the soil side of drainage pipes. This is also the level assumed for the inverts of cross drains and side drains installed in typically dry drainages.
2	This level applies where low abrasive conditions exist. Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 fps or less.
3	This level applies where moderately abrasive conditions exist. Moderately abrasive conditions exist in areas of moderate bed loads of sand and gravel and velocities between 5 fps and 15 fps.
4	This level applies where severely abrasive conditions exist. Severely abrasive conditions exist in areas of heavy bed loads of sand, gravel, and rock and velocities exceeding 15 fps.

Table 7. Guidelines for the selection of corrosion resistance levels (Courtesy of Colorado DOT)

CR level	Soil			Water		
	Sulfate (SO4) % max	Chloride (Cl) % max	pH	Sulfate (SO4) ppm	Chloride (Cl) ppm	pH
CR 0	0.05	0.05	6.0 – 8.5	50	50	6.0 – 8.5
CR 1	0.10	0.10	6.0 – 8.5	150	150	6.0 – 8.5
CR 2	0.20	0.20	6.0 – 8.5	1,500	1,500	6.0 – 8.5
CR 3	0.50	0.50	6.0 – 8.5	5,000	5,000	6.0 – 8.5
CR 4	1.00	1.00	5.0 – 9.0	7,500	7,500	5.0 – 9.0
CR 5	2.00	2.00	5.0 – 9.0	10,000	10,000	5.0 – 9.0
CR 6	> 2.00	> 2.00	< 5** or > 9	> 10,000	> 10,000	< 5** or > 9

Table 8. Table 624-1 in the section of the CDOT construction specification book (Courtesy of Colorado DOT)

Material allowed**	Class of pipe*										
	0	1	2	3	4	5	6[4]	7	8	9	10[4]
CSP	Y	N	N	N	N	N	N	N	N	N	N
Bit. Co. CSP	Y	Y[1]	N	N	N	N	N	N	N	N	N
A.F. Bo. CSP	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
CAP	Y	Y[2]	Y[2]	Y[2]	Y[2]	Y	N	N	N	N	N
PCSP – both sides	Y	Y	Y	Y	N	N	N	N	N	N	N
PVC	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
PE	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
RCP (SP0) [3,5]	Y	Y	N	N	N	N	N	Y	N	N	N
RCP (SP1) [3,5]	Y	Y	Y	N	N	N	N	Y	Y	N	N
RCP (SP2) [3,5]	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N
RCP (SP3) [3,5]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Notes:

* As determined by the Department in accordance with the CDOT Pipe Selection Guide. Determination is based on abrasion and corrosion resistance.

** Y = Yes; N = No.

1. Coated Steel Structural Plate Pipe of equal or greater diameter, conforming to Section 510, may be substituted for Bi. Co. CSP at no additional cost to the project.
2. Aluminum Alloy Structural Plate Pipe of equal or greater diameter, conforming to Section 510, may be substituted for CAP at no additional cost to the project.
3. SP = Class of Sulfate Protection required in accordance with subsection 601.04 as revised for this project. RCP shall be manufactured using the cementitious material required to meet the SP class specified.
4. For pipe classes 6 and 10, the RCP shall be coated in accordance with subsection 706.07 when the pH of either the soil or water is less than 5. The Contract will specify when RCP is to be coated.
5. Concrete shall have a compressive strength of 4,500 psi or greater.

Table 9. Minimum pipe thickness for metal pipes based on the resistivity and pH of the adjacent soil (Courtesy of Colorado DOT)

Soil side		Minimum required gauge thickness for metal pipe material
Resistivity, R (Ohm-cm)	pH	
≥1,500	5.0-9.0	0.052 (18 Gauge) Aluminized Type 2
≥250	3.0-12.0	0.052 (18 Gauge) Polymer Coated

1.2.5 Florida DOT

Florida DOT recognizes four driving environmental factors that have direct effect on service life durability of pipes. These factors are pH, resistivity, and chloride and sulfate ion concentrations. Therefore, they suggested to conduct environmental tests to measure these parameters before selecting any type of pipe. Florida DOT has developed a computerized culvert service life estimator software to help with the selection of pipe material for a given design service life. See Figure 7. The first through thickness penetration is considered to be the end of service life of metal culvert piping. Fill height requirements for any pipe materials are also provided to aid detailed pipe material selection [11].

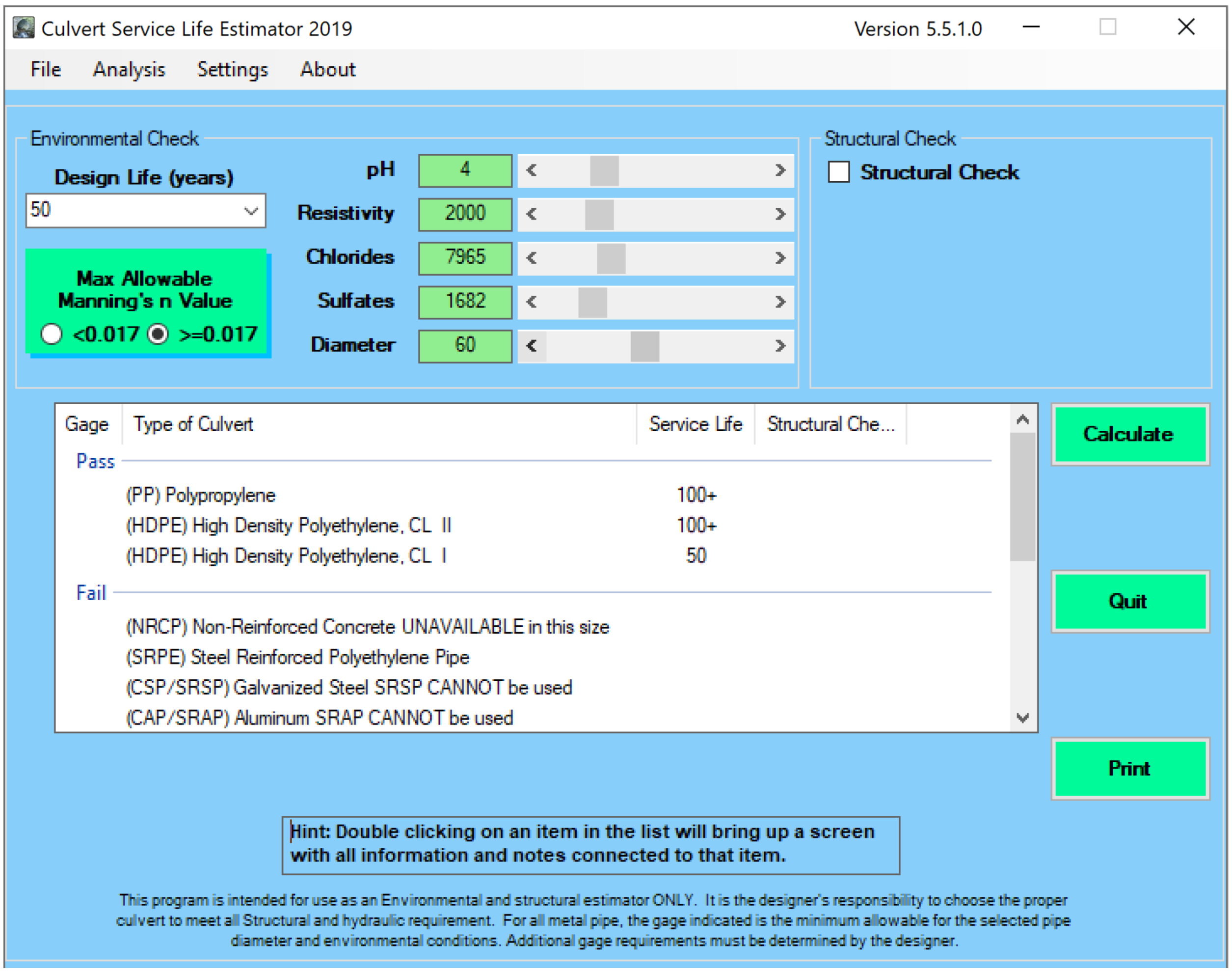


Figure 7. Florida DOT culvert service life estimator 2019 (Courtesy of Florida DOT)

1.2.6 Georgia DOT

Georgia DOT uses Table 10 to select the type of pipe materials. Pipe materials are provided with different installation types. Table 11 shows the allowable pH range (soil and water) and minimum resistivity (ohm-cm) for different type of metal pipe. In Georgia DOT manual, only metal pipe has the pH and resistivity requirements, while for concrete or plastic pipe no specific criterion is given regarding the site conditions [12].

Table 10. Selection guideline for culvert, slope, and underdrain pipe for Georgia DOT (Courtesy of Georgia DOT)

PIPE TYPE	INSTALLATION TYPE									
	STORM DRAIN							SIDE DRAIN	PERMANENT SLOPE DRAIN	PERFORATED UNDERDRAIN
	TRAVEL BEARING (Inside Roadbed)					NON-TRAVEL BEARING (Outside Roadbed)				
	GRADE ≤ 10%				Grade > 10%	Interstate	Non-Interstate			
	ADT < 1500	ADT ≥ 1500 < 5000	ADT ≥ 5000 < 15,000	ADT ≥ 15,000 & Interstates						
Concrete Pipes Section 843										
Reinforced Concrete AASHTO M 170	YES	YES	YES	YES	NO	YES	YES	YES	NO	NO
Steel Pipes Section 884	See Table 1 below for Site Condition Restrictions									
Corrugated Steel Aluminum Coated (Type 2) AASHTO M 36	YES	YES	NO	NO	NO	NO	YES	YES	YES	YES
Corrugated Steel Plain Zinc Coated AASHTO M 36	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES
Polymer Coated Steel AASHTO M 245	YES	YES	NO	NO	YES	NO	YES	YES	YES	NO
Aluminum Alloy Pipes Section 840	See Table 1 below for Site Condition Restrictions									
Corrugated Aluminum AASHTO M 196	YES	YES	NO	NO	NO	NO	YES	YES	YES	YES
Thermoplastic Pipes Section 845										
Corrugated HDPE AASHTO M 252	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES
Corrugated Smooth Lined HDPE AASHTO M 294 Type "S"	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES
Corrugated Smooth Lined Polypropylene AASHTO M 330	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES
PVC Corrugated Smooth Interior ASTM F 949	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES
PVC Profile Wall	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES

Table 11. Site condition restrictions for metal pipe in Georgia DOT (Courtesy of Georgia DOT)

Pipe type	**Allowable pH range (soil or water)**		**Allowable resistivity range**
	Minimum	**Maximum**	**Minimum**
Steel pipes (Section 844)			
Corrugated steel aluminum coated (Type 2) AASHTO M 36	4.5	5.0	5,000
	5.0	9.0	1,500
Corrugated steel plain zinc coated AASHTO M 36	6.0	10.5	8,000
Polymer coated steel AASHTO M 245	4.0	9.0	750
Aluminum alloy pipes Section 840			
Corrugated aluminum AASHTO M 196	4.5	9.0	1,500
Note: If environmental conditions fall outside the specified requirements listed above, the Office of Materials and Testing will make recommendations concerning allowable high-performance corrosion protection systems.			

1.2.7 Idaho DOT

The Idaho DOT provides Table 12 which shows the limits of pH values for various types of culverts to use when selecting culvert materials. The pH value drives the selection, and the limitation of the resistivity value seems to be 1,000 ohm-cm. The Idaho DOT suggests using non-metallic pipe, bituminous-coated aluminum pipe or bituminous-coated aluminized steel pipe if the soil resistivity is less than 1,000 ohm-cm and the pH is above 5. The estimated life of steel or aluminum culverts can be determined by using the AISI method. They also consider abrasion; however, it is stated briefly than other states where consider the abrasion level [13,14].

Table 12. Culvert materials selection table (Courtesy of Idaho DOT)

Pipe	pH value									
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Galvanized steel				×	×	×				
Bituminous-coated galvanized steel*			×	×		×	×	×		
Aluminized steel			×	×	×	×				
Bituminous-coated aluminized steel*			×	×	×	×	×	×		
Polymer-coated steel		×	×	×	×	×	×	×		
(AASHTO M245/M246)										
Aluminum			×	×	×	×				
Bituminous-coated aluminum*		×	×	×	×	×	×	×		
Reinforced & non-reinforced concrete			×	×	×	×	×	×	×	×
Plastic		×	×	×	×	×	×	×	×	×

*Use bituminous-coated ONLY when required (increasing metal thickness by one gauge increment is an acceptable substitute for bituminous coating whenever pipe life is 20 years or more).

1.2.8 Louisiana DOT

Louisiana DOT selects pipes based on the application as shown in Table 13. Table 14 shows the abbreviations for material types [15-17].

Table 13. Design service life and material selection for culverts and storm drains (Courtesy of Louisiana DOT)

Application	Design service life	Joint type	Materials
Storm drain pipes, flumes, other watertight systems	70 years	T3	RCP(A), RPVCP
Storm drain pipe (outfall) {See Section F.1}	50 years	T3	BCCSP(A), CAP(A), CSP(A), RPVCP
Cross drain pipes for: Freeways: F-1, F-2, F-3 Urban Arterial: UA-1, UA-2, UA-3 Rural Arterial: RA-1, RA-2, RA-3 Urban Collector (4 lanes): UC-1, UC-2 Rural Collector (4 lanes): RC-3 Suburban Arterial: SA-1, SA-2	70 years	T3	RCP(A), RPVCP
Cross drain pipes for: Urban Collector (2 lanes): UC-1, UC-2 Rural Collector (2 lanes): RC-1, RC-2, RC-3 Urban Local: UL-1, UL-2 Rural Local: RL-1, RL-2, RL-3 Suburban Collector: SC-1, SC-2, SC-3	50 years	T2	RCP(A), BCCSP(A), CAP(A), RPVCP, CPEPDW (See Note 1 below)
Side drain	30 years	T1	RCP(A), BCCSP(A), CAP(A), CSP(A), RPVCP, CPEPDW
Side drain (erosion) {See Section F.2}	30 years	T1	BCCSP(A), CAP(A), CSP(A), RPVCP, CPEPDW
Side drain (bridge drains) {See Section F.3}	50 years	T1	BCCSP(A), CAP(A), CSP(A), RPVCP, CPEPDW

Table 14. Material type abbreviations and definitions (Courtesy of Louisiana DOT)

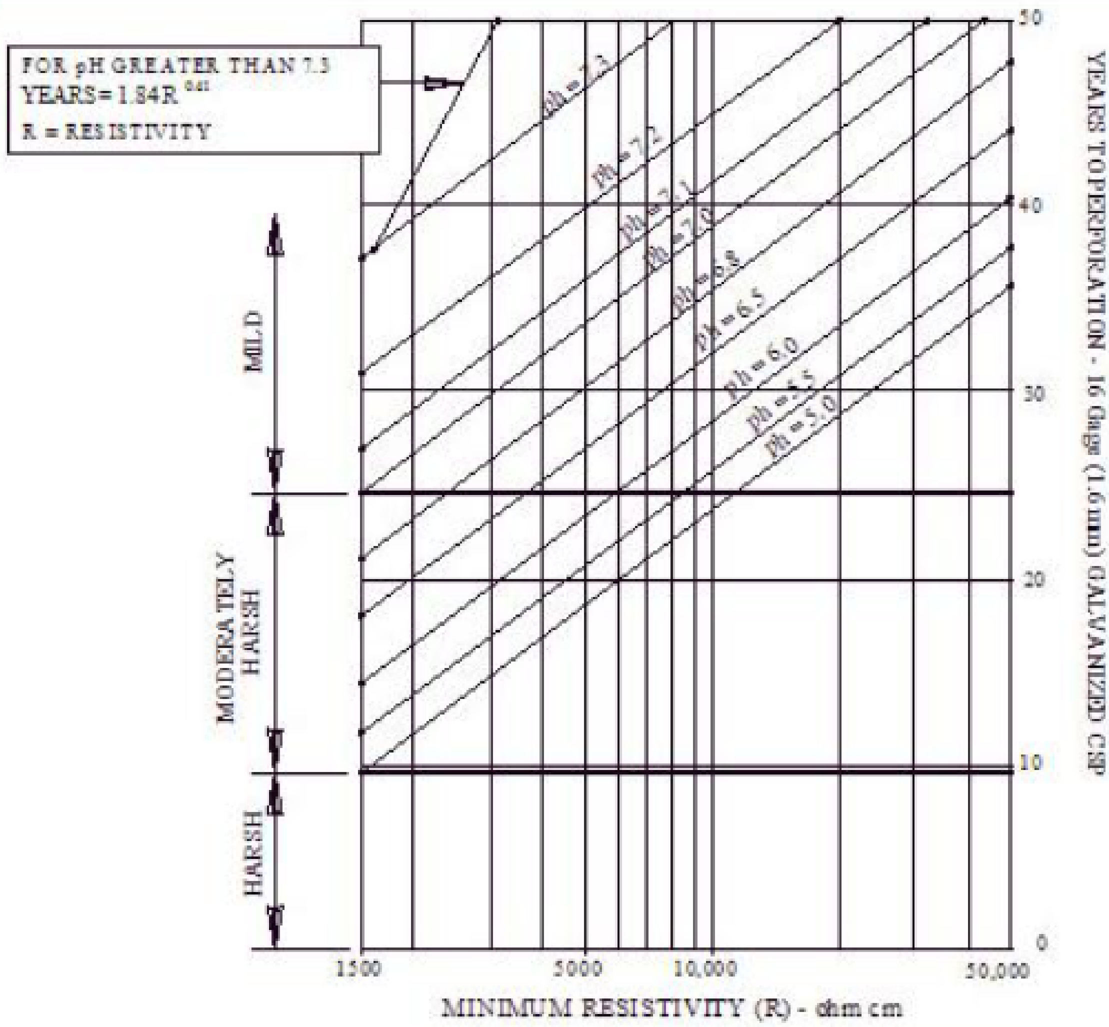
Abbreviation	Definition
RCP	Reinforced Concrete Pipe
RCPA	Reinforced Concrete Pipe Arch
CMP	Corrugated Metal Pipe
CMPA	Corrugated Metal Pipe Arch
CAP	Corrugated Aluminum Pipe
CAPA	Corrugated Aluminum Pipe Arch
CSP	Corrugated Steel Pipe
CSPA	Corrugated Steel Pipe Arch
BCCSP	Bituminous Coated Corrugated Steel Pipe
BCCSPA	Bituminous Coated Corrugated Steel Pipe Arch
PP	Plastic Pipe
RPVCP	Ribbed Polyvinyl Chloride Pipe: (ASTM F794 or ASTM F949)
CPEPDW	Corrugated Polyethylene Pipe Double Wall: (AASHTO M294 – Type S)

Figure 8 is a chart for estimating years to perforation of galvanized corrugated steel pipe based on the pH and resistivity of the surrounding soil and water. The chart is divided into two parts according to the exposure. The “Harsh” environment is not clearly defined. "Moderately Harsh" and “Mild” environments are identified based on the combination of pH and resistivity, For pH greater than 7.3, Equation (1) is used to estimate the service life of pipe, while equation (2) is used for pH less than or equal to 7.3. For increase in metal thickness, factors can be used to multiply years are also provided [15-17].

$$Years = 1.84R^{0.41} \quad (1)$$

$$Years = 17.24[\log_{10} R - \log_{10}(2160 - 2490 \log_{10} pH)] \quad (2)$$

Where: R = minimum resistivity[27-29].



FOR pH LESS THAN OR EQUAL TO 7.3
YEARS = 17.24[LOG$_{10}$ R – LOG$_{10}$ (2160-2490 LOG$_{10}$ pH)]
R = MIN. RESISTIVITY

GAGE	14	12	10	8
THICKNESS (in.)	0.079	0.109	0.138	0.168
THICKNESS (mm)	2.0	2.8	3.5	4.3
FACTOR	1.2	1.5	1.8	2.1
MULTIPLY YEARS TO PERFORATION BY FACTOR FOR INCREASE IN METAL THICKNESS				

Figure 8. Chart for estimating years to perforation of galvanized corrugated steel pipe (Courtesy of Louisiana DOT)

1.2.9 Maryland DOT

Maryland DOT requires soil and water testing for pH and resistivity at all stream crossings to ensure proper pipe material selection. However, the criteria is simply stated in the manual. For reinforced concrete pipe, protective measures are necessary if water soluble chlorides exceed 400 ppm, and if soils have a high corrosion potential, additional protective measures may be necessary. The acceptable pH range and minimum soil resistivity are from 5.5 to 8.5 and 1,500 ohm-cm, respectively [18].

1.2.10 Minnesota DOT

The Minnesota DOT divides the State into four zones which are shown in Figure 9 based on their soil characteristics; Table 15 provides the possibility of use of prefabricated corrugated galvanized steel culvert and structural plate culvert based on the condition of water for each zone. The California and AISI methods are provided as a guidance for the service life estimation of galvanized steel pipe and aluminized Type 2 pipe. For pH of environment normally greater than 7.3, the equation (3) is used, while for pH normally less than 7.3, the equation (4) is used. Adjustment factors are also given to adjust the service life of culverts for different environmental locations [19].

$$Years = 1.47R^{0.41} \tag{3}$$

$$Years = 13.79[\log_{10} R - \log_{10}(2160 - 2490 \log_{10} pH)] \tag{4}$$

Where:

R = minimum resistivity [19].

No detailed criteria are given for the selection of concrete and plastic pipe. For the selection of concrete pipe, sulfate concentrations of 1,000 ppm or less is recommended [19].

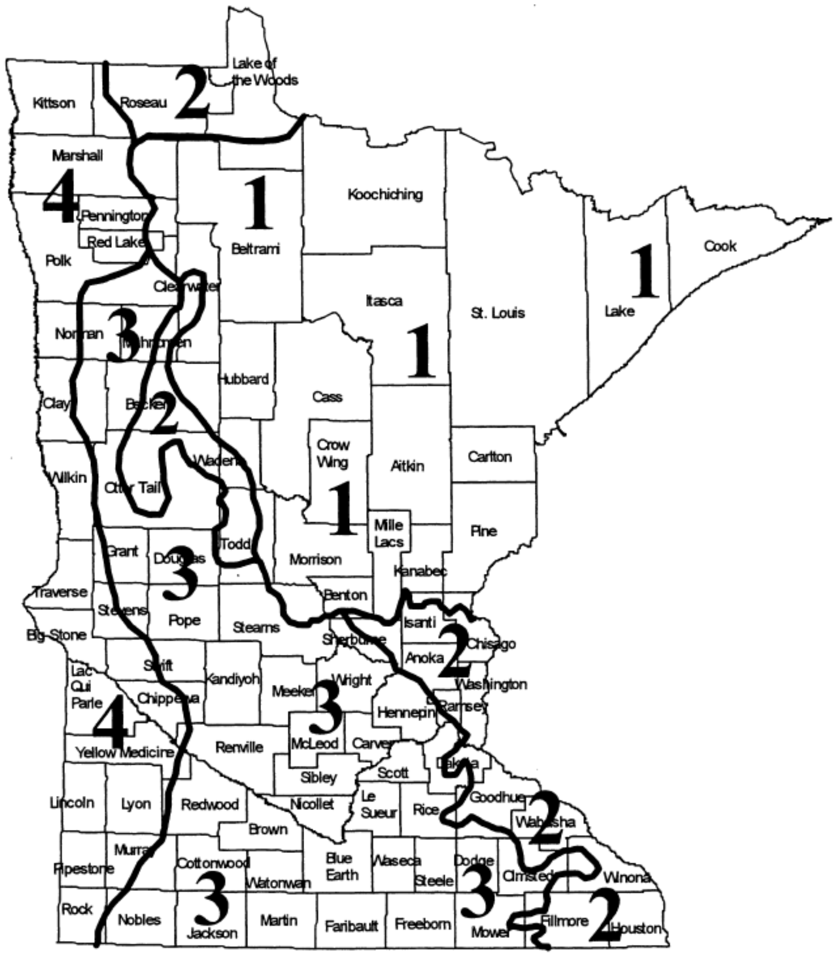


Figure 9. Four soil zones of Minnesota (Courtesy of Minnesota DOT)

Table 15. Drainage condition at culvert location (Courtesy of Minnesota DOT)

Zone[4]	Water[1]	Prefabricated corrugated galvanized steel culvert	Structural plate culvert
1	Dry	Yes	Yes
	Wet	No	Yes[3]
2	Dry	Yes	Yes
	Wet	Yes, if not acid[2]	Yes[3]
3	Dry	Yes	Yes
	Wet	No	Yes[3]
4	Dry	Yes	Yes
	Wet	Yes	Yes

Notes:

1. Dry refers to structures that drain out after rainfall or snow melt and Wet is when there is standing or flowing water practically the entire year.
2. District Soils Engineers should make pH determinations of samples from drainage area of the proposed culvert.
3. Provided the location is not in a swamp or that the soil or water does not have a pH of 6.5 or less. The District Soil Engineer should take samples from the drainage area for pH determination.
4. The Zones referred to in the Table 2.1 criteria for selecting prefabricated and structural plate culverts are shown in Figure 9.

1.2.11 Mississippi DOT

The Mississippi DOT determines the type of pipe materials based on its application and specific requirements which is shown in Table 16. For the estimation of the service life of steel culverts, the California method is used [20].

Table 16. Mississippi DOT pipe culvert material design criteria (Courtesy of Mississippi DOT)

Application	Design life (years)	Alternate pipe
Cross-drains	50	Rural Collectors and Local Roads – where Average Daily Traffic (ADT) ≤ 4,000 and Average Daily Truck (T) ≤ 400 and pipe size ≤ 48 inch (1,200 mm) diameter
		Concrete, galvanized steel, galvanized steel bituminous-coated, aluminized Type 2 steel, polymer-coated, aluminum alloy, HDPE, PVC
		All other functional classifications or other Collectors and Local Roads, urban or rural, where ADT and/or T and/or pipe size exceeds limits
		Concrete only
Side-drains	Urban: 50 Rural: 25	Concrete, galvanized steel, galvanized steel bituminous-coated, aluminized Type 2 steel, polymer-coated, aluminum alloy, HDPE, PVC
Storm-drains	50	Pipe sizes ≤ 48 inch (1,200 mm) diameter, in locations outside the travel and auxiliary lanes and beyond the alignment of the curb and gutter inlets
		Concrete, galvanized steel, galvanized steel bituminous-coated, aluminized Type 2 steel, polymer-coated, aluminum alloy, HDPE, PVC
		Pipe sizes > 48 inch (1,200 mm) diameter and/or locations under the travel and auxiliary lanes and/or locations within the alignment of the curb and gutter inlets and/or for storm-drains used as under-drains
		Concrete only
Under-drains	50	Pipe sizes ≤ 6 inch (150 mm) diameter
		Concrete, galvanized steel, galvanized steel bituminous-coated, aluminized Type 2 steel, polymer-coated, aluminum alloy, Type PSM Poly Sewer Pipe, Acrylonitrile-Butadiene-Styrene (ABS) Sewer Pipe, PVC Class PS46, corrugated Polyethylene
		Pipe sizes > 6 inch (150 mm) diameter and in locations outside the travel and auxiliary lanes
		Concrete, galvanized steel, galvanized steel bituminous-coated, aluminized Type 2 steel, polymer-coated, aluminum alloy, HDPE, PVC

1.2.12 Missouri DOT

Unlike other state DOTs, the Missouri DOT simply states pH and resistivity requirements of backfill material for corrugated metallic-coated steel culvert pipe (galvanized and aluminized), bituminous coated corrugated metal culvert pipe, corrugated aluminum alloy culvert pipe, and polymer coated corrugated metal culvert pipe. The requirements are as follows: 1) pH in the range of 5 to 9 (4 to 9 for polymer coated pipe), 2) The resistivity of backfill material that has greater than 35% passing the #200 sieve shall be >1,500 ohm-cm (> 750 ohm-cm for polymer coated pipe)[21].

1.2.13 Montana DOT

Montana DOT adopted the modified AISI chart for estimating the average service life of steel pipe. The following equations are from the modified AISI chart using pH and minimum resistivity to estimate the average service life of steel pipe with R is minimum resistivity and pH is soil pH or water pH. Where the pH of the environment is greater than or equal to 7.3, they suggest using equation (5). If the pH of the environment is less than 7.3, they suggest using the equation (6) [22].

$$Years = 2.94R^{0.41} \tag{5}$$

$$Years = 27.58[\log_{10} R - \log_{10}(2160 - 2490 \log_{10} pH)] \tag{6}$$

Where: R = minimum resistivity.

For different type of coatings, thickness, and gage, they provide a modifying multiplication factor. This factor is used to modify the years of life; see Table 17 [22].

Table 17. Modifying factor with regard to different metals and thickness (Courtesy of Montana DOT)

Thickness (in)	**0.064**	**0.079**	**0.109**	**0.138**	**0.168**
Gage	16	14	12	10	8
Galvanized	1.0	1.3	1.6	2.2	2.8
Type 2 aluminized	1.5	1.8	2.1	2.7	3.3
Aluminum	2.6	2.9	3.5	4.1	4.7

Table 18 reports the limits for the conditions in terms of resistivity and pH in which various types of materials can be used. In addition, an estimate of the potential for abrasion is required at each pipe location in order to determine the need for invert protection. Abrasion potential is estimated based on flow velocity in the pipe during a 2-year flood. The abrasion potential is low where velocity is less than 5 feet per second, and in such a condition no special considerations are required. However, where the velocity is greater than 5 feet per second and there is a coarse gravel bed material, or the existing pipe shows signs of abrasion, potential for abrasion exists. In this case, either the thickness of the pipe need to be increased by one standard thickness or invert protection consisting of invert paving or concrete lining is required [22].

Table 18. Acceptable pH and resistivity value for each pipe types (Courtesy of Montana DOT)

Soil pH	Resistivity	Steel	Type 2 aluminized steel	Aluminum	Concrete
pH > 8.5	R > 1,000	Note 1	Note 5	No	Note 3
	800 < R < 1,000	Note 1	No	No	Note 3
	500 < R < 800	No	No	No	Note 3
	R < 500	No	No	No	Note 3
6 < pH < 8.5	R > 2,200	OK	OK	OK	Note 3
	1,000 < R < 2,200	Note 1	OK	OK	Note 3
	800 < R < 1,000	Note 1	No	OK	Note 3
	500 < R < 800	No	No	No	Note 3
	R < 500	No	No	No	Note 3
5 < pH < 6	R > 1,000	Note 1	OK	OK	Note 4
	800 < R < 1,000	Note 1	No	OK	Note 4
	500 < R < 800	No	No	No	Note 4
	R < 500	No	No	No	Note 4
3 < pH < 5	All	No	No	No	Note 4
pH < 3	R > 300	No	No	No	Note 4
	R < 300	No	No	No	No

Notes:

1. Use an approved bituminous or polymeric coating.
2. Where marble pH is higher than pH by 0.2 or more, steel pipe shall have an approved bituminous or polymeric coating.
3. Where sulfate content is between 0.20% to 2.00%, use Type Ⅴ cement, a maximum water-cementitious ratio of 0.45 and a minimum design compressive strength of 4,500 psi (31 MPa). Where sulfate content is over 2.00%, use Type Ⅴ cement, a maximum water-cementitious ratio of 0.40 and a minimum design compressive strength of 5,000 psi (34 MPa).
4. Use Type Ⅴ cement and either an approved bituminous coating or "C Wall" pipe.
5. Use an approved bituminous coating. No gage reduction allowed for the difference between Type 2 aluminized steel and galvanized steel.

1.2.14 New Mexico DOT

All culverts to be used in New Mexico DOT projects are assessed based on the criteria given in Table 19. Soil resistivity, pH, amount of salts in water need to be defined in order to make a proper determination of corrosion resistance number. Corrosion resistance number ranges from

CR1 up to CR7. A rating of CR1 is for the most benign of conditions in soil and water where corrosion is not likely. CR7 rating represents very harsh environments significantly affecting a culvert's serviceable life. New Mexico DOT recommends using the data of electrical conductivity, pH, and/or other chemical properties data provided by National Resources Conservative Service (NRCS). For the service life estimation of galvanized steel pipe with 16 Gage, New Mexico DOT adopted the National Corrugated Steel Pipe Association (NCSPA) method where for pH values of 7.3 or lower, resistivity and pH value govern the service life and Equation (7) is applies. For pH greater than 7.3, resistivity governs the service life and Equation (8) is used. Estimated material service life is defined as 25% removal of the thickness of the culvert wall at the invert, where most damage usually occurs [23].

$$Years = 35.85[\log_{10} R - \log_{10}(2160 - 2490 \log_{10} pH)] \tag{7}$$

$$Years = 3.82R^{0.41} \tag{8}$$

Where:

R = minimum resistivity [23].

Figure 10 shows the chart for estimating service life of 16 Gage galvanized steel pipe. Table 20 shows coefficients that are used as multiplier for the selected gage thickness of culvert. For an aluminized steel culvert, a pH equal to or greater than 5.5 (up to pH 9) and a resistivity of 1500 ohms-cm or greater gives a service life of 50 years or more. Otherwise, service life is less than 50 years which is deemed unacceptable. Concrete culverts are resistant to most soil conditions that pose problems with metallic culverts. They are, however, sensitive to dissolved salts containing chlorine (Cl), or sulphates (SO_4) where it affects the pH. A pH values of less than or equal to 5 will require further testing such as a rapid chloride permeability test to check for readings greater than 1200 coulombs (ASTM 1202) for a Type V cement. Otherwise, additives may need to be added to the concrete mixture. Plastic pipe includes High Density Polyethylene (HDPE) culverts and Polyvinyl Chloride (PVC) culverts can handle all of soil and water conditions given in Table 19 [23].

Table 19. Corrosion resistance table for 50-year service life (Courtesy of New Mexico DOT)

Date: March 4, 2018	CORROSION RESISTANCE NUMBER						
JSL-DT	CR1	CR2	CR3	CR4	CR5	CR6	CR7
METALLIC	ACCEPTABILITY / RECOMMENDATIONS						
Galvanized Steel	yes	no	no	no	no	no	no
Aluminized Steel (Type II)	yes	yes	yes	no	no	no	no
Aluminum Alloy	yes	yes	yes	yes	yes	no	no
Polymeric Precoated Galvanized Steel (250 µm both sides)	yes	yes	yes	yes	yes	yes	no
Aramid Fiber Bonded Galvanized Steel	yes	yes	yes	yes	yes	yes	yes
CONCRETE RCP & CIPCP*							if soil has a pH<5.0, provide concrete with rapid chloride permeability of ≤1200 coulombs as tested in accordance with with ASTM 1202. or if pH>12.0, use Epoxy coating (280 mils, total)
Cement: (Ref. Spec. Section 510)							
Type II	yes	yes	yes	yes	yes	yes	no
Type V	yes	yes	yes	yes	yes	yes	yes
THERMOPLASTIC							
HDPE & PVC	yes	yes	yes	yes	yes	yes	yes
STRUCTURAL PLATE (STEEL& ALUMINUM)	Use the Service Life Expectancy methods given in 801.1 to determine thickness or gage required for a fifty year service life. See Electrochemical Criteria Table (571.5.5:1) of 2014 Edition of Standard Specifications for backfill and bedding requirements.						
	CONCRETE and METAL ATTACK						
	Negligible			Positive		Considerable	Severe
	CONDUCTIVITY mS/cm (MILLISIEMENS PER CENTIMETER) for BOTH SOIL & WATER**						
	≤0.5	≤ 0.67		≤ 1.0	≤ 1.0	≤ 3.64	GREATER THAN 3.64
	MINIMUM RESISTIVITY (OHM-CM) for BOTH SOIL & WATER						
	≥2000	≥1500		≥1000	≥1000	≥275	<275
	pH LEVELS						
	6.0 - 9.0	5.0 - 9.0			4.0 - 12.0		<4.0 OR >12.0
	SOIL CHARACTERISTICS (from Alkali samples)						
Soluble Salts (Cl) & SO_4 (% by weight)	≤0.0500		≤0.0750		≤0.1250	≤0.2000	>0.2000
	WATER CHARACTERISTICS (from Water samples)						
Soluble Salts (Cl) & SO_4 (% by weight)	≤0.0250		≤0.0375		≤0.0625	≤0.1000	>0.1000

** NOTE ** METALLIC Pipe: CR# based primarily on pH and minimum resistivity.

NON-METALLIC Pipe: CR# based primarily on pH and % salts.(1%=10,000 ppm)

* RCP -Reinforced Concrete Pipe: CIPCP - Cast in Place Concrete Pipe

** Values given for milliseimens per centimter (mS/ cm) can be substituted with deciseimens per meter (dS/ m)

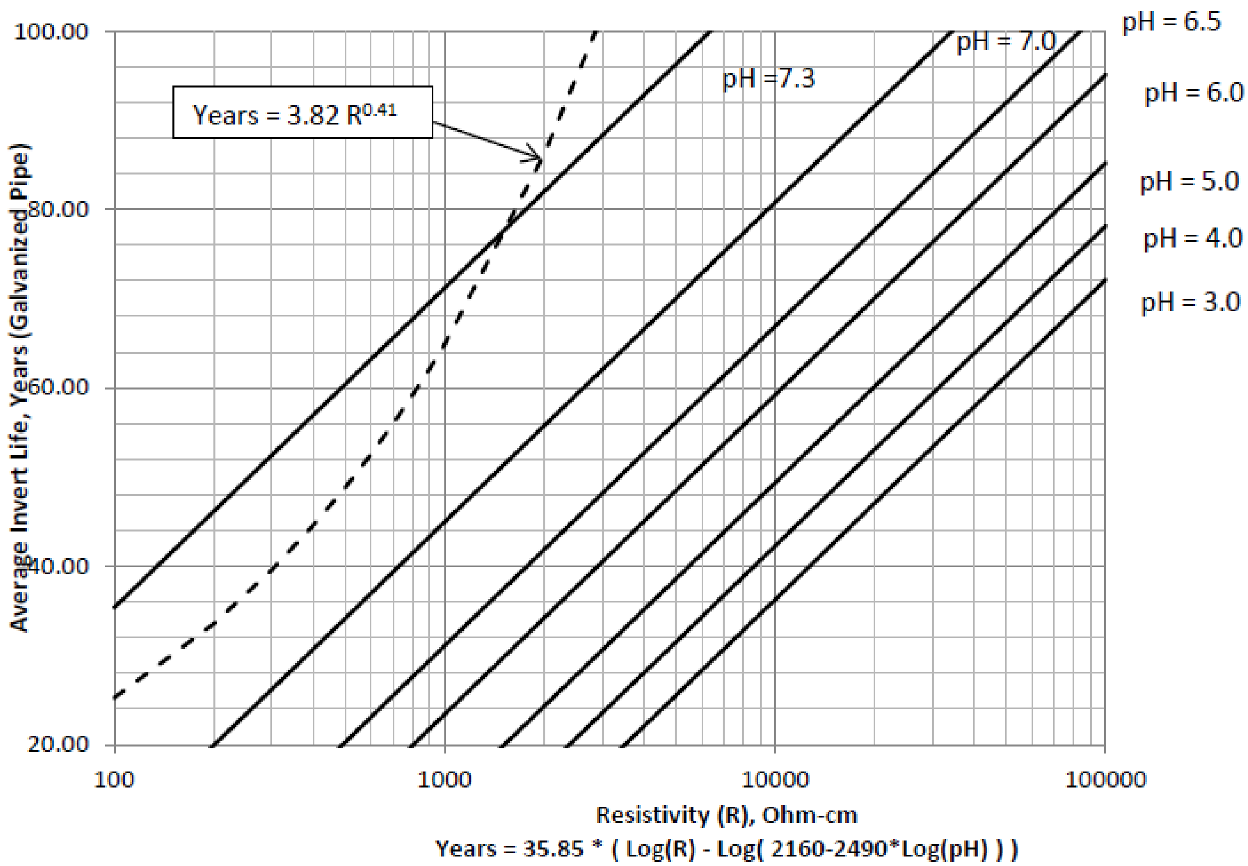


Figure 10. Average invert life (years) for 16 Gage galvanized steel pipe (Courtesy of New Mexico DOT)

Table 20. Modifying factor with regard to different metals and thickness (Courtesy of New Mexico DOT)

Gage	18	16	14	12	10	8
Thickness (mm)	1.3	1.6	2	2.8	3.5	4.3
Thickness (inches)	0.052	0.064	0.079	0.109	0.138	0.168
Factor (F)	0.7	1	1.3	1.8	2.3	2.8

New Mexico DOT also provide abrasion levels from level 1 to level 4 which are shown in Table 21. Table 22 shows applicable adjustments for abrasion made to various culvert types under different abrasion conditions.

Table 21. Abrasion levels for invert protection coatings (Courtesy of New Mexico DOT)

Level	Degree of abrasiveness	Description
1	Non-abrasive	No bedload. Velocities can be greater than 15 ft/s.
2	Low abrasion	Minor bedloads of sand and gravel with velocities at 5 ft/s or less. Level 2 is applicable for storm drain applications.
3	Moderate abrasion	Bedloads of sands and gravels with velocities between 5 ft/s and 15 ft/s.
4	Severe abrasion	Heavy bedloads of gravel and rock with velocities exceeding 15 ft/s.

Table 22. Recommended adjustments for abrasion (Courtesy of New Mexico DOT)

Material	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 2	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*	Do not use
Polymer precoated 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	Do not use

* A field applied concrete paved invert per ASTM A 849 may be substituted for one (1) gage thickness

1.2.15 North Dakota DOT

The pipe material selection procedure of the North Dakota DOT consists of three parts based on the type of drainage structures: Mainline Drainage, Approach Drainage and Storm Drain Trunk Lines & Lateral pipes. The minimum desired service life for Mainline Drainage and Storm Drain Trunk Lines & Lateral pipes is 75 years, while Approach Drainage pipes have a minimum desired service life of 40 years. For the selection of Mainline Drainage and Approach Drainage pipe, abrasion requirements are considered first, and then the corrosion requirements are considered, while abrasion requirements are not considered for the selection of Storm Drain Trunk Lines & Lateral pipes. Table 23 shows the criteria of abrasion level and its description. Table 24 and Table 25 represent applicable pipe materials for different abrasion level for Mainline Drainage and Approach Drainage pipe, respectively [24].

Table 23. Criteria of abrasion level (Courtesy of North Dakota DOT)

Abrasion level	**Description**
1	No bedload, regardless of velocity
2	Bedload of sand, gravel, and debris with velocities of 0 to 5 ft/s
3	Bedload of sand, gravel, and debris with velocities of 5 to 10 ft/s
4	Bedload of sand, gravel, and debris with velocities of 10 to 15 ft/s
5	Bedload of sand, gravel, and debris with velocities greater than 15 ft/s

Table 24. Mainline Drainage abrasion table (Courtesy of North Dakota DOT)

Pipe material (830.01)	**Abrasion level**				
	1	**2**	**3**	**4**	**5**
Concrete pipe (Section 830.01)	Y	Y	Y	Y	Y
Metal pipe (Section 830.02)					
Zinc coated corrugated steel	Y	Y			
Aluminum coated corrugated steel (Type 2)	Y	Y	Y		
Polymeric coated steel (over zinc or aluminum coated steel)	Y	Y	Y	Y	
Plastic pipe (Section 830.03)					
Polypropylene pipe (Type S)	Y	Y	Y	Y	Y

Table 25. Approach Drainage abrasion table (Courtesy of North Dakota DOT)

Pipe material (830.01)	**Abrasion level**				
	1	**2**	**3**	**4**	**5**
Concrete pipe (Section 830.01)	Y	Y	Y	Y	Y
Metal pipe (Section 830.02)					
Zinc coated corrugated steel	Y	Y			

Aluminum coated corrugated steel (Type 2)	Y	Y	Y		
Polymeric coated steel (over zinc or aluminum coated steel)	Y	Y	Y	Y	
Plastic pipe (Section 830.03)					
High-density polyethylene (Type S)	Y	Y	Y	Y	Y
Polypropylene pipe (Type S)	Y	Y	Y	Y	Y

Figure 11 shows the corrosion zone map of North Dakota which consists of 4 zones based on soil resistivity extracted from United States Environmental Protection Agency's (EPA) Environmental Monitoring Assessment Program. After the consideration of the abrasion level, specific pipe material and its gauge is determined based on the corrosion zone, which is shown in Tables 26 to 28 for different applications. The gauge of Table 26 and Table 28 is calculated using the California method, while the gauge of Table 27 is calculated using the AISI method [24].

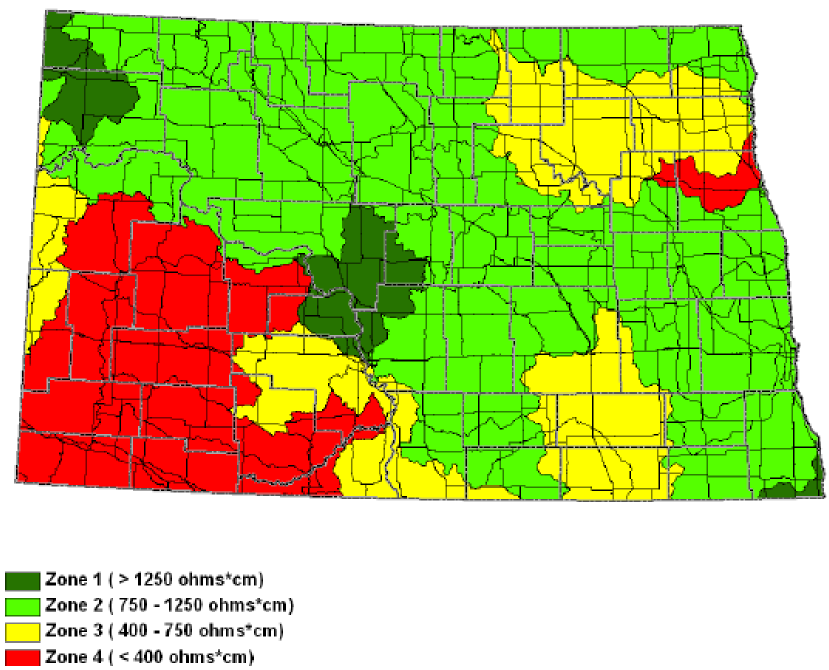


Figure 11. Corrosion zone map of the North Dakota (Courtesy of North Dakota DOT)

Table 26. Mainline Drainage corrosion table for the service life of 75 years
(Courtesy of North Dakota DOT)

Pipe material		Corrosion Zone			
		Zone 1	Zone 2	Zone 3	Zone 4
Concrete pipe (Section 830.01)		Y	Y	Y	Y
Metal pipe (Section 830.02)	Gauge				
Zinc coated corrugated steel	16				
	14				
	12				
	10	Y			
	8	Y	Y		
Aluminum coated corrugated steel (Type 2)	16				
	14				
	12	Y			
	10	Y	Y		
	8	Y	Y	Y	
Polymeric coated steel (over zinc or aluminum coated steel)	16	Y	Y	Y	Y
	14	Y	Y	Y	Y
	12	Y	Y	Y	Y
	10	Y	Y	Y	Y
	8	Y	Y	Y	Y
Plastic pipe (Section 830.03)					
Polypropylene pipe (Type S)		Y	Y	Y	Y

Table 27. Approach Drainage corrosion table for the service life of 40 years (Courtesy of North Dakota DOT)

Pipe material		Corrosion Zone			
		Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Concrete pipe (Section 830.01)		Y	Y	Y	Y
Metal pipe (Section 830.02)	Gauge				
Zinc coated corrugated steel	16	Y	Y	Y	Y
	14	Y	Y	Y	Y
	12	Y	Y	Y	Y
	10	Y	Y	Y	Y
	8	Y	Y	Y	Y
Aluminum coated corrugated steel (Type 2)	16	Y	Y	Y	Y
	14	Y	Y	Y	Y
	12	Y	Y	Y	Y
	10	Y	Y	Y	Y
	8	Y	Y	Y	Y
Polymeric coated steel (over zinc or aluminum coated steel)	16	Y	Y	Y	Y
	14	Y	Y	Y	Y
	12	Y	Y	Y	Y
	10	Y	Y	Y	Y
	8	Y	Y	Y	Y
Plastic pipe (Section 830.03)					
High-density polyethylene (Type S)		Y	Y	Y	Y
Polypropylene pipe (Type S)		Y	Y	Y	Y

Table 28. Storm Drain Trunk Line & Lateral Drainage corrosion table for the service life of 75 years (Courtesy of North Dakota DOT)

Pipe material		**Corrosion Zone**			
		Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Concrete pipe (Section 830.01)		Y	Y	Y	Y
Metal pipe (Section 830.02)	Gauge				
Zinc coated corrugated steel	16				
	14				
	12				
	10	Y			
	8	Y	Y		
Aluminum coated corrugated steel (Type 2)	16				
	14				
	12	Y			
	10	Y	Y		
	8	Y	Y	Y	
Polymeric coated steel (over zinc or aluminum coated steel)	16	Y	Y	Y	Y
	14	Y	Y	Y	Y
	12	Y	Y	Y	Y
	10	Y	Y	Y	Y
	8	Y	Y	Y	Y
Plastic pipe (Section 830.03)					
High-density polyethylene (Type S)		Y	Y	Y	Y
Polypropylene pipe (Type S)		Y	Y	Y	Y

1.2.16 Oregon DOT

Oregon DOT requires testing of the pH and resistivity of water and soil and suggests using Table 29 to select pipe materials. Table 29 only shows the effect of mildly to moderately corrosive environments on pipe service life. Soil resistivity or pH value readings outside of the indicated limits will require special design considerations, and the Oregon DOT suggests consulting with experts for appropriate material selection. For galvanized steel, the service life will be modified to account for increased soil resistivity as seen in Table 30. The service life in the Table 29 are for 0.060-inch-thick aluminum pipe or 0.064-inch-thick steel pipe. Table 31 is used for different pipe materials by multiplying the service life with the appropriate factor for different thickness. Abrasion levels and countermeasures are defined in Table 32. Abrasion levels are consisted of four levels, which are low, medium, high and severe. General site characteristics and recommended invert protection are provided to assure that the service life of the pipe is as long or longer than its design life [25].

Table 29. Pipe material service lives (Courtesy of Oregon DOT)

Materials	Location East or West of Cascades	Water and soil pH	Soil resistivity (ohm-cm)	Service life (Years)
Galvanized steel CSP, CSPA, PCSP, SSP/OHSR	East	4.5 - 6.0	1,500 – 2,000	30
		6.0 - 7.0		35
		7.0 - 10.0		40
	West	4.5 - 6.0		15
		6.0 - 7.0		20
		7.0 - 10.0		25
Aluminum CAP, CAPA, PCAP, SAP/OHSR	All locations	4.5 - 10.0	More than 1,500	75
Aluminized steel CSP-Alzd., CSPA-Alzd., PCSP-Alzd., SSP/OHSR-Alzd	All locations	5.0 - 9.0	More than 1,500	75
Concrete CIPCP, NRCP, PCP, RCP, RCBC	All locations	4.5 - 10.0	More than 1,500	75+
Plastic CPP, CPEP, PPVCP, SWPEP-PR, SWPVC, SWPVC-PR, SRPEP	All locations	4.5 - 10.0	More than 1,500	75

Table 30. Modifying factor with regard to resistivity (Courtesy of Oregon DOT)

Resistivity	Factor
$2,000 \le R < 3,000$	1.2
$3,000 \le R < 4,000$	1.4
$4,000 \le R < 5,000$	1.6
$5,000 \le R < 7,000$	1.8
$R > 7,000$	2.0

Table 31. Modifying factor with regard to different metals and thickness (Courtesy of Oregon DOT)

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

Table 32. Pipe abrasion levels (Courtesy of Oregon DOT)

Abrasion level	General site characteristics	Recommended invert protection
Low	Little or no bed load, Slopes less than 1% abrasive, Velocities less than 3 ft/s	Generally, the protective treatments required for corrosion will provide adequate abrasion protection under these conditions.
Medium	Minor bed loads of sands, silts, and clays, Slopes 1% to 2%, Velocities less than 6 ft/s	Generally, the protective treatments required for corrosion will provide adequate abrasion protection under these conditions. An additional increment of wall thickness should be specified for metal pipes if existing metal pipes in the vicinity have abrasion damage.
High	Moderate bed loads of sands and gravels, with stone size up to 3 inches, Slopes 2% to 4%, Velocities from 6 ft/s to 15 ft/s	Unprotected pipes or pipes with coatings intended to resist corrosion, only, will often have reduced life expectancies, sometimes lasting only a few years. Polymer coatings provide adequate abrasion protection. Metal pipe thickness should be increased at least two increments, or the pipe invert should be paved with wire reinforced concrete. Reinforced concrete box culverts with an increased thickness of concrete between the surface of the bottom slab and the reinforcing bar are preferred over standard box culverts or reinforced concrete pipes.
Severe	Heavy bed loads of sands, gravels, and rocks, with stone sizes greater than 3 inches, Slopes steeper than 4%, Velocities greater than 15 ft/s	Unprotected pipes or pipes with coatings intended to resist corrosion, only, will often have extremely short life expectancies, sometimes lasting only a few months to a few years. Sacrificial metal plates, linings, or rails may need to be installed in the pipe or box invert to increase the service life. It is recommended the ODOT Geo-Environmental Section's Engineering and Assets Management Unit be contacted for additional guidance if this type of invert may be needed. A bridge or open-bottom culvert may be a more suitable choice.

	Thermoplastic pipe often has better abrasion resistance than metal or concrete. However, it seldom can be adequately reinforced to provide additional invert protection and it is not recommended for this abrasion level.

1.2.17 Pennsylvania DOT

Pennsylvania DOT's pipe selection guide is based on environmental factors, as presented in Table 33. For design purposes, the pH of the water at the construction site need to be determined in the field using ASTM D-1293. They suggest testing it seasonally, if possible, and the worst set of conditions are used in selecting the type of pipe. For the use of AASHTO T-288 standard, a 6 to 8 lbs (2.7 to 3.6 kg) sample of the site soil is used to determine the soil pH and resistivity for further consideration of the proper pipe type. They also recommend considering the future land use. For example, a pipe placed in an area not being mined presently, but which ultimately may be mined, should be designed to handle the acid mine drainage [26].

Table 33. Pipe selection criteria for corrosion protection based on pH and resistivity values (Courtesy of Pennsylvania DOT)

Type of pipe	**Coating**	**Water and/or soil pH**	**Soil resistivity (ohm-m)**	**Abrasion coating required**
Aluminum alloy	Uncoated	4.0 to 8.5	> 15	Paved invert
Concrete	Uncoated	4.0 or greater	All	Epoxy lined
Concrete	Vitrified clay	< 4.0	All	None required
Thermo-plastic		All	All	None required
Steel	Metallic coated	5.5 to 8.5	> 60	Paved invert
Steel	10 mil polymer-Type C	5.5 to 8.5	> 60	None required

1.2.18 Texas DOT

The Texas DOT selects pipe type for a culvert or storm drain system based on strength, hydraulic conductivity, constructability, and durability. For evaluating strength and hydraulic conductivity, they recommend using published methods and values which are not specified in their manual. Constructability is evaluated based on experience on previous projects. For the evaluation of pipe durability, it is recommended to test soil using methods outlined in the NCHRP 474: Service Life of Culverts manual [27] summarizes the methods for pipe materials selection, protection, repair rehabilitation and replacement, and inspection. Texas DOT follows the guidance of American Concrete Pipe Association for reinforced concrete pipes, of National Corrugated Steel Pipe Association for corrugated metal pipe, of Federal Highway Association for aluminized Type 2 corrugated metal pipe [28].

1.2.19 Utah DOT

The Utah DOT considers pH, minimum resistivity and total soluble salts (expressed as percentage) in their guidelines. Specifically, sulfate content is taken into account when selecting concrete pipes. Whenever the sulfate content exceeds 0.5 %, the cement should be specified as Type Ⅴ. Alternate pipes are classified into 5 categories which is shown in Table 34. For selecting proper types with expected service life, Figure 12 and Figure 13 are utilized for concrete and other types of pipes respectively. The line beside the pipe class indicates expected life. After defining pH, minimum resistivity and soluble salts of specific site, the line can be used to expect the service life of each class of pipes. Testing procedures are in the Utah DOT pipe selection guide [29].

Table 34. Categories in pipe classes (Courtesy of Utah DOT)

Pipe class	Material
A	Plain corrugated steel
B	Bituminous coated corrugated steel pipe, Aluminum alloy pipe, Pitch-resin adhesive coated corrugated steel pipe (coated on exterior side only).
C	Asbestos bonded bituminous coated corrugated steel pipe, Pitch-resin adhesive coated corrugated steel pipe (coated on both sides)
D	Plain corrugated steel structural plate pipe
E	Bituminous coated corrugated steel structural plate pipe, Aluminum alloy structural plate pipe
F	Portland cement concrete pipe Type-Ⅱ cement Portland cement concrete pipe Type-Ⅴ cement

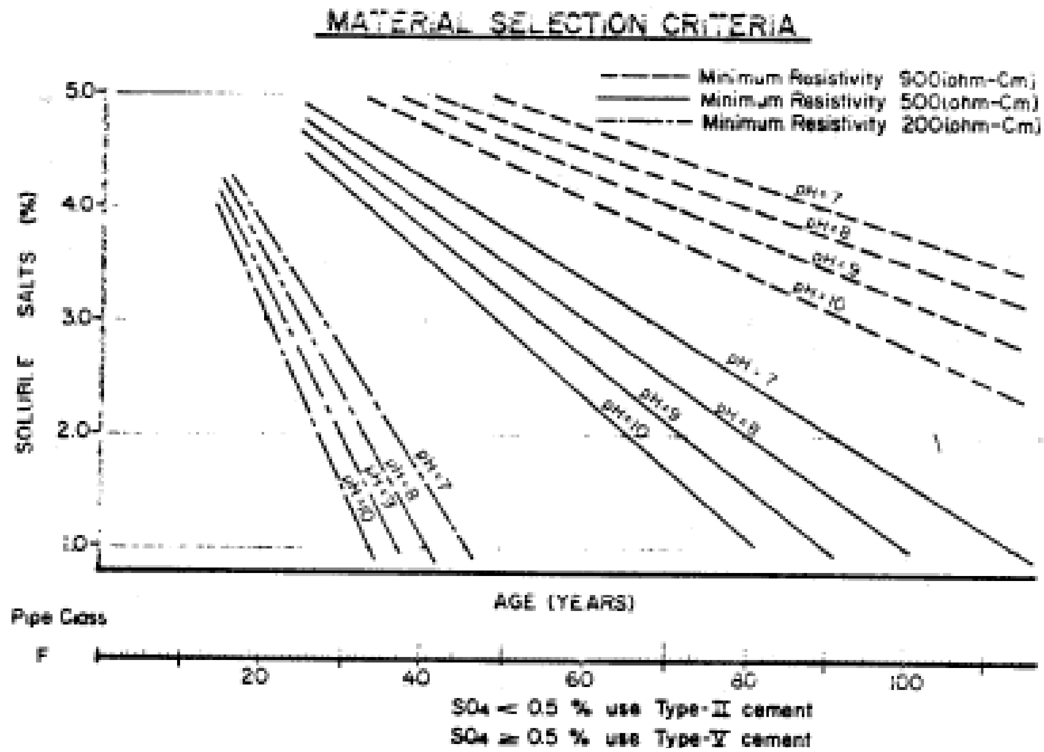


Figure 12. Material selection chart for concrete pipe (Courtesy of Utah DOT)

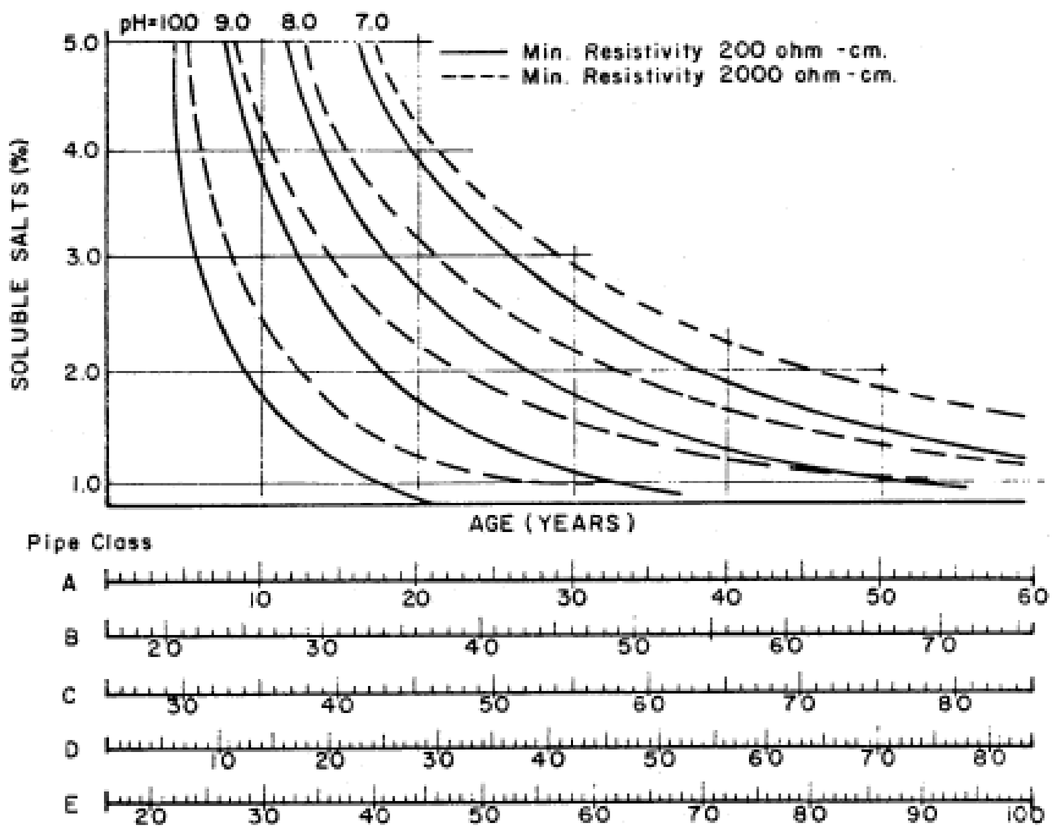


Figure 13. Material selection chart for pipe classes A through E (Courtesy of Utah DOT)

1.2.20 Virginia DOT

Table 35 shows allowable types of pipe culvert based on functional classification of roads system under which a pipe is to be installed where in higher functional class a design life of 75 years is applied and in lower functional class, design life of 50 years is applied. Allowable pH range (AASHTO T 289 for soil, ASTM 1293 for water), resistivity range (AASHTO T 288), and maximum velocity (ft/s) are also used to make a proper decision which are shown in Table 36. Required metal gauge thickness after considering the possibility of abrasion is also provided by the Virginia DOT in Road & Bridge Standards [30,31].

Table 35. Allowable type of pipe culvert (Courtesy of Virginia DOT)

FUNCTIONAL CLASSIFICATION OF ROADS SYSTEM UNDER WHICH PIPE IS TO BE INSTALLED					ENTRANCE PIPE
HIGHER FUNCTIONAL CLASS - HFC 75 - YEAR DESIGN LIFE RURAL PRINCIPAL ARTERIAL, URBAN PRINCIPAL ARTERIAL, RURAL MINOR ARTERIAL, URBAN MINOR ARTERIAL, RURAL COLLECTOR ROADS, URBAN COLLECTOR STREETS, SUBDIVISION STREETS WITH AN ADT GREATER THAN 4000			LOWER FUNCTIONAL CLASS - LFC 50 - YEAR DESIGN LIFE RURAL LOCAL ROADS, URBAN LOCAL STREETS, SUBDIVISION STREETS WITH AN ADT LESS THAN OR EQUAL TO 4000		
ALLOWABLE PIPE CULVERTS NOTES 1 & 2	STATEWIDE EXCEPT LOCATIONS SHOWN IN TABLE B	LOCATION SHOWN IN TABLE B	STATEWIDE EXCEPT LOCATIONS SHOWN IN TABLE B	LOCATION SHOWN IN TABLE B	STATEWIDE
CONCRETE	✓	✓	✓	✓	✓
ALUMINUM COATED TYPE 2 CORRUGATED STEEL NOTE 3	✓		✓		✓
POLYMER COATED (10/10) CORRUGATED STEEL NOTE 3	✓	✓	✓	✓	✓
UNCOATED GALVANIZED CORRUGATED STEEL NOTES 3 & 4					✓
GALVANIZED STEEL STRUCTURAL PLATE NOTE 3			✓		✓
GALVANIZED STEEL STRUCTURAL PLATE WITH THICKENED INVERT NOTE 3, 5	✓		✓	✓	✓
CORRUGATED ALUMINUM ALLOY NOTE 3	✓	✓	✓	✓	✓
CORRUGATED ALUMINUM ALLOY STRUCTUAL PLATE NOTE 3	✓	✓	✓	✓	✓
POLYVINYLCHLORIDE (PVC) PROFILE WALL PIPE (SMOOTH INTERIOR)	✓	✓	✓	✓	✓
POLYETHYLENE (PE) CORRUGATED TYPE C	✓	✓	✓	✓	
POLYETHYLENE (PE) CORRUGATED TYPE S	✓	✓	✓	✓	✓
POLYPROPYLENE (PP) TYPE D OR S	✓	✓	✓	✓	✓

Table 36. Allowable pH range, resistivity range, and maximum velocity values (Courtesy of Virginia DOT)

Pipe type	Allowable pH range		Allowable resistivity range (ohms-cm)		Allowable velocity (FPS)
	Min.	**Max.**	**Min.**	**Max.**	**Maximum**
Uncoated galvanized corrugated steel	6.0	10.0	2,000	10,000	5
Galvanized steel structural plate	6.0	9.0	2,000	10,000	5
Galvanized steel structural plate with thickened invert	6.0	9.0	2,000	10,000	15
Aluminum coated Type 2 corrugated steel	5.0	9.0	1,500	-	5
Aluminum coated Type 2 spiral rib	5.0	9.0	1,500	-	5
Corrugated aluminum alloy	4.0	9.0	1,500	-	5
Corrugated aluminum alloy structural plate	4.0	9.0	1,500	-	5
Aluminum spiral rib	4.0	9.0	1,500	-	5
Polymer coated (10/10) corrugated steel	4.0	9.0	750	-	10
Polymer coated corrugated steel spiral rib	4.0	9.0	750	-	10
Polymer coated corrugated steel double wall	4.0	9.0	750	-	10

1.2.21 Washington DOT

To simplify the selection procedure of pipe material, Washington State has been divided into three corrosion zones based on the general corrosive characteristics of that particular zone. Corrosion Zones and their descriptions are defined in Table 37. Figure 14 to 16 represent material selection procedures for each Corrosion Zone in Washington State. When the pH is less than 5 or greater than 8.5, and the resistivity is less than 1,000 ohm-cm, the site will be considered as Corrosion Zone Ⅲ. For each Corrosion Zone, acceptable pipe materials are recommend. The thickness of corrugated steel pipes can be increased to compensate for loss of metal due to corrosion or abrasion with reference to the California method. Moreover, four abrasion levels have been developed to quantify the abrasion potential of a site and to apply proper invert protection method. See Table 38 [32].

Table 37. Corrosion Zone in Washington State and the degree of corrosivity (Courtesy of Washington DOT)

Corrosion Zone	Ⅰ	Ⅱ	Ⅲ
Location	Most of eastern Washington State	Most of western Washington	Where not Corrosion Zone Ⅰ and Ⅱ
Degree of corrosivity	Least corrosive area	Moderate corrosive area	Severely corrosive areas

Table 38. Pipe abrasion levels (Courtesy of Washington DOT)

Abrasion level	General site characteristics	Recommended invert protection
Non-abrasive	Little or no bed load, Slope less than 1%, Velocities less than 3 ft/s	Generally, most pipes may be used under these circumstances, if a protective treatment is deemed necessary for metal pipes, any of the protective treatments specified in Section 8-5.3.1 would be adequate.
Low abrasive	Minor bed loads of sands, silts, and clays, Slopes 1% to 2%, Velocities less than 6 ft/s	For metal pipes, an additional gauge thickness may be specified if existing pipes in the vicinity show susceptibility to abrasion, or any of the protective treatments specified in Section 8-5.3.1 would be adequate.
Moderate abrasive	Moderate bed loads of sands and gravels, with stone sizes up to about 3 inches, Slopes 2% to 4%, Velocities from 6 to 15 ft/s	Metal pipes shall be specified with asphalt paved inverts and the pipe thickness shall be increased one or two standard gauges. The PEO may want to consider a concrete-lined alternative. Concrete pipe and box culverts shall be specified with an increased wall thickness or an increased concrete compressive strength. Thermoplastic pipe may be used without additional treatments.
Severe abrasive	Heavy bed loads of sands, gravel, and rocks, with stones sizes up to 12 inches or larger, Slopes steeper than 4%, Velocities greater than 15 ft/s	Asphalt protective treatments will have short life expectancies, sometimes lasting only a few months to a few years. Metal pipe thickness shall be increased at least two standard gauges, or the pipe invert shall be lined with concrete. Box culverts shall be specified with an increased wall thickness or an increased concrete compressive strength.

	Sacrificial metal pipe exhibits better abrasion characteristics than metal or concrete. However, it generally cannot be reinforced to provide additional invert protection and is not recommended in this condition.

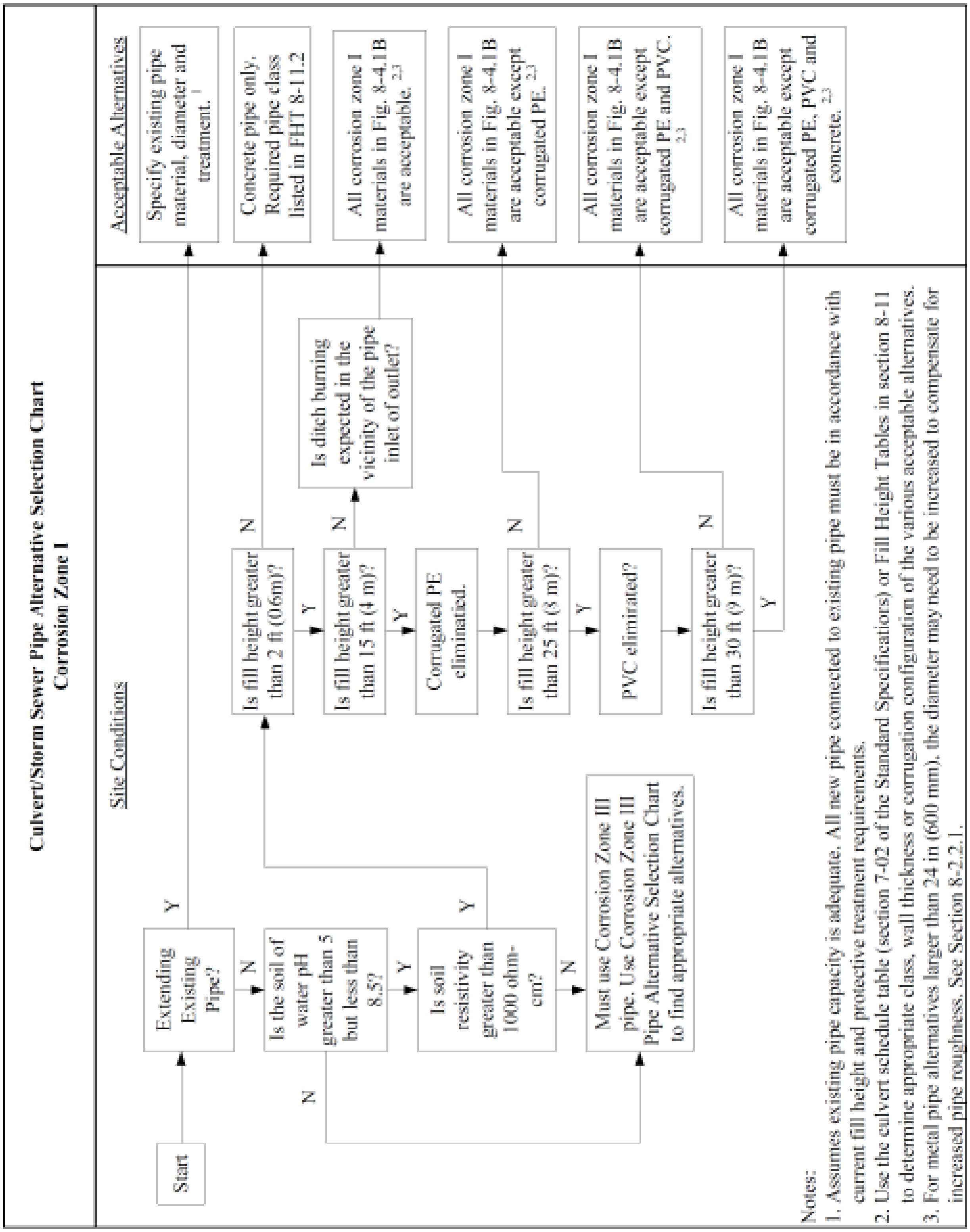


Figure 14. Material selection procedure for Corrosion Zone 1 (Courtesy of Washington DOT)

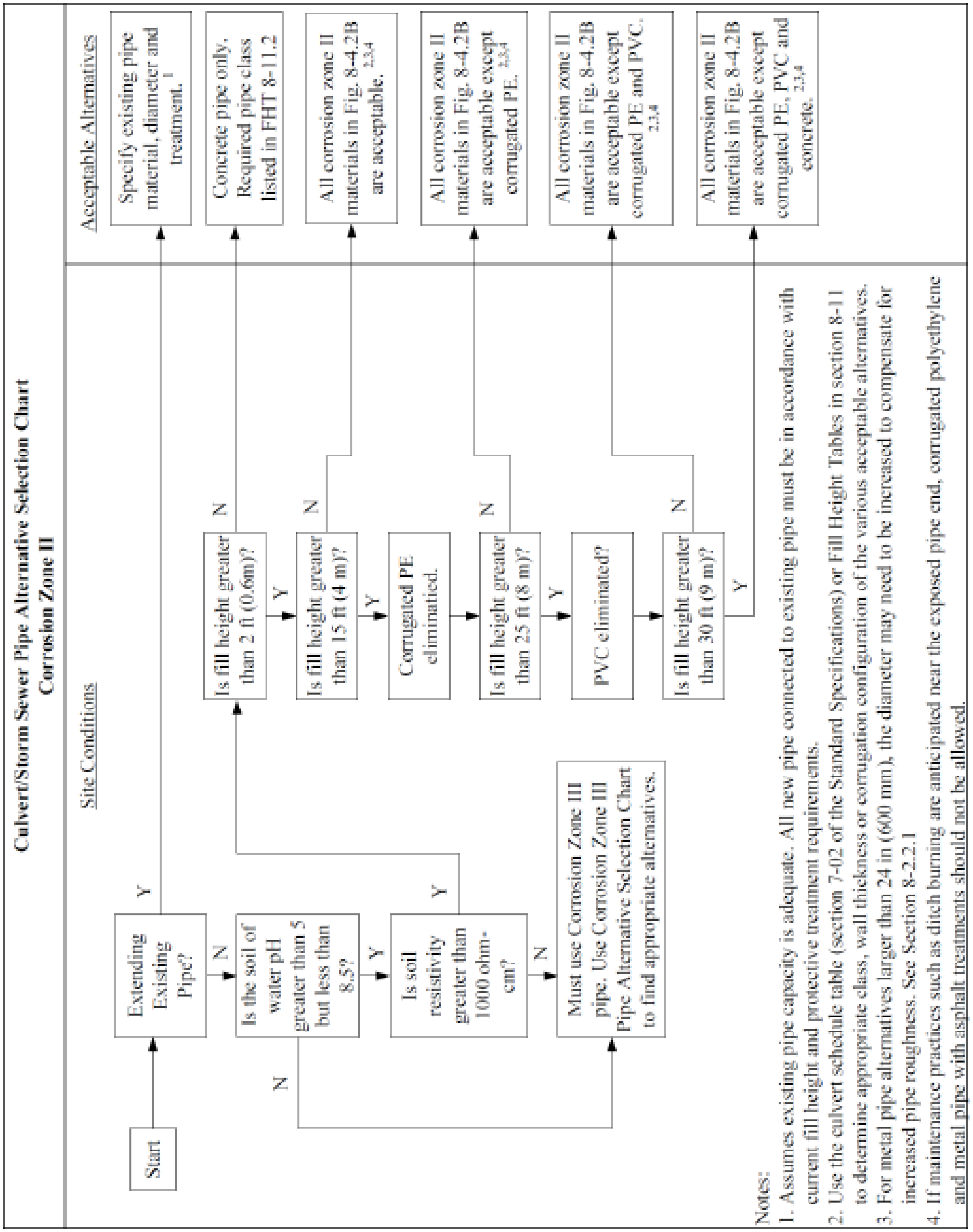


Figure 15. Material selection procedure for Corrosion Zone 2 (Courtesy of Washington DOT)

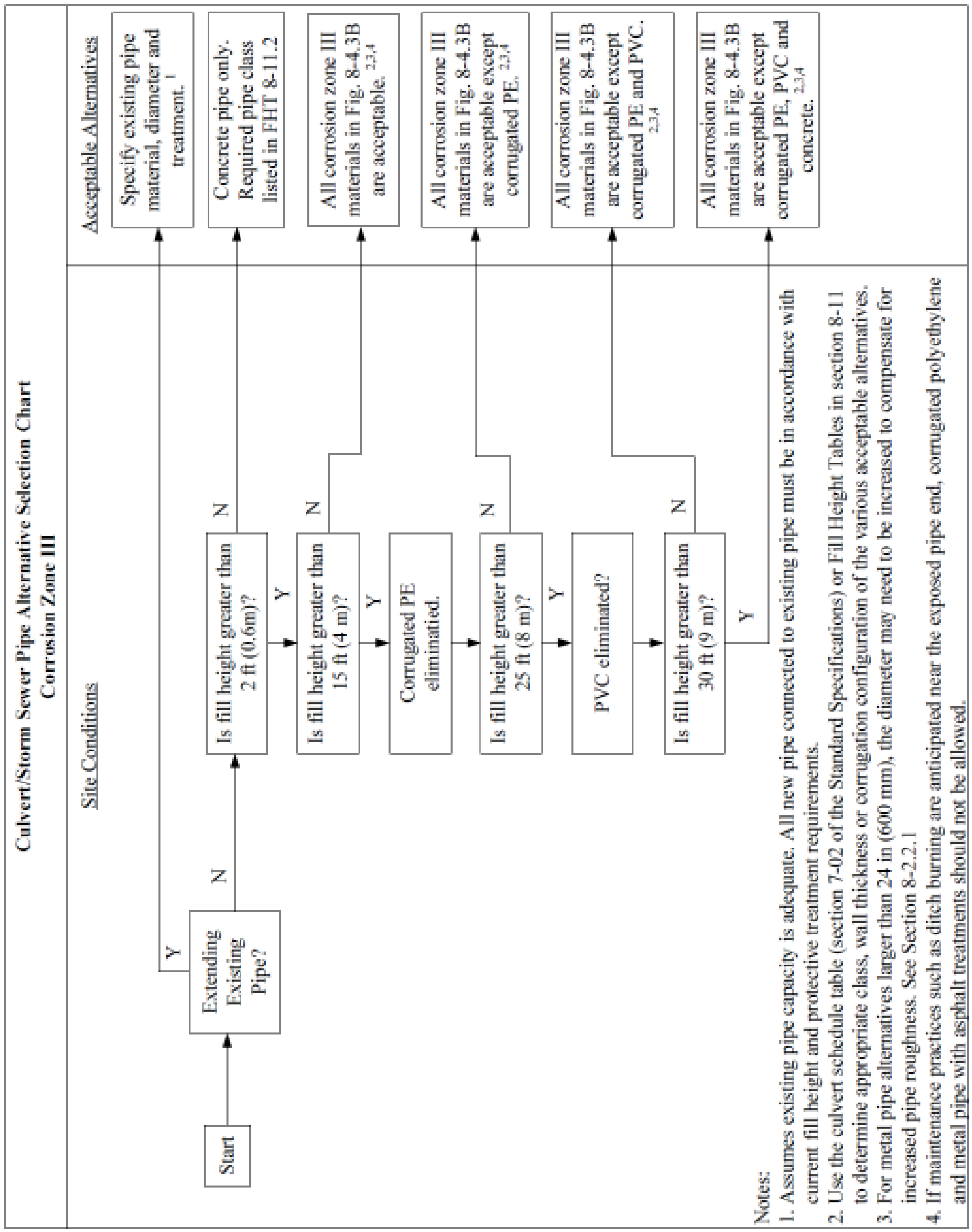


Figure 16. Material selection procedure for Corrosion Zone 3 (Courtesy of Washington DOT

1.2.22 Wisconsin DOT

The Wisconsin DOT primarily select the type of materials based on average daily traffic (ADT) which is shown in Table 39. Under the consideration of design ADT, materials, allowable pipe sizes (inches), maximum and minimum fill heights are decided. Table 40 shows different materials that can be used in different conditions in Wisconsin. Figure 17 shows zone in Wisconsin with high probability of bacterially induced corrosion of zinc galvanized steel culvert pipes. In Area 1 and 2, corrosion of steel pipe is mainly due to the activity of anaerobic sulfate reducing bacteria (ASR) in the surface water. These ASR bacteria do not attack the steel directly but create an environment favorable to corrosion. While in Area 3, corrosion is more commonly related to local conditions such as high electrical conductivity of water and fine-grained soil. For these reasons, pipes having resistance to corrosion are recommended being used for each area [33-35].

Table 39. Culvert material selection criteria for the Wisconsin DOT (Courtesy of Wisconsin DOT)

Design Year ADT < 7,000			
Bid item (culvert pipe)	**Design ADT**	**Allowable sizes (inches)**	**Notes**
Class Ⅲ-A, Class Ⅲ-A Non-metal	Under 7,000	12 - 36	- Max fill height of 11 ft. - Min. fill height 2 ft. from top of subgrade. - For culvert pipe class Ⅲ-A indicate required thickness for steel culverts in Misc. Qualities. - Use non-metal bid items in corrosive environments.
Class Ⅲ-B, Class Ⅲ-B Non-metal	Under 7,000	12 - 36	- Max fill height of 15 ft. - Min. fill height 2 ft. from top of subgrade. - For culvert pipe class Ⅲ-B indicate required thickness for steel culverts in Misc. Quantities. - Use non-metal bid items in corrosive environments.
Corrugated steel	Under 7,000	42 - 84	- Not to be used in corrosive environments unless polymer or aluminum coated. See FDM 13-1-15.4. - 2 – 36 -inch sizes can only be used in special situations. See FDM 13-1-15.3. - Refer to FDM 13-1 Attachment 25.2 and 25.3. for appropriate fill heights. - Indicate required thickness in Misc. Quantities.
Reinforced concrete	Under 7,000	42 – 84	- Consider for use in corrosive environments. - 12 – 36 -inch sizes can only be used in special situations. See FDM 13-1-15.3. - Refer to FDM 13-1 Attachment 25.1 and 25.2 for appropriate fill heights.
Polyethylene	Under 7,000	12 – 36	- Max fill height of 11 ft. - Min. fill height 2 ft. from top of subgrade.

			- Consider for use in special situations. See FDM 13-1-15.3.
Polypropylene	Under 7,000	12 – 36	- Max fill height of 11 ft. - Min. fill height 2 ft. from top of subgrade. - Consider for use in special situations. See FDM 13-1-15.3
Corrugated aluminum	Under 1,500	42 - 84	- Consider for use in corrosive environments. - 12 – 36 -inch sizes can only be used in special situations. See FDM 13-1-15.3. - Refer to FDM 13-1 Attachment 25.2 and 25.6 for appropriate fill heights. - Indicate required thickness in Misc. Quantities.
Design Year ADT > 7,000			
Reinforced concrete	≥ 7,000	12 - 84	- Refer to FDM 13-1 Attachment 25.1 and 25.2 for appropriate fill heights.

Table 40. Allowable materials for culvert pipe (Courtesy of Wisconsin DOT)

Class	Allowable materials
Ⅲ	Class Ⅲ reinforced concrete, corrugated steel pipe of the thickness contract designates
Ⅲ-A	Class Ⅱ and Class Ⅲ reinforced concrete, corrugated steel of the thickness the contract designates, corrugated polyethylene, corrugated polypropylene
Ⅲ-A Non-metal	Class Ⅱ and Class Ⅲ reinforced concrete, corrugated polyethylene, corrugated polypropylene
Ⅲ-B	Class Ⅲ reinforced concrete, corrugated steel of the thickness the contract designates, corrugated polypropylene
Ⅲ-B Non-metal	Class Ⅲ reinforced concrete, corrugated steel of the thickness the contract designates, corrugated polypropylene
Ⅳ	Class Ⅳ reinforced concrete, corrugated steel pipe of the thickness contract designates
Ⅴ	Class Ⅴ reinforced concrete, corrugated steel pipe of the thickness contract designates

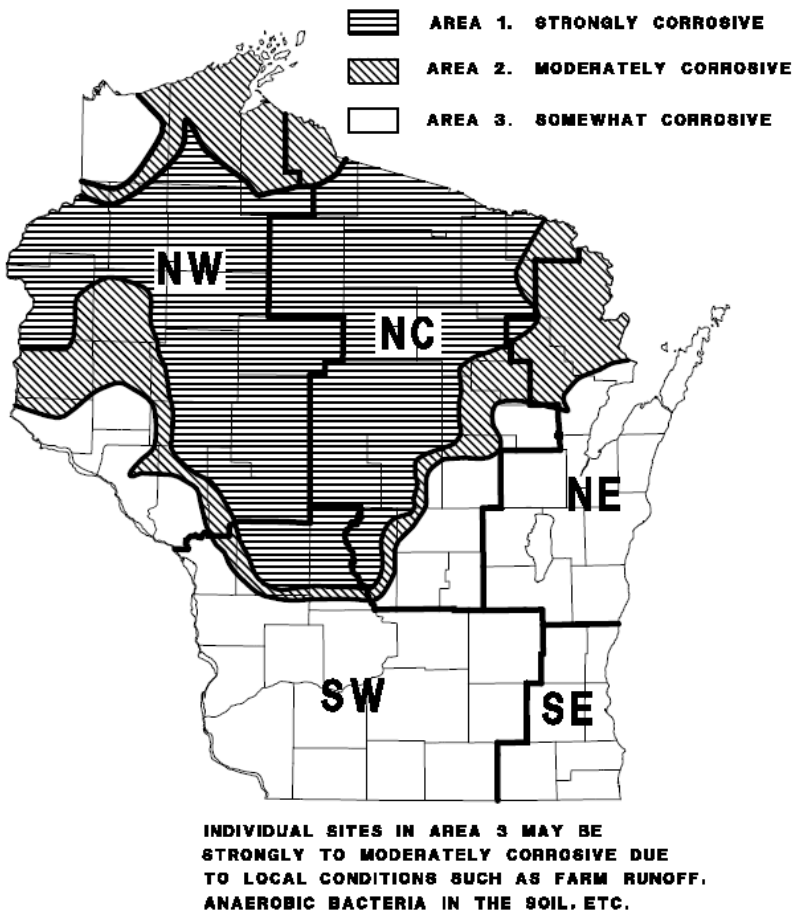


Figure 17. Potential for bacterial corrosion of zinc galvanized steel culvert pipe (Courtesy of Wisconsin DOT)

1.2.23 Wyoming DOT

The type of culvert that is to be used at a given site is governed by the minimum cover, maximum fill height, corrosion resistance number, and hydraulic characteristics. The pipe material selection in Wyoming follows the corrosion resistance number in Table 41. Table 42 defines the corrosion resistance number which is based on minimum resistivity and soluble salts, sulphates and pH of soil and water. Wyoming DOT suggests using the resistivity and pH values for selecting metallic pipe, the sulphate and pH value for non-metallic pipe and structural concrete. Concrete pipe is not allowed where pH is less than 5.0 unless special coating recommendations are provided [36,37].

Table 41. Allowable pipe materials based on corrosion resistance number (Courtesy of Wyoming DOT)

Type of pipe	**Corrosion resistance number**								
	CR1	**CR2**	**CR3**	**CR4**	**CR5**	**CR6**	**CR7**	**CR8**	**CR9**
Galvanized steel	Yes	No	No	No	No	No	No	No	No
Aluminized coated steel (Type 2)	Yes	No	No	No	No	No	No	No	No
Bituminous coated galvanized steel	Yes	Yes	No	No	No	No	No	No	No
Aluminum alloy	Yes	Yes	Yes	Yes	No	No	No	No	No
Polymeric precoated galvanized steel	Yes	Yes	Yes	Yes	Yes	No	No	No	No
RCP (Type Ⅱ cement)	Yes	Yes	Yes	Yes	Yes	No	No	No	No
RCP (Type Ⅴ cement)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
RCP (Type Ⅴ cement/Fly ash)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Epoxy coated RCP (Type Ⅱ or Type Ⅴ cement)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 42. Corrosion resistance table for concrete pipe (Courtesy of Wyoming DOT)

				Soil			**Water**		
Class & type of concrete	**Concrete attack**	**Corrosion resistance number**	**Minimum resistivity (ohm-cm)**	**Soluble salts % max**	**SO_4 % max (Sulphates)**	**pH**	**Soluble salts ppm max**	**SO_4 ppm max**	**pH**
Class B Type Ⅱ	Negligible	CR1	1,000	0.05	0.05	6.0–9.0	250	250	6.0–9.0
Class B Type Ⅱ	Negligible	CR2	750	0.075	0.075	5.0-9.0	375	375	5.0-9.0
Class B Type Ⅱ	Negligible	CR3	550	0.10	0.10	5.0-9.0	500	500	5.0-9.0
Class B Type Ⅱ	Negligible	CR4	500	0.125	0.125	5.0-9.0	625	625	5.0-9.0
Class B Type Ⅱ	Negligible	CR5	275	0.20	0.20	5.0-12.0	1,000	1,000	5.0-12.0
Class B Type Ⅴ	Considerabl e	CR6	120	0.50	0.50	5.0-12.0	2,000	2,000	5.0-12.0
Class B Type Ⅴ	Severe	CR7	-	> 0.50	> 0.50	>5.0->12.0	> 2,000	> 2,000	>5.0- >12.0

1.2.24 Indiana DOT

Indiana DOT uses an online program for pipe material selection. A pH value can be obtained from Engineer's report, pH testing or the pH map, which is shown in Figure 18, and the lowest value is determined as the pH value. If the pH value obtained from a report on pH testing is greater than the pH map value, the obtained value is ignored, and the map value is used. The possibility of abrasion is indicated in the Excel sheet using "Y" or "N" for Yes and No, respectively. A site is considered abrasive if it is probable that runoff will transmit materials which can damage the pipe. Each mainline culvert site or each site where a public-road-approach or drive culvert is installed in a natural channel is considered having a risk of abrasion [38,39].

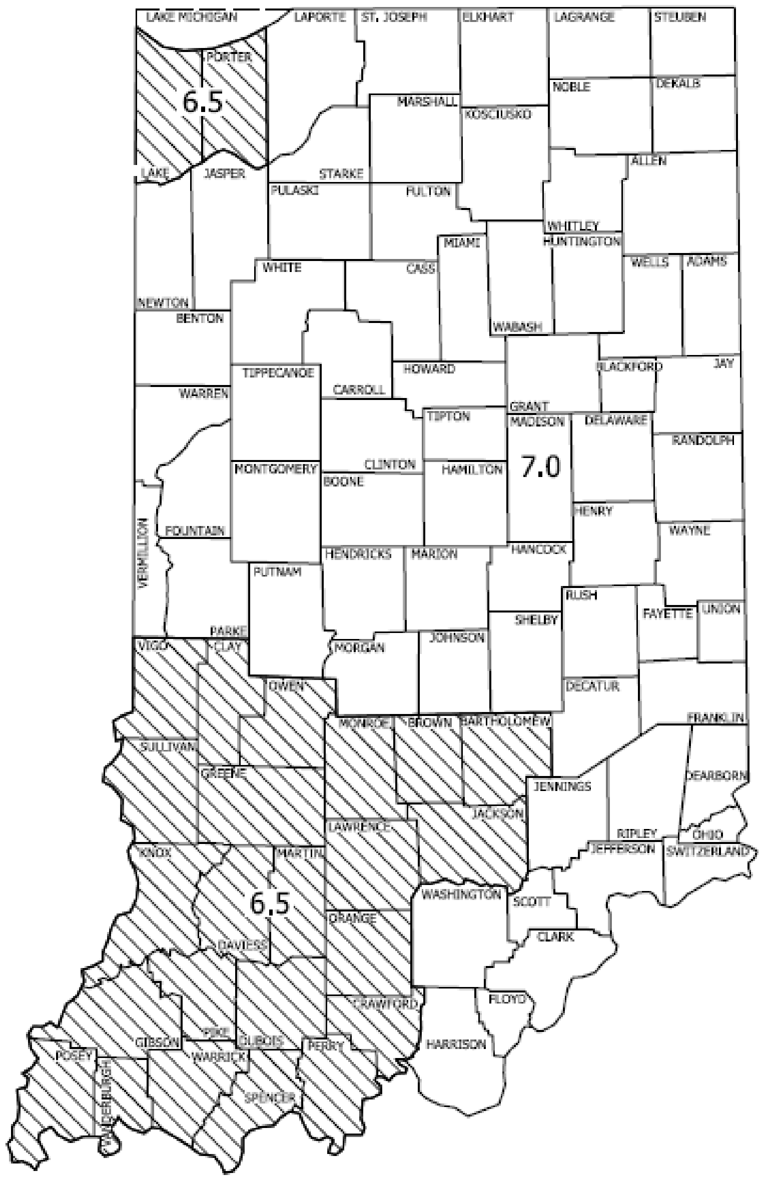


Figure 18. pH map of Indiana State (Courtesy of Indiana DOT)

The list of columns is in the Table 43. The file is uploaded to the internet site (https://hma.indot.in.gov/pipes/) after saving the excel file. Then a page which shows available alternate pipe materials is popped up. See Figure 19 [38,39].

Table 43. List of columns and acceptable values for data entry (Courtesy of Indiana DOT)

Column	Acceptable values for data entry
Project	Any value is acceptable.
Structure number	Any numerical or alpha-numeric value is acceptable.
Height of cover	Any positive whole numerical value is acceptable.
pH	Any positive numerical value is acceptable.
Deformed	Enter "Y" for deformed pipes; Enter "N" for circular pipes.
Slope in %	Any positive numerical value is acceptable. Do not place "%" in the cell.
Interior diameter / Area smooth	Enter the pipe diameter or area required for a smooth interior. For circular pipes, enter the diameter in inches. For deformed pipes, enter the area in square feet. The pipe diameter or area must match the diameter or area shown on the INDOT Standard Drawings. See Standard Drawing series 715-PHCL and 717-PHCL. If semi-smooth are not desired input "0".
Interior diameter / Area semi-smooth	Enter the pipe diameter required in inches for a semi-smooth interior. The pipe diameter or area must match the diameter or area shown on the INDOT Standard Drawing series 715-PHCL and 717-PHCL. If smooth pipes are not desired input "0".
Interior diameter / Area corrugated	Enter the pipe diameter or area required for a corrugated interior. For circular pipes, enter the diameter in inches. For deformed pipes, enter the area in square feet. The pipe diameter or area must match the diameter or area shown on the INDOT Standard Drawings. See Standard Drawing series 715-PHCL and 717-PHCL. If semi-smooth are not desired input "0".
Service life	Enter either 50 or 75
Pipe type	Enter pipe type 1, 2, 3, or 5. See Standard Specifications 715.02 for pipe types.
Abrasive	Enter "Y" for abrasive site; "N" for non-abrasive.

Pipe Material Selection Software
Ver. 1.01214

VALID PIPES:

Project Number no.: 10th St Bridge
Structure #: (121)
Height of Cover = 54 ft
Site Is Abrasive
pH Value = 3
Required Design Service Life = 50 years
Pipe Type = 1
Pipe Slope = 3.5 %
Pay Item Diameter For Smooth Interior Pipe = 36 inches.
Pay Item Diameter For Corrugated Interior Pipe = 36 inches.
Pay Item Diameter For Semi-Smooth Interior Pipe = 24 inches.

- **2 2/3" x 1/2" CORRUGATED STEEL PIPE (LOCK SEAM)**
  - (0.1090) Polymer Precoated Galvanized
  - (0.109) Polymer Precoated Galvanized Type IA(S)
- **3/4" x 3/4" x 7 1/2" SPIRAL RIB STEEL PIPE**
  - (0.1090) Polymer Precoated Galvanized
- **5" x 1" CORRUGATED STEEL PIPE (LOCK SEAM)**
  - (0.1090) Polymer Precoated Galvanized
- **SMOOTH WALL POLYETHYLENE PIPE**
  DIMENSION RATIO = 21

Figure 19. Result of the Indiana DOT Pipe Material Selection Software (Courtesy of Indiana DOT)

1.2.25 Kentucky DOT

Kentucky DOT provides allowable coatings, linings and paving for different pH range. The pH value less than 5 is considered acidic, pH values 5 to 9 is moderate, and pH values higher than 9 is basic condition. Table 44 shows pipe material and its required coatings and paving for different pH ranges [40,41].

Table 44. Coatings and Paving for pipe materials with different pH range
(Courtesy of Kentucky DOT)

Pipe material	**pH range**					
	(ACID) L (< 5)		**M (5 – 9)**		**(BASE) H (> 9)**	
	Coating	**Paving**	**Coating**	**Paving**	**Coating**	**Paving**
Steel galvanized	P	I	BP	I	P	I
Aluminum-coated Type 2 steel	-	-	HB	I	-	-
Aluminum alloy	B	I	HB	I	B	I
Reinforced concrete	-	EP	-	-	-	EP
Plastic	-	-	-	-	-	-

Abbreviations are as following: HB: Half asphalt coated; B: Fully asphalt coated; BP: Fully asphalt coated or polymeric coated; P: Polymeric coated (precoated galvanized); EP: Extra protection; I: Paved invert.

1.2.26 Ohio DOT

Ohio DOT uses an excel sheet for the selection of type of pipe materials. The inputs to use the excel sheet are just conduit use (culvert, storm sewer, or liner pipe), pH and abrasion level. The estimated service life is shown for different material with different thicknesses in Figure 20 (an example of result with the input culvert, the pH of 7.0, and the abrasion level of 2.0). The abrasion level consists of 6 level from 1 to 6. Cells that appear in green meet service life requirements, while cells that appear in red do not meet service life requirements. Table 45 represents each abrasion level and description [42].

County Station		Route Station		Section		PID	

User Input			Constants and Calculated Values			
Conduit Use	pH_	Abrasion Level	pHs	Sediment/Rise	End of Service Life GA	Service Life Required
Culvert	7.0	2.0	7.6	0	4	75

Material		707.01 , 707.02, or 707.03 Metallic coated (galvanized)	707.01 or 707.02 or 707.03 Metallic coated (galvanized) with Concrete Invert Paving	707.01 or 707.02 Metallic coated (Aluminized)	***707.01 or 707.02 Metallic coated (aluminized) with Concrete Invert Paving	707.04 Polymeric Coated over galvanized steel	***707.04 Polymeric Coated with Concrete Invert Paving	707.05 or 707.07 (707.01 or 707.02 galvanized) 1/2 Bituminous coated with Bituminous paved invert	***707.05 or 707.07 (707.01 or 707.02 aluminized) 1/2 Bituminous coated with Bituminous paved invert
Conduit Use and Shap		Culvert or Liner Pipe -Round or Pipe Arch	Culvert-Round, Pipe Arch, and Arch	Culvert or Liner Pipe -Round or Pipe Arch	Culvert -Round or Pipe Arch	Culvert or Liner Pipe -Round or Pipe Arch	Culvert-Round or Pipe Arch	Culvert -Round or Pipe Arch	Culvert -Round or Pipe Arch
Gauge	*...ess (inches*								
16	0.064	45.9	65.9	80.9	100.9	95.9	115.9	55.9	90.9
14	0.079	48.2	68.2	83.2	103.2	98.2	118.2	58.2	93.2
12	0.109	52.8	72.8	87.8	107.8	102.8	122.8	62.8	97.8
10	0.138	57.2	77.2	92.2	112.2	107.2	127.2	67.2	102.2
8	0.168	61.7	81.7	96.7	116.7	111.7	131.7	71.7	106.7
7	0.188	64.7	84.7	99.7	119.7	114.7	134.7	74.7	109.7
5	0.218	69.3	89.3	104.3	124.3	119.3	139.3	79.3	114.3
3	0.249	74.0	94.0	109.0	129.0	124.0	144.0	84.0	119.0
1	0.28	78.7	98.7	113.7	133.7	128.7	148.7	88.7	123.7
Casing	0.5								

Concrete Conduit Durability Results

Material	**706.01 Non-reinforced Concrete Pipe	**706.02 Reinforced Concrete Circular Pipe	**706.03 Reinforced Concrete Pipe, Epoxy Coated	Reinforced Concrete Elliptical Culvert, Storm Drain, and	**706.05 Precast Reinforced Concrete Box Sections	Reinforced Concrete Three-Sided Flat Topped Culverts	706.052 Precast Reinforced Concrete Arch Sections	706.053 Precast Reinforced Concrete Round Sections
Conduit Use and Shap	Culvert or Storm Sewer -Round	Culvet or Storm Sewer -Round	Sewer -Round or Elliptical	Culvert or Storm Sewer -Elliptical	Culvert or Storm Sewer -Box	Culvert - 3 Sided Box	Culvert - 3 Sided Arch	Culvert - Arch or Elliptical
	153.0	153.0	epoxy not required	153.0	153.0	75.0	75.0	153.0

Plastic Conduit Durability Results

Material	707.33 Corrugated Polyethylene Smooth Lined Pipe	707.34 Polyethylene Plastic Pipe Based on Outside Diameter (OD)	707.35 Polyethylene Profile Wall Pipe	707.42 Polyvinyl Chloride Corrugated Smooth Interior Pipe	707.43 Polyvinyl Chloride Profile Wall Pipe	707.45 Polyvinyl Chloride Solid Wall Pipe	707.46 Polyvinyl Chloride Drain Waste and Vent Pipe	707.47 ABS and Polyvinyl Chloride Composite Pipe
Conduit Use and Shap	Culvert, Storm Sewer, or Liner Pipe - Round	Culvert, Storm Sewer, or Liner Pipe - Round	Culvert, Storm Sewer, or Liner Pipe - Round	Storm Sewer or Liner Pipe - Round	Storm Sewer or Liner Pipe - Round	Storm Sewer - Round	Storm Sewer - Round	Storm Sewer - Round
	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0

Figure 20. Example result of Ohio DOT pipe selection excel sheet (Courtesy of Ohio DOT)

Table 45. Abrasion level of Ohio DOT (Courtesy of Ohio DOT)

Abrasion level	General site characteristics
1	Bedloads of silts and clays or clean water with virtually no abrasive bed load
2	Moderate bed loads of sand or gravel
3	Moderate bed load volumes of sand, gravels, and small cobbles
4	Moderate bed load volumes of angular sands, gravels, and cobbles/rocks
5	Moderate bed load volumes of angular sands and gravel or rock
6	Moderate bed load volumes of angular sands and gravel or rock OR Heavy bed load volumes of angular sands and gravel or rock

1.2.27 New York State DOT

New York DOT divides the state into 11 regions, and each region is divided into 2 zones based on metal loss rates for steel (shown in Table 46.) Table 47 indicates the anticipated service life and Table 48 shows coating measures to implement for extending the service life [43].

Table 46. Metal loss rates for steel by geographic location (Courtesy of New York State DOT)

Zone Ⅰ (2 mils/yr)		Zone Ⅱ (4 mils/yr)
Region 1	except	Albany, Greene, and Schenectady Co.
Region 2	except	Montgomery Co.
Region 3	except	Cortland, Tompkins Co.
Region 4	-	-
Region 5	except	Cattaraugus Co.
-	-	Region 6
Region 7	-	-
-	-	Region 8
-	-	Region 9
-	-	Region 10
-	-	Region 11

Table 47. Anticipated service life (in years) for steel (with and without additional coating) (Courtesy of New York State DOT)

Gauge	Metallic coated (galvanized)		Metallic coated (aluminum coated – Type 2) & Metallic coated (galvanized) w/ paved invert or fully paved		Metallic coated (galvanized) w/ polymer coating		Metallic coated (galvanized) w/ polymer coating and paved invert		Metallic coated (galvanized) w/ paved invert (structural steel plate)	
	§707-02/ §707-09		§707-02		§707-02		§707-02		§707-09	
	Zone I	Zone II	Zone I	Zone II	Zone I	Zone II	Zone I	Zone II	Zone I	Zone II
18	26	13	51	38	51	38	66	53	Gauge not manufactured	
16	32	16	57	41	57	41	72	56		
14	40	20	65	45	65	45	80	60		
12	54	27	79	52	79	52	94	67	89	62
10	69	34	94	59	Gauge not manufactured with this coating				104	69
8	84	42	109	67					119	77
7	94	47	Coating option not specified for these gauges						129	82
5	109	54							144	89
3	124	62							159	97
1	140	70							175	105

Notes: 1. For culverts whose diameter, or equivalent diameter, is 10 ft or greater:

a. in Zone Ⅰ – specify a paved invert for 12 gauge culverts, or specify a 10 gauge culvert.

b. in Zone Ⅱ – specify a paved invert for all culvert regardless of gauge.

2. Use caution in designing culverts on grades steeper than 6 ±% carrying potentially abrasive bed loads. Do not rely on polymer coating alone to increase the service life in abrasive conditions. Use fully paved pipe or paved invert. In very severe conditions, consider use of concrete or polyethylene. Aluminum is not recommended due to the potentially abrasive bed load.

3. The Aluminum Coated – Type 2 metallic coating is expected to have the same anticipated service life as metallic coated (galvanized) pipe with a paved invert or fully paved. Additional coating (i.e., paved invert or fully paved) adds 25 years to the anticipated service life of metallic coated (galvanized) steel pipe.

4. Additional coating (i.e., polymer coating) adds 25 years to the anticipated service life of galvanized steel pipe.

5. Additional coating adds 40 years to the anticipated service life of galvanized steel pipe. 6. Additional coating adds 35 years to the anticipated service life of galvanized steel pipe.

Table 48. Additional coating options (Courtesy of New York State DOT)

Additional coating	**Corrugated steel (ξ707-02)**	**Corrugated structural steel plate (ξ707-09)**
Paved invert (bituminous)	Type Ⅰ and Ⅱ only	Not available
Fully paved (bituminous)	Type Ⅰ and Ⅱ only	Not available
Polymer	Type Ⅰ and Ⅱ only	Not available
Polymer & paved invert (bituminous)	Type Ⅰ and Ⅱ only	Not available
Paved invert (Portland cement concrete)	Not available	Available

1.3 Corrosion of pipe materials in soil

Corrosion is defined as the electrochemical degradation of a metal or loss of properties because of its reaction in the environment, but does not include mechanical degradation such as abrasion or damage due to impact or wearing forces [44]. Corrosion is an electrochemical process, which tends to be promoted when materials are placed in highly conductive media. Generally, a low pH and resistivity is conducive to corrosion.

Steel dissolution occurs in an acidic environment (low pH), whereas in an alkali environment (high pH), steel forms an oxide film. The oxide film formed on the surface of the steel can stabilize steel dissolution in an alkaline environment. Steel dissolution is thus more severe in an acidic environment. However, this protective film can be broken down in the presence of some ions (such as chloride ions) and when the pH is below approximately 8.0. Soils with low resistivity values provide an easy path for ions to migrate from an anode (corroding area) to a cathode (non-corroding area), which accelerates corrosion. Soils with high resistivity values impede the migration of these ions and slow down corrosion rate [27].

Previous research has been trying to identify the factors influencing the soil corrosiveness and its impact to the corrosion of pipes. However, the complexity of underground environment which causes different soil conditions even in closely located geographic regions hinders finding clear pipe corrosion inducing factors. According to the previous research [45-51], the factors that highly influence corrosion rate include: pH, resistivity, moisture content, temperature, soil type, temperature, differential aeration, soil particles and permeability, the presence of sulphate-reducing bacteria, and/or the extent of soluble salts [52].

As was presented in Figure 2, state agencies consider pH and resistivity as parts of the criteria for the risk of corrosion. However, Penhale (1984), Rajani and Makar (2000) and Doyle et al. (2003) examined correlation between pH value and steel plate or steel pipe samples buried in specific soil sites and found poor or little correlation between them [45,46,55]. In other words, noticeable correlation between pH and corrosion rates in the underground environment was not found. Moreover, studies on developing a relationship between resistivity and corrosion of buried pipes were carried out by others [53-59]. In general, soils with low resistivity accelerate the corrosion, whereas soils with high resistivity impede the corrosion. However, the researchers noted that this relationship does not always exist and there are some exceptions to this rule [53-56]. From these studies, it can be said that because of the complexity of the corrosion mechanism in soils, the pH and resistivity values alone might not be direct factors affecting the corrosion of pipe in soil environment; pH and resistivity values may be used as indicators of corrosive environments but the rate of corrosion may not be accurately estimated based on these factors [4].

1.4 Abrasion

All types of pipe material are subject to abrasion and can experience damage in the vicinity of the pipe invert if not adequately protected. Abrasion is the wearing away of pipe material by water carrying sands, gravels and rocks and is dependent upon size, shape, hardness and volume of bed load in conjunction with volume, velocity, duration and frequency of stream flow in the culvert. Protective barrier layers or scaling in the invert side of culverts will improve performance in abrasive conditions. Hence, state agencies that are concerned with abrasive environments recommend coating or paving the invert of culverts with asphalt or concrete either after fabrication or after installation, which can provide additional add-on life [3,7].

1.5 Summary

In this literature review, the guidelines of State DOTs nationwide and research related to material selection procedure were reviewed. A summary of the findings, based on the reviewed literature, is provided below:

- Of the 50 state agencies, 26 state agencies have material selection guides and 22 of them considered pH and resistivity. Three state agencies considered pH only, and New York State DOT divides the state into two zones and specifies materials based on the zones. State agencies that consider pH and resistivity provide minimum and maximum values for both factors.
- In general, the pH and resistivity of soil does affect the degradation of culverts in soils. However, there is no clear correlation between pH values and corrosion rates. Moreover, it should be noted that this relationship does not always exist, and there are some

exceptions to this rule. However, pH and resistivity can be used for determining the risk of corrosion.

- Despite the fact that the pH and resistivity value of soils have little or no correlation with corrosion rates in soils, these factors are widely used in the procedure of pipe material selection because they are considered as the indicators of corrosive environments. However, it is clear that only with pH and resistivity, pipe material selection would not be appropriate. Therefore, other factors such as chloride ion contents, sulfate contents, and/or abrasive environment should be considered to make a proper material selection.

1.6 Recommendations based on literature review

Based on the findings of the literature review, the research team proposes to use pH and resistivity of the soil, the presence of chlorides and sulfates, and abrasion to develop a pipe materials selection guide for NCDOT. In addition, these parameters will be used to quantitatively correlate to the effect of coating thickness on service life of galvanized and aluminized metallic pipes.

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APPENDIX C:

Literature Review on HDPE and PVC Pipes

Service Life of Plastic Pipes

The service life assessment of all infrastructure including pipes has become an area of renewed interest in the United States with the aging infrastructure approaching the end of their service lives. While the serviceability of above ground infrastructures is readily inspected at a regular time interval, the underground structures (pipes) are not inspected as frequently. Pipes have diversified applications that include drainage, gas and water transport as well as waste transport etc. These pipes are made of different materials i.e., steel, aluminum, plastic etc. Plastic pipes are mainly used for their non-corroding properties. However, the exposure conditions including sustained loading, and associated creep, UV exposure, temperature fluctuation, oxidation etc. can have significant impact on the service life of plastic pipes. There are two types of plastic pipes that are commonly used: High Density Polyethylene (HDPE) and Polyvinyl Chloride (PVC) pipes.

HDPE pipes

It is commonly known that HDPE pipes exhibit 3 types of failure:

1) Type (i) Ductile failure that happens under very high stress conditions
2) Type (ii) Brittle failure that happens in moderate stress conditions and
3) Type (iii) failures occur due to chemical degradation

Type (i) failure is unlikely to happen in HDPE pipes that used for low pressure drainage or gravity flow conditions. Type (ii) failure is the most common failure that occurs in HDPE pipe. However, our focus here is on the third type of failure that occurs due to chemical degradation. To prevent the initiation of such failure, antioxidants are added during manufacturing process (Pluimer, 2011). The service life of HDPE pipe is expected to be over 100 years. The main factors that cause the chemical degradation of HDPE pipe materials are discussed below.

<u>Oxidation</u>

Antioxidants are added to HDPE pipes as a protection against oxidation by free radicals. Therefore, the antioxidant is added to the HDPE resin during manufacturing in order to extend the service life.

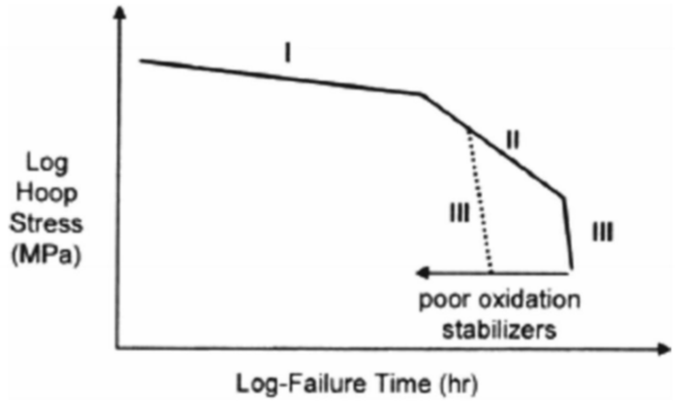

Figure 36. A lack of antioxidants will shift stage III failures to the left, potentially limiting the service life (after Pluimer, 2011)

Figure 1 shows the three stages of polymer degradation. The first shows the time to deplete the antioxidant, the second is the time overcome the innate ability of the polymer to counteract oxidation, and the third shows accelerated age. A lack of antioxidant or improper antioxidant can't shift the failure curve to the left and causes a reduction in service life. Nonetheless, the presence of enough antioxidants can delay the initiation of stage 3 failure as much as by 500 years (Pluimer, 2011).

According to an assessment conducted by Florida DOT, there are two tests that are available to monitor the antioxidant level in polyethene formulation and also the Florida DOT protocol is in accordance with international standards. The two tests are:

1) The indication of temperature (IT) test (known as thermal stability) and
2) The oxidation induction time (OIT) test

Furthermore, the Florida DOT requires a physical property test in addition to the OIT requirement, to ensure no degradation has been occurred. They have specified a minimum value of Melt Index that is required for the pipe to be considered oxidation resistant. The final melt index value after 195 days of immersion requires to be greater than 80% and less than 120% of the initial value.

<u>Abrasion</u>

A common source of degradation of drainage pipes is abrasion, especially when the effluent velocity is high. But multiple tests in USA and Europe indicated that polyethylene shows 10 times lower wear rate than steel. Several states along with the Federal Lands Highway (FLH) design guide allows unrestricted use of plastic pipes for abrasive environments (Durability and service life, Plastic pipe institute).

<u>UV Degradation</u>

Surface damage (discoloration, minor change in tensile strength) may occur in plastic pipes (HDPE and PVC) due to UV degradation. FDOT specified an exposure limit of 2 years for UV-susceptible plastic pipes. Carbon black is used as a UV stabilizer in HDPE pipes as a protection against prolonged sun or UV exposure (Service life of culverts, 2015). Nevertheless, if the pipe walls are smooth, corrugated HDPE pipes show good resistance to UV. Even if the inner wall is pierced, the outer walls remain undamaged (Service life of culverts, 2015).

Corrosion

Chemical degradation may occur in buried polymeric pipes if surrounding soil contains acids, alkalis, dissolved salts, or industrial wastes. However, polyethylene pipes being non-conductors are not susceptible to electrochemical attack and have resistance against electrochemical corrosion. Aggressive salts, pH extremes have minimal impact on HDPE pipes, given the high molecular weight of the polymer used in their manufacturing. According to the Federal Lands Highway (FLH), plastic pipes can serve as alternatives regardless of the resistivity and pH of the site. Experimental investigations show when the pH drops form neutral (pH=7) to medium-low acidic conditions (pH=4), the effect is negligible on HDPE pipes. A field study demonstrated that polymeric pipes are not affected by acid mine run-off of pH ranging 2.55 to 4.0 (Durability and service life, Plastic pipe institute).

Chlorine Exposure

It is not time-efficient to study the natural aging behavior of HDPE and therefore, accelerated aging tests are conducted on HDPE pipes to predict their degradation pattern. Heim and Dietrich 2007, Durand and Dietrich 2006, Mitroka et al. 2010, Colin et al. 2009 and Hassinen et al. 2004 suggest that chlorine exposed HDPE pipe materials consume free chlorine (in solution) which contributes to the oxidation process by forming carbonyl compounds. Carbonyl formation on pipe surface is an indication of a notable loss of Oxidation Induction Time, which is an index used to assess the chemical degradation of the polymer due to the depletion of the antioxidant compounds in the polymer mix. The laboratory-aged pipes when exposed to chlorine showed a decrease of OIT with time. Data in Figure 2 shows the reduction in OIT of HDPE and Cross-linked Polyethylene (PEX) resins as a result of exposure to chlorinated water with respect to time.

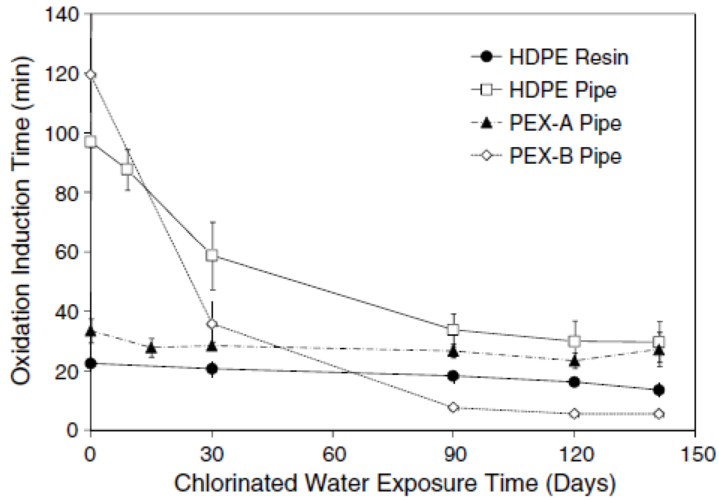

Figure 2. Change in oxidation induction time for HDPE resin, HDPE pipe, PEX-A pipe and PEX-B pipe during accelerated aging in 45 mg/L as Cl2, 50 mg/L as CaCO3 at 37◦ C (after, Whelton et al. 2011).

As shown in Table 1, the laboratory-aged pipes showed similar behavior as the ones collected (taken out for replacement at the end of service life) from water distribution systems. Water utility pipe samples also indicated low OIT values and carbonyl compounds could be found on pipe surfaces (Whelton et al. 2011).

Table 1. Attributes of water utility high-density polyethylene pipes (after Whelton et al., 2011)

Pipe characteristic	Pipe PE 1	Pipe PE 2	Pipe PE 3
Service and disinfectant exposure history[a]	7 years in service: combined chlorine only	20 years in service: 18 years free available chlorine; 2 years chloramines	25 years in service: free available chlorine only
	Bulk properties[b]		
Thickness (mm)	3.37 ± 0.06	2.52 ± 0.03	2.65 ± 0.03
Bulk density (g/cm^3)	0.9504 ± 0.0003	0.9513 ± 0.0001	0.9504 ± 0.0004
Crystallinity (percent)	66.4 ± 0.2	67.0 ± 0.0	66.5 ± 0.2
OIT (min)	0.0 ± 0.0	4.8 ± 4.2	8.3 ± 4.0

Sulphate Exposure

To evaluate the durability of HDPE pipes under sulphate environment, Mouallif et al. (2011) exposed pipes to sulphuric acid solution in laboratory. The solvent absorption was measured as a function of immersion time at various temperatures. Tensile testing was performed on the laboratory-aged samples after a 92 days immersion time.

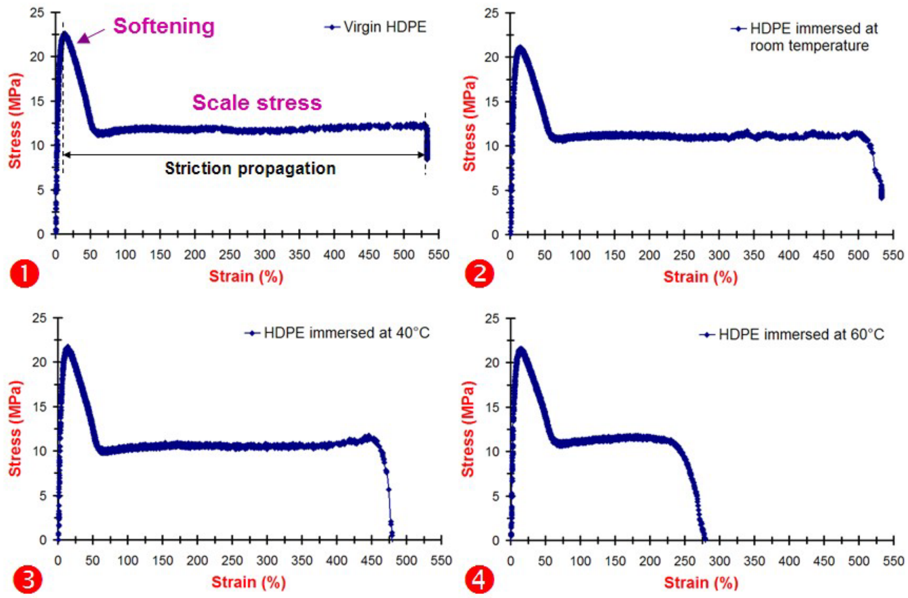

Figure 3. Effect of aging temperature on tensile curves of specimens HDPE: unaged (1), aged at 25 (2), aged at 40◦C (3) and at 60◦C (4) for 92 days of immersion in acid H2SO4(pH=1) (after Mouallif et al., 2011)

The mechanisms that lead to degradation according to Mouallif et al. (2011) are as follows:

a) Polymer chain breaking due to homolytic and heterolytic dissociation

b) Branching and cross-linking

c) Oxidation

Formation of carbonyl compounds in the core of the HDPE polymeric structure indicates a chemical change. The impact of such change in apparent at the elevated temperature of *60◦C*. In this case elevated temperature simulates aging, through accelerated chemical reaction.

PVC pipes

The common factors that impact the service life of PVC pipes by incurring chemical degradation in pipe material are discussed below:

Oxidation

Yoshika et al. (1999) examined the degradation potential of PVC pipes experimentally by producing oxalic acids using widely available rigid PVC (R-PVC) pellets. R-PVC pellets were oxidized in NaOH solutions under high temperature of 250oC. The production of oxalic acid and degradation of PVC (expressed in terms of weight loss) escalated with time, as shown in Figure 4.

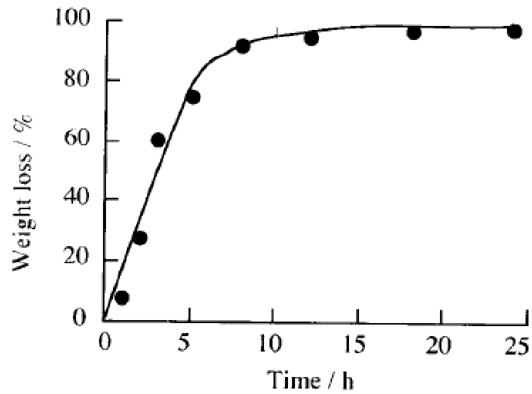

Figure 4. Weight loss curve for rigid-PVC pellet in 15 m NaOH at 250 ◦C and pressure of 5 MPa (after T.Yoshika et al. ,1999)

Abrasion

California DOT conducted a 5-year long abrasion study on different pipe materials in 2007 in Nevada County, California. The results of the study suggest that PVC pipe degrades at a slower rate than HDPE (Service life of culverts, 2015). DeCou and Davies 2007, reported that, the annual wear rate for HDPE around 110 mils/yr and for PVC pipe the annual wear rate is 40 mils/yr.

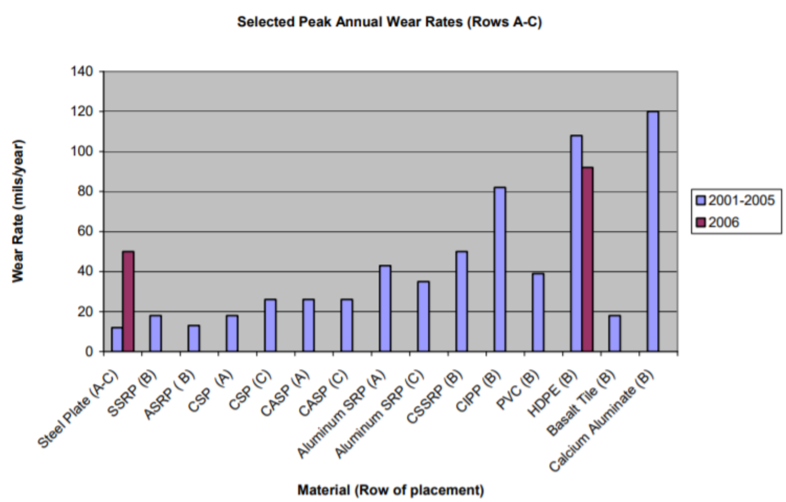

Figure 5. Peak annual wear rate for different pipe materials (after DeCou, G., & Davis, P., 2007)

UV Degradation

To protect against UV degradation, UV stabilizers such as carbon black are used in HDPE and PVC pipes. However, the lifetime of these stabilizers is not experimentally proven. Therefore, it is recommended to use protective measures while pipes are stored on site as well as for the exposed ends (in case of buried pipes and culverts) of the polymeric pipes. The FDOT developed a protocol for using short corrugated metal pipe sections at the ends of PVC pipes when the ends of the PVC pipes are exposed to UV. (Service life of culverts, 2015).

Corrosion

Sustainable solutions corporation 2017, used a 100-year service life for PVC in their study depending on 60 years of extensive field investigation and laboratory testing although studies predict that the anticipated service life for PVC pipes is over 100 years (Stahmer and Whittle, 2004, Whittle and Tennakoon, 2005, Rockaway et al. 2008). PVC pipes are resistant to internal and external corrosion which is the main cause of this longevity. An examination of "Innovative Methods Used in the Inspection of Wastewater Systems," published by the Water Environment and Reuse Foundation (WERF) stated that 'If a utility has primarily PVC pipes it would be pointless to invest in an inspection system designed to measure the amount of wall loss due to corrosion' (Sustainable solutions corporation, 2017). Figure 6 provides a general comparison of failure rates of different pipe materials:

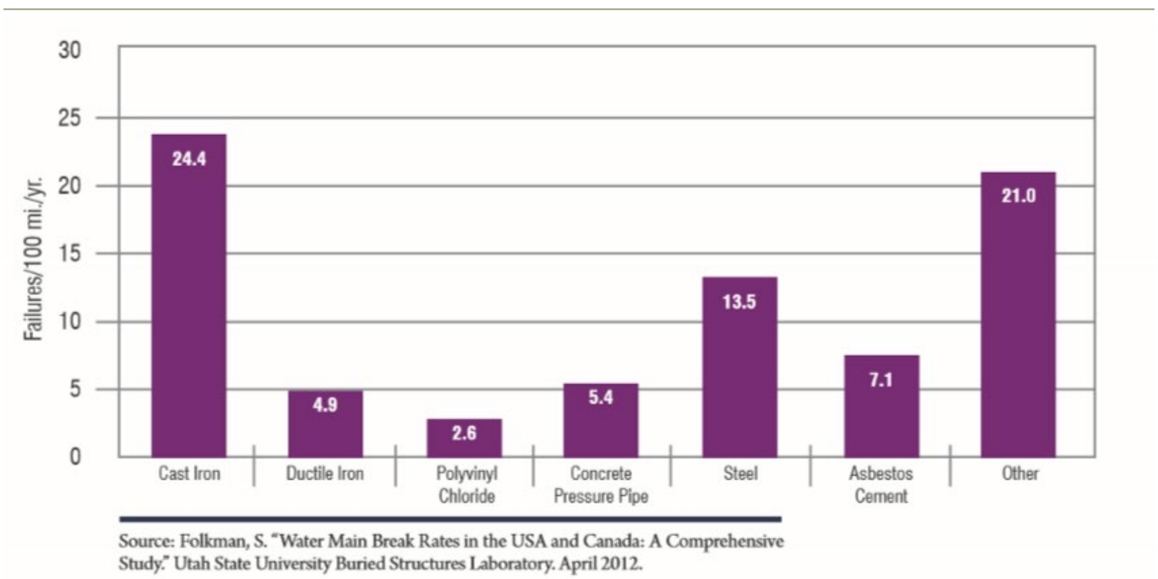

Figure 6. Failure rates of each pipe material per 100 miles over a one-year period (after Verified, L. C. A., 2017)

Summary

In general, chemical degradation of polymeric pipe is shown to be minimal. The majority of polymeric pipes used in subsurface drainage or for water and sewer applications are either HDPE or PVC. In the case of the HDPE polymer, research is done extensively since the polymer is also used in landfill membrane liners. The main concern for the HDPE is the creep of the material that takes place with time under sustained loading as well as damage that may occur during installation. In the case of the PVC polymer, creep is of less concern compared to HDPE polymer. However, the potential of PVC polymer chain breakdown due to dissolution and hydrolysis, and therefore degradation of the material, is of more concern compared to the HDPE polymer.

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APPENDIX D:

Literature Review on the Effect of Chloride and Sulfate on the Corrosion Behavior of Metal Pipes

Galvanized coatings are being used on steel pipe culverts since 1900's. Galvanized steel pipes are basically steel-sheets that are zinc-coated through hot-dip manufacturing method. Zinc used for galvanizing metal pipes has to be at least 98% zinc and the minimum coating thickness has to be 2 oz/ft^2 or 0.0017 in on each side of the metal (steel) sheet.

Aluminized Type 2 pipes use a coating of commercially pure aluminum (type 2 aluminum) by hot-dip method. The minimum coating thickness has to be 1oz/ft^2 or 1.9 mils on each side of the metal (steel) sheet. However, the maximum coating thickness may vary for both pipes based on the installed environment, surrounding soil and service life expectancy.

A Caltrans (California DOT) study on two aluminized type 2 sites and 7 galvanized sites, concluded that Aluminized type 2 pipes depicted slightly advantageous behavior over Galvanized pipes. Furthermore, a 5-year-long study conducted by Florida DOT at their own corrosion laboratory suggested that the performance of aluminized type 2 pipes are 2.9 times better than galvanized pipes in identical environment. In addition to these, the California Highway Design Manual states that Aluminized Type 2 pipes show better performance. However, Aluminized Type 2 pipes indicated accelerated corrosion in multiple field investigations (Dexter site on Maine and Natchez Trace Parkway) conducted by the Federal Highway administration (Ault and Ellor 2000).

From literature it seems that regardless of the coating material (aluminized type 2 or galvanized), steel pipes are subjected to degradation, and corrosion plays a major role in the degradation process of metal pipes and in reducing the service life of metal pipes. Several environmental and chemical factors are responsible for corrosion of steel pipes. This review article will specifically focus on the effect of sulphate and chloride on metal pipe corrosion.

Department of Highways in Colorado provides a chart that takes sulphate, chloride and pH levels of soil and water both as input and provides a corrosion rating (CR) value ranging from 1 to 6 as output. The chart is provided below (Ault and Ellor 2000):

Table 24. Corrosion rating (CR) table used by Colorado DOT (after Ault and Ellor, 2000)

	Soil Characteristics			Water Characteristics		
CR Level	Sulfate (SO_4) % max	Chloride (Cl) % max	PH	Sulfate (SO_4) Ppm max	Chloride (Cl) ppm max	PH
CR 0*	0.05	0.05	6.0 – 8.5	250	250	6.0 - 8.5
CR 1	0.15	0.15	6.0 – 8.5	250	250	6.0 - 8.5
CR 2	0.05	0.05	6.0 – 8.5	500	500	6.0 - 8.5
CR 3	0.15	0.15	6.0 – 8.5	500	500	6.0 - 8.5
CR 4	0.50	1.00	5.0 - 9.0	1000	1000	5.0 - 9.0
CR 5	1.00	1.50	5.0 - 9.0	2000	2000	5.0 - 9.0
CR 6	>1.00	>1.50	<5.0 or >9.0	>2000	>2000	<5.0 or >9.0

* No special corrosion protection recommended when values are within these limits.

For both Aluminized Type 2 and Galvanized steel pipe alkalinity and hardness parameters play a vital role in revealing their corrosion resistance or in other words calculating their corrosion rate. It has been observed that the presence of corrosive Cl^- and SO^{-2} salts impacts the resistance of the pipe material against corrosion. Corrosion resistance of pipe decreases with increasing Cl^- and SO^{-2} content. Furthermore, the presence of carbonic acid (CO^{-2}) decreases the service life of pipe by magnifying the unfavorable effect of SO^{-2} and Cl^- on galvanized and aluminized type 2 steel pipe. Acidic environment (presence of free moving CO^{-2}) would be considered as a severe exposure condition for most pipe materials. The following figure provides a comparison between service life of 1.62 mm thick aluminized steel and 2.0 mm thick galvanized steel as a function of water chemistry (Bednar, 1993).

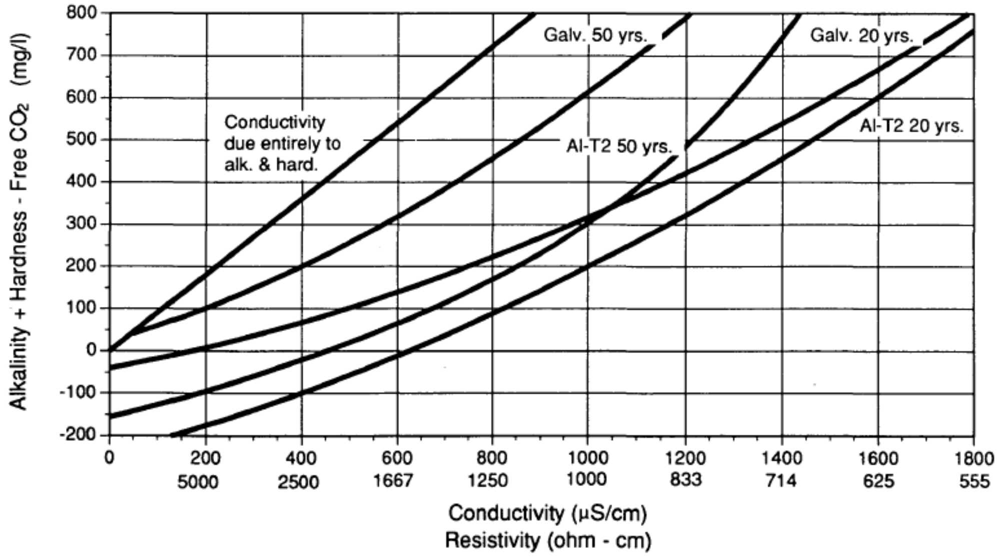


Figure 1. Comparative minimum service life for 1.62-mm-thick Type 2 aluminized steel and 2.0-mm-thick galvanized steel as a function of water chemistry (μS/cm = umho/cm, mg/l = ppm, 1.62 mm = 16 gauge, 2 mm = 14 gauge) (after Bednar, 1993)

Figure 1 indicates a 50-year service life of aluminized type 2 pipe over a wide range of alkalinity and resistivity values. This chart includes conditions that are so severe that for some cases the service life of galvanized pipe is found to be only 20 years. Nevertheless, the study suggested that the use of aluminized type 2 pipes can help overcoming the limitations of galvanized pipes by offering enhanced corrosion resistance.

Xu et al. (2010) proposed that in the same environment corrosion rate of steel is higher with the presence of sulphate reducing bacteria (SRB) than without that. In addition to that, sulphate reducing bacteria (SRB) is also responsible for pitting corrosion of galvanized steel pipes (Xu-gang et al. 2013).

Maki 2019 conducted a study where aluminized type 2 pipe specimens of 50x200 mm were placed in unveiled environmental condition for 50 years in Kitakyushu,Japan. The exposure site corresponds to a severe corrosion environment. Upon 50 years of environmental exposure, the pipe samples were recovered and examined for corrosion behavior and corrosion level. After 50 years of environmental subjection, the maximum corrosion thickness of steel coating was 0.025mm and the advancement was minimal after 31 years of exposure.

Chloride ion (Cl^-) being one of the highest corrosive anions, plays a major role in corrosion of buried pipes. Chloride ion perforates the protective coatings (galvanized coating) and reacts with steel and creates soluble corrosion products. Additionally, the chloride ion and sulfate reducing bacteria (SRB) can increase the localized corrosion in steel and create small holes. Yan, F.J et al. (2013) observed the corrosion behavior of galvanized steel in alkaline environment by conducting accelerated corrosion test by burying specimens in alkaline soil the laboratory and the rate of corrosion was determined through electrochemical testing. The electrochemical test results illustrated that the corrosion rate increased in the later stages than in the initial stage of corrosion. The galvanized steel specimens were 50mmx30mmx5mm in dimension and had a coating thickness of 85 µm. The following table shows the chemical composition of the specimens used in the study.

Table 25. Chemical composition of galvanized steel (after Yan,F.J et al.,2013)

Material	Elements, wt.%						
	Zn	C	Mn	Fe	S	P	Si
Q235	—	0.14~0.22	0.30~0.65	Residua	0.050	0.045	0.3
Galvanized layer	Residua	—	—	1.98	—	—	—

The physical and chemical properties of soil in which the specimens were buried are summarized in the following tables.

Table 26. Chemical composition of galvanized steel (after Yan,F.J et al.,2013)

Cl^-, %	SO_4^{2-}, %	NO_3^-, %	HCO_3^-, %	Total salt, %
0.0918	0.0209	0.0052	0.2733	0.5615

Table 27. Physical properties of test soil (mas%) (after Yan,F.J et al.,2013)

pH value(1:2.5)	Conductivity of soil leaching solution (mS/cm 1:5)	Conductivity of clay coating,(mS/cm 1:2.5)	Soil water content , %
9.23	885.000	536.000	16.34

Note: 1:2.5 and 1:5 express the mass ratio of the soil to the water

Corrosion potential of specimens buried for 600 hours were much higher than that of the specimens buried for 20 hours. The electrochemical test results are provided below for test specimens buried for 20 hours and 600 hours.

Table 28. Ecorr, icorr, and CR of the galvanized steel specimens (after Yan,F.J et al.,2013)

Test time	Corrosion stage	Corrosion potential (mV)	Corrosion current icorr ($\mu A/cm^2$)	Corrosion rate V^- ($g/(m^2 \cdot h)$)
Test specimens buried for 20 hours	In the initial stage	-718	3.167	38.392×10^{-3}
Test specimens buried for 600 hours	In the later stage	-661	6.08	73.705×10^{-3}

Padilla et al. 2013 studied the effect of common de-icing agents (sodium chloride, magnesium chloride and potassium acetate) on corrosion behavior of galvanized steel when subjected to (installed in) soil that has high sulphate concentration. Electrochemical testing was conducted on galvanized steel specimens subjected to sodium sulphate containing solution to determine the corrosion rate of galvanized steel. The experimental results depicted a significant increase in corrosion rate due to sulphate exposure. The results of the study presented below:

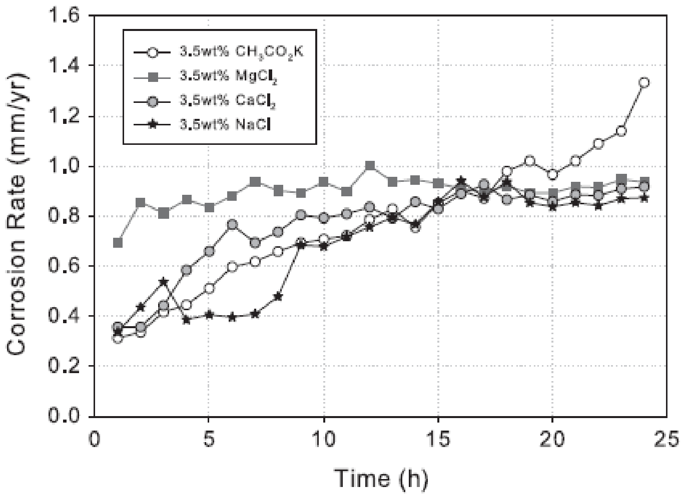


Figure 37. 24 h Linear Polarization Resistance measurements for galvanized steel samples immersed in solutions containing 3.5 wt.% of NaCl, $MgCl_2$, $CaCl_2$, and CH_3CO_2K at 25°C (after Padilla et al., 2013)

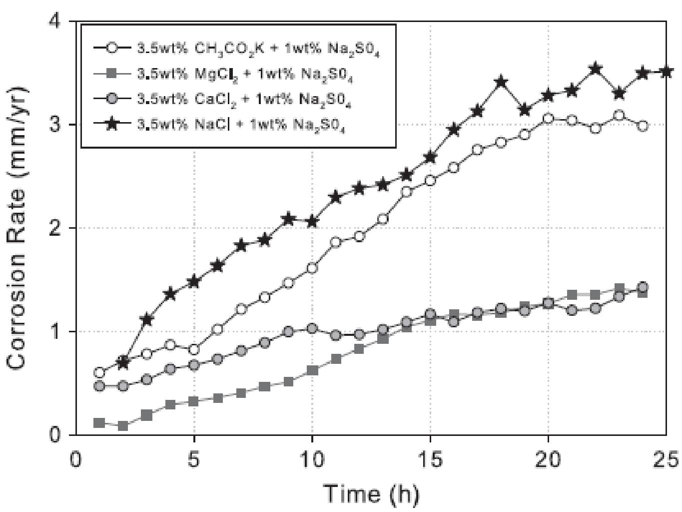


Figure 38. 24 h Linear Polarization Resistance measurements for galvanized steel samples immersed in solutions containing 3.5 wt.% of NaCl, $MgCl_2$, $CaCl_2$, and CH_3CO_2K with 1 wt.% Na_2SO_4 added at 25°C (after Padilla et al., 2013)

References:

Ault, J. P., & Ellor, J. A. (2000). Durability analysis of aluminized type 2 corrugated metal pipe.

Bednar, L. (1993). Updated Environmental Limits for Aluminized Steel Type 2 Pipe Application. Transportation Research Record, 1393, 193.

Maki, J. (2019). Corrosion Behavior of Aluminized Steel Sheets in 50-Year Outdoor Exposure Test. ISIJ International, 59(10), 1870-1877.

Padilla, V., Ghods, P., & Alfantazi, A. (2013). Effect of de-icing salts on the corrosion performance of galvanized steel in sulphate contaminated soil. Construction and building materials, 40, 908-918.

Sun, C., Xu, J., Wang, F. H., & Yu, C. K. (2010). Effects of SRB on cathodic protection of Q235 steel in soils. Materials and Corrosion, 61(9), 762-767.

Yan, F. J., Li, X. G., & Wang, X. G. (2013). The corrosion behavior of galvanized steel in alkaline soil. In Applied Mechanics and Materials (Vol. 331, pp. 416-420). Trans Tech Publications Ltd.

APPENDIX E:
Mechanical Failure of Plastic Pipes

Failure of Plastic Pipes

A literature review was performed on the mechanical failure of plastic pipes. Krishnaswami (2005) performed creep rupture testing at several temperatures to predict the service life and design stress of HDPE pipes. This test was conducted in the laboratory by applying hydrostatic pressure (hoop stress) on the pipe until failure. Continuous loss of pressure within the pipe indicates failure or leakage. The failure time for expected useful service life was extrapolated from a log-log plot of hoop stress versus time. The hoop stress at expected service life and temperature is considered to be the design stress (Krishnaswami 2005).

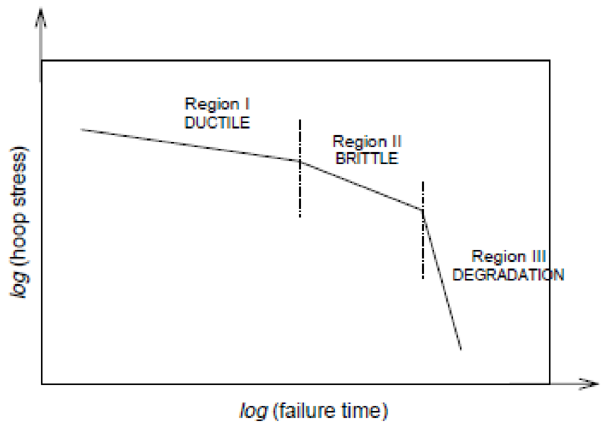


Figure 1. Schematic of the typical hoop stress versus failure time plot for polyethylene pipe (after Krishnaswami 2005)

Figure 1 illustrates three different failure regions. Region-I corresponds to ductile failure mode of pipes which occurs in high stress condition. Region-II corresponds to brittle failure that occurs in lower stresses when a crack propagates slowly. This failure mode is also referred to as slow crack growth or SCG. The transition from ductile to brittle failure mode is referred to as the 'knee'. However, the most common failure mode for pressure pipes in field is the brittle failure mode or the SCG. Some external factors (i.e. rock impingement, bending due to differential settlement) accelerates the SCG fractures in HDPE pressure pipes.

Krishnaswami 2005 also studied the mechanical behavior of a wide range of HDPE pipes of different molecular architecture. The melt index, density and molecular weight of each of the HDPE pipes are listed in table 1. The average molecular weights *(M_w)* of the investigated pipe samples varied within a range between 200 to 500 kg/mol and the molecular weight distribution *(M_w/M_n)* varied within a range of 10 to 60. This range typically corresponds to what is defined in industry as high-density polyethylene

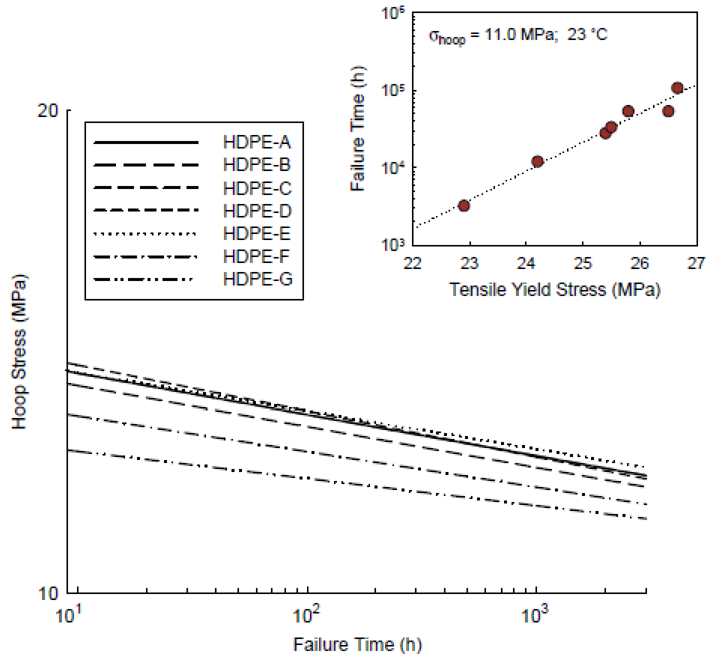


Figure 2. Pipe hoop stress versus failure time data for all subject HDPE pipes at 23◦C. At least 15 failure data points were fitted to produce the best-fit lines shown in the plot. The inset shows failure time for an applied hoop stress of 11.0 MPa plotted as a function of the tensile yield stress of the polymer (after Krishnaswami 2005)

Table 1: Molecular characteristics of the polymers that were employed in the investigation ((after Krishnaswami 2005)

Polymer ID	Pellet density ASTM D1505 (g/cm^3)	Pellet HLMI ASTM D1238 (g/10 min)	M_w (kg/mol)	M_w/M_n
HDPE-A	0.950	2.4	460	51
HDPE-B	0.950	5.3	374	53
HDPE-C	0.949	2.2	500	59
HDPE-D	0.950	7.5	250	20
HDPE-E	0.952	5.7	227	14
HDPE-F	0.947	7.7	328	33
HDPE-G	0.943	13.0	200	25
HDPE-H	0.947	8.0	350	31

Accelerated testing method is used to estimate the useful service life and design stress of HDPE pressure pipes. Elevated temperature is used for the failure to occur at a shorter time for a given pipe at a given hoop stress. As temperature is elevated the “knee” in the stress versus time curve shifts to a lower hoop stress level and shorter times. In order to predict the design stress and failure time using creep-rupture test method, the principle of time-temperature superposition is utilized.

Krishnaswami 2005, concluded that for a specific hoop stress and temperature, the failure time for ductile fracture has an exponential relation with the tensile yield stress of the HDPE polymer. This suggests that density or crystallinity is the main material property that contributes to the ductile failure of HDPE pipes. Hence, the ductile failure of HDPE pipes does not depend on the molecular weight or distribution and branching distribution. Lu X et al. 1997 and Hubert L. et al 2001 suggest that the resistance to SCG can be increased with short chain branches along the longest molecules of the molecular weight distribution. Furthermore, some investigators proposed that the regions with low molecular mass along the edge of a crystalline structure are more susceptible to brittle failure (Gedde and Jansson 1985).

The design life or durability of an HDPE pipe decreases with the occurrence of early brittle failure during the creep rupture testing. Creep-rupture test data for HDPE-A and HDPE-D at 80◦ are provided in figure 3. The figure clearly depicts the transition from ductile failure at high stresses to brittle failure at low stresses for both pipes.

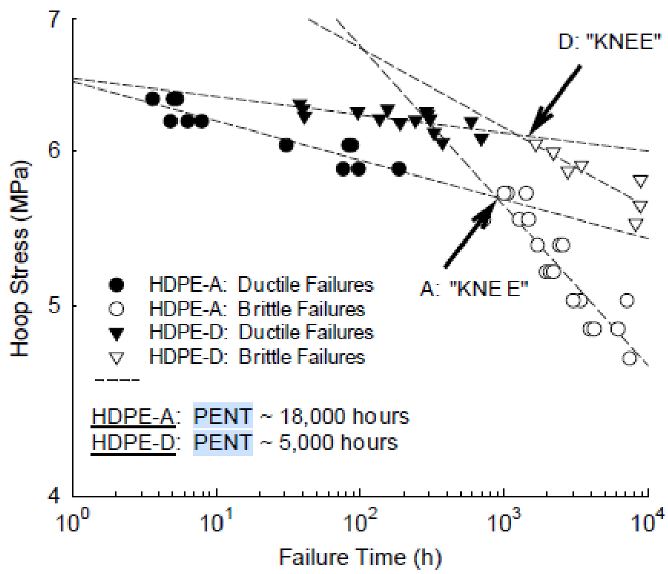


Figure 3. Pipe hoop stress versus failure time data for HDPE-A and HDPE-D at 80◦C.

Since SCG is the most common mode of failure in HDPE pipe applications, significant study has been conducted to replicate the brittle fracture process through accelerated lab testing (i.e., the development of Pennsylvania edge-notch tensile test (PENT) (ASTM F1473) method and the full notch creep test (FNCT, ISO 16770.3)). However, Krishnaswami 2005 did not find any correlation between brittle failures in HDPE pressure pipes and PENT failure time.

While HDPE material is highly susceptible to creep and ratchetting, PVC shows comparatively better resistance to creep and ratcheting. (Jeya et al. 2017) experimentally studied the impact of compressive creep and thermal ratcheting on mechanical behavior of HDPE and PVC. The experimental investigation was performed in two phases. The first phase is the compressive creep analysis of both materials for short period (4-5 days) under varying stress and temperatures. The second phase in the thermal ratchetting evaluation that consists of a 20 thermal cycles between the target and ambient temperature. This testing was performed on the first or second day of creep test. The test conditions and parameters are described in Tables 2 and 3.

Table 2: Creep test parameters (after Jeya et al. 2017)

High Density PolyEthylene & PVC			
Test #	Temperature (°C)	Stress (MPa)	Time Period of test
# 1	23	7, 14 & 21	5 days
# 2	50	7 & 14	5 days
# 3	60	7 & 14	5 days
# 4	70	7, 14 & 21	5 days
# 5	45	20 & 30	5 days

Table 3: Thermal Ratchetting test conditions (after Jeya et al. 2017)

Test #	Applied Stress (MPa)	Creep Temp (°C)	Ratcheting Temp (°C)	Days of creep + # of thermal cycles
High Density Polyethylene				
T1	14	23	28 - 55	1 + 20
T2	7	23	28 - 55	1 + 20
T3	14	-	28 - 55	0 + 20
PolyVinyl Chloride				
T5	21	23	28 - 55	1 + 20
T6	27	23	28 - 55	1 + 20

The creep and thermal ratchetting test results indicate that the creep strain for both materials increase with an increase in compressive stress. It is also evident that depending on the magnitude of the applied stress it takes different time periods for the materials to reach secondary creep condition.

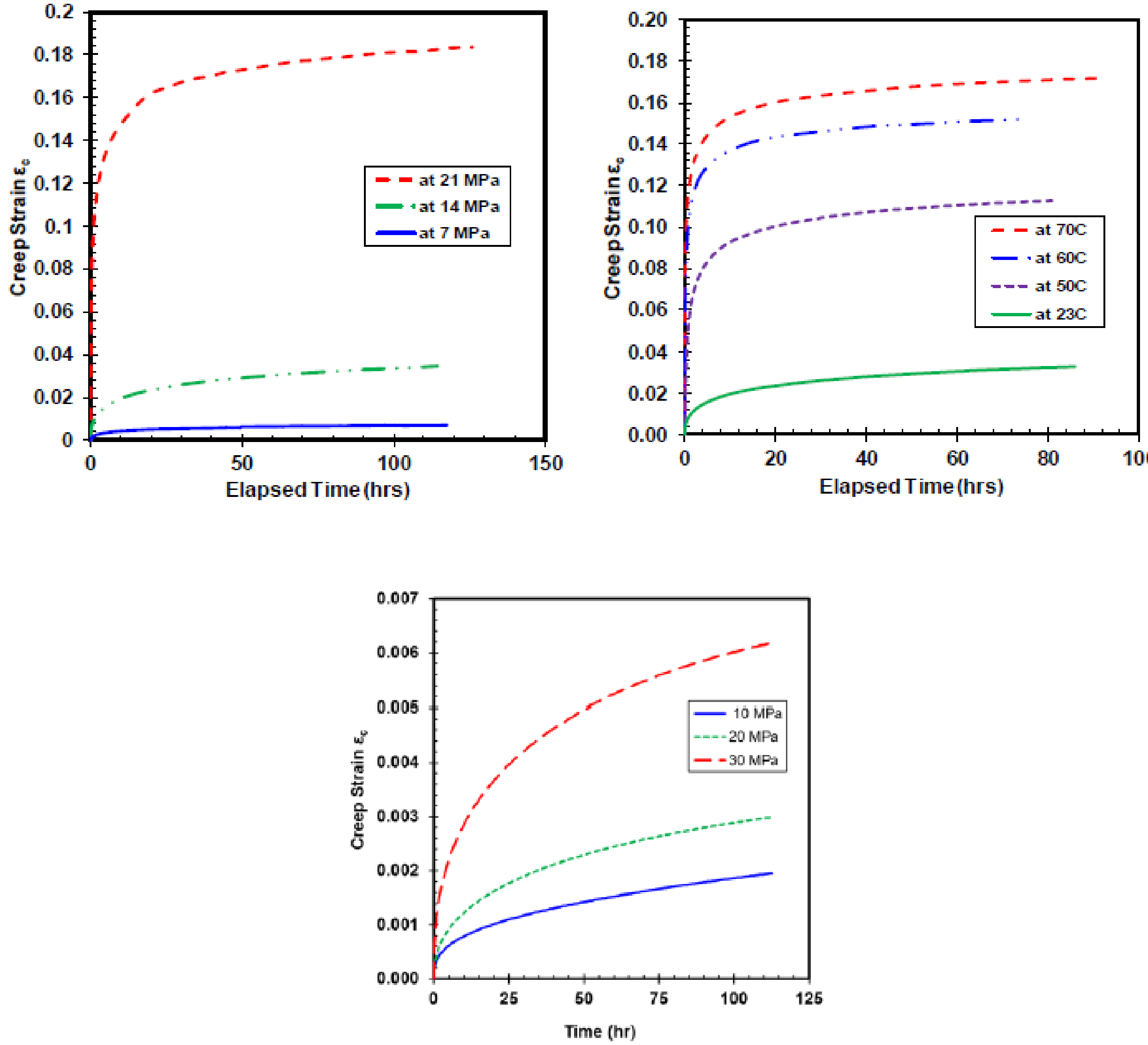


Figure 4. Creep strain (a) HDPE under different loads at room temperature, (b) DDPE under 14 MPa at different temperature, (c) PVC under different loads at 45◦C (after Jeya et al. 2017).

Another significant mechanical property of polymer materials is creep modulus. The creep modulus is the varying instantaneous elastic modulus of a material. The creep modulus can be determined by diving the creep stress with creep strain. Figure 5. indicates a decrease in creep modulus over time under various stresses for HDPE and PVC.

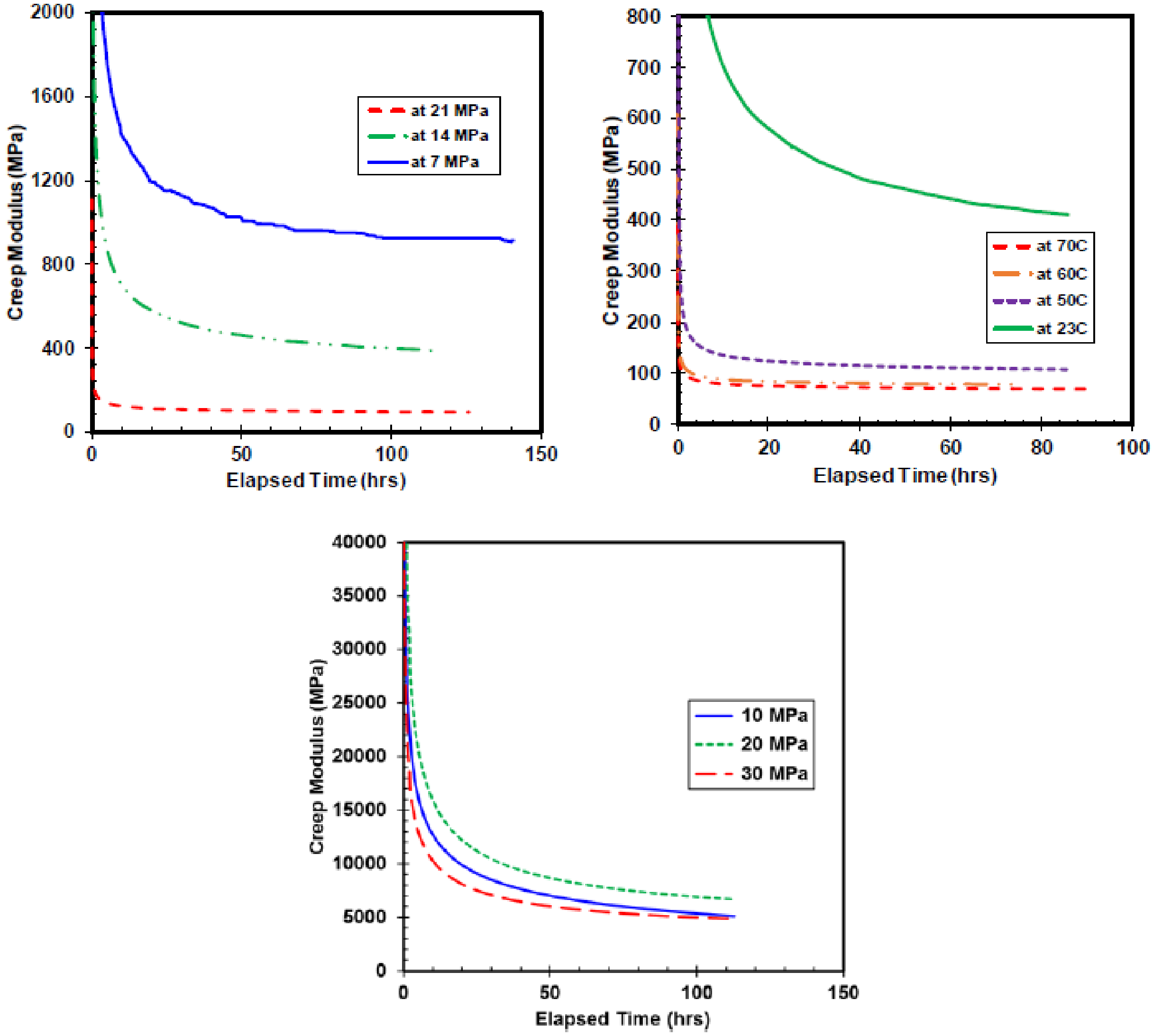


Figure 5. Creep modulus (a) HDPE under different loads at room temperature, (b) DDPE under 14 MPa at different temperature, (c) PVC under different loads at 45◦C (after Jeya et al. 2017)

The thermal ratchetting of HDPE and PVC pipes causes cumulative deformation in the material. The application of cyclic fluctuation of temperature harms the structure of the polymers and changes the physical dimensions of the structure.

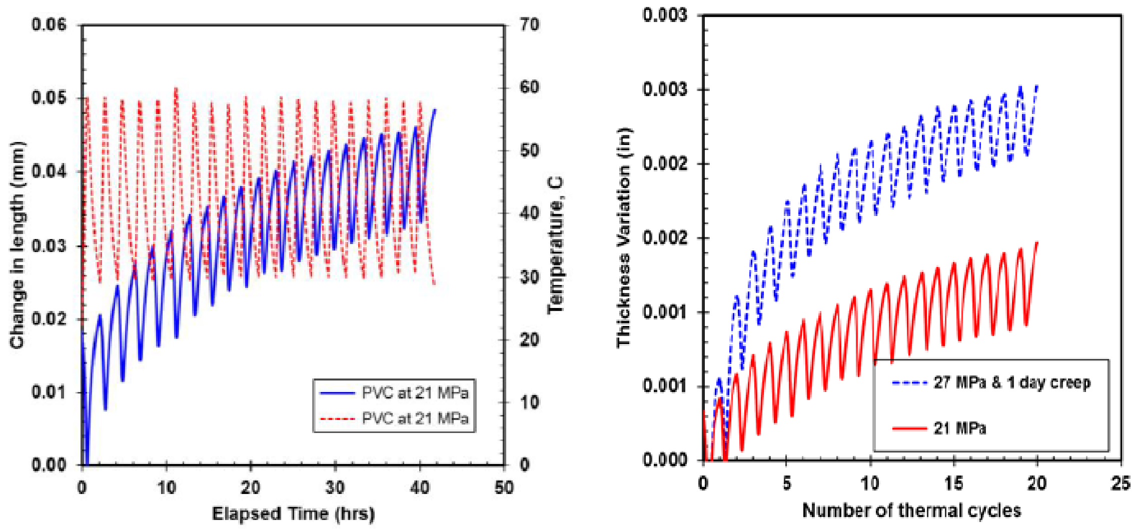


Figure 6. Change in length under thermal ratcheting of a (a) PVC with 1 day creep at 21 Mpa (b) HDPE with and without 1 day creep at 14 Mpa (after Jeya et al. 2017)

References:

Gedde, U. W., & Jansson, J. F. (1985). Molecular fractionation in melt-crystallized polyethylene: 4. Fracture. *Polymer*, *26*(10), 1469-1476.

Hubert, L., David, L., Seguela, R., Vigier, G., Degoulet, C., & Germain, Y. (2001). Physical and mechanical properties of polyethylene for pipes in relation to molecular architecture. I. Microstructure and crystallisation kinetics. *Polymer*, *42*(20), 8425-8434.

Kanthabhabha Jeya, R. P.,Zhao, Z. , Bouzid, A. H. (2017). Creep and Thermal Ratcheting Behavior of Polymeric Materials under Compression, The 2017 World Congress on Advances in Structural Engineering and Mechanics (ASEM17), 28 Aug – 1 Sept, 2017, Seoul, Korea.

Krishnaswamy, R. K. (2005). Analysis of ductile and brittle failures from creep rupture testing of high-density polyethylene (HDPE) pipes. *Polymer*, *46*(25), 11664-11672.

Lu, X., Zhou, Z., & Brown, N. (1997). A sensitive mechanical test for slow crack growth in polyethylene. *Polymer Engineering & Science*, *37*(11), 1896-1900.

APPENDIX F:

VBA codes for PASS

Module 1: pH calculation

PASS_ver04.xlsm - Module1 (Code)

(General) | Main_Process

```
Sub Main_Process() 'pH calculation

    'Define variables and data type
    Dim cntR As Double
    Dim Var_DB(1 To 4) As Variant
    Dim Val_X As Double, Val_Y As Double, Val_Result As Variant, Val_Temp As Variant
    Dim Ws As Worksheet, rng As Range

    With Sheets("PIPE MATERIAL SELECTION GUIDE")


        If .Cells(4, "G").Value = "" Then                       'If the longitude cell is empty
            MsgBox "Please input longitude value.", vbCritical, "" 'A pop-up box will appear on screeen
            Exit Sub                                            'Exit this procedure

        ElseIf .Cells(4, "H").Value = "" Then                   'If the latitude cell is empty
            MsgBox "Please input latitude value.", vbCritical, ""  'A pop-up box will appear on screeen
            Exit Sub                                            'Exit this procedure
        End If

        Val_X = .Cells(4, "G").Value 'longitude value
        Val_Y = .Cells(4, "H").Value 'latitude value

    End With

    Val_Result = 999999

    For Each Ws In Worksheets
        If Ws.Tab.Color = vbBlue Then
            With Ws
                cntR = .Cells(Rows.Count, 1).End(xlUp).Row
                If cntR > 1 Then
                    Set rng = .Range(.Cells(2, 1), .Cells(cntR, 1))
                    For Each rng In rng
                        Val_Temp = Sqr((Val_X - .Cells(rng.Row, 3).Value) ^ 2 + (Val_Y - .Cells(rng.Row, 4).Value) ^ 2)
                        If Val_Result > Val_Temp Then

                            Val_Result = Val_Temp

                            Var_DB(1) = .Cells(rng.Row, 3).Value
                            Var_DB(2) = .Cells(rng.Row, 4).Value
                            Var_DB(3) = .Cells(rng.Row, 2).Value
                        End If
                    Next
                End If
            End With
        End If
    Next

    With Sheets("PIPE MATERIAL SELECTION GUIDE")
        .Cells(4, 1).Value = Var_DB(3)
        .Cells(5, 1).Value = Var_DB(1)
        .Cells(5, 2).Value = Var_DB(2)
    End With


End Sub
```

Module2: resistivity calculation

PASS_ver04.xlsm - Module2 (Code)

(General) | Main2_Process

```
Sub Main2_Process() 'Resistivity calculation

    'Define variables and data type
    Dim cntR As Double
    Dim Var_DB(1 To 4) As Variant
    Dim Val_X As Double, Val_Y As Double, Val_Result As Variant, Val_Temp As Variant
    Dim Ws As Worksheet, rng As Range

    With Sheets("PIPE MATERIAL SELECTION GUIDE")


        If .Cells(4, "G").Value = "" Then                          'If the longitude cell is empty
            MsgBox "Please input longitude value.", vbCritical, "" 'A pop-up box will appear on screeen
            Exit Sub                                               'Exit this procedure

        ElseIf .Cells(4, "H").Value = "" Then                      'If the latitude cell is empty
            MsgBox "Please input latitude value.", vbCritical, ""  'A pop-up box will appear on screeen
            Exit Sub                                               'Exit this procedure
        End If

        Val_X = .Cells(4, "G").Value 'longitude value
        Val_Y = .Cells(4, "H").Value 'latitude value

    End With

    Val_Result = 999999

    For Each Ws In Worksheets
        If Ws.Tab.Color = vbYellow Then
            With Ws
                cntR = .Cells(Rows.Count, 1).End(xlUp).Row
                If cntR > 1 Then
                    Set rng = .Range(.Cells(2, 1), .Cells(cntR, 1))
                    For Each rng In rng
                        Val_Temp = Sqr((Val_X - .Cells(rng.Row, 3).Value) ^ 2 + (Val_Y - .Cells(rng.Row, 4).Value) ^ 2)
                        If Val_Result > Val_Temp Then

                            Val_Result = Val_Temp

                            Var_DB(1) = .Cells(rng.Row, 3).Value
                            Var_DB(2) = .Cells(rng.Row, 4).Value
                            Var_DB(3) = .Cells(rng.Row, 2).Value

                        End If
                    Next
                End If
            End With
        End If
    Next

    With Sheets("PIPE MATERIAL SELECTION GUIDE")
        .Cells(4, 2).Value = Var_DB(3)
        .Cells(5, 3).Value = Var_DB(1)
        .Cells(5, 4).Value = Var_DB(2)
    End With


End Sub
```

Module 3: chloride calculation

PASS_ver04.xlsm - Module3 (Code)

(General) | Main3_Process

```
Sub Main3_Process() 'Chloride calculation

    'Define variables and data type
    Dim cntR As Double
    Dim Var_DB(1 To 4) As Variant
    Dim Val_X As Double, Val_Y As Double, Val_Result As Variant, Val_Temp As Variant
    Dim Ws As Worksheet, rng As Range

    With Sheets("PIPE MATERIAL SELECTION GUIDE")


        If .Cells(4, "G").Value = "" Then                             'If the longitude cell is empty
            MsgBox "Please input longitude value.", vbCritical, ""   'A pop-up box will appear on screeen
            Exit Sub                                                  'Exit this procedure

        ElseIf .Cells(4, "H").Value = "" Then                         'If the latitude cell is empty
            MsgBox "Please input latitude value.", vbCritical, ""    'A pop-up box will appear on screeen
            Exit Sub                                                  'Exit this procedure
        End If

        Val_X = .Cells(4, "G").Value 'longitude value
        Val_Y = .Cells(4, "H").Value 'latitude value

    End With

    Val_Result = 999999

    For Each Ws In Worksheets
        If Ws.Tab.Color = vbRed Then
            With Ws
                cntR = .Cells(Rows.Count, 1).End(xlUp).Row
                If cntR > 1 Then
                    Set rng = .Range(.Cells(2, 1), .Cells(cntR, 1))
                    For Each rng In rng
                        Val_Temp = Sqr((Val_X - .Cells(rng.Row, 6).Value) ^ 2 + (Val_Y - .Cells(rng.Row, 7).Value) ^ 2)
                        If Val_Result > Val_Temp Then

                            Val_Result = Val_Temp
                            Debug.Print "Distance: " & Val_Temp & " / X: " & .Cells(rng.Row, 6).Value & " / Y: " & .Cells(rng.Row, 7).Value
                            Var_DB(1) = .Cells(rng.Row, 6).Value
                            Var_DB(2) = .Cells(rng.Row, 7).Value
                            Var_DB(3) = .Cells(rng.Row, 5).Value

                        End If
                    Next
                End If
            End With
        End If
    Next

    With Sheets("PIPE MATERIAL SELECTION GUIDE")
        .Cells(4, 4).Value = Var_DB(3)
        .Cells(5, 5).Value = Var_DB(1)
        .Cells(5, 6).Value = Var_DB(2)
    End With

End Sub
```

Module 4: Recalling aggregates data to PASS

PASS_ver04.xlsm - Module4 (Code)

(General) (Declarations)

```
Option Explicit

Sub MasterMacro()

    Application.Calculation = xlCalculationManual

    Call Main_Process
    Call Main2_Process
    Call Main3_Process

    Application.Calculation = xlCalculationAutomatic

    MsgBox "Complete", vbInformation, ""
End Sub
```

```
Sub Main_Gethering()

    Dim i As Double
    Dim cntR As Double, cntC As Double
    Dim rng As Range
    Dim Wb As Workbook
    Dim str_File As String
    Dim Var_Sheet(1 To 2) As Variant

    Var_Sheet(1) = "Latest Data Fine Aggregate"
    Var_Sheet(2) = "Latest Data Coarse Aggregate"

    str_File = ThisWorkbook.Path & "\" & "ElectroChemical Aggregates.xlsm"
    If Dir(str_File, vbNormal) = "" Then
        MsgBox "ElectroChemical Aggregates.xlsm file does not be included in the folder.", vbCritical, ""
        Exit Sub
    End If

Application.ScreenUpdating = False

    On Error Resume Next
    Application.DisplayAlerts = False
    For i = 1 To UBound(Var_Sheet)
        ThisWorkbook.Sheets(Var_Sheet(i)).Delete
    Next i
    Application.DisplayAlerts = True
    On Error GoTo 0

    Set Wb = Workbooks.Open(str_File, False)
    With Wb
        For i = 1 To UBound(Var_Sheet)
            With Wb.Sheets(Var_Sheet(i))
                .Activate

                cntR = .Cells(Rows.Count, 1).End(xlUp).Row
                cntC = .Cells(1, Columns.Count).End(xlToRight).Column

                Set rng = .Range(.Cells(1, 1), .Cells(cntR, cntC))
                rng.Copy

                rng.PasteSpecial xlPasteValues

                .Copy after:=ThisWorkbook.Sheets(ThisWorkbook.Sheets.Count)
            End With
        Next i

        Wb.Close False
    End With
```

Module 4 continued

PASS_ver04.xlsm - Module4 (Code)

(General) | Main_Gethering

```
    With ThisWorkbook.Sheets("PIPE MATERIAL SELECTION GUIDE")

        With .DropDowns("List_Type")
            .RemoveAllItems
            For i = 1 To UBound(Var_Sheet)
                .AddItem Var_Sheet(i)
            Next i
        End With

        With .DropDowns("List_Desc")
            .RemoveAllItems
        End With

        .Range(.Cells(10, 3), .Cells(14, 10)).ClearContents
        .Activate
    End With
Application.ScreenUpdating = True

    MsgBox "Completed", vbInformation, ""
End Sub

Sub Select_Material_Type()

    Dim i As Double
    Dim str_Temp As String
    Dim Obj_List As DropDown, Obj_Desc As DropDown, rng As Range
    Dim cntR As Double
    Dim C As New Collection
    Dim Ws As Worksheet

    With Sheets("PIPE MATERIAL SELECTION GUIDE")
        Set Obj_List = .DropDowns("List_Type")
        Set Obj_Desc = .DropDowns("List_Desc")

        With Obj_List
            str_Temp = .List(.ListIndex)
        End With

        Obj_Desc.RemoveAllItems
    End With

    If str_Temp <> "" Then
        Set Ws = Sheets(str_Temp)
        With Ws
            cntR = .Cells(Rows.Count, 4).End(xlUp).Row
            Set rng = .Range(.Cells(2, 4), .Cells(cntR, 4))

            On Error Resume Next
            For Each rng In rng
                If rng.Value <> "" Then
                    C.Add rng.Value, rng.Value
                End If
            Next
            On Error GoTo 0
        End With
    End If

    With Obj_Desc
        For i = 1 To C.Count
            .AddItem C.Item(i)
        Next i
    End With
```

Module 4 continued

PASS_ver04.xlsm - Module4 (Code)

(General) | Select_Material_Type

```
End Sub

Sub Search_NearDistance()

    Call Search_Detail(Return_Selected("List_Type"), Return_Selected("List_Desc"))

End Sub

Sub Search_Detail(str_A As String, str_B As String)

    Dim i As Double, i2 As Double
    Dim Val_Result As Variant, Val_Temp As Double
    Dim Ws As Worksheet, Sh_Main As Worksheet, rng As Range
    Dim cntR As Double
    Dim Val_X As Double, Val_Y As Double
    Dim C As New Collection

    Dim Var_DB() As Variant

    Set Sh_Main = Sheets("PIPE MATERIAL SELECTION GUIDE")
    With Sh_Main
        Val_X = .Cells(4, "G").Value 'longitude value
        Val_Y = .Cells(4, "H").Value 'latitude value

        .Range(.Cells(10, 3), .Cells(14, 10)).ClearContents
    End With

    If str_A <> "" And str_B <> "" Then
        Set Ws = Sheets(str_A)

        With Ws
            cntR = .Cells(Rows.Count, 1).End(xlUp).Row
            Set rng = .Range(.Cells(2, 1), .Cells(cntR, 1))

            Val_Result = 999999

            For Each rng In rng
                If .Cells(rng.Row, 7).Value <> "" Then
                    If .Cells(rng.Row, 7).Value <> 0 Then
                        If .Cells(rng.Row, 4).Value = str_B Then
                            Val_Temp = Sqr((Val_X - .Cells(rng.Row, 9).Value) ^ 2 + (Val_Y - .Cells(rng.

                            i = i + 1
                            ReDim Preserve Var_DB(1 To 2, 1 To i)
                            Var_DB(1, i) = rng.Row
                            Var_DB(2, i) = Val_Temp

                        End If
                    End If
                End If
            Next
        End With

        If Check_Array(Var_DB) = True Then
            Var_DB = Return_Sort(Var_DB)
            For i = 1 To UBound(Var_DB, 2)
                C.Add Var_DB(1, i)
            Next i
        End If

        i2 = 0
        With Sh_Main
            For i = 1 To C.Count
```

Module 4 continued

PASS_ver04.xlsm - Module4 (Code)

(General) | Search_Detail

```
            For i = 1 To C.Count
                .Cells(10 + i2, 3).Value = Ws.Cells(C.Item(i), 2).Value
                .Cells(10 + i2, 4).Value = Ws.Cells(C.Item(i), 5).Value
                .Cells(10 + i2, 5).Value = Ws.Cells(C.Item(i), 13).Value
                .Cells(10 + i2, 6).Value = Ws.Cells(C.Item(i), 12).Value
                .Cells(10 + i2, 7).Value = Ws.Cells(C.Item(i), 14).Value
                .Cells(10 + i2, 8).Value = Ws.Cells(C.Item(i), 15).Value
                .Cells(10 + i2, 9).Value = Ws.Cells(C.Item(i), 16).Value
                .Cells(10 + i2, 10).Value = Ws.Cells(C.Item(i), 17).Value

                i2 = i2 + 1
                If i2 = 4 Then Exit For
            Next i
        End With
    End If
End Sub

Function Check_Array(Var_Temp As Variant) As Boolean

    Dim a As Double

    On Error Resume Next
        a = UBound(Var_Temp) + 1
    On Error GoTo 0

    If a > 0 Then
        Check_Array = True
    Else
        Check_Array = False
    End If
End Function
Function Return_Sort(Var_DB As Variant)

    Dim i As Double, i2 As Double
    Dim Var_Temp(1 To 2) As Variant

    For i = 1 To UBound(Var_DB, 2)
        For i2 = i + 1 To UBound(Var_DB, 2)
            If Var_DB(2, i) > Var_DB(2, i2) Then
                Var_Temp(1) = Var_DB(1, i)
                Var_Temp(2) = Var_DB(2, i)

                Var_DB(1, i) = Var_DB(1, i2)
                Var_DB(2, i) = Var_DB(2, i2)

                Var_DB(1, i2) = Var_Temp(1)
                Var_DB(2, i2) = Var_Temp(2)
            End If
        Next i2
    Next i

    Return_Sort = Var_DB
End Function
Function Return_Selected(str_Temp As String)

    Dim Obj_List As DropDown

    With Sheets("PIPE MATERIAL SELECTION GUIDE")
        Set Obj_List = .DropDowns(str_Temp)

        With Obj_List
            Return_Selected = .List(.ListIndex)
        End With
    End With
End Function
```

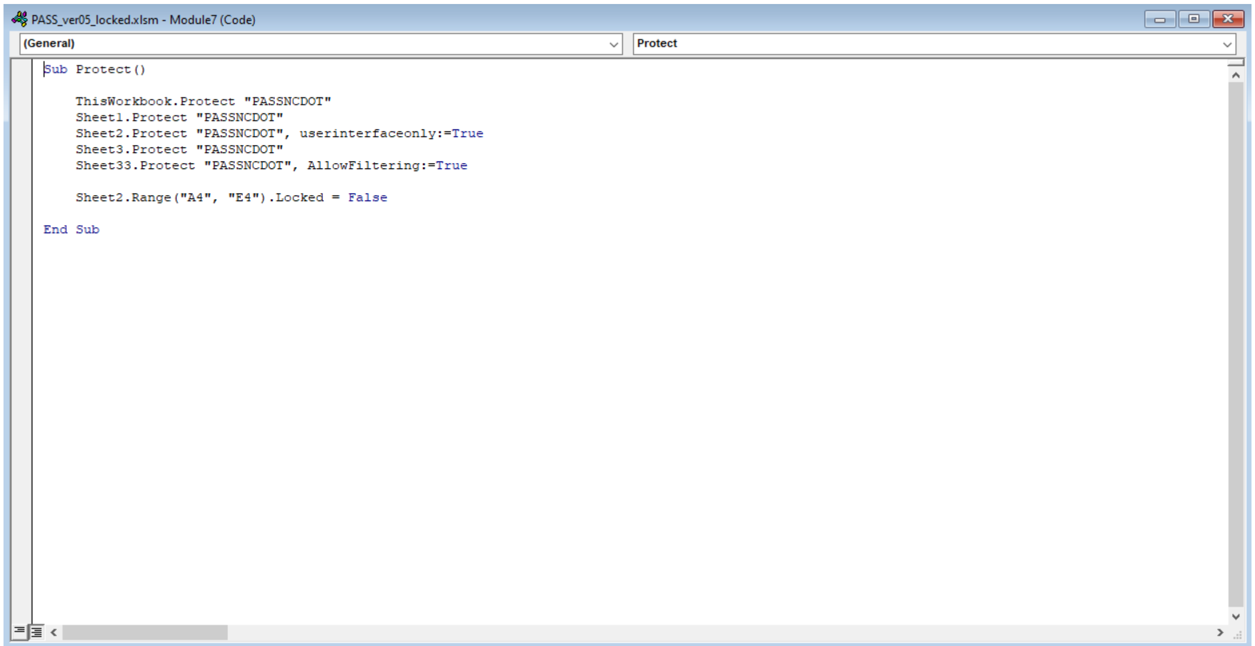
Module 5: check box to recall quarry data to the user input box

PASS_ver04.xlsm - Module5 (Code)

(General) | CheckBox16_Click

```
Sub CheckBox11_Click()

    If ActiveSheet.Shapes("Check Box 11").ControlFormat.Value = 1 Then

        With Sheets("PIPE MATERIAL SELECTION GUIDE")
            .Cells(4, 1).Value = .Cells(10, 5).Value
            .Cells(4, 2).Value = .Cells(10, 6).Value
            .Cells(4, 4).Value = .Cells(10, 7).Value
        End With
    Else

    End If

End Sub
Sub CheckBox12_Click()

    If ActiveSheet.Shapes("Check Box 12").ControlFormat.Value = 1 Then

        With Sheets("PIPE MATERIAL SELECTION GUIDE")
            .Cells(4, 1).Value = .Cells(11, 5).Value
            .Cells(4, 2).Value = .Cells(11, 6).Value
            .Cells(4, 4).Value = .Cells(11, 7).Value
        End With
    Else

    End If

End Sub
Sub CheckBox13_Click()

    If ActiveSheet.Shapes("Check Box 13").ControlFormat.Value = 1 Then

        With Sheets("PIPE MATERIAL SELECTION GUIDE")
            .Cells(4, 1).Value = .Cells(12, 5).Value
            .Cells(4, 2).Value = .Cells(12, 6).Value
            .Cells(4, 4).Value = .Cells(12, 7).Value
        End With
    Else

    End If

End Sub
Sub CheckBox16_Click()

    If ActiveSheet.Shapes("Check Box 16").ControlFormat.Value = 1 Then

        With Sheets("PIPE MATERIAL SELECTION GUIDE")
            .Cells(4, 1).Value = .Cells(13, 5).Value
            .Cells(4, 2).Value = .Cells(13, 6).Value
            .Cells(4, 4).Value = .Cells(13, 7).Value
        End With
    Else

    End If

End Sub
```

Module 6: Protecting excel file (for the locked version)




```
Sub Protect()

    ThisWorkbook.Protect "PASSNCDOT"
    Sheet1.Protect "PASSNCDOT"
    Sheet2.Protect "PASSNCDOT", userinterfaceonly:=True
    Sheet3.Protect "PASSNCDOT"
    Sheet33.Protect "PASSNCDOT", AllowFiltering:=True

    Sheet2.Range("A4", "E4").Locked = False

End Sub
```

APPENDIX G:

PASS user manual

PASS overview – instruction and reference tab:

PASS has 4 different tabs: instruction, discount rate, pipe material selection guide, and reference tabs. Figure 1 shows the instruction tab which briefly explains PASS program. In the reference tab, shown in Figure 2, there are acceptable ranges for different pipe materials and abrasion levels from FHWA. These references are all applied in calculating estimated service life of pipe materials in pipe material selection guide tab.

User Instructions: **USER INPUT & GPS COORDINATES**

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

BACKFILL MATERIAL

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

Discount Rate

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

Figure 1. Instruction tab of PASS

Acceptable ranges for different pipe materials

Material	pH (soil)	Resistivity (Ohm-cm)	In Soil: Chloride (%)	In Soil: Sulfate (%)	Abrasion level
Reinforced concrete pipe (RCP)	5.5 < pH < 12.0	All	< 0.5	< 0.5	< 3
Galvanized CSP	6.0 < pH < 10.0	R > 2,000	< 0.2	< 0.2	< 2
Aluminized Type 2 CSP	5.0 < pH < 9.0	R > 1,500	< 0.2	< 0.2	< 2
Aluminum	4.5 < pH < 9.0	R > 1,500	< 0.5	< 0.5	< 2
Steel pipe	6.0 < pH < 8.5	R > 2,200	< 0.05	< 0.05	< 2
Cast iron pipe	5.0 < pH < 9.0	R > 2,000	< 0.05	< 0.05	< 2
Plastic (PVC, PP, HDPE)	1.25 < pH < 15.0	All	-	-	< 3

Abrasion level (FHWA)

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

Figure 2. Reference tab of PASS

Using PASS – estimating service life of pipe materials

In Figure 3, one can input their GPS coordinates of the project in the section highlighted in a red box. It should be noted that the value of longitude should be a **negative** value. By pressing the "GET the values of pH, resistivity, and chloride" button, the values are populated for the project coordinates. For example, putting Raleigh coordinates (-78.638, 35.779) will result in pH of 6.2, resistivity of 10,000 ohm-cm, and low chloride concentration as shown in Figure 4. To consider abrasion and cast iron pipe, one needs to input abrasion level and nominal diameter (inner diameter) of cast iron pipe as shown in Figure 4. As soon as values are provided estimated service life for different materials with different gages will be presented in the service life estimation (year) section as shown in Figure 5.

GPS COORDINATES[2]	
LONGITUDE	LATITUDE
-78.638	35.779

*Note that the value of longitude should be negative

GET the values of pH, resistivity, and chloride

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

Figure 3. PASS example – inputting GPS coordinates and pushing the button

Raleigh coordinates

GPS COORDINATES[2]	
LONGITUDE	LATITUDE
-78.638	35.779

*Note that the value of longitude should be negative

GET the values of pH, resistivity, and chloride

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

Figure 4. PASS example – getting parameters and inputting abrasion level and nominal diameter (inside diameter) of cast iron pipe

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

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

Figure 5. PASS example – getting a service life estimation

Definition of service life of each material:

The following definitions for service life of different materials are used

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

Updating information of quarries:

Since the physiochemical aggregates data could be updated continuously, PASS was programmed to transfer the excel data from the original dataset as two separate tabs (Latest data on fine aggregate and Latest data on coarse aggregate) as shown in Figure 6. Note that the name and the type of file of the original dataset must be "**ElectroChemical Aggregates.xlsm**". In addition to that, the original dataset **must be in the same folder** where PASS program is in. After inputting project GPS coordinates and pressing "Update Aggregate Data" that is highlighted with a red box in Figure 7, engineers can select material type and material description that fit with their objective.

Figure 6. PASS example – tabs before and after recalling physiochemical data of aggregates

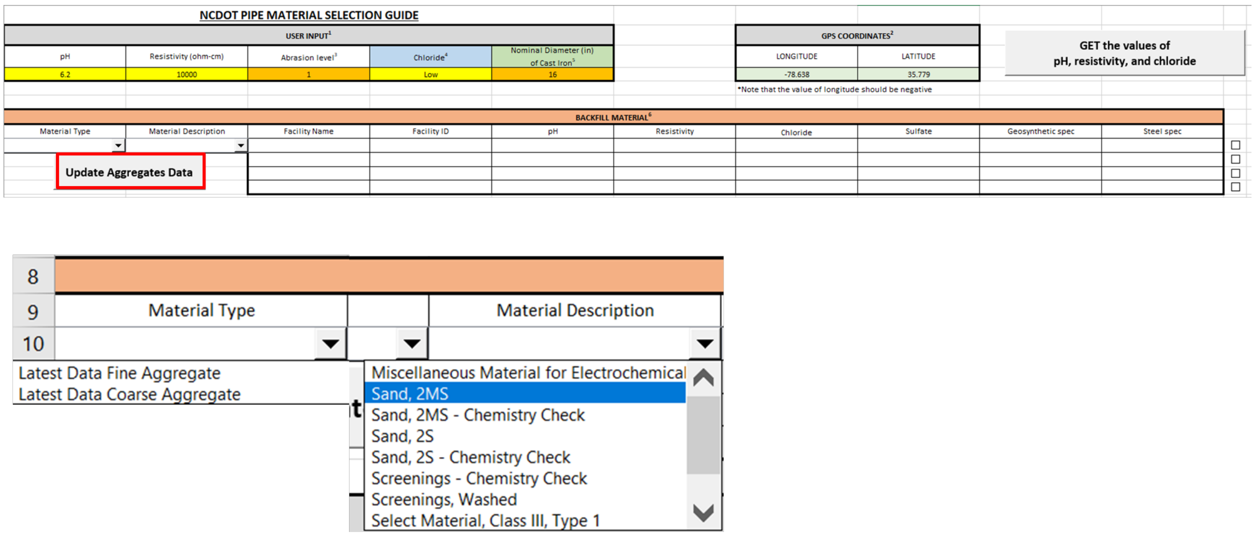


Figure 7. PASS example – recalling physiochemical data of aggregate and selecting material type and material description

Four closest quarries to a given project location will be identified in PASS automatically based on the GPS coordinates, selected Material Type, and Material Description as shown in Figure 8. There are boxes next to identified four closest quarries; by checking one of the boxes, achievable parameters (pH, resistivity, and chloride concentration) will be changed based on the selected quarry condition. The service life estimation section will be adjusted referring to the changed condition as shown in Figure 9.

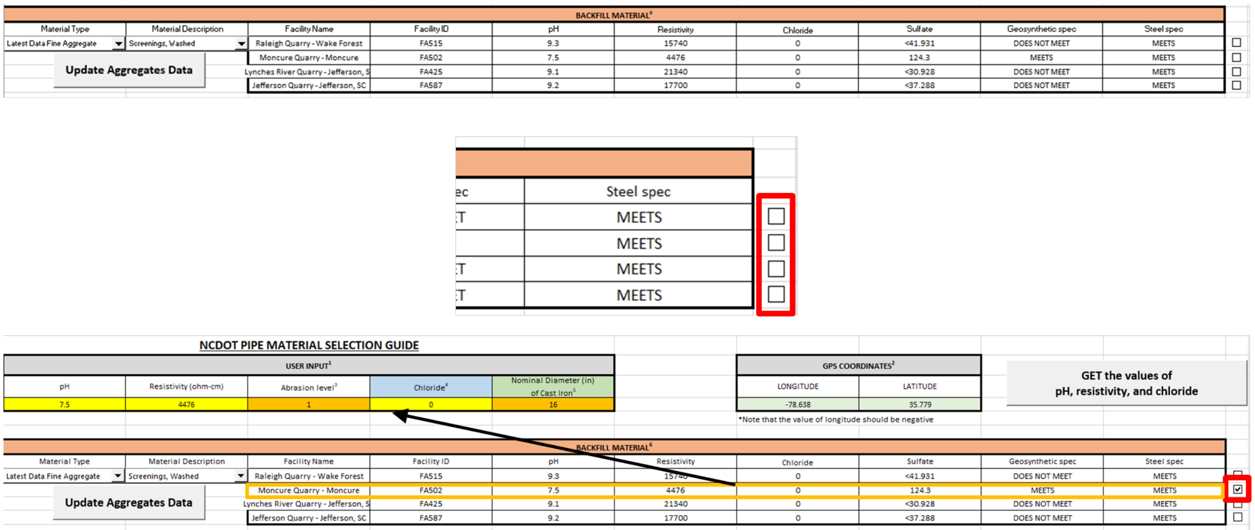
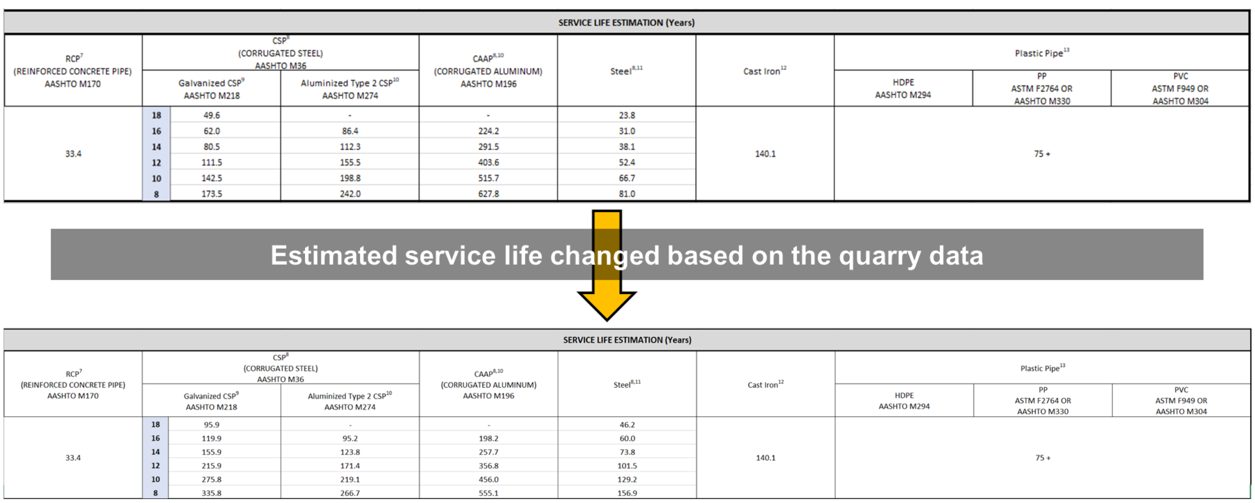


Figure 8. PASS example – identified four closest quarries and recalling the condition of selected quarry



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

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

Figure 9. PASS example – service life estimation before and after checking quarry data

Usage of PASS – discount rate:

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

Figure 10 shows the platform that engineers can use to calculate the discount rate of desired pipe materials; after engineers select their desired material types and sizes, discount rate in percent will be calculated in the green box automatically as soon as engineers input the averaged coating thickness (µm) from their measurement.

Figure 11 shows the variable parameters for discount rate calculation in PASS. Different values will be changed in accordance with the types and sizes of pipes.

DISCOUNT RATE

Aluminized Type 2 pipe	10 Ga
Measured coating thickness (µm)	60
Discount rate (%)	0.0

Figure 10. Discount rate calculation user interface in PASS

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

Figure 11. Variable parameters for discount rate calculation

APPENDIX H:

Results of coating thickness measurements

Coating Thickness Measurements

The mean coating thickness values obtained using 3, 6, 10, and 15 measurements were compared using ANOVA and Tukey's HSD analysis with R studio. The statistical analyses seek to discern the mean coating thickness is dependent on the number of measurements per pipe segment, and assess the minimum number of measurements to eliminate such dependency using an electromagnetic measuring device. Table 1 compares the average values obtained using different number of coating thickness measurements. In Table 1, "O" means that the mean values of each of the compared number of measurement groups are not significantly different (P-value > 0.05) and "X" means that the means of the compared groups are significantly different (P-value < 0.05).

The results from vendor 1 show high variability in 12- and 16-gauge aluminized pipe except for the comparison of 10 and 15 times. However, the results from the vendor 2 indicate quite consistent coating thickness with different number of measurements. Since the measuring procedure cannot be different from vendor to vendor (e.g., 10 times for vendor 1 and 3 times for vendor 2), we suggested that at least 10 measurements would be required to properly represent the coating thickness at a given pipe location, regardless of vendors.

Table 29. Comparison of the coating thickness measurement results

	3-6**	3-10**	3-15**	6-10**	6-15**	10-15**
12-V1-Al*	X	O	O	X	X	O
14-V1-Al*	O	O	O	O	O	O
16-V1-Al*	X	X	X	X	X	O
16-V2-Al*	O	O	O	O	O	O
16-V2-Ga*	O	O	O	O	O	O

*: gauge (12, 14, and 16) - vendor (1 or 2) – material (aluminized or galvanized)
**: comparison in different number of measurements

Result 1: 12 gauge, vendor 1, aluminized pipe

```
> fit=aov(Al12$thickness~as.factor(Al12$time))
> summary(fit)
                       Df Sum Sq Mean Sq F value   Pr(>F)
as.factor(Al12$time)    3   5364  1788.0   10.63 1.37e-06 ***
Residuals             240  40355   168.1
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> TukeyHSD(fit,ordered=T)
  Tukey multiple comparisons of means
    95% family-wise confidence level
    factor levels have been ordered

Fit: aov(formula = Al12$thickness ~ as.factor(Al12$time))

$`as.factor(Al12$time)`
           diff       lwr       upr     p adj
15-6   8.029836  1.955360 14.104312 0.0040762
10-6   9.531475  3.457000 15.605951 0.0003857
3-6   12.724754  6.650278 18.799230 0.0000009
10-15  1.501639 -4.572836  7.576115 0.9190890
3-15   4.694918 -1.379558 10.769394 0.1910112
3-10   3.193279 -2.881197  9.267754 0.5257207
```

Figure 1. ANOVA and Tukey's HSD results for 12-V1-Al

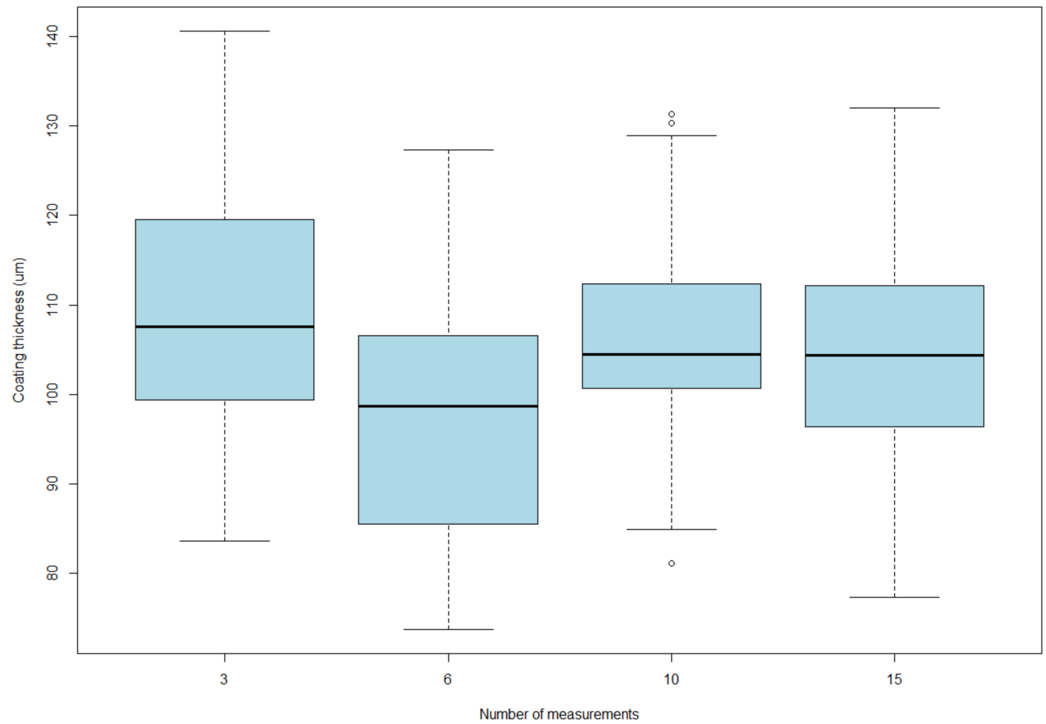


Figure 2. Box plot for 12-V1-Al

Result 2: 14 gauge, vendor 1, aluminized pipe

```
> fit=aov(Al14$thickness~as.factor(Al14$time))
> summary(fit)
                      Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Al14$time)   3    925   308.4   2.386   0.07 .
Residuals            220  28444   129.3
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> TukeyHSD(fit,ordered=T)
  Tukey multiple comparisons of means
    95% family-wise confidence level
    factor levels have been ordered

Fit: aov(formula = Al14$thickness ~ as.factor(Al14$time))

$`as.factor(Al14$time)`
           diff        lwr       upr     p adj
10-6  0.7673214 -4.7955998  6.330243 0.9843630
15-6  3.8294643 -1.7334570  9.392386 0.2847034
3-6   4.8616071 -0.7013141 10.424528 0.1101352
15-10 3.0621429 -2.5007784  8.625064 0.4851032
3-10  4.0942857 -1.4686355  9.657207 0.2287754
3-15  1.0321429 -4.5307784  6.595064 0.9633844
```

Figure 3. ANOVA and Tukey’s HSD results for 14-V1-Al

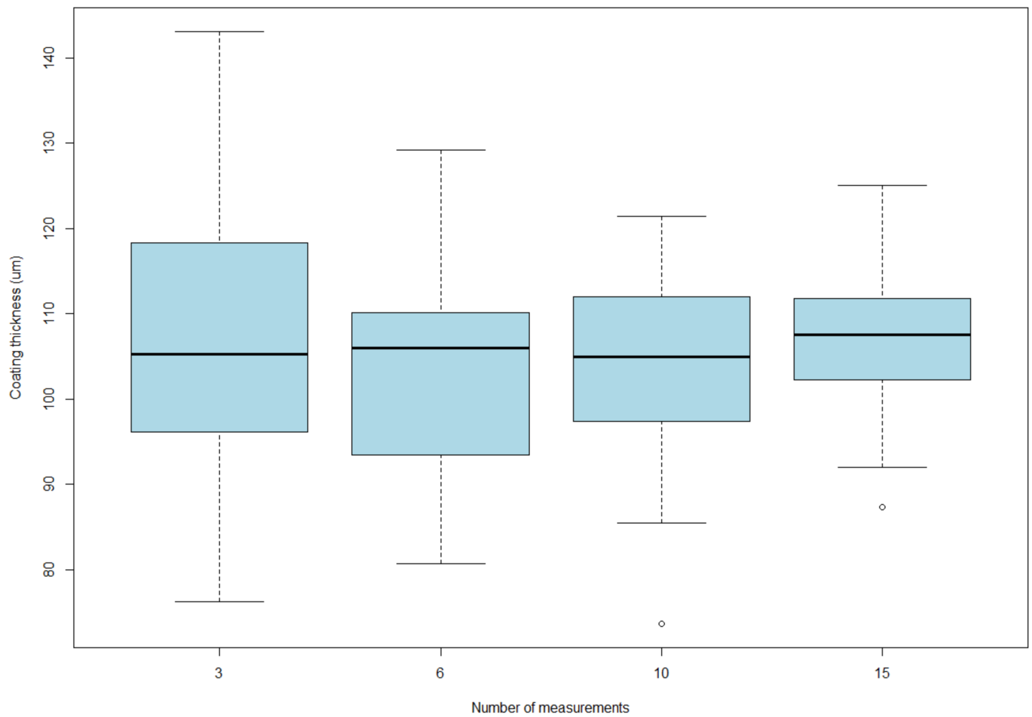


Figure 4. Box plot for 14-V1-Al

Result 3: 16 gauge, vendor 1, aluminized pipe

```
> Al16<- read.csv("SSAl16summary.csv",header=T)
> fit=aov(Al16$thickness~as.factor(Al16$time))
> summary(fit)
                      Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Al16$time)   3  11955    3985   41.86 <2e-16 ***
Residuals            240  22849      95
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> TukeyHSD(fit,ordered=T)
  Tukey multiple comparisons of means
    95% family-wise confidence level
    factor levels have been ordered

Fit: aov(formula = Al16$thickness ~ as.factor(Al16$time))

$`as.factor(Al16$time)`
           diff       lwr       upr     p adj
6-3    7.256230  2.685435 11.827024 0.0003191
10-3  15.874754 11.303959 20.445549 0.0000000
15-3  17.349016 12.778222 21.919811 0.0000000
10-6   8.618525  4.047730 13.189319 0.0000116
15-6  10.092787  5.521992 14.663582 0.0000002
15-10  1.474262 -3.096532  6.045057 0.8380288
```

Figure 5. ANOVA and Tukey's HSD results for 16-V1-Al

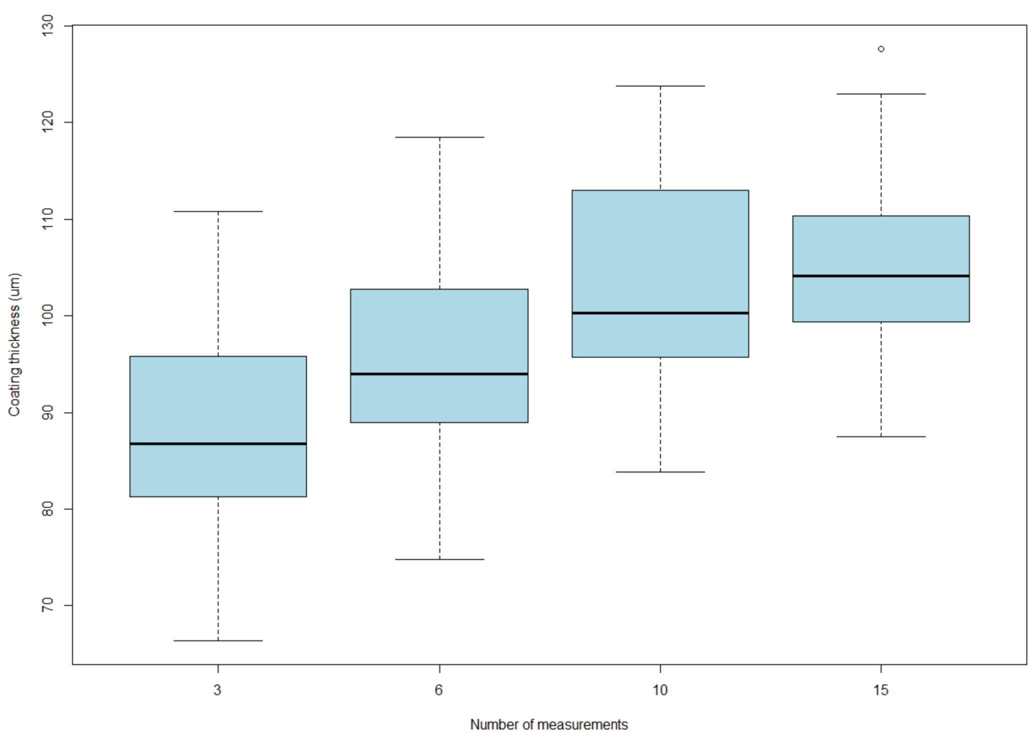


Figure 6. Box plot for 16-V1-Al

Result 4: 16 gauge, vendor 2, aluminized pipe

```
> fit=aov(Al16E$thickness~as.factor(Al16E$time))
> summary(fit)
                       Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Al16E$time)   3    508   169.5   1.651  0.178
Residuals             276  28338   102.7
> TukeyHSD(fit,ordered=T)
  Tukey multiple comparisons of means
    95% family-wise confidence level
    factor levels have been ordered

Fit: aov(formula = Al16E$thickness ~ as.factor(Al16E$time))

$`as.factor(Al16E$time)`
           diff        lwr      upr     p adj
15-10 2.0544286 -2.3725982 6.481455 0.6276799
6-10  2.9535714 -1.4734553 7.380598 0.3129292
3-10  3.5595714 -0.8674553 7.986598 0.1627869
6-15  0.8991429 -3.5278839 5.326170 0.9530056
3-15  1.5051429 -2.9218839 5.932170 0.8158639
3-6   0.6060000 -3.8210268 5.033027 0.9847833
```

Figure 7. ANOVA and Tukey's HSD results for 16-V2-Al

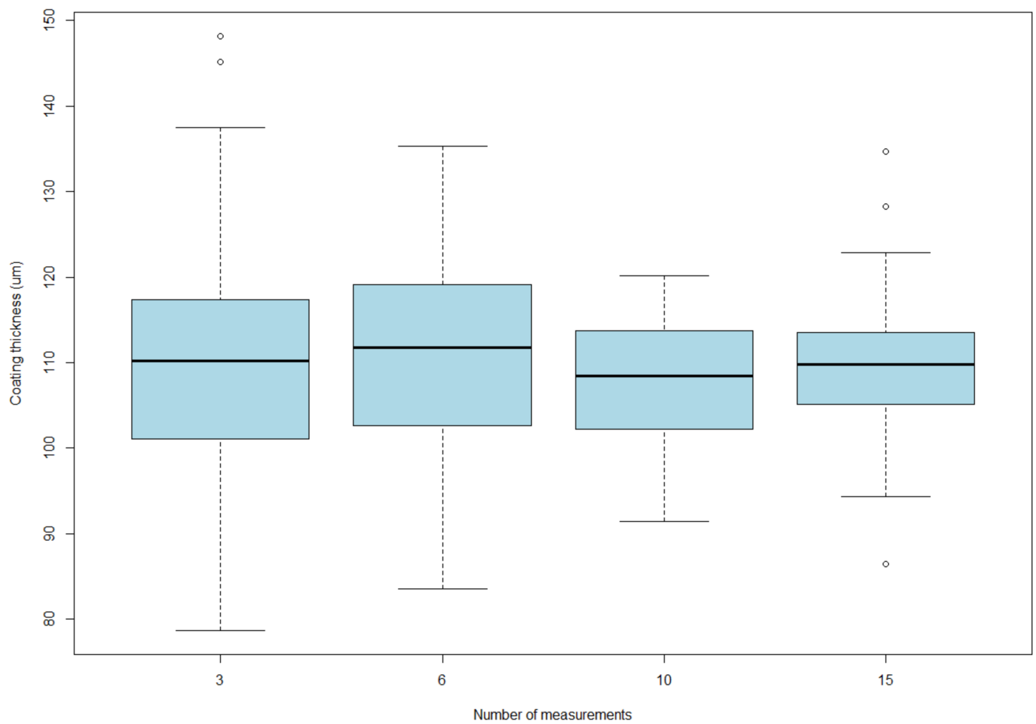


Figure 8. Box plot for 16-V2-Al

Result 5: 16 gauge, vendor 2, galvanized pipe

```
> fit=aov(Ga16E$thickness~as.factor(Ga16E$time))
> summary(fit)
                        Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Ga16E$time)    3    348  115.88   2.411 0.0671 .
Residuals              284  13650   48.06
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> TukeyHSD(fit,ordered=T)
  Tukey multiple comparisons of means
    95% family-wise confidence level
    factor levels have been ordered

Fit: aov(formula = Ga16E$thickness ~ as.factor(Ga16E$time))

$`as.factor(Ga16E$time)`
           diff        lwr      upr     p adj
15-10 0.4743056 -2.5117478 3.460359 0.9766209
6-10  2.3536111 -0.6324423 5.339664 0.1769401
3-10  2.4612500 -0.5248034 5.447303 0.1460778
6-15  1.8793056 -1.1067478 4.865359 0.3653730
3-15  1.9869444 -0.9991089 4.972998 0.3153642
3-6   0.1076389 -2.8784145 3.093692 0.9997098
```

Figure 9. ANOVA and Tukey's HSD results for 16-V2-Ga

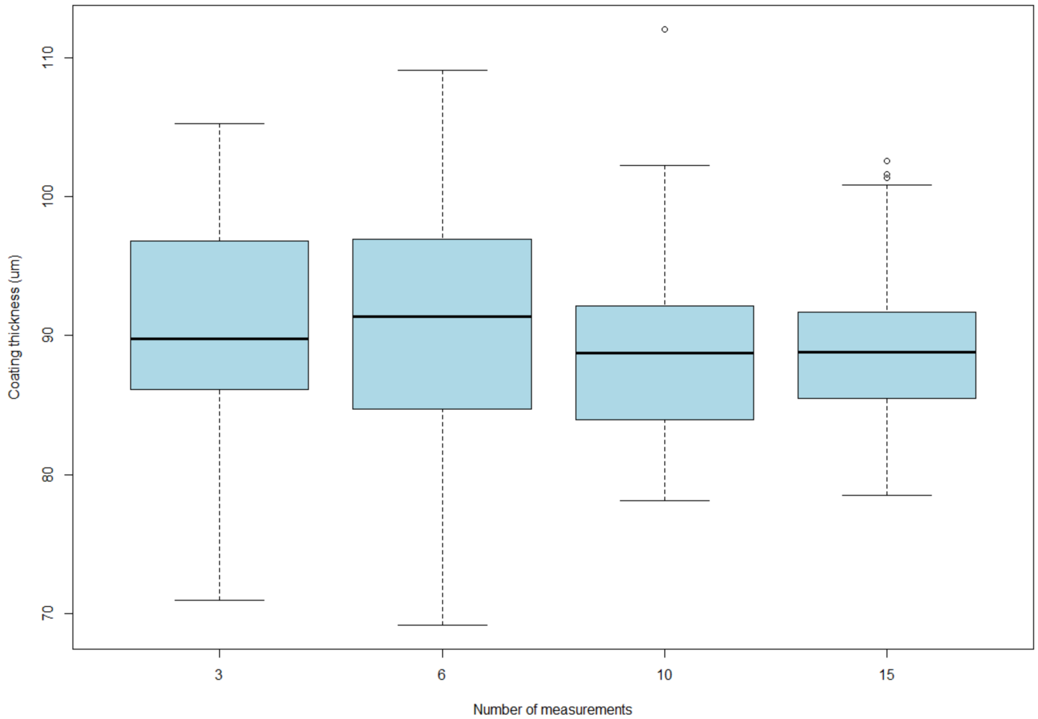


Figure 10. Box plot for 16-V2-Ga

APPENDIX I:

Monte Carlo simulations to establish uncertainty in service life estimations

The Monte-Carlo simulations was conduced to illustrate the service life prediction uncertainties. Following steps are followed:

Step 1: Calculation of mean and standard deviation

Initially the pH, resistivity and chloride data for Coastal, Piedmont and Mountain regions in "PASS_ver04.xlsm" are extracted and saved in csv files.

Then a python code "mean_standard_deviation.py" is used to calculate the mean and standard deviation of pH, resistivity and chloride. However, the chloride data are not required/used in any calculations as the models used to calculate service life do not require chloride value as input. The output of the calculations is saved in "Parameters.csv"

Table 1: pH and Resistivity Summary for Coastal Region:

ITEM	MEAN	STD	MEAN + 2*STD	MEAN – 2*STD
pH	4.915725	0.614084	6.143892	3.687558
Resistivity	9805.952	1367.413	12540.78	7071.126

Table 2: pH and Resistivity Summary for Piedmont Region:

ITEM	MEAN	STD	MEAN + 2*STD	MEAN – 2*STD
pH	5.348812	0.591319	6.53145031	4.166174
Resistivity	10000	N/A	10000	10000

Table 3: pH and Resistivity Summary for Mountain Region:

ITEM	MEAN	STD	MEAN + 2*STD	MEAN – 2*STD
pH	5.190433	0.473857	6.138147	4.242719
Resistivity	10000	N/A	10000	10000

Step 2: Run Monte-Carlo simulation

"MonteCarloSimulation.py" contains all three function that calculates the Service Life based on pH and resistivity. The code generated 100000 random set of pH value and resistivity value based on the mean and standard deviation of pH and resistivity respectfully. The random values that fall within two standard deviations of the pH and Resistivity have been used to calculate the service life in years on the FDOT, AISI, CALTRANS models. The results are saved in "ServiceLife_Distribution.xlsx". The mean and standard deviation of these Service Life are also calculated. The summary is provided below:

Table 4: Service Life Summary for Coastal Region:

	pH	R	CALTRANS (YEARS)	AISI (YEARS)	FDOT (YEARS)
mean	4.916989	9802.432	18.71385	48.65058	67.85297
std	0.539879	1197.88	1.850182	4.809936	6.708419
mean+2*std	5.996747	12198.19	22.41421	58.27045	81.2698
mean-2*std	3.837231	7406.671	15.01348	39.0307	54.43613

Table 5: Service Life Summary for Piedmont Region:

	pH	R	CALTRANS (YEARS)	AISI (YEARS)	FDOT (YEARS)
mean	5.350234	10000	20.34586	52.89333	73.77034
std	0.520109	0	1.930911	5.019808	7.001127
mean+2*std	6.390452	10000	24.20768	62.93295	87.77259
mean-2*std	4.310017	10000	16.48404	42.85372	59.76808

Table 6: Service Life Summary for Mountain Region:

	pH	R	CALTRANS (YEARS)	AISI (YEARS)	FDOT (YEARS)
mean	5.191063	10000	19.70742	51.23357	71.45546
std	0.416596	0	1.413604	3.67496	5.125468
mean+2*std	6.024255	10000	22.53462	58.58349	81.7064
mean-2*std	4.357871	10000	16.88021	43.88365	61.20453

Step 3: Plot the distribution

Based on the results in “ServiceLife_Distribution.csv” the distributions and probability distribution functions are plotted below.

Service Life Distribution for Coastal Region:

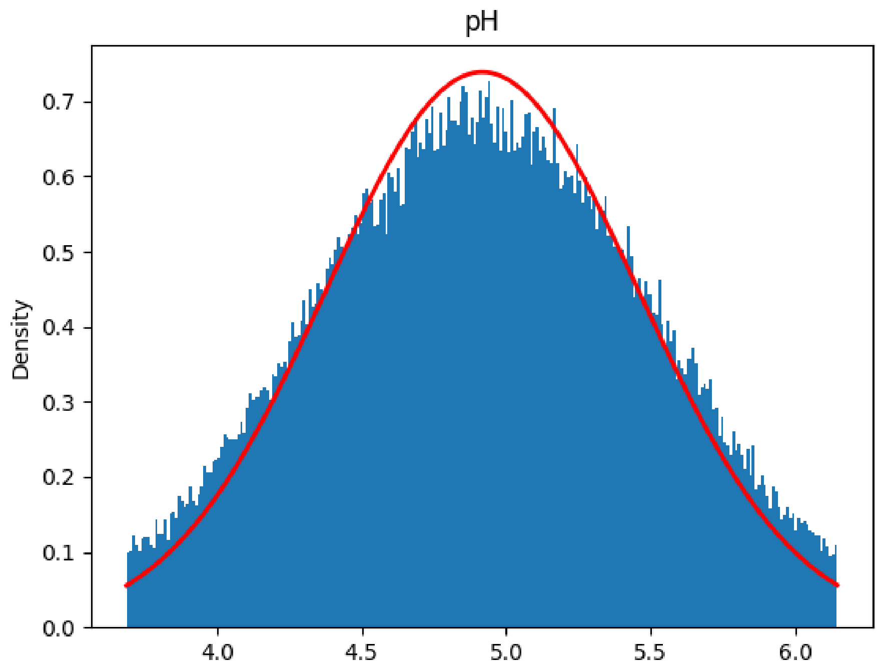


Figure 1: pH Distribution

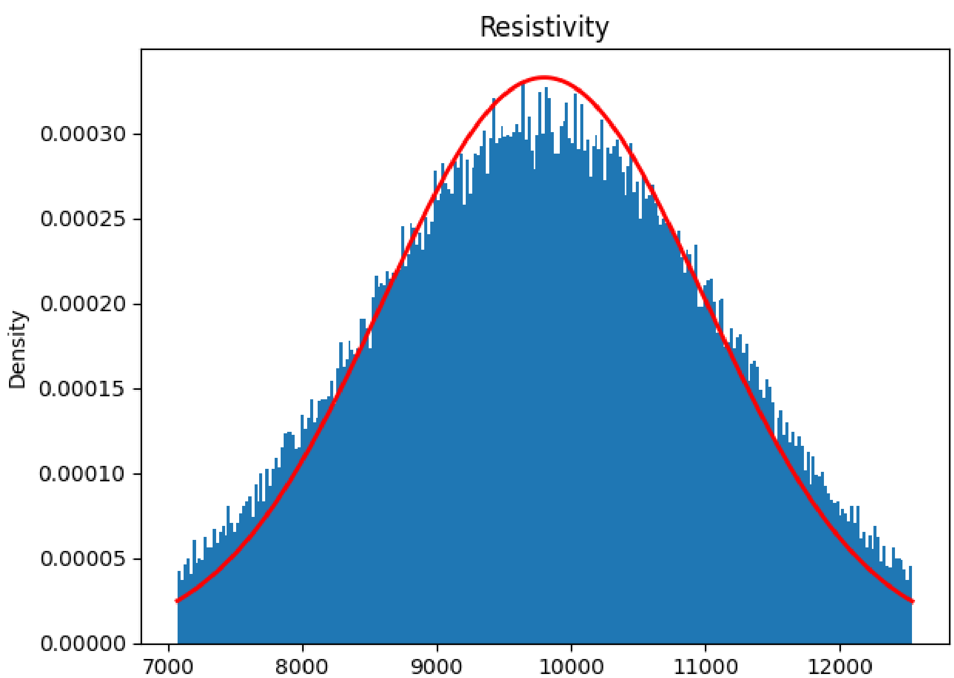


Figure 2: Resistivity Distribution

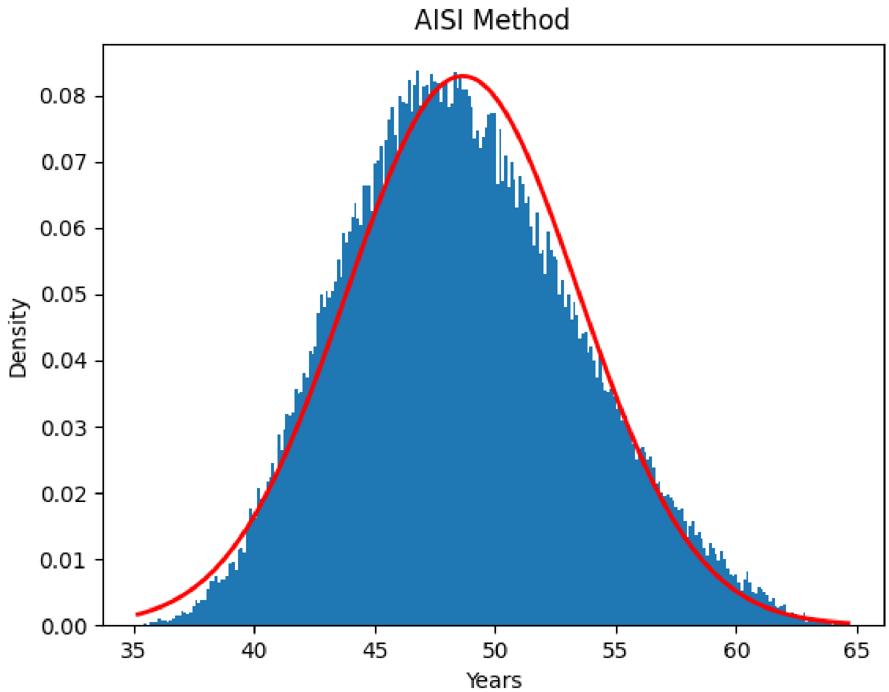


Figure 3: Service Life using AISI Method

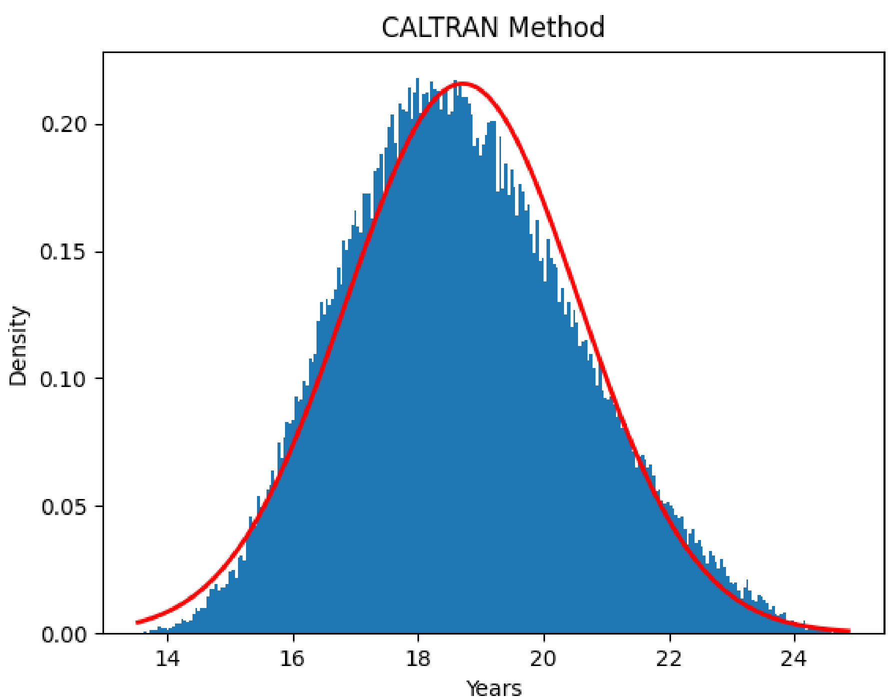


Figure 4: Service Life using CALTRANS Method

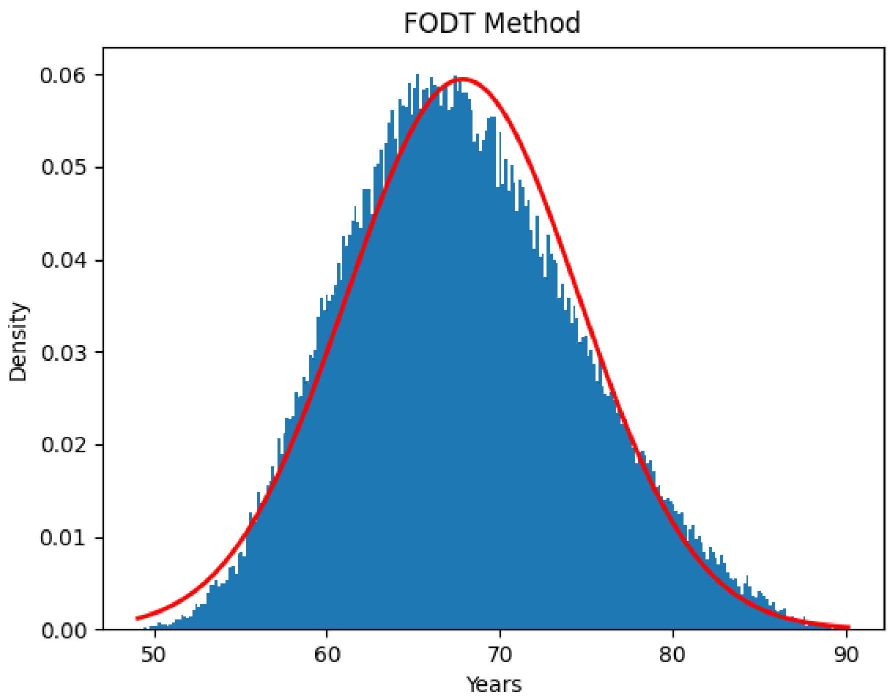


Figure 5: Service Life using FDOT Method

Service Life Distribution for Piedmont Region:

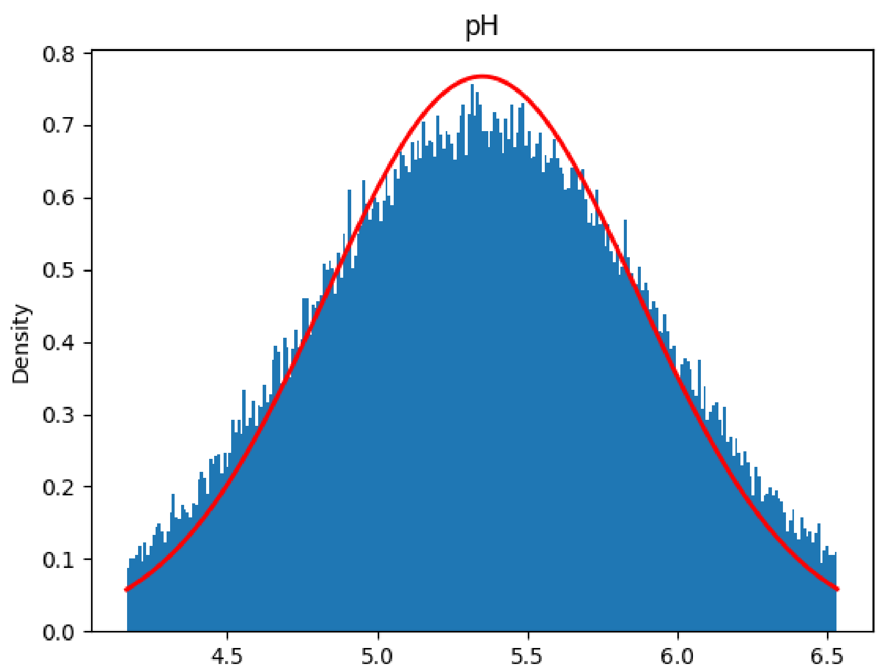


Figure 6: pH Distribution

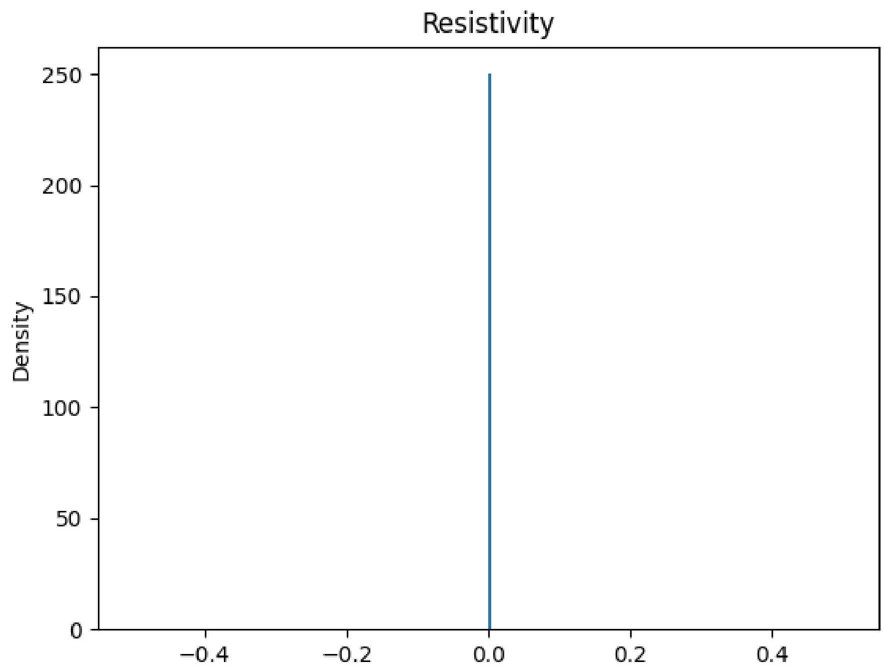


Figure 7: Resistivity Distribution

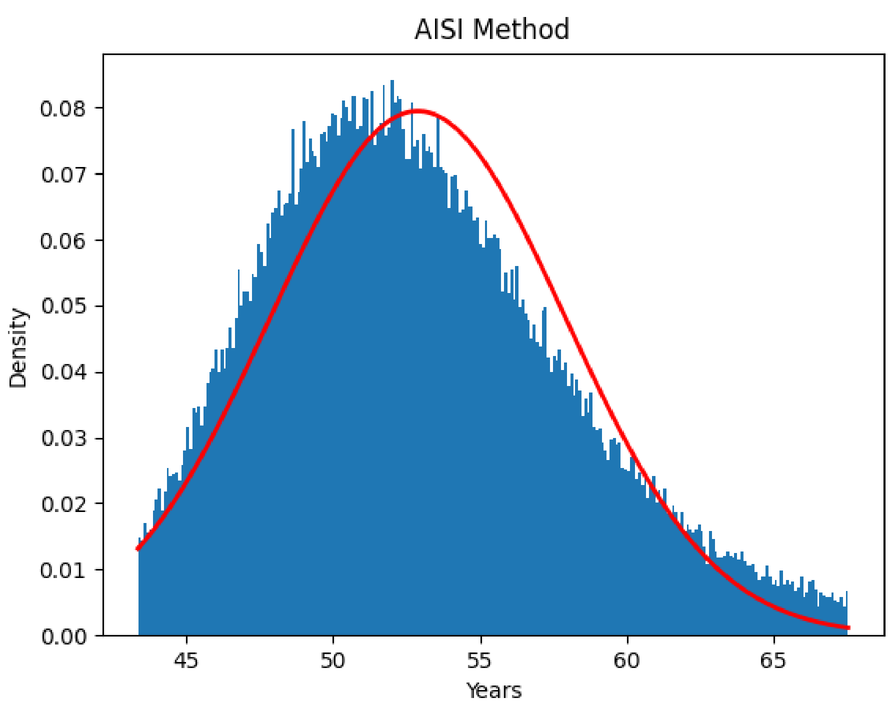


Figure 8: Service Life using AISI Method

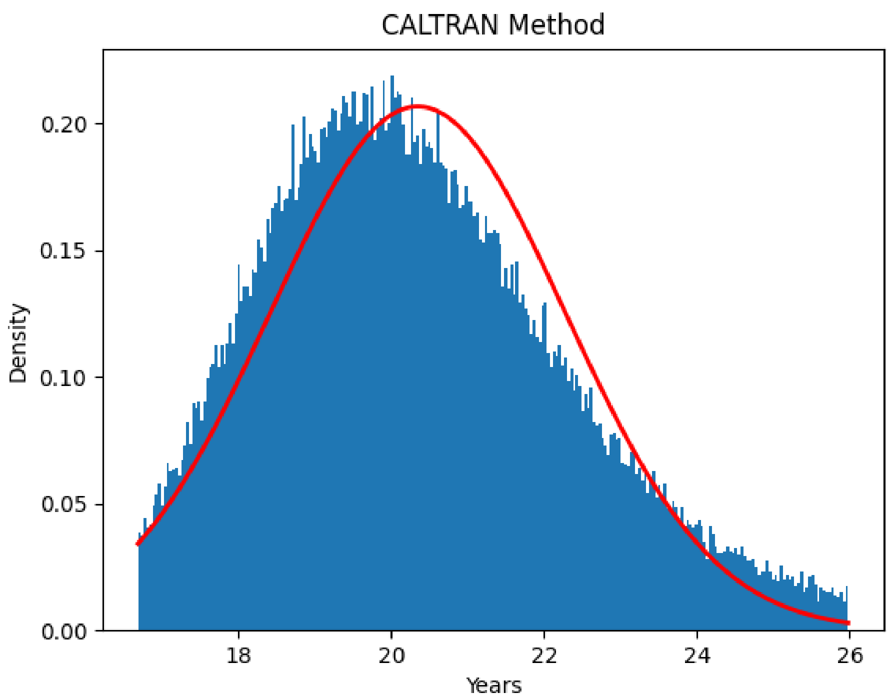


Figure 9: Service Life using CALTRANS Method

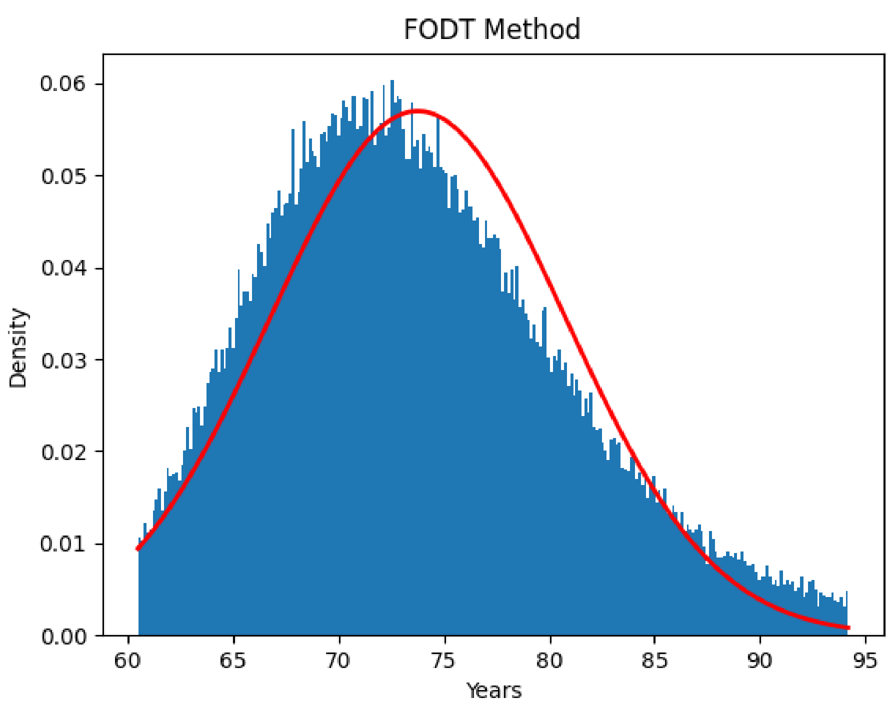


Figure 10: Service Life using FDOT Method

Service Life Distribution for Mountain Region:

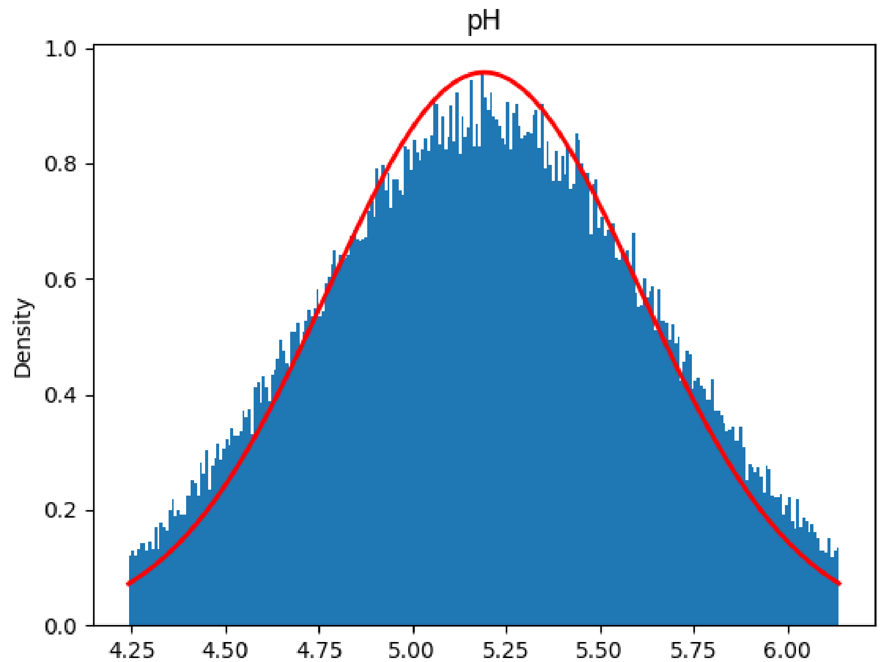


Figure 11: pH Distribution

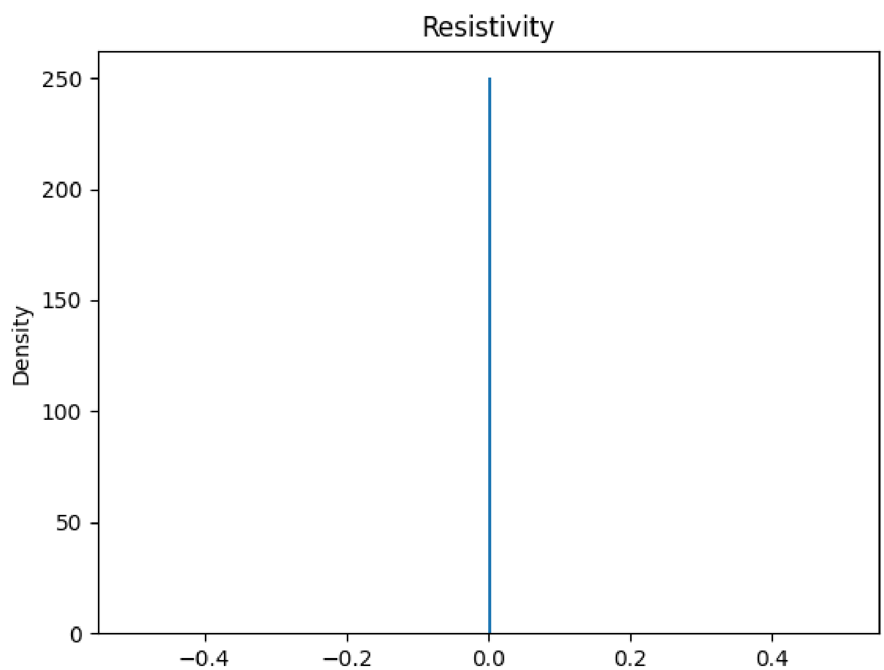


Figure 12: Resistivity Distribution

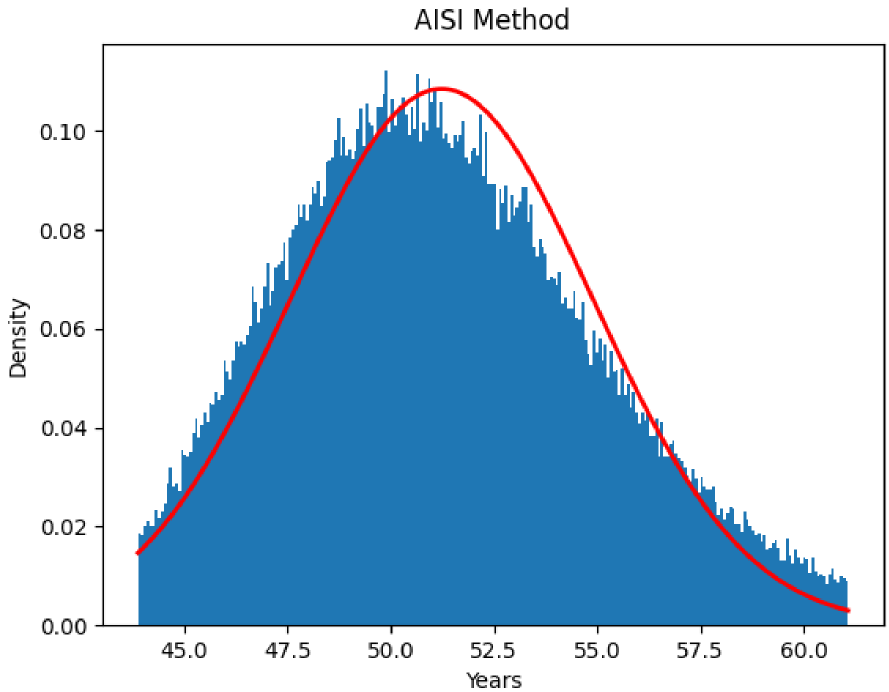


Figure 13: Service Life using AISI Method

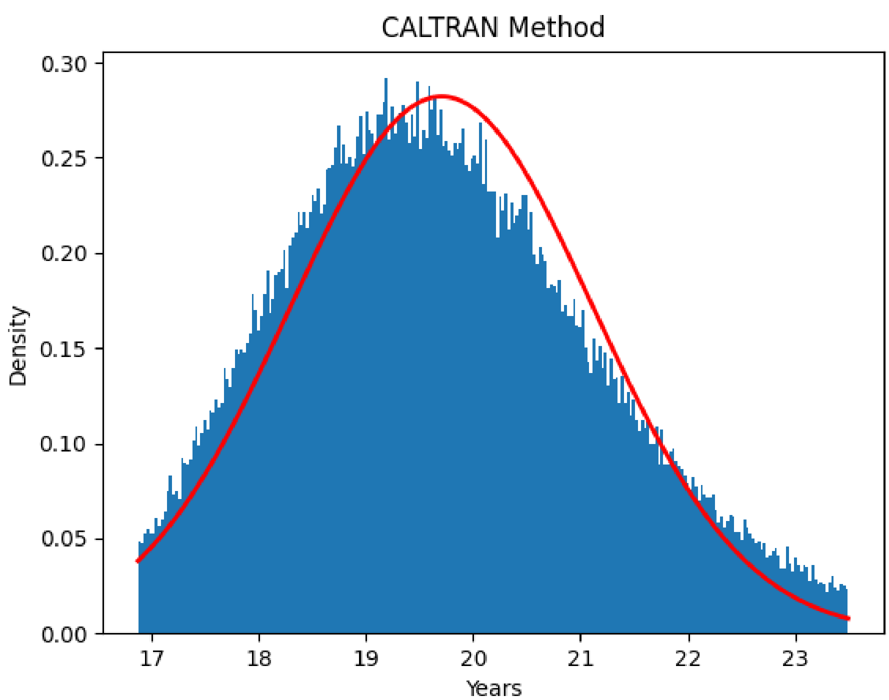


Figure 14: Service Life using CALTRANS Method

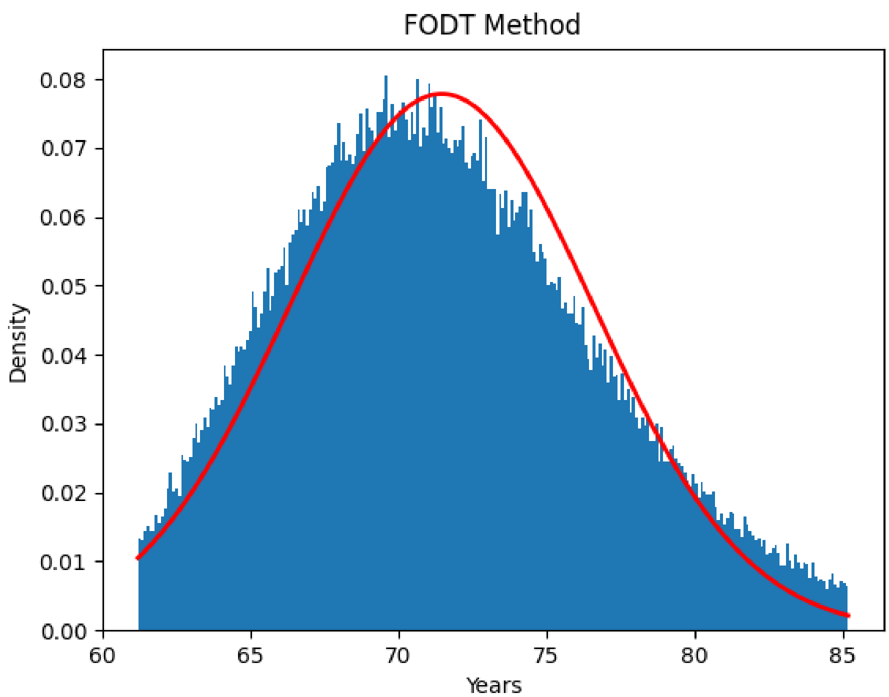


Figure 15: Service Life using FDOT Method

mean_standard_deviation.py

```
def get_mean_std(filename,column):
   for i in range(len(filename)):
            PH_1=np.loadtxt(filename[i],delimiter=',',skiprows=1,dtype=str)
      if i==0:
         PH_1_data=np.transpose(PH_1)[column[i]].astype(float)
      else:
         PH_1_data=np.append(PH_1_data,np.transpose(PH_1)[column[i]].astype(float))
         PH_1_mean=np.mean(PH_1_data)
         PH_1_std=np.std(PH_1_data)
         return PH_1_mean,PH_1_std
    if True:
   PH_mean,PH_std=get_mean_std(['pH_coastal_plains_1.csv',
                        'pH_coastal_plains_2.csv',
                        'pH_coastal_plains_3.csv',
                        'pH_coastal_plains_4.csv',
                        'pH_coastal_plains_5.csv',
                        'pH_coastal_plains_6.csv',
                        'pH_coastal_plains_7.csv'
```

```
                    ],
                   [3,
                    3,
                    3,
                    3,
                    3,
                    3,
                    3])
    print(PH_mean,PH_std)
    resistivity_mean,resistivity_std=get_mean_std(['Resistivity_coastal_plains_1.csv',
                                 'Resistivity_coastal_plains_2.csv',
                                 'Resistivity_coastal_plains_3.csv',
                                 'Resistivity_coastal_plains_4.csv',
                                 'Resistivity_coastal_plains_5.csv',
                                 'Resistivity_coastal_plains_6.csv',
                                 'Resistivity_coastal_plains_7.csv'
                                 ],
                                [3,
                                 3,
                                 3,
                                 3,
                                 3,
                                 3,
                                 3])
    print(resistivity_mean,resistivity_std)
    #chloride_mean,chloride_std=get_mean_std(['Chloride.csv'],[4])
    #print(chloride_mean,chloride_std)
    data=open('Parameters.csv','w')
    data.write('Item,mean,std\n')
    data.write('Ph,{},{}\n'.format(PH_mean,PH_std))
    data.write('Resistivity,{},{}\n'.format(resistivity_mean,resistivity_std))
    data.write('Chloride,NA,NA\n')
    data.close()
```

MonteCarloSimulation.py

```
import numpy as np
def get_random_value(mu,sigma):
    return np.random.normal(mu, sigma, 1)[0]
def get_AISI_years(pH,R):
    if pH>7.3:
```

```
        return 3.82*R**0.41
    else:
        return 35.85*(np.log10(R)-np.log10(2160.0-2490.0*np.log10(pH)))
def get_FDOT_years(pH,R):
    if pH<7.0:
        return 50.0*(np.log10(R)-np.log10(2160.0-2490.0*np.log10(pH)))
    elif pH>=7 and pH<8.5:
        return 50.0*(np.log10(R)-1.746)
    else:
        return 50.0*(np.log10(R)-np.log10(13.0*2160.0-2490.0*np.log10(7.0-4.0*(pH-8.5))))
def get_CALTRANS_years(pH,R):
    if pH>7.3:
        return 1.47*R**0.41
    else:
        return 13.79*(np.log10(R)-np.log10(2160.0-2490.0*np.log10(pH)))
#####################################################################################
############
parameters=np.loadtxt('Parameters.csv',
                  delimiter=',',
                  dtype=str)
ph_mean=float(parameters[1][1])
ph_std=float(parameters[1][2])
resistance_mean=float(parameters[2][1])
resistance_std=float(parameters[2][2])
#chloride_mean=float(parameters[3][1])
#chloride_std=float(parameters[3][2])
#####################################################################################
############
year_distribution=open('Year_distribution.csv','w')
year_distribution.write('No,pH,R,CALTRANS(years),AISI(years),FDOT(years)\n')

def is_Ph_R_in_range(pH,R,ph_mean,ph_std,resistance_mean,resistance_std):
    if pH<ph_mean-2.0*ph_std or pH>ph_mean+2.0*ph_std:
        return False
    elif R<resistance_mean-2.0*resistance_std or R>resistance_mean+2.0*resistance_std:
        return False
    else:
        return True
  count=0
while count<100000:
    pH=get_random_value(ph_mean,ph_std)
```

```
    R=get_random_value(resistance_mean,resistance_std)
    if is_Ph_R_in_range(pH,R,ph_mean,ph_std,resistance_mean,resistance_std):
        ##
        y_caltran=get_CALTRANS_years(pH,R)
        y_AISI=get_AISI_years(pH,R)
        y_FODT=get_FDOT_years(pH,R)
        ##
        year_distribution.write('{},{},{},{},{},{}\n'.format(
            count,pH,R,y_caltran,y_AISI,y_FODT))
        count+=1
year_distribution.close()
```