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DEVELOPMENT OF NEW CORROSION /ABRASION GUIDELINES FOR SELECTION OF CULVERT PIPE MATERIALS

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16. Abstract

In this research effort, literature surveys and reviews of the current methodologies employed by various state DOTs were conducted. The literature survey identified the pertinent parameters in estimating the service life of various pipe materials. Following the literature survey, field visits to culvert sites were made to collect data. Selection of culvert sites was jointly made by engineers from Staff Bridge, Staff Hydraulics, and members of the study panel.

Field surveying of 21 sites where failed pipe installations were observed was conducted in Colorado along I-70, I-25, and SH 58 to obtain a good cross-section of soil type samples. At these sites, soil and water samples were obtained and soil resistivities were determined using applicable Colorado Procedures, AASHTO test methods, or ASTM test methods. Soil and water samples from these sites were analyzed for sulfate/chloride level concentrations, and pH levels. Relevant culvert inspection data from Staff Bridge inspection programs was obtained and used in the analysis where needed.

Data collected from literature searches, the Staff Bridge database, actual field surveys, and other unbiased reliable sources was analyzed. The service life was correlated with various parameters including type of material, pH level, chloride and sulfate level concentrations, specific resistivity, abrasion data (steep pipe slopes, high sediment loads, high flow velocity in pipes, etc.) and other factors that could have influenced premature deterioration or failures.

A new service life chart for steel pipes was developed based on the information collected from the field observations and data analysis. Data from Colorado pipe failure cases was used in relating service life of pipes to soil resistivity. Pipe failure criteria were established in accordance with the ongoing culvert evaluation procedure along I-70 and I-25. For the steel pipe failure cases along I-70 and I-25, the previously published service life predictors for steel pipes deviated from observations by as much as 10 times. Service life multipliers to account for steel pipe thickness effects had been greatly exaggerated. For aluminum pipes, the research identified chloride and sulfate concentrations as factors that reduced the service life of these pipes dramatically.

Implementation:
It is anticipated that the results of this study will be adopted by cities, counties, and other states where selection of pipe materials for corrosion/abrasion resistance is required during the design and construction of transportation projects. Training courses provided to the CDOT engineering community and to the general consulting engineering community can be used as an implementation tool.

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DEVELOPMENT OF
NEW CORROSION/ABRASION GUIDELINES FOR SELECTION OF CULVERT PIPE MATERIALS

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EXECUTIVE SUMMARY

The existing Colorado Department of Transportation (CDOT) corrosion guidelines for pipe material type selection do not specify the service life for any pipes used for drainage. A 50-year service life is assumed for any pipe that satisfies the corrosion level criteria in the existing guidelines. New design and retrofit procedures are needed in order to incorporate corrosion and abrasion factors in selecting proper types of pipes for specific drainage applications with realistic estimates of service life. Soil and water resistivity and/or abrasion factors as well as pH, chloride, and sulfate concentration levels are investigated in areas where drainage pipes failed. Locations of pipe failure have been identified in a comprehensive culvert pipe inspection effort conducted by the CDOT Bridge Branch along the I-70 mountain corridor and I-25. Using data from these sites, existing methodologies for service life estimations for drainage pipes were critically reviewed and modifications were made. The following tasks were accomplished to achieve the objectives of the research project:

1. *<u>A comprehensive literature review of corrosion/abrasion.</u>*

This task aims at identifying the corrosion/abrasion experiences and technical data within CDOT and nationwide. The research team delineated the following sources for information:

i) State of Colorado: CDOT, local government entities, and state universities;
ii) National: Other DOTs, AASHTO, FHWA, ASTM, universities and other institutions, etc.; and
iii) Transportation Research Board: Existing and current research studies available from the Transportation Research Information Service (TRIS) database.

2. *<u>Investigation of the applicability and effectiveness of the CDOT's current corrosion resistance (CR)table</u>.*

CDOT's CR table uses chloride and sulfate ion concentrations and pH levels in water and soil environments to specify the required CR level that a pipe material can accommodate without adversely affecting its service life. The applicability of CDOT's CR table was investigated. It was found that the use of the CR table was limited to concrete pipes and some of the ranges of sulfate and chloride concentration levels did not conform to current literature.

3. *<u>Field surveys of specific culvert sites.</u>*

Culvert sites were jointly determined by the Staff Hydraulics Engineer and the research panel that included members from Region Hydraulics Engineers, Region Materials Engineers, Region Maintenance personnel, and the Staff Bridge Branch. Field surveying of 21 sites where failed pipe installations were observed was conducted along I-70 and I-25 to obtain a good cross-section of soil type samples. At these sites, soil and water samples were obtained, and soil resistivities were determined using applicable Colorado Procedures, AASHTO test methods, or ASTM test methods. Soil and water samples from these sites were analyzed for sulfate and chloride level concentrations, and pH levels. Relevant culvert inspection data from Staff Bridge inspections was obtained and used in the analysis where needed.

4. *<u>Data Analysis</u>*

Data collected from the literature review, the Staff Bridge database, actual field surveys, and other unbiased reliable sources was analyzed. The service life was correlated with various parameters including type of material, pH level, chloride and sulfate concentration levels, resistivity, abrasion data

(steep pipe slopes, high sediment loads, high flow velocity in pipes, etc.) and other factors that could have influenced premature deterioration or failures.

5. Development of a new corrosion/abrasion service life chart

A new service life chart for steel pipes based on the information collected from Task 4 was developed. Data from Colorado pipe failure cases was used in relating service life of pipes to soil resistivity. Pipe failure criteria were established through discussions with CDOT research panel members and were in accordance with the ongoing culvert evaluation along I-70 and I-25. It was found that for the 21 failure cases, the previously published service life predictors for steel pipes deviated from observations by as much as 10 times and that pipe thickness effects were greatly exaggerated.

6. Preparation of the Final Report

This task involved the documentation of the entire research effort including the literature review; field sampling and testing; laboratory analyses; data collection and analyses; presentation of the results, findings, recommendations, conclusion and implementation plans; and the preparation of the final report.

IMPLEMENTATION PLAN

Some of the products derived from this research study include:

- Design service life prediction charts for steel pipes along the I-70 and I-25 corridors;
- Identification of corrosion parameters for aluminum pipes that dramatically reduce their service life;
- Revised service life multipliers for steel pipes to account for pipe thickness effects; and
- Documentation of the methodology.

These products were limited in their scope and require further test cases to make their findings applicable on a statewide basis for Colorado. However, these products are conclusive within their scope.

The approach for putting this research into practice is to find ways to implement findings of this research into CDOT projects. Inclusion of the research study into CDOT's Drainage Design Manual as a chapter is one of the immediate means of implementation. This will allow immediate access to the methodology by practitioners and will make the methodology part of the CDOT design process.

The findings of the research will also be disseminated through professional societal meetings, presentations, and development of journal publications. The research team members will jointly prepare conference and professional societal journal articles that will disseminate the knowledge to the engineering community.

It is anticipated that the results of this study will be adopted by cities, counties, and other states where selection of pipe materials for corrosion/abrasion resistance is required during the design and construction of transportation projects. Training courses provided to the CDOT engineering community and to the general consulting engineering community can be used as an implementation tool. Appropriate training materials should be developed and made available to hydraulic designers, materials and project engineers. These materials can be used in training classes to introduce the new procedures to the CDOT engineering community and other practitioners involved in the design of highway drainage structures. In these classes, engineers will be trained to apply the guidelines in their actual design work.

It is expected that the implementation plan will require minimal commitment from CDOT in terms of resources. The results of this work are anticipated to have cost-saving impacts on the life-cycle costs of culvert pipes, provide uniformity in design approach, and offer realistic information on the service life of commonly used pipes in CDOT construction projects.

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INTRODUCTION

The Colorado Department of Transportation's (CDOT's) existing corrosion guidelines for pipe material type selection do not specify the service life for any pipes used for drainage. A 50-year service life is assumed for any pipe that satisfies the corrosion level criteria in the existing guidelines. New design and retrofit procedures are needed in order to incorporate corrosion and abrasion factors in selecting proper types of pipes for specific drainage applications with realistic estimates of service life. Soil and water resistivity and/or abrasion factors as well as pH, chloride, and sulfate concentrations are investigated in areas where drainage pipes failed. Locations of pipe failure were identified in a comprehensive culvert pipe inspection effort conducted by the CDOT Staff Bridge Branch along the I-70 mountain corridor and I-25. Using data from these sites, existing methodologies for service life estimations for drainage pipes were critically reviewed and modifications were made.

The Statement of Work delineated 6 tasks for the project following a logical sequence and covering all aspects of the research. This report is intended to summarize the findings of the entire research effort. The tasks in the Statement of Work are listed below.

Task 1. Perform a comprehensive literature review of corrosion/abrasion

This task aims at identifying corrosion/abrasion experiences and technical data within CDOT and nationwide. The study team worked with Federal highway agencies such as the American Association for State Highway Transportation Officials (AASHTO), National Cooperative Highway Research Program (NCHRP), and Federal Highway Administration (FHWA). In conducting the literature search, these agencies were contacted and the methodologies adopted by these agencies were inquired. The research team also delineated the following sources for information:

i) Within the State of Colorado: CDOT, local government entities, and state universities.

ii) Nationwide: Other DOTs, AASHTO, FHWA, ASTM, universities and other institutions, etc.

iii) Transportation Research Board: Existing and current research studies available from the TRIS database.

Task 2. Investigate applicability and effectiveness of the CDOT's current corrosion resistance (CR) table.

CDOT's CR table uses chloride and sulfate ion concentrations and pH levels in water and soil environment to specify the required CR level that a pipe material can accommodate without adversely affecting its service life. In this task, actual pipe experiences (failure or success and service life) in the field will be correlated with the corresponding corrosion levels specified by the CR table for these pipes. If there is a correlation but some of the cases do not reflect agreement with the table, other factors such as soil types, hydraulic, climatic, geologic, geographic and/or topographic (eastern plains or mountainous regions, etc.) factors must be influencing the service life. These factors will be identified to the extent possible within the source of information in available database. In order to expand the applicability, the literature review was extended to search U.S. Army Corps of Engineers in Task 1 to obtain the latest corrosion table or other procedures that the Corps uses or may have used in the past for corrosion/abrasion potential determination.

Task 3. Perform field surveys of specific culvert sites.

Culvert sites were jointly determined by the Staff Hydraulics Engineer and the research panel that included members from Region Hydraulics Engineers, Region Materials Engineers, Region Maintenance personnel, and the Staff Bridge Branch. Field surveying of 21 sites where failed pipe installations were observed was conducted along I-70 and I-25 to obtain a good cross-section of soil type samples. At these sites, soil and water samples were obtained and soil resistivities were determined using applicable Colorado Procedures, AASHTO test methods, or ASTM test methods. Soil and water samples from these sites were analyzed for sulfate and chloride level concentrations, pH levels. Relevant culvert inspection data from the Staff Bridge culvert inspection program was obtained and used in the analysis where needed.

Figure 1. Soil resistivity testing by ASTM G57-95a

Task 4. Data analysis.

In this task the data collected from a review of the literature, the Staff Bridge database, actual field surveys, and other unbiased reliable sources was analyzed. The service life was correlated with various parameters including type of material, pH level, chloride and sulfate level concentrations, resistivity, abrasion data (steep pipe slopes, high sediment loads, high flow velocity in pipes, etc.) and other factors that might or could have influenced premature deterioration or failures.

Task 5. Develop new corrosion/abrasion table.

New corrosion/abrasion tables based on the information collected from Task 4 were developed. Relationships between service life and resistivity similar to those utilized in Figure 2 were developed. Data from the Colorado database was used to calibrate the coefficients of these relationships to reflect local conditions. The failure criteria was established through discussions with CDOT research panel members and was in accordance with the ongoing culvert evaluations along I-70 and I-25. Depending upon the availability of data, the corrosion/abrasion table may be customized to Colorado's various geographical areas. A procedure to estimate the service life of pipes based on the information from this table will be developed. It is anticipated that this procedure will differentiate between different pipe materials such as steel pipes, aluminum pipes, concrete pipes, plastic HDPE pipes, galvanized steel pipes, etc.

Task 6. Final Report.

This task involved the documentation of the entire research effort including the literature review; field sampling and testing; laboratory analyses; data collection and analyses; presentation of the results, findings, recommendations, conclusion and implementation plans; and the preparation of the final report.

Natural processes of corrosion, abrasion and erosion can be considered the principal nonstructural factors that affect durability; such processes deteriorate and destroy culvert material of all types. It has been theorized that proper analysis of soil and water at the drainage site and the associated watershed can form the basis for selection of materials and types of pipe that should be used to obtain the required service life.

Corrosion is the deterioration or dissolution of or destructive attack on a material by chemical or electrochemical reaction with its environment. The main corrosion medium affecting culverts is water and the chemicals dissolved in or transported by water. Metal corrosion is an electrical process involving an electrolyte (moisture), an anode (the metallic surface where oxidation or loss of electron occurs), a cathode (the metallic surface that accepts electrons and does not corrode), and a conductor (the metal pipe itself).

Abrasion is the wearing or grinding away of material by water laden with sand, gravel, or stones. Often abrasion acts with corrosion to produce greater deterioration than either mechanism would by itself.

Field and laboratory tests have been used to predict deterioration rates for a given environment. Corrosion and abrasion indicators used include pH of soil and water, soil resistivity or conductivity, polarization curves, oxidation-reduction potential, soil chemical and physical properties, precipitation, and stream velocities.

Materials used for culvert pipes include steel, aluminum, concrete, vitrified clay, stainless steel, cast iron, and plastic. Culvert pipe protection measures include extra material thickness, coatings of various types, linings, and cathodic protection.

A comprehensive literature review was performed for information pertaining to corrosion and abrasion of culvert pipe materials. The publications are presented in chronological order.

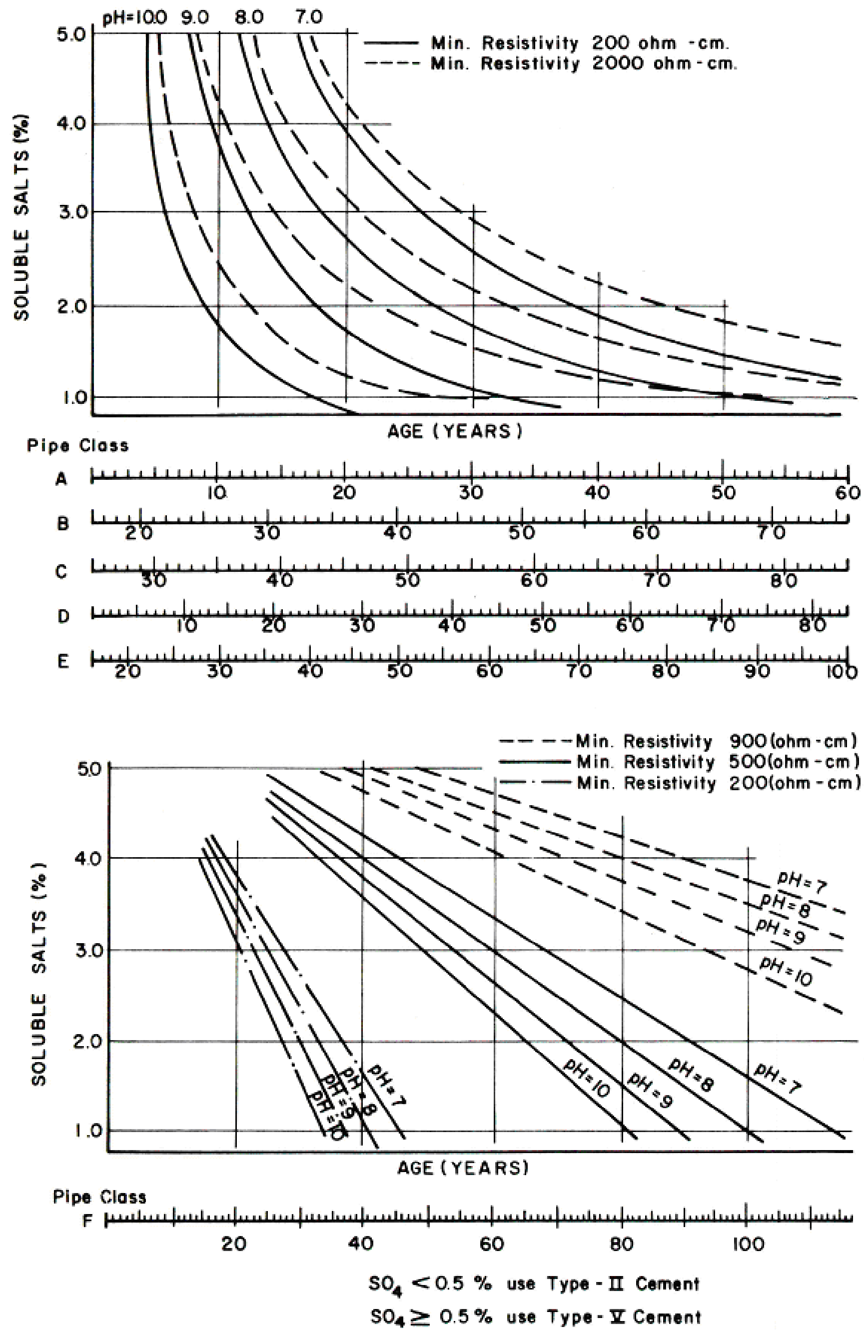
LITERATURE REVIEW

1978: Durability of Drainage Pipe

Prior to 1970, there were many studies to examine the various aspects of corrosion and abrasion as related to culverts. However, it was not until 1978 that a synthesis of the state of practice related to the durability of drainage pipe was compiled.

The chapter on service life estimation was of particular importance for this study. In order to discuss service life estimation, a general definition for service life must be presented. For the purposes of this report, we will define the service life of a culvert in by the number of years of relatively maintenance-free performance. Typically, designers are looking for a service life of at least 25 to 50 years. This publication presents four types of approaches for determining service life: (a) field performance surveys, (b) field prototype tests, (c) laboratory tests, and (d) analytical methods. In general, the field performance and prototype surveys/tests tend to require large amount of data and time. Laboratory tests tend to not be indicative of field conditions. Therefore, the most widely used approach is based on analytical methods. This report presents analytical methods developed and used by Utah and California DOTs.

The Utah DOT method is to obtain soil and water samples from proposed culvert sites and test the samples for resistivity, pH and soluble salt and sulfate content. Charts are then used to estimate the expected life of various pipe materials as shown in Figure 2.



Pipe Class A = Plain corrugated steel

Pipe Class B = Bituminous-coated corrugated steel pipe, aluminum alloy pipe, galvalume pipe, pitch-resin adhesive-coated corrugated steel pipe (coated on exterior side only)

Pipe Class C = Asbestos-bonded bituminous-coated corrugated steel pipe, pitch-resin adhesive-coated corrugated steel pipe (coated on both sides)

Pipe Class D = Plain corrugated steel structural-plate pipe

Pipe Class E = Bituminous-coated corrugated steel structural-plate pipe, aluminum alloy structural-plate pipe

Pipe Class F = Portland cement concrete pipe

Figure 2. Utah DOT charts for determining service life of culverts

The California DOT method presented in this publication for estimating service life is based on the evaluation of pH, sulfate-ion concentration and chloride-ion concentration in the soil and/or water environment for metal culverts. The test method is numbered 643-C, dated 1972. See Figure 3 for the California DOT's chart for estimating years to perforation of metal culverts based on pH.

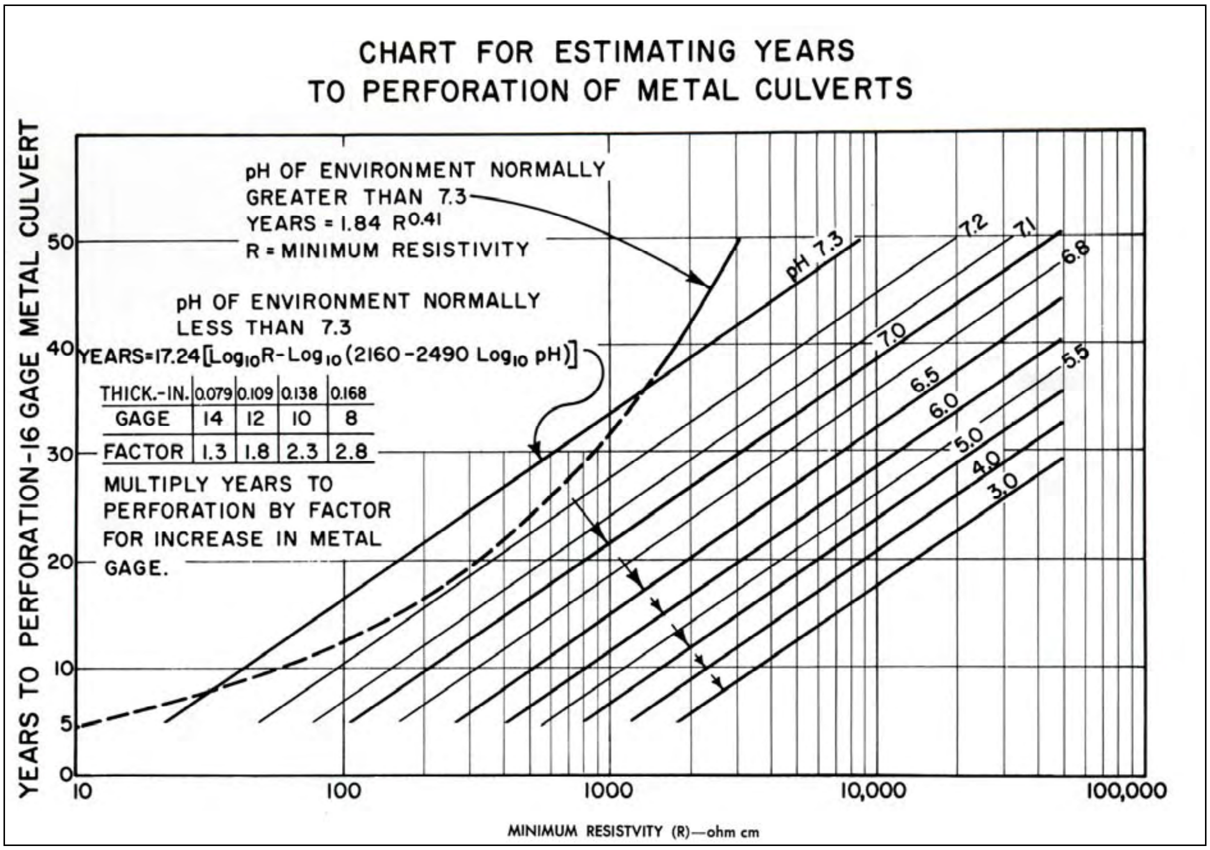


Figure 3. California DOT method for determining service life for steel pipes

1983: Handbook of Steel Drainage & Highway Construction Products

From this publication, a chapter on durability presents relevant information for the literature review. Highlights of important information from this chapter are:

- Typical design life for a highway culvert is 50 years.
- The best way to determine how a steel pipe is going to resist corrosion and abrasion is to look at performance of a culvert in a similar environment.
- The most widely used methods for determining resistance to corrosion and abrasion use properties of the soil and the water. Typically these are pH and Resistivity of the native soil.
- Generally metal loss is calculated from the aforementioned methods, where metal loss corresponds to first perforation. Evaluation of most other pipe materials is based on average service life. Thus a method is needed to relate first perforation and average service life.
- Using data from the National Bureau of Standards, a relationship between average metal loss and first perforation was developed. First perforation was found to correspond to approximately 13% average loss of metal thickness. Loss of function is defined at an average metal thickness loss of 25%, which is approximately twice the value of first perforation. Thus service life is determined to be twice the first perforation. Figure 4 presents the resulting information.

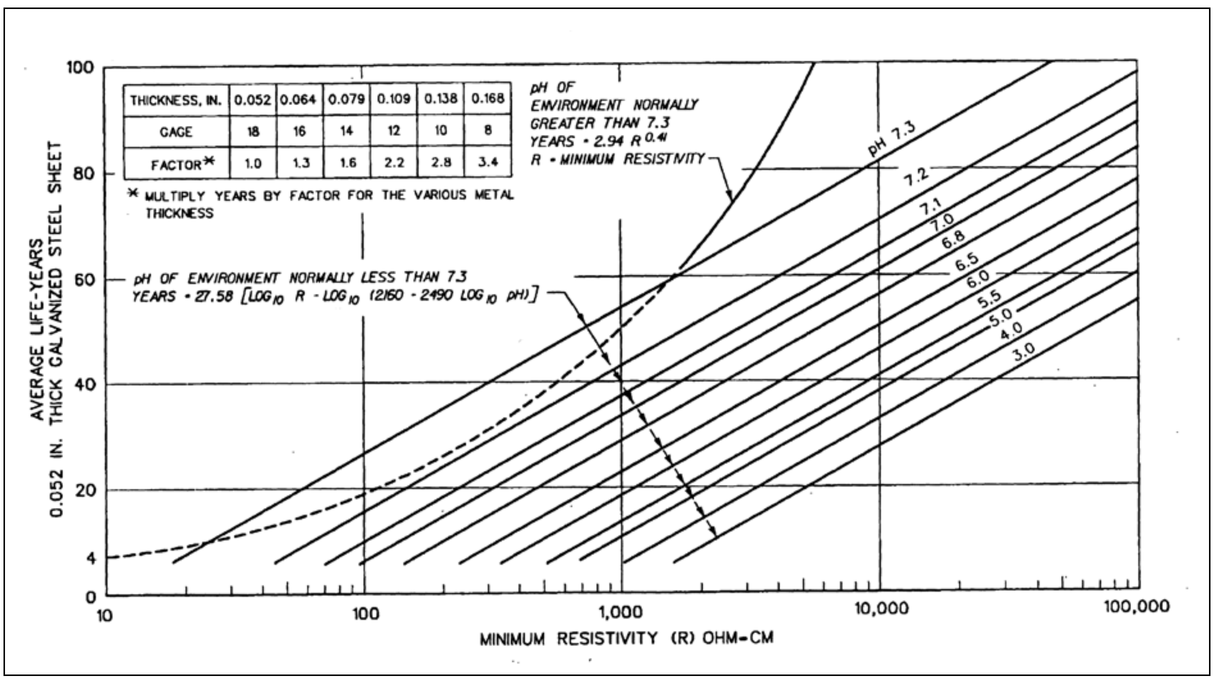


Figure 4. Chart for estimating average life of plain galvanized culverts

Table 1. Typical resistivity values

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

Table 2. Relationship of soil corrosion to electrical resistivity

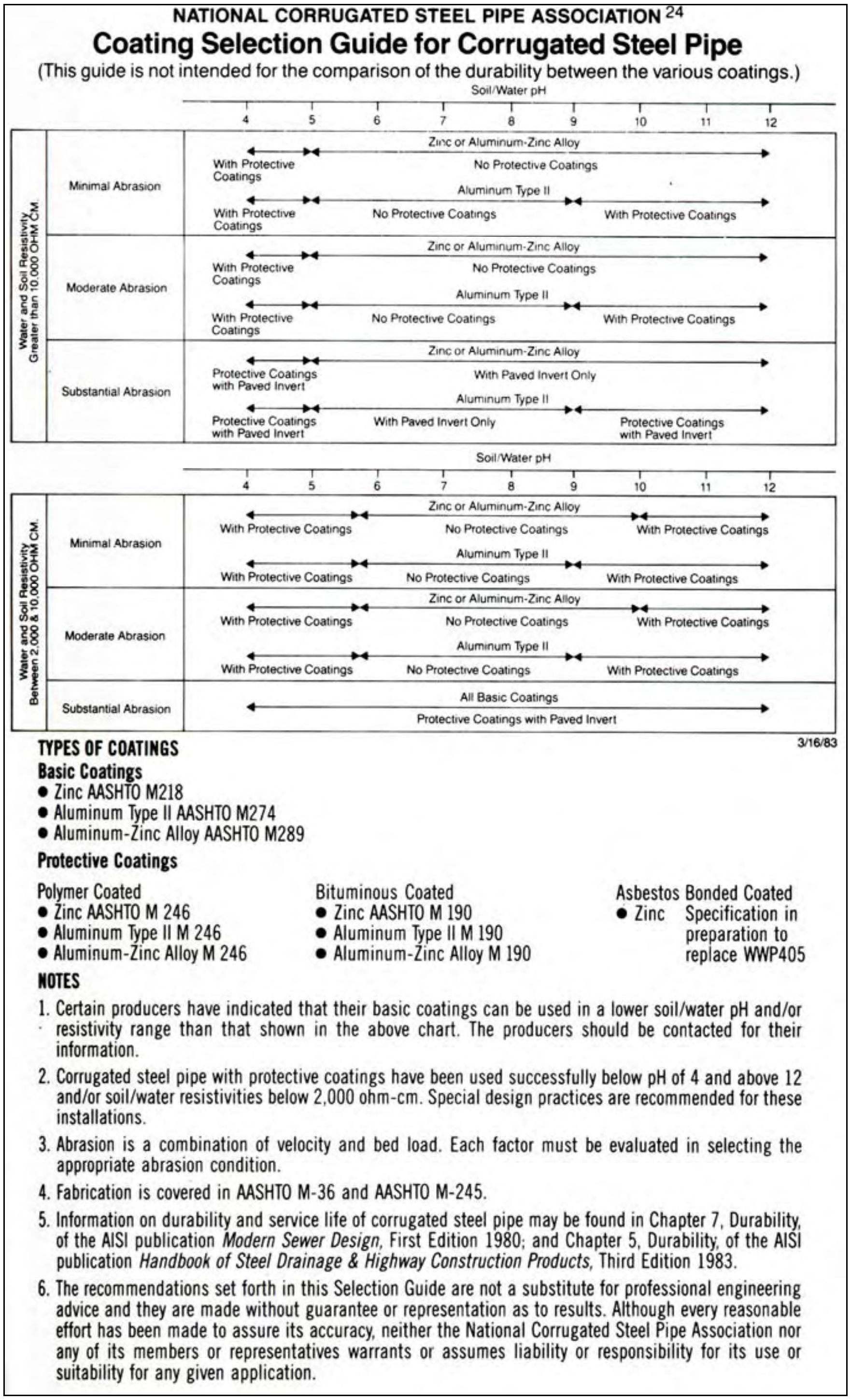
Soil Type	Degree of Corrosiveness	Electrical Resistivity Ohm-cm
1	Very low	10,000-6,000
2	Low	6,000-4,500
3	Moderate	4,500-2,000
4	Severe	2,000-0

Table 3. Corrosiveness of soils

Soil Type	Description of Soil	Aeration	Drainage	Color	Water Table
I - Lightly Corrosive	1. Sands or sandy loams 2. Light textured silt loams 3. Porous loams or clay loams thoroughly oxidized to great depths	Good	Good	Uniform Color	Very low
II - Moderately Corrosive	1. Sandy loams 2. Silt loams 3. Clay loams	Fair	Fair	Slight mottling	Low
III - Badly Corrosive	1. Clay loams 2. Clays	Poor	Poor	Heavy texture Moderate mottling	2ft to 3 ft below surface
IV - Unusually Corrosive	1. Muck 2. Peat 3. Tidal marsh 4. Clays and organic soils	Very poor	Very Poor	Bluish grey mottling	At surface; or extreme impermeability

- The effects of abrasion included in Figure 4 were previously used for determining service life. The chart is based on steel pipe studies conducted in environments in California with pH less than 7.3, located in high rainfall mountainous areas in which significant abrasion could occur. Investigations in states with less abrasive environments found the chart to actually be conservative. Effects of abrasion are best determined from studies completed specific to a site.

- Tables are presented identifying correlation between soil resistivity and corrosiveness. Also presented are the typical corrosive characteristics of certain soil types. The associated tables are Tables 1 through 3.
- The majority of culvert inspections have found that corrosion is greatest in the invert. One solution is the installation of a paved invert and a coated steel pipe. Bituminous coating has been applied to the interior of a steel pipe to protect against corrosion and/or abrasion. New York State has found the addition of bituminous paving to extend service life by 25 years.
- It has been observed that bituminous paving will erode with heavy abrasion.
- Bituminous coating can also be completed when exterior corrosion of a steel pipe is a factor.
- Asbestos coated with bituminous coating and paving has been used to protect steel pipe from corrosion and abrasion.
- A variety of polymer coatings are available for corrosion and abrasion protection of steel pipe. Generally these are applied as a film laminate or as a liquid dispersion or an epoxy powdered coating.
- A design aid has been created by the National Corrugated Steel Pipe Association to simplify selection of steel pipe and protective coatings as presented in Figure 5.


NATIONAL CORRUGATED STEEL PIPE ASSOCIATION [24]

Coating Selection Guide for Corrugated Steel Pipe

(This guide is not intended for the comparison of the durability between the various coatings.)

TYPES OF COATINGS

Basic Coatings

- Zinc AASHTO M218
- Aluminum Type II AASHTO M274
- Aluminum-Zinc Alloy AASHTO M289

Protective Coatings

Polymer Coated
- Zinc AASHTO M 246
- Aluminum Type II M 246
- Aluminum-Zinc Alloy M 246

Bituminous Coated
- Zinc AASHTO M 190
- Aluminum Type II M 190
- Aluminum-Zinc Alloy M 190

Asbestos Bonded Coated
- Zinc Specification in preparation to replace WWP405

NOTES

1. Certain producers have indicated that their basic coatings can be used in a lower soil/water pH and/or resistivity range than that shown in the above chart. The producers should be contacted for their information.
2. Corrugated steel pipe with protective coatings have been used successfully below pH of 4 and above 12 and/or soil/water resistivities below 2,000 ohm-cm. Special design practices are recommended for these installations.
3. Abrasion is a combination of velocity and bed load. Each factor must be evaluated in selecting the appropriate abrasion condition.
4. Fabrication is covered in AASHTO M-36 and AASHTO M-245.
5. Information on durability and service life of corrugated steel pipe may be found in Chapter 7, Durability, of the AISI publication *Modern Sewer Design*, First Edition 1980; and Chapter 5, Durability, of the AISI publication *Handbook of Steel Drainage & Highway Construction Products*, Third Edition 1983.
6. The recommendations set forth in this Selection Guide are not a substitute for professional engineering advice and they are made without guarantee or representation as to results. Although every reasonable effort has been made to assure its accuracy, neither the National Corrugated Steel Pipe Association nor any of its members or representatives warrants or assumes liability or responsibility for its use or suitability for any given application.

Figure 5. Coating selection guide for corrugated steel pipe

1988: Life Cycle Cost for Drainage Structures

In this publication, service life guidelines are presented for various types of drainage materials. A summary listing of important information from this chapter is presented below for each material type.

Metal Pipe:

- Table 4 presents the Corps of Engineers' table for identifying material, soil and water pH, and Minimum soil resistivity for an expected design service life of 50 years. Table 4 only applies to pipes that meet the adequate structural design requirements presented in "Handbook of Steel Drainage and Highway Construction Products."

Table 4. Properties for design service life

Type of Material Used to Make Pipe	Soil and Water pH	Minimum Soil Resistivity ohm-cm
Galvanized Steel (AASHTO M218)	6 - 8.0	$\geq$ 2,500
Aluminized Steel, Type 2 (AASHTO M274)	5 - 9.0	$\geq$ 1,500
Aluminum (Alclad 3004)	5 - 9.0 or 5.5 - 8.5	$\geq$ 1,500 $\geq$ 500
Stainless Steel, Type AISI 409	5 - 9.0	$\geq$ 1,500
Cast Iron	6 – 9.0	$\geq$ 1,500

- Stainless steel can be used to carry acidic water from coal mine activity, without regard to pH
- Service life can be calculated as the sum of the lives of the nonmetallic protective coating, the metallic protective coating, and the basic metal pipe.
- A chart was created by the California Department of Transportation in 1972 to predict the time to first perforation of a galvanized corrugated steel pipe culvert. This generally occurs in the invert of the culvert. Time of first perforation is identified as a function of pH of environment and minimum soil resistivity. The chart was based on a survey of over 7,000 culverts in California in the 1950's. This method was used by more states than any other rational method in the 1980s; the chart is shown in Figure 3.
- The AISI in 1983 created a similar chart for service life of the culvert assuming that service continues until most of the invert is lost. This metal loss corresponds to nearly double that of first perforation. AISI assumed that service life was double the time to first perforation. For service life to exist past first perforation installation must be completed in non-erodible granular bedding. If the culvert is installed in highly erodible materials and/or the culvert is pressurized, then the time of first perforation will be the service life.
- The California Corrugated Steel Pipe Association found that the AISI chart is only appropriate for the upper 270 degrees of a pipe, and that the AISI chart should only be used when the invert is paved completely. An additional table was presented providing adjusted correction factors for the service life given varying gages of steel used in construction of the culvert. Adjusted correction factors were based on field data. Actual life of installations may vary.

- Aluminum-alloy protective coatings provide better protection for steel pipe than zinc coatings. Long-term field data suggests that the aluminum coatings (Aluminized Type 2, AASHTO M274) last much longer than the galvanized coatings (AASHTO M218). The only data available on the performance of this aluminum coating is contained in an Armco study, published in a refereed journal with technical discussions. An independent study showed that Aluminized Type 2 coated pipe could last 2 to 6 times longer than galvanized pipe. An adjusted correction factor for the service life for the AISI chart was created for Aluminized Type 2 culverts. These culverts are not to be used for sanitary or industrial sewers carrying salt water or acid mine runoff or heavy metals.
- Galvalume (Al-Zn alloy, AASHTO M289) performs better than standard galvanized steel in atmospheric exposures, but insufficient published performance data, for typical erosive-corrosive conditions, are available to establish this. Due to this it is recommended to calculate life expectancy for Galvalume as standard galvanized steel pipe.
- Most studies for determining aluminum pit-rate are based on geographical location and not on environmental parameters such as pH and Resistivity.
- Additional service life can be achieved with the application of a nonmetallic coating to the pipe and metal coating. A combination of industry and government agency policies and recommendations resulted in the following conclusions. Bituminous coating and paving adds 20 to 25 years to the average life of the pipe. Bituminous coating alone (AASHTO M190) adds approximately 8 years to the service life of a pipe where water side corrosion controls. Bituminous coatings are not intended for applications where effluents contain petroleum products. Polymer coatings (AASHTO M246) add approximately 10 years to the average service life of a pipe. Ethylene acrylic films, at the time of publishing of the report, added an additional 9.5 years service life to a pipe, but were expected to perform much better. Anticipated service life was 20 years for this coating, but no data was published to support this prediction.
- Typical abrasion was included in the above procedures for predicting service life. If conditions are highly abrasive than service life could be considerably less, or if conditions are minimally abrasive than predicted service life may be conservative.
- Abrasion in pipes is a function of velocity and bed load. Typically abrasive materials will not be transported by flows less than 5 ft/sec. More specifically abrasion is a problem when abrasive bed loads are present during events with velocities high enough to transport them. Invert protection should be provided when abrasion is above "average". A bed load carrying material larger than sand is likely to produce above average abrasion.

Concrete Pipe:

- Concrete pipes deteriorate from various factors including freeze-thaw weathering, acid corrosion, sulfate disruption, velocity-abrasion of the concrete, and chloride corrosion of the reinforcing steel. Reinforcing steel may be subject to corrosion from sulfuric acid, but generally this only occurs in sanitary sewers.
- Precast concrete pipe is generally immune to freeze thaw and chloride corrosion problems. Cast in place concrete with a high compressive strength (4000 to 6000 psi), limiting the water-cement ratio and the proper use of admixtures can mitigate freeze thaw and chloride corrosion.
- Problems caused by acid are negligible when soil and effluent pH remain between 5 and 7, and total acidity is less than 25 mg equivalent to acid per 100g of soil. Soil alkalinity up to a pH of nine causes no damage to the pipe.
- Sulfate disruption can occur on concrete pipe causing concrete spalling. This is caused by the reaction of sodium, magnesium, or alumina in the concrete. Concrete spalling can occur if sulfates are in solution, if there is a differential head between the inside and outside of the concrete pipe, and if evaporation is taking place, concentrating the sulfates on the concrete pipe. Generally problems occur when sulfate concentrations exceed 1,000 parts per million. To

mitigate this, the use of Type II or Type V cement is recommended. A table was generated by the US Department of Labor presenting guidelines for selection of concrete given sulfate concentrations as shown in Table 5.

- Abrasion in concrete pipes is not a factor when velocities are less than 15 ft/sec. Additional protection is required for velocities between 15 ft/s and 40 ft/sec where bed load is present. Generally this protection can be provided by increased cement content, increased concrete cover over the reinforcing, or harder aggregates. Velocities over 40 ft/sec can cause serious damage to pipe joints from cavitation.
- The service life of concrete pipes varies significantly given the wide range of operational environments. A survey completed by the New York State Department found that useful life of concrete pipes from 20 to 75 years with an average of 56.3 years.
- Generally concrete pipe service life increases greatly with pH levels above 4.

Table 5. Guidelines for selection of concrete pipes for various sulfate concentrations

Relative Degree of Sulfate Attack	**Percent Water Soluble Sulfate (as SO_4) in Soil Sample**	**Parts per Million Sulfate (as SO_4) in Water Samples**
Negligible	0.0 to 0.10	0 to 150
Positive*	0.10 to 0.20	150 to 1,500
Severe**	0.20 to 2.00	1,500 to 10,000
Very Severe+	2.00 or more	10,000 or more
Notes: * Use Type II cement. ** Use Type V cement or approved Portland-pozzolan cement providing comparable sulfate resistance is used in concrete. + Use Type V cement plus approved pozzolan which has been determined by tests to improve sulfate resistance when used in concrete with Type V cement.		

Plastic Pipe:

- Plastics are vulnerable to ultra-violet light and need to be buried or protected in some other manner. Plastics are also combustible.
- Plastic pipes can provide much more than 50 years of service as long as it is not exposed to ultraviolet light and the structural design is based on the long term creep behavior of the plastic.
- Two types of plastic pipe exist: thermoplastic and thermosetting. Thermoplastics are polyvinyl chloride (PVC), polyethylene (PE), and acrylonitrile butadiene-styrene (ABS). Thermosetting plastic pipes are found in reinforced mortar pipe (RPMP) and reinforced thermosetting resin pipe (RTRP).
- A characteristic of these plastic pipes is that the long term elastic modulus is lower than the short-term modulus due to creep in the loaded material. This creep is a function of loading and temperature. General design procedures used today use the long-term elastic modulus to account for long term pipe behavior.
- AASHTO has a procedure for designing plastic pipes in Section 18: Soil Thermoplastic Pipe Interaction Systems. This method uses the long-term elastic modulus method.
- Pipes manufactured from thermosetting plastics should be designed and installed in accordance with ASTM D 3839-79.

- In the design and installation of thermoplastic pipes 6-in nominal size and smaller, ASTM D 2321-83 should be followed.
- High density polyethylene pipe has shown abrasion resistance 3 to 5 times greater than mild steel, ETL 1110-3-332 (Headquarters, Department of the Army 1986).

Clay Pipe

- Of the common pipe materials, vitrified clay is perhaps the least corrodible. Only hydrofluoric acid and concentrated caustics have proven to corrode clay pipe. Vitrified clay has also proven to be very resistant to abrasion.
- The National Clay Pipe Institute compiled a list of over 50 clay pipe systems still functioning. Some of these systems have been functioning for up to 170 years. In spite of this, the design service life of vitrified clay pipe is limited to 100 years.

1996: Arizona DOT – Pipe Selection Guidelines and Procedures

A summary listing of important information from this document is presented below.

- Service life for galvanized steel pipe shall be based on the AISI chart, where total expected pipe service life is dependent upon pipe gage and the bituminous coating's service life. For galvanized steel to be a viable option, the environmental conditions must fall within the AISI chart limits.
- Aluminized steel pipe service life shall be determined from the corresponding AISI chart. For aluminized steel pipe to be considered a viable option, the environmental conditions must be within the AISI chart limits.
- Aluminum pipe installed in an environment with a soil pH of 5 to 9 and a resistivity of 500 ohm-cm or greater shall be given a service life of 50 years for 16 gage aluminum, 62.5 years for 14 gage aluminum, and 87.5 years for 12 gage aluminum. A bituminous coating shall contribute an additional 20 years to the service life of an aluminum pipe.
- Concrete pipe installed in an environment with a pH of 5 or greater shall be given a service life of 100 years. Where pH levels are below 5, the investigation of admixtures should be completed.
- Corrugated high-density polyethylene plastic pipe installed in an environment with soil pH of 1.25 to 14 shall be assigned a service life of 75 years.
- If velocities exceed 6.5 ft/sec through a metal pipe, abrasion might become a factor if the bed load is abrasive. This can be countered with an increase in gage of the pipe or the use of concrete or polyethylene pipe.
- When velocities exceed 40 ft/sec in concrete pipes, it is necessary to increase the compressive strength of the concrete or increase the specific hardness of the aggregate used.
- In cases where high sulfate levels exist in the soil, the concrete pipe must be constructed of Type V cement.
- Table 7 shows the allowable types of culvert pipe for various pH and resistivity ranges.

Table 6. Types of culvert pipe or coating

A	Corrugated Galvanized Steel Pipe (CGSP), Spiral Rib Galvanized Steel Pipe (SRGSP_, and Concrete Lined Corrugated Galvanized Steel Pipe (C/LCGSP), AASHTO M 36/M 36M, and Corrugated Galvanized Steel Structural Plate Pipe (CGSSPP), AASHTO M 167/M 167M and Use pH and Resistivity Ranges in the AISI Chart

B	Corrugated Aluminized Steel Pipe (CASP) and Spiral Rib Aluminized Steel Pipe (SRASP), AASHTO M36.M 36M The pH Range is 5 to 9 (except for Resistivity range 1000-1499 – see footnote 1)
C	Corrugated Aluminum Pipe (CAP), AASHTO 196/M 196M and Corrugated Aluminum Structural Plate pipe (CASPP), AASHTO 219/M 219M. The pH range is 5 to 9
D	Corrugated High Density Polyethylene Plastic Pipe (CHDPEPP), AASHTO M 294. The pH range is 1.25 to 14 and all ranges of Resistivity
E	Use Bituminous Coating on A, B, or C when needed, AASHTO M190 and AASHTO M243.

Table 7. Allowable types of culvert pipe for various pH & resistivity ranges

Resistivity (ohm-cm)	$\geq$ 2000	1500-1999	1000-1499	500-999	<500
Allowable Pipe or Coating	A-B-C-D-E	A-B-C-D-E	A-B[1]-C-D-E	A-C-D-E	A-D-E

Notes:
1) Not allowed when pH is less than 7.2

1997: USFS: Relief Culverts

Acceptable conditions for resisting corrosion as adopted from Oregon DOT are presented in this document. See Tables 8, 9, and 10.

Table 8. Corrosion service life for different pipe materials

Material	Suitable Performance Conditions	Corrosion Service Life	UV Degradation
Reinforced or unreinforced concrete	pH[a] >4.5 – 10 R[b] >1500	75+ years	H[c]
Galvanized steel dry climate	pH: 4.5 – 6 pH: 6 – 7 pH: 7- 10 R 1500 - 2000 for all	30 35 40	H
Galvanized steel rainy climate	pH: 4.5 – 6 pH: 6 – 7 pH: 7- 10 R 1500 - 2000 for all	15 20 25	H
Aluminum coated steel	pH: 5 – 9 R > 1500	50 rainy 65 dry	H H
Aluminum	pH: 4.5 – 10 R > 1500	75	H
Vitrified clay	N/A	Very Durable	H
PVC	N/A	N/A	L
Polyethylene	pH 4.5 – 10 R > 1500	N/A	M

Notes:

a. pH = pH of water or soil surrounding pipe

b. R = Resistivity, an electrical measurement in ohm-cm, which is one of the factors for estimating the corrosivity of a given soil to metals.

c. H, M, and L are high, medium, and low Resistivity, respectively

Table 9. Increase in galvanized steel service life based on soil resistivity (ODOT 1990)

Resistivity	Multiply life by this factor
2,000 < 3,000	1.3
3,000 < 4,000	1.4
4,000 < 5,000	1.6
5,000 < 7,000	1.8
> 7,000	2

Table 10. Increase in metal pipe service life based on metal thickness (ODOT 1990)

Gage	Multiply life by this factor
16	1.0
14	1.3
13	1.7
10	2.2
8	2.9

1997: EM1110-2-2909 – Conduits, Culverts, and Pipes

A summary listing of important information from this document is presented below.

- In general, concrete will provide a service life twice that of steel or aluminum.
- Most studies indicate a service life of 70 to 100 years for concrete pipes.
- Corrugated steel pipe typically fails due to corrosion of the invert. Properly selected coatings can extend the service life of most steel pipes to at least 50 years.
- Aluminum pipe is generally affected by soil side metal erosion rather than corrosion of the invert. Since application of aluminum pipe is fairly new, little is known about the extended service life of aluminum pipe. Generally, the designer should not count on greater than 50 years of service life for aluminum pipes.
- Like aluminum, the service life of plastic pipes is fairly unknown, as it has recently been installed. Again, a designer should not expect a service life of greater than 50 years.

1998: NCHRP Synthesis 254 - Service Life of Drainage Pipe

A summary listing of important information from this document is presented below.

- Corrosion can begin either on the inside or outside of buried metallic drainage pipes. This can either be identified as uniform corrosion or localized corrosion. Uniform corrosion is identified by corrosion progressing at the same rate over the entire surface of the pipe. Pitting corrosion or crevice corrosion identifies localized corrosion.
- Service life of metal and concrete pipe is greatly affected by the chemistry of the groundwater, with dissolved minerals and salts.
- Crevice corrosion is defined as the corrosion that occurs at the interface between gaskets and pipe walls, between protective films or liners and pipe walls, or between overlapping plates at pipe wall fastenings, set up a mechanism similar to that of pitting corrosion.
- Stress corrosion and cracking is defined as a combination of corrosion and tensile stress, including residual tensile stress.
- Microbiologic corrosion is defined as abnormally quick corrosion caused by sulfate reducing bacteria.
- Perforation or the complete penetration of the metal signals the need for action to maintain or replace the pipe. Continuation of this deterioration can lead to exfiltration of water and/or infiltration soil. This infiltration of local soil can typically cause failure of support provided by the sub grade.
- Abrasion and corrosion tend to perpetuate each other. Metal corrodes to a more brittle state and abrasion carries away the brittle product of the corrosion. This exposes new metal to be further corroded. This causes far quicker deterioration.
- Cavitation can also cause deterioration problems from gas bubbles striking the surface of the pipe. This can be caused by rivets or lapped joints, sharp bends, at pipe entrances, etc. Cavitation is typically not a problem in culverts given the lower velocities.
- Abrasion is a function of the square of the velocity, so an increase to double the velocity will increase abrasion four fold. Theoretically, doubling of the velocity of a stream increases its ability to transport rock fragments of a given size by as much as a factor of 32.
- The Federal Lands Highway Division of FHWA has defined measures of abrasion as follows:
    1. Non-abrasive-no bed load and very low velocities,
    2. Low abrasive-minor bed loads of sand and velocities less than 5ft/sec,
    3. Moderate abrasive-moderate bed loads of sand and gravel and velocities between 5 and 15 ft/sec, and

4. Severe abrasive-heavy bed loads of sand, gravel and rock velocities exceeding 15 ft/sec. The velocities noted are those typical of flows.

- The most vulnerable areas for corrosion and abrasion in storm drainage are typically the invert.
- Entrance and exit ends of pipes are often vulnerable to degradation by sunlight. These ends are also exposed to temperature changes as well as dry and wet cycles.
- Settling of the pipe can also create cracks in the coatings applied to a pipe exposing the steel to the elements beginning the cycle of corrosion and abrasion. Settling can also crack concrete exposing the reinforcement.
- Soil pH is commonly used as the primary index of corrosion potential for concrete and metal pipes. For bare steel installed in soil with a pH between 4 and 10, the corrosion rate is independent of pH and depends only on how rapidly oxygen diffuses to the metal surface.
- Resistivity is a function of dissolved salts in the soil and is also affected by the temperature, moisture content, soil compactness and presence of inert materials such as stones and gravels. Soil resistivity generally decreases as depth increases. Due to this, it is important to take measurements of the resistivity at the depth where the culvert is to be installed. Resistivity is measured in ohm-cm and is defined as the electrical resistance between opposite faces of an isolate 1 cm^3 at 60 degrees Fahrenheit. A table of common values for resistivity of varying soils is presented in Table 11. Several procedures have been developed to determine the corrosion rates for pipes from resistivity of local water and soil, such as the California Test 643 method.

Table 11. Typical resistivity values for soil and water

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

- Another method of measuring electrical current is the polarization curve. This method predicts the corrosion rate of the exterior surface of buried structures. These measurements can be completed from the highway surface eliminating the need for excavation of the existing pipe. This method uses Faraday's law to calculate total weight loss of the metal. Pitting or local deterioration cannot be measured with this method.
- If soil has a high resistivity, this can create large resistive potential drops causing errors in polarizing resistance measurements. Electrochemical impedance spectroscopy can be used to overcome this error. In this method, small amplitude alternating potential signals of widely varying frequencies may be applied to the pipeline to obtain a compensated polarizing resistance.
- Oxidation-reduction potential or redox is used as an indicator of anaerobic bacterial corrosion. This type of deterioration occurs at the interface between the soil and the metal and is amplified by wet, poorly drained soil, common to swamps, marshes and brackish water with pH in the neutral range. Generally in these environments sulfate-reducing bacteria exist corroding the iron giving off an odor of hydrogen sulfide gas. Table 12 provides typical redox values and corresponding corrosiveness.

Table 12. Redox potential versus corrosiveness for steel pipe

Soil Redox Potential (millivolts)	Classification of Corrosiveness
Below 100	Severe
100-200	Moderate
200-400	Slight
Above 400	Noncorrosive

- Investigations into the effects of varying soil types on corrosiveness have been completed, while not discussed in detail. In this book it was stated that DOTs generally restrict the amount of organic material that is allowed to backfill around culverts. Chlorides and other dissolved salts increase the electrical conductivity of a soil adding to the corrosiveness of a soil.
- In addition to physical barriers, it has been found that cathodic protection can control corrosion. This process involves applying a current to the pipe restricting movement of ions thus preventing deterioration.

- Four primary materials are used in construction of drainage pipes: metal, plastic, concrete, and clay. Metal pipes can be fabricated from steel, ductile iron, or aluminum. Concrete pipes can be steel-reinforced, earth-reinforced, unreinforced, pre-cast or cast-in-place. Plastic pipes can be classified as thermosetting resins (e.g., glass-reinforced epoxy or polyurethane) or thermoplastic resins (e.g., polyvinyl chloride).
- Much of the durability of a concrete pipe depends on the quality of the concrete mixture. In the cases where concrete cracks or spalls, exposed reinforcement corrodes very quickly with the concrete acting as an electrolyte.
- High sulfate concentration in the Great Plain states and the arid western states causes deterioration of concrete pipes. Evaporation causes concentration of the sulfates on the surface of the concrete speeding deterioration.
- In locations with high sulfate concentration, permeability of the concrete pipe becomes a consideration. Permeability can be reduced by a low water/cement ratio and/or the use of a mineral admixture, such as fly ash, calcium nitrite or silica fume.
- The American Concrete Institute states that if water-soluble sulfates in soil are less than 0.1 percent and the sulfate solution in water is less than 150 ppm, the exposure is considered mild. Exposure is considered moderate when water-soluble sulfates in soil are in concentration between 0.1 percent and 0.2 percent and the sulfate solution in water is between 150 ppm and 1500 ppm. Exposure is considered severe when water-soluble sulfate in soil are present in concentrations greater than 0.2 percent and/or the sulfate solution in water is greater than 1500 ppm.
- No Portland cement is resistant to acid attack although, Type II cement is considered moderately sulfate resistant, up to a maximum of 8 percent C_3A; Type V cement, identified as sulfate resisting, is limited to 5 percent C_3A.
- Freeze thaw cycles have posed problems for concrete pipe where the concrete spalls due to water freezing in voids in the concrete, expanding, and breaking the concrete. This can be avoided with properly selected air entrainment and the use of frost compatible aggregates.
- Abrasion is a function of the environment. For concrete pipe velocities above 15 ft/sec may require a stronger concrete mixture, and velocities above 40ft/sec cavitation can occur at pipe joints. Acid attack on the invert of a concrete pipe magnifies the effect of abrasion by weakening the concrete on the invert.

- Corrosion of the steel reinforcing in concrete pipes can also lead to spalling and increase the pace of deterioration of the concrete pipe. Epoxy coated rebar can be used to counter corrosion of the reinforcing bars.
- Service life for concrete pipe varies from state to state. Generally, it is accepted that the service life of concrete pipe is significantly greater than 50 years.
- Table 13 provides guidelines for use of sulfate resistant cements.

Table 13. Guide for sulfate-resistant pipe and concrete drainage structures*

Water-Soluble Sulfate (SO^{4-}) in Soil Sample (%)	Sulfate (SO^{4-}) in Water (Parts per Million)	Type of Cement	Cement Factor
0-0.2	0-2,000	II	Minimum required by specifications
0.2-0.5	2,000-5,000	V or II	Minimum required by specifications 7 sacks+
0.5-1.5	5,000-15,000	V or II	Minimum required by specifications 7 sacks
Over 1.5	Over 15,000	V	7 sacks

Notes:
*Recommended measures for cement type and factor based on sulfate content of soil and water (California 7-851.3 D)
+7-sack cement = 390 kg of cement per m3 of concrete.

- No specifications are presented for the hardness of aggregates in a concrete mixture; however, the use of harder aggregates increases the resistance to abrasion.
- Equations have been developed for the prediction of service life for a concrete pipe. These equations are typically very environment specific, where the equation is only applicable to pipes that are installed in the same environment. Several of these equations are presented in the publication. Two of which are the Hurd and Hadipriono equations.
- Calcium carbonate carried in drainage water can actually form a protective coating on galvanized steel pipe.
- It can be generalized that sulfate, chloride, nitrate and phosphate ions either disrupt or inhibit scale formation on steel pipes creating corrosive environments.
- As with concrete pipes, the specifications for use of pH and resistivity in selecting metal pipes vary widely from state to state. Many of these specifications are listed in the publication.
- Different institutions define Service life of metal pipe differently. AISI defines the service life as an average invert life, which is considerably longer than first perforation. Some states define service life as the time from installation to failure of the pipe structurally. The California Test Method is also widely used; this method generally predicts a service life half of that predicted by the AISI method.
- A modified California method has been defined to account for a parameter of scaling tendency as a function of alkalinity, hardness and free carbon dioxide, for metal pipes.
- For metal pipes, some states do not correlate service life with pH; rather, they use geographical location of the installation.

- Application of deicing salts has also been found to expedite the deterioration process of metal pipes.
- An Army Corps of Engineers study found that bituminous coatings provide little additional life for galvanized steel pipe.
- Aluminum pipes form an aluminum oxide layer on the outside that protects the metal from corrosion in the middle range of pH 4 to 9. This protective layer is soluble outside of this range.
- Aluminum pipes are vulnerable to pitting in environments with high concentration of copper, bicarbonate, chloride, sulfate, and oxygen ions.
- A serious mode of deterioration of aluminum pipes is stress corrosion cracking, which occurs under the combined influence of tensile stress and a corrosive environment.
- Aluminum is much softer than the sediment carried in bed load. Due to this, abrasion is the typical mode of failure for aluminum pipe.
- Limitations of pH and Resistivity vary widely from state to state for aluminum pipes.
- Aluminum pipes are susceptible to corrosion caused by many different chemicals present in soils and water. Due to this, the success of aluminum pipe installations varies widely with geographical location.
- Plastic pipes are highly resistant to pH and to chemically and electrochemically induced corrosion.
- Generally there is no pH or Resistivity restrictions on the use of HDPE or PVC pipes.
- Plastic pipe is typically resistant to abrasion from small aggregates and fine sands. It is not known what the effects of continual large sediment abrasion are on plastic pipe.
- Exposure of plastic pipe to sunlight has also been identified as corrosive. Titanium dioxide is a UV light absorber often added to PVC to counter this. However, some studies show that PVC exposed to UV light actually exhibited an increase in tensile strength and a decrease in brittleness.
- Plastic pipe has been shown to be fairly resistant to burning. PVC will self extinguish once the heat source is removed.
- Thermoplastic pipes are constructed of a material categorized as viscoelastic. Their mechanical properties are time dependent and include strain and creep under a sustained load. Due to these mechanical properties such as the effective modulus of elasticity may dominate service life expectations.
- Due to rubber gaskets in ductile iron pipe it is fairly immune to stray current accumulation that can cause corrosion.
- Ductile Iron pipes have many of the same causes and types of corrosion that exist for steel pipe. Some states use a polyethylene jacket for lower Resistivity and pH environments.
- A unique form of corrosion for ductile iron pipes is graphitic corrosion, a result of electrochemical action between the ferrite and graphitic constituents in the cast iron.
- The most cost effective corrosion protection for ductile iron pipe is the application of a polyethylene film encasement. Where the polyethylene is loosely wrapped around the pipe during installation. Groundwater will penetrate the wrap but due to the limited amount of oxygen the corrosion will be limited as well.
- Vitrified clay pipes have been used for more than 100 years. Due to this much is known about their behavior when buried. Typically vitrified clay pipes are used in sanitary sewers. These pipes have an excellent resistance to acid attack.
- With vitrified clay pipe the usual concerns for corrosion (Resistivity, pH, chlorides, and sulfides) do not apply. However clay pipe is vulnerable to corrosion caused by high temperatures, which are not common environments for concern in hydrofluoric acid and concentrated caustics at highway drainage.

- The National Clay Pipe Institute states the service life of vitrified clay pipe is 150 years, the Army Corps of Engineers states the service life of vitrified clay pipe is 100 years. Some states identify the service life of vitrified clay pipe to be the life of the facility.
- Coatings, claddings, and linings are designed to inhibit the process of electrochemical corrosion that will degrade metal pipes or metal reinforcement within concrete pipes. These treatments for pipes can also be protecting against abrasion.
- Nonconducting barriers are applied to pipes to interrupt the flow of ions from the pipe minimizing deterioration.
- Another form of protection is passive insulating film in this process a film is applied to reduce potential differences between the attracting cathodes and the feeding anodes. Examples of these are aluminum and zinc. These metals are sacrificial and once deteriorated will leave the steel pipe open to deterioration. In these cases thickness of the coating and the permeability of the coating affect the life of the coating.
- Most galvanized pipes are treated with a two-ounce zinc coating where 2 oz. /ft^2 are applied to the pipe. Thicker applications are available but not practical.
- Aluminum coatings are applied to steel pipe at 1 oz/ft^2 typically. Aluminum barriers perform differently than zinc; zinc barriers are sacrificial, while aluminum serves as a barrier.
- Studies have shown that pipes installed in a naturally occurring surface water, with soil and water pH between 5 and 9 and with minimum soil resistivity no less than 1500 ohm-cm, aluminum coated steel pipe provides twice the service life of galvanized steel.
- Galvalume has also been applied to pipes as a combination of zinc and aluminum.
- An Indiana study also found that aramid fiber-bonded bituminous-coated pipe is more durable than the formerly used asbestos fiber-bonded metallic-coated pipe in highly acidic conditions.

1999: Florida DOT – Drainage Handbook: Optional Pipe Materials

A summary listing of important information from this document is presented below.

- Service life of a pipe is defined as the point at which significant deterioration is visible. Once this point is reached major rehabilitation or replacement should be considered. For a metal pipe the point of first perforation is considered the end of the service life. For a concrete pipe the service life ends at the time the pipe experiences corrosion related cracks.
- Estimated service life is predicted from an analysis of the corrosiveness of the culvert site. Rates of corrosion are to be determined from both the water and the soil of the environment.
- Of importance when designing culverts is the corrosion of the metal whether it is a steel culvert or the reinforcing in a concrete culvert. There are four primary factors of the environment that affect the selection of a culvert including: pH, resistivity, sulfates concentration, and chlorides concentration.
- Ideally, field testing should be completed before selection of a culvert. If this is not possible, then soil maps from the Soil Conservation Service (SCS) can be used. Analysis of the test data should use the most corrosive value from the native soil, water, and backfill soil. It is imperative to test the fill material to ensure that it is no more corrosive than the native soil.
- The Florida Department of Transportation wrote a computer program, Culvert Service Life Performance and Estimation Program, for determining types of culvert material that have expected service life that meet or exceed the required design service life. A design service life is defined as the minimum number of years that a material has to meet or exceed for a particular application.
- Environmental factors used in this computer program are pH, resistivity, chloride concentration, sulfate concentration, and pipe diameter. The pH is defined as the measure of alkalinity or acidity in the soil or water. Environments where the pH is to low (5) or high (9) cause the protective layers on metal to corrode and speeds the deterioration. Resistivity is defined as a measure of the

electrical conductivity of a soil or water sample. High resistivity values (>3000 Ohm-cm) impede the movements of ions in soil and slow corrosion, where low resistivity values (< 1000 Ohm-cm) provide an easier path for ions to migrate and increase corrosiveness. Chloride concentrations define the amount of chloride ions in the water. Chloride ions have the tendency to break down the protective layer that forms on metal. High (>2000 ppm). Sulfate concentration defines the number of sulfate ions present in an environment. Sulfate ions also break down the protective layers on metal. Sulfate ions also deteriorate concrete. High (>1500 ppm).

- There have been instances for jack and bore culvert installations where the bored casing was used as the conduit pipe. The computer program created by the Florida Department of Transportation can be used to calculate if the bore casing will be sufficient to meet the design service life. This process involves using the galvanized steel return value, subtracting 10 years from the expected service life, finding the pitting rate, and determining if the bore casing thickness is sufficient.

2001: Corrosion Resistance and Service Life of Drainage Culverts

A summary listing of important information from this document is presented below.

- Reinforced concrete deteriorates due to chemical degradation of the concrete itself due to the presence of acidity and sulfates in the soil. The most notable cause of deterioration is actually caused by corrosion of the steel reinforcement. Generally, this corrosion of reinforcement is caused by chloride ions penetrating the concrete. Once the reinforcement begins to corrode cracks form in the concrete and further reinforcement corrosion is initiated. Of importance in this study is the ability for concrete to resist chloride penetration. Two types of concrete pipe were tested; unblended Type II Portland cement and Type II Portland cement blended with fly ash. Two test were completed for the concrete pipe specimens; a continual immersion test, and a cyclical ponding test
- Average porosity for concrete culvert segments tested were 11.2% and 13.5% for without fly ash and with fly ash respectively. There appeared to be no significant performance differences between the culverts in testing.
- During testing the concrete specimens underwent a corrosion initiation period. During this testing infiltration of sodium ions was observed.
- Next a period of corrosion propagation was observed. In this stage of the concrete life cycle the specimens experienced some corroding. This was minimal and cracking was expected in the next several years, but widespread damage was not expected for decades. Apparent corrosion rate was higher in constant immersion specimens; even though immersed conditions are known to reduce the incidence of corrosion induced cracking. During this period corrosion was observed on the order of 1 micrometer per year to 10 micrometer per year.
- Overall it was found that typical production culvert pipe does not provide any significant protection for the steel reinforcement from chloride ions. This may be due to the low cement content in both concrete pipes that were tested.
- More conclusions from the laboratory testing and chloride ion infiltration rates are located in the paper.
- Evidence from yard culvert testing suggests that corrosion initiation period in a few years of exposure to aggressive conditions. Aggressive conditions were considered to be cyclical ponding of water with a high salt concentration.
- Field culverts analyzed were in service from 12 to 43 years at 8 different locations.

2003: Caltrans DIB 83

A summary listing of important information from this document is presented below.

- Service life for a reinforced concrete pipe is considered the point when deterioration exposes reinforcement at any location in the culvert.
- Non-reinforced concrete pipe fails at the point of perforation or major cracking with soil loss.
- Glass fiber reinforced polymer mortar fails at the point when deterioration reaches the point of perforation or major cracking with soil loss. This pipe is made by mixing a high strength thermosetting polyester resin, aggregate/sand and chopped glass fiber roving, forming a type of concrete.
- Metal pipe service life is considered the number of years from installation until the deterioration reaches the point of perforation at any location on the culvert.
- Both PVC and HDPE are not affected by corrosive and chemical elements typically found in soil and water. These types of pipe have also exhibited excellent resistance to abrasion. However have drawbacks such as weakness caused from ultraviolet radiation and vulnerability to heat.
- Coatings are installed in concrete pipe to protect against chemical attack. Typically concrete pipe is acceptable for conditions where pH ranges from 7 to 3 and sulfate concentrations between 1500 and 15000 ppm. Outside of these ranges the designer must specify another material or provide a physical barrier from the elements.
- Metal pipe generally requires coatings to provide a corrosion barrier covering the entire pipe or a sacrificial layer of abrasive resistant material concentrated in the invert of the pipe.
- HDM Table 854.3A lists all of the plant-applied approved coatings for steel culverts and constitutes a guide for estimating the added service life that can be achieved based upon abrasion resistance characteristics only.
- Generally galvanizing a steel pipe provides sufficient protection, yet, when highly corrosive or abrasive environments exist other coatings can be applied. Coatings that are common are polymeric sheet and polymerized asphalt; the Department of Fish and Game (DFG) approve these. However, bituminous coatings are restricted by the DFG. Polymeric sheet coating was originally developed for protection from corrosion but has also been found to prevent abrasion. Polymerized asphalt was developed for abrasive environments.
- Environments where significant soil side corrosion and abrasion are present a metal pipe can be externally pre-coated with a polymeric sheet, and internally coated with a polyethylene sheet to add service life.
- Table 14 identifies pipe materials and corresponding limitations for abrasion.

Table 14. Abrasion levels and materials

Abrasion Level	General Site Characteristics	Invert/Pipe Materials
Non Abrasive	• Little or no bedload • Velocities less than 3ft/sec with bedload	All allowable pipe materials listed in HDM table 853.1A No abrasive resistant coatings needed for metal pipe
Low Abrasive	• Minor bedload of sand, silts, and clays • Velocities less than 5ft/sec	All allowable pipe materials listed in HDM table 853.1A with the following considerations: Generally, no abrasive resistant protective coatings needed for steel pipe; polymeric, polymerized asphalt 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, particularly if a corrosive environment exists.
Moderate Abrasive (A)	• Moderate bedload of sands, gravels, and small cobbles with maximum stone sizes up to about 150mm • Velocities from 5ft/sec to 10ft/sec	All allowable pipe materials listed in HDM table 853.1A with the following considerations: Steel pipe will typically need one of the abrasive resistant protective coatings listed in HDM table 854.3 or additional gauge thickness. Aluminum pipe not recommended for sharp and angular bedload, otherwise OK. Lining alternatives: PVC, Corrugated or solid wall HDPE, CIPP
Moderate Abrasive (B)	• Moderate bedload of sands, gravels, and small cobbles with maximum stone sizes up to about 150 mm. For larger stone sizes within this velocity range see "severe abrasive." • Velocities from 10ft/sec to 15ft/sec	Aluminum pipe not recommended. Corrugated HDPE pipe or liners allowed. PVC pipe or liners allowed, but not recommended for upper range of stone sizes in bedload if freeze thaw conditions are often encountered, otherwise OK for stone sizes up to 75 mm. Generally, for sharp and angular bedload, the abrasive resistant coatings listed in HDM table 854.3A are not recommended for steel pipe except CSSRP. A concrete invert lining or additional gauge thickness is recommended. For bedload stone sizes greater than 75mm, concrete cover over reinforcing steel should be increased for RCP and inverse thickness increased for RCB. A harder aggregate than the bedload, decreased water-cement ratio, and increased concrete compressive strength may also be specified. Lining alternatives: PVC, Corrugated or Solid Wall HDPE, CIPP, RPMP
Severe Abrasive	• Heavy bedload of sands, gravel, and rocks, with stone sizes 150 mm or larger • Velocities greater than 10ft/sec **OR**	Aluminum pipe not recommended. None of the abrasive resistant protective coatings listed in HDM table 854.3A are recommended for protecting steel pipe except CSSRP. CSP with concrete invert lining with harder aggregate than the bedload, decreased water-cement ratio, and an increased concrete compressive strength specified. Additional gauge thickness should be considered. Concrete invert lining not recommended for bedload stone sizes greater than 75mm. Alternative invert linings

Abrasion Level	General Site Characteristics	Invert/Pipe Materials
Severe Abrasive (Cont)	• Heavy bedload of sands, gravel, and small cobbles, with stone sizes up to about 150 mm • Velocities greater than 15ft/sec	may include steel plate, rails, or concreted RSP. For new/replacement construction, consider "bottomless" structures. PVC pipe or liners only allowed for sand and gravel bedload (less than 50mm) for velocities less than 20ft/sec. Corrugated HDPE pipe or liners allowed for velocities less than 20 ft/sec and angular stone sizes up to 150mm. For bedload stone sizes less than 75 mm, concrete cover over reinforcing steel should be increased for RCP and invert thickness increased for RCB. A harder aggregate than the bedload, decreased water-cement ratio, and increased concrete compressive strength recommended. RCP /RCB not recommended for bedload stone sizes greater than 75mm and velocities greater than 15ft/sec. Lining alternative: HDPE, SDR (Solid wall), CIPP.

- Abrasion is defined as the wearing away of pipe material by water carrying sands, gravels and rocks (bed load) 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. It has been shown that angularity of the bed load significantly effects the abrasion experienced by a pipe. Generally the invert of a pipe is the most vulnerable to abrasion. Four abrasion levels were developed by FHWA to quantify the abrasion potential of a site. Table 854.3 A of the HDM uses the same four levels of abrasion. The tables presented below are similar to those developed by the FHWA. It should be noted that these tables do not consider hydrologic characteristics or bed load angularity. Generally sampling of the streambed is not necessary, visual inspection of the site paying attention to material size and angularity should suffice for determining abrasive characteristics. Stream velocity should be based on typical intermittent flows and not an extreme event, due to the fact that abrasion typically occurs during these more frequent smaller events. Typically this corresponds to a 2 to 5 return interval.
- Generally, corrugated steel pipe is the most susceptible to abrasion. There have been instances where the addition of steel plate to a pipe has been completed to combat abrasion.
- Aluminum pipe has also been found to display inferior abrasion resistance to steel pipe. Aluminized steel can be considered equivalent to galvanized steel in abrasive resistance.
- Resistance to abrasion of concrete pipe depends on concrete quality, strength, and hardness of the aggregate and density of the concrete as well as the velocity of the water flow coupled with abrasive sediment content and acidity. Concrete can counter abrasion with an increase cover of concrete over reinforcement.
- Types of corrosion include: atmospheric, microbiological, and galvanic corrosion. These types of corrosion are influenced by the structure of the soil. Criteria used to determine corrosiveness include; pH, the specific electrical resistance, and the chloride and sulfate content of both soil and water. Stray electrical currents from power lines or electrified rails can also expedite the corrosion of pipes. Tables 15 and 16 illustrate typical resistivity values, relationship of soil corrosion to electrical resistivity, and corrosiveness of soils. Generally, areas with high rainfall have acidic soils and high electrical resistivity.

Table 15. Resistivity of different soil types

Soil Type	Degree of Corrosiveness	Electrical Resistivity Ohm-cm
1	Very low	10,000-6,000
2	Low	6,000-4,500
3	Moderate	4,500-2,000
4	Severe	2,000-0

Table 16. Degree of corrosiveness of different soil types

Soil Type	Description of Soil	Aeration	Drainage	Color	Water Table
I - Lightly Corrosive	1. Sands or sandy loams 2. Light textured silt loams 3. Porous loams or clay loams thoroughly oxidized to great depths	Good	Good	Uniform Color	Very low
II - Moderately Corrosive	1. Sandy loams 2. Silt loams 3. Clay loams	Fair	Fair	Slight mottling	Low
III - Badly Corrosive	1. Clay loams 2. Clays	Poor	Poor	Heavy texture Moderate mottling	2ft to 3 ft below surface
IV - Unusually Corrosive	1. Muck 2. Peat 3. Tidal marsh 4. Clays and organic soils	Very poor	Very Poor	Bluish grey mottling	At surface; or extreme impermeability

2003: Montana DOT – Culvert Service Life Guidelines

In this document a survey of culvert service life guidelines was distributed to all 50 states. The responses of the 20 states that answered are as follows:

- Eleven of the twenty states have Culvert Service Life Guidelines.
- Only two of the twenty states use AISI (American Iron and Steel Institute) chart to determine the average life of steel pipe.
- Thirteen of the twenty states require watertight joints for irrigation crossings.
- Eight of the twenty states require watertight joints for mainline crossings.
- The add-on life expectancy (additional years for coating pipe) for polymeric, bituminous, and Type II aluminized varied dramatically
    - Polymeric additional years – ranges from 0 to 50 years. Only three states use 50 years, three states use 20 years, two states use 16 and the remaining 12 states use 0 years or do not consider polymeric coatings
    - Bituminous additional years – ranges from 0 to 25 years. Only two states use 25 years, one state uses 20 years, one state uses10 years, one state uses 8 years, one state uses 5 years, one state uses 3 years, and the remaining thirteen states use 0 years or do not consider or did not comment on bituminous coatings
    - Type II Aluminized – Ranges from 0 to 50 years. Only three states use 50 years, one state uses 35 years, one state uses 25 years, three states use 20 years, one state uses 16 years, and the remaining eleven states use 0 years or do not consider or did not comment on Type II aluminized coatings.
- Thirteen of the twenty states use open bottom arches on active streams and three of these states require scour protection. Seven states do not use open bottom arches.
- Two of the twenty states limit the use of reinforced concrete pipe (RCP) based on sulfates. Eighteen states do not.
- Three of the twenty states require third party certification for all pipe material. Seventeen states do not.
- The use of high-density polyethylene (HDPE) varies from state to state. Eight states require the HDPE to have a smooth wall interior and corrugated exterior.
- Eight of the twenty states have fill height tables for HDPE pipe.
- Two of the twenty states consider non-corrosive backfill material around pipes as a means of increasing life. The other states do not.
- Three of the twenty states consider polymeric and bituminous coatings as a means of minimizing abrasion.
- Nine of the twenty states require special construction specifications for the installation of plastic pipe. The Arkansas DOT does not allow plastic pipe as a pipe option.
- Five of the twenty states have a resistivity requirement/limitation for the use of steel, RCP, Type II aluminized, and aluminum pipe. (2003, Montana Department of Transportation, p.3)

2004: New Mexico DOT Corrosion/Abrasion Guidelines

Current corrosion and abrasion guidelines from New Mexico DOT were provided to the research team from CDOT. Corrosion guidance is presented below as Table 17. Abrasion guidelines are presented in Table 18.

Table 17. New Mexico DOT corrosion guidelines

CORROSION RESISTANCE TABLE FOR 50 YEAR SERVICE LIFE							
NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT							
Date: July 1, 2000	CORROSION RESISTANCE NUMBER						
JSL	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 pH<5.0, use a rapid chloride permeability ≤1200 coulumbs 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 Exspectancy Equations on Sheet two to determine thickness or gage required for a fifty year service life. Backfill and bedding are granular and have electro-chemical requirements according to the metal used as per Section 571.						
CONCRETE and METAL ATTACK							
	Negligible			Positive		Considerable	Severe
MINIMUM RESISTIVITY (OHM-CM) for BOTH SOIL & WATER							
	≥2000	≥1500		≥1000	≥500	≥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)

Table 18. New Mexico DOT abrasion guidelines

Water Side Abrasion

On the water side, the final step to determine service life is to analyze for potential abrasion. Use the (5) five year design velocity to check for a potential abrasive enviroment. Where low bedloads are present ("ie"a closed system such as a storm sewer.), higher velocities are not of concern.

Abrasion : **Invert Protection/Productive coatings can be applied in accordance with the following criteria. Abrasion velocities should be evaluated on the basis of frequency and duration. Consideration should be given to a Q5 or less for velocity determination. Perennial streams with longer peaks should be a consideration for increased abrasion.**

Level 1: **Non-abrasive - No bedload, velocities can be greater then 15 ft./sec**
Level 2: **Low-abrasion - Minor bedloads of sand and gravel with velocities of 5 ft/sec. or less. Also use for storm drain applications.**
Level 3: **Moderate abrasion - Bedloads of sand and gravel with velocites between 5 and 15 ft./sec.**
Level 4: **Severe abrasion - Heavy bedloads of gravel and rock with velocities exceeding 15 ft./sec.**

Material	RECOMMENDED ADJUSTMENTS FOR ABRASION			
	Low Abrasion Level 1	Mild Abrasion Level 2	Moderate Abrasion Level 3	severe Abrasion Level 4
Concrete Pipe	No Addition	No Addition	No Addition	Modify Mix Design
Aluminized Steel Type II	No Addition	No Addition	Add One Gage	Add One Gage and Pave Invert
Galvanized Steel (2 & 3 oz. Coating)	No Addition	Add One Gage *	Add Two Gages *	N/A
Polymer 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	N/A

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

Review of CDOT's Current Corrosion Resistance Table

CDOT's current guidelines for corrosion/abrasion are based on the Corrosion Resistance (CR) table that was developed in 1983 (Table 19). The guidelines given in Table 19 use primarily the pH, chloride, and sulfate concentrations to determine the corrosion resistance levels, rated from 0 to 6. These levels, in turn, are associated with various pipe materials as acceptable limits. 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. Since its development, the CR table guidelines were used by CDOT in installing various culvert pipe sizes with different types of materials (CMP, RCP, HDPE, etc.) in Colorado roadways. However, the performance of these culvert pipes was not evaluated to assess their structural and operational integrity.

Table 19. CDOT's guidelines for selection of corrosion resistance levels

CR LEVEL	SOIL			WATER		
	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.

Neighboring state DOTs including Utah and Arizona have adopted guidelines that incorporate pH, chloride, sulfate, total dissolved solids, resistivity, water velocity, and slope to assess the impact of corrosion and abrasion on various types of pipes. Some of these factors are associated with estimated service life of the pipes.

In these guidelines, soil resistivity is related to service life of culverts through logarithmic relationships with additional variables such as pH and gage thickness appearing as modifying factors. However, the information presented in Figure 2 has limitations. Due to the conditions used in its derivation, it may not be totally applicable to Colorado's unique site conditions. The temperature, soil moisture and environmental factors may shift the slope of the pH lines or move them up or down. Service life data from Colorado can be used in calibrating these equations and modify them to fit our State's geographic, soil, and environmental conditions. The results from the ongoing inspection effort conducted by the Staff Bridge Branch along the I-70 mountain corridor and along I-25 provided a unique opportunity to supply data that was used in the development of new guidelines for culvert pipe materials selection procedure. This data supplied failure cases along major Colorado interstate highways.

Summary

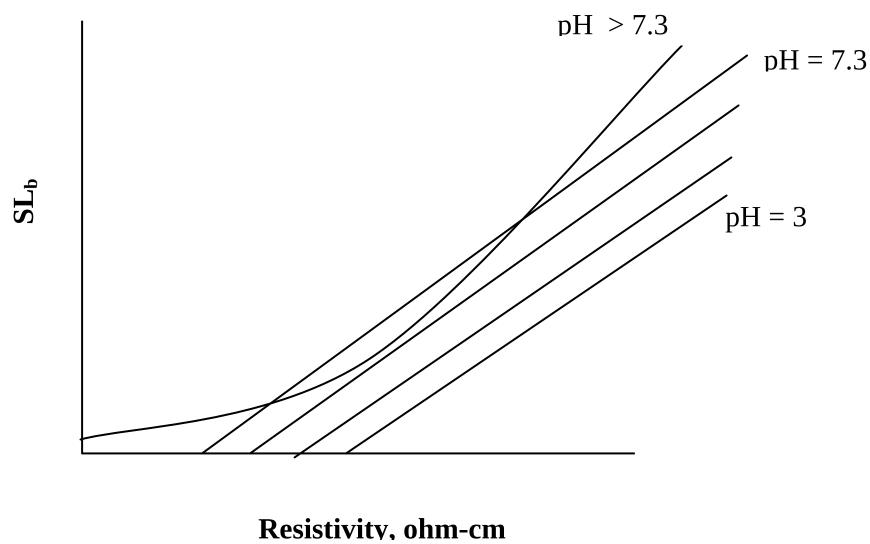
The major findings of the literature review may be summarized under the following categories:

A. Steel Pipe

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

  SL = (Thickness/1.3mm) * SL_b + C(Coating)

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



B. Aluminum Pipe

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

  SL = (Thickness/1.5mm) * SL_b + C(Coating)

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

C. Concrete Pipe

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

D. Plastic HDPE

- Expected service life is 75 years.
- pH and resistivity are rarely constraints.
- Functions well for all levels of pH (1.25 to 14) and for all values of resistivity.
- Applicability if a function of diameter (18 inches to 36 inches), joints, and fill height (less than 30 ft).

E. Galvanized Steel

- Service life is a function of pH and resistivity.

METHODOLOGY

Corrosion in Metal Pipes

As shown in the literature review, service life for steel pipes is a function of pH and soil resistivity. In general, service life (SL) can be expressed as:

$$SL = M_t \cdot SL_b + C(Coating)$$

in which SL_b = base service life determined from resistivity-pH-service life chart; and C = a constant that is a function of coating type; and M_t = multiplication factor to accommodate variations in pipe gauge thickness from 16 or 18 gauge pipes. The Resistivity-pH-Service Life chart is shown in Figure 6. The diagonal lines corresponding to different pH lines are developed from the equation (CALTRANS, 1972):

$$SL_b = 17.24\ [\log R - \log (2160 - 2490 \cdot \log R)\ ]$$

in which R is the soil resistivity, in ohm-cm. For pH values greater than 7.3, the service life equation becomes (CALTRANS, 1972):

$$SL_b = 1.84 \cdot R^{0.41}$$

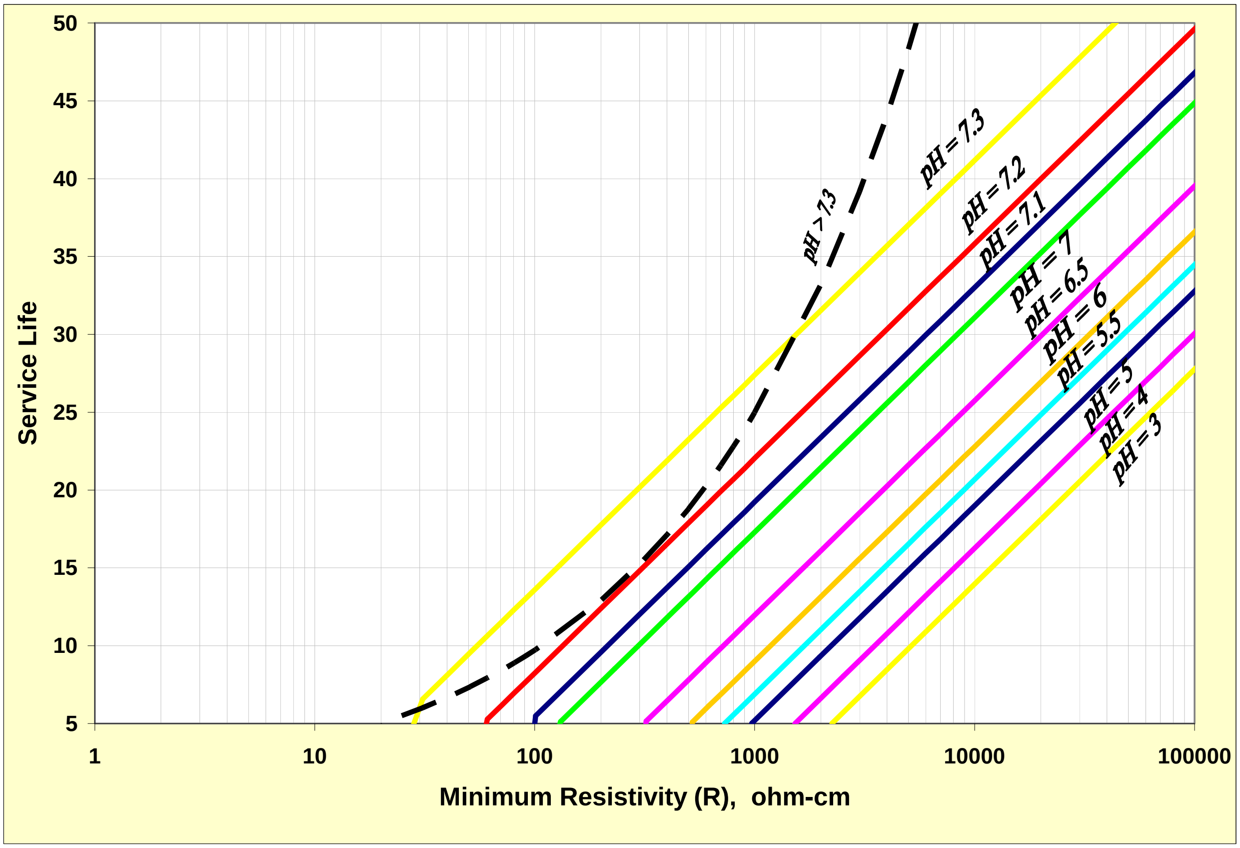


Figure 6. Service life as a function of soil resistivity and pH

According to CALTRANS, 1972 and the AISI, the thickness adjustment factors for different gauge material are given in Table 20. These factors vary between 0.8 and 3.4. In other words, computed service life may be tripled going from 18 gage pipe (0.052 in) to 10 gage pipe (0.138 in).

Table 20. Multiplication factor for thickness adjustment, M_t, for various gage metal pipes

Thickness mm	Thickness in.	Gage	AISI Thickness Multiplier	CALTRANS Thickness Multiplier
1.3	0.052	18	1	0.8
1.6	0.064	16	1.3	1
2.0	0.079	14	1.6	1.3
2.8	0.109	12	2.2	1.8
3.5	0.138	10	2.8	2.3
4.3	0.168	8	3.4	2.8

One of the objectives of the current analysis is to investigate the validity of the multiplication factors given in Table 20 with the field measurements. It is believed that the variation of thickness multiplier is not related to pipe thickness linearly, but through some relationship in the form of

$$M_t = a \cdot (\text{Thickness in mm}/1.3\text{ mm})^b$$

In which a and b are factors to be determined from field data. In Table 20, values of a and b are assumed to be 1. This implies that corrosion takes place uniformly through time at a constant rate. The observed corrosion patterns are more of a spreading pattern, which implies once the process is initiated, material removal proceeds in at a different rate.

Corrosion in Concrete Pipes

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

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

Tables 21 and 22 describe the levels of sulfates and chlorides as they affect the levels of corrosion in concrete pipes.

Table 21. Levels of sulfate attack in cement pipe

Relative Degree of Sulfate Attack	Percent Water-Soluble Sulfate (as SO_4) in Soil Sample	Parts Per Million Sulfate in Water Samples	Cement Mixture Type
Negligible	0.00 – 0.10	0 – 150	
Positive	0.10 – 0.20	150 – 1,500	Type II
Severe	0.20 – 2.00	1,500 – 10,000	*Type V
Very Severe	2.00 or more	10,000 or more	+Type V + pozzolan

Notes:
* Type V cement or approved Portland-pozzolan cement providing comparable sulfate resistance is used in concrete
\+ Type 5 cement plus approved pozzolan determined by tests to improve sulfate resistance when used in concrete with type 5 cement.

Table 22. Levels of corrosion in cement pipes (New Mexico DOT criteria for concrete pipes)

Relative Degree of Corrosion	Soil (Percent Chlorides and Sulfates)	Water (Percent Chlorides and Sulfates)
CR-1	≤ 0.05	≤ 0.025
CR-2	≤ 0.05	≤ 0.025
CR-3	≤ 0.075	≤ 0.0375
CR-4	≤ 0.075	≤ 0.0375
CR-5	≤ 0.125	≤ 0.0625
CR-6	≤ 0.200	≤ 0.100
CR-7	> 0.200	> 0.100

Abrasion in Pipes

The final step to determine the service life in metal pipes is to analyze for abrasion potential due to the flow of water and sediment. The literature review suggests several approaches for this purpose. Due to lack of data, in this study the abrasion effects are classified using CALTRANS approach that considered all significant factors identified in the literature review.

According to CALTRANS approach, in determining the abrasion potential, the five-year design velocity is used to check for a potential abrasive environment. Where low bedloads are present, higher velocities are not of concern. Abrasive velocities should be evaluated on the basis of frequency and duration. Consideration should be given to a Q5 or less for velocity determination. Perennial streams with longer peaks should be a consideration for increased abrasion. Table 23 presents the levels of abrasion according to CALTRANS. Invert protection/productive coatings can be applied in accordance with the criteria presented in Table 3.4 for different abrasive environments. Table 24 provides adjustments for different materials commonly encountered in drainage pipes.

Table 23. Levels of abrasion

Level of Abrasion	Description
Low Abrasion Level 1	Non-abrasive. No bedload, velocities can be greater than 15 ft/sec
Mild Abrasion Level 2	Low-abrasion. Minor bedloads of sand and gravel with velocities of 5 ft/sec or less.
Moderate Abrasion Level 3	Moderate Abrasion. Bedloads of sand and gravel with velocities between 5 and 15 ft/sec.
Severe Abrasion Level 4	Severe Abrasion. Heavy bedloads of gravel and rock with velocities exceeding 15 ft/sec.

Table 24. Recommended adjustments for abrasion

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	No addition	No addition	Add one gage	Add one gage and pave invert
Galvanized Steel (2 and 3 oz coating)	No addition	Add one gage	Add two gages	N/A
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 (PVC and HDPE)	No addition	No addition	No addition	N/A

FIELD MEASUREMENTS

Description of Sites Selected for the Study

For the research study, 21 sites were selected for field visits to collect soil and water samples and specific resistivity measurements. The field sites were selected jointly by the Staff Hydraulics Engineer and the research panel and were chosen to be locations where pipe failures had been discovered by the extensive culvert inspection program carried out by the Staff Bridge Branch.

The 21 visited sites included:

- 6 sites along I-25
- 14 sites along I-70
- 1 site along SH-58

Data obtained at each site included:

- Culvert size
- Year installed
- GPS coordinates
- Water sample (when available)
- Soil samples
- Culvert wall thickness
- Culvert type (i.e. – steel, aluminum, concrete, etc.)
- Soil resistivity measurements
- Soil and water pH measurements
- Soluble sulfate and chloride measurements

Table 25 provides the site information and pertinent pipe material type, size, age, and other properties for each of the sites. Tables 26, 27, and 28 provide results of water and soil analysis for pH measurements and specific soil resistivity measurements at locations identified in Table 25. Table 29 shows the soil sulfate and chloride concentrations at concrete and aluminum pipe failure locations.

Figure 7. Culvert pipe corrosion near Castle Rock, I-25

Figure 8. Soil resistivity measuring equipment

Figure 9. Field measurement of soil resistivity

Table 25. Summary of culvert pipe locations, material types and sizes, and relevant project data

No.	Site No.	Major Highway	Mile post	Approximate Location	CDOT Description	Type	Size (in)	Year Installed	CDOT Code	GPS	Water Sample	Soil Samples	Resistivity	Thickness (in)	Gauge	CSU Field Inspection Comments
1	4	25	59.09	North of Walsenburg	6' x 6' Concrete Box Culvert	Concrete	72	1966	0PA1N2I	Yes	Yes (W04)	Yes (S10-S13)	No (concrete)	8" Concrete	n/a	Severe Concrete Corrosion
2	5	25	65.61	South of Apache City	4' CMP	Steel	48	1941	0PA1TGY	Yes	No (Dry)	Yes (S14-S16)	Yes (14pts, 5pts)	0.178	8	Significant rust
3	6	25	79.19	North of Colorado City	4' CMP	Steel	48	1965	0PA275A	Yes	Yes (W06)	Yes (S17-S18)	Yes (5pts)	0.085	13	Significant rust
4	7	25	145.12	Colorado Springs	14' x 12' Concrete Box Culvert	Concrete	168	1959	0PA413C	Yes	Yes (W07)	Yes (S19-S20)	No (concrete)	24 " Concrete	n/a	Exposed Rebar and rust, Undermining and alignment problems
5	1	25	182.00	Castle Rock	Wolfensberger Exit	Steel	84	1957	0PA5200	Yes	Yes (W01)	Yes (S01 - S03)	Yes (14 pts)	0.075	14	Many holes, severe rust
6	3	25	237.72	South of Longmont	Corrugated Metal Arch	Steel	48	1957	0PA6LK0	Yes	Yes (W03)	Yes (S07 - S09)	Yes (14 pts)	0.11	12	Severe Holes/Damage
7	8	70	77.05	West of Rifle	54" CMP under East lanes	Aluminum	54	1980	1YA251E	Yes	No (Dry)	Yes (S21-S22)	Yes (5pts)	0.06	16	Severe Aluminum Corrosion
8	9	70	77.06	West of Rifle	54" CMP under West lanes	Aluminum	54	1980	1YA251O	Yes	No (Dry)	Yes (S23-S25)	Yes (5pts)	0.06	16	Severe Aluminum Corrosion
9	10	70	77.78	West of Rifle	65" CMP under all lanes	Aluminum	66	1980	1YA25LO	Yes	Yes (W10)	Yes (S26-S28*)	Yes (5pts*)	0.075	14	Severe Aluminum Corrosion - West Lanes, East Lanes in good shape
10	11	70	117.82	Glenwood Springs	W. of tunnels at No Name	Concrete and Steel	48	1965	1YA39MSZ	Yes	Yes (W11)	Yes (S29,S37)	Yes (5pts)	0.06	16	Concrete Abrasion and Severe Holes in Steel at D/S End

No.	Site No.	Major Highway	Mile post	Approximate Location	CDOT Description	Type	Size (in)	Year Installed	CDOT Code	GPS	Water Sample	Soil Samples	Resistivity	Thickness (in)	Gauge	CSU Field Inspection Comments
11	12	70	186.10	East of Vail	Vail Pass Narrows	Steel	36	1978	1YA562SZ	Yes	Yes (W12)	Yes (S38)	Yes (5pts)	0.064	16	Repaired - Shotcrete
12	13	70	198.98	West of Frisco	Ten Mile Canyon Structures	Steel	42	1979	1YA5IR8Z	Yes	Yes (W13)	Yes (S39)	Yes (5pts)	0.075	14	Repaired - New 30 inch HDPE
13	14	70	205.05	West of Silverthorne	W. of Silverthorne Exit	Steel	54	1969	1YA5P1EZ	Yes	Yes (W14	Yes(S4 0)	Yes (5pts)	0.08	14	Repaired - Concrete Channel Floor
14	15	70	211.68	East of Silverthorne	Straight Creek	Steel	48	1969		Yes	Yes (W15)	Yes (S35-S36)	Yes (5pts)	0.08	14	Repaired - Shotcrete
15	16	70	217.39	East of Eisenhower Tunnel	East of Eisenhower Tunnel	Steel	54	1972	1YA61AUZ	Yes	Yes (W16)	Yes (S33-S34)	Yes (5pts)	0.07	15	Repaired - New 48 inch HDPE
16	17	70	237.60	West of Idaho Springs	Fall River Road	Steel	36	1966	1YA6LGOZ	Yes	No (Dry)	Yes (S32)	Yes (5pts)	0.11	12	Repaired - New 24 inch HDPE
17	18	70	244.92	East of Idaho Springs	Floyd Hill	Steel	54	1970	1YA6SPKZ	Yes	Yes (W18)	Yes (S41)	Yes (5pts)	0.07	15	Repaired - New Cured-in-Place Liner - Approx. 52 inch
18	19	70	247.62	Near Jefferson County Line	Beaver Brook	Steel	54	1975	1YA6VH8Z	Yes	Yes (W19)	Yes (S30-S31)	Yes (5pts)	0.08	14	Repaired - Concrete Channel Floor
19	20	70	256.13	Genesee Exit	Genesee	Steel	36	1971	1YA743MZ	Yes	Yes (W20)	Yes (S42-S43)	Yes (5pts)	0.07	15	Repaired - Shotcrete
20	21	70	256.80	Genesee Exit	Genesee	Steel	48	1971	1YA74M8Z	Yes	Yes (W21)	Yes (S44-S45)	Yes (5pts)	0.11	12	Repaired - New 36 inch HDPE
21	2	58	0.70	Washington Street	Washington Street	Steel	48	1966		Yes	Yes (W02)	Yes (S04 - S06)	Yes (13 pts)	0.075	14	Repaired - New 42 inch HDPE

Table 26. Summary of pH values for water sample data

Site Number	Sample ID	pH Reading	Water Temp. at Time or Reading (C)	Temperature Correction	Actual pH
1	W01	7.6	18	-0.21	7.4
2	W02	8.1	10	-0.45	7.7
3	W03	7.7	10	-0.45	7.3
4	W04	8.3	23	-0.06	8.2
5	There was no water available at this site, thus no water sample				
6	W06	7.7	27	0.06	7.7
7	W07	7.9	30	0.15	8.1
8	There was no water available at this site, thus no water sample				
9	There was no water available at this site, thus no water sample				
10	W10	8.3	26	0.03	8.3
11	W11	8.2	27	0.06	8.2
12	W12	8.2	25	0.00	8.2
13	W13	7.6	26	0.03	7.7
14	W14	7.2	26	0.03	7.2
15	W15	7.3	25	0.00	7.3
16	W16	7.3	25	0.00	7.3
17	There was no water available at this site, thus no water sample				
18	W18	7.9	28	0.09	8.0
19	W19	7.7	28	0.09	7.8
20	W20	7.9	26	0.03	7.9
21	W21	7.9	26	0.03	7.9

Table 27. Summary of pH values for soil sample data

Site Number	Sample ID	Description	pH Reading
1	S01	Sample from bottom of Culvert Pipe	7.8
1	S02	Material taken from corrosion hole in pipe	7.8
1	S03	85 feet from outlet at separated pipe joint	7.6
2	S04	Outlet side of culvert	7.5
2	S05	Outlet side of culvert in fill on top of culvert	7.4
2	S06	Inlet side of culvert above culvert crown	8.0
3	S07	Outlet side above crown	7.9
3	S08	Outlet side above crown	7.5
3	S09	Bottom of culvert	7.7
4	S10	90 ft from east end from floor of culvert	8.7
4	S11	60 ft from east end in floor near exposed concrete	8.5
4	S12	Sample from east end of culvert above crown	7.6
4	S13	at downstream edge of culvert, 4 ft lower than culvert invert	8.7
5	S14	east side above crown	7.9
5	S15	Median, near apparent sink hole above culvert	7.8
5	S16	above west side of culvert	7.8
6	S17	30 ft from east side at joint with corrosion, joint separation	7.8
6	S18	Near median inlet	7.9
7	S19	downstream bar	7.9
7	S20	downstream right bank shale material	7.6
8	S21	taken from inside culvert through hole in culvert	8.0
8	S22	at site of resistivity test	7.8
9	S23	taken from inside culvert through hole in culvert	7.9
9	S24	sample of corrosive residual in pipe	6.0
9	S25	at site of resistivity test	8.0
10	S26	taken from inside culvert through hole in culvert crown	8.2
10	S27	at site of resistivity test	8.0
10a	S28*	in median over section of culvert with no corrosion	7.7
11	S29	entrance of culvert - abrasion	8.4
11	S37	at site of resistivity test	7.9
12	S38	taken at culvert outlet above crown	7.2
13	S39	taken at culvert outlet above crown	5.1
14	S40	at site of resistivity test	4.3
15	S35	taken at culvert inlet	6.2
15	S36	at site of resistivity test	5.5
16	S33	at site of resistivity test	7.8
16	S34	at site of resistivity test - 1 foot deep	8.0
17	S32	taken at median inlet between I-70 and frontage road to north	6.8
18	S41	at site of resistivity test	7.5
19	S30	taken at culvert inlet	7.4
19	S31	at site of resistivity test	6.7
20	S42	at site of resistivity test	7.3
20	S43	taken at culvert outlet above crown	7.5
21	S44	taken from silty sand trapped in silt fence d/s from culvert outlet	8.7
21	S45	taken at culvert outlet above crown	7.1

Table 28. Summary of soil resistivity measurement results

Site Number	Ground Rod Resistance, R (Ω)	Electrode Spacing, A (ft)	Soil Resistivity, p (Ω-cm)	Summary Statistics	
1	0.7	3	402		
1	1.4	3	804		
1	2.1	3	1206		
1	2.9	3	1666		
1	2.6	3	1494		
1	3.1	3	1781		
1	2.4	3	1379	Average	1057
1	1.65	3	948	Standard Deviation	405
1	1.1	3	632	Minimum	402
1	1.1	3	632	Maximum	1781
1	1.5	3	862		
1	1.6	3	919		
1	1.8	3	1034		
1	1.8	3	1034		
2	10.1	3.5	6770		
2	11.2	3.5	7507		
2	12.4	3.5	8311		
2	9.4	3.5	6300		
2	8.5	3.5	5697		
2	6	3.5	4022	Average	4980
2	5.4	3.5	3619	Standard Deviation	1731
2	5.4	3.5	3619	Minimum	3217
2	5.3	3.5	3552	Maximum	8311
2	5.6	3.5	3753		
2	7	3.5	4692		
2	5.5	3.5	3686		
2	4.8	3.5	3217		
3	12.6	2	4826		
3	13.7	2	5247		
3	15.4	2	5898		
3	17.9	2	6856		
3	18.9	2	7239		
3	15.2	2	5822		
3	13.7	2	5247	Average	5272
3	12.2	2	4673	Standard Deviation	1021
3	14.8	2	5668	Minimum	3600
3	9.7	2	3715	Maximum	7239
3	12.4	2	4749		
3	9.4	2	3600		
3	12.5	2	4788		
3	14.3	2	5477		
4	N/A Concrete Culvert				

Site Number	Ground Rod Resistance, R (Ω)	Electrode Spacing, A (ft)	Soil Resistivity, p (Ω-cm)	Summary Statistics	
5a	9	3	5171		
5a	11.2	3	6434		
5a	11.3	3	6492		
5a	10.8	3	6205		
5a	12.2	3	7009		
5a	12.8	3	7354		
5a	7.3	3	4194	Average	5724
5a	7	3	4022	Standard Deviation	1104
5a	7.9	3	4539	Minimum	4022
5a	8.2	3	4711	Maximum	7354
5a	8.8	3	5056		
5a	12.2	3	7009		
5a	10.5	3	6032		
5a	10.3	3	5917		
5b	16.3	3	9364		
5b	11.4	3	6549	Average	5688
5b	6.8	3	3907	Standard Deviation	2383
5b	6	3	3447	Minimum	3447
5b	9	3	5171	Maximum	9364
6	3.2	5	3064		
6	2.8	5	2681	Average	2279
6	2.2	5	2107	Standard Deviation	599
6	2.1	5	2011	Minimum	1532
6	1.6	5	1532	Maximum	3064
7	N/A Concrete Culvert				
8	6.8	3	3907		
8	8.8	3	5056	Average	4113
8	5.2	3	2987	Standard Deviation	755
8	7.6	3	4366	Minimum	2987
8	7.4	3	4251	Maximum	5056
9	11.6	3	6664		
9	13.1	3	7526	Average	9043
9	24.9	3	14305	Standard Deviation	3268
9	17.6	3	10111	Minimum	6607
9	11.5	3	6607	Maximum	14305
10	0.8	4	613		
10	0.8	4	613	Average	751
10	1.6	4	1226	Standard Deviation	278
10	1	4	766	Minimum	536
10	0.7	4	536	Maximum	1226
10a	6.9	4	5285		
10a	3.6	4	2758	Average	2267
10a	1.5	4	1149	Standard Deviation	1835
10a	1.5	4	1149	Minimum	996

Site Number	Ground Rod Resistance, R (Ω)	Electrode Spacing, A (ft)	Soil Resistivity, p (Ω-cm)	Summary Statistics	
10a	1.3	4	996	Maximum	5285
11	137	5	131178		
11	157.5	5	150806	Average	148164
11	142.1	5	136061	Standard Deviation	21725
11	193	5	184798	Minimum	131178
11	144.1	5	137976	Maximum	184798
12	77.8	1	14899		
12	59	1	11299	Average	15171
12	107	1	20491	Standard Deviation	3352
12	72.7	1	13922	Minimum	11299
12	79.6	1	15243	Maximum	20491
13	39.3	2	15052		
13	80.7	2	30908	Average	23302
13	88.2	2	33781	Standard Deviation	8437
13	49.5	2	18959	Minimum	15052
13	46.5	2	17810	Maximum	33781
14	21.1	2	8081		
14	26.2	2	10035	Average	9514
14	33.8	2	12945	Standard Deviation	2389
14	25.9	2	9920	Minimum	6588
14	17.2	2	6588	Maximum	12945
15	3.4	20	13022		
15	3.6	20	13788	Average	12562
15	2.9	20	11107	Standard Deviation	1565
15	3.7	20	14171	Minimum	10724
15	2.8	20	10724	Maximum	14171
16	32.5	4	24895		
16	26.5	4	20299	Average	17342
16	13.3	4	10188	Standard Deviation	5626
16	18.6	4	14248	Minimum	10188
16	22.3	4	17082	Maximum	24895
17	45.8	2	17541		
17	26	2	9958	Average	17610
17	54.3	2	20797	Standard Deviation	4444
17	52	2	19916	Minimum	9958
17	51.8	2	19839	Maximum	20797
18	9.9	15	28438		
18	10.8	15	31023	Average	40215
18	22.9	15	65780	Standard Deviation	15126
18	14.5	15	41651	Minimum	28438
18	11.9	15	34183	Maximum	65780
19	30.4	6	34930		
19	42.5	6	48833	Average	42789
19	48.5	6	55727	Standard Deviation	9854

Site Number	Ground Rod Resistance, R (Ω)	Electrode Spacing, A (ft)	Soil Resistivity, p (Ω-cm)	Summary Statistics	
19	27.6	6	31712	Minimum	31712
19	37.2	6	42743	Maximum	55727
20	26.4	3	15167		
20	31.1	3	17867	Average	16764
20	35.1	3	20165	Standard Deviation	2245
20	25.7	3	14765	Minimum	14765
20	27.6	3	15856	Maximum	20165
21	18.2	3	10456		
21	70.8	3	40675	Average	41720
21	132.6	3	76179	Standard Deviation	23365
21	65.9	3	37860	Minimum	10456
21	75.6	3	43432	Maximum	76179

Table 29. Sulfate and chloride concentrations for concrete and aluminum pipe failure sites

Site No.	Sample Location	Sample ID	Chloride Concentration (percent)	Chloride Concentration (parts per million)	Sulfate Concentration (Percent)	Sulfate Concentration (parts per million)
4	North of Walsenburg	S-10	0.0853%	853	1.6800%	16,800
4	North of Walsenburg	S-11	0.0673%	673	1.1200%	11,200
4	North of Walsenburg	S-12	0.0146%	146	0.0000%	0
4	North of Walsenburg	S-13	0.0235%	235	2.0800%	20,800
8	West of Rifle (EB)	S-21	1.6335%	16,335	2.0000%	20,000
8	West of Rifle (EB)	S-22	0.0157%	157	0.0000%	0
9	West of Rifle (WB)	S-23	0.0582%	582	0.4700%	4,700
9	West of Rifle (WB)	S-24	4.6984%	46,984	0.2300%	2,300
9	West of Rifle (WB)	S-25	0.0884%	884	0.0000%	0
10	West of Rifle (All)	S-26	2.1296%	21,296	3.7600%	37,600
10	West of Rifle (All)	S-27	0.0488%	488	0.0000%	0
10	West of Rifle (All)	S-28	0.0137%	137	0.0000%	0

Table 30. Summary of measurement results for metal pipes

Site No.	Hwy	Mile-Post	Approx. Location	Size (in)	Year Installed	Age	Average Resistivity ohm-cm	Culvert Thickness (in)	Gauge	Water Sample ID	Water pH	Soil Sample ID	Soil pH
1	25	182.00	Castle Rock	84	1957	49	1057	0.075	14	W01	7.4	S02	7.8
2	58	0.70	Washington Street	48	1971	35	4980	0.075		W02	7.7	S05	7.4
3	25	237.72	Longmont	48	1957	49	5272	0.11	12	W03	7.3	S08	7.5
5	25	65.61	South of Apache City	48	1941	65	5688	0.178	8	N/A		S15	7.8
6	25	79.19	North of Colorado City	48	1965	41	2279	0.085	13	W06	7.7	S18	7.9
8	70	77.05	West of Rifle	54	1980	26	4113	0.06	16	N/A		S22	7.8
9	70	77.06	West of Rifle	54	1980	26	9043	0.06	16	N/A		S25	8.0
10	70	77.78	West of Rifle	66	1980	26	751	0.075	14	W10	8.3	S27	8.0
11	70	117.82	Glenwood Springs	48	1965	41	148164	0.06	16	W11	8.2	S37	7.9
12	70	186.10	East of Vail	36	1978	28	15171	0.064	16	W12	8.2	S38	7.2
13	70	198.98	West of Frisco	42	1979	27	23302	0.075		W13	7.7	S39	5.1
14	70	205.05	W. of Silverthorne	54	1969	37	9514	0.08	14	W14	7.2	S40	4.3
15	70	211.68	E. of Silverthorne	48	1969	37	12562	0.08	14	W15	7.3	S36	5.5
16	70	217.39	E. of Eisenhow. Tunnel	54	1972	34	17342	0.07	15	W16	7.3	S33	7.8
17	70	237.60	W. of Idaho Springs	36	1966	40	17610	0.11	12	N/A		S32	6.8
18	70	244.92	E. of Idaho Springs	54	1970	36	40215	0.07	15	W18	8.0	S41	7.5
19	70	247.62	Near Jefferson Co. Line	54	1975	31	42789	0.08	14	W19	7.8	S31	6.7
20	70	256.13	Genesee Exit	36	1971	35	16764	0.07	15	W20	7.9	S42	7.3
21	70	256.80	Genesee Exit	48	1971	35	41720	0.11	12	W21	7.9	S45	7.1

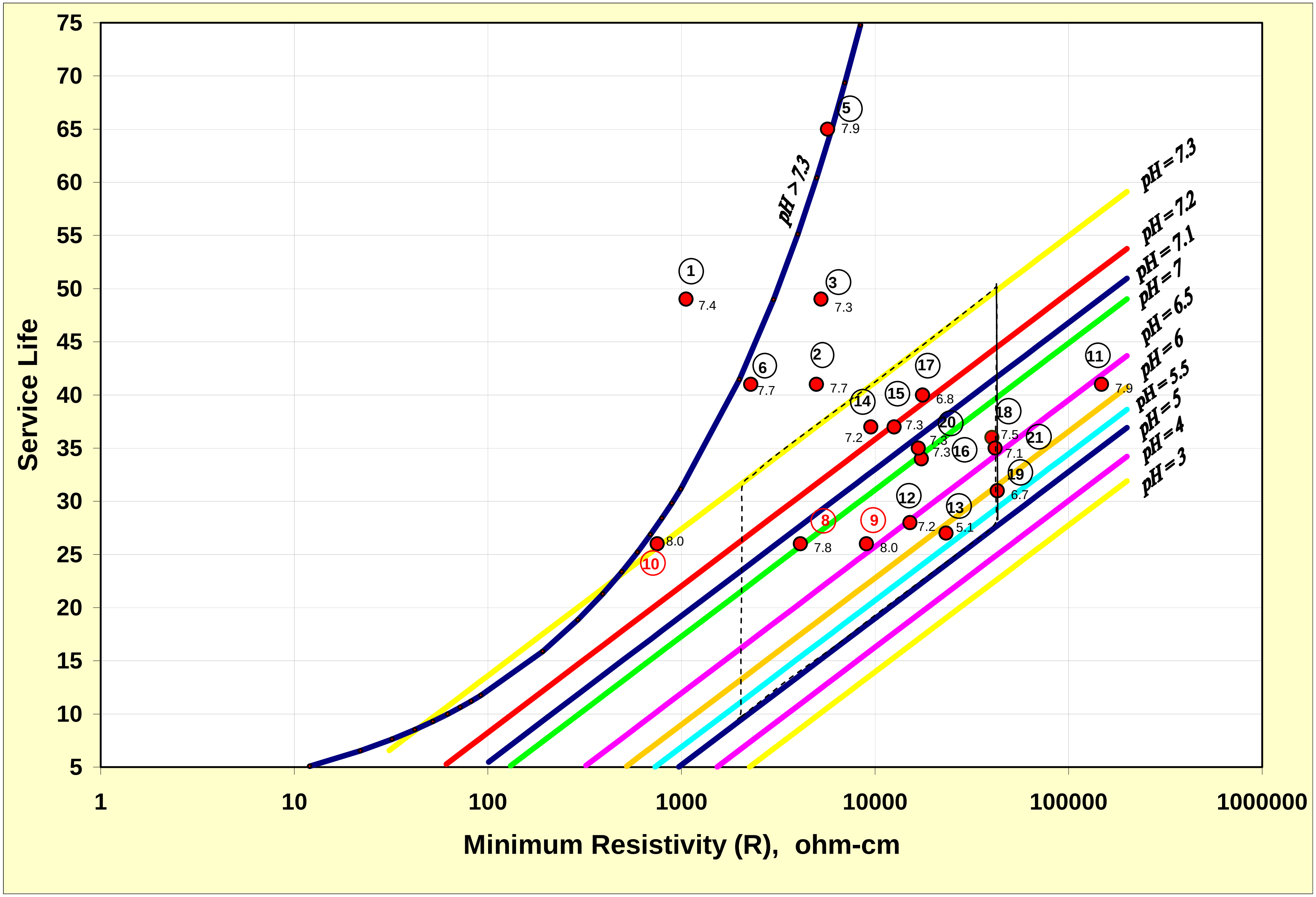


Figure 10. Service life versus resistivity chart for the corrugated pipes visited in the field study

Results of Field Measurements

Table 30 and Figure 10 provide results of field measurements for the metal pipes included in the analysis. Table 31 presents a summary of causes for failure for the 21 cases used in the study. As shown in this table, there are 2 cases of concrete pipe failures; 3 cases of aluminum pipe failures, and 16 cases of steel pipe failures. Table 32 presents ranges of parameters covered in the analysis of the 21 failure cases. The data included a wide range of sizes, gauge thicknesses of pipes, pH, and soil resistivity.

Table 31. Summary of failure cases included in the study

CAUSE OF FAILURE	NO. OF CASES
Corrosion of Steel Pipe	**12**
Corrosion of Aluminum Pipe	**3**
Corrosion of Concrete Pipe	**1**
Abrasion of Steel Pipe	**4**
Abrasion of Concrete Pipe	**1**
TOTAL:	**21**

Table 32. Range of parameters for the failure cases included in the study

Range of Variation	Size (in)	Age	Culvert Thickness (in)	Gauge	Water pH	Soil pH	Average Resistivity ohm-cm
Minimum	36	26	0.060	8	7.2	4.3	750
Maximum	168	65	0.178	16	8.3	8.5	150,000

ANALYSIS

Corrosion in Metal Pipes

The governing equations for estimating service life of steel pipes are given by:

CALTRANS

- Service Life = 1.47 * $R^{0.41}$; for pH > 7.3
- Service Life = 13.79 * [log (R) - log (2160-2490*log (R)]; for pH < 7.3

American Iron and Steel Institute (AISI)

- Service Life = 2.94 * $R^{0.41}$
- Service Life = 27.58 * [log (R) - log (2160-2490*log (R)

In which R is the Resistivity of soil in ohm-cm. Comparing the two approaches, it can be seen that the service life estimates predicted by AISI differ from CALTRANS results by a factor of 2. This difference is due to the definition of "pipe failure" between the two approaches. While AISI assumes that failure occurs when lower portion of a pipe is completely corroded, CALTRANS defines failure at the occurrence of first perforation. Using data from the National Bureau of Standards, a relationship between average metal loss and first perforation was developed. First perforation was found to correspond to approximately 13% average loss of metal thickness. AISI defines "loss of function" at an average metal thickness loss of 25%, which is approximately twice the value of first perforation and accordingly defines service life to be twice the duration corresponding to the first perforation. However, this definition is very conservative and is based on structural "loss of function." The Research Panel for the present CDOT study has adopted the CALTRANS definition of "failure," which reflects hydraulic performance of pipes.

As explained in section 3, service lives estimated by the equations which are given above are multiplied further by a thickness adjustment factor:

$$\text{Service Life} = (\text{Service Life})_{\text{base}} * \text{Thickness Multiplier}$$

Previously, the thickness multiplier was defined as:

$$\text{Thickness Multiplier} = (T / T_{ref})$$

In which T_{ref} = 1.3 mm; T=thickness of pipe in millimeters.

As a result of the present study, a newly proposed relationship was developed (Molinas, 2007):

$$\text{Thickness Multiplier } (M_t) = a\,(T/T_{ref})^{b}$$

In which values of a and b were determined statistically by selecting values that resulted in the least deviation of service lives from field measurements. According to the best-fit analysis, these values were found to be a = 1; b = 0.16. In other words,

$$\text{Thickness Multiplier } (M_t) = (T/T_{ref})^{0.16}$$

Comparing this multiplier with the previously used values of a=1 and b=1 reveals that Colorado data shows much less of an increase in expected service life due to the gage thickness.

Figure 11 presents measured and computed service lives using the CALTRANS thickness adjustments from Table 20 (filled red circles) and the newly-proposed CSU-HT thickness adjustments (filled green triangles). As observed from Figure 11, the newly proposed adjustment factor does not change the trend of the CALTRANS relationship, but reduces the scatter from the mean (perfect agreement line).

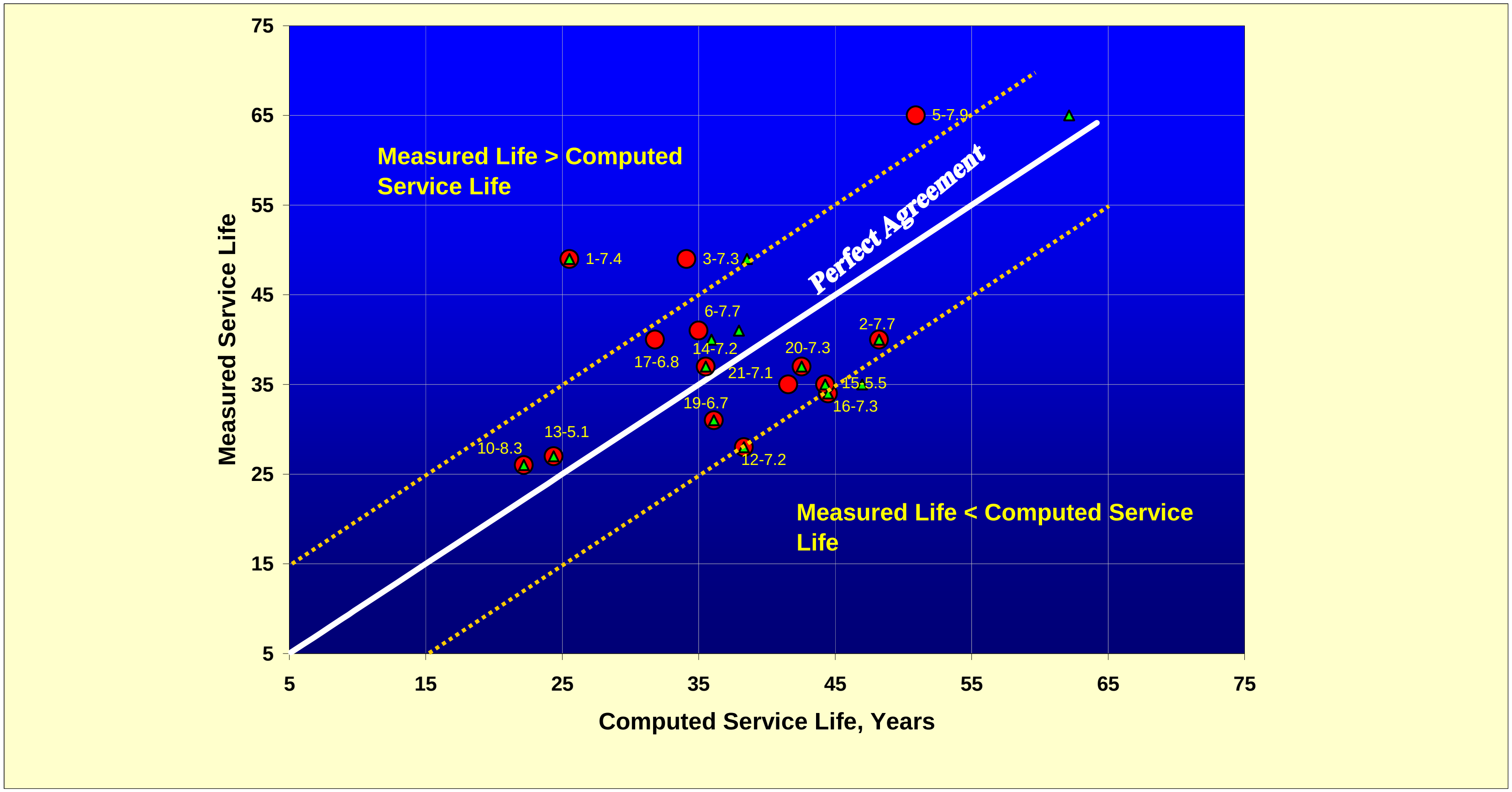


Figure 11. Service life in metal pipes using CALTRANS and CSU-HT (Molinas) thickness adjustments

Corrosion in Concrete Pipes

As shown in Table 29, soil samples from the failed box culvert site (Site 4, North of Walsenburg), indicate that while the chloride concentrations were below 1,000 ppm, sulfate concentrations were extremely high. Three of the samples from this site had 16,800 ppm, 11,200 ppm and 20,800 ppm. These values are an order of magnitude larger than the severely corrosive environment identified by CDOT as CR-6.

Figure 12. Concrete pipe corrosion at Site 4 (North of Walsenburg)

Figure 13. Concrete pipe corrosion at Site 4 (North of Walsenburg)

COMPARISON AND VERIFICATION

In Figure 14, measured service lives from the field study are plotted against the computed service lives according to the AISI, CALTRANS, and CSU-HT adjusted CALTRANS approaches using the relationships given in Section 5. In computing the service lives, the measured field data are used for soil resistivity, pH, and pipe thickness.

The computed service lives from the AISI equation are identified with filled squares; the line passing through these points is identified as "AISI Service Life" line. In computing these service lives, thickness adjustments were made as suggested by AISI, according to Thickness Multiplication Factors given in Table 20.

Figure 14 also shows the service life computations following the CALTRANS and CSU-HT modified (Molinas, 2007) CALTRANS methodologies. Service life computations using CALTRANS relationships are indicated by filled circles; CSU-HT computations are indicated by filled triangles. The lines describing these relationships are identified as "CALTRANS" and "CSU-HT Service Life" lines.

Since the 45-degree line corresponds to measured life equal to computed life, this line is labeled as "Perfect Agreement" line. To denote the range of variation in computations, ±10 percent variation lines are also indicated in Figure 14.

The slope of the AISI service life line that represents the trend line for the computations using AISI relationships significantly deviates from the perfect agreement line. As can be observed from the measured versus computed service life chart, on the average, the AISI computations for galvanized steel over-predict service lives by a factor of more than 3.

Both CALTRANS and CSU-HT relationships, on the average, follow the 45 degree perfect agreement line. The majority of the CALTRANS computations fall within the ±10 percent variation lines, indicating a general agreement trend.

Close examination of the CSU-HT adjusted service life computations shows a narrower band of variation (±5 percent variation). The adjustments in CSU-HT computations are made to service life estimates through reduced thickness multiplication factors. In other words, Colorado failures data indicate a smaller effect due to pipe thickness than that suggested by CALTRANS and AISI corrections.

As an important observation, in defining the measured service life in Figure 14, the time of failure was assumed to be the date of field observation. In reality, for most of the cases the failure had occurred years before the field visit and therefore the discrepancies between measured and computed "service life estimates" were even more pronounced.

Among the visited sites, sites 11, 12, 16, and 18 showed signs of abrasion effects. At the outlets of these sites, bedmaterial deposits were observed; indicating significant transport of bed material and therefore reduction in service life due to abrasion. The analysis was performed with and without these data points with no difference in the conclusions.

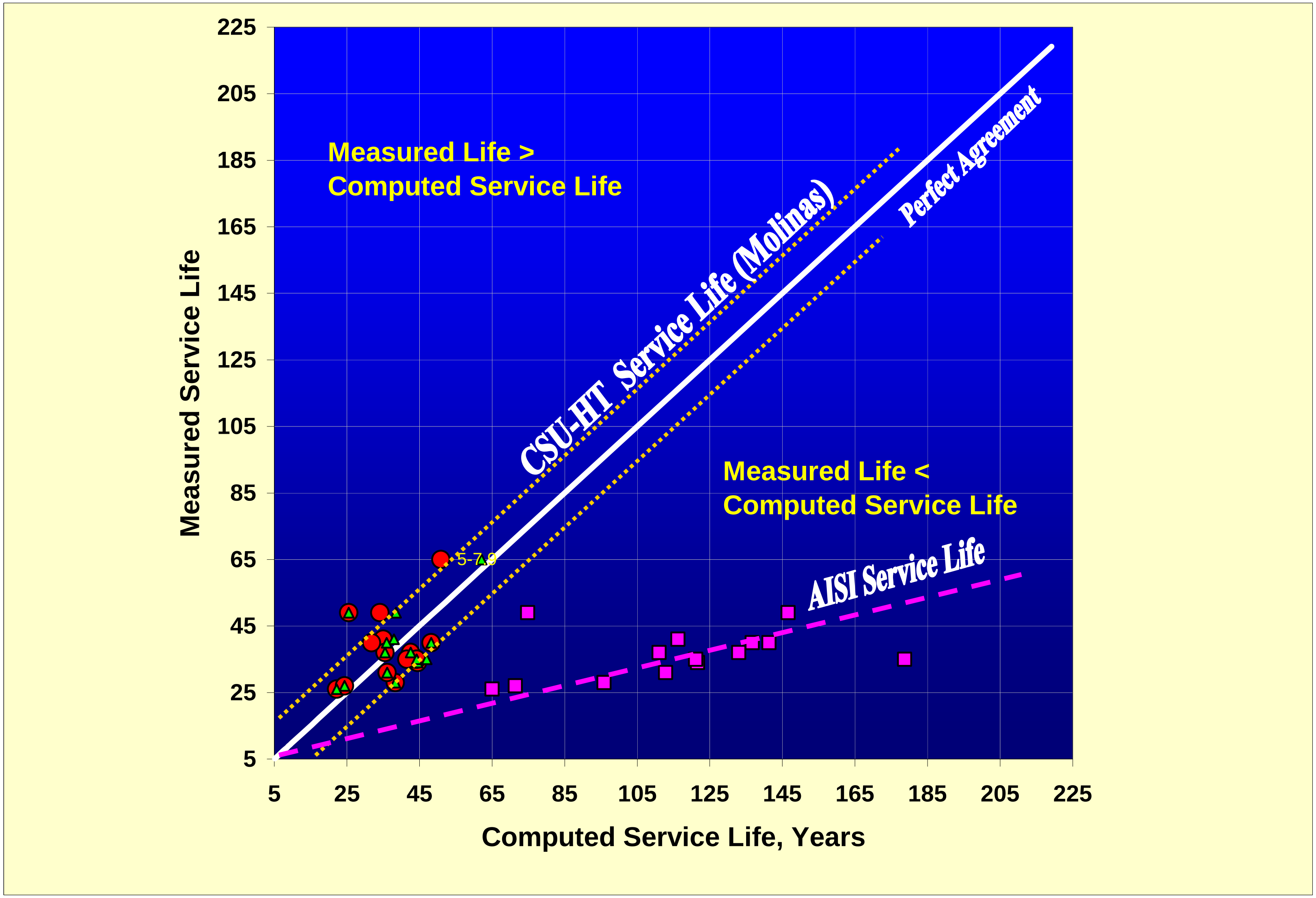


Figure 14. Measured and computed service lives using: i) AISI eq. ; ii) CALTRANS eq.; iii) Modified CALTRANS equation (CSU-HT)

SUMMARY AND CONCLUSIONS

In this study, effects of abrasion and corrosion were investigated in regards to the service life of different pipe materials. Due to the limited scope of the study, this report is limited to 21 failure sites along the I-25 and I-70 corridors. These sites were selected due to their accessibility and the availability of information about their physical properties. Despite the limited number of case studies, however, the conclusions of the study are definitive for the regions from which they were derived in Colorado. The data obtained from the failure sites follows trends and to some extent is consistent with previous observations. The conclusions from the study are:

1. Service life of galvanized steel pipes is related to soil resistivity, pipe thickness and the pH of the water flowing through the pipe, and the soils in which the pipes are installed. These parameters were identified by previous research and were found to be valid parameters.
2. The service life estimates from AISI using soil resistivity, pH, and pipe thickness are not reliable for the I-70 and I-25 corridors.
3. The AISI service lives predicted from existing published handbooks and publications are more than 3 times longer than the observed service lives. The predicted service lives systematically deviate from the measured service lives.
4. On the average, the service lives predicted by CALTRANS service life relationships for steel pipes are in agreement with observed service lives.
5. CALTRANS service life estimates over-predict effects of gage thickness. The thickness multiplier suggested by CALTRANS assumes a linear relationship between corrosion and pipe thickness. The data from Colorado sites suggest a power relationship. The effects due to increased thickness occur at a reduced rate.
6. A new relationship between gauge thickness of pipes and service life multiplication factor was developed. This relationship results in a significant reduction in scatter of data from the mean.
7. For aluminum pipes, the salt content of the surrounding soil was found to be a primary factor affecting the service life. Three of the failure sites had aluminum pipes of the same size and age. While the site with low chloride concentration exhibited little damage after 26 years of operation, sites with high sulfate and chloride concentrations showed dramatic reduction in service life. After 26 years of operation, the pipes were riddled with perforations.
8. For concrete pipes, the existing literature presents ranges of salt contents to define the corrosivity of the environment. For the Colorado failure cases, these limits were exceeded by an order of magnitude. Even under these extreme conditions, the structural integrity of the pipe was not totally compromised.
9. Other factors such as flow duration, geographic location, etc. are expected to affect the service life of steel pipes. The AISI has most recently introduced “hardness” of water as an additional parameter along with resistivity. The effects of these factors could not be studied due to the sample size of service life data.
10. Further investigations are needed to verify the applicability of the findings of this study to other regions of Colorado and to an expanded range of materials and parameters.

REFERENCES

1. ACI Manual of Concrete Practice, Part I, American Concrete International, "Chapter 2: Aggressive Chemical Exposure," American Concrete Institute (January 1996).
2. Alberta Infrastructure and Transportation. May 2002, "Section 7 – Geotechnical Considerations," Engineering Consultant Guidelines for Highway and Bridge Projects.
3. Alexander, J.A., Sandford, T.C., and Seshadri, A., "Rehabilitation of Large Diameter Steel Culverts," Maine Department of Transportation, Technical Services Division, Augusta, Maine, December 1994.
4. Aluminum Association, The, "Aluminum Drainage Products Manual," The Aluminum Association, Washington, D.C. (1983)
5. American Association of State Highway and Transportation Officials (AASHTO), "AASHTO Highway Drainage Guidelines: Volume 14—Culvert Inspection, Material Selection and Rehabilitation," AASHTO, Washington, D.C., August 1999, 60 pp.
6. American Association of State Highway and Transportation Officials (AASHTO), Bridge Design Specification, Section 18, paragraph 18.4.3.1.1., Washington, D.C.
7. American Iron and Steel Institute, 1983, Handbook of Steel Drainage and Highway Construction Products, Chapters 5 and 6.
8. American Iron & Steel Institute, 1994, "Steel Drainage and Highway Construction Products," American Iron & Steel Institute Handbook, 5th Edition.
9. American Society for Metals, Corrosion Resistance of Aluminum and Aluminum Alloys, Metal Handbook, Desk Edition, Materials Park, Ohio.
10. American Waterworks Association, Fiberglass Pipe Design Manual M-45, manual of Water Supply Practices, Denver, Colorado (1996).
11. American Waterworks Association, "Glass-Fiber-Reinforced Thermosetting-Resin Pressure Pipe," C 950-81. (1981).
12. Arnoult, J.D., Culvert Inspection Manual: Supplement to the Bridge Inspector's Training Manual, Report FHWA-IP-86-002, Federal Highway Administration, McLean, Va., July 1986, 215 pp.
13. Aryani, C. and Al-Kazily, J. , Culvert Restoration Techniques, FHWA/CA/93-14, California State University, Sacramento (1993).
14. Attewell, P.B., and Fry, R.H., "The Effects of Explosive Detonations and Mechanical Impacts upon Adjacent Buried Pipelines," Europipe '83 Conference, Basle, Switzerland, Paper 16, (1983).
15. Ault, J.P. and J.A. Ellor, Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe, Report FHWA-RD-97-140, Federal Highway Administration, McLean, Va., January 2000, 106 pp.
16. Azar, D.G., "Drainage Pipe Study." Research Rep. No. 57, Louisiana Dept. of Hwys. (May 1971).
17. Ballinger, C.A. and Drake, P.G., Culvert Repair Practices Manual, Vols. 1 and 2, Reports FHWA-RD-94-096 and FHWA-RD-95-089, Federal Highway Administration, McLean, Va., May 1995, (Vol. 1) 265 pp. and (Vol. 2) 354 pp.
18. Bauman, E.E., and Lewis, D.W., "Five-Year Field Corrosion Study of Steel Pipe to Determine Effects of Backfill materials." Hwy. Res. Record No. 140 (1966) pp. 1-8.

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

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

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

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

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

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

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

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

27. Bellair P.J. and Ewing, J.P., Metal-Loss Rates of Uncoated Steel and Aluminum Culvert in New York, New York State Department of Transportation, State Campus, Albany (1984).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

46. California Department of Transportation, 2003, DIB 83.

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

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

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

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

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

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

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

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

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

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

57. Colorado Department of Transportation, 2003, "Summary of I-70 Culvert Inspections."

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

77. “Duracoat, National Steel’s Pre-Coated Culvert Sheet,” Sales Brochure No. C-679-1M, National Steel Corporation, Pittsburgh, PA.

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

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

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

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

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

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

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

85. Federal Highway Administration, 1995, “Errata Sheet,” Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges.

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

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

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

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

90. Florida Department of Transportation, 2003, FDOT Drainage Manual.

91. Florida Department of Transportation, 2003, “FDOT Drainage Manual Revisions,” FDOT Drainage Manual.

92. Florida Department of Transportation, 2004, “FDOT Drainage Manual Revisions,” FDOT Drainage Manual.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

116. Havens, J.H., Young, J.L., and Field, H.J., “A Survey of Acidity in Drainage Waters and the Condition of Highway Drainage Installations,” Progress Report No. 2, Commonwealth of

Kentucky Department of Highways, Highway Materials Research Laboratory, Lexington, Ky. (Dec. 1952).

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

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

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

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

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

122. Hirsch, C. "NYDOT Proposed Recommendations," NCSPA Memorandum, Washington, D.C. (1985).

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

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

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

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

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

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

129. Hurd, J.O. "Field Performance of Protective Linings for Concrete and Corrugated Steel Pipes," in Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C. (1984).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

147. Johnson, D. and J. Zollars, Culvert Renewal, Minnesota Department of Transportation, Office of Materials and Research, St. Paul (1992).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

207. Okpala, D. and W. Anderson, Culvert Pipe Rehabilitation Using Slip-Liners, Wisconsin Department of Transportation, Madison, February 1997, 9 pp.

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

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

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

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

212. Patenaude, Robert, 2003, Experimental Culvert Pipe, STH 80 Juneau and Wood Counties, Wisconsin, Wisconsin Department of Transportation.

213. Peabody, A.W., "Control of Pipeline Corrosion." Natl. Assn. of Corrosion Eng., Houston (Dec. 1967).

214. Pennsylvania Department of Highways, "Culvert Pipe Study," (Nov. 1950).

215. Peterson, D.E., "Evaluation of Aluminum Alloy Pipe for Use in Utah's Highways." Utah State Hwy. Dept. (June 1973) 43 pp.

216. Petroff, L.J., "Performance of Low Stiffness Plastic Pipe in Stiff Soils," Pipeline Materials and Design, American Society of Civil Engineers National convention, San Francisco, Calif. (Oct. 1984) pp 24-35.

217. Peyer, J.H., et al., "Final Report on a Study of the Durability of Asbestos Bonded Metal Pipe in Sewer Service to ARMCO Steel Corporation," Battelle Columbus Laboratories, Columbus, OH, (July 1976) 202 pp.

218. Pipe Selection for Corrosion Resistance, Implementation Package UDOT-IMP-76-1, Utah Department of Transportation, Research and Development Unit, Salt Lake City.

219. Pipe Selection Guidelines and Procedures, Arizona Department of Transportation, Phoenix (February 1, 1996).

220. "Pipeline Risk Assessment, Rehabilitation and Repair," in When to Renew a Pipeline, Gulf Publishing Company and Scientific Surveys Ltd., Houston, Texas (1991).

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

222. Potter, J.C., Lewandowsky, L., and White, D.W. Jr., Durability of Special Coatings for Corrugated Steel Pipe, FHWA-91-FLP-006, U.S. Army Waterways Experiment Station, Geotechnical Laboratory, Vicksburg, Mississippi (1991).

223. Potter, J.C., "Aluminum Coated Corrugated Steel Pipe Field Performance," Journal of Transportation Engineering ASCE, Vol. 116, No. 2 (March/April 1990).

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

225. Progress on Durability Study of Corrugated Aluminum Drainage Pipe, Sponsored by the Aluminum Association, Committee A2C06, Report to Transportation Research Board, National Research Council, Washington, D.C. (January 1987).

226. Puterman, M., "Natural and Accelerated Weathering of PVC and Polyethylene Wastewater pipes," Materials and Construction, Vol. 22, No. 129 (1989) pp. 170-175.

227. Pyskaldo, R.M., Experimental Culvert Test Plates, Engineering Research and Development Bureau, New York Department of Transportation, Albany (1988).

228. Pyskaldo, R.M., “Polymer Coatings for Corrugated Steel,” Special Report #64 FHWA/NY/SR-79/64, NYSDOT, Engineering Research & Development Bureau, NYSDOT State Campus, Albany, N.Y. (Oct. 1979) 17 pp.

229. Rao, P. and Miller, R.L., “Applied Econometrics,” Wadsworth Publishing Co., Belmout, Calif. (1971).

230. Ray, A.A., “SAS User’s Guide: Basics,” 1982 Edition, SAS Institute Inc., Cary, N.C.

231. Ray, D., and Croteaun, J., “Corrosion of Corrugated Metal Pipe.” Final rep., New Jersey DOT, unpublished (Feb. 1974) 30 pp.

232. Renfrew, W.W. and R.M. Pyskadio, National Survey of State Culvert Use and Policies, Special Report 68, New York State Department of Transportation, Albany (May 1980).

233. “Republic PolyCote Polymer Coated Galvanized Corrugated Steel Pipe,” G-180, Republic Steel Corporation, Drainage Products Division, Canton, OH (1982) 4 pp.

234. Ring, G.W., “Culvert Durability: Where Are We?” in Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C. (1984).

235. Roadway Engineering Group Design Section, 1996, Appendix A: Pipe Selection Guidelines and Procedures.

236. Romanoff, M., “Underground Corrosion.” Circ. 579, Natl. Bur. Of Standards, U.S. Govt. Printing Ofc. Washington, D.C. (Apr. 1957) 227 pp.

237. Romanoff, M., “Performance of Ductile Iron in Soils,” Journal of the American Water Works Association, Vol. 60, No. 6 (June 1968) pp. 645-655.

238. Ropke, J.C., “Concrete Problems Causes and Cures,” McGraw-Hill, Inc. (1982).

239. Sagues, A.A., 2001, Corrosion Resistance and Service Life of Drainage Culverts. Florida Department of Transportation.

240. Sagues, A.A., Kranc, S.C., Presuel-Moreno, F., Rey, D. Torres-Acosta, A., Yao, L., 2001, Corrosion Forecasting for 75-Year Durability Design of Reinforced Concrete. Florida Department of Transportation.

241. Sagues, A.A., Corrosion Measurement of Aluminum Alloys and Reinforced Concrete for Determination of Culvert Service Life, University of South Florida, Tampa (1989).

242. Schrock, B.J., “Plastic Pipe Overview- 1983,” Europipe ’83 Conference, Basle, Switzerland, Paper No. 12. (1983).

243. Schwerdtfeger, W.J., “Soil Resistivity as Related to Underground Corrosion and Cathodic Protection.” Hwy. Res. Record No. 110 (1966) pp. 20-21.

244. Sears, E.C., “Comparison of the Soil Corrosion Resistance of Ductile Iron pipe and Gray Cast Iron Pip,” Materials Protection. Vol 7, No. 10 (1968) pp. 33-36.

245. Seed, R.B., and Duncan, J.M., “Earth Pressure and Surface Load Effects on Buried Pipelines,” 2nd International Conference: Advances in Underground Pipeline Engineering, Madison, Wis., (Aug. 1985) pp 21-329.

246. Sewer Manual for Corrugated Steel Pipe, National Corrugated Steel Pipe Association, Washington, D.C. (1949).

247. Sheppard, D. M. and Renna, R., 2003, "Florida Bridge Scour Research," AASHTO proceedings, Cody, WY.

248. Sikora, E., "Predicted Vs. Actual Field Measured Deflections of PVC Sewer Pipe," N.C.P.I, Crystal Lake, Ill. (Nov. 1977).

249. Singhal, A.C., and Veliz, V., "Experimental and Field Observation of Dynamic Behavior of Buried Pipelines," 2nd International Conference American Society of Civil Engineers: Underground Pipeline Engineering, Madison, Wis. (1985).

250. Slack, S.B., and Abercrombie, W.F., "Report on Study of Culvert Durability," State Highway Board, Georgia State Highway Department Bureau of Investigations. (1928).

251. Spangler, M.G., "Structural Design of Flexible Pipe Culverts," Bulletin 153, Engineering Experiment Station, Iowa State University, Iowa. (1941).

252. Statement Attributed to California Legislative Analyst Elizabeth G. Hill, Sacramento Bee, Forum 3, Sacramento, California (December 3, 1975).

253. Stephens, J.W., and Gill, B.W., "Service Failure Experience of UPVC Pressure Pipes in the Water Industry," Plastic Pipes V, 5th International Conference, University of York, London (1982) pp 33.1-33.15

254. Stratfull, R.F., "Report one the Experimental Placing of a Cement Mortar Coating in Corrugated Metal Culverts in District 1." California Div. of Hwys. Memo. Unpublished (May 1954) 14 pp.

255. Stratfull, R.F., "A New Test for Estimating Soil Corrosivity Based on Investigation of Metal Highway Culverts." Corrosion, Vol. 17, No. 10 (Oct. 1961).

256. Stratfull, R.F., "Highway Corrosion Problems, Metal Culverts and Reinforced Concrete Bridges." Western Region Conf. Natl. Assn. of Corrosion Eng. (Oct. 1962) 20 pp.

257. Stratfull. R.F., "Field Method of Detecting Corrosive Soil Conditions." Proc., 15th Ann. Street and Hwy. Conf., ITTE and Univ. Extension, Univ. of California at Los Angeles (Jan. 1963).

258. Stratton, F.W., J.A. Frantzen and J.A. Meggers, Cause of Deterioration of Corrugated Metal Pipe Installed After 1974, Kansas Department of Transportation, Topeka, Kansas (1990).

259. Stroud, T.F., Control Measures for Ductile Iron Pipe, Corrosion/89, National Association of Corrosion Engineers, Houston, Texas (1989).

260. Stroud, T.F., "Polyethylene Encasement versus Cathodic Protection," Ductile Iron Pipe News (Spring/Summer 1968).

261. Sudol, J.J., Pipe Coating Study, Indiana Department of Highways, Indianapolis, Indiana (1982).

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

263. Summerson, T.J., "1981 Survey of Type II Aluminized Steel Riveted Culvert Test Sites," Kaiser Aluminum and Chemical Corporation – Center for Technology, Report ZCFT-82-35-TJS, Pleasanton, Calif. (1982).

264. Swan, J.D., "The Field Service Performance of USS Nexon Culverts," United States Steel Bulletin, Unite States Steel Corp., Pittsburgh PA (Nov. 1975).

265. Swan, J.D., "Steel Products for Culvert Applications." Paper presented at 51st Ann. Meet. Of HRB unpublished (Jan. 1972).

266. Swanson, H.N., and Donnelly, D.E., “Performance of Culvert Materials in Various Colorado Environments,” Colorado Department of Highways Report No. CDOH-P&R-R-77-7, Denver, CO, (1977).

267. Symposium on Durability of Culverts and Storm Drains,” Transportation Research Record 1001, Transportation Research Board, National Research Council, Washington, D.C., 1984, 114 pp.

268. “Symposium on Effects of Aggressive Fluids on Concrete.” Hwy. Rees. Record No. 113, 6 reps. (1966) 117 pp.

269. Table 6-1, Culvert Material Application and Design Services Life (DSL) Drainage Manual, Vol. I Standards, Florida Department of Transportation, Tallahassee (1993).

270. Temple, W.H., S.L. Cumbaa and B.J. Gueho, “Evaluation of Drainage Pipe by Field Experimentation and Supplementary Laboratory Experimentation,” FHWA/LA-85/174, Louisiana Department of Transportation, Baton Rouge (1985).

271. Temple, W., Rasoulian, M., and Gueho, B.J., “Louisiana Highway Research Evaluation of Drainage Pipe by Field Experimentation and Supplemental Laboratory Experimentation,” Interim Report No. 3 (Nov. 1981) 52 pp.

272. Thompson, R.E., Culvert Management System (CMS) for Local Governments, Federal Highway Administration, McLean, Va., 2000.

273. “Time Dependant Properties of Embedment Soils Back-Calculated from Deflections of Buried Pipes,” Specialty Geomechanics Symposium: Interpretation of Field Testing for Design Parameters, Adelaide, Australia. (1986).

274. Transportation Research Board, 2002, “Assessment and Rehabilitation of Existing Culverts,” NCHRP Synthesis 303.

275. Tymkowicz, S., Pipe Rehabilitation with Polyethylene Pipe Liners—Construction Report, Iowa Department of Transportation, Ames, March 1996, 59 pp.

276. Uhlig, H.H., Corrosion and Corrosion Control: an Introduction to Corrosion Science and Engineering, 2nd ed., Wiley (June 1971) 419 pp.

277. “U.S.S Nexon-Precoated Culvert Sheets,” Brochure no. ADUSS 30-5201-99, U.S. Steel Corporation, Pittsburgh, PA, (May 1975) 24 pp.

278. Vancrombrugge, R., “Fracture Propagation in Plastic Pipes,” Plastic Pipes V, 5th International Conference, University of York, London (1982).

279. Velasquez, Larry, 2002, “Design Insight,” vol. 1, edition IV.

280. Ward, I.M., “Mechanical Properties of Solid Polymers,” Wiley (Inter-science), New York, (1971).

281. Washington State Highway Commission, “Culvert Performance Evaluation,” Olympia, Wash. (1965).

282. Watkins, R.K., Reeve, R.C., and Goddard, J.B., “Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe,” Transportation Research Record no. 903.

283. Welborn, J.Y., and Olsen, R.E., “Report on Inspection of Bituminous Coated and Uncoated Galvanized Metal Culvert Pipe.” Bur. of Pub. Roads, Ofc. of Res. & Dev. (Oct. 1964) 11pp. + tables.

284. Welch, B.H., “Pipe Corrosion and Protective Coatings.” Utah State Hwy. Dept. (Nov. 1974) 72 pp. (Also published in Transp. Res. Record 604, 1976, pp. 20-24)

285. West Virginia Department of Transportation, 2003, DD-503: Design of Alternative Pipe Materials.

286. Wheeling Corrugation Company, "Wheeling Plasticote Corrugated Steel Pipe Case Histories for NCSPA Service Life Manual," Letter Report for NCSPA, Wheeling, W. Va. (1983).

287. Wheeling Corrugation Company, "Corrosion Performance of Metallic Coated Steel Culvert," Test Report No. 20-663, Wheeling, W. Va. (1980).

288. Wilson, C.L., and Oates, J.A., Corrosion and the Maintenance Engineer, 2nd ed., Hart (1968) 196 pp.

289. Wolfe, V.D., and Macnab, S.H., "Corrugated Metal Pipe Comparison Study," Oregon Department of Transportation Official Publication 76-3, Salem, Oreg. (1976).

290. Woods, H., "Durability of Concrete Construction." Monograph No. 4, ACI (1968) 187 pp.

291. Worley, H. E., "Effectiveness of Bituminous Coatings on Corrugated Metal Pipe." State Hwy. Comm. Of Kansas (1970) 9 pp.

292. Worley, H.E., and Curbpton, C.F., "Corrosion and Service Life of Corrugated Metal Pipe in Kansas." Hwy. Res. Record No. 412 (1972) pp. 35-40.

APPENDIX A - FIELD TRIP PHOTOS

I-25 – Milepost 59.09

I-25 Milepost - 59.09

I-25 – Milepost 59.09

I-25 – Milepost 59.09

I-25 – Milepost 59.09

I-25 – Milepost 65.61

I-25 – Milepost 65.61

I-25 – Milepost 65.61

I-25 – Milepost 79.19

I-25 – Milepost 79.19

I-25 – Milepost 79.19

I-25 – Milepost 145.12

I-25 – Milepost 145.12

I-25 – Milepost 182.00

I-25 – Milepost 182.00

I-25 – Milepost 182.00

I-25 – Milepost 182.00

I-25 – Milepost 182.00

I-25 – Milepost 182.00

I-25 – Milepost 237.72

I-25 – Milepost 237.72

I-25 – Milepost 237.72

SH-58 – Milepost 0.70

SH-58 – Milepost 0.70

SH-58 – Milepost 0.70

I-70 – Milepost 77.05

I-70 – Milepost 77.05

I-70 – Milepost 77.06

I-70 – Milepost 77.06

I-70 – Milepost 77.06

I-70 – Milepost 77.06

I-70 – Milepost 77.78

I-70 – Milepost 77.78

I-70 – Milepost 117.82

I-70 – Milepost 117.82

I-70 – Milepost 117.82

I-70 – Milepost 186.10

I-70 – Milepost 186.10

I-70 – Milepost 186.10

I-70 – Milepost 186.10

I-70 – Milepost 198.98

I-70 – Milepost 198.98

I-70 – Milepost 198.98

I-70 – Milepost 205.05

I-70 – Milepost 205.05

I-70 – Milepost 211.68

I-70 – Milepost 211.68

I-70 – Milepost 211.68

I-70 – Milepost 211.68

I-70 – Milepost 211.68

I-70 – Milepost 217.39

I-70 – Milepost 217.39

I-70 – Milepost 217.39

I-70 – Milepost 217.39

I-70 – Milepost 237.60

I-70 – Milepost 237.60

I-70 – Milepost 237.60

I-70 – Milepost 237.60

I-70 – Milepost 244.92

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I-70 – Milepost 247.62

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I-70 – Milepost 256.13

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I-70 – Milepost 256.80

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APPENDIX B – AASHTO and ASTM Specifications Related to Culvert Pipes

1. AASHTO M 36: Corrugated Steel Pipe, Metallic-Coated, for Sewers and Drains
2. AASHTO M 55: Steel Welded Wire Fabric, Plain, for Concrete Reinforcement
3. AASHTO M 86: Concrete Sewer, Storm Drain, and Culvert Pipe
4. AASHTO M 167: Corrugated Steel Structural Plate, Zinc-Coated, for Field-Bolted Pipe, Pipe-Arches, and Arches
5. AASHTO M 170: Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe
6. AASHTO M 190: Bituminous Coated Corrugated Metal Culvert Pipe and Pipe Arches
7. AASHTO M 196: Corrugated Aluminum Pipe for Sewers and Drains
8. AASHTO M 197: Aluminum Alloy Sheet for Corrugated Aluminum Pipe
9. AASHTO M 198: Circular Concrete Sewer and Culvert Pipe Using Flexible Watertight Gaskets
10. AASHTO M 207: Reinforced Concrete Elliptical Culvert, Storm Drain and Sewer Pipe
11. AASHTO M 219: Corrugated Aluminum Alloy Structural Plate for Field-Bolted Pipe, Pipe-Arches, and Arches
12. AASHTO M 243: Field Applied Coating of Corrugated Metal Structural Plate for Pipe, Pipe Arches, and Arches
13. AASHTO M 245: Corrugated Steel Pipe, Polymer Precoated, for Sewers and Drains
14. AASHTO M 246: Steel Sheet, Metallic-Coated and Polymer Precoated for Corrugated Steel Pipe
15. AASHTO M 294: Corrugated Polyethylene Pipe, 300- to 1200-mm Diameter
16. AASHTO M 304: Polyvinyl Chloride (PVC) Profile Wall Drain Pipe and Fittings Based on Controlled Inside Diameter
17. AASHTO Standard Specifications for Bridge Construction
18. ASTM A 849: Post-Applied Coatings, Pavings, and Linings for Corrugated Steel Sewer and Drainage Pipe
19. ASTM C 443: Standard Specification for Joints for Concrete Pipe and Manholds, Using Rubber Gaskets
20. ASTM D 1784: Standard Specification for Rigid Poly (Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds
21. ASTM D 3212: Joints for Drain and Sewer Plastic Pipes Using Flexible Elastomeric Seals
22. ASTM D 3350: Standard Specification for Polyethylene Plastics Pipe and Fittings Materials
23. ASTM F 477: Elastomeric Seals (Gaskets) for Joining Plastic Pipe