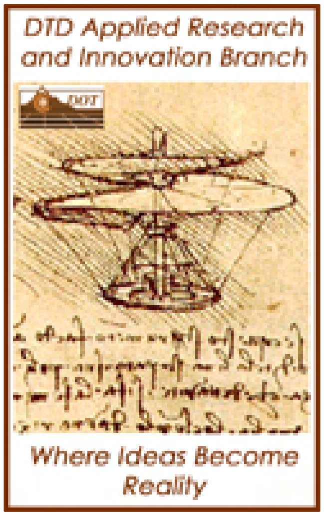
Report No. CDOT-2009-11
Final Report



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

**Albert Molinas, Amanullah Mommandi**

November 2009

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

**Technical Report Documentation Page**

1. Report No.
CDOT-2009-11

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
DEVELOPMENT OF NEW CORROSION/ABRASION GUIDELINES FOR SELECTION OF CULVERT PIPE MATERIALS

5. Report Date
November 2009

6. Performing Organization Code

7. Author(s)
Albert Molinas and Amanullah Mommandi

8. Performing Organization Report No.
CDOT-2009-11

9. Performing Organization Name and Address
Colorado State University and Hydrau-Tech, Inc.
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Fort Collins, CO 80523

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
106.00

12. Sponsoring Agency Name and Address
Colorado Department of Transportation - Research
4201 E. Arkansas Ave.
Denver, CO 80222

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

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.

17. Keywords
culverts, material selection, service life, metal pipes, steel pipes, concrete pipes, aluminum pipes, hydrology, chlorides, sulfates, soil resistivity

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service Springfield, VA 22161; www.ntis.gov

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
120

22. Price

**Form DOT F 1700.7** (8-72) Reproduction of completed page authorized

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

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## Report No. CDOT-2009-11

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**Federal Highway Administration**

**November 2009**
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# ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Colorado Department of Transportation’s financial support during the course of this study. The authors sincerely appreciate Dr. Christopher Thornton, Colorado State University for providing project administration and Mr. Michael Robeson, Colorado State University for his assistance in the data collection and literature review. The authors would also like to extend their deep appreciation to the members of the Colorado Department of Transportation Research Study Panel consisting of Jeffrey Anderson (CDOT Staff Bridge Branch), Mr. Mike Banovich (CDOT-DTD Environmental), Mr. Alfred Gross (CDOT R-1 Hydraulics), Mr. Mohan Sagar (CDOT Specifications), Mr. Keith Powers (Region 5 Program Engineer), Mr. Fred Schultz (CDOT Region Maintenance Superintendent), Mr. C. K. Su (Materials and Geotechnical Branch), Mr. David Wieder (Area Engineer in CDOT Project Development Branch), Mr. Robert Locander (Materials and Geotechnical Branch), Mr. Scott Roalofs (Materials and Geotechnical Branch) and Mr. Matt Greer (FHWA, Colorado Division) for their technical assistance, guidance, and review of this document.

# 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.

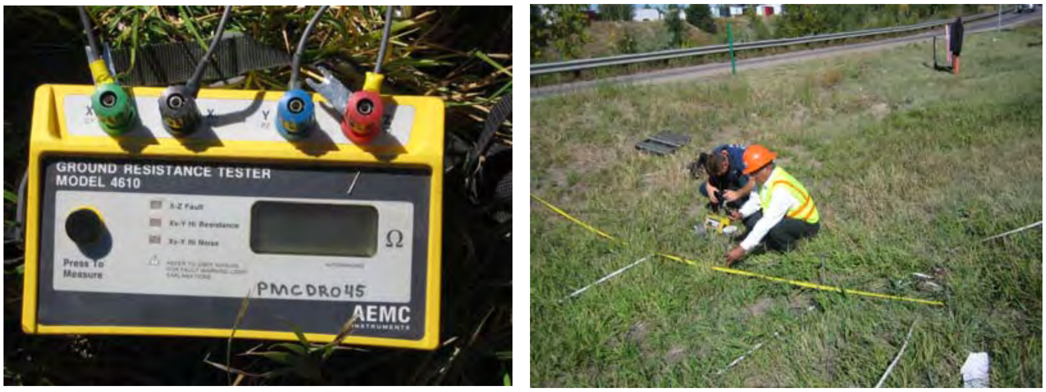


**Figure 1.  Soil resistivity testing by ASTM G57-95a**

**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.

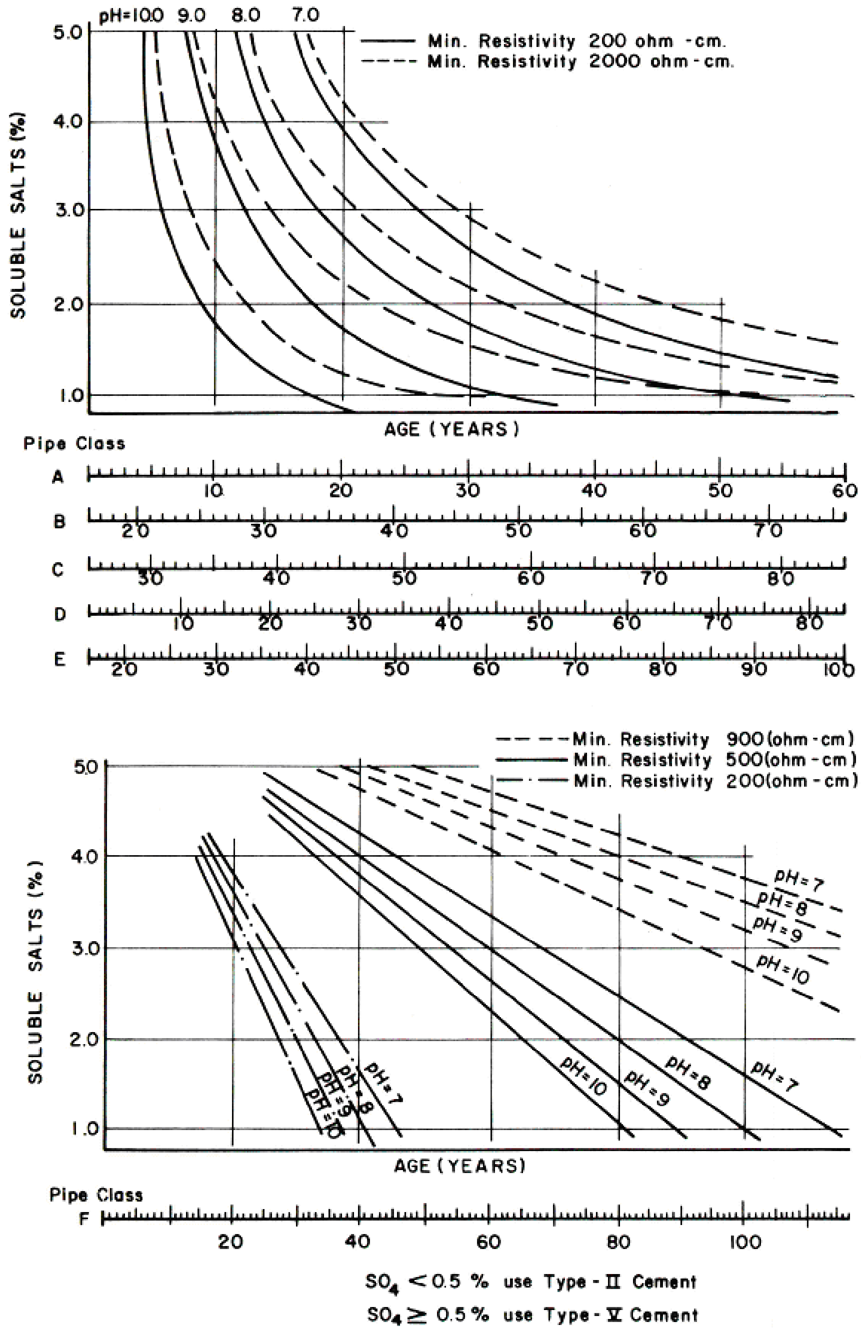
# LITERATURE REVIEW

## 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.

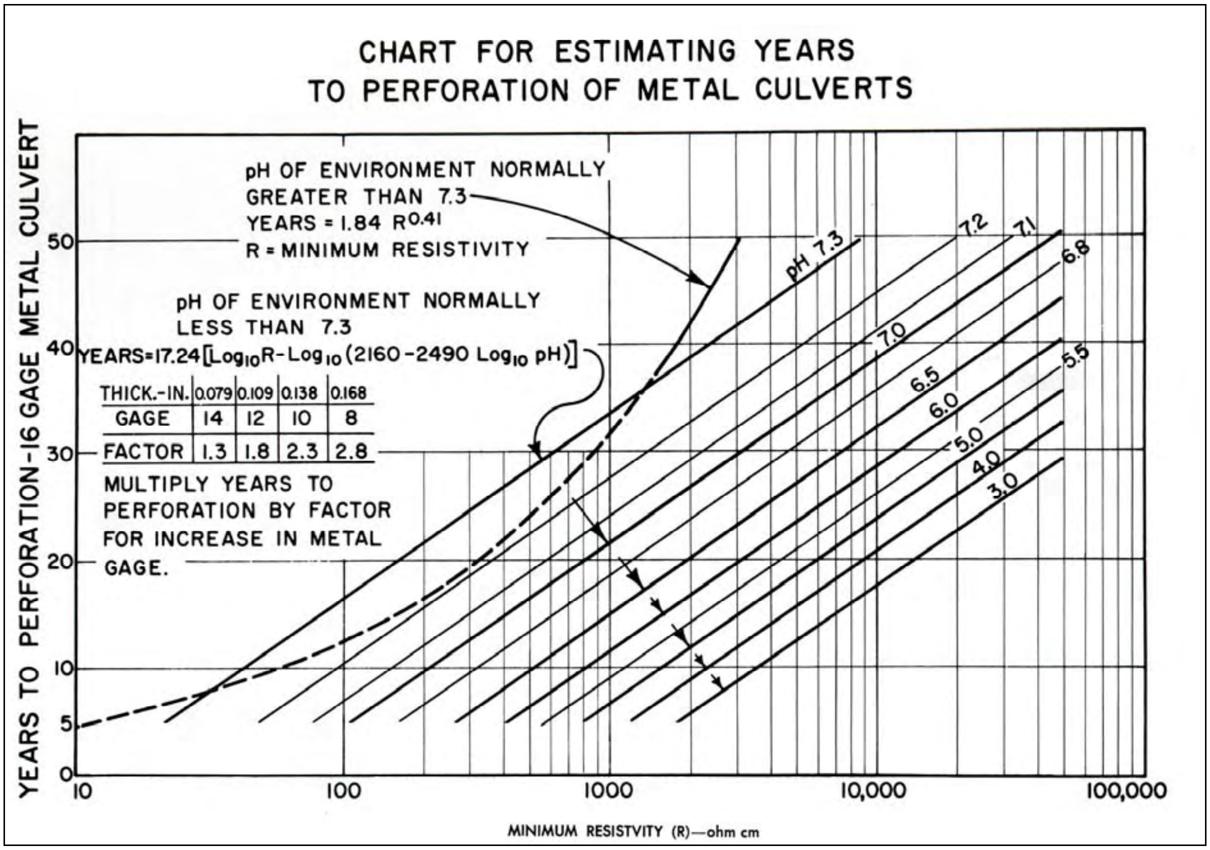
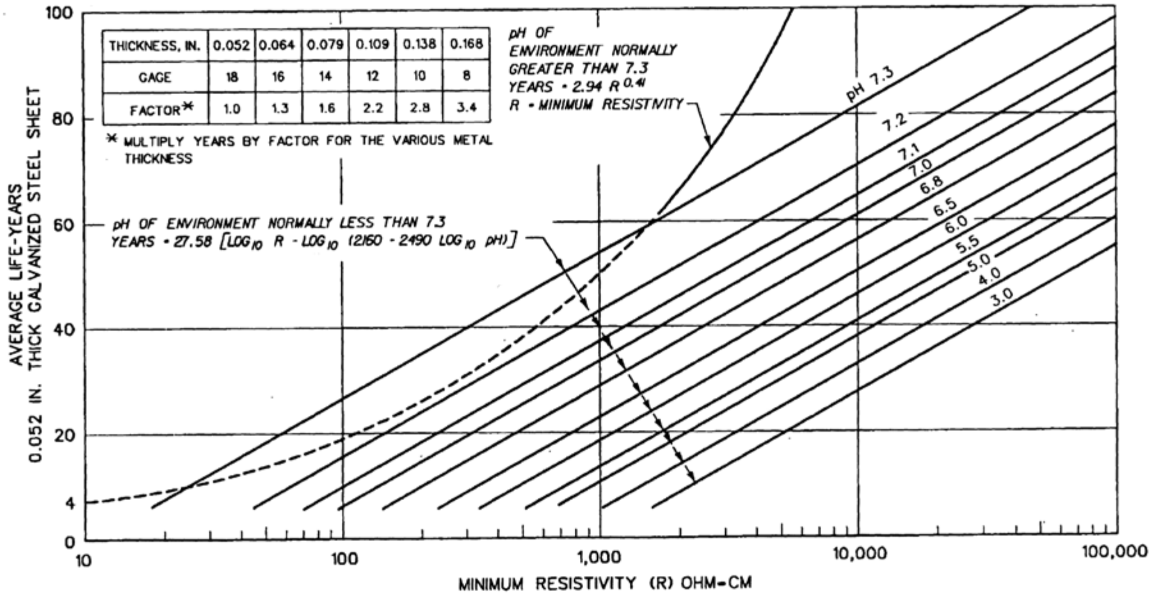


**Figure 3. California DOT method for determining service life for steel pipes**

## 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.



| THICKNESS, IN. | 0.052 | 0.064 | 0.079 | 0.109 | 0.138 | 0.168 |
|---|---|---|---|---|---|---|
| GAGE | 18 | 16 | 14 | 12 | 10 | 8 |
| FACTOR* | 1.0 | 1.3 | 1.6 | 2.2 | 2.8 | 3.4 |

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**

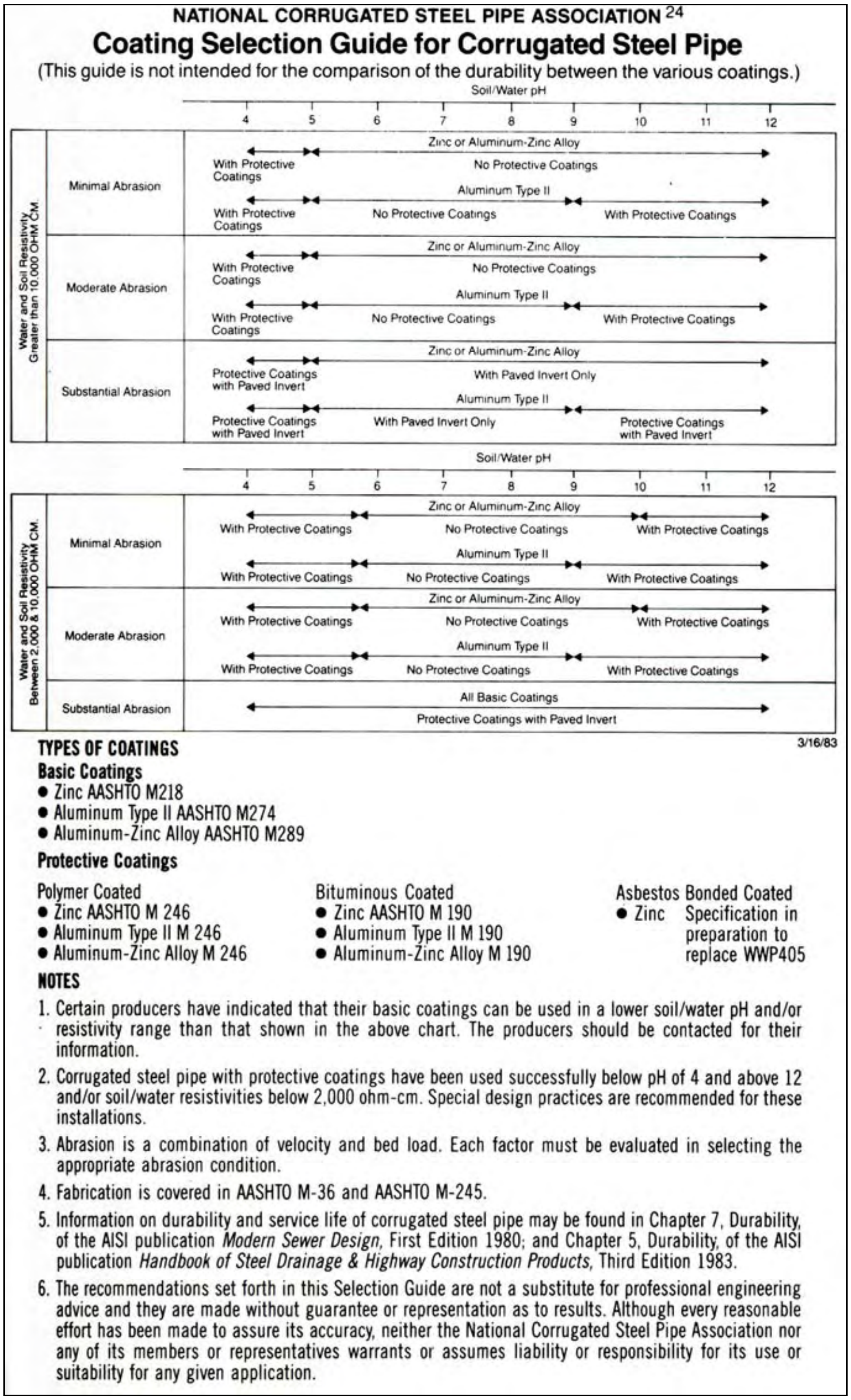
| Soil Type | Degree of Corrosiveness | Electrical Resistivity Ohm-cm |
|---|---|---|
| 1 | Very low | 10,000-6,000 |
| 2 | Low | 6,000-4,500 |
| 3 | Moderate | 4,500-2,000 |
| 4 | Severe | 2,000-0 |

**Table 3. Corrosiveness of soils**

| Soil Type | Description of Soil | Aeration | Drainage | Color | Water Table |
|---|---|---|---|---|---|
| I - Lightly Corrosive | 1. Sands or sandy loams<br>2. Light textured silt loams<br>3. Porous loams or clay loams thoroughly oxidized to great depths | Good | Good | Uniform Color | Very low |
| II - Moderately Corrosive | 1. Sandy loams<br>2. Silt loams<br>3. Clay loams | Fair | Fair | Slight mottling | Low |
| III - Badly Corrosive | 1. Clay loams<br>2. Clays | Poor | Poor | Heavy texture<br>Moderate mottling | 2ft to 3 ft below surface |
| IV - Unusually Corrosive | 1. Muck<br>2. Peat<br>3. Tidal marsh<br>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 | ≥ 2,500 |
| Aluminized Steel, Type 2 (AASHTO M274) | 5 - 9.0 | ≥ 1,500 |
| Aluminum (Alclad 3004) | 5 - 9.0<br>or 5.5 - 8.5 | ≥ 1,500<br>≥ 500 |
| Stainless Steel, Type AISI 409 | 5 - 9.0 | ≥ 1,500 |
| Cast Iron | 6 – 9.0 | ≥ 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<br>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<br>The pH Range is 5 to 9<br>(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.<br>The pH range is 5 to 9 |
| D | Corrugated High Density Polyethylene Plastic Pipe (CHDPEPP), AASHTO M 294.<br>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) | ≥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<br>R[b] >1500 | 75+ years | H[c] |
| Galvanized steel dry climate | pH: 4.5 – 6<br>pH: 6 – 7<br>pH: 7- 10<br>R 1500 - 2000 for all | 30<br>35<br>40 | H |
| Galvanized steel rainy climate | pH: 4.5 – 6<br>pH: 6 – 7<br>pH: 7- 10<br>R 1500 - 2000 for all | 15<br>20<br>25 | H |
| Aluminum coated steel | pH: 5 – 9<br>R > 1500 | 50 rainy<br>65 dry | H<br>H |
| Aluminum | pH: 4.5 – 10<br>R > 1500 | 75 | H |
| Vitrified clay | N/A | Very Durable | H |
| PVC | N/A | N/A | L |
| Polyethylene | pH 4.5 – 10<br>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<br>or II | Minimum required by specifications<br>7 sacks+ |
| 0.5-1.5 | 5,000-15,000 | V<br>or II | Minimum required by specifications<br>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<br>• Velocities less than 3ft/sec with bedload | All allowable pipe materials listed in HDM table 853.1A<br>No abrasive resistant coatings needed for metal pipe |
| Low Abrasive | • Minor bedload of sand, silts, and clays<br>• Velocities less than 5ft/sec | All allowable pipe materials listed in HDM table 853.1A<br>with the following considerations:<br>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<br>• Velocities from 5ft/sec to 10ft/sec | All allowable pipe materials listed in HDM table 853.1A<br>with the following considerations:<br>Steel pipe will typically need one of the abrasive resistant protective coatings listed in HDM table 854.3 or additional gauge thickness.<br>Aluminum pipe not recommended for sharp and angular bedload, otherwise OK.<br>Lining alternatives:<br>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."<br>• Velocities from 10ft/sec to 15ft/sec | Aluminum pipe not recommended.<br>Corrugated HDPE pipe or liners allowed.<br>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.<br>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.<br>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.<br>Lining alternatives:<br>PVC, Corrugated or Solid Wall HDPE, CIPP, RPMP |
| Severe Abrasive | • Heavy bedload of sands, gravel, and rocks, with stone sizes 150 mm or larger<br>• Velocities greater than 10ft/sec<br>**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.<br>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<br>• Velocities greater than 15ft/sec | may include steel plate, rails, or concreted RSP. For new/replacement construction, consider "bottomless" structures.<br>PVC pipe or liners only allowed for sand and gravel bedload (less than 50mm) for velocities less than 20ft/sec.<br>Corrugated HDPE pipe or liners allowed for velocities less than 20 ft/sec and angular stone sizes up to 150mm.<br>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.<br>Lining alternative:<br>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<br>2. Light textured silt loams<br>3. Porous loams or clay loams thoroughly oxidized to great depths | Good | Good | Uniform Color | Very low |
| II - Moderately Corrosive | 1. Sandy loams<br>2. Silt loams<br>3. Clay loams | Fair | Fair | Slight mottling | Low |
| III - Badly Corrosive | 1. Clay loams<br>2. Clays | Poor | Poor | Heavy texture Moderate mottling | 2ft to 3 ft below surface |
| IV - Unusually Corrosive | 1. Muck<br>2. Peat<br>3. Tidal marsh<br>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<br>RCP & CIPCP*** | | | | | | | if pH<5.0, use a rapid chloride permeability ≤1200 coulumbs<br>or<br>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

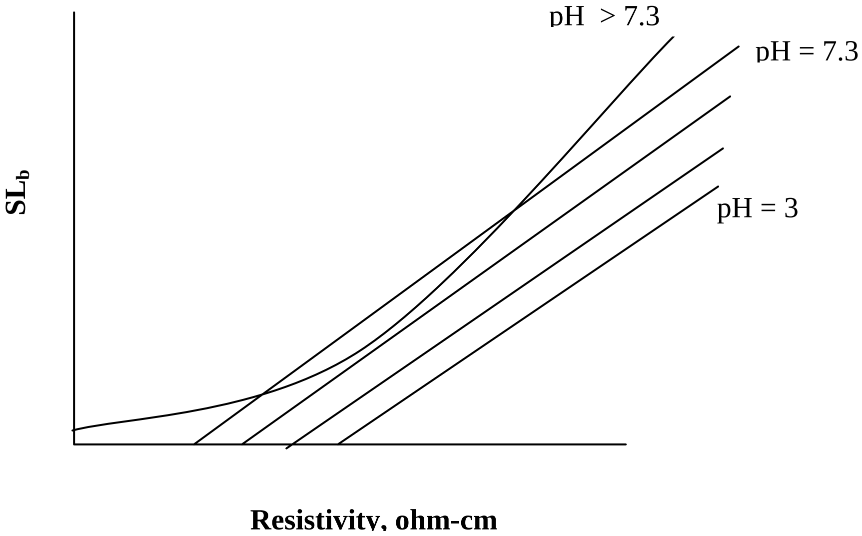
The major findings of the literature review may be summarized under the following categories:

**A. Steel Pipe**

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

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

  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

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

  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):

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

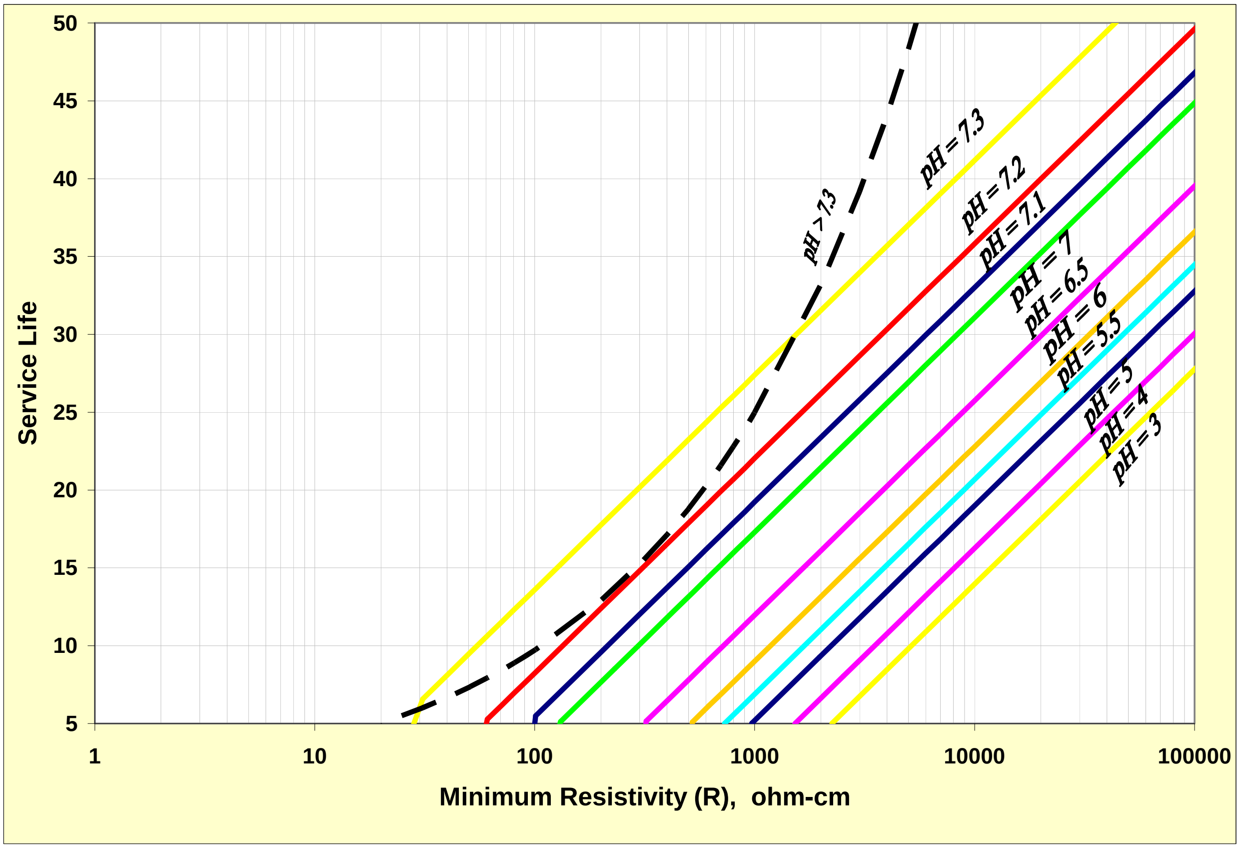


**Figure 6. Service life as a function of soil resistivity and pH**

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(S40) | 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 |

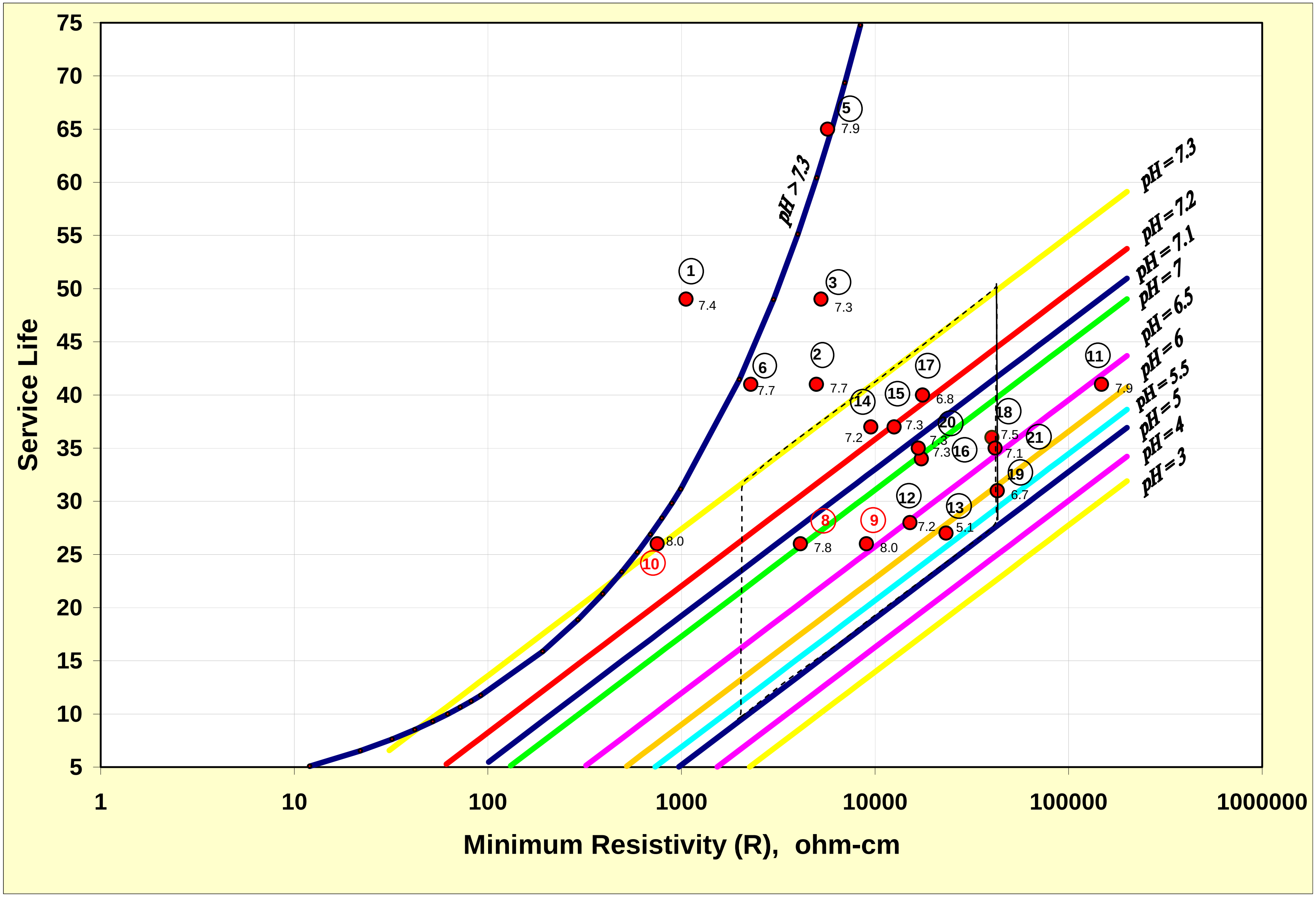


Figure 10.  Service life versus resistivity chart for the corrugated pipes visited in the field study

# 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:

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

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).

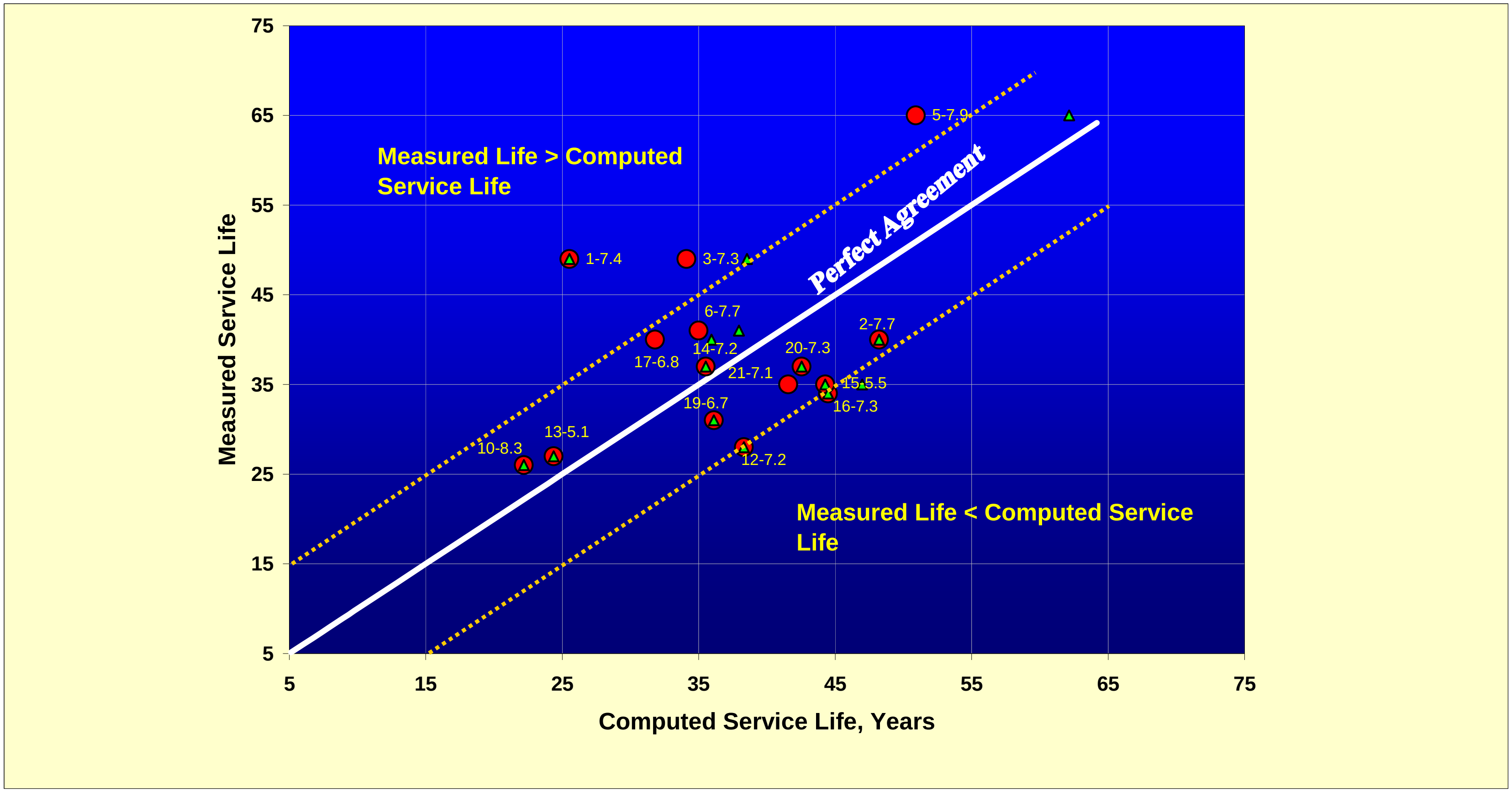


**Figure 11. Service life in metal pipes using CALTRANS and CSU-HT (Molinas) thickness adjustments**

## 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.

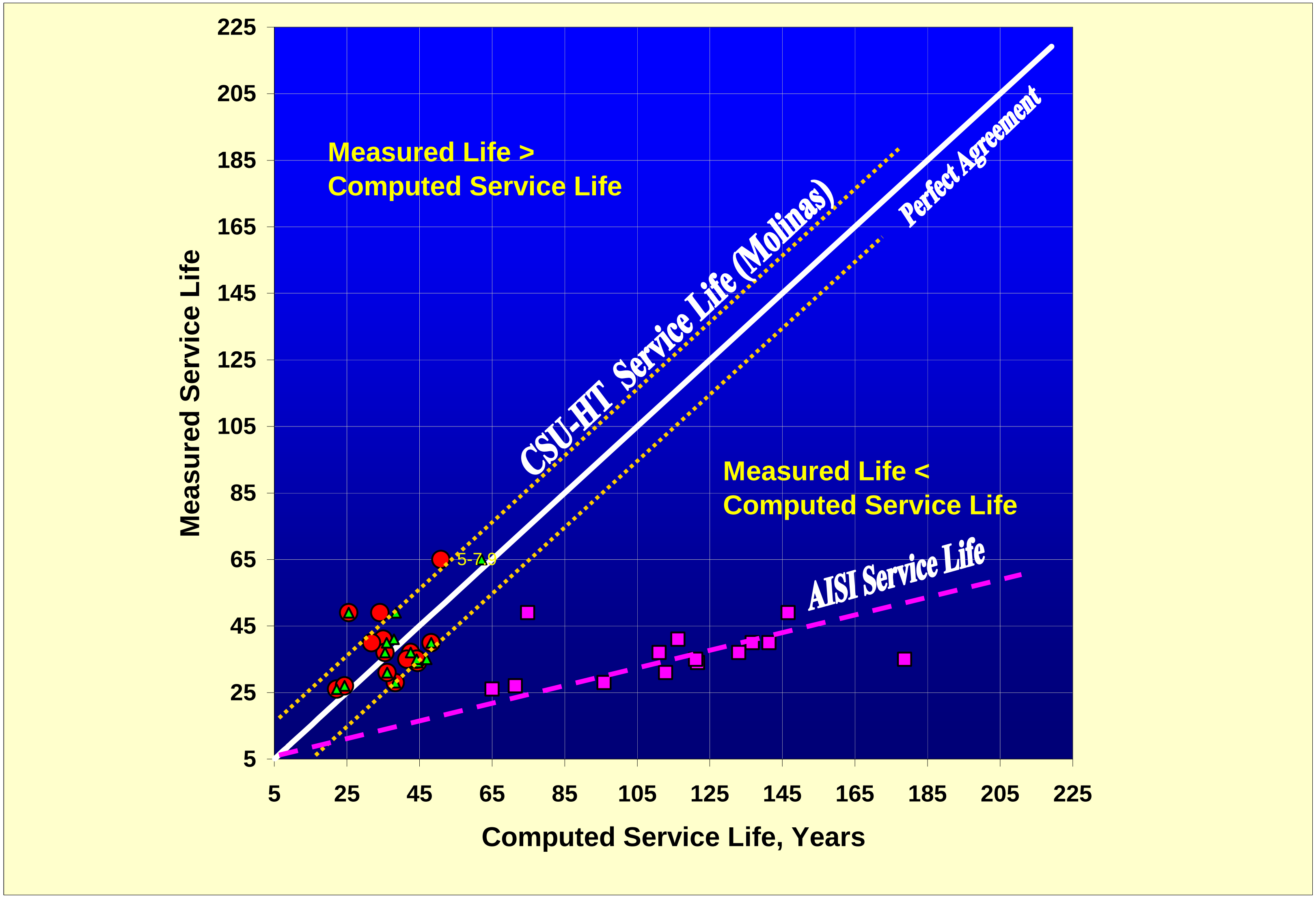


Figure 14. Measured and computed service lives using: i) AISI eq. ; ii) CALTRANS eq.; iii) Modified CALTRANS equation (CSU-HT)

# 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.

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# 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

I-70 – Milepost 244.92

## I-70 – Milepost 244.92

## I-70 – Milepost 247.62

I-70 – Milepost 247.62

I-70 – Milepost 247.62

I-70 – Milepost 247.62

I-70 – Milepost 256.13

I-70 – Milepost 256.13

I-70 – Milepost 256.13

I-70 – Milepost 256.80

I-70 – Milepost 256.80

I-70 – Milepost 256.80

I-70 – Milepost 256.80

# APPENDIX B – AASHTO and ASTM Specifications Related to Pipe Culverts

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