Performance and Policy Related to Aluminum Culverts in Wisconsin

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16. Abstract

Current Wisconsin Department of Transportation policy severely limits the use of aluminum drainage structures (pipe and box culverts) based on the observation of pitting corrosion from deicing salts that led to the failure of an aluminum culvert in Wisconsin in 1993. The research goal is to establish best practices for aluminum culvert use and formulate recommendations for updated aluminum culvert policy in Wisconsin. The research process reviewed policy from Wisconsin DOT, policy from federal agencies, policy from other state departments of transportation, industry-wide technical information and previous aluminum culvert performance research, demographic and performance data from Wisconsin and federal databases, aluminum culvert alloy specifications, technical data on durability factors and corrosion mechanisms, and trends of deicer chemical usage on Wisconsin roadways. The research developed and administered a stakeholder survey and conducted a field investigation. Based on natural environmental conditions in Wisconsin, aluminum culverts should provide 50 to 75 yrs or more of service life if installed in sites that meet generally accepted abrasion, pH, and resistivity limits. Infiltration of chloride-based deicing chemicals though soil fill and contact with aluminum leads to pitting corrosion that may lead to premature culvert failure. Best practices to prevent this mechanism include installing an impermeable isolation membrane within the backfill, testing and limiting the chloride content of the embedment backfill, and using free-draining backfill below the membrane and as embedment around the buried structure.

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EXECUTIVE SUMMARY

Current Wisconsin Department of Transportation (WisDOT) policy severely limits the use of aluminum drainage structures. These limitations are based on observation of pitting corrosion, likely resulting from chloride-based deicing salt infiltration through cracked pavement and unpaved embankments or shoulders, that led to the failure of an aluminum culvert in Wisconsin in 1993. Field investigation of other aluminum culverts in Wisconsin at the time identified relatively widespread corrosion at the tops of the structures, likely initiating from soil-side contact with infiltrating deicing salts. WisDOT currently allows use of corrugated aluminum pipe where average daily traffic (ADT) is < 1,500 with an allowable size of 42 to 84 in. diameter but recommends limiting its use to side drains and highways with traffic volumes under 1,500 design ADT unless some provision is made to insulate the upper surface of the structure from infiltrating road salt.

The objective of this research is to develop recommendations and guidelines for the validation of WisDOT's current policy limiting the use of aluminum culverts or provide information that may be used as the basis of revised policy and guidelines for inclusion of aluminum culverts on WisDOT-administered transportation projects. The research includes recommendations for updates to WisDOT standards for use of aluminum culverts on state or local roads in Wisconsin and will provide necessary information for training WisDOT employees on the reinforced or updated policy in the form of a presentation prepared by the research team for delivery by WisDOT summarizing the best practices and requirements.

To achieve these objectives, our research team performed the following tasks:

- Reviewed existing WisDOT policy, previous research reports, and industry-wide technical literature to synthesize information on practices and performance of aluminum culverts, document findings, and establish best practices to consider in developing updates to WisDOT aluminum culvert policy.

- Reviewed information on current use of deicer chemicals on Wisconsin roadways.

- Developed and administered a survey on aluminum culvert use and performance to aluminum culvert stakeholders, including several state DOTs and aluminum culvert suppliers.

- Reviewed aluminum culvert inventory, demographic, condition, and performance data from WisDOT and FHWA databases and inspection records.

- Performed a field inspection of three in-service aluminum culverts in Wisconsin to gather site environmental and aluminum culvert performance data.

- Reviewed metallurgical and chemical aspects of the specific alloys used in culvert construction and chemistry of their susceptibility to corrosion, including a small corroded sample removed from one of the field inspection culverts.

- Performed additional literature review related specifically to the corrosion mechanisms observed in the field inspection and in recent WisDOT aluminum culvert inspections, as well as the process behind those mechanisms specific to a buried culvert environment.

- Prepared this research report and PowerPoint training slides to summarize information from the above tasks.

Key findings from the research include the following:

- Two primary factors that affect aluminum culvert durability are abrasion and corrosion.

- Aluminum culvert abrasion can be evaluated on a site-specific basis with design for prevention following well-established, published methods.

- Corrosion on aluminum culverts manifests in two possible ways: general corrosion or localized pitting corrosion. Existing policies for aluminum culvert usage throughout the US appear to be set with general corrosion in mind. Few, if any policies are geared toward prevention of pitting corrosion.

- Aluminum has a rapidly forming, tough aluminum oxide protective film on its outer surfaces that develops when the aluminum is exposed to oxygen. This durable, stable film contributes to aluminum's resistance to general corrosion in suitable environments.

- Current policies to prevent general corrosion include limiting aluminum culvert use to low- or non-abrasive sites with pH between 4.5 and 9.0 and with soil and water resistivities greater than 500 Ω-cm. In such environments, aluminum culverts are durable against general corrosion and will have a minimum service life of 50 to 75 yrs when not influenced by other corrosion mechanisms, such as contact with chloride-based roadway deicing salts.

- Pitting corrosion will occur if certain concentrated salts are allowed to adsorb (dry and form a film) on the aluminum surface. The primary salts identified as causing pitting corrosion are those that contain chlorides and can release chloride (Cl^-) ions. If the chloride ions are allowed to adsorb on the surface in sufficient concentration, they will become embedded in the aluminum oxide protective film, work their way through it, and form a pit in the aluminum core through chemical reactions. Once pits develop, they will continue to drill their way through the aluminum core. The aluminum oxide protective film seals the pit environment, allowing the pit mechanisms to stay concentrated and promoting pit growth through the thickness.

- In seawater or brackish environments, such as coastal tidal zones, aluminum culverts should be installed in free-draining backfill. Pitting corrosion has not been observed in these applications, likely due to the frequent wetting or flushing across the aluminum surface.

- Review of information in WisDOT and federal databases shows that in regions where deicing salts are used, increased culvert age and prevalence of pavement cracks appear to correlate with aluminum culverts that are identified as corroded. Other metrics such as span, ADT, geographic location, culvert length, and fill depth do not suggest a strong correlation with corrosion of aluminum culverts.

- Usage of chloride-containing salt brine for anti-icing has increased by several orders of magnitude in Wisconsin in the last few decades, while usage of deicing chemicals, including chloride-based road salt and others, has been steady. Other chemicals that may be used for deicing, such as beet juice, are typically added to chloride-based salt or brine mixtures, decreasing chloride concentrations but not eliminating the presence of these aggressive ions.

- To ensure pitting corrosion does not initiate on aluminum culverts in regions that use deicing chemicals, aluminum should be isolated from contact with chloride-containing salts that can migrate vertically from the roadway surface (through cracked pavement and soil fill) and through unpaved shoulders and embankments. Two methods for preventing contact of aluminum culverts with infiltrating chloride-based deicing chemicals include isolation membranes embedded in the backfill envelope over the structure and bonded coatings applied directly to the culvert surface.

- The most economical method to isolate aluminum culverts from such chemicals is through inclusion of an impermeable membrane in the backfill envelope. This protection method is specified for protection of steel reinforcement in the backfill of mechanically stabilized earth walls. At such an installation for aluminum culverts, additional measures to prevent pitting include testing and limiting the chloride content of this backfill below the membrane and specifying free-draining backfill in this area.

- Alternate options to prevent initiation of pitting corrosion in buried aluminum culverts and boxes include providing durable, well bonded exterior (soil-side) coatings. Such coatings have been adopted for other metallic culverts to increase resistance to general corrosion; the adequacy of and specifications for such coatings have not typically been considered in the aluminum culvert industry to date, as aluminum is relatively resistant to general corrosion. There is currently no consensus specification for coating aluminum culverts. Adequate surface preparation and cleanliness prior to application of coatings have a direct effect on bonded coating durability; therefore, bonded coatings on metal culverts are typically factory applied and touched up as needed in the field. Considering the cost of coating, surface preparation, and repair of coating, coatings are typically more expensive than an isolation membrane embedded in the backfill envelope and limiting chloride content in free-draining backfill below the membrane.

Recommendations from the research include the following:

- Develop provisional updates to Wisconsin DOT policy and specifications to allow use of aluminum culverts (pipe, structural plate structures, and box culverts) at sites where soil and water pH ranges from 4.5 to 9, resistivity is greater than 500 Ω-cm, and abrasion classification is Abrasion Level 1 to 3.

- Require laboratory testing of soil and water samples from all potential aluminum culvert sites to ensure the environment is acceptable for aluminum culvert use per the bullet above prior to design.

- Require abrasion classification of all new culvert sites in accordance with Caltrans/FHWA recommendations (or bring those to the WisDOT specifications) to determine acceptable culvert materials and any special protective measures to be taken for a given site and culvert material. Base abrasion classification on a visual survey of bedload materials and flow velocities from a 2 to 5 yr flood event.

- Revise the ADT limit for aluminum culvert use to make it comparable to other flexible culvert types, such as corrugated steel, corrugated steel structural plate, and thermoplastic.

- Specify use of an impermeable isolation membrane in the backfill above aluminum culverts. The membrane should be sloped away from the structure, extending down the embankment for at least 10 ft from pavement or to the end of the culvert, and at least equal to the trench width. Base the membrane specification on, for example, existing New Hampshire DOT or Ohio DOT specifications that rely on several ASTM standards to specify membrane material and mechanical requirements. In the long term, it would likely be beneficial to work with other states and stakeholders to synthesize information from FHWA and any other states that specify such membranes for culverts or MSE walls to develop a single, common material specification for such membranes to be published by AASHTO and/or ASTM.

- Require chloride ion concentration testing of the backfill below isolation membranes and limit its chloride ion content to 100 ppm, based on expected chloride concentrations of backfill soils in Wisconsin and available recommendations for chloride concentration limits in steel-reinforced MSE wall backfill. Consider specification of free-draining backfill below the impermeable isolation membranes.

- Perform inspections and document the performance of a few aluminum culverts installed below impermeable isolation membranes at sites that meet the above recommendations. Document the performance of those structures yearly for approximately 5 yrs, then on a less frequent basis, and pair the inspection data with data from WisDOT winter maintenance and pavement databases over the service life of those culverts.

- Consider updating WisDOT culvert fill tables to be based on current buried structure design provisions of the AASHTO LRFD Bridge Design Specifications and any state-specific modifications, as the design specification are intended to give comparable levels of safety across the range of culvert materials.

- Consider updating WisDOT policy to include equal footing for all culvert materials in a similar manner to that used by the Ohio DOT in their Culvert Design Process Flow Chart.

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1. INTRODUCTION

1.1 Background

Current Wisconsin Department of Transportation (WisDOT) policy severely limits or prohibits use of aluminum drainage structures based on limited studies on the performance of in-service aluminum drainage structures in Wisconsin conducted between the 1980s and 2003. WisDOT expects at least 20 yrs of service from any metallic culvert pipe prior to the appearance of the first perforation. WisDOT allows use of corrugated aluminum pipe where average daily traffic (ADT) is < 1,500 with an allowable size of 42 to 84 in. diameters but recommends limiting its use to side drains and highways with traffic volumes under 1,500 design ADT unless some provision is made to insulate the upper surface of the structure from infiltrating road salt.

The above aluminum culvert usage limitations are based on observation of pitting corrosion, likely from chloride-based deicing salt infiltration through cracked pavement and unpaved embankments or shoulders, that led to the failure of an aluminum culvert in Wisconsin in 1993. Field investigation of other aluminum culverts in Wisconsin at the time identified relatively widespread corrosion at the tops of the structures, likely from contact with infiltrating deicing salts. This corrosion had not been noted in earlier inspection reports of some of the structures, possibly because inspectors were looking for corrosion or deterioration in the lower regions of the culverts, as had been observed in other metallic culverts, or because this corrosion initiates on the soil side of the culvert.

1.2 Research Objectives

The objective of this research is to develop recommendations and guidelines for the validation of WisDOT's current policy limiting the use of aluminum culverts or provide information that may be used as the basis of revised policy and guidelines for inclusion of aluminum culverts on WisDOT-administered transportation projects. The research will include recommendations for updates to the WisDOT standard documents to reinforce existing policy or updated policy for use of aluminum culverts on state or local roads in Wisconsin, and provide necessary information for training WisDOT employees on the reinforced or updated policy in the form of a presentation prepared by the research team for delivery by WisDOT summarizing the best practices and requirements.

1.3 Research Approach

To achieve this objective, our research team performed the following tasks:

- Reviewed existing WisDOT policy, previous research reports, and industry-wide technical literature to synthesize information on practices and performance of aluminum culverts, aluminum material durability, aluminum culvert specification, document lessons learned, and establish best practices to consider in developing updates to WisDOT aluminum culvert policy.

- Reviewed information from WHRP 0092-17-03 Evaluation of the Effects of Deicers on Concrete Durability, including the final report and phone interviews with the principal investigator.

- Review policies and procedures from US federal agencies and more than five state departments of transportation (DOTs) related to use, specification, and performance of corrugated aluminum culverts.

- Collected information from industry members who manufacture aluminum culverts.

- Developed and administered a survey on aluminum culvert use and performance to aluminum culvert stakeholders including several state DOTs and aluminum culvert suppliers.

- Reviewed aluminum culvert inventory, demographic, condition, and performance data from the WisDOT Highway Structures Information System (HSIS) database, WisDOT North-Central District small diameter aluminum culvert inspection data, and US Federal Highway Administration (FHWA) Long-Term Bridge Preservation Portal (LTBP).

- Developed a field inspection plan and selected and performed a field inspection of three in-service aluminum culverts in Wisconsin to gather site environmental and aluminum culvert performance data.

- Reviewed metallurgical and chemical aspects of the specific alloys used in culvert construction and chemistry of their susceptibility to corrosion, including small pieces removed from a damaged section of a severely corroding culvert in the field inspection.

- Performed additional literature review related specifically to the corrosion mechanisms observed in the field inspection and in North-Central Region aluminum culvert inspections, and the process behind those mechanisms specific to a buried culvert environment.

- Prepared this research report and training slides to summarize information from the above tasks.

1.4 Organization of Report

This report is organized into seven chapters including this introduction, with the remaining six chapters addressing the points identified in the bullets above. Subsequent chapters include the following:

- Chapter 2: Literature review of existing WisDOT policy; previous research reports on aluminum culvert performance in Wisconsin and environmental conditions for culverts in Wisconsin; aluminum material information including material and product standards, alloy designations, and material durability considerations; US federal policies for aluminum culverts; state DOT policies for aluminum culverts; aluminum culvert manufacturer literature; and research reports on buried aluminum structures.

- Chapter 3: Aluminum culvert stakeholder survey and survey responses from five aluminum culvert manufacturer respondents and nine DOT respondents.

- Chapter 4: Aluminum culvert inventory and inspection data from the WisDOT HSIS database, WisDOT North-Central District small diameter aluminum culvert inspection data, and FHWA LTBP database.

- Chapter 5: Information on field inspection of three aluminum culverts in Wisconsin selected from the HSIS database and North-Central District inspection data, including inspection plan, demographic information on culverts inspected, and results of the inspection including field and laboratory test results.

- Chapter 6: Discussion, synthesizing information from a variety of sources in the first five chapters into broad headings regarding aluminum culvert use, specification, and historical performance; corrosion mechanisms and mitigation; best practices; expected performance in Wisconsin, and potential policy updates for WisDOT.

- Chapter 7: Conclusions, which presents conclusions and recommendations from the topics reviewed in the discussion.

2. LITERATURE REVIEW

The following sections summarize our extensive literature review. Appendix A provides the complete set of notes collected during the review.

2.1 Existing Wisconsin DOT Policy for Use of Aluminum as a Culvert Material

Existing WisDOT policy for use of aluminum box culverts is identified in the WisDOT Bridge Manual, Chapter 36 [*1*], which identifies aluminum box culverts as not permitted by the Bureau of Structures.

The WisDOT Facilities Development Manual (FDM) [*2*] provides policy, procedural requirements, and guidance for the development of transportation facilities in Wisconsin, including culverts and pipes. The FDM states that pipe materials for culverts are to be selected based on traffic volume and fill height, with considerations given to special situations. Corrugated aluminum pipe is allowed where ADT is < 1,500 with an allowable size of 42 to 84 in. diameters, with a note to consider for use in corrosive environments. Diameters from 12 to 36 in. can only be used in special situations, such as acidic soils/water, local preference, limited cover, extending existing culvert pipes, unusual loading from high embankments, steep gradients, or other pertinent reasons.

The FDM identifies any type of metal culvert pipe as being expected to provide at least 20 yrs of service before perforation. It identifies places on the zinc corrosion map where corrosion-resistant pipe should be used, such as where the pH is outside the range of 5 to 9 and the resistivity is below 2,000 Ω-cm, or where the resistivity is less than 1,000 Ω-cm regardless of pH. Aluminum is identified as an acceptable corrosion-resistant pipe, with notification of past issues of localized corrosion of the tops and sides of several aluminum pipes likely related to the use of chlorides for snow and ice removal. This notification recommends limiting the use of aluminum pipe to side drains and highways with traffic volumes under 1,500 Design ADT unless some provision is made to insulate the upper surface of the structure from infiltrating road salt.

The FDM also identifies abrasion considerations and fill height tables for use of aluminum pipe. Fill height tables are provided for corrugated aluminum with 2 in. by 2/3 in. and 3 in. by 1 in. corrugations, aluminum alloy structural plate pipe with 9 in. by 2-1/2 in. corrugations, corrugated aluminum pipe arches with 2-2/3 in. by 1/2 in. corrugations, and aluminum alloy structural plate pipe arches with 9 in. by 2-1/2 in. corrugations. Aluminum pipe and plate are not allowed for storm sewers.

The WisDOT Standard Specifications for Highway and Structure Construction [*3*] require that corrugated aluminum pipe meet American Association of State Highway and Transportation Officials (AASHTO) M196 and aluminum structural plate meet AASHTO M219.

Review of excavation and backfill requirements showed no mention of a membrane that could be specified to protect aluminum culverts from deicing salts if included in the backfill envelope and no requirement for testing of salt content in backfill. There is also no requirement for protective coatings on aluminum culverts.

2.2 Culvert Research and Performance Reports by Robert Patenaude, Wisconsin DOT Geophysical Engineer

Robert Patenaude, WisDOT geophysical engineer, compiled reports on the performance of a variety of culverts in Wisconsin. In 1981 [*4*] he reported performance of new and replacement culverts installed between 1962 and 1965 to evaluate corrosion. The study focused on galvanized steel culverts with comparison to aluminum and concrete culverts. Aluminum culverts appeared to be performing well, based on visual internal inspection, at sites that were highly corrosive to steel.

In 1988 [*5*] Patenaude reported on the in-service performance of 44 culverts in Wisconsin with installation dates between 1962 and 1981. The culvert materials included galvanized steel, aluminum, aluminized steel, epoxy bonded steel, and polymeric coated steel. Three of seventeen aluminum pipes had evidence of pitting or loss of surface cladding, but no pitting or perforation of the core alloy. For aluminum culverts, the least evidence of corrosion came at sites with flowing water; the few sites with pitting of cladding were occasionally dry, and the pitting may have been from a reaction between the cladding and soil. At two sites that had both corrugated steel and aluminum pipes, the aluminum pipes showed less corrosion than the galvanized steel pipes.

In 1993 [*6*], Patenaude issued a memo to WisDOT District Engineers following the collapse of a 24 in. corrugated aluminum culvert pipe in May of 1993 on State Highway 54 in southern Wood County, approximately in the center of the state. The culvert was made of Kaiser 14 ga aluminum alloy 3004 and was installed in 1969. The culvert had about 1 ft of cover, including fill and pavement, and the ends appeared to be in good condition. The collapse was due to mid-length corrosion perforations and greatly reduced thickness. The corroded area was covered with a white corrosion product.

Following the collapse in 1993, WisDOT inspected additional aluminum structures in the area (State Highways 54 and 82), with focus on the mid-length crowns of the structures. Some structures were found to have severe deterioration. Two 8 ga Kaiser alloy 5052, 7 by 12 ft aluminum plate arches on State Highway 54, near the failed pipe, were found to have local perforations up to 2 in. across at the crown near mid-length, with white oxidation running down the wall interior. The structures were installed in 1969 with about 18 in. of cover. A sample removed from one of the arches and examined under scanning electron microscope showed evidence of heavy metal ions, such as copper and iron, plus chloride ions. Soil samples taken from the backfill above the aluminum plate arch were found to be slightly alkaline and to have chloride concentrations between 148.5 and 274.5 ppm. Natural soil in Wisconsin that is not exposed to fertilizer, road salt, or other sources of chlorides generally has a chloride ion concentration between 10 and 20 ppm.

Of ten aluminum drainage structures examined on State Highway 82 west of Mauston in southwestern Juneau County, nine were in an advanced state of deterioration at the crown, particularly near the center of the pavement. There were typically perforations with white precipitate found (Figure 1). These structures were covered with cracked flexible pavement and were at a range of soil cover depths. Based on the wide geographic distribution of aluminum culvert sites exhibiting corrosion, composition of soil was not considered to be strongly correlated to corrosion. Having the inverts of the structures below the flow lines of many pipes indicated that the corrosion was not related to chemistry of the water flowing through the pipes. Conclusions from review of the ten structures included that the corrosion was more severe on more heavily traveled and heavily salted roads and that the corrosion correlated well with extensive pavement cracking. Soil cover height and soil type did not correlate well with corrosion. The report noted that collapse of the top of a structure may be potentially more serious than collapse of the invert. Based on the findings, the report recommended that use of aluminum culverts be restricted on heavily salted roads unless the installation included protection for the outer surface of the structures from road salt.

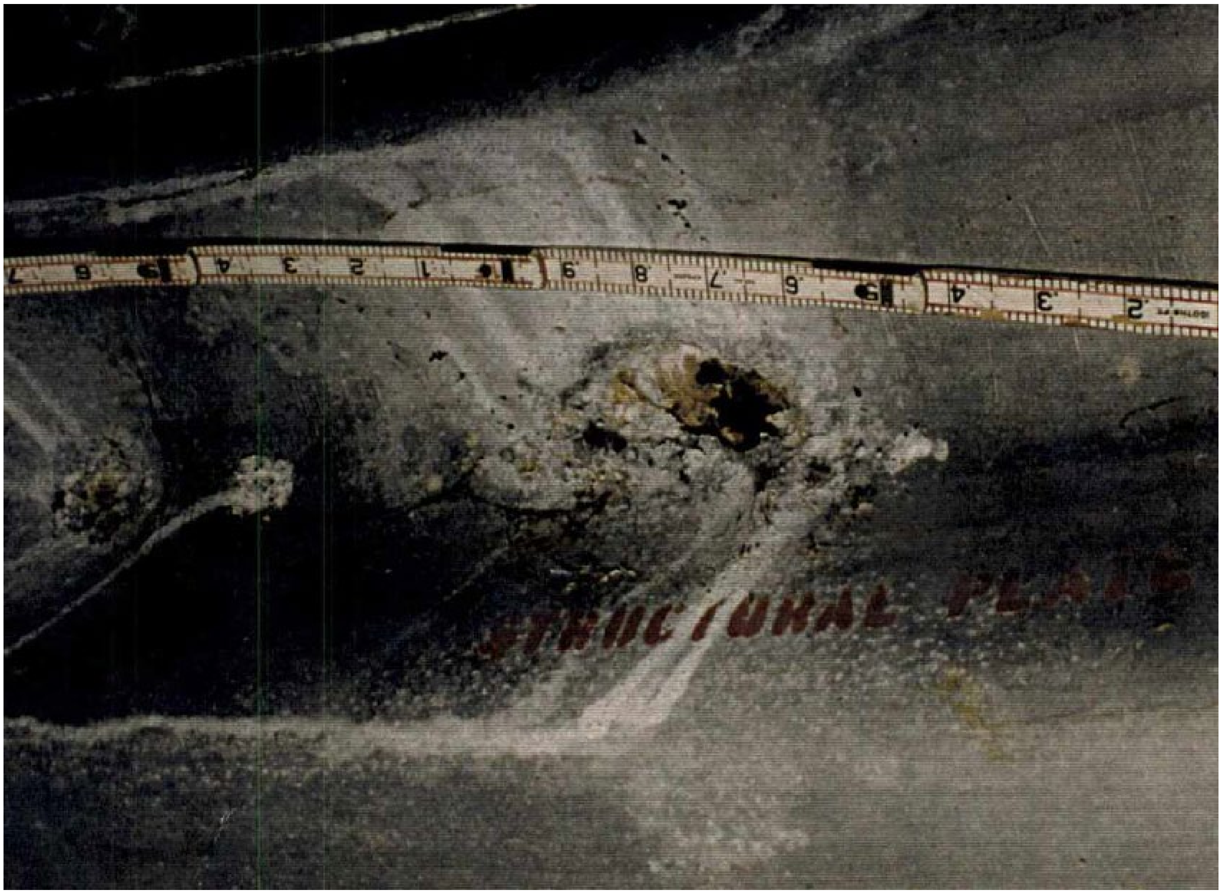

Figure 1 – Aluminum Structural Plate Culvert Installed in 1969 with 2 In. Perforation from Corrosion Observed in 1993 (Reproduced from [*6*])

In 2003 [*7*], Patenaude reported on the ongoing experimental culvert installations from his previous reports. The culvert installations were in Juneau and Wood counties and included polymeric coated steel galvanized pipes, epoxy bonded steel pipes, aluminized steel pipes, and aluminum pipes. Of the four pipe types, Patenaude noted that aluminum pipes exhibited the most severe distress and corrosion, with several having thinning, perforation, and failures at the crown, likely from the presence of chemical road deicers; the aluminum pipes, however, appeared immune to corrosion in the natural environment away from roadways. He noted that aluminum culverts with protective coatings over the tops were being installed in Wisconsin, but their locations were not noted in the report. The white precipitate forming on one of the aluminum culverts was examined and found to be aluminum oxide, suggesting the road salt may act as a catalyst and increase the electrical conductivity of the soil adjacent to the pipe.

2.3 Typical Soil Conditions and Chemistry in Wisconsin

Figure 2 indicates that the pH of soil in Wisconsin generally ranges from extremely acidic (pH < 4.5 at isolated locations in the west-central part of the state) to slightly alkaline

(7.4 < pH < 7.9) in the eastern third of the state. Most of the state is moderately to slightly acidic (5.6 < pH < 6.6).

Patenaude [*6*] noted that natural soil in Wisconsin not exposed to fertilizer, road salt, or other sources of chlorides generally has a chloride ion concentration between 10 and 20 ppm.

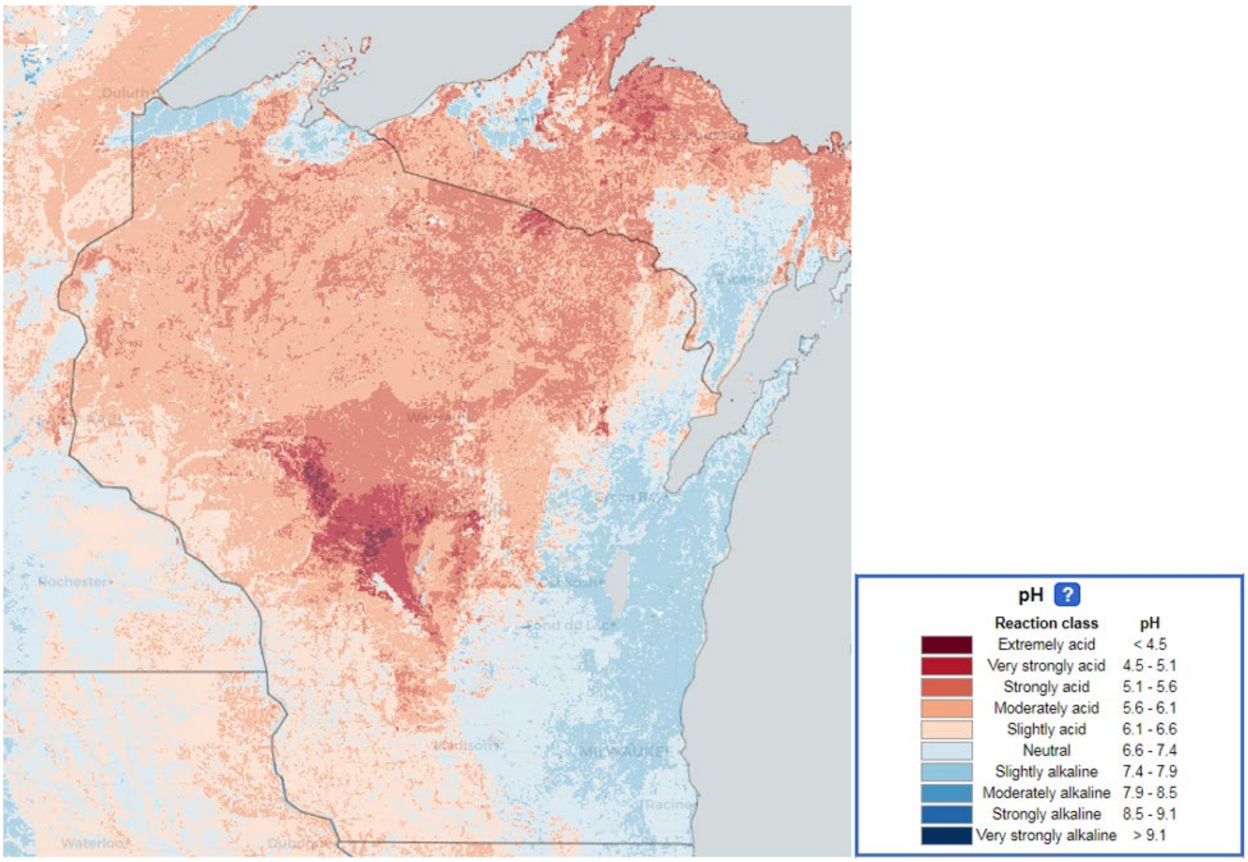

Figure 2 – Wisconsin Soil pH (Reproduced from [*8*])

2.4 Usage of Deicing Chemicals on Wisconsin Highways

WHRP Project 0092-17-03 [*9*], [*10*], [*11*] was focused on the effect of chemical deicers on concrete durability. Research findings and interviews with the project Principal Investigator, Dr. Xiao, provided valuable information related to deicer types and usage in Wisconsin. The project included a survey of nine cities and forty-four counties in Wisconsin related to their use of deicing chemicals and winter operations. Fifty respondents use sodium chloride deicing and forty-four use it for anti-icing, followed by calcium chloride (ten for deicing and four for anti-icing), and Beet 55 beet juice (nine for deicing, six for anti-icing). Available but less used chemicals include magnesium chloride, potassium acetate, standard beet juice, and proprietary products GeoMelt, FreezeGuard, AMP, IceBan M80, M90, ThawRox, M95, and SuperBlend. Based on examination of proprietary product safety data sheets (SDS) as reported in Appendix D of [*11*], most of these products contain chloride-based salts. Those that do not, such as sugar beet juice, which forms the primary component of products like Beet 55 and GeoMelt, are typically used as additives to traditional rock salt-based deicers and brines. This reduces the concentration of chlorides but does not eliminate chlorides from being present and applied to roadways when these products are used.

When asked what factors lead to a jurisdiction's choice in deicing chemical, respondents rated the material's effectiveness as the top factor (thirty respondents) followed by precipitation from weather forecast, temperature from weather forecast, cost, availability, environmental concerns, wind speed from weather forecasts, and other unique factors. When asked if specific distresses associated with roads can be attributed to application of deicing and/or anti-icing materials, eleven respondents reported issues with bridge joints and/or bridge decks, and one of those eleven respondents noted premature degradation of storm drain piping. It does not appear that maintenance concerns and durability of structures influence any jurisdiction's material selection choices.

Winter storm maintenance is performed by counties for state routes and interstates. WisDOT has two winter maintenance tracking database systems available including Storm Report and Automatic Vehicle Location (AVL). Counties are not required to enter data into the databases, though many do. Information is manually entered into the Storm Report database. Storm Report includes 89,050 records, ranging from 1998 to 2017. Data includes snow depth, total amount of deicers used in a county, time of a storm and the crew operation, and deicer types (salt, salt brine, $CaCl_2$, $MgCl_2$, sand, prewetting, anti-icing, and others).

For the AVL database, information is automatically populated from AVL/GPS sensors. Data ranges from 2010 to 2017, but only includes 55% of the state highway system. In 2017, there were 6,239 total records in the AVL database with data including the quantities of deicers used in a winter operation segment (typically tons/lane-mile/year). Deicer types are entered as liquid $CaCl_2$, salt, brine, sand, or left unspecified.

Application rates of the products for a particular storm event are highly variable depending on weather conditions but do meet Wisconsin DOT Winter Maintenance Guidelines. Rates for deicing in a single storm event are typically in the 200 to 400 lbs per lane-mile range, although usage varies from 50 to 600 lbs per lane-mile. The typical application rate for anti-icing is between 20 and 50 gal per lane-mile per event. Cumulatively, each lane mile of roadway received an average of 13.78 tons of sodium chloride, 0.31 tons of calcium chloride, and 0.16 tons of magnesium chloride each winter according to Storm Report. According to the AVL database, cumulative totals for rock salt were 9.9 tons and 39.3 gal of salt brine. Figures in Chapter 4 of the project final report [*11*] do not show trends that would indicate increased deicer usage in major cities or areas that would be expected to have increased traffic over more rural portions of the state.

Traditionally, rock salt (sodium chloride) has been the primary deicing chemical used on Wisconsin roadways. Dr. Xiao noted that two recent changes to deicer usage in Wisconsin include 1) usage of a variety of new chemicals, including calcium chloride, magnesium chloride, and beet juice, and 2) the introduction of anti-icing. Anti-icing operations apply high-concentration liquid solutions of deicers to dry pavement ahead of winter weather events. Application of anti-icing solutions can be much more detrimental to structures below since the wet solution is applied to dry pavement before precipitation, rather than to wet, potentially saturated surfaces after precipitation starts.

During the winter of 2016 to 2017, Dr. Xiao reported that WisDOT used 526,199 tons of salt, 2,783,720 gal of salt brine for pre-wetting, and 1,865,565 gallons of salt brine for anti-icing on 34,620 lane-miles of roadways. For that winter, salt use was 32% higher than the previous year and sand use was 38% less than the average of the five previous winters. Of the seventy-two counties in Wisconsin, sixty-six were equipped to perform anti-icing operations.

Per Figure 3, salt usage has remained steady over the last two decades and brine usage has increased by several (two to three) orders of magnitude. Liquid brine materials, including salt brine, $CaCl_2$, Freeze Guard ($MgCl_2$), and Beet 55 beet juice, account for more than 98% of brine usage. Salt brine accounts for between 92% and 95% of usage depending on whether usage is for prewetting salt or sand or for anti-icing. Review of product information for Beet 55 and other potentially noncorrosive products identifies them as typically being used as additives to existing chloride-based deicers.

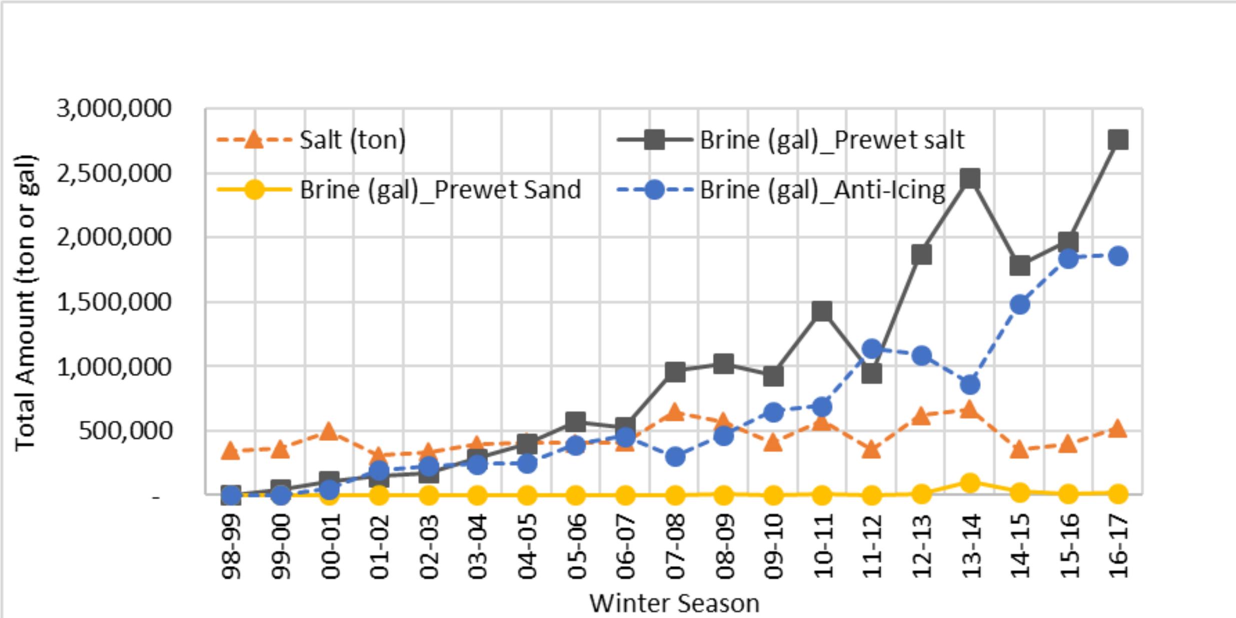

Figure 3 – Salt and Brine Application to Wisconsin Roadways (Reproduced from [*9*])

2.5 Aluminum Material Information – Material and Product Standards, Alloy Designations, Material Durability

2.5.1 Overview of Aluminum and Aluminum Alloy Materials for Culvert Applications

The Aluminum Association [*12*] identifies aluminum as the most abundant metal in the earth's crust. Aluminum ore, typically bauxite, which is the most prevalent source of aluminum, is generally mined from topsoil in many tropical and subtropical regions of the world. The ore is chemically processed to produce alumina (aluminum oxide). Alumina is then smelted using an electrolysis process to produce pure aluminum metal.

Aluminum alloys are identified as chemical compositions where other elements are added to molten aluminum to enhance properties such as strength, density, workability, electrical conductivity, and corrosion resistance. Other elements include iron, silicon, copper, magnesium, manganese, and zinc, which can be combined and can make up as much as 15% of the alloy by weight. Alloys are designated by series, where the first digit identifies the principal alloying element and the other three digits identify secondary alloys.

Typical alloys used for aluminum pipe and culvert materials include alloy 3004 (core alloy in corrugated aluminum pipe that comprises 90% of the thickness) clad with alloy 7072 (cladding over alloy 3004 in corrugated pipe, about 5% of overall thickness on the inner and on the outer surfaces) for aluminum pipe, and alloy 5052 (unclad) for aluminum structural plate. Table 1 identifies the eight series of aluminum alloys, their primary alloying elements, general attributes, and typical uses.

Table 1 – Series of Aluminum Alloys

Series	Primary Alloying Elements	Heat Treatable?	Attributes	Typical Uses and/or Other Comments
1XXX	None; ≥ 99% pure Al	N/A	Corrosion resistant, workable, high thermal and electrical conductivity	Power grid transmission lines; 1350 is used in electrical applications; 1100 is used for food packaging
2XXX	Copper	Yes	High strength and toughness, not as atmospherically corrosion resistant as other alloys	Typically painted or clad with other alloys such as 6XXX series for atmospheric exposure corrosion resistance; 2024 is widely used in aircraft
3XXX	Manganese	No	3003 is popular as a general-purpose alloy with moderate strength and good workability	Only a small percentage of manganese can be effectively added to Al; magnesium is often also added; 3003 is used in heat exchangers and cooking utensils; 3004 and its modifications are used in beverage cans
4XXX	Silicon	No	Silicon is added to lower the melting point without producing brittleness	4XXX series typically used in welding wire and brazing alloys; 4043 is widely used for welding 6XXX series alloys for structural and automotive applications
5XXX	Magnesium	No	Moderate to high strength, good weldability, and resistance to corrosion in the marine environment	Building and construction; storage tanks; pressure vessels; marine applications; 5052 is used in electronics; 5083 in marine applications; anodized 5005 sheet in architectural applications; 5182 for the aluminum beverage can lid
6XXX	Silicon and Magnesium	Yes	Highly formable, weldable, moderately high strength, excellent corrosion resistance	Architectural and structural applications; 6061 is used for truck and marine frames; iPhone 6 was made from this series
7XXX	Zinc	Yes with Magnesium	Very high strength if it includes magnesium, which allows for heat treating	Other elements such as copper and chromium may be added in small quantities; 7050 and 7075 are widely used in aircraft; Apple Watch was 7XXX
8XXX	Others	N/A	N/A	N/A

The “International Designation System for Wrought Aluminum and Wrought Aluminum Alloys,” [*13*], commonly referred to as the “Teal Sheets,” contains an international register of aluminum alloys and their composition. Chemical compositions for the three primary aluminum alloys used in aluminum culvert manufacturing are reproduced in Table 2.

Table 2 – Aluminum Alloy Compositions for the Three Primary Alloys Used for Culverts (Reproduced from [*13*])

Element	Alloy Designation and % Composition by Weight[(1)]		
	3004	**5052**	**7072**
Silicon (Si)	0.30	0.25	-
Iron (Fe)	0.7	0.40	-
Copper (Cu)	0.25	0.10	0.10
Manganese (Mn)	1.0 – 1.5	0.10	0.10
Magnesium (Mg)	0.8 – 1.3	2.2 – 2.8	0.10
Chromium (Cr)	-	0.15 – 0.35	-
Zinc (Zn)	0.25	0.10	0.8 – 1.3
Total Silicon and Iron (Si+Fe)	-	-	0.7
Others – Each, Maximum	0.05	0.05	0.5
Others – Total	0.15	0.15	0.15

1. Compositions given are a % maximum by weight unless shown as a range.

Aluminum alloys 3004, 5052, and 7072 were all first registered in the Teal Sheets with the above compositions in 1954.

ASTM B209-14 – Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate [*14*] provides requirements for aluminum and aluminum alloy sheet and plate, including mechanical properties. For clad 3004 aluminum alloy, depending on the temper, the range of mechanical properties includes 0.2% offset yield strength ranging from 8.0 to 27.0 ksi, tensile strength ranging from 21.0 to 40.0 ksi, and minimum elongation ranging from 1% to 16%. For aluminum alloy 5052, the range of 0.2% offset yield strength is from 9.5 to 32.0 ksi, with a tensile strength ranging from 25.0 to 44.0 ksi and 2% to 20% minimum elongation.

2.5.2 Aluminum Durability – Abrasion

In 2007, DeCou and Davies prepared a final report [*15*] for the California Department of Transportation (Caltrans) in coordination with the FHWA following a 5 yr study of abrasion of various culvert materials in service. The focus was on providing adequate information on abrasion performance for current (as of 2000 to 2007) pipe and pipe lining materials to help maintain, rehabilitate, and replace existing culverts and on providing guidance for new culvert material selection at potentially abrasive sites. The research resulted in defining different levels of abrasion, preliminary estimates of abrasion potential for material selection, predicted wear rates for each abrasion level, and recommendations for allowable culvert and lining materials in abrasive environments. The research was adopted by Caltrans and has been put into action through inclusion in the Caltrans Highway Design Manual [*16*].

The Caltrans Highway Design Manual defines abrasion as the wearing away of pipe material by water carrying sands, gravels, and rocks (bed load), which is dependent upon the size, shape, hardness, and volume of the bed load in conjunction with the volume, velocity, duration, and frequency of stream flow in the culvert. To evaluate a culvert site for abrasion, sampling of streambed materials is generally not necessary, but visual examination and documentation of the size, shape, and volume of abrasive materials in the streambed and estimation of the average stream slope will provide the designer data needed to determine the expected level of abrasion. Caltrans provides a table identifying six abrasion levels, reproduced here as Table 3 with notes particular to aluminum culvert use or restriction for each abrasion level.

Table 3 – Abrasion Levels Based on Bed Load and Flow Characteristics Related to Aluminum Culvert Use (Adapted from [*16*])

Level	Bed Load Description	Flow Velocity(1)	Notes Related to Aluminum Culvert Use
1	Bed loads of silts and clays or clear water with virtually no abrasive bed load.	No velocity limitation.	All standard pipe materials allowed; no abrasive-resistant protective coatings needed for metal pipe.
2	Moderate bed loads of sand or gravel.	1 to 5 ft/sec(2)	Generally no restriction. Polymeric or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential.
3	Moderate bed load volumes of sands, gravels, and small cobbles.	> 5 to 8 ft/sec(2)	Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential.
4	Moderate bed load volumes of angular sands, gravels, and/or small cobbles/rocks.(3)	> 8 to 12 ft/sec	Aluminum pipe not recommended. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
5	Moderate bed load volumes of angular sands and gravel or rock.(3)	> 12 to 15 ft/sec	Aluminum pipe not allowed. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
6a	Moderate bed load volumes of angular sands and gravel or rock.(3)	> 15 to 20 ft/sec	Aluminum pipe not allowed. Abrasion-resistant coatings over steel pipe are not expected to provide acceptable service life. Lining alternatives include specific polymeric liners or cementitious liners/invert pavement with conditions. For new/replacement structures, consider "bottomless" structures.
6b	Heavy bed load volumes of angular sands and gravel or rock.(3)	> 12 ft/sec	

1. Flow velocity ranges in this table should be compared to those generated by a 2 to 5 yr return frequency flood or storm.
2. If bed load volumes are minimal, a 50% increase in velocity is permitted.
3. For minor bed load volumes, use Level 3.

Abrasion flow rate design guidance is found in the AASHTO Highway Drainage Guidelines [*17*] and includes a recommendation to use the velocity generated from a 2 to 5 yr event when considering velocity effects.

The Caltrans Highway Design Manual [*16*] also references flow velocities based on those generated in a 2 to 5 yr return frequency flood. It notes that corrugated metal structural plate pipe and arches provide a viable option for pipes or arches with equivalent diameter of 60 in. or larger in abrasive environments because the thickness of the invert plates can be easily increased without having to increase the thickness in the rest of the barrel. Pipe arches, which have a relatively larger invert area than circular pipe, generally will provide a lower abrasion potential due to bed load being less concentrated.

Caltrans also notes that under similar conditions, aluminum culverts will abrade 1.5 to 3 times faster than steel culverts; therefore, aluminum culverts are not recommended where abrasive materials are present and where flow velocities would encourage abrasion to occur. Culvert flow velocities that frequently exceed 5 ft/sec where abrasive materials are present should be carefully evaluated prior to use of aluminum.

Caltrans Highway Design Manual Table 855.2B provides velocities and flow depths necessary to move various bed materials, and is reproduced here as Table 4.

Table 4 – Bed Materials Moved by Various Flow Depths and Velocities (Reproduced from [*16*])

Bed Material	Grain Dimensions (in.)	Approximate Nonscour Velocities(1) (ft/sec)			
		Mean Depth(2) (ft)			
		1.3 ft	3.3 ft	6.6 ft	9.8 ft
Boulders	> 10	15.1	16.7	19.0	20.3
Large Cobbles	10 – 5	11.8	13.4	15.4	16.4
Small Cobbles	5 – 2.5	7.5	8.9	10.2	11.2
Very Coarse Gravel	2.5 – 1.25	5.2	6.2	7.2	8.2
Coarse Gravel	1.25 – 0.63	4.1	4.7	5.4	6.1
Medium Gravel	0.63 – 0.31	3.3	3.7	4.1	4.6
Fine Gravel	0.31 – 0.16	2.6	3.0	3.3	3.8
Very Fine Gravel	0.16 – 0.079	2.2	2.5	2.8	3.1
Very Coarse Sand	0.079 – 0.039	1.8	2.1	2.4	2.7
Coarse Sand	0.039 – 0.020	1.5	1.8	2.1	2.3
Medium Sand	0.020 – 0.010	1.2	1.5	1.8	2.0
Fine Sand	0.010 – 0.005	0.98	1.3	1.6	1.8
Compact Cohesive Soils					
Heavy Sandy Loam		3.3	3.9	4.6	4.9
Light		3.1	3.9	4.6	4.9
Loess Soils in the Conditions of Finished Settlement		2.6	3.3	3.9	4.3

1. Bed materials may move if velocities are higher than the nonscour velocities.
2. Mean depth is calculated by dividing the cross-sectional area of the waterway by the top width of the water surface. If the waterway can be subdivided into a main channel and an overbank area, the mean depths of the channel and the overbank should be calculated separately. For example, if the size of the moving material in the main channel is desired, the mean depth of the main channel is calculated by dividing the cross-sectional area of the main channel by the top width of the main channel.

The Caltrans Highway Design Manual abrasion levels and recommended restrictions on use of certain materials in Table 3 (above) are established with the goal of achieving a 50 yr maintenance-free service life. Caltrans allows aluminum culverts to generally be used without restriction at nonabrasive to low-abrasive sites that classify as Abrasion Level 1 or 2. For moderately abrasive sites that classify as Abrasion Level 3, there may be additional gauge thickness required to resist abrasion. Caltrans generally does not recommend aluminum for use as a culvert material at sites that classify as Abrasion Level 4, but where it is used at Abrasion Level 4 sites, they recommend an invert thickness of 0.075 to 0.164 in. where there is abrasive channel material and maximum expected flow velocities in the 8 to 12 ft/sec range. Closed invert aluminum culverts (e.g., corrugated aluminum pipe and corrugated aluminum structural plate structures, such as structural plate arch pipes) are generally not allowed at sites that classify as Abrasion Level 5 or 6 unless the structure is bottomless, such as an arch on foundations with a natural streambed.

2.5.3 Aluminum Durability – Corrosion

2.5.3.1 Corrosion in the Buried Environment

ASM International's Metals Handbook, Desk Edition [*18*] identifies aluminum as having good corrosion resistance in natural atmospheres, attributing resistance to the "very thin, compact, and adherent film of aluminum oxide on the metal surface." When a fresh surface is created, the film reforms rapidly and grows to a stable thickness. When formed in air at ambient temperatures, the film is about 5 nm thick, and it increases in the presence of water and at higher temperatures. It notes that the oxide is soluble in alkaline solutions and strong acids, while being stable over a pH range of 4.0 to 9.0.

The ASM Handbook also identifies different types of corrosion and various interactions with induced or imposed stresses and notes that the surface may become unattractive from pitting with little effect on durability or function. However, other corrosion phenomena, such as stress-corrosion-induced cracking, localized severe corrosion due to heavy metal ions in solutions, stray electrical currents, or galvanic couples with more anodic metals can be quite damaging. It notes the 3XXX alloys as generally among those having the greatest corrosion resistance and the 5XXX series alloys as the best alloys for marine environments. In a table of wrought aluminum alloys, 3004 and 5052 are both listed as having an "A" rating for general corrosion resistance and for stress corrosion cracking resistance. Alloy 7072 (used for cladding of aluminum pipes with a core of 3004 alloy) is not listed in the table.

Aluminum corrosion can be categorized into two types: general corrosion and local or pitting corrosion. General corrosion acts over the entire surface of a metal and results in widespread section loss. Local or pitting corrosion results in isolated section loss of a small area, with the perimeter of the area typically largely intact throughout most of its thickness. The ASM Handbook notes that most corrosion in service is localized.

Buried aluminum culverts can be subject to soil-side corrosion due to humidity and moisture, chemical composition of backfill, backfill compaction level, soil oxygen content, and differences in electric potential. Differences in electric potential between the culvert and soil can be gross or local. Gross differences in electric potential include the general soil mass at the site differing in electric potential compared to the culvert material. Local differences in electric potential include where a local portion of the culvert and an adjacent backfill particle or chemical, such as a chloride ion from deicing salts at a single point on the surface of the culvert, differ in electric potential.

Aluminum culverts conveying water can be subject to general corrosion throughout the wetted surface (typically the invert or bottom) of the culvert. The wetted surface (the extents of which will vary with changes in flow) can be consistently wet (such as at the invert of a pipe with constant flow) or can include the walls, which are subject to wetting and drying cycles dependent on flow. Corrosion associated with the area subject to repeated wetting and drying is referred to as waterline corrosion. Waterline corrosion and invert corrosion have been identified as occurring in corrugated steel pipes that do not have appropriate coating.

Flow-side corrosion is uncommon in aluminum culverts based on the typically self-restoring aluminum oxide protective skin and typical range of chemistry of the flow generally found at roadway culvert sites. Exceptions to this are where the environment is particularly aggressive (e.g., where the culvert is subject to mining runoff), or if the culvert is at an abrasive site, where abrasion not only wears away the aluminum but also contributes to aluminum depletion by repeatedly exposing a fresh surface to corrosion and subsequent reformation of aluminum oxide film. Vargel [*19*] identified the electromechanical mechanisms of waterline corrosion in aluminum as scattered, superficial pitting with a depth not exceeding a few tenths of a millimeter.

Industry specifications for selection of a culvert material at a given site commonly include testing pH of soil, pH of groundwater, and soil resistivity. These tests consider general or overall site conditions that contribute to general corrosion, but do not address local corrosion from mechanisms such as deicing salt on the soil-side of the structure.

Per the ASM Handbook [*18*], buried aluminum culvert corrosion mechanisms include galvanic corrosion, stray current corrosion, hydrogen embrittlement, pitting corrosion, stress-corrosion cracking, intergranular corrosion, deposition corrosion, exfoliation corrosion, filiform corrosion, and corrosion fatigue. Galvanic corrosion, stray current corrosion, and hydrogen embrittlement typically manifest as general corrosion, spread over a portion of the culvert surface. The other types of corrosion generally manifest as local corrosion, many forms of which will lead to pitting. Bacterial corrosion, which may affect other metals, is not listed as a corrosion mechanism for aluminum. Relevant types of aluminum corrosion are explored in greater detail in the following subsections.

2.5.3.2 General Corrosion

General corrosion is identified as corrosion distributed over the surface of a metal that results in an approximately uniform depletion of the metal throughout the corroding area. Aluminum has high resistance to general corrosion. For a buried aluminum culvert, galvanic corrosion would be a type of general corrosion. Vargel [*19*] notes that galvanic corrosion requires three conditions: 1) metals with different electrical potentials (one location or metal must be more electronegative than the other, with the more electronegative one acting as the anode and the other as the cathode), 2) an electrolyte, and 3) electrical connectivity.

Gabriel [*20*] notes that oxygen-starved or -concentrated locations create sites along the culvert with different electrical potential. Areas with greater access to oxygen become cathodic, and the oxygen-starved areas become anodic. Pipes are usually placed on compacted or undisturbed soil at the bottom of a trench (the trench may be in native soil or previously formed embankment). Backfill materials are typically more permeable than surrounding soils, which provides a less resistive pathway to the top of the structure, making the surface more accessible to diffused oxygen. The portion of a culvert under pavement usually has less access to oxygen than other parts of the culvert, such as under unpaved shoulders. The electrolyte can be soil moisture or groundwater. The conductor can be the metal culvert. Corrosion would be accelerated where moist soil contains chloride ions. In this situation, the most aggressive corrosion will occur near the pavement edges, where there is a high gradient between soil-side oxygen concentrations coupled with likely increased chloride content from ingress through shoulders or adjacent embankment. This process is illustrated in Figure 4.

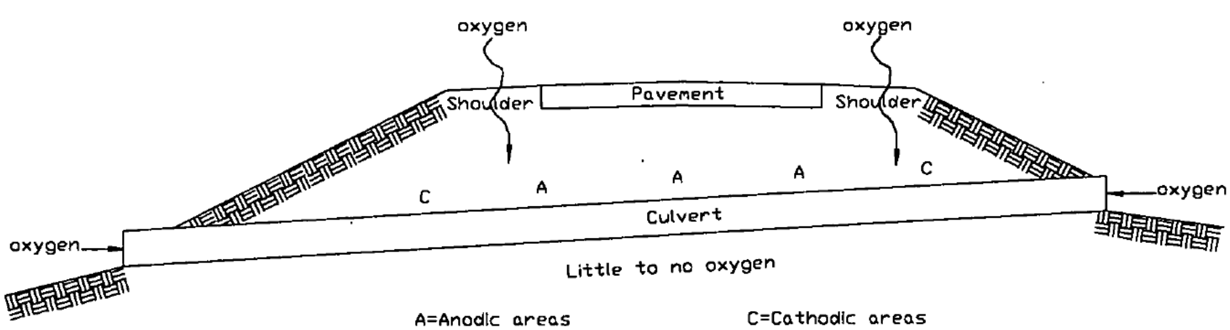

Figure 4 – Oxidation Corrosion Cells in a Buried Metallic Culvert (Reproduced from Figure 1 of [*20*])

Regarding galvanic corrosion of aluminum, the ASM Handbook [*18*] notes that aluminum may be corroded in an area of anodic reaction in proportion to a current when an electric current is conducted from aluminum to an environment such as water, soil, or concrete. However, general current densities in the ground are typically low, even in the case of stray currents, and at low current densities, the corrosion typically manifests in the form of pitting. In soil, this can occur where aluminum is close to other buried metal systems protected by impressed current cathodic protection systems, where ground current can leak onto a buried aluminum structure at one point, then off at another point (where the corrosion occurs) through a low-resistance path between the aluminum structure and the structure being protected. The handbook identifies common bonding (isolation) of all nearby buried metal systems as the usual way to avoid such attack.

NACE SP0169-2013, "Standard Practice – Control of External Corrosion on Underground or Submerged Metallic Piping Systems," [*21*] notes that aluminum can experience corrosion in alkaline (pH > 8.5) or acidic (pH < 4) environments. Melchers [*22*] states that when aluminum alloys corrode, it will usually be by pitting rather than by uniform corrosion.

2.5.3.3 Pitting Corrosion

The ASM Handbook [*18*] notes that pitting is the most common form of localized corrosion, but it is difficult to associate with specific metallographic features. The Handbook notes that 5XXX series alloys have the lowest pitting probabilities among commercial alloys, followed by 3XXX series.

Melchers [*22*] identifies the following steps for pitting corrosion in aluminum: 1) aluminum oxide forms in a moist environment, 2) highly acidic aluminum-chloride byproducts form, 3) corrosion topography becomes nonuniform and nonhomogeneous, 4) an oxygen reduction reaction occurs, releasing gaseous hydrogen, and 5) extremely local cathodic cells form. Melchers and the ASM Handbook identify the rate of aluminum corrosion as generally decreasing with time. Melchers identified a maximum pit depth for aluminum alloy 5052 of about 0.022 in. for 20 yrs of exposure in a marine environment, giving an average pit growth rate of 0.0011 in./yr, though much of this growth occurred in the first 5 yrs. A study described in the ASM Handbook included exposure for up to 30 yrs in industrial or seacoast environments, with weight loss, pit depth, and strength all showing a decrease and leveling off with time. Alloy 3004 specimens were included in the study. The ASM Handbook notes that the maximum pit depth observed with time has a decreasing rate that may follow an approximate cube-root law, meaning a doubling of thickness results in an increase in time to perforation by a factor of eight.

Szklarska-Smialowska [*23*] provides significant detail, summarized in the following paragraphs, on pitting corrosion of buried aluminum based on 60 yrs of studies. Much of the information presented in [*23*] is confirmed by Vargel [*19*]. Szklarska-Smialowska notes aluminum alloys can be subject to pitting in the right environment and with the right electrical potential. Pitting corrosion takes place almost exclusively on metals that are in the passive state and possess good resistance to general corrosion. Addition of magnesium, manganese, or silicon to aluminum does not affect the pitting potential in synthetic seawater. Addition of tin and zinc decreases the pitting potential in a sodium chloride solution. The primary alloying elements of 3XXX, 5XXX, and 7XXX aluminum culvert alloys are manganese, magnesium, and zinc.

Pit growth on pure aluminum in aqueous 0.1M NaCl + 0.3M $NaNO_3$ solution is shown in Figure 5. The ASM Handbook [*18*] notes that components of natural waters that increase likelihood of pitting in aluminum include copper ions, bicarbonate, chloride, sulfate, and oxygen.

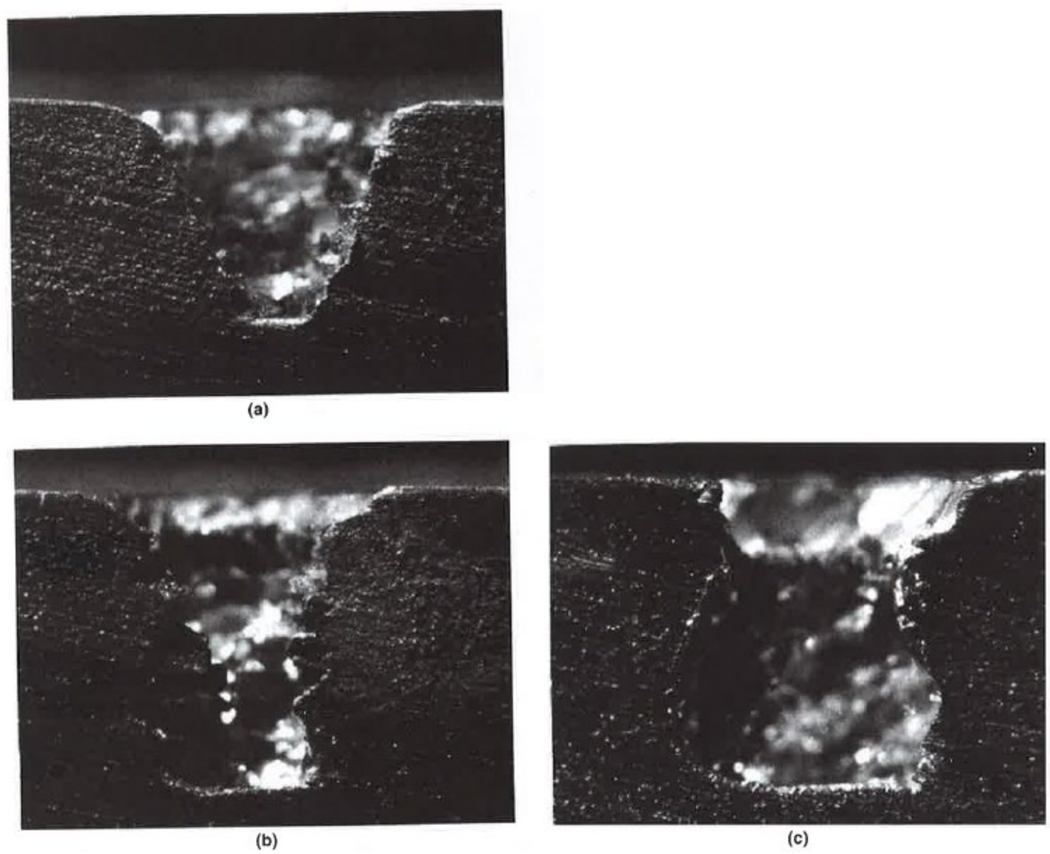

Figure 5 – Pit Growth in Pure Aluminum Subject to NaCl and $NaNO_3$ Solution and Constant Voltage Potential of 0.8 V from a Saturated Calomel Electrode after 2 Hrs, 4 Hrs, and 6 Hrs of Exposure (Reproduced from Figure 3.11 of [*23*])

Szklarska-Smialowska [*23*] identified mechanisms that lead to aluminum corrosion pit development in the presence of salts. Analysis of the pit's content showed very concentrated chlorides of dissolved metal cations and pH as low as 1. A salt film also was found at the bottom of the pits, and the pits are usually covered by a remnant of the protective aluminum oxide passive film that helps to maintain a concentrated aggressive environment. Stable pit growth depends on 1) alloy composition, 2) the composition and the concentration of the solution within the pit, 3) the presence of salt at the pit bottom, 4) the concentration of aggressive and nonaggressive substances in the bulk solution outside the pit, and 5) temperature.

Vargel [*19*] notes that it has long been known that pitting corrosion of aluminum develops in the presence of chlorides. Szklarska-Smialowska [*23*] identifies the first step in pitting corrosion as the adsorption of chloride anions on the passive film. In general, adsorption is the adhesion of an extremely thin layer of molecules to a surface; in this case, a thin film of chloride ions dries and adheres to the aluminum (or aluminum oxide) surface. Research suggest that there is no threshold for the chloride concentration below which pitting will not occur and that the presence of an inhibitor will delay but not prevent the onset of pitting. In Section 9.4, Aluminum, Szklarska-Smialowska [*23*] presents information related particularly to the interaction of chloride ions with the aluminum oxide passive film. Szklarska-Smialowska [*23*] noted a study by Maitra and Verink that identified chloride uptake by polarized aluminum in 0.1M NaCl solution with polarization potential below the pitting potential. The study reported that the amount of chloride increased with increasing polarization time and that chloride was present in the oxide film, with greater concentration at the oxide surface and no evidence of chloride at the oxide/base metal interface. This shows that the chloride appeared from the outside surface, making its way through the oxide film. Szklarska-Smialowska [*23*] identified other research by Natishan et al. that found chloride ions present in the passive film of pure aluminum at potentials below the pitting potential.

Szklarska-Smialowska [*23*] noted that pitting occurs when halogen ions (mainly Cl^-) are in contact with a passive metal. When exposed to water, a dissociative adsorption of water on the oxide film occurs and leads to the formation of a hydrolated surface layer. The concentration of OH^- on the surface equals that of H^+ at a pH of zero charge. The adsorption of Cl^- does not occur if the pH is greater than the pH of zero charge; however, if the pH is less than the pH of zero charge, Cl^- and other negatively charged anions can be adsorbed. The pH of zero charge for aluminum oxide is 9.1. Szklarska-Smialowska [*23*] identified a study by Yu et al. that identified the ingress of chloride into aluminum prior to pitting corrosion on samples of 99.9995% pure aluminum in 0.1M NaCl solution at different potentials below the pitting potential. Chloride was found to be present as an adsorbed species at the surface and as an incorporated species within the film. This evaluation concludes that chloride migrated from the solution/aluminum oxide interface into the passive film prior to pit initiation.

The chemistry and mechanism for pitting corrosion of aluminum and its alloys are best displayed in Figure B.2.2. of Vargel [*19*], reproduced here as Figure 6. While the figure shows the mechanism with an alloy that includes copper and/or iron, copper and iron are not necessary for the reaction, though, if present, they would accelerate pit growth.

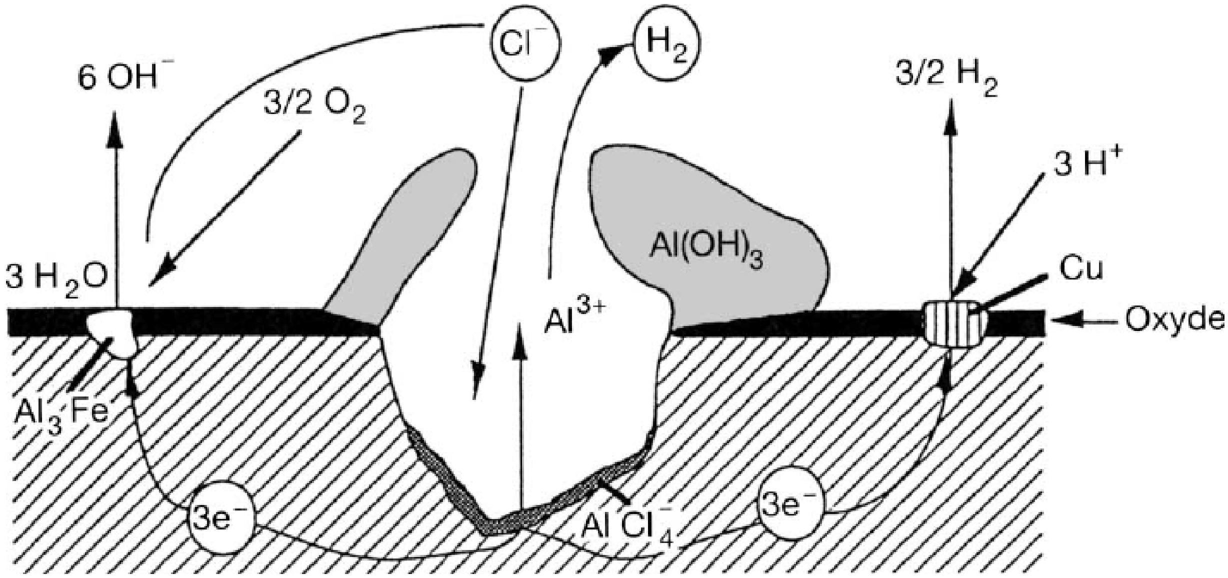

Figure 6 – Mechanism for Pitting Corrosion in Aluminum (Reproduced from Figure B.2.2 of [*19*])

Szklarska-Smialowska [*23*] notes that it is not easy to stop the growth of pits and that the main effort in preventing pitting is by protecting the metal from access by aggressive anions. Temperature plays a role in the effectiveness of corrosion inhibitors by affecting the kinetics of metal dissolution and oxide film formation and influencing the processes of adsorption and desorption. The effectiveness of an inhibitor can increase, decrease, or not change with temperature changes; however, most studies have been focused on evaluating effectiveness of inhibitors at temperatures much greater than those encountered outdoors in Wisconsin.

2.5.3.4 Stress-Induced Corrosion Cracking

Szklarska-Smialowska [*23*] identifies that stress corrosion cracking (SCC) has been observed to nucleate from corrosion pits on a variety of metals including aluminum and aluminum alloys. Multiple aluminum alloys are noted to have a reduced fatigue life in the presence of chlorides. All aluminum alloys in unstressed conditions are attacked by pitting and crevice corrosion in solutions containing chloride ions. The pits (crevices) not only damage the metals but in the presence of mechanical stresses can act as sites for the initiation of stress corrosion or fatigue cracks. Transition from pitting corrosion to SCC is a result of the formation of different surface films when the environmental conditions undergo changes. The ASM Handbook [*18*] notes that SCC occurs in humid air and is accelerated in chloride-containing environments and when the metal is under tension. Jones [*24*] notes that aluminum alloys that contain magnesium and zinc are susceptible to SCC. Magnesium and zinc, the primary alloying elements of 5XXX and 7XXX series alloys, are used for aluminum structural plate and protective cladding of corrugated aluminum pipe, respectively.

Chu et al. [*25*] investigated SCC of aluminum alloy 7075 under compressive stress and in an aqueous solution of 3.5% NaCl. Results showed that SCC could occur if the compressive displacement was larger than a critical value, noting that this critical value was greater than the value under similar tension stress. The different behavior for compression and tension suggests that under typical bending conditions, specimens will crack in tension first. Compression is the primary stress state of many buried culverts, with the inside surface at the springlines typically having the greatest compression stresses due to combined compression and bending forces at that location. Conclusions noted that the incubation period for SCC under compressive stress is ten times longer than that under tensile stress for the same stress intensity factor, and the threshold stress intensity factor to initiate SCC under compressive stress is four times that for SCC initiation under tensile stress. Therefore, aluminum under compressive stress can be subject to SCC when exposed to high-magnitude compressive stresses over a long period of time. Such an environment can be typical for a buried aluminum culvert.

2.6 Federal Policies for Aluminum Culverts

Federal policies for aluminum culverts, including requirements from the US Code of Federal Regulations, AASHTO, and FHWA related to culvert material selection, aluminum culvert material standards, service life, and coating and protection for aluminum culverts are reviewed in the following subsections.

2.6.1 Culvert Material Selection

The Code of Federal Regulations [*26*] states, “State transportation departments (State DOTs) shall have the autonomy to determine culvert and storm sewer material types to be included in the construction of a project on a Federal-aid highway.” Additional guidance for selection of culvert materials is provided in AASHTO and FHWA publications. In general, AASHTO and FHWA policies include aluminum culvert materials without detailed restrictions other than generally accepted limitations based on site soil and water chemistry, and abrasion classification.

The AASHTO Drainage Manual [*27*] notes that the selection of culvert material should consider the service life based on site-specific requirements and the total cost over the design life. Site-specific requirements include abrasion, corrosion, fill height, and replacement cost. Total design life cost is based on durability (abrasion and corrosion resistance), structural strength, hydraulic roughness, watertightness requirements, constructability and bedding conditions, initial cost, replacement cost, bedding conditions, and special conditions such as aquatic organism passages. The Manual identifies corrugated aluminum pipe and pipe arches, corrugated aluminum structural plate pipe, and corrugated aluminum structural plate structures of various shapes on a list of over a dozen common culvert shapes and materials. The AASHTO Highway Drainage Guidelines [*17*] provides similar guidance for selection of culvert materials based on service life and cost.

The FHWA Office of Federal Lands Highway Project Development and Design Manual (FLH PDDM) [*28*] notes that all suitable pipe materials, including reinforced concrete, steel, aluminum, and plastic, will be considered as alternatives for all new cross culverts and storm drain pipes and references similar service life requirements to the AASHTO Drainage Manual. The FLH PDDM recommends that soil and water samples be taken to evaluate typical pH and resistivity and that site abrasion levels be classified, similar to methods in the Caltrans Highway Design Manual [*16*].

The AASHTO Highway Drainage Guidelines [*17*] note that environmental conditions that are generally considered to contribute to corrosion of metal culvert pipe are acidic and alkaline conditions in the soil and water and the electrical conductivity of the soil. It also notes that the frequency and duration of flows transporting bed loads contribute to corrosion through causing abrasion or other damage to protective coatings. The section on culvert service life notes that saltwater causes corrosion of steel and, depending on the concentration of salt, will corrode aluminum, although it also notes that experience to date indicates aluminum culverts are fairly resistant to corrosion in such locations. The culvert service life section also notes that coated aluminum may be considered in alkaline environments or where other metals (such as iron or copper) or their salts may be present. It identifies that protection of metal culverts from corrosion is typically through bituminous fiber-bonded coating or mill-applied thermoplastic coating, while noting that some states have reported significant increases in service life with coating while others have concluded coatings are not cost effective. It notes that fiber-bonded coatings appear to give better resistance to deterioration than bituminous coating, and that mill-applied thermoplastic coatings are less subject to damage during shipping and installation, typically have fewer flaws, and are generally superior to bituminous coatings in abrasion resistance. Section 14.4.2 is identified as a reference for more information on protective coatings.

The AASHTO Highway Drainage Guidelines [*17*] note that soil resistivity is the ability of a soil to conduct electrical current and that it is affected by the nature and concentration of dissolved salts, temperature, moisture content, compactness, and presence of inert materials such as stones and gravel. The greater the resistivity of the soil, the less capable the soil is of conducting electrical current and the lower the corrosion potential. Resistivity values of about 5,000 Ω-cm offer limited potential for corrosion. Resistivities between 1,000 and 3,000 Ω-cm will usually require some level of pipe protection from corrosion depending on the accompanying pH level. If $pH < 5$, protection may be necessary; however, if $pH > 6.5$, enhanced pipe protection may not be needed. Typical resistivity values for common soils and liquids include 25 Ω-cm for seawater, 750 to 2,000 Ω-cm for clays, and 3,000 to 10,000 Ω-cm for loams. Granular soils can have resistivities much higher than loams.

The AASHTO Highway Drainage Guidelines [*17*] note that aluminum pipe can provide higher corrosion resistance than galvanized steel pipe when installed within acceptable pH and soil resistivity ranges, typically 4.0 to 9.0 and > 500 Ω-cm. It is therefore possible to use aluminum pipe in lieu of a thicker-walled galvanized steel pipe. It notes that aluminum is softer than steel and is thus more susceptible to abrasion. Use of aluminum should be carefully evaluated for 2 to 5 yr storm flow velocities greater than 15 ft/sec when carrying an abrasive bed load (Caltrans does not recommend aluminum pipe for potentially abrasive sites with flows greater than 8 ft/sec [*16*]). The AASHTO Guidelines note that dissolved salts containing chloride ions can be present in soil or water surrounding a culvert and may also be a concern in coastal locations or near brackish water sources.

The FLH PDDM [*28*] identifies the minimum wall thickness for aluminum alloy pipe in fill height tables based on minimum service life of 50 yrs with site pH between 4 and 9 and resistivity greater than 500 Ω-cm. Aluminum pipe can be used in salt and brackish environments when embedded in granular, free-draining materials. At abrasive sites, the aluminum pipe wall thickness is increased by one standard metal thickness or invert protection is provided.

2.6.2 Aluminum Culvert Material Standards

The FLH Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FLH Standard Specs) [*29*] require that aluminum alloy corrugated pipe conform to AASHTO M 196, that spiral rib pipe conform to AASHTO M 196 Types IR or IIR, and that aluminum alloy structural plate and fasteners conform to AASHTO M 219.

The AASHTO Highway Drainage Guidelines [*17*] and FLH PDDM [*28*] reference AASHTO M 196 for aluminum pipe.

AASHTO M 196 – Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains [*30*] is the product standard for corrugated aluminum pipe. Its ASTM International analog is ASTM B745. The AASHTO specification covers use in storm water drainage, underdrains, and culverts. The specification references AASHTO M 197 for the aluminum alloy sheet. The specification allows steel, stainless steel, or aluminum alloy fasteners, with the aluminum alloy bolts specified to be fabricated from alloy 6061-T4. Historic versions of M 196, dating back to 1965, specified the same aluminum alloys as the current standards. The standard makes no mention of coatings for aluminum culvert pipe.

AASHTO M 197 – Standard Specification for Aluminum Alloy Sheet for Corrugated Aluminum Pipe [*31*] is the AASHTO specification for the corrugated aluminum sheet from which corrugated pipes are produced. The ASTM analog is ASTM B744. It specifies aluminum alloy sheets or coils to conform to requirements of ASTM B209 [*14*] for alclad alloy 3004-H34 for annular pipe and alclad alloy 3004-H32 for helical pipe. The specification identifies chemical composition limits for the aluminum alloy 3004 core and aluminum alloy 7072 cladding. The specification requires that the nominal cladding thickness on each side (skin) be 5% of the total composite thickness of the sheet. The 1965 version of the standard is for corrugated aluminum alloy pipe underdrains, which is a specific use of corrugated pipe made to M 196 and is not generally analogous to the current version. The standard makes no mention of coatings on the aluminum.

AASHTO M 219 – Standard Specification for Corrugated Aluminum Alloy Structural Plate for Field-Bolted Pipe, Pipe Arches, and Arches [*32*] is the AASHTO product standard for corrugated aluminum structural plate. The ASTM analog is ASTM B746. The AASHTO specification covers corrugated aluminum alloy structural plate used in the construction of pipes, pipe-arches, arches, underpasses, and special shapes for field assembly generally used for drainage purposes, pedestrian and vehicular underpasses, and utility tunnels. The specification requires that the flat plate material used to fabricate structural plates conform to the requirements of ASTM B209 [*14*] and be fabricated from aluminum alloy 5052-H141. Structural stiffeners shall be fabricated from aluminum alloys 6061-T6 or 6063-T6 conforming to ASTM B221. Fasteners may be steel with zinc coating, stainless steel, or aluminum. If fabricated from aluminum, the fasteners shall be made from aluminum alloy 6061-T6 in accordance with ASTM F468. Historic versions of M 219, dating back to 1966, specified the same aluminum alloys as the current standards. The standard makes no mention of coatings on the aluminum structural plate.

2.6.3 Culvert Service Life

AASHTO Highway Drainage Guidelines [*17*] identifies design service life as the period of service without a need for major rehabilitation. For corrugated aluminum pipes, this is normally the number of years from installation until corrosion perforation, some specified percent of metal loss, or another measure of distress showing the culvert to be at or near the point of collapse. It notes that the ability to accurately estimate service life has proven difficult at best and more often totally incorrect. This difficulty can be traced to the variety of conditions that affect service life. Factors that affect service life (identified in [*17*] with reference to [*20*]) include water pH, soil pH, soil resistivity, chlorides and sulfates in the soil, bed load, streamflow, culvert material, chances in the upstream watershed, industrial runoff, and possible effects of severe climates or climate change. Factors that affect the need for rehabilitation include debris damage, erosion from major storms, improper manufacture or handling, and improper installation or backfilling.

The AASHTO LRFD Bridge Design Specification [*33*] provides design methods for bridges and other highway structures, such as culverts of all material types. The design specification has been developed to achieve objectives of constructability, safety, and serviceability for a design life of 75 yrs.

2.6.4 Coating and Protection for Aluminum Culverts

The aluminum culvert material standards (Section 2.6.2) make no mention of coatings for protection of aluminum culverts. Such standards for other metallic culvert types include specific language for coating specification, inspection, and repair or rejection if the coating is damaged prior to completion of construction.

The AASHTO Highway Drainage Guidelines [*17*] provide guidance on protective coatings for metal culverts, though the guidance appears to be focused on steel culvert pipe. It notes that recent advances have led to coatings that have adequate bonding and wearability characteristics that make them attractive for abrasion resistance, which could be useful for aluminum at abrasive sites. It notes that selection of an appropriate coating will require consideration of the pH and resistivity ranges to be encountered, both on the soil and water sides of the culvert, and the potential for abrasion. AASHTO notes that soil side (bonded) protection can provide 25 yrs of additional service life where conditions are not unduly severe. It notes that applied coating quality is dependent on its bond with the base culvert material and emphasizes the importance of a clean application process to provide the expected level of protection. AASHTO identifies mill-applied thermoplastic coatings as generally having superior performance to bituminous coatings, and that fiber-bonded coatings fall in between in terms of durability of the coating and extension of service life for the culvert, although some states report mixed results regarding the increase in service life versus the added cost of coatings. AASHTO notes that some states no longer allow asphalt mastic or bituminous coatings due to environmental concerns and that all coatings on the water side are susceptible to abrasion. The AASHTO recommendations are general to metallic culvert materials, not specifically geared toward aluminum culverts, and there is no specification within AASHTO for coating of aluminum culverts.

FLH Standard Specs [*29*] require that when aluminum pipe may contact other metals, the contacting surfaces shall be coated with asphalt mastic or a preapproved impregnated caulking compound.

Impermeable membranes are widely used to protect mechanically stabilized earth (MSE) retaining wall installations with metallic components from contact with deicing salts. MSE walls often use metal tieback strips extending from the wall face into the backfill. In locations with significant deicing salts, the metal strips closest to the surface can corrode quickly due to runoff. MSE wall design provisions in the AASHTO LRFD Bridge Design Specifications [*33*] recommend installing an impervious membrane below the pavement structure to protect wall reinforcement. The design specifications recommend that a roughened PVC, HDPE, or LLDPE membrane be used to intercept deicing salts and protect the metal strips, as shown in Figure 7. The guidance from [*33*] recommends that the membrane be at least 30 mils thick (0.03 in.) and be sloped away from the structure and tied to a drainage system. All seams in the membrane should be glued or welded to prevent leakage.

Sample membrane installation photos from a similar installation of a buried corrugated steel culvert are shown in Figure 8. Berg et al. [*34*] specified a similar approach to AASHTO for MSE walls in FHWA-sponsored research developed for FHWA training courses. Minimum tear

(ASTM D1004) and puncture (ASTM D4833) resistances of 10 lbf and 32 lbf, respectively, are recommended in [*34*]. Similar requirements are planned for publication in the upcoming revision to the Canadian Highway Bridge Design Code [*35*].

Berg et al. [*34*] recommends that MSE wall fill with steel reinforcement be tested for chloride content in accordance with ASTM D4327 with a recommended limit of < 100 ppm.

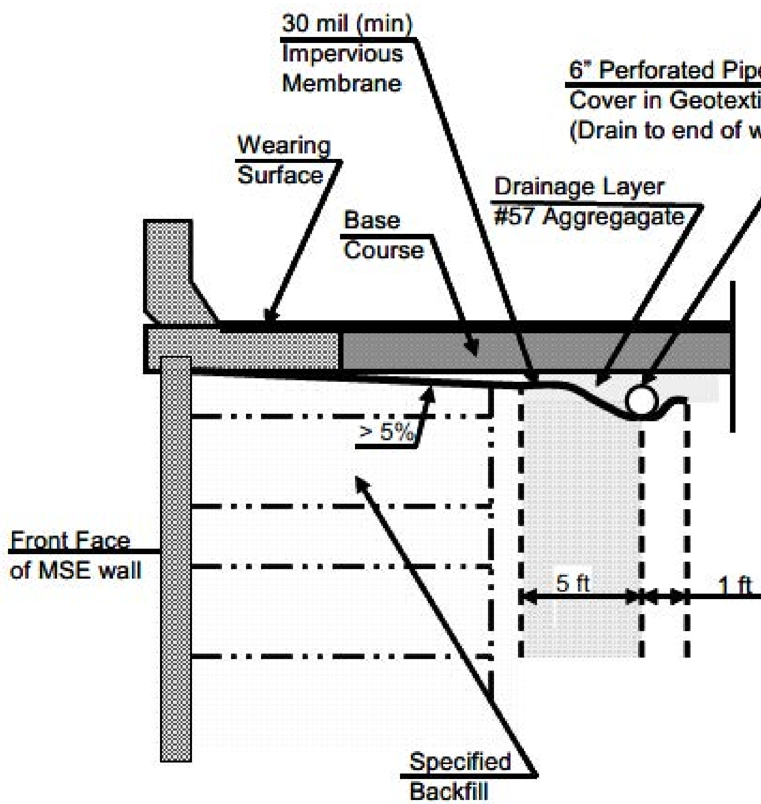

Figure 7 – Schematic of Membrane Protecting Metal MSE Wall Straps from Deicing Salts (Reproduced from [*34*])

Figure 8 – Membrane Installation Adjacent To and Over Culvert (Courtesy of Big R Bridge)

The ASM Handbook [*18*] identifies acrylic, alkyl, polyester, and vinyl paints as suitable coatings for aluminum depending on the specific environment. It identifies surface preparation as key, similar to coating any metal, and recommends that conversion coatings, such as chromate or phosphate types, be used for coating preparation of aluminum alloys. For aggressive environments, such as those that could contain chlorides, a chromated primer is recommended to be applied first.

While limited to factory-applied applications and more expensive than other types of coating, the ASM Handbook [*18*] identifies anodized coatings as providing excellent protection to aluminum alloys. Anodized coatings are applied through an electrolytic process that converts the surface of the alloy to aluminum oxide, similar to the natural oxide film but much thicker (0.2 to 1.2 mils). In atmospheric weathering tests, the number of pits that develop in the base metal was found to decrease exponentially with coating thickness.

2.7 State Department of Transportation Policies for Aluminum Culverts

This section summarizes policy related to the use of aluminum as a culvert material in five states with similar climates to Wisconsin, including Maine DOT, Michigan DOT, Minnesota DOT, New York State DOT, and Ohio DOT and two other states with relevant policies. Virginia DOT road and bridge standard drawings are summarized for allowable pipe types for culverts and storm sewers, as recommended following our aluminum culvert stakeholder survey. Information is also included for sites where Caltrans allows use of aluminum as a culvert material, based on Caltrans’s widely accepted policies for culvert abrasion design.

2.7.1 DOT Culvert Material Selection and Specification

Caltrans Corrosion Guidelines [*36*] states “For a 50-year maintenance-free service life, aluminum can only be used if the soil, backfill, and drainage water meet the following: 1) Minimum resistivity must be greater than 1,500 Ω-cm, and 2) pH must be between 5.5 and 10.0.”

The Michigan DOT Drainage Manual [*37*] states, “Select a culvert which best integrates engineering, economic, and environmental considerations. The chosen culvert shall meet the selected structural and hydraulic criteria and shall be based on: construction and maintenance costs, risk of failure or property damage, traffic safety, environmental or aesthetic considerations, political or nuisance considerations, and land use requirements.” Similar requirements are included in manuals for the other states evaluated herein.

The Minnesota DOT Drainage Manual [*38*] states “if, for engineering reasons, the use of corrugated metal pipe is necessary in areas that have been detrimental to this type of pipe, the designer must take proper precautions such as increasing the thickness of the base metal or providing a protective coating to assure required serviceability.” The drainage manual provides fill height tables for corrugated aluminum pipe, pipe arches, and spiral rib pipe and pipe arches. Section 5.4 notes that structural design is by fill height table without much guidance identifying how the fill heights in the tables were determined. The Minnesota DOT Standard Specifications for Construction [*39*] references AASHTO M 196 as the specification for corrugated aluminum pipe and AASHTO M 219 for aluminum alloy structural plate and fasteners. The Minnesota DOT has a technical memorandum [*40*] specific to metal box culverts for their use as a bid alternate to other types of box culverts with specific parameters that must be satisfied for their use. The technical memorandum requires design and construction in accordance with AASHTO specifications with some additional restrictions on size, ADT, and fill depth. The technical memorandum is not specific to corrugated aluminum or steel. During the stakeholder survey portion of this research project, the Minnesota DOT respondent indicated that the failure of a county-built demonstration metal culvert in the 1970s or 1980s resulted in a reluctance to use longer span corrugated metal culverts in Minnesota. The survey respondent also provided a spreadsheet file [*41*] with an inventory of sixteen in-service aluminum box culverts with spans ranging from 10 ft-11 in. to 23 ft-2 in. The Minnesota DOT [*38*] is performing a statewide condition assessment of culverts of culverts with correlation of performance to soil and water properties, including resistivity and pH, to develop a revised policy for culvert material selection and use of metal culverts.

The Michigan DOT Standard Specifications for Construction [*42*] allow corrugated and spiral rib aluminum pipe for all culvert classes except for Class E culverts, which have up to 3 ft of cover and only reinforced concrete pipe is allowed. These specifications reference ASTM B790 [*43*] and AASHTO LRFD Bridge Design Specifications [*33*] for design of corrugated aluminum structural plate and AASHTO M 196 [*30*] for corrugated aluminum alloy pipe. ASTM B790 references other ASTM specifications for aluminum culvert materials. AASHTO LRFD gives reference to AASHTO M 196 [*30*] and AASHTO M 219 [*32*] for aluminum culvert material requirements.

The Maine DOT's Highway Design Guide [*44*] lists aluminum alloy pipe exclusively as recommended for use in salt water areas. The Maine DOT's Bridge Design Guide [*45*] recommends that "All metal buried structures in tidal waters should be aluminum. In inland waters, steel is preferred due to lower initial cost, although aluminum should be used if the existing steel structure is being replaced after less than 50 years of service."

The Maine DOT's Standard Specifications for Construction [*46*] require that corrugated aluminum pipe and pipe arches conform to AASHTO M 196 Type I, IR, or II, and aluminum sheet conform to AASHTO M 197. For aluminum alloy structural plate pipe, pipe arches, arches, box culverts, and fasteners, the specifications require that the plates conform to AASHTO M 219 and nuts and bolts conform to ASTM F468M alloy 6061-T6 and F467 alloy 6061-T6.

The New York State DOT Highway Design Manual [*47*] notes that aluminum is an acceptable culvert material and that the design criteria consist of design life, anticipated service life, structural criteria, hydraulic criteria, and economics. Appendix A includes aluminum culvert fill height tables, and tables in the manual list various types of aluminum pipes/pipe arches and aluminum structural plate structures. The manual indicates that the most appropriate type of short-span structure is selected by the designer from corrugated metal box structure or arch, concrete box culvert, concrete arch, or short-span bridge. The material specified shall be the most economical which satisfies all the pipe criteria (design life, anticipated service life, and structural criteria) in addition to meeting the hydraulic criteria (allowable headwater, etc.). In the New York State DOT Standard Specifications [*48*], aluminum culverts are specified to meet AASHTO M 196M, and aluminum structural plate, nuts, and bolts are specified to meet AASHTO M 219.

The Ohio DOT Location and Design Manual [*49*] requires evaluation of site conditions for abrasion and environmental characteristics to ensure all conduits will meet their design service life. The manual allows corrugated aluminum box culverts and references design by the manufacturer in accordance with the AASHTO LRFD Bridge Design Specifications. The Ohio DOT Construction and Material Specifications [*50*] provide the requirements for corrugated aluminum pipe meeting AASHTO M 196, aluminum structural plate structures meeting AASHTO M 219, and aluminum box culverts meeting ASTM B864. Box culverts are required to be supplied by preapproved manufacturers with calculations and shop drawings. Culvert material selection must follow the Ohio DOT Culvert Design Process Flow Chart [*51*], reproduced here as Figure 9, with references in the figure corresponding to sections in the Ohio DOT Location and Design Manual. Material selection deviations from culvert materials that would be allowed by [*51*] can only be made in accordance with specific considerations outlined in [*49*] based on sound engineering judgement and life cycle cost analysis.

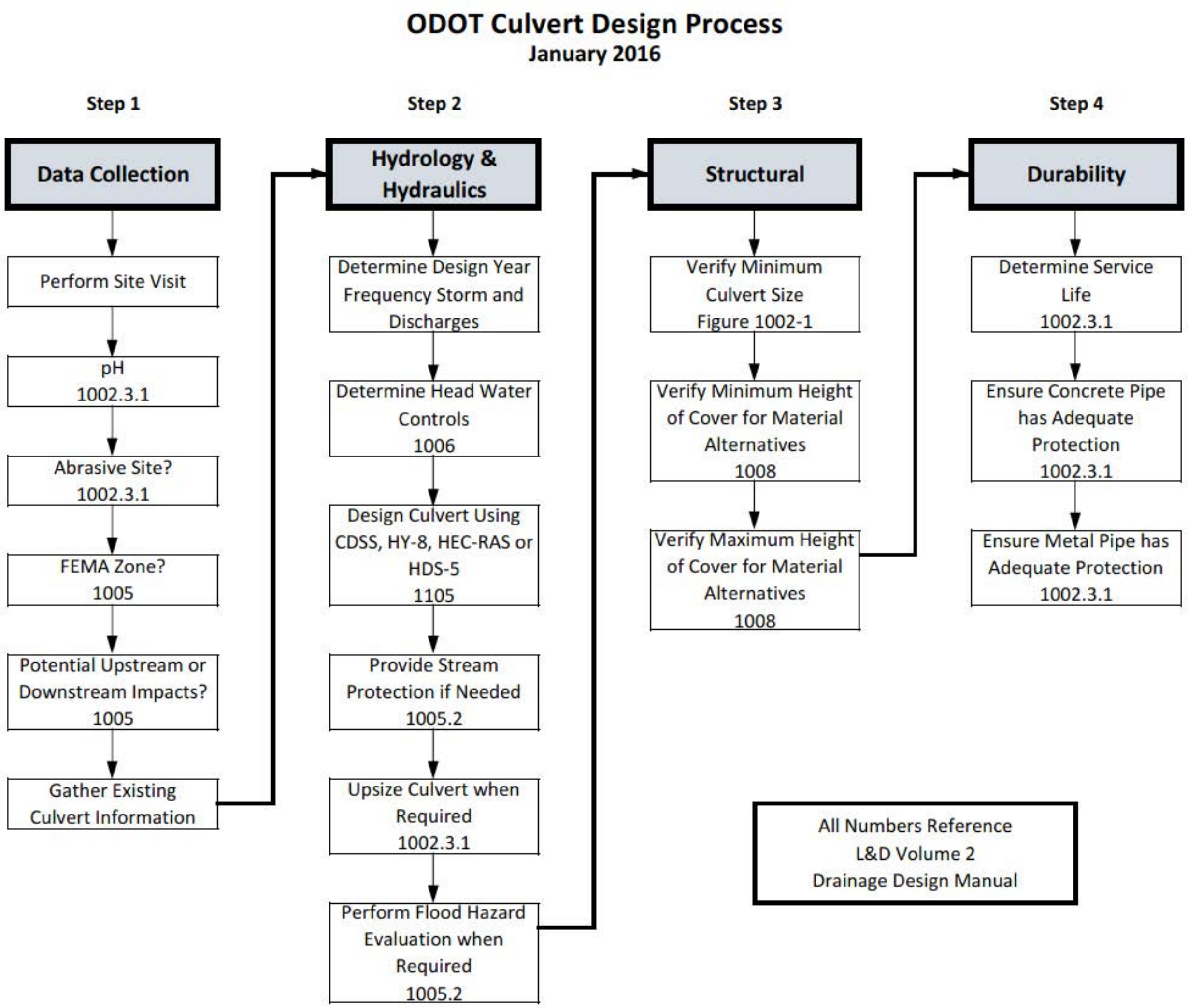

Figure 9 – Ohio DOT Culvert Design Process Flow Chart [*51*]

2.7.2 DOT Culvert Service Life

Caltrans Corrosion Guidelines [*36*] note that Caltrans has adopted AASHTO's requirement for a 75 yr structure design life; however, "culverts and drainage facilities typically require a 50-year maintenance free design life." Environmental requirements (resistivity and pH ranges) given by Caltrans are intended to give a 50 yr maintenance-free service life. The Michigan DOT Drainage Manual [*37*], states "The design life for culverts will be 50 years, except driveway culverts will be 25 years." We did not observe environmental restrictions for aluminum culvert use in Michigan DOT literature.

The Minnesota DOT Drainage Manual [*38*] and AASHTO Highway Drainage Guidelines [*17*] define service life as the period of little to no rehabilitative maintenance required; for metal culverts, this is considered as the time to first perforation or some specified percent of metal loss. The Minnesota DOT Drainage Manual [*38*] specifies limits on soil resistivity and water and soil pH and provides general information about limiting chlorides and sulfates in the soil or water, but no specific limitations are given for aluminum culvert use. Abrasion is limited by stating that flow velocities less than 5 ft/sec are not considered abrasive and velocities in excess of 15 ft/sec which carry abrasive bed load are considered very abrasive and require culvert protection. Metal culvert policy is likely to be revised in the near future following completion of the Minnesota DOT's culvert condition assessment research noted in Section 2.7.1 above.

The Maine DOT's Bridge Design Guide [*45*] references an anticipated service life of 50 yrs. The guide provides fill height tables for corrugated steel and aluminum structural plate. Notes indicate that additional metal thickness of 0.055 in. has been added to the values in the tables to resist abrasion and corrosion and the designer should consider specifying further additional thickness where corrosion or abrasion is known to be severe, and that structural design should use the tabulated thickness minus 0.055 in. We did not observe environmental restrictions for aluminum culvert use in Maine DOT literature.

The New York State DOT's Highway Design Manual [*47*] defines culvert design life as the "number of years of in-service performance which the pipe is desired to provide," and it considers initial cost, installation and backfill; cost to rehabilitate, and disruption to traffic during rehabilitation. It also defines anticipated service life of a culvert as the "number of years it is anticipated the culvert pipe material will perform as originally designed or intended." In normal conditions, the anticipated service life for aluminum culverts is 70 yrs; however, 70 yrs should not be expected where there are high flow velocities and potentially abrasive bed loads, or high concentrations of industrial waste. Regarding design life, a 70 yr design life is required for significant locations, a 20 yr design life is required for driveway pipes, and a 50 yr design life is required for other locations. Aluminum is not recommended where grades exceed 6% and may have abrasive bed loads. We did not observe environmental restrictions for aluminum culvert use in New York State DOT literature.

The Ohio DOT Standard Specifications [*50*] define design service life as the “average usable life of a conduit or structure.” The Ohio DOT Location and Design Manual [*49*] identifies Type A and Type B Conduits, where Type A are designed for soil-tight, sealed joint open-ended cross drains under pavements and paved shoulders. Type A conduits under state and federal routes have minimum service life of 50 yrs or a service life of 75 yrs for fill height ≥ 16 ft, on interstates, or when defined as a bridge. Type B conduits are designed for soil-tight, sealed joint sewers under pavements, paved shoulders, and commercial or industrial drives. Design service life for Type B conduits is 75 yrs. Ohio requires a 75 yr service life for important or deep structures, requires durability evaluation to ensure that the service life is met, and requires increased durability resistance for certain structures even if abrasion is not anticipated to impact design life. The Ohio DOT Location and Design Manual [*49*] requires field measurement of pH of the normal stream flow in the field. The streambed is classified as abrasive or nonabrasive by observation using a method similar to the six abrasion levels from Caltrans. The Ohio DOT provides a Durability Design Spreadsheet [*52*]. The spreadsheet shows service life as a function of environmental conditions (pH, abrasion level), culvert material and thickness, and coatings or invert paving. The spreadsheet prohibits use of aluminum as a culvert material where pH is outside the range of 5.0 to 9.0. It allows use of aluminum at abrasive sites with concrete invert paving.

2.7.3 DOT Information on Coatings and Protection of Metal Culverts

Ohio is the only state that was part of this research that had a waterproofing membrane or coating requirement for culvert installations. The Ohio DOT Location and Design Manual [*49*] requires that a waterproofing membrane be applied to the external side of all precast reinforced concrete box culverts, three-sided flat-topped culverts, arch culverts, and round sections. The membrane is to be Item 512 Waterproofing, Type 2 along the vertical sides, and Types 2 or 3 across the top. Type 3 is to be used if pavement will be directly on top of the structure (for box culverts). A minimum overlap of 12 in. is required between the top and vertical membranes. Ohio DOT Standard Specs [*50*] Item 512 is titled “Treating Concrete” and gives reference to sections 711.24, 711.25, and 711.29 for waterproofing fabric (roofing felt), Type 2 sheet membrane waterproofing, and Type 3 sheet membrane waterproofing, respectively. Applicable material requirements from Section 711.25 Type 2 Membrane Waterproofing include 0.06 in. minimum thickness when measured in accordance with ASTM D1777, 300% minimum elongation in accordance with ASTM D412 (Die C), and 40 lb puncture resistance in accordance with ASTM E154.

The Ohio DOT Construction and Material Specifications [*50*] require that exterior coatings and membrane waterproofing be applied to structural plate and corrugated metal box structures, including aluminum structures. They require coating the exterior of the culvert above the limits of the bedding and within the limits of backfill and ensuring that all plate seams and bolts are thoroughly sealed, and they specify coating materials meeting AASHTO M243. Asphalt mastic materials must dry 48 hrs and tar base materials must dry 28 hrs before backfill is placed against them. Buried liner waterproofing membrane protection must be a continuous sheet placed over the conduit and extend at least 10 ft (3.3 m) outside of the paved shoulder and for the width of the trench. Seams may not be constructed in the field. Ohio also has specifications on invert paving of new or existing conduits with concrete, including aluminum structures.

Caltrans Corrosion Guidelines [*36*] recommend that imported backfill that is placed around the culvert be less corrosive than the native soil material and that the imported backfill be tested in accordance with Caltrans Test Methods 643 (Caltrans Method for Estimating the Service Life of Steel Culverts; 1999), 417 (Caltrans Method of Testing Soils and Waters for Sulfate Content; 2013), and 422 (Caltrans Method of Testing Soils and Waters for Chloride Ion Content; 2000) prior to placement. Caltrans T 643 covers measurement of soil resistivity and soil and water pH and uses a chart to estimate years to perforation of a steel culvert based on resistivity and pH. There is no reference to coatings, linings, or pavings that may help protect aluminum culverts from corrosion. The guidelines note that tests for chlorides and sulfates are required at sites where soil and water resistivity are less than 1,000 Ω-cm. For structural elements, Caltrans considers the site to be corrosive if soil and/or water chloride concentration is 500 ppm or greater, sulfate concentration is 2,000 ppm or greater, or the pH is 5.5 or less.

For MSE wall installations, Caltrans Corrosion Guidelines [*36*] references Caltrans Standard Specifications that require the MSE wall structure backfill to have a minimum resistivity of 2,000 Ω-cm, chloride concentration less than 250 ppm, sulfate concentration less than 500 ppm, and pH between 5.5 and 10.0.

The Wisconsin DOT Bridge Manual [*1*] chapter on retaining walls identifies aggressive environments in Wisconsin as being associated with salt spray and recommends that retaining wall steel reinforcement be protected by an impervious membrane. The impervious membrane should be installed below the pavement and above the first level of reinforcement. The section references FHWA-NHI-00-043 (2001) for details on the impervious membrane and collector pipes; this document is an older version of [*34*]. The Bridge Manual does not reference the Wisconsin Standard Specifications for membrane specification.

The Maine DOT Bridge Design Guide [*45*] favors aluminum or concrete box culverts, arches, and other structures over steel, but lacks information specifically related to protection of these structures from deicing salts. The same holds for the Maine Standard Specifications [*46*].

The Minnesota DOT Standard Specifications [*39*] do not provide any special requirements for installation of aluminum or other corrugated metal pipe, such as requirements for installation of protective membranes, etc., to protect the structures from deicing salts.

The New York State DOT Standard Sheets [*53*] do not reference special coatings or membranes in the backfill envelope to protect metal pipes of culverts from exposure to deicing salts. The New York State DOT Standard Specifications [*48*] require that a geotextile cover a minimum of 12 in. beyond each side of a joint for its entire length and have a 12 in. overlap at any longitudinal discontinuities for joints in corrugated structural plate pipes and structural plate pipe arches. Select granular fill to be used as backfill around aluminum pipes is required to be free from Portland cement unless thoroughly coated with zinc chromate primer, and the select granular fill used around Type IR and IIR corrugated aluminum pipe must pass a 2 in. sieve. There is no other reference to protection of aluminum culverts from chemicals such as deicing salts.

Many state DOTs in climates that require deicing salts specify use of impermeable protective membranes above MSE wall installations that typically use metal straps buried within the wall backfill. New Hampshire DOT MSE wall special provisions [*54*] require 30 mil (0.03 in.) thick PVC membrane with material properties specified per ASTM standards, as shown in Figure 10. Maine DOT has an additional requirement that the membrane extend 1 ft past the structure. Vermont DOT has additional requirements for dielectric seam connections or 6 in. overlaps with solvent to bond the adjacent pieces.

Property	Test Method	Property Requirements
Thickness [mil (mm)]	ASTM D 1593	30 (0.75) ± 5% min.
Specific Gravity	ASTM D 792	1.20 min.
Dimensional Stability (% change)	ASTM D1204	5 max.
Tensile Strength [pounds per square inch (kPa)]	ASTM D 882	2300 (16,000) min.
Tear Resistance [pounds (N)]	ASTM D 1004 Die C	8 (35) min.
Low Temperature Brittleness [°F (°C)]	ASTM D 1790	-20 (-30) min.
Resistance to Soil Burial (% strength retained)	ASTM D 3083	95 min.
Hydrostatic Resistance [pounds per square inch (kPa)]	ASTM D 751 Method A	75 (520) min.

Figure 10 – New Hampshire DOT MSE Wall Special Provision Membrane Material Requirements [*54*]

2.8 Manufacturer Literature

We reviewed literature from Big R Bridge (which supplies aluminum culverts manufactured by AIL of Canada), Contech Engineered Solutions, and Lane Enterprises. In general, manufacturer literature aligns with information from state DOT and other agency specifications identified above, particularly with regard to aluminum culvert material and product specification, aluminum alloys, and identification of environmental limits related to corrosion and abrasion for sites suited for aluminum culvert use. Specific items of note are identified below.

The Contech Corrugated Metal Pipe Design Guide [*55*] recommends aluminum alloy for use at sites where soil and water pH range from 5 to 9 and where the minimum resistivity is 500 Ω-cm. It includes abrasion limitations based on FHWA Abrasion Levels 1 to 4 with flow velocities based on a 2 yr storm event and provides minimum thickness requirements based on site abrasion level. The Contech Structural Plate Design Guide [*56*] recommends protection of buried metal culverts from deicing chemicals through either an asphalt coating on the exterior of the structure or a polymeric membrane embedded in the backfill; it notes impermeable clays as another option. Ref. [*56*] provides a detail (Figure 11) for installation of such a membrane. In tidal brackish and saltwater environments, the manufacturer [*56*] recommends backfilling with free-draining backfill material. It also identifies galvanized steel fasteners as compatible with aluminum culverts, while noting that ungalvanized "black" steel must be isolated from aluminum.

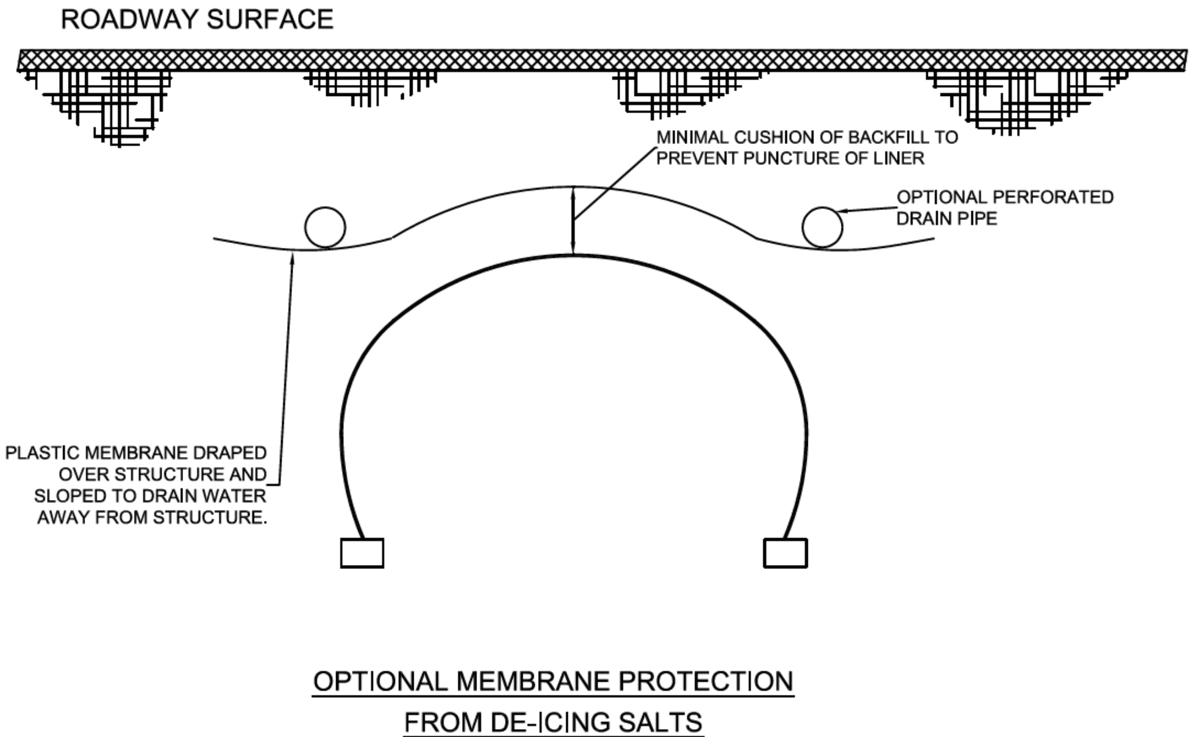

Figure 11 – Manufacturer Detail for Buried Metal Culvert Isolation Membrane to Protect Culvert from Infiltration of Deicing Salts (Reproduced from [*56*])

The Lane Enterprises Corrugated Metal Pipe Technical Guide [*57*] identifies aluminum pipe as providing a minimum 75 yr service life in the recommended environment with pH of 4 to 9 and resistivity greater than 500 Ω-cm. For brackish and seawater environments, which can have resistivity of approximately 35 Ω-cm, it recommends the use of clean, free-draining granular material. There is specification for membranes or other protection of metallic culverts from deicing chemicals.

No manufacturer provided a specification for coatings (interior or exterior) for aluminum culverts, as they have shown good resistance to general corrosion when installed in the recommended environment and they are typically not coated in the shop or field.

2.9 Research Reports on Buried Aluminum Structures

New York State DOT research, in cooperation with FHWA [*58*], reported on laboratory methods to measure section loss of coupons removed from metallic culverts throughout the state. The study included measurements of metal loss from 190 galvanized steel and 35 aluminum culverts, plus a field study of 30 culverts to identify sample size and locations necessary to characterize metal loss. Statistical analysis identified measurements along a single longitudinal line (i.e., single clock position) of worst visual condition at eight random locations along that line as a method with a reasonable level of accuracy to determine metal loss in a single culvert.

Thickness measurements were performed on 35 uncoated aluminum culverts, of which 3 were in service for up to 5 yrs, 7 were in service for 6 to 10 yrs, and 25 were in service for 11 to 15 yrs. The 35 culverts were mostly located in town and county rights of way. None of the aluminum culverts showed a loss rate greater than 0.001 in./yr. The researchers identified a conservative metal loss rate of 0.0005 in./yr for aluminum while noting that a 0.035 in. metal thickness would be required for a 70 yr design life. The report concluded that structural design would require a greater thickness than 0.035 in.; therefore, no special durability considerations are required for aluminum.

Earlier New York State DOT research by Haviland et al. [*59*], the continuation of which was described in [*58*], identified the environmental characteristics at 21 aluminum culvert sites with 34 aluminum culverts in New York. Water pH ranged from 6.2 to 8.8, and soil pH ranged from 5.2 to 8.4 over a twelve-month period.

A metallic culvert durability study in Ohio by Hurd and Sargand [*60*] mainly focused on steel culverts. The researchers noted influence of deicing salts on durability, identifying that the Ohio DOT used sodium chloride for roadway deicing, resulting in seepage of salts through bolted seams on many structures, and that the amount of deposits and corrosion were always greatest beneath the edge of the pavement. They noted a potential crown corrosion problem for shallow buried structures, although increased cover height (varying from 1.25 to 5.7 ft) did not reduce the severity of seepage or corrosion.

A 1984 study in Maine by Jacobs [*61*] included measurements of metal loss through field measurements or cores of several different types of culverts, including 44 clad aluminum pipes in normal service and some test installations. Average metal loss was 0.0002 in. with a standard deviation of 0.0004 in., with up to 20 yrs of service. All sites had pH in the “normal range” and resistivities greater than 10,000 Ω-cm. Reasons for the metal loss, such as whether it occurred from corrosion or abrasion, were not given. Conclusions included that 16 ga aluminum would result in over 100 yrs of service life prior to perforation when aluminum is used in salt water with free-draining granular fill.

A 1986 paper by Koeph and Ryan [*62*] reported on the in-service performance and durability of abrasion of aluminum culverts that had been in service for approximately 20 yrs. The paper is focused on gaining an understanding the mechanics of aluminum culvert abrasion and correlation with field performance to develop guidelines that can be considered in design. The research identifies abrasive sites as not corrosive sites for aluminum alloys based on expected water chemistry in chemically inactive bedload. It notes that "loss of metal from aluminum alloy culvert becomes dependent on abrasion energy without the addition of corrosion effects," identifying the relatively robust performance of aluminum culverts against general corrosion to be from the aluminum oxide passive coating.

A 1969 paper by Lowe et al. [*63*], all authors of which were associated with aluminum manufacturers with the research sponsored by the Aluminum Association, identified pitting corrosion as a means of attack of buried aluminum; however, the thinking at the time was that the aluminum oxide protective layer helped to arrest pit growth. Other research above has shown that this is not completely true, although recent research tends to agree that growth in pit depth slows with time.

A 1971 study of aluminum culvert performance in Virginia by McKeel [*64*] included observations of performance of six sites with diameters that ranged from 18 to 48 in. One of the sites was identified as having acidic water with pH as low as 3.2 from nearby mine runoff. The invert of the aluminum pipe was noted as severely pitted after 1 yr, and completely removed by corrosion after 2 yrs. Conclusions from this paper included an absolute lower limit of pH of 4.0 for use of aluminum culverts.

Research by Molinas and Mommandi [*65*] in Colorado reviewed policies and procedures for selection and service life of culverts in five states and reported on Colorado DOT field measurements at three sites with aluminum culverts and several more with steel. Aluminum culverts at the three sites had severe corrosion after 26 yrs of service (they were installed in 1980), although soil resistivity and pH (and water pH at one site where water was available for pH measurements) all indicated acceptable natural environments (pH and resistivity) for aluminum culvert installations as defined in a variety of state and federal policies reviewed above. High chloride and sulfate concentrations were identified as the reasons for corrosion of the aluminum culverts.

Research in 1973 by Peterson [*66*] for the Utah State Department of Highways reviewed aluminum culvert performance at sites in Utah with installation dates between 1962 and 1967. The research also included a survey of fifty states plus the District of Columbia regarding aluminum culvert use and performance. Given the relatively short time period evaluated, since the introduction of aluminum in the early to mid-1960s to 1973, there is not much information on long-term performance, although the aluminum pipes were reported as having short service lives (4.5 to 5.5 yrs) when installed with pH between 2.9 and 3.1. The report recommended allowing the use of bare aluminum alloy pipe where the pH of soil or water is between 4.5 and 9 and where the soil resistivity is not less than 1,000 Ω-cm.

A major 1957 study by Romanoff [*67*] for the US National Bureau of Standards appears to be the seminal research on underground corrosion of buried metals and is referenced in a variety of other work. The study presents a map of eight major soil groupings in the U.S. (after Marbut, 1935), referred to as the "Great Soil Groups," and includes dots locating the buried metal corrosion test sites that were part of the study. The eight soil groupings are referenced in several other documents reviewed in the current work. Note that Wisconsin has two groups, Group I podsol soils to the north, and Group II gray-brown podsolic soils to the south. These soil groups are also found in Ohio (only Group II), Maine, Michigan, Minnesota, and New York, which were the other states whose specifications were reviewed above. The map showing the major soil groupings of the US is reproduced here as Figure 12.

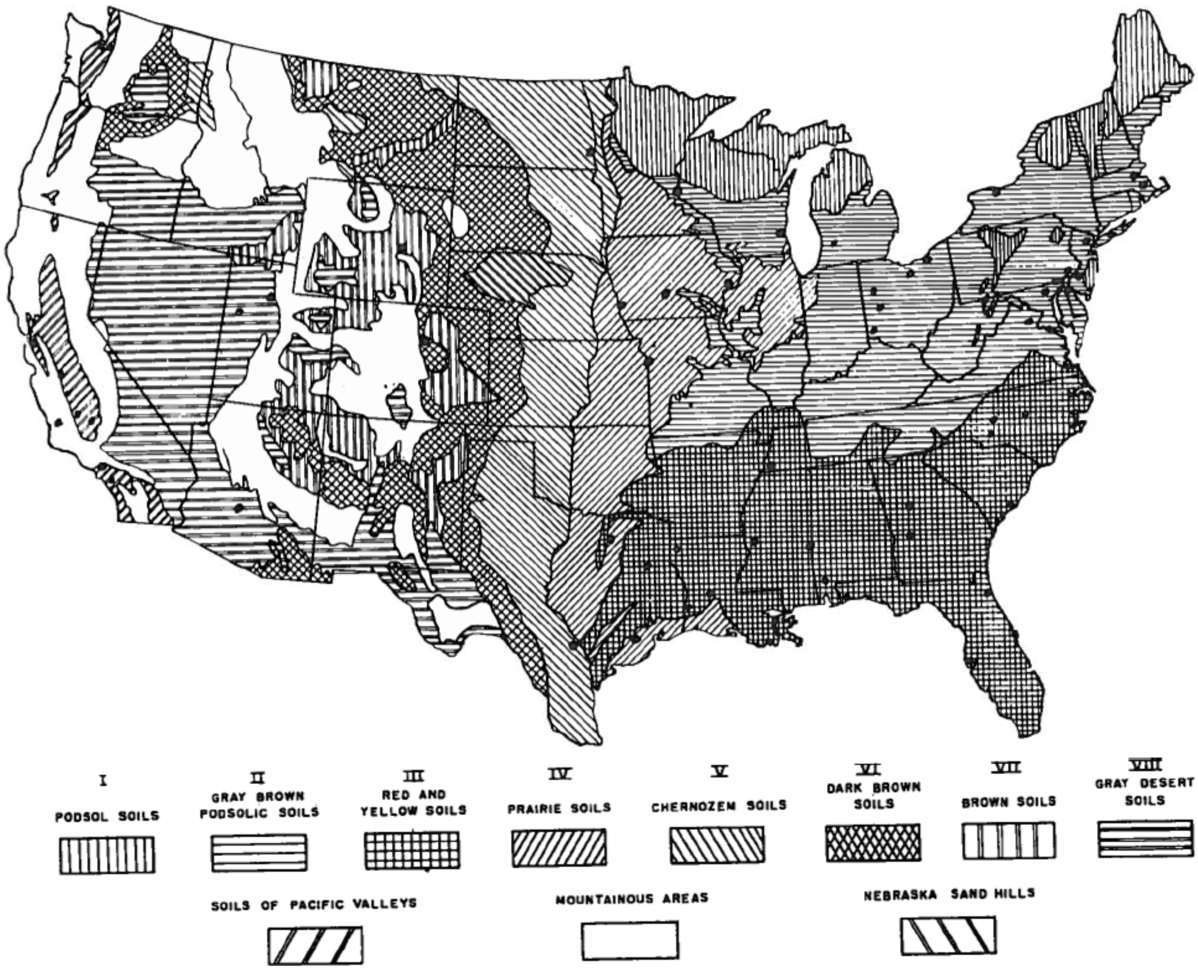

Figure 12 – Major Soil Groupings in the US (Reproduced from Figure 1 of [*67*] after Marbut)

Regarding theory of underground corrosion, Romanoff notes, "underground corrosion that has occurred can be explained, but, even today, theory does not permit accurate prediction of the extent of corrosion to be expected to occur and is dangerous unless complete information is available regarding all of the factors present and their individual and interrelated effects." Factors that affect underground corrosion include aeration (oxygen stimulates corrosion; areas with the least oxygen are generally anodic), electrolyte (soil furnishes the electrolyte that carries the current to promote corrosion), electrical factors (variation in electrical potential between two points on the metal), and miscellaneous (combinations of the above effects, or other contributors, such as backfill placement and compaction or bacterial influences, etc). Electrical factors include any variation in the homogeneity of the structure and composition of the metal, which can include strains, inclusions, intermetallic compounds, or separate constituents, such as graphite in cast iron. Potential differences as high as 0.9 V have been observed in the laboratory when one portion of a soil in contact with a steel plate was kept moist and thereby was deficient of oxygen in comparison to an adjacent portion of soil that was drier and more permeable to oxygen.

Much of Romanoff is dedicated to testing of buried metal coupons at a variety of sites throughout the US between 1910 and 1955. Aluminum coupons were not of the more modern alloys used in culvert construction and did not perform well at the time. He expected more suitable aluminum alloys being developed at the time of his work to provide better in-ground performance.

West et al. [*68*] presented a poster and handout in 2014 regarding field performance and best practices for aluminum structural plate culverts. A figure identifies pH and soil or water resistivity ranges from twelve organizations. The majority of the organizations have a pH range of 4 to 9 (one organization allows as high as 10) and minimum resistivity of between 500 and 1,500 Ω-cm (one organization has a minimum resistivity of 200 Ω-cm). Resistivity is allowed in several jurisdictions to be as low as 25 to 35 Ω-cm in brackish environments with free-draining backfill. There is also more limited guidance on abrasion.

The study provided field inspection results from inspections by the authors of six aluminum structural plate structures across New Brunswick, Canada. Ages of the culverts ranged from 10 to 22 yrs at the time of inspection, and uses ranged from residential areas to highway culverts and areas with tidal flows below the TransCanada Highway. Of note, the oldest structure, installed in 1992, is a round structure with aluminum invert that had water a resistivity of 111 Ω-cm and water pH of 7.2, with a structure rating of 8. This resistivity was the lowest of the six culverts in the study and is much lower than typically allowed in non-coastal installations. A structure rating of 8 corresponds to “No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift.” All six structures were rated 8 or better. Aside from the above site and one additional site with water resistivity measurement of 5,945 Ω-cm, the four remaining sites had water with resistivity greater than 25,000 Ω-cm.

3. ALUMINUM CULVERT STAKEHOLDER SURVEY

3.1 Stakeholder Survey

A complete blank survey is provided in Appendix B. A summary of the content of the aluminum culvert stakeholder survey questions is provided here. Survey questions included having the respondent identify their position within their agency and division and the responsibilities for the division for which they work.

A series of questions then followed about whether metallic pipes or culverts are allowed within the jurisdiction, specifically whether aluminum pipes or culverts are allowed, and whether there are any policies limiting their use based on site conditions such as soil resistivity, pH, stream abrasion classification, type of roadway, traffic volume, pipe size, or any other factor related to corrosion or abrasion. The respondents were then asked if they were aware of any policies or past research related to the use of aluminum pipes or culverts or aluminum used for any other buried applications. The respondents were also asked separately if aluminum box culverts and aluminum structural plate culverts, including buried bridges (structures with spans exceeding 20 ft), are allowed and used in their jurisdictions. Other questions included whether the respondent was aware of any policy changes or other efforts to disallow or introduce aluminum buried structures in their jurisdiction, and what methods, if any, are used to predict aluminum pipe or culvert service life.

Several questions related to agency culvert inventories and culvert inspection requirements followed, including whether records would allow specifically for identification of aluminum culverts in the inventory or inspection records. Questions followed on current and historical aluminum alloys, coatings, or other product standard information and aluminum culvert performance, as well as whether the agency has special details that isolate aluminum from contact with deicing chemicals that may permeate downward through pavement and soil. The respondents were asked if they are aware of any current projects being developed, out to bid, or under construction using aluminum pipe or culverts and whether they have heard anecdotally of any performance benefits or detrimental performance issues with aluminum. Finally, respondents were asked whether they have any additional information they felt would be of use to the research team that they could provide and whether they had any additional contacts they would recommend for the survey.

3.2 Survey Responses

A summary of survey responses by manufacturers and by owner agencies follows.

3.2.1 Manufacturer Survey Responses

Of the five aluminum culvert manufacturers or suppliers surveyed, responses included the following:

- Four of five respondents manufacture aluminum pipe and culverts; one respondent supplies them.
- Manufacturers reported up to 36 yrs of experience supplying aluminum pipe in Wisconsin, including at least eighty-five locations in the Wisconsin DOT right of way.
- They are aware of restrictions based on pH and limitations of aluminum, particularly 3004 alloy corrugated aluminum pipe, in areas with heavy deicing salt usage.
- One manufacturer was aware of the research reports on aluminum culvert performance by Robert Patenaude, Wisconsin DOT Geophysical Engineer, and one manufacturer provided a related self-authored conference paper.
- Four of five manufacturers have confidential internal databases, including one manufacturer that has a record of about 700 aluminum plate structures in Wisconsin, including on local and county roads.
- No manufacturer conducts inspections unless there is a specific issue identified for them to review.
- No manufacturer identified aluminum alloys used for buried culvert structures other than 3004 pipe, 3004 clad with 7072 for pipe, and 5052 for structural plate.
- Five of five manufacturers were aware of current aluminum culvert projects in the US or Canada.
- Regarding special details to electrically isolate aluminum, one manufacturer was aware of isolating for contact with dissimilar metals, and one other was aware of using spray-on coatings in low cover applications. Another manufacturer reported relatively common use of HDPE membranes within the backfill envelope over metal culverts (steel and aluminum).
- Three of five manufacturers provide or supply aluminum box culverts.
- The only potential policy changes the manufacturers were aware of regarding aluminum culverts would be as an outcome of this research in Wisconsin.
- No manufacturer reported on proprietary information used to predict the service life of aluminum culverts. Note that one manufacturer provided a self-authored research paper, and the paper references Florida DOT service life estimates, based on the estimate of time to first perforation.

- Regarding anecdotal impressions of aluminum culvert performance, two of five manufacturers responded that aluminum culverts perform well in the right environment, one identified that owners are generally happy, and one identified that counties appear to like aluminum culverts and that they perform well in acidic environments that may not be well suited for steel.

3.2.2 Owner Agency Survey Responses

We conducted phone interviews and received written survey responses from contacts at departments of transportation in nine states: California, Kentucky, Maine, Minnesota, New York, Ohio, Pennsylvania, Virginia, and Washington. Responses included the following:

- Eight of nine states allow aluminum pipes, although four respondents reported that aluminum pipes are not typically used, and one respondent reported that they have only seen aluminum pipes being used in the last 10 yrs, though they have been allowed much longer. Maine reported favoring aluminum culverts over steel for increased corrosion resistance; however, contractors are reluctant to use aluminum based on increased cost over other options. Washington State does not allow metal culverts of any kind, therefore the below results are limited to the eight remaining respondents.

- Regarding limitations on aluminum culvert use, seven of eight respondents have usage limitations specifically for aluminum culverts, and one respondent has limitations for all types of metal culverts grouped together. The most common limiting criteria is pH, followed by resistivity and abrasion. One state limits use of aluminum based on cover, and one state limits use based on span. New York State divides the state into regions and does not allow aluminum culverts in the Syracuse region based on heavy deicing salt usage there. Virginia requires all pipe alternates available for a particular project that meet required and anticipated service life to be listed in the project documents.

- For past research on aluminum culverts, two states identified research undertaken by their state on culvert durability. New York provided a research report on metal loss rates of uncoated steel and aluminum culverts from 1984 [*58*]. Ohio identified their 1988 metal culvert durability study [*60*], although that study was focused on performance of steel culverts and has very limited information on aluminum, mainly a single aluminum culvert that had shown good performance after 6 yrs of service.

- Regarding whether states have an inventory database that would allow identification of aluminum culverts, four states (Minnesota, New York, Ohio, and Pennsylvania) reported having inventories, with Minnesota having an inventory of sixteen aluminum culverts installed between 1981 and 2002 [*41*] in their inspection records. Ohio has an extensive database of 86,000 structures with spans from 1 to 10 ft, with 154 culverts listed as having corrugated aluminum or spiral rib aluminum materials, with spans ranging from 12 in. to 9.6 ft [*69*]; however, the Ohio DOT survey respondent noted it is likely the data has unreliable classification of aluminum as a culvert material, expecting that many galvanized steel culverts are entered as aluminum, or vice versa, and therefore cautioned about drawing conclusions from the aluminum culvert data set. New York has an inventory but does not allow public access. California has an inventory, but aluminum cannot be distinguished from steel. Kentucky may have an inventory, but the respondent was not sure. Maine reports sparse information in their inventory. Virginia reports only having data for structures with spans greater than 7 ft while noting that the contractor chooses the culvert material from the approved list for each project, so there may generally be no record of culvert materials for specific sites.

- Five of eight respondents conduct culvert inspections at some frequency. Minnesota regularly inspects culverts with spans greater than 10 ft diameter, and Virginia reports no regular inspections on culverts less than 7 ft diameter. Maine inspects culverts only if performance issues are identified.

- No respondent reported knowledge of historic aluminum alloy usage or differences from currently specified alloys, and seven of eight referred to current AASHTO material specifications.

- Six of eight respondents reported not being aware of current projects in their jurisdiction using aluminum culverts, with one additional state identifying that there were no current projects due to the cost of aluminum culverts. The Ohio respondent reported being aware of one current aluminum box culvert project.

- California, Kentucky, and Pennsylvania reported having special details to isolate aluminum from deicing chemicals that may permeate through pavement and soil. Ohio requires coating or a waterproofing membrane on the exterior of corrugated metal plate structures. Kentucky reports that contractors are required to seal the structures prior to backfill, but the response was unclear whether sealing is required only at joints (as waterproofing) or throughout the barrel. New York reported that the only special requirements are to isolate aluminum from contact with concrete.

- Regarding whether aluminum boxes are allowed, California does not allow boxes but does allow arch-topped aluminum structural plate structures. Conversely, Minnesota allows aluminum box culverts but not arch-topped aluminum structural plate structures. Kentucky and Maine both allow boxes, as well as New York and Virginia, who both report that aluminum boxes are rarely used. Ohio and Pennsylvania allow both aluminum box culverts and arch-topped aluminum structural plate structures.

- Regarding whether states have any recent or upcoming policy changes related to aluminum culvert use, Maine reported that they now require use of aluminum bolts on aluminum structural plate structures, which are particularly used in the coastal regions, and Ohio noted that they are moving to a 75 yr service life requirement. Kentucky reported that the use of aluminum culverts is increasing (not a policy change), and Virginia reported that there was no change in usage, even after completely updating their pipe standards about 3 yrs earlier. The California, Minnesota, New York, and Pennsylvania respondents reported that they were not aware of policy changes related to aluminum culvert use.

- For a method to estimate service life of aluminum culverts, responses varied by state. The California respondent reported using the Caltrans/FHWA service life charts. For aluminum pipe, the chart has a set minimum thickness for corrosion allowance when aluminum is installed at sites that meet environmental (pH, resistivity) and abrasion limits. Kentucky reports no specific method. Maine fill height tables provide a required thickness that includes additional thickness for corrosion and abrasion added to the thickness required for structural design. Minnesota provides fill height tables for aluminum culvert thicknesses without guidance on prediction of service life. The New York respondent reported that service life is calculated in design. In Ohio, a 75 yr service life is assumed for aluminum based on observations of acceptable performance. In Pennsylvania, the Koepf and Ryan [*62*] abrasion loss rates are used. In Virginia, aluminum service life is treated similarly to polymer-coated steel pipe.

- Regarding anecdotal impressions of aluminum culvert performance, no respondent reported concerns, and four respondents specifically reported no concerns and no reasons to question aluminum culvert performance. Minnesota noted a single demonstration metal culvert collapse in the 1970s or 1980s (conditions are unknown), which generally led to a reluctance to use any metal pipe. New York reported no known issues even in locations where use is restricted, although some of the structures in the restricted-use locations were proactively coated before installation. Ohio noted that the state prefers aluminum over steel culverts, and they are considering removing coated steel from their specifications.

- In addition to the above information, The Minnesota Department of Transportation Office of Bridges and Structures provided a spreadsheet [*41*] inventory of sixteen aluminum culverts, identified as aluminum box culverts, with spans ranging from 10 ft-11 in. to 23 ft-2 in. and installation dates from 1980 to 2012. One structure is owned by a city, two are within the State DOT right of way, and thirteen are owned by counties (six total counties are represented; St. Louis County has four). All structures are listed as single-span structures, and barrel lengths range from 26 to 72 ft. Inspection or condition data were not included.

4. ALUMINUM CULVERT INVENTORY AND INSPECTION DATA

4.1 WisDOT HSIS Database Information

We reviewed data from the Wisconsin DOT Highway Structures Information System (HSIS) database [*70*] in July 2018. Data presented herein are for a total of fifty-three aluminum culverts that were identified when the search term "aluminum" was entered into the database. Fifty-five results were returned, but two of the returned structures are specifically identified as galvanized steel and those two structures have been excluded from the summary. The structures contained in the database are generally built from aluminum structural plate and have spans of 5 ft or greater. There are many smaller-diameter corrugated aluminum pipes in service in Wisconsin; however, the smaller pipes are not typically captured in the HSIS inventory. Information gathered from smaller-diameter aluminum culverts in the North-Central District of Wisconsin is reviewed in the next section of this report.

We viewed photos in the most recent PDF field inspection reports from the HSIS database. We compared the photos to extents and descriptions of corrosion reported in the inspection reports and assigned levels of corrosion to each culvert as: no corrosion, minor corrosion, or significant corrosion. These corrosion levels are identified as:

- **No corrosion (39 of 53 culverts)**: No level of corrosion was noted in the inspection report.
- **Minor corrosion (8 of 53 culverts)**: Includes minor corrosion of bolts, localized/small areas of corrosion on barrel, minimal spread of surface corrosion/staining, etc. Corrosion is not (expected to be) structurally significant at the time of inspection.
- **Significant corrosion (2 of 53 culverts)**: Noted on two culverts with remedial action recommended based on the observed level of corrosion. The two culverts with significant corrosion have two of the lowest National Bridge Inventory (NBI) ratings.

Low NBI ratings can be based on other system component condition, such as headwall condition, barrel alignment, etc., so it is possible to have a low rating for a culvert with no corrosion, though culverts identified with significant corrosion do have the lowest ratings in this inventory subset. Note that the typical fasteners used in multiple-piece aluminum culverts, such as aluminum structural plate structures, are galvanized steel bolts. Minor corrosion, therefore, would include light corrosion of the galvanized steel bolts and/or minor surface corrosion of the aluminum culvert barrel.

The geographic distribution of aluminum culverts in the HSIS database that are classified as having No Corrosion, Minor Corrosion, or Significant Corrosion as of their most recent inspection report is shown in Figure 13.

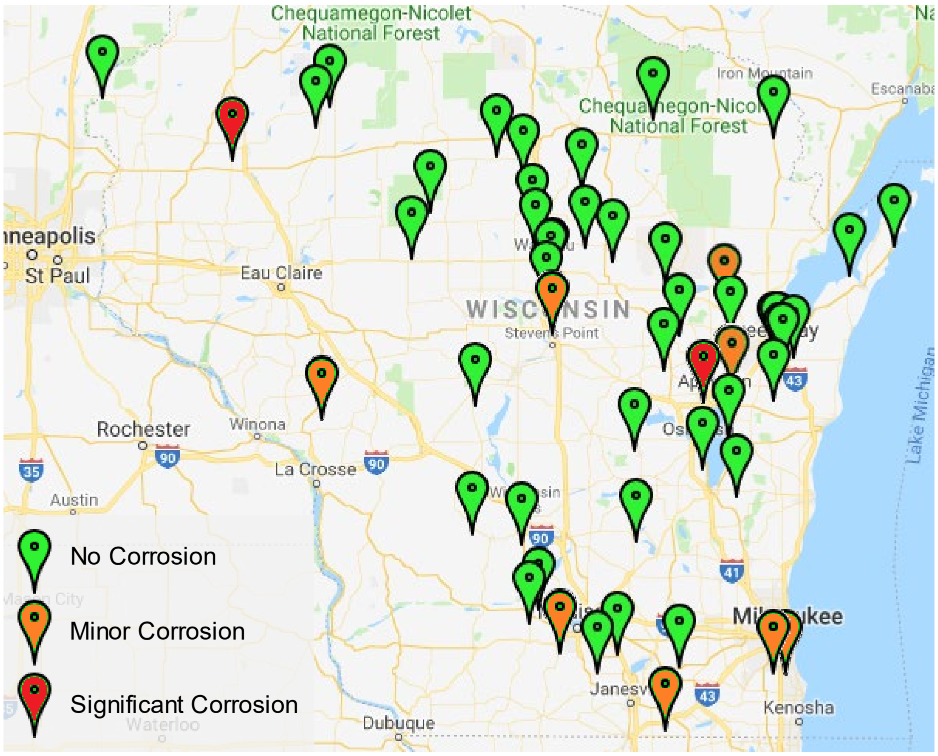

Figure 13 – Geographic Distribution of Aluminum Culverts in Wisconsin HSIS Database with Corrosion Level Based on Most Recent Inspection Report (Figure Generated from HSIS [*70*] July 2018 Output)

Additional figures utilized to understand trends in the data and a complete description of the figures and data are provided in pp. C1 to C8 of Appendix C. Overall conclusions from the HSIS data on aluminum structures include the following:

- **Geographic Distribution (Figures 13 above and C.1 in Appendix C)**: The geographic distribution of culverts with no corrosion, minor corrosion, and significant corrosion appears to be random, with no particular geographic region showing a higher likelihood of corroded aluminum culverts.

- **Span (Figures C.2 and C.3)**: Spans range from 5 to 37 ft, with an average of 16.4 ft and median of 14.8 ft. The data show small correlation between corrosion level and culvert span, with smaller-span structures showing increased corrosion. This is evident in Figure C.3, where a higher proportion of culverts in the 0 to 10 ft and 10 to 20 ft span ranges have minor or significant corrosion than the culverts with spans greater than 20 ft. Of the forty-nine culverts in the database with data on corrosion, ten were identified as having corrosion, and two had significant corrosion. Both culverts with significant corrosion had spans of 11 ft or less, and most culverts with minor corrosion had spans of 13 ft or less. Only two of the twenty-six culverts with spans greater than 13 ft were identified as having corrosion, both of which had minor corrosion.

- **Age (Figures C.4 and C.5)**: Culvert service ages range from 1 to 68 yrs, with an average age of 19.8 yrs and median of 15.0 yrs. Older structures generally show more corrosion. The two culverts with the most significant corrosion are in the middle range of ages of culverts from the database (20 to 40 yrs). The data are unclear about whether any of the oldest culverts have been rehabilitated or replaced.

- **Fill Depth (Figures C.6 and C.7)**: Fill depths range from 0 to 9.25 ft, with an average of 2.8 ft and median of 2.7 ft. Nearly all culverts in the database have shallow fill depths; only one culvert has greater than 5 ft. All culverts with corrosion noted have fill depths between 1.2 ft and 4.3 ft. Two culverts are reported as having 0 in. fill depths in the inspection data.

- **Length (Figures C.8 and C.9)**: Barrel lengths ranged from 22.7 to 130.5 ft, with an average of 57.7 ft and median of 50.0 ft. Lengths in the 60 to 80 ft range appear to be more likely to have minor or significant corrosion, as shown in Figure C.9. However, it is unclear whether barrel length is consistently reported as the length of individual barrels of multi-barrel culverts or the total length of all barrels. Culverts with greater road width do tend to have greater length (both as reported and when normalized by number of barrels), but there is not a clear trend when comparing length or normalized length with fill depth.

- **Average Daily Traffic (ADT, Figure C.10)**: ADT ranges from 10 to 25,000 vehicles, with an average of 1,959 vehicles and median of 203 vehicles. The data do not show significant correlation between corrosion level and ADT. This is surprising, considering the likelihood for increased use of deicing salts and chemicals as well as increased loading on roadways with higher ADT.

- **Pavement Cracking (Figures C.11 and C.12)**: Of the fifty-three culverts in the database, pavement was identified as cracked for twenty-one culverts. Twenty-seven culverts did not have cracked pavement noted, and the remainder did not have an entry related to pavement. The data show correlation between pavement cracking and level of corrosion, with increased corrosion in culverts where the pavement condition was noted as cracked in culvert inspection reports. The data do not provide pavement history, preventing direct correlation of pavement condition over time with levels of corrosion.

4.2 WisDOT North-Central District Aluminum Culvert Inspection Data

The North-Central District of Wisconsin was undertaking a small-diameter culvert inspection program and performing remedial actions based on their findings concurrently with our research. We were provided with a spreadsheet [*71*] of inspection data for 204 culverts identified as corrugated aluminum structures in the district. Most of these culverts are round pipe, and spans range from 1.5 to 5 ft. As with the HSIS data above, some structures have missing data fields, the figures referenced below do not always represent all 204 culverts.

The provided data includes condition rating for the roadway (cracking) and corrosion condition of each culvert on a scale from 1 to 4, as defined in Part 4, Ancillary Structures, of the Wisconsin DOT Structure Inspection Manual [*72*] as follows:

- **Corrosion Condition State 1 (22 of 204 culverts)**: Good. No corrosion.
- **Corrosion Condition State 2 (121 of 204 culverts)**: Fair. Minor surface corrosion, light bolt corrosion.
- **Corrosion Condition State 3 (28 of 204 culverts)**: Poor. More advanced corrosion, significant section loss.
- **Corrosion Condition State 4 (17 of 204 culverts)**: Severe. Significant corrosion, near complete section loss.

Sixteen of the 204 culverts had no data entry for corrosion condition state.

Figure 14 shows the geographic distribution of culverts in the North-Central District Inventory (NCI) spreadsheet. Culverts with Corrosion Condition States 1 to 4 are shown with green, blue, orange, and red circles, respectively. Unknown Corrosion Condition State culverts are shown with black circles. One additional culvert had a Corrosion Condition State of 1 but did not have latitude and longitude listed and is not plotted.

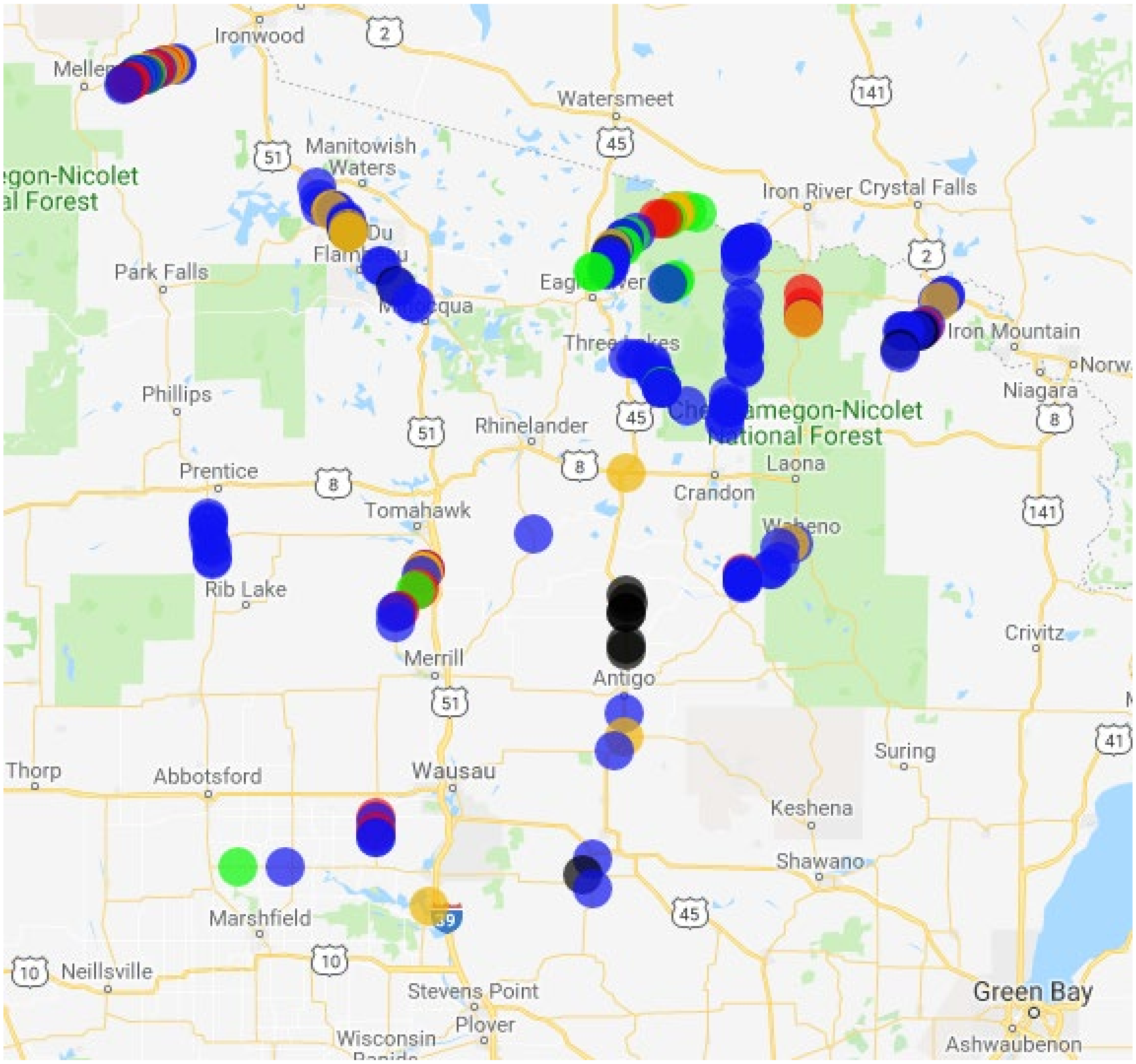

Figure 14 – North-Central District Aluminum Culvert Inspection Inventory with Corrosion Condition States 1 to 4 Shown as Green, Blue, Orange, and Red, Respectively (Culverts with No Rating are Black) [*70, 73*]

Additional figures utilized to understand trends in the data and a complete description of the figures and data are provided in pp. C9 to C13 of Appendix C. Overall conclusions from the North-Central District data on aluminum structures include the following:

- **Geographic Distribution (Figure 14 above and Figure C.13 in Appendix C)**: The geographic distribution of corroded culverts appears to be random, with no particular geographic region appearing to have a higher likelihood of highly corroded aluminum culverts.

- **Span (Figure C.14)**: Spans range from 1.5 to 5 ft, with an average age of 2.3 ft and median of 2.0 ft. Almost all culverts in the NCI data (94%) have a span of 3 ft or less. For this small range of spans, there is no significant correlation between span and Corrosion Condition State. None of the larger spans, greater than 4 ft, are severely corroded, but there are only 9 culverts of this size in the data (4% of total).

- **Fill Depth (Figure C.15)**: Fill depths range from 2 to 20 ft, with an average of 4.9 ft and a median of 5.0 ft. There does not appear to be a strong correlation between fill depth and corrosion rating.

- **Length (Figure C.16)**: Reported lengths ranged from 30 to 180 ft (only a single culvert has a length greater than 120 ft) with an average of 62.7 ft and median of 60 ft. There does not appear to be a significant correlation between length and reported corrosion rating. While the 50 to 70 ft range of length has the greatest number of culverts with corrosion ratings of 3 and 4, this range also has the greatest number of culverts with a benign corrosion rating of 1.

- **Culvert Function (Figure C.17)**: For culvert function, 144 culverts were identified as cross culverts and 44 were identified as stream crossings. The reported function of the culvert does not have significant correlation with the Corrosion Condition State.

- **Pavement Cracking (Figures C.18 and C.19)**: For roadway rating, 88, 80, 19, and 3 culverts had a Roadway Condition State of 1, 2, 3, and 4, respectively. For cracking rating, 166, 13, 7, and 1 culverts had a Cracking Condition State of 1, 2, 3, and 4, respectively. More culverts fall into the lower condition states for these two metrics. However, culverts with higher Corrosion Condition State are more likely to have higher Cracking Condition State (Figure C.16). The discrepancy between roadway rating and cracking rating correlation may be due to other factors considered in roadway rating beyond pavement cracking.

Figure 15 shows a photo of a severely corroded aluminum pipe after removal for replacement in north-central Wisconsin in August 2018, submitted by a North-Central District maintenance engineer. The pipe was located on State Highway 32 and shows characteristics of pitting corrosion and white precipitate consistent with the aluminum oxide corrosion products observed by Patenaude [*7*] and in our field investigation.

Figure 15 – Photo of Corroded Aluminum Pipe after Removal for Replacement in North-Central Wisconsin in August 2018 on State Highway 32 (Wisconsin DOT Photo)

4.3 FHWA Long-Term Bridge Performance Database

We reviewed data from the FHWA Long-Term Bridge Performance (LTBP) InfoBridge database [*74*] in fall 2018. We focused our review on structures the met the combination of having "*Aluminum, Wrought Iron or Cast Iron*" populate the "*Main Span Material*" field in combination with "*Culvert*" populating the "*Main Span Design*" field. This combination gives 1,442 results. There was no field that separated aluminum from wrought or cast iron, so the data presented is limited to "aluminum, wrought iron, or cast iron" culverts, with a high likelihood that typical culverts in the database would be made from aluminum and not iron. We hereafter refer to these 1,442 structures as likely aluminum culverts.

The likely aluminum culverts in the database are spread geographically throughout the US and have spans listed with a range from 0 to 22.7 m (0 to 74.5 ft). We compared data in the LTBP database with data from the HSIS database for structures identified by structure number that were present in both and found some discrepancies with the data. For example, with the 37 structures present in both the HSIS and LTBP databases, we found the difference in span to range from -29.1 ft to +20.9 ft when subtracting the HSIS-reported span from the LTBP-reported span. We also note that the earliest year of construction for LTBP database likely aluminum culverts was 1900, much earlier than the 1960s, when corrugated aluminum culvert standards were first published by AASHTO. Of the 1,442 culverts, 20 have year of construction listed as earlier than 1960, with 50% of those 20 culverts having been constructed in the 1950s. The LTBP database also has a “bridge age” field, which does not match taking the data year (2018) and subtracting the year of construction. The difference when the listed bridge age is subtracted from the age calculated as current year minus construction year ranges from -43 to +76 yrs.

Given the above discrepancies, the conclusions drawn from the data contained in the LTBP database for likely aluminum culverts should be taken with some degree of caution, although we expect that given the number of structures, some trends may be identified.

The data we reviewed from the LTBP database include “structural evaluation” and “culvert” rating fields, with ratings that range from 1 to 9 and appear analogous to the NBI rating system. In the NBI system a rating of 9 is excellent condition and rating of 0 is failed condition. The “structural evaluation” and “culvert” rating data appear identical except that some structures do not have an entry for structural evaluation rating. We base our further analysis on culvert ratings and omit structural evaluation ratings.

Culvert ratings for the 1,442 likely aluminum culverts ranged from 3 to 9, with an average culvert rating of 6.9 and median of 7. Note that culverts may receive a particular rating for a variety of factors including but not limited to corrosion, settlement, holes, wingwall or headwall deficiencies, scour, or erosion. Observations specifically related to metal culvert barrels that may result in a particular culvert rating are identified in Table 5. Note that it is impossible to know from the data whether individual culverts received their rating based on barrel distress or corrosion or on any of the other numerous factors identified above, as the database does not provide a direct indication of corrosion. The number of culverts versus culvert rating for the 1,442 likely aluminum culverts is plotted in Figure 16. An LTBP database-generated map with average rating by state is shown in Figure 17.

Table 5 – Metal Culvert Barrel Distress Observation and Corresponding Culvert Rating

Observed Distress in Metal Culvert Barrel	Corresponding Rating	Rating Description
Metal culverts have extreme distortion and deflection in one section, extensive corrosion, or deep pitting with scattered perforations.	3	Serious Condition
Metal culverts have significant distortion and deflection throughout, extensive corrosion or deep pitting.	4	Poor Condition
Metal culverts have significant distortion and deflection in one section, significant corrosion or deep pitting.	5	Fair Condition
Metal culverts have a smooth curvature, non-symmetrical shape, significant corrosion or moderate pitting.	6	Satisfactory Condition
Metal culverts have a smooth symmetrical curvature with superficial corrosion and no pitting.	7	Good Condition
No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift.	8	Very Good Condition
No deficiencies.	9	Excellent Condition

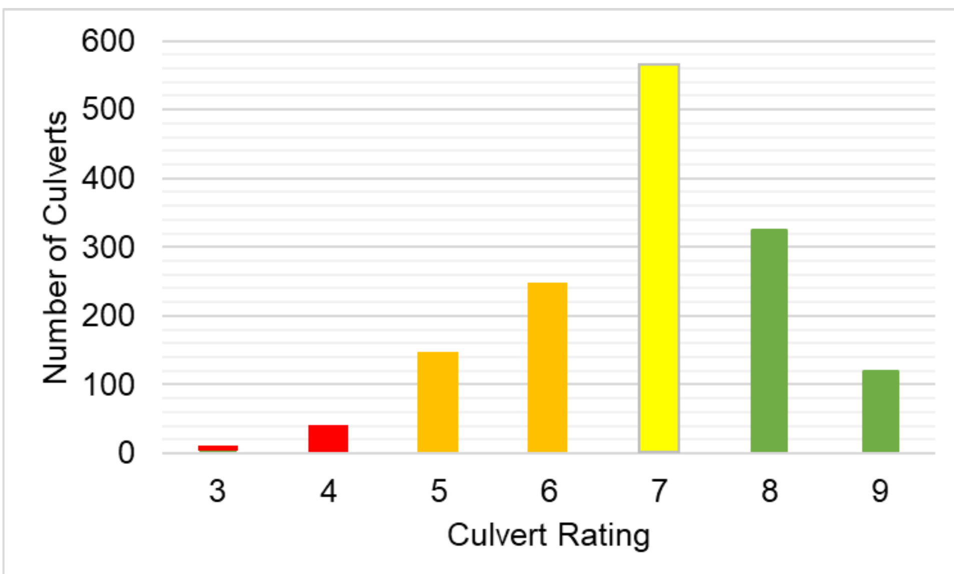

Figure 16 – Number of Likely Aluminum Culverts by Culvert Rating from LTBP Database

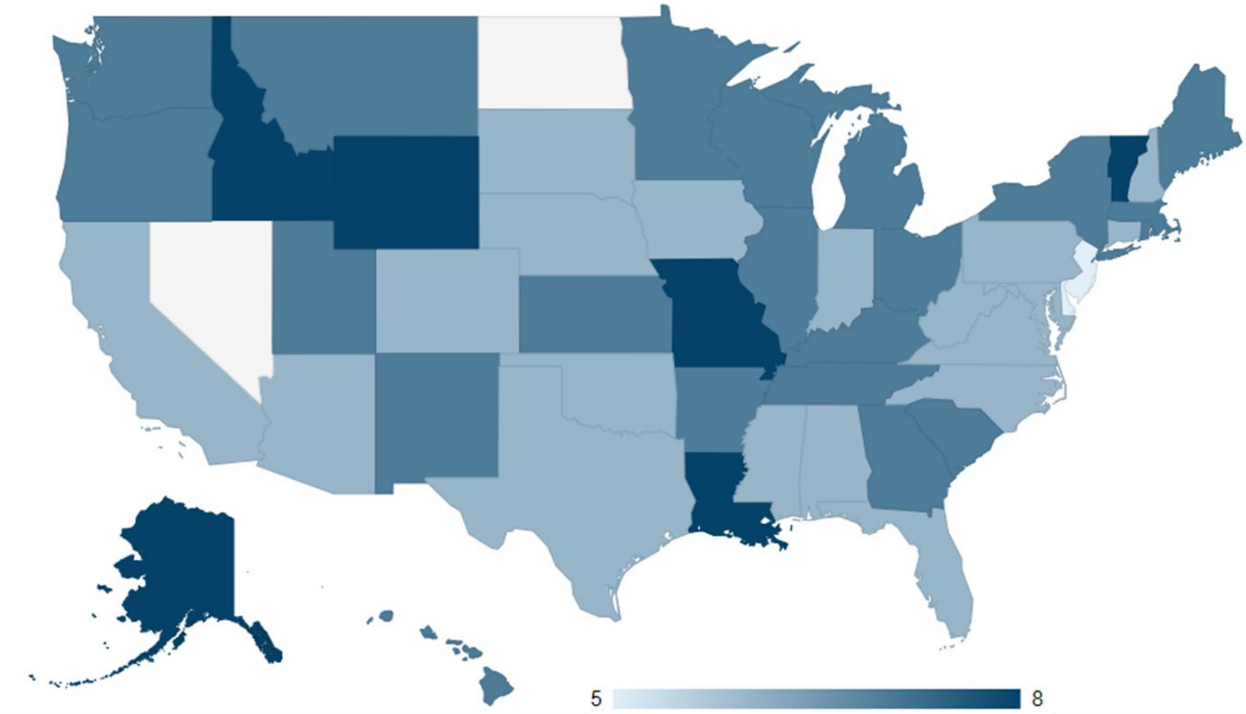

Figure 17 – FHWA LTBP Database Map [*74*] for Average Culvert Rating by State of Likely Aluminum Culverts (Darker Shading is More Favorable Rating)

Note that Washington State, which does not allow metal culverts in the state DOT right of way, does have likely aluminum culverts in its inventory. The LTBP data includes information from several sources, including other custodians, such as counties and local agencies, with structures not in the state DOT right of way. It is also possible the aluminum culverts were installed through a special provision, or prior to the DOT prohibition of metal culverts if they were allowed at some prior time.

Given the above information, we group the culverts from the LTBP database as follows:

- **Low Rating (44 of 1,442 culverts)**: Culvert rating of 3 to 4, serious to poor condition.
- **Medium Rating (390 of 1,442 culverts)**: Culvert rating of 5 to 6, fair to satisfactory condition.
- **Good Rating (564 of 1,442 culverts)**: Culvert rating of 7, good condition.
- **High Rating (444 of 1,442 culverts)**: Culvert rating of 8 to 9, very good to excellent condition.

The geographic distribution of likely aluminum culverts in the LTBP database with culvert ratings classified as Low (red), Medium (orange), Good (yellow), and High (green) superimposed based on their latitude and longitude on an equirectangular map of the US is shown in Figure 18.

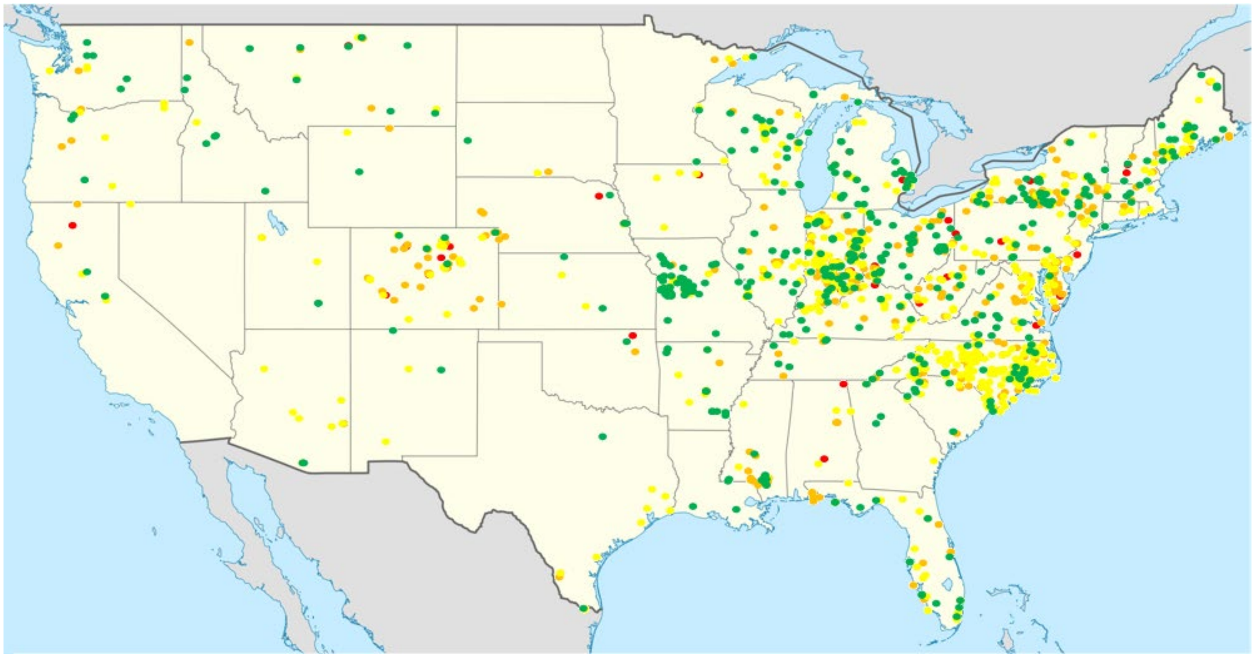

Figure 18 – Geographic Distribution of Likely Aluminum Culverts in LTBP Database with Low, Medium, Good, and High Culvert Condition Ratings (Culvert Locations Superimposed on Equirectangular Map from [*75*])

The red and orange dots representing likely aluminum culverts with Low and Medium Culvert Rating, respectively, are scattered throughout the US without any obvious correlation.

Although the LTBP database does not provide a direct indication of culvert corrosion, we checked for correlation between culvert rating and various metrics in a similar manner to the HSIS and North-Central Wisconsin District data, above. Detailed figures utilized to understand trends in the available LTBP data and a complete description of the figures and data are provided in pp. C14 to C22 of Appendix C. Overall conclusions from the LTBP data for likely aluminum culverts include the following:

- **Geographic Distribution (Figures 17 and 18 above and C.20 and C.21 in Appendix C)**: The geographic distribution of likely aluminum culverts with Low, Medium, Good, and High Culvert Ratings appears to be random, with no particular geographic region appearing to have a higher likelihood of culvert distress.

- **Span (Figures C.20 and C.21)**: Excluding the fourteen likely aluminum culverts listed with spans of 0 m (0 ft), the remaining spans range from 0.6 to 74.5 ft., with an average of 21.0 ft and median of 22.0 ft. Considering this is a national database with many structures entered into the database because of federal NBI requirements, which require inventory and inspection data for bridge-length structures, it makes sense that the majority of structures are in the 20 to 30 ft span range. The data show no strong correlation between culvert rating and span. On a percentage basis, the distribution of colors in Figure C.19 appears relatively consistent between the four different groups.

Figure C.20 does show that culverts with the lowest ratings (culvert rating of 3 or 4) all have spans of about 35 ft or less.

- **Age (Figures C.22 and C.23)**: Ages range from 1 to 118 yrs for these likely aluminum culverts, with an average age of 21.1 yrs and median of 20.0 yrs. Older structures generally show lower ratings, which is evident in both figures.

- **Length (Figures C.27 to C.29)**: Barrel lengths range from 20 to 600 ft, with an average of 30.4 ft and median of 24.9 ft. The proportions of low, medium, good, and high ratings on the histograms in Figures C.27 (lengths up to 60 ft) and C.28 (lengths greater than 60 ft) appear evenly distributed aside from the two structures listed with barrel lengths in the 140 to 180 ft range, which both have a culvert rating of 8. The distribution of culvert ratings by barrel length is shown in Figure C.29.

- **Average Daily Traffic (ADT, Figures C.30 and C.31)**: ADT ranges from 0 to 139,500 vehicles, with an average of 1,547 vehicles and median of 220 vehicles. The data shows that the lowest-rated structures also have relatively low ADT. Figure C.30 provides an adjusted scale limited to a maximum ADT of 10,000; this figure shows that the majority of the culverts with lowest ratings have 2,000 or less vehicles ADT. This is surprising, considering the likelihood for increased use of deicing salts and chemicals on roadways with higher ADT, but may reflect rehabilitation efforts being applied to higher-importance roadways.

5. FIELD INSPECTION OF THREE ALUMINUM CULVERTS IN WISCONSIN

5.1 Goals of Inspection and Inspection Plan

We selected three aluminum culverts in Wisconsin for field inspection and performed site visit inspections in July 2018. The goals of the inspection were to assess the barrels of the structures for acceptable performance or signs of distress, quantify environmental conditions at the sites to potentially correlate the environmental conditions with in-service performance, assess the culverts for abrasion based on FHWA and Caltrans abrasion classification from site observations, collect soil and water samples for laboratory testing, make observations of any other conditions at the sites that may be of value to the research, and confirm findings from other phases of the research.

We performed the culvert inspection and rating based on the new Culvert and Storm Drain System Inspection Manual developed under National Cooperative Highway Research Program Project 14-26 [*76*] that has been recently adopted by AASHTO as a Guide for publication in early 2019. The detailed culvert inspection plan, including inspection tasks, equipment lists, references to standards for the soil and water test standards, sampling details, and blank inspection and rating checklists is provided in Appendix D. The culverts were rated on a 5-point scale, where 1 indicates good condition and 5 indicates failed condition.

5.2 Culverts Selected for Inspection

We reviewed the most recent inspection reports and conditions of several aluminum culverts from the HSIS database, the North-Central District inspection results, and the geographic distribution of several candidate culverts. We selected two corrugated aluminum structural plate pipe arches from the HSIS database [*70*] and one corrugated aluminum pipe from the North-Central District inspection file [*71*].

Culvert 1 (WisDOT Structure C030048) is a single-span corrugated aluminum structural plate arch pipe with 11 ft nominal span below State Highway 25 near Barron, Wisconsin. The culvert is a cross-culvert in an agricultural area with corn fields to either end. The most recent inspection report for Culvert 1 was issued 15 May 2018, identifying 1983 as the original construction date, and inspection results identified 21 ft of the 63 ft barrel length rated as Condition State 3, which for metal barrels is poor condition with more advanced corrosion and significant section loss. The inspection report noted 12 ft and 9 ft long sections with pitting and perforations, and the culvert was recommended for replacement with medium priority. The roadway over the structure was rated Condition State 1, good condition.

Culvert 2 (WisDOT Structure P580065) is a three-span corrugated aluminum structural plate arch pipe with 9.5 ft nominal spans below a local road near Birnamwood, Wisconsin. The three spans carry the middle branch of the Embarrass River below Church Road, with wooded and rural residential areas nearby. The most recent inspection report for Culvert 2 was issued on 2 November 2016, identifying 1971 as the original construction date, and inspection results identified all 130 ft of the barrel rates as Condition State 1, which for metal barrels is good condition, no corrosion. The inspection report did not have a rating for pavement cracking. No remedial action was recommended for the barrel of Culvert 2.

Culvert 3 (WisDOT Structure 190700670) is a single-span 36 in. diameter corrugated aluminum pipe below State Highway 70 near Florence, Wisconsin. The structure carries a stream below the highway with wooded and rural residential areas nearby. The culvert was listed in the North-Central District aluminum culvert inspection spreadsheet as having been inspected most recently on 20 November 2017. The pipe barrel was rated with Condition Rating 3 for corrosion, with inspection notes identifying the end walls as completely corroded through and the pipe barrel showing signs of corrosion and cracking. The roadway over the structure was rated as Condition Rating 3 for cracking. Recommendations from the report included replacement of the pipe.

The three structures are shown on a map in Figure 19, and information from above is summarized in Table 6. Inspection results are discussed in the following sections, and detailed inspection results and photographs are provided in Appendix D. Results from laboratory testing of soil and water samples collected during inspection are included in Appendix E.

Figure 19 – Geographic Distribution of Three Culverts Selected for Field Inspection [*73*]

Table 6 – Summary of Information from Three Inspection Culverts Prior to Research Team Field Inspection

Property	Culvert 1	Culvert 2	Culvert 3
Structure Number	C030048	P580065	190700670
Coordinates	45°26’57.1”N, 91°50’50.7”W	44°56’35.0”, 89°8’47.0”W	45°54’33.1”N, 88°16’27.0”W
Descriptive Name	Highway 25 over Drainage	Church Rd over M BR Embarrass River	Highway 70 over Stream
Custodian	State	Town	State
Year Built	1983	1971	Unknown
No. of Spans	1	3	1
Individual Span (ft)	11	9.5	3
Rise (ft)	7.2	Not Reported	3
Length (ft)	63	44 each	60
Cover (ft)	3.5	0.5 to 1	5
ADT	Not Reported	206	Not Reported
Comments	2018 inspection notes pitting and perforations; dry bed at time of photos	No barrel distress noted; selected for low cover and “good” condition	2017 inspection notes pipe showing signs of corrosion, recommended for replacement

5.3 Inspection Results

A summary of observations from the field inspection and results from laboratory testing of samples of soil and water collected during the inspection is presented in Table 7. Detailed observations for each culvert follow the summary table.

Table 7 – Summary of Findings from Field Inspection

	Property	Culvert 1	Culvert 2	Culvert 3
Field Observations	Span	11.5 ft	3 at 5.5 ft	3 ft
	Rise	6.8 ft	6.8 ft	3 ft
	Length	64.5 ft	3 at 44 ft	55.5 ft
	Fill Depth	3 to 3.5 ft	0.75 to 1.5 ft	3 to 4 ft
	Average Measured Wall Thickness (UT Gage)	0.092 in.	0.137 in.	0.096 in.
	Barrel Condition	Corrosion pits have coalesced to large through-wall perforations between springlines to shoulders	Intermittent quarter-size white corrosion stains above springline	Surficial white stains emanating from seams; no visible pitting, white staining is spread throughout the pipe length
	Barrel Condition Rating	3	2	3
	Pavement Condition	Sealed Cracks	Narrow Cross Cracks	Sealed and unsealed cracks
	Pavement Condition Rating	2	2	2
	Water pH	6	7	6
	Soil Resistivity	5,481 Ω-cm	33,863 Ω-cm	12,492 Ω-cm
Laboratory Tests	Soil pH	6.27	5.33	6.33
	Soil Description	Moist red silt	Moist dark brown silt	Moist dark brown silt
	Soil Resistivity	5,682 Ω-cm	2,270 Ω-cm	12,396 Ω-cm
	Soil Chloride Ion Content	< 10 ppm	< 10 ppm	< 10 ppm
	Soil Sulfate Ion Content	24 ppm	34 ppm	60 ppm
	Water Chloride Ion Content	65 mg/L	12 mg/L	< 5 ppm
	Water Sulfate Ion Content	10 mg/L	6.8 mg/L	< 5 ppm

Field-measured soil resistivities reported in Table 7 are average values for four measurements per culvert, two pair of readings along both roadway shoulders, with one reading from each pair to either side of the culvert. Each soil resistivity reading was performed with the Wenner electrode arrangement, with the first electrode about 10 ft away from the culvert and with an electrode spacing selected to approximately match the fill depth to the culvert springline.

There was no active flow in Culvert 1 at the time of inspection. Culvert 1 had two areas of white corrosion staining from just below the springline across the crown starting from about 13 ft from the upstream end (Figure 20) over about a 10 ft length, then starting again 39 ft from the upstream end again for about a 10 ft length, approximately aligned with the roadway shoulders. At the springlines, it was evident that the corrosion was pitting corrosion, and several of the pits had coalesced to have through-wall holes (Figure 21). There was no evidence of pitting corrosion on the flat portion of the culvert at the invert. The roadway over the structure had a wide, sealed cross crack (Figure 22) with other smaller unsealed pavement cracks running across the roadway and along the wheel paths. The pavement cracking over the culvert was representative of pavement condition along the roadway for long distances in both approach directions. The fill depth above the culvert was about 3 to 3.5 ft including roadway crown. The plate sections at locations other than below the roadway shoulders generally appeared bright and shiny, without evidence of corrosion staining or other distress aside from a few local anomalies. The plate was marked Kaiser Aluminum Structural Plate, H-141 5052, 125 in. thk, 7/6/83. We measured the thickness with calipers at either end at five locations, with an average measurement of 0.101 in. at the upstream end and 0.106 in. at the downstream end. The ultrasonic thickness gage measurement taken along the length was very consistent, with an average of 0.092 in. Although we verified readings on the steel calibration block included with the UT gage, we were did not compare readings on the aluminum culvert directly at the same location as the caliper readings. The ratio of the sound velocity of aluminum to the sound velocity of steel is 1.087. The resulting average measured UT thickness is 0.100 in. Other than the presence of three boulders up to 2 ft length inside the barrel, there was no evidence of distress from abrasion, although the invert did have some darker staining and minor surficial corrosion, particularly on the galvanized steel fasteners.

In addition to the resistivity readings described above, we performed two soil resistivity tests several hundred yards away from the culvert and at least 40 ft away from the roadway in a grassy area at the edge of a field near Culvert 1. The average soil resistivity for two readings at that location was 8,558 Ω-cm, about 1.5 times the resistivity near the culvert along the edges of the roadway. The field- and laboratory-measured pH and resistivity readings would have the Culvert 1 site environment meeting FHWA, AASHTO, WisDOT, and other state DOT guidelines reviewed in this research for aluminum culvert use.

Figure 20 – Pitting Corrosion with White Staining below West Roadway Shoulder in Culvert 1; Similar Area Exists at Far Shoulder in Photo

Figure 21 – Coalesced Through-Wall Pitting Corrosion below Roadway Shoulders at Springline of Culvert 1 (East Shoulder Shown); Red Arrow Indicates Location where Small Sample of Corrosion Products and Corroded Aluminum Was Removed for Laboratory Examination (see Section 5.4)

Figure 22 – Pavement Condition with Sealed Cross Crack Directly above Culvert 1, with Additional, Smaller Cracks Nearby

Culvert 2 is a three-barrel culvert of similar corrugated aluminum structural plate pipe arch construction to Culvert 1. Culvert 2 is below a local road and carries a river branch that had active flow through each of the three barrels at the time of inspection. We measured the fill depth above the culvert to range from 0.75 to 1.5 ft including slight roadway crown and variation in fill depth over the width of the road. The pavement above had narrow, unsealed cross cracks and slight rutting of the wheel paths with map cracking in the wheel paths (Figure 23). The pavement cracking directly above the culvert was less severe than the more prominent map-type cracking and deeper rutting observed on the roadway about 100 ft away from the culvert.

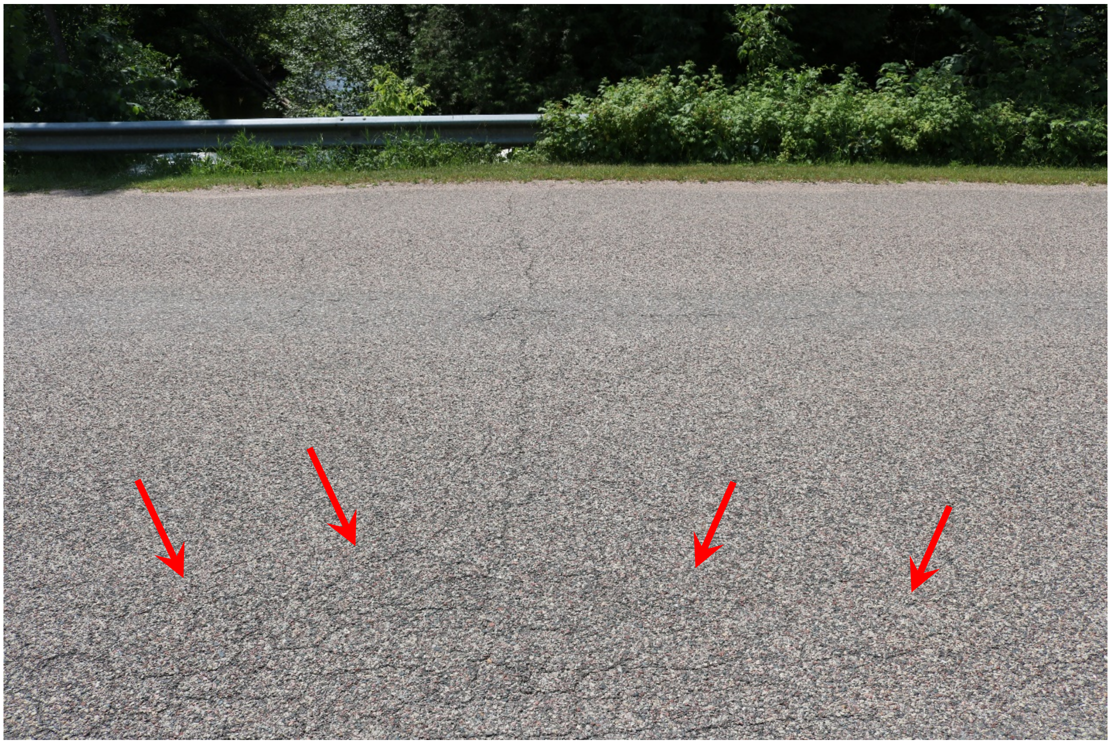

Figure 23 – Pavement Cracks above Culvert 2 Including Pavement Transverse Crack above Culvert Barrel (Center of Photo) and Map Cracking in a Wheel Path (Red Arrows at Lower Portion of Photo)

Inside the culvert barrels, we observed quarter-sized white corrosion stains on the east and west barrels below the approximate centerline of the roadway, with about an 8 in. distance between the quarter-sized stains (Figure 24). The corrosion staining was in the upper portions of the culvert, between the 10:00 and 2:30 clock positions. There was no evidence of corrosion staining below the springlines.

Figure 24 – White Corrosion Staining Emanating from Approximately Quarter-Sized Areas of Likely Pitting Corrosion (Red Circles) Near Mid-Length of West Barrel at 2:30 Clock Position (Looking Downstream)

The culvert barrels were stamped Kaiser Aluminum Structural Plate 5052-H-141 GA.150. We measured an average thickness with calipers of 0.150 in. and 0.149 in. at the upstream and downstream ends of the center barrel, respectively. We measured an average thickness along the length of the center barrel of 0.149 in. (0.137 in. before factoring by the ratio of the sound velocity of aluminum to the sound velocity of steel). Other than the occasional, spread-out areas of corrosion staining from likely corrosion pits, we observed no other evidence of distress in the culvert barrel aside from very minor surficial corrosion of the galvanized fasteners. Although the bed load consisted of sandy silt with rocks and occasional rounded boulders up to 18 in. in length, the culvert did not appear to be suffering detrimental effects of abrasion.

The field- and laboratory-measured soil resistivities differed greatly at the Culvert 2 site. The field measurements were taken as described earlier in this section, along the edges of the roadway, and were quite high compared to other measurements in this research. The soil sample on which the laboratory measurements were performed was taken along the river bank approximately 25 ft from the roadway embankment, in a relatively high-vegetation area at approximately the same elevation as the culver invert. The field- and laboratory-measured pH and resistivities at the Culvert 2 site meet environmental condition limits for aluminum culvert use.

Culvert 3 was a single-barrel 36 in. diameter riveted corrugated aluminum pipe that appeared to have extensions at the upstream and downstream ends, likely from road widening. The culvert had active flow at the time of our inspection. The main portion of the barrel had riveted circumferential seams at 24 in. on center, with one longitudinal seam in each 24 in. long ring (Figure 25). The galvanized steel end structures, upstream and downstream of the aluminum barrel extensions, were corroded through without any remaining material below the flowline (5:00 to 7:00 position across invert). A 20 ft length of the culvert below the center of the roadway had heavy white corrosion staining widespread over the inside surface at the upper portion of the circumference that appeared to be emanating from the seams (Figures 26 and 27). The seams alternated for each 24 in. long culvert section, present at either at the 10:30 or 1:00 clock positions. No white corrosion staining was visible in the lower flow area of the culvert.

Figure 25 – Typical View Inside Culvert 3 with Riveted Circumferential Seams at 24 In. On Center and One Longitudinal Seam per 24 In. Long Ring; Note White Staining Emanating from Seams

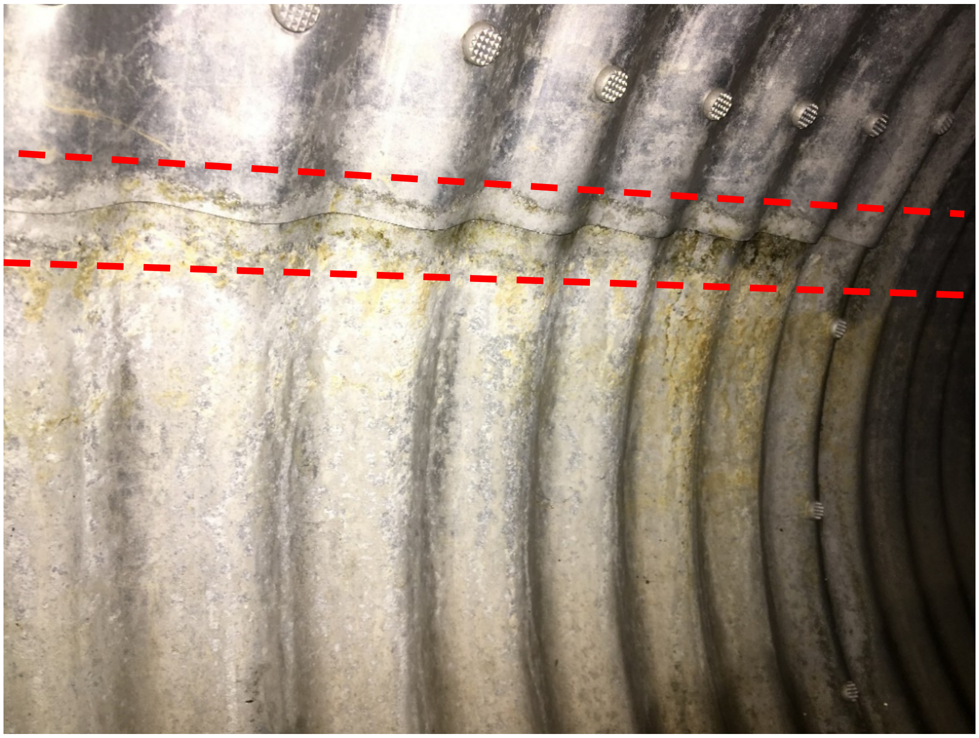

Figure 26 – Heavy White Corrosion Staining below Longitudinal Seam (between Dashed Red Lines) where Upper Section Nests Inside Lower Section at the 10:30 Clock Position near Center of Roadway

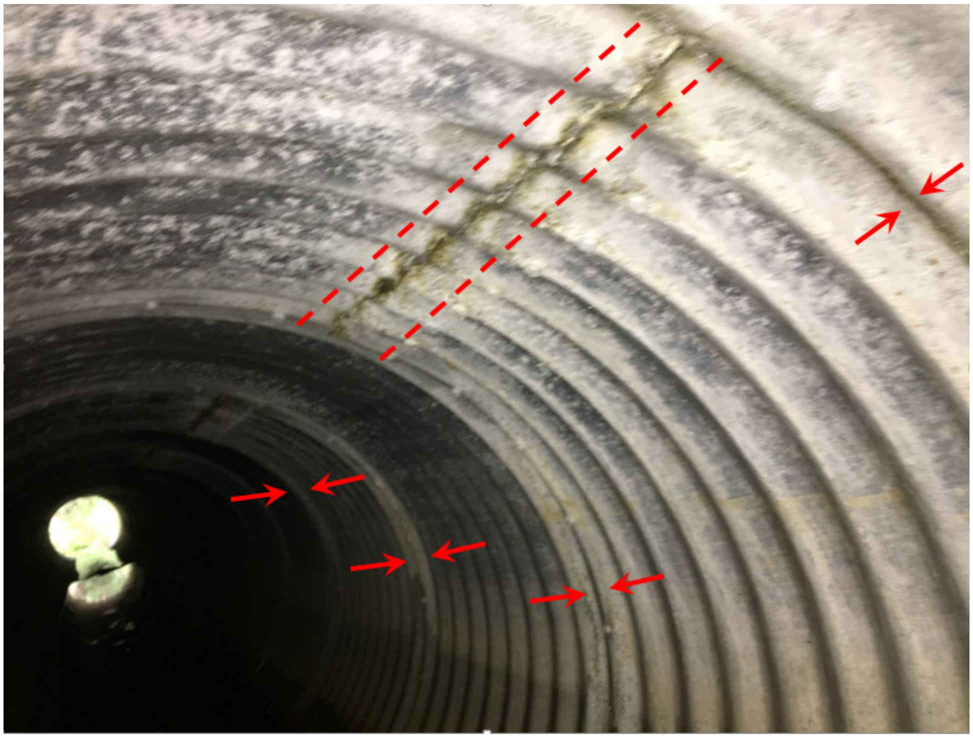

Figure 27 – Heavy White Corrosion Staining Emanating from Longitudinal Seam (between Dashed Red Lines) and at Circumferential Seams (between Pairs of Red Arrows) Further Into Photo; Photo Location Is Below Roadway Travel Lane

The white staining in Culvert 3 differed from the observations of confirmed and likely pitting corrosion on Culverts 1 and 2. We were unable to get reliable ultrasonic thickness measurements of the white-stained areas as the surface was irregular and would not give a reliable reading. In the end sections, we measured an average ultrasonic thickness value of 0.104 in. (0.096 in. before factoring by the ratio of the sound velocity of aluminum to the sound velocity of steel), which was lower than average caliper measurements of 0.124 and 0.117 in. at the upstream and downstream ends, respectively. Note that approximately 2.5 ft of the culvert at each end was not riveted and may have been from a different construction than the rest of the barrel, where the ultrasonic readings were performed. Such extensions are common from roadway widening projects. There was no marking visible on the culvert barrel.

We measured 3 to 4 ft of fill over the culvert including the roadway crown and noted that pavement over the culvert had unsealed cracks across and along the roadway (Figure 28). These cracks over the culvert were representative of the pavement condition for several hundred feet in both approach directions. We observed a single large rock inside the culvert, 12 in. maximum length, and a few locations with rounded gravel. We did not observe evidence of distress from abrasion at the invert. The field- and laboratory-measured pH and resistivities at the Culvert 3 site meet environmental condition limits for aluminum culvert use.

Figure 28 – Pavement Condition over Culvert 3 Showing Unsealed Cracks Across and Along Roadway

5.4 Laboratory Examination of Small Samples from Culvert 1

We removed two small samples from previously damaged areas of Culvert 1. One sample was from the downstream end of the culvert, where the top of the culvert was exposed and not in contact with soil and had been previously damaged by impact from some sharp object, potentially a mower blade (Figure 29). The second sample was taken from the edge of the through-wall corrosion at the location indicated by the red arrow in Figure 21 and included white corrosion products and a small fragment of corroded aluminum.

Figure 29 – Previously Damaged Location from which Small Sample of Uncorroded Aluminum Was Removed from Culvert 1 for Laboratory Examination (Red Oval)

Scanning electron microscopy (SEM) of the uncorroded aluminum sample after polishing the surface with 1,200 grit silicon carbide sand paper showed that the aluminum consisted of a single material across its thickness, with no visible evidence of corrosion or cladding (Figure 30). Further SEM examination using energy dispersive spectroscopy (EDS) showed that the aluminum alloy sample included 0.12% silicon, 0.36% copper, 0.13% manganese, 3.0% magnesium, 0.18% chlorine, 0.11% sulfur, and the balance consisting primarily of aluminum (values are % by weight). These results agree well with the chemical composition of a 5XXX series aluminum alloy. Chlorine and sulfur content in this sample are very small, indicating that this area of culvert was not exposed to a corrosive environment containing chlorine or sulfur.

EDS analysis on the corroded aluminum and its corrosion products revealed a relatively high level of chloride, indicating exposure of aluminum to a corrosive medium in the areas from where the corroded samples were taken. EDS analysis showed 12.75% silicon (likely from comingling of corrosion products and backfill in the sample, taken from the edge of the corroded area at a through-hole), 0.22% copper, 0.15% manganese, 1.24% magnesium, 1.6% sodium, 1.4% chlorine, 0.42% sulfur, and the balance consisting primarily of aluminum. The measured sodium content in this sample is as high as chlorine, suggesting presence or accumulation of sodium chloride salt in these areas.

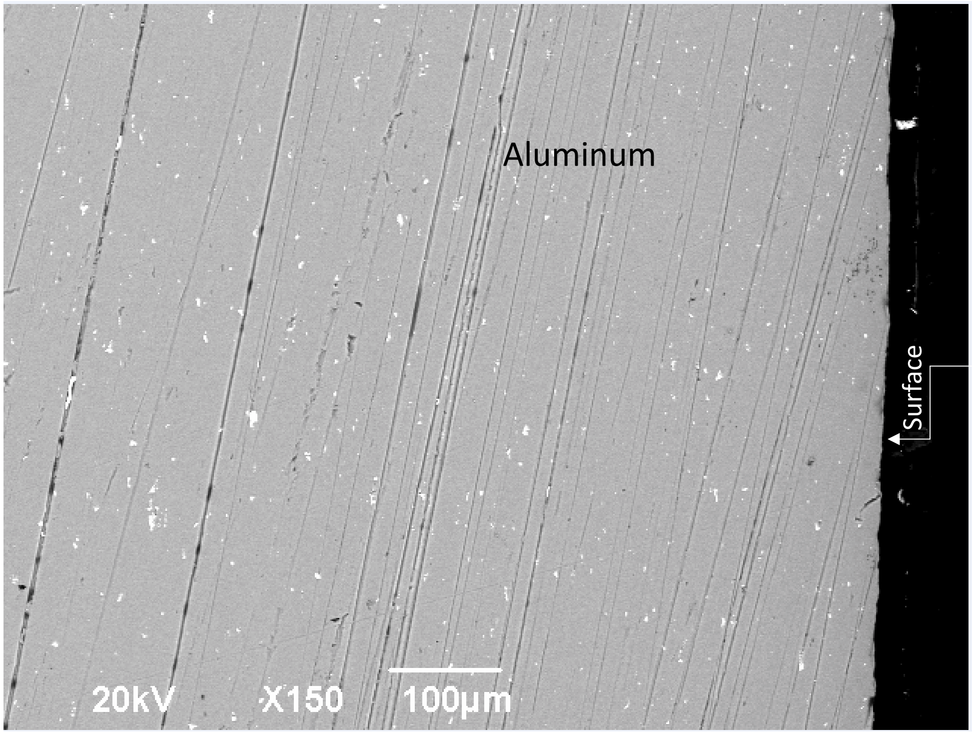

Figure 30 – Scanning Electron Microscope View of Uncorroded Aluminum Sample from Culvert 1 Showing No Visible Evidence of Corrosion or Cladding

6. DISCUSSION

The following sections provide discussion compiled from the above information regarding aluminum culvert historical use and performance, corrosion mechanisms, best practices, expected performance in the Wisconsin environment, and recommended updates to WisDOT policies and literature. Themes from this section are carried into PowerPoint slides, with a brief summary of the research project, background and identification of the pitting corrosion phenomenon, strategy for mitigation, and recommended updates to WisDOT literature, attached as Appendix F. The slides are intended to be a training tool for WisDOT designers and project planning staff to understand the research, recommended best practices, and proposed policy updates as an outcome of the research.

6.1 Aluminum Culvert Specification, Use, and Historical Performance

Aluminum has been used as a culvert material since the early 1960s. AASHTO material and product specifications dating to the 1960s show that corrugated aluminum pipe and corrugated aluminum structural plate have been specified as made from the same aluminum alloys since the introduction of aluminum culvert standards in AASHTO between 1962 (introduction of M 196 and M 197) and 1966 (introduction of M 219).

Policies in most states and federal agencies reviewed in this research (Table 8) have restrictions on aluminum culvert use in some manner, typically based on environmental conditions including site soil and water chemistry (pH, resistivity) and site abrasion classification. In addition, Federal Lands Highway and Maine recommend aluminum structures for use as culverts in tidal or brackish waters when installed with free-draining backfill. A few agencies also require protection to isolate the metal culverts from infiltrating roadway salts using exterior (soil-side) coating or impermeable membrane placed in the soil above the culvert.

Of the states whose policies were reviewed in this research, only Wisconsin and Washington State have current policies that put blanket prohibitions or severe limitations on the use of aluminum culverts and pipes (Washington State prohibits all types of metal culverts). Minnesota has restrictions on use of metal box culverts that may not be well founded; the Minnesota DOT is currently performing a statewide condition survey to develop a revised policy for culvert material selection based on documented in-service performance.

Aside from abrasion, which can be addressed following well-accepted guidelines on a site-by-site basis, the general consensus for environmental limitations at sites where aluminum culvert use is allowed is that the site pH be between 4.5 and 9 and backfill or effluent resistivity be greater than 500 Ω-cm. Some jurisdictions allow lower pH (4.0) while others require above 5.0, and some have minimum resistivity requirements of 1,500 Ω-cm. Installations meeting these requirements have generally had good performance of buried aluminum culverts. Exceptions include locations where chloride-based deicing salts have led to severe pitting corrosion. Installations in tidal or brackish waters with resisitivities as low as 25 Ω-cm installed in free-draining backfill have also shown acceptable performance over several decades of use and inspection.

Surveyed manufacturers all responded with positive impressions of aluminum culverts from their customers when aluminum is installed in the right environment. For the eight state agencies that provided survey responses, no agency reported concerns or reasons to question aluminum culvert performance when installed in the right environment, and Ohio and Maine indicated a preference for aluminum culverts over other metal culvert options. Installations in coastal regions with free-draining backfill and routine flushing of the areas of the culverts in contact with salt water either through tidal action or fresh water from precipitation draining through free-draining backfill perform well. Maine recently reviewed their specification for aluminum culverts and updated it to require aluminum fasteners in place of galvanized steel in most installations based on recent performance observations.

Review of aluminum culverts in the Wisconsin HSIS database, Wisconsin North-Central District small-diameter culvert inspection findings, and data of likely aluminum culverts in the FHWA LTBP database suggest no discernable link between geographic location and corrosion level or culvert condition rating. Even the structures in the LTBP database, spread throughout most states, and in many states that see significant frozen precipitation and have a high likelihood of deicing chemical usage on roadways, do not show a significant increase in corrosion when compared to warmer, southern regions. Culverts with higher corrosion levels and poor to severe condition ratings for the aluminum culvert barrels appear to be randomly distributed within each database subset, with acceptably performing culverts nearby.

Data from the HSIS and LTBP database suggest older structures are more likely to be identified as corroded (the North-Central Inventory did not include culvert age data). The HSIS and North-Central data had no notable correlation between corrosion level and fill depth, though median fill depths for the two data sets were both less than 5 ft. The LTBP data did not include fill depth.

The HSIS data did not suggest a correlation between ADT and culvert corrosion level; the LTBP data suggested culverts with lower ADT tend to have a poorer culvert barrel condition rating. The North-Central data did not include ADT. The LTBP trend of poorer culvert barrel rating correlating with lower ADT is surprising considering the likelihood that higher ADT may correlate with increased use of road deicers; however, data from WHRP Project 0092-17-03 do not show general increases in road deicer usage in areas that would be expected to have greater ADT.

Data from the HSIS database suggest a greater corrosion potential for shorter-span culverts, with most culverts identified as having corrosion having spans less than 13 ft even though the majority of the culverts in the database had spans greater than 13 ft. Data from LTBP did not have a significant correlation between culvert barrel condition rating and span, and all structures in the North-Central Inventory had relatively short spans, which made it impossible to discern a correlation. The HSIS database culvert length data suggest that barrel lengths in the 60 to 80 ft range may be more prone to corrosion than barrels with shorter or longer lengths, though it is unclear if the lengths reported were the lengths of individual barrels or the total length of all barrels for multi-barrel culverts. The North-Central data and LTBP data tended to show that all ranges of barrel length have proportionally similar distributions of low, medium, good, and highly rated culvert barrels.

The strongest correlation between aluminum culvert corrosion and the various metrics available in the three databases was that increased corrosion correlates well with increased pavement cracking. This trend was identified in the HSIS and North-Central databases (the LTBP data had no metric to identify level of pavement cracking). This correlation was also identified by Patenaude and is supported by the findings of the field inspection component of this research. The field observations also identified that pavement cracking directly over the culverts was representative of the pavement condition for several hundred feet in either approach direction; therefore, the cracking was not attributable to the presence of the culvert.

Table 8 – Summary of Aluminum Culvert Usage Limitations, Design Life, and Protection by Agency

Agency/ State DOT	Notes on Aluminum Pipe Use	Notes on Aluminum Structural Plate Use	Desired Service Life	Coatings, Membrane, Backfill Requirements
AASHTO	Resistivity > 500 Ω-cm, pH between 4.0 and 9.0 Carefully evaluate for abrasion if flows are 15 ft/sec or greater	No specific notes for structural plate	75 yrs for structures	General statement: soil-side coating can add 25 yrs to metal
Caltrans	Resistivity > 1,500 Ω-cm, pH must be between 5.5 and 10.0; aluminum not recommended or allowed for abrasive sites with flow greater than 8 ft/sec (sites with Abrasion Level ≥ 4)	Same as for aluminum pipe	50 yrs	Test backfill, less corrosive than native soil
Federal Lands Highway	Resistivity > 500 Ω-cm, pH between 4.0 and 9.0 Use in salt and brackish environments if embedded in granular, free-draining material, additional requirements considering abrasion	No specific notes for structural plate	50 yrs	None
Maine	Recommends aluminum for salt water	Recommends aluminum for salt water; adds thickness for corrosion/abrasion; aluminum box culverts allowed and preferred over steel; requires aluminum nuts and bolts	50 yrs	None
Michigan	No particular notes or restrictions found	References ASTM B790 for material and not AASHTO M 219	50 yrs	None
Minnesota	No notes or restrictions particular to aluminum	Metal box culverts allowed but with limitations, aluminum not specifically mentioned in metal box technical memorandum	Not specifically mentioned in docs reviewed	None
New York	No notes or restrictions particular to aluminum	No notes or restrictions particular to aluminum; metal box culverts (including aluminum) are noted as cost effective with corrosion is not an issue	50 yrs typical, 70 yrs for significant locations such as interstates	None
Ohio	Allowed only where pH is between 5 and 9 and with Abrasion Levels 1 or 2	Allowed only where pH is between 5 and 9 and with Abrasion Levels 1 or 2; aluminum boxes are allowed, subject to above restrictions	75 yrs for important or deep fill structures	Yes, over all conduits
Wisconsin	ADT < 1,500; aluminum recommended over steel where pH is outside the range of 5 to 9 and resistivity is below 2,000 Ω-cm, or where resistivity is less than 1,000 Ω-cm regardless of pH	Aluminum structural plate use is restricted in a similar manner to aluminum pipe; aluminum structural plate box culverts are not allowed	20 yrs to first perforation	Aluminum use limited to side drains and highways with less than 1,500 ADT unless isolated from infiltrating deicing salts; no additional guidance on how to isolate from salts

6.2 Aluminum Culvert Corrosion Mechanisms and Mitigation

Aluminum will perform well as a culvert material in a natural environment where the soil and water pH range from 4.5 to 9, resistivity is greater than 500 Ω-cm, site abrasion classification is between Abrasion Level 1 and 3, and soil chloride concentrations are not excessive. At such sites, aluminum is robust against general corrosion and is expected to provide a long service life with little or no uniform section loss.

Aluminum and its alloys, however, will corrode when exposed to chlorides, typically by pitting corrosion following adsorption or drying of the chloride and formation of a concentrated chloride film on the surface. Research suggests that there is no threshold for the chloride concentration below which pitting will not occur and that the presence of an adsorption inhibitor will delay but not prevent the onset of pitting. Adsorption of chlorides will not occur if the pH is greater than the zero charge threshold; however, this threshold is pH 9.1 for aluminum oxide, and the pH of soil in Wisconsin is less than this threshold. If there are chlorides present in soil that is in contact with a buried aluminum culvert in Wisconsin, and these chlorides are not rinsed by regular water flow, such as in brackish tidal areas or through free-draining backfill, the chlorides are likely to adsorb on the aluminum surface and form pits.

Once adsorbed, chlorides become embedded in the aluminum oxide film, with greater concentration at the outer surface and no initial evidence of chloride at the oxide/base metal interface. Research showed that chlorides migrate through the aluminum oxide layer over time, eventually contacting the underlying aluminum or aluminum alloy. The tough and durable aluminum oxide passive film on the surfaces of aluminum works well for general corrosion resistance. However, this film also works as a barrier that encloses and conceals the pit environment, allowing the pit to work its way through the thickness of aluminum. The pit cover acts as a physical barrier against current flow and diffusion that helps to maintain a concentrated, aggressive, extremely acidic environment inside the pit. If the critical concentration of the solution in the pit can be maintained and will not change in time, the pit will grow. With the pit cover acting as a physical barrier against current flow, the current from differences in electrical potential within the saline pit is required to flow through the aluminum, contributing to the anodic depletion of aluminum inside the pit.

Pitting corrosion was observed on two of the three culverts in the field investigation phase of this research (Culverts 1 and 2). In North-Central Wisconsin, the DOT District has undertaken in-depth inspection and remediation of small-diameter culverts exhibiting corrosion-type distress, including many aluminum culverts displaying evidence of pitting. Pitting corrosion was also observed by Patenaude in the 1990s and early 2000s and found to be the cause of aluminum culvert distress that led to the current WisDOT policy limiting aluminum culvert use.

The pitting corrosion phenomenon has not been observed to affect structures in tidal or brackish environments with dissolved salts when installed in free-draining soils and subject to rinsing. This is based on inspection data and findings from Maine and other coastal regions, which report no major corrosion of aluminum culverts (aside from the galvanized steel fasteners formerly used in Maine). Several coastal jurisdictions allow aluminum culverts to be installed in free-draining backfill with backfill or water resistivities as low as 25 Ω-cm.

The most effective means to avoid pitting corrosion in buried aluminum that may be subject to chloride-based deicing salts leaching through cracked pavement is to prevent pitting initiation. This can be achieved through protection of the aluminum surfaces from contact with chlorides or by inhibiting pit formation and growth.

Regarding general coating of aluminum as a material that may be exposed to chlorides (not necessarily in a culvert environment), conversion coatings, such as chromate or phosphate types, are recommended for use in coating of aluminum alloys. Chromates have been shown to be an effective inhibitor of aluminum pitting in research; however, the effectiveness of chromate as an inhibitor decreases with a decrease in pH, and it may not function well for inhibition of pitting in aluminum if there is an acidic pH. Acrylic, alkyl, polyester, and vinyl paints may be suitable coatings for aluminum depending on the specific environment. For very corrosive environments with high levels of chlorides, a chromated primer is recommended to be applied first, though, as noted above, chromate inhibitors may not be effective with an acidic pH. While limited to factory-applied applications and potentially more expensive than other types of coating, anodized coatings provide excellent protection to aluminum alloys with a coating thickness of 0.2 to 1.2 mils. As with any coated metal, surface preparation will be key to long-term coating performance. Adequate surface preparation and cleanliness prior to application of coatings have a direct effect on bonded coating durability; therefore, bonded coatings are typically factory applied and touched up as needed in the field. Specific coating types identified in this paragraph have not been evaluated for suitability of use in a buried aluminum culvert environment.

There is currently no AASHTO or ASTM specification for coating aluminum culverts. Such standards for other metallic culvert types include specific language for coating specification, inspection, and repair or rejection if the coating is damaged prior to completion of construction.

For general coating of metal culverts (generally applicable to steel), AASHTO notes that soil-side bonded protection can provide 25 yrs of additional service life to metallic culverts where conditions are not unduly severe. It notes that the quality of applied coating is dependent on the coating bond with the base culvert material and emphasizes the importance of a clean application process to provide the expected level of protection. Mill-applied thermoplastic coatings are identified as having the best performance in comparison to fiber-bonded coatings (second best), followed by bituminous coatings. The AASHTO information is generic to metallic culverts, not specifically for aluminum.

Stress-corrosion cracking can occur in aluminum alloys that have significant compression stress and appreciable amounts of soluble alloying elements, a list of which includes magnesium and zinc, which are the primary alloying elements of aluminum culvert alloys. Compression stress is found in culvert walls and is highest at the culvert springline. Compression stress can contribute to pitting corrosion and cracking of the thin-film protective layer if the stress is present over a long period of time, which is typical for buried culverts.

The worst-case pitting corrosion with through-wall holes at coalesced pits occurred near the springline of Culvert 1 in the field inspection component of this research. It was likely exacerbated by compression stresses, coupled with high gradient of soil-side oxygen concentration at the transition from unpaved shoulders or embankment and increased chloride concentration from deicing salt migration vertically through unpaved shoulders or embankment and/or pavement cracks.

In terms of corrosion susceptibility, the aluminum alloys used for corrugated aluminum pipes and structural plate are from the best-suited alloy series for performance in the culvert environment and when subjected to chlorides.

6.3 Best Practices for Aluminum Culverts

Buried aluminum culverts can be susceptible to general corrosion if installed at sites that do not meet soil and water pH, resistivity, and abrasion guidelines. Best practices to counteract general corrosion and abrasion are to limit aluminum culvert installations to non- or low-abrasive sites in

Wisconsin with soil and water pH between 4.5 and 9.0 and soil and water resistivities greater than 500 Ω-cm. These limitations on pH should be met by nearly all locations in Wisconsin except for some extremely acidic locations just west of the central portion of the state. Abrasion can be evaluated on a site-specific basis using existing guidelines from Caltrans or the FHWA.

Where aluminum culverts are installed at sites that meet the requirements in the above paragraph and are isolated from contact from concentrated chlorides, aluminum culverts have been shown to be very durable against general corrosion. Therefore, there is no general corrosion loss rate associated with design of aluminum culverts when these environmental conditions (pH, resistivity, abrasion limits, and isolation from chlorides) are met.

Buried aluminum culverts in regions with deicing chemical usage are susceptible to pitting corrosion attack from chlorides if measures are not taken to eliminate potential contact of chlorides and adsorption on the aluminum surface. Once pit growth starts, it cannot be easily arrested in a typical buried environment.

Chloride adsorption and formation of pits can be limited by a variety of methods that prevent chloride concentration on the metallic surface, including rinsing by water flows through free-draining soils (even of relatively low-saline solutions such as seawater), potentially coating the exterior surface of the structure, or adding in-ground features to divert roadway surface water runoff.

As noted in the section above, appropriate surface preparation, primers, and paints may be used, as well as anodized coatings, for coating aluminum materials, though there is currently no coating speciation for aluminum culverts. Mill-applied thermoplastic coatings may also show promise. AASHTO notes that some states have reported significant increases in service life for coated metal culverts and that some of the coatings are not considered cost effective. Maine does not require coating on aluminum culverts but did note in their survey responses that contractors prefer steel culverts over aluminum because of cost (when bidding options) while the state prefers aluminum over steel for the increased corrosion resistance.

Several culvert manufacturers now have standard details to include coatings and/or impermeable thermoplastic membranes over metallic culverts within the backfill envelope. The purpose of this protection is to limit the potential for chloride ingress from deicing salts leaching through pavement or unpaved shoulders and the soil fill to contact and dry onto the buried metal structures.

Considering the cost of coating, surface preparation, and repair of coating, using coatings is typically more expensive than using an isolation membrane embedded in the backfill envelope and limiting chloride content in free-draining backfill below the membrane.

Membrane protection of culverts has been implemented in recent buried bridge-type culvert projects in states with aggressive winter environments, where culverts may otherwise be prone to contact with deicing salts from vertical migration through soil. Culvert membrane protection details are based on provisions for membrane protection of metallic components of MSE wall systems to protect them from ingress of chlorides from deicing salts along the soil-wall interface, a very similar corrosion protection need. From our literature review, it does not appear there is a generally accepted specification for these membranes at the current time. Best practices for membrane specification include the following:

- Membranes should be made from PVC, HDPE, or LLDPE with roughened surfaces and have a minimum thickness of 0.03 in.
- Membranes should be sloped away from the structure and should extend at least 10 ft outside the paved shoulder and for the width of the trench.
- Seams should be glued or welded (field seams should be avoided where at all possible) with a minimum overlap of 12 in.
- Minimum material requirements for membranes should include a minimum ASTM D1004 tear resistance of 10 lbf, a minimum ASTM D4833 puncture resistance of 32 lbf (or alternatively a minimum ASTM E154 puncture resistance of 40 lbs; the merits and applicability of ASTM E154 versus ASTM D4833 should be evaluated), and an applicable minimum elongation (Ohio DOT requires 300% in accordance with ASTM D412 Die C, but there may be other, more suitable specifications and requirements).

Caltrans [*36*] recommends that backfill for culvert installations be less corrosive than the native material and gives reference to backfill material test specifications, including chloride ion content of backfill. Caltrans MSE wall structural backfill is limited to a chloride ion concentration of less than 250 ppm based on protecting steel reinforcement from corrosion. FHWA-sponsored research by Berg et al. [*34*] recommends testing MSE wall backfill surrounding steel reinforcement for chlorides with a recommended limit of < 100 ppm. Patenaude, the WisDOT geophysical engineer, identified native soils in Wisconsin not exposed to fertilizer, road salts, or other chlorides to generally have a chloride concentration between 10 and 20 ppm.

Neither the Caltrans or FHWA limits nor the Patenaude expectations for Wisconsin soil chloride content were derived based on chloride exposure from free-draining soils in contact with buried aluminum. An appropriate limit for backfill should be established and enforced for backfill below isolation membranes. Ahead of possible further research specific to establishing this limit for backfill soils in contact with buried aluminum culverts in Wisconsin, we recommend following the FHWA guidelines from steel MSE wall reinforcement with an upper limit of 100 ppm, which is expected to be achievable for available soils in Wisconsin. Additional corrosion prevention may be achieved through requiring the embedment adjacent to and covering aluminum culverts to be free-draining soils, which will allow rinsing and will not concentrate chlorides on the aluminum that can be adsorbed.

Where aluminum may be in contact with other metals or concrete, there should be a dielectric barrier of asphalt mastic or other caulking compound. This is true for concrete invert pavement or where, for example, steel end structures or extensions are added to existing aluminum culverts, or other large potential contact areas for dissimilar metals. Regarding fasteners, experience, including in the field inspection component of this research, has shown that galvanized steel fasteners appear to provide acceptable performance even in culverts with severe pitting corrosion when installed in nonbrackish, noncoastal environments. In Wisconsin, galvanized steel fasteners should provide sufficient service life for buried aluminum structural plate culverts without the need for dielectric barriers between the fastener and culvert barrel or for requiring aluminum fasteners as in coastal areas.

Field- and laboratory-based research has suggested chloride-induced pit growth rates decrease with time. It may be possible to specify additional thickness for culverts to offset pit growth rates and to potentially reach a required service life without other measures to protect and isolate aluminum culverts. However, there is not enough research on this phenomenon at this time to accurately quantify pit depth growth rates considering the variety of exposure conditions in a buried culvert environment and, of the three culvert alloys, only limited previous results are available from alloy 3004. This could be a potential topic for future research or laboratory study. As noted above in this section, there is no general corrosion loss rate recommended for aluminum culvert design when environmental criteria are met.

6.4 Expected Aluminum Culvert Performance in Wisconsin Environment

The natural environment in Wisconsin is, in general, well suited for aluminum culvert use. However, considering the increases in chloride-based anti-icing brine usage and steady usage of chloride-based deicing salts over the last several decades, unprotected aluminum culverts will be subject to deicing salt contact from migration of the salts through shoulder areas and cracked pavement.

Buried metallic culverts will have different electric potentials throughout their lengths (e.g., below pavement compared to below unpaved shoulders), and around the circumference (e.g., top of culvert compared to outside bottom). Different electrical potentials and exposure to deicing salts will make some areas more prone to corrosion than others. High compression stress, such as may be present at culvert springlines, may also contribute to the likelihood of pitting. Aluminum culverts will suffer from pitting corrosion if left unprotected from exposure to chloride-based deicing salts or where not rinsed by water flow through free-draining backfill.

Culvert 1 from the field inspection was below a state highway and had reached the end of its service life based on large through-wall holes from coalesced corrosion pits at the springlines below the roadway shoulders. It was installed 35 yrs prior to the field inspection. Culvert 2 had evidence of less developed pits that were beginning to show through to the inside of the culverts between the 10:00 and 2:00 regions. This culvert, below a local road, had been in service for 47 yrs at the time of inspection and was still performing in an acceptable manner. The third culvert inspected in this research had an unknown year of installation and appeared to be nearing the end of its useful service life, and was slated for replacement based on its most recent DOT inspection. Other small-diameter buried aluminum culverts in North-Central Wisconsin have been identified as at or nearing the end of their service life, with several showing evidence of pitting corrosion when excavated for replacement. While pitting corrosion appears to be most prevalent at the outside crests of Culvert 1 (Figure 21), with pits beginning at a similar area in Culvert 2 (Figure 24), the pitting eventually occurs at the inside crest of the corrugations, and the pits coalesce (Figure 21). In Culvert 3, chloride contamination appears to be emanating from circumferential and longitudinal seams (Figures 25 to 27). Pitting corrosion or white staining was not observed in the lower portions of the culverts near the inverts.

Pavement cracking over each of the three culverts was representative of the pavement condition for several hundred feet in either approach direction, suggesting the cracking was not caused by the presence of the culvert. Field and laboratory tests performed for the three culverts inspected in this research show environments generally suited to aluminum culvert usage aside from the influence of exposure to deicing salts. Comparison of field and laboratory measurements of soil resistivity showed similar results when resistivity was measured in the field and when it was measured in the laboratory on samples collected from the field (Culvert 2 shows different results, but the sample collected in the field for laboratory tests was not consistent with the roadway embankment material, where the field resistivity measurements were taken). None of the three culverts was suffering from durability issues associated with abrasion. Abrasion can be evaluated on a site-specific basis when specifying new culverts.

For aluminum culverts to perform acceptably in the Wisconsin environment, they must be isolated from contact with chloride-based deicing salts. Of the three methods to prevent or offset pitting corrosion (increased aluminum thickness, factory-applied coating, or impervious membrane inclusion in the backfill layer), inclusion of a properly specified impervious membrane in the backfill envelope appears to be the most economically feasible. Such a membrane should be sloped away from the structure, extending down the embankment for at least 10 ft from pavement or to the end of the culvert, and at least equal to the trench width.

While time-demonstrated field performance of such impervious membranes over culverts has not been formally documented, use of membranes is standard practice for protecting steel reinforcement for MSE walls. WisDOT Bridge Manual retaining wall design includes recommendations for such membranes below pavement and above MSE wall reinforcement. Culvert manufacturers have adapted such membranes into metallic culvert installation specifications where required to by owners. As example, Ohio DOT has a blanket requirement for membrane waterproofing over concrete culverts and requires either membrane waterproofing or coating on metallic culverts. While there is no currently available consensus specification giving material and product requirements for such a membrane, FHWA NHI-10-024 [*34*], NH DOT MSE Wall Special Provisions [*54*], and Ohio DOT Standard Specifications [*50*] Section 711.25 Type 2 Membrane Waterproofing provide minimum requirements that may be used as the basis for potential Wisconsin DOT membrane requirements.

In addition to specifying an impervious membrane between the top of the aluminum culvert and the bottom of pavement, structural backfill below the membrane should likely be specified as free-draining material and tested for chlorides to ensure that the backfill in contact with the structure and below the membrane is below a threshold limit. Ahead of possible further research specifically performed to establish a limit of chloride concentration for backfill soils in contact with buried aluminum culverts in Wisconsin, we recommend following the FHWA guidelines from steel MSE wall reinforcement with an upper limit of 100 ppm, which is expected to be achievable for available soils in Wisconsin.

6.5 Potential Policy Updates for Aluminum Culvert Usage in Wisconsin

Suggested updates to the WisDOT Bridge Manual include the following:

- Update Chapter 36 to identify other types of box culverts other than “reinforced concrete closed rigid frames” and remove the prohibition on aluminum box culverts. Identify aluminum structural plate structures as acceptable closed and three-sided culverts when designed in accordance with the AASHTO LRFD Bridge Design Specifications. Identify requirements for isolating aluminum box culverts from chloride-based deicing salts by impermeable isolation membrane, use of free-draining backfill, and limiting free-draining backfill chloride content below such membranes.

- Update Chapter 9 to include aluminum as a culvert material.

Suggested updates to the WisDOT Facilities Development Manual include the following for Chapter 13-1-15 Culvert Material Selection Standard:

- Update Section 15.2 to include corrugated aluminum in Classes III-A, III-B, and any other applicable class. Consider removing the restriction on culvert materials other than reinforced concrete for sites with ADT greater than 7,000 unless sound engineering judgment and explanation are provided. Consider updating culvert material selection to use a similar process as the Ohio DOT culvert design process flow chart. Indicate that environmental conditions at aluminum culvert sites must meet pH, resistivity, and abrasion requirements and that an impermeable isolation membrane must be installed above the top of the structure and below pavement, with a limit on the chloride ion content of the free-draining backfill and a recommendation for free-draining backfill between the membrane and structure.

- Update Table 15.2 to allow corrugated aluminum culvert pipe with diameters up to 60 in., corrugated aluminum arch pipes, and corrugated aluminum structural plate structures, including arches, closed-bottom culverts, and box culverts, to have similar ADT restrictions to other flexible culverts, and make reference to the environmental limitations and isolation membrane notes in the bullet above.

- Update Section 15.4 to include pH and resistivity testing of soil and water samples collected from all new culvert sites, update the note on aluminum culvert restrictions to make the ADT limitation in line with other flexible culverts, and add description of environmental limits and impermeable membrane with free-draining, low-chloride-content backfill below the membrane as described in the bullet above. Add a sentence noting that new culvert sites should be evaluated for abrasion and aluminum shall only be used at sites with Abrasion Levels 1 to 3, with appropriate limits for other culvert material types.

- Update Section 15.5 to include abrasion classification for all culvert sites based on Caltrans and FHWA guidelines and include relevant information to assess culvert sites. Abrasion classification should be based on a visual survey of bedload material with flow velocity based on a 2 to 5 yr flow event.

- Update Section 15.6 and Table 15.3 to ease the restrictions on aluminum culvert use based on ADT, and update with reference to the updated versions of Sections 15.2 and 15.4, described above.

Suggested updates to the WisDOT Facilities Development Manual include the following for Chapter 13-1-25 Fill Height Tables:

- Update text in Section 25.2 to note all fill height tables should be based on design in accordance with AASHTO LRFD Bridge Design Specifications. Consider potential fill height increase for aluminum culverts with free-draining granular backfill, and perhaps compaction.

- Update fill height table Attachments 25.2, 25.6, 25.7, and 25.8 for corrugated aluminum pipe and corrugated aluminum structural plate structures of standard shapes. Consider anticipated abrasion section losses over the design life when developing minimum thickness requirements and fill height tables, and ensure that other metallic structures are similarly designed with appropriate corrosion and abrasion loss rates.

Suggested updates to the WisDOT Standard Specifications for Highway and Structure Construction include the following:

- Update Table 520-1 to include aluminum as an allowable culvert material for applicable classes of culvert pipe defined in updates to FDM 13-1-15 Section 15.2.

- Update Section 520.3 to identify where the impermeable isolation membrane should go within the backfill envelope, require that the membrane be sloped away from the structure, extending down the embankment for at least 10 ft from pavement or to the end of the culvert, and at least equal to the trench width, and recommend free-draining granular backfill, potentially with compaction (depending on fill height table inputs).

- Either develop a material and product specification or a performance-based specification for impermeable backfill membranes and include it in a new section in the Standard Specs, with reference from Section 520.3, or add the information directly to Section 520.3 if that is the only location the membrane would be used.

- Update Sections 525 and 527 to include requirements that backfill between the isolation membrane and structure must be tested for chloride ion concentration and have a concentration less than 100 ppm. Give reference to a WisDOT standard method to measure chloride ion content of backfill soils. Consider recommending or requiring free-draining backfill for aluminum culverts, and consider compaction requirements for this material (depending on fill height table inputs).

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Conclusions from the above information include the following:

- Two factors that affect aluminum culvert material durability are abrasion and corrosion.

- Abrasion can be evaluated on a site-specific basis with design for prevention following methods developed by the California Department of Transportation and FHWA with flow velocities based on a 2 to 5 yr event.

- Corrosion on aluminum culverts manifests in two possible ways: general corrosion or localized pitting corrosion. Existing policies for aluminum culvert usage throughout the US appear to be set with general corrosion in mind. Few, if any policies are geared toward prevention of pitting corrosion.

- Aluminum has a rapidly forming, tough aluminum oxide protective film on its outer surfaces that develops when aluminum is exposed to oxygen. This durable, stable film is thought to contribute to aluminum's resistance to general corrosion in suitable environments.

- Current policies to prevent general corrosion include limiting aluminum culvert use to low- or non-abrasive sites, generally with pH between 4.5 and 9.0 and with soil and water resistivities greater than 500 Ω-cm. In such environments, aluminum culverts are very durable against general corrosion. At such sites, aluminum culverts will have a minimum service life of 50 to 75 yrs when not influenced by other corrosion mechanisms, such as contact with chloride-based roadway deicing salts. There is no general corrosion loss rate associated with design of aluminum culverts when these environmental conditions (pH, resistivity, abrasion limits, and isolation from chlorides) are met.

- Regarding corrosion, the natural environment in Wisconsin has typical conditions (pH, soil resistivity, and soil chemistry, including natural chloride content) that are considered favorable to and meet generally accepted parameters for aluminum culvert use and durability at low- or non-abrasive sites.

- Pitting corrosion will occur if certain concentrated salts are allowed to adsorb (dry and form a film) on the aluminum surface. The primary salts identified as causing pitting corrosion are those that contain chlorides and can release chloride (Cl^-) ions that can be particularly aggressive to aluminum. If the chloride ions are allowed to adsorb on the surface in sufficient concentration, they will become embedded in the aluminum oxide protective film, work their way through it, and form a pit in the aluminum core through chemical reactions. Once pits develop, they will to drill their way through the aluminum core. The aluminum oxide protective film protects the pit environment, allowing the pit mechanisms to stay concentrated and promoting pit growth through the thickness.

- In seawater or brackish environments, such as coastal tidal zones, aluminum culverts should be installed in free-draining backfill. Pitting corrosion has not been observed in these applications, likely due to the frequent wetting or flushing across the aluminum surface.

- The aluminum alloys currently used for corrugated aluminum pipe and aluminum structural plate structures are some of the most corrosion-resistant alloys and have been in use since the early to mid-1960s.

- Review of aluminum culvert information in Wisconsin DOT and FHWA databases suggests that geographic location, span, barrel length, and fill depth do not have strong correlation with corrosion levels of the culverts identified in the most recent inspection reports. This information is corroborated by decades of published literature from studies throughout the US.

- There is no strong correlation between ADT and aluminum culvert performance in Wisconsin; FHWA data suggest aluminum culverts with lower ADT tend to have a poorer culvert barrel condition rating.

- Aluminum culvert structural design is required to meet the same load and resistance factor design methods as are required for other culvert types. Consequently, there is no technical basis for limitations for usage based on ADT or highway application type.

- Culvert age and pavement condition both suggest a correlation with reported corrosion levels; older culverts and culverts at sites with cracked pavement had higher levels of reported corrosion.

- Conclusions drawn in 1993 from the study of a failed aluminum culvert that led to the current Wisconsin DOT restrictions on aluminum culvert use included the following: 1) chloride ingress from deicing salts through cracked pavement was the likely cause of severe perforation-type corrosion (pitting corrosion) of the upper regions of aluminum culverts observed in Wisconsin following the failure; 2) pavement cracking and higher traffic levels appeared to correlate with prevalence of aluminum corrosion, 3) aluminum culvert use in Wisconsin should be restricted to low-traffic-volume rights of way unless measures are taken to protect the culvert from deicing salts, and 4) the inverts of the culverts were largely uncorroded, indicating that the water and natural environment in Wisconsin was not significantly contributing to the corrosion. Findings from the current research agree with these earlier conclusions aside from the earlier conclusion linking higher traffic volume to increased likelihood of corrosion.

- The usage of chloride-based salt brine in Wisconsin has increased substantially in the last several decades, and usage of chloride-based deicing salts has remained steady. While relatively new products like beet juice appear to be more environmentally friendly, they are still added to traditional chloride-based salt mixtures that are corrosive to aluminum.

- It may be possible to add additional thickness to aluminum culverts to account for pit growth rates with time, though there is not sufficient data at the current time to understand pit depth growth rates for the specific aluminum alloys used for culverts, and such growth rates are likely sensitive to other parameters that may be difficult to control in a culvert environment (e.g., chemicals used for roadway deicing, effects of nearby stray currents or galvanic cells, precise chemistry of the pit initiation site given the variability of backfill).

- The only way to prevent pits from occurring in aluminum and aluminum alloys when chloride ions are present is to prevent the chlorides from contacting, concentrating, and adsorbing (drying) onto the aluminum surface. This may be accomplished by flushing the culvert soil-side, as in tidal regions, having a durable coating on the aluminum soil-side surfaces, or installing an impermeable membrane in the backfill between the top of culvert and bottom of pavement and limiting chloride content in the backfill between the membrane and the structure.

- The most economical method to isolate aluminum culverts from chloride-based deicing chemicals is through inclusion of an impermeable membrane in the backfill envelope. This protection method is specified for protection of steel reinforcement in the backfill of mechanically stabilized earth walls; such recommendations are included in the WisDOT Structures Manual chapter on MSE walls. At such an installation for aluminum culverts, additional measures to prevent pitting include testing and limiting the chloride content of the backfill below the membrane and specifying free-draining backfill in this area.

- Alternate options to prevent initiation of pitting corrosion in buried aluminum culverts and boxes include providing durable, well bonded exterior (soil-side) coatings that will protect the aluminum from infiltrating chloride-based deicing salts. Such coatings have been adopted for other metallic culverts to increase resistance to general corrosion; the adequacy of and specifications for such coatings have not typically been considered in the aluminum culvert industry to date, as aluminum is relatively resistant to general corrosion. There is currently no consensus specification for coating aluminum culverts. Adequate surface preparation and cleanliness prior to application of coatings have a direct effect on bonded coating durability; therefore, bonded coatings on metal culverts are typically factory applied and touched up as needed in the field. Considering the cost of coating, surface preparation, and repair of coating, coatings are typically more expensive than an isolation membrane embedded in the backfill envelope and limiting chloride content in free-draining backfill below the membrane.

- Common tests and specifications for acceptable backfill for MSE walls with steel reinforcement include testing the backfill for chloride content and limiting the content to between 100 and 250 ppm, followed by the installation of an impermeable membrane above the tested backfill to prevent ingress of contaminants, such as deicing salts, from the roadway surface.

- The WisDOT Bridge Manual, Facilities Development Manual, and Standard Specifications for Highway and Structure Construction require updates to allow for proper specification of aluminum culverts, impermeable isolation membranes, and free-draining backfill with limited chloride ion content in accordance with the text in Section 6.5 above, including potentially updating culvert material selection and design to use a process similar to that shown in the Ohio DOT Culvert Design Process Flow Chart. Updates should include testing soil and water pH and resistivity on samples collected from new culvert sites, as well as abrasion level evaluation and classification at all new culvert sites based on existing FHWA and Caltrans requirements.

7.2 Recommendations

Recommendations drawn from the above conclusions include the following:

- Require soil and water pH and resistivity tests on samples from all new culvert sites along with abrasion classification based on visual survey of bedload materials and flow velocities from a 2 to 5 yr event.

- Develop provisional updates to Wisconsin DOT policy and specifications to allow use of aluminum culverts (pipe, structural plate structures, and box culverts) at Abrasion Level

1 to 3 sites where soil and water pH ranges from 4.5 to 9 and resistivity is greater than 500 Ω-cm.

- Revise the ADT limitation for aluminum culverts to be in line with other flexible culvert types, such as corrugated steel and plastic.

- Specify use of an impermeable isolation membrane in the backfill above aluminum culverts. The membrane should be sloped away from the structure, extending down the embankment for at least 10 ft from pavement or to the end of the culvert, and at least equal to the trench width. Synthesize information from Ohio DOT culvert membrane specifications, NH DOT MSE wall membrane special provisions, or any other states that specify such membranes for culverts or MSE walls to develop a common material specification for such membranes.

- Require chloride ion testing of the backfill used below isolation membranes and limit its chloride ion content to 100 ppm, based on expected chloride concentrations of backfill soils in Wisconsin and available recommendations for chloride concentration limits in steel-reinforced MSE wall backfill. Consider specification of free-draining backfill below the impermeable isolation membranes.

- Perform inspections and document the performance of a few aluminum culverts installed below impermeable isolation membranes at sites that meet the above recommendations. Document the performance of those structures yearly for approximately 5 yrs, then on a less frequent basis, and pair the inspection data with data from WisDOT winter maintenance and pavement databases over the service life of those culverts.

- Consider updating WisDOT policy to include equal footing for all culvert materials in a similar manner to that used by the Ohio DOT in their Culvert Design Process Flow Chart. Update fill height tables for all culvert material types based on design in accordance with the current version of the AASHTO LRFD Bridge Design Specifications with any state-specific modifications.

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APPENDIX A

Literature Review

Literature Review

Date: February 2019

To: WHRP 0092-17-05 Project Overtight Committee

From: Brent J. Bass, Jesse L. Beaver

Project: 170848 – Wisconsin Highway Research Program Aluminum Culvert Policy

This document summarizes information relevant to this study from references identified in the Task 1 literature review. A full list of references reviewed is also provided at the beginning, organized under the headings that occur in the sections that follow.

1. REFERENCES REVIEWED

This section presents a full list of the references reviewed for this literature review, presented in the order in which they appear below.

Existing Wisconsin DOT Policy:

- Wisconsin Department of Transportation, Bureau of Structures, Structures Development Section, "WisDOT Bridge Manual," with updates through July 2017.

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2. CURRENT WISCONSIN DOT POLICIES FOR ALUMINUM CULVERTS

2.1 Wisconsin Department of Transportation, Bureau of Structures, Structures Development Section, “WisDOT Bridge Manual,” with updates through July 2017.

This document provides key definitions for culverts, bridges, box culverts, and materials for bridge and bridge-size culverts as summarized in the following bullets:

- Chapter 2, General, Section 2.9, Terminology, defines culvert as “a structure not classified as a bridge having a span of 20 ft or less spanning a watercourse or other opening on a public highway.”

- Chapter 3, Section 3.1, Specifications and Standards, states, “All bridges in the State of Wisconsin carrying highway traffic are to be designed to the American Association of State Highway and Transportation Officials (AASHTO) LRFD Design Specifications… and Wisconsin Department of Transportation Standards. The material in this Bridge Manual is supplemental to these specifications and takes precedence over them. All highway bridges are to be constructed according to State of Wisconsin, Department of Transportation, Division of Transportation Systems Development Standard Specifications for Highway and structure Construction and applicable supplemental specifications and special provisions as necessary for the individual project.”

- Chapter 36, Box Culverts, Section 36.2, General, states, “Box culverts are reinforced concrete closed rigid frames which must support vertical earth and truck loads and lateral earth pressure,” and “Aluminum box culverts are not permitted by the Bureau of Structures.” Section 36.3, Limit States Design Method, provides an LRFD design method for cast-in-place, precast, or three-sided reinforced concrete box culverts.

- Chapter 9, Materials, Section 9.5, Miscellaneous Metals, identifies applications where specific metals may be used on WisDOT projects. Aluminum is listed for uses such as sign bridges and some railings without mention of any type of buried structure such as pipes or culverts.

2.2 Wisconsin Department of Transportation, Division of Transportation Systems Development, "Facilities Development Manual," individual chapters downloaded from web on 16 October 2017.

This document includes the current policy on aluminum culverts, identifying in Section 15.4 the limitations on use of aluminum drainage structures that were put in place following observation of several corroded aluminum drainage structures in 1993. Other information in the document includes information on service life; allowable culvert materials for certain applications such as roadway classification, ADT, and cover heights; reference to fill height tables and their basis; and different types of pipe and corrugation geometries included in the fill height tables. Relevant information is summarized in the bullets below:

- Chapter 1, Introduction, Section 1, General, 1.2 Application, states, "this manual provides policy, procedural requirements, and guidance encompassing the facilities development process within the Wisconsin Department of Transportation, Division or Transportation Systems Development (DTSD). It is applicable to all types of highway improvements on the state trunk highway system, other street/highway systems for which federal-aid highway funds may be utilized, state facilities road systems funded with state funds administered by the department, and other highways and roads for which the department may act as an administrative agent. Adherence to the requirements contained herein will provide for the uniform development of highway systems and contact [contract?] plans that reflect sound engineering practice and sensitive environmental concern."

- Chapter 13, Drainage, Section 1, Drainage Practice, 13.1.15 Culvert Material Selection Standard, provides the following relevant information under the heading 15.1 Application:

    - "In general, WisDOT has approved steel, aluminum, concrete and thermoplastic as suitable materials for culvert pipe. Coating systems for steel culvert pipe may be either zinc-coated (galvanized), aluminum or polymer."
    - "The standards in this procedure apply to all shapes of culvert pipe (circular, arch or elliptical) and to pipes in the range of 12 to 84 inches in diameter. The selection of larger drainage conduit is addressed in FDM 13-1-20."
    - "Service life depends primarily on how durable the material is when subjected to corrosive or abrasive site conditions. Service life also depends on the proper structural design and installation of the pipe. These factors are considered in the Fill Height Tables of FDM 13-1-25 as well as the standard specifications and appropriate special provisions for individual projects."

The following information is provided in 13.1.15 Culvert Material Selection Standard, 15.2 Selection Standard:

- "Standard Spec 520 – Pipe Culverts, categorize culvert pipe strengths by class, ranging from Class II with a maximum allowable fill height of 15 ft for reinforced concrete to Class V with a maximum fill height of 35 feet. Selection of pipe materials is to be based on traffic volume and fill height with consideration given to special situations or site conditions as described in FDM 13-1-15.3 to FDM 13-1-15.6."

- "Beginning with the 2016 Standard Specifications, four new series of bid items were added to Standard Spec 520 Pipe Culverts: Culvert Pipe Class III-A, Culvert Pipe Class III-A Non-Metal, Culvert Pipe Class III-B, and Culvert Pipe Class III-B Non-Metal. These Class III-A and Class-III B [sic.] bid items allow the contractor to choose from multiple pipe materials including thermoplastic pipe (corrugated polyethylene and corrugated polypropylene) for sizes up to 36 inches in diameter. Previously, corrugated polyethylene pipe was the only thermoplastic pipe that met one of the optional material requirements for Class III culvert pipes. As described in FDM 13-1-17.3.1, the intent of these Class III-A and Class-III B [sic.] items is to introduce potential project cost reductions into the competitive bid process by allowing the contractor to select from multiple material options for pipes sized up to 36 inches. The four subclasses of Class III culverts are as follows:"

- "Class III-A – includes Class II and III reinforced concrete, corrugated steel, corrugated polyethylene, and corrugated polypropylene. Class III-A has a maximum fill height of 11 ft."

- "Class III-B – includes Class III reinforced concrete, corrugated steel and corrugated polypropylene. Class III-B has a maximum fill height of 15 ft."

- Class III-A, Non-metal and Class III-B, Non-metal – these non-metallic subclasses are for corrosive environments where it is not advisable to use metal pipe. Therefore corrugated steel is removed."

- "As conditions allow, and with the exceptions listed, Culvert Pipe Class III-A, Culvert Pipe Class III-A Non-metal, Culvert Pipe Class III-B, and Culvert Pipe Class III-B Non-metal under Standard Spec 520 shall be specified for culverts where ADT is less than 7,000."

- "Reinforced concrete pipe is required for culverts under high volume roadways (ADT > 7,000) because it is a proven and dependable material that is not likely to need replacement because of corrosion or substandard installation. Replacement of culvert pipe under a high volume roadway is costly and disruptive to the traveling public."

- "Table 15.2 lists the preferred materials permitted for culvert pipe by traffic volume range." Corrugated aluminum is allowed where design year ADT is < 1,500 with an allowable size of 42 to 84 in. with the following notes, "Consider for use in corrosive environments, 12 to 36 inch sizes can only be used in special situations (See FDM 12-1-15.3), refer to FDM 13-1 Attachment 25.2 and 25.6 for appropriate fill heights, and indicate required thickness in Misc. Quantities."

- 15.2.1, Local Approval of Culvert Pipe Materials, includes allowances for local agencies to approve the type of pipe used in their projects generally when the local agency funds more than 50% of the cost of the pipe. In addition, it states, "The local approval is intended to come from the local unit of government or agency participating in the cost of the project, which may not necessarily be the entity responsible for maintenance. In addition, a participating local unit of government or agency may specifically request the installation of concrete, metal, thermoplastic, or the four subclasses of Class III pipe listed in Standard Spec 520 for projects meeting the criteria described in this part."

- 15.3, Special Situations, states, “Special conditions at the proposed culvert site may require that a specific type of pipe be used. Such special conditions include acidity of soils/water or other corrosive conditions, local preference with meeting the conditions described above in FDM 13-1-15.2.1, limited cover (see FDM 13-1-15.6), extending existing culvert pipes, unusual loading from high embankments, steep gradients, or other pertinent reasons.”

- 15.4, Corrosion Concerns About Steel Culvert Pipe, states in part, “A Wisconsin map outlining the potential areas for bacterial corrosion of zinc galvanized steel culvert pipes is shown on Attachment 15.1.”…“Metal culvert pipe of any type should provide a minimum service life of 20 years before perforation occurs.”…“Corrosion resistant pipe may be necessary where drainage originates in bogs, swamps, barnyards or low-lying lands drained by ditches or tile. An acceptable corrosion resistant pipe should be specified in Area 3 when the pH is outside the range of five to nine and the resistivity is below 2000 ohm centimeters, or when the resistivity is below 1000 ohm centimeters regardless of the pH. Acceptable corrosion resistant pipe materials are concrete, aluminum, aluminized steel, polymer coated steel, polyethylene and polypropylene. *Note: Inspection of several aluminum drainage structures in 1993 revealed localized corrosion of the top and sides of the center sections of the structures. The corrosion appears to be related to the use of chlorides for snow and ice removal. The use of aluminum pipe should therefore be limited to side drains and highways with traffic volumes under 1500 Design ADT unless some provision is made to insulate the upper surface of the structure from infiltrating road salt. Information about the corrosive characteristics of the soil or water at a site may already be available from region soils or maintenance records. In some cases it may be necessary to conduct field and laboratory tests to determine whether corrosive conditions exist. The region Soils Engineer can normally advise the designer about the need for such tests and conduct them if needed.”

- 15.5, Abrasion Concerns, states, “The thickness of metal pipe should be increased or the pipe invert paved where water velocity combined with a bed load of sand, gravel or stone is likely to cause significant erosion or abrasion of the pipe invert. The existence of abrasive conditions at a proposed culvert site can be determined from inspection of the existing metal pipe at the site or inspection of other pipes in the same general area or on the same watercourse.”

- 15.6, Limited Clearance Installations, states, “When a low clearance pipe is required, the designer may call for any of the following: reinforced concrete elliptical or arch pipe, corrugated steel or aluminum pipe arch, structural plate pipe arch, aluminum structural plate pipe arch.” Table 15.3, Culvert Material for Arch or Elliptical Culverts, is provided, listing applicability of the above materials from Section 15.6, and with aluminum pipe-arch listed with < 1,500 allowable design ADT with allowable sizes of 17 x 13 to 71 x 47 in. for pipe arches, with notes to indicate the required thickness in Misc. Quantities, to refer to FDM 13-1 Attachment 25.7 for appropriate fill heights, and that it can only be specified as an “SPV item.”

- 15.8, Height of Cover for Culvert Pipes, states, “Height of cover for the pipe materials in Table 15.2 and Table 15.3 shall be in accordance with the fill height tables referenced in the table notes and as described in FDM 13-1-25. Required minimum cover for Culvert Pipe Class III-A, Culvert Pipe Class III-A Non-metal, Culvert Pipe Class III-B, and Culvert Pipe Class III-B Non-metal shall be 2 feet measured from top of pipe to top of subgrade. For steel and concrete pipe the desired minimum cover shall be 2 feet below subgrade. Exception to this requirement can be made based on pipe class and the minimum cover values listed in the fill height tables."

- FDM 13.1.17 Storm Sewer Material Selection Standard, 15.2 Selection Standard "provides guidelines for the selection of storm sewer materials. Standard Spec 608 – Storm Sewer, categorizes storm sewer pipe strengths by class, ranging from Class II with a maximum allowable fill height of 11 feet for reinforced concrete to Class V with a maximum fill height of 35 feet." Standard Specification Section 608 lists reinforced concrete, corrugated polyethylene, corrugated polypropylene, and ABS/PVC composite pipes as applicable for storm sewers. Aluminum pipe is not allowed.

- FDM 13-1-20 Large Drainage Conduit, 20.1 Introduction, states in part, "Large drainage conduit is defined in general as conduit larger than 84 inches in equivalent diameter, which equates in cross-sectional area to 38.5 square feet. This size was selected because it is near the top of the range of sized at which pipe can be factory assembled while still being a practical size for transporting. The types of large conduit available include structural plate pipe and structural plate pipe arch (AASHTO M167) aluminum alloy structural plate pipe and pipe arch (AASHTO M219), steel pipe with 3 [in.] x 1 [in.] corrugations (AASHTO M36), reinforced concrete pipe (AASHTO M170), reinforced concrete arch pipe (AASHTO M206), reinforced concrete elliptical pipe (AASHTO M207), and cast-in-place or precast box culverts (AASHTO M259)."…Regarding the selection of material for large conduits, "…factors that should be considered include…the existence of corrosive or abrasive conditions at the site." "Two or more conduit types may be specified as equal alternates when either type will satisfy design requirements. For example, aluminum structural plate pipe arch and [steel] structural plate pipe arch could be specified as equal alternates."

- FDM 13-1-25 Fill Height Tables, 25.1 Design Criteria, states in part, "The fill height tables included in this procedure are based on the following design criteria:"…"4. Safety factors: 4 for longitudinal seams; 2 for buckling." 25.2 Design Methods states, "The fill height tables for flexible conduit were developed using the service load design method described in the AASHTO LRFD Bridge Design Specifications. The fill height table for reinforced concrete pipe was developed using the design procedure included in the Concrete Pipe Design Manual prepared by the American Concrete Pipe Association."

- FDM 13-1-25 Fill Height Tables, 25.5 Abrasive of Corrosive Conditions, states, "Metal thicknesses shown in the fill height tables are adequate for structural requirements only. Where corrosive and/or abrasive conditions exist, either greater thicknesses or protective coatings should be provided. For structural plate pipe, greater thicknesses may be specified for the plates in the invert."

- FDM 13-1-25 Fill Height Tables, has Attachments 25.1 to 25.9, which include fill height tables for various types of pipe and culvert products, including Attachment 25.2, "Fill Height Table – Corrugated Steel, Aluminum, Polyethylene, Polypropylene and

Reinforced Concrete Pipe, HS20 Loading, 2 [in.] x 2/3 [in.] Corrugations," Attachment 25.6, "Fill Height Tables: Corrugated Aluminum Pipe, 3in x 1in Corrugations; and Aluminum Alloy Structural Plate Pipe, 9in x 2 1/2in Corrugations," Attachment 25.7, "Fill Height Table, Corrugated Aluminum Pipe Arch, 2 2/3in x 1/2in Corrugations," and Attachment 25.8, "Fill Height Table, Aluminum Alloy Structural Plate Pipe Arch, 9in x 2- 1/2in Corrugations."

2.3 "Standard Specifications for Highway and Structure Construction," State of Wisconsin Department of Transportation, 2017 ed., 2017.

This document contains the standard specifications for highways and structures in Wisconsin. Specifications relevant to our research are summarized below:

- Section 101 General Information, Definitions, and Terms, 101.3 Definitions, defines a bridge as "A structure having a span of more than 20 feet from face to face of abutments or end bents, measured along the centerline of the roadway, spanning a water course or other opening or obstruction, such as a highway or railroad, including the substructure, superstructure, and trestle work approaches." Culvert is defined as "A structure not classified as a bridge that provides an opening under a roadway."

- Section 504 Culverts, Retaining Walls, and Endwalls, 504.1 Description, states, "This section describes providing culverts whether defined as a culvert or bridge under 101.3,"…"This work does not include providing pipe culverts under 520 through 525." All requirements in Section 504 relate to concrete structures.

- Section 520 Pipe Culverts, 520.1 Description, states, "This section describes providing culvert pipe, cattle pass, and apron endwalls where the material used is a contractor option; providing and removing temporary culvert pipe; and cleaning existing culvert pipes." Section 520.2 Materials, 520.2.1 Culvert Pipe, states, "Furnish culvert pipe consistent with the diameter the bid item indicates. Furnish materials for the various classes of pipe as follows:" and provides Table 520-1, shown below, which does not include aluminum materials.

TABLE 520-1 ALLOWABLE MATERIALS FOR CULVERT PIPE

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

- Section 525 Corrugated Aluminum Pipe Culverts, 525.1 Description, states, “This section describes providing corrugated aluminum culvert pipe and aluminum or steel apron endwalls.” Section 525.2 Materials, 525.2.1 Corrugated Aluminum Pipe, requires pipe to conform to AASHTO M 196. Construction is to be in accordance with Section 520.3 for pipe culverts. Section 520.3 includes written description of backfill materials, procedures, and boundaries (e.g. trench width); there is no reference to standard installation details such as standard drawings. Also, there is no mention of installing membranes or other means of protection from roadway deicing salts in Section 520.3.

- Section 527 Structural Plate Pipe and Pipe Arches. 527.1 Description, states, “This section describes providing structural plate pipe, or structural plate pipe arches.” 527.2 Materials, includes, “Furnish structural plate pipe or structural plate pipe arches fabricated from zinc coated corrugated steel or aluminum alloy structural plates unless the contract specifies otherwise.”… “Furnish erection bolts and aluminum alloy structural plates conforming to AASHTO M219, except do not use aluminum bolts and nuts.” Section 527 includes additional requirements for fabrication, erection, backfilling, and others, which include relatively typical provisions for such work. There is no mention of installing membranes or other means of protection from roadway deicing salts.

- Based on reviewing WisDOT Standard Specifications, fill height tables, manuals, and website, it does not appear that WisDOT has standard drawings for installation of pipe or culverts.

3. REPORTS ON CULVERT PERFORMANCE IN WISCONSIN BY ROBERT PATENAUDE

3.1 Patenaude, R., “Corrosion Evaluation of Culvert Pipe in Wisconsin, Progress Report V,” Wisconsin Department of Transportation, Division of Highways and Transportation Facilities, Materials Section, Soils Unit, 1981.

This is the Phase V report from a research project that started in 1965 to evaluate corrosion performance of culvert pipe and predict performance of replacement pipe and corrosion potential of new culvert sites. Specific information from the study follows:

- Sixty in-service galvanized steel culvert pipes were examined; eighteen were found to be corroded to perforation. Field observations generally reflected estimated time to perforation according to CalTrans Test Method 643-B (test method to estimate time to perforation based on pH and resistivity of soil and water).

- There appeared to be three principal drivers of steel culvert corrosion in Wisconsin: 1) acidity of soil/water, 2) the presence of active anaerobic sulfate reducing bacteria, and 3) low resistivity of soil/water.

- Tests of sulfur content of water (where bacteria get the sulfur) did not show a strong correlation between sulfur content and corrosion, though contents will vary as will water flow, etc.

- They were also looking at whether dissolved oxygen and temperature may have had an effect.
- The report notes in-service aluminum pipe and culverts were showing good performance at sites where they had been installed since 1962, even at sites that would have been highly corrosive to steel.
- Two sites with in-service aluminum culverts (pp. 17 and 18) are described, and soil and water test results are provided.
- Recommendations include using aluminum or concrete pipe or culverts at sites in Wisconsin that would be classified as corrosive to steel.

3.2 Patenaude, R., "Corrosion Evaluation of Experimental Metal Culvert Pipe in Wisconsin, Progress Report VI," Wisconsin Department of Transportation, Division of Highways and Transportation Facilities, Central Office Materials, Soils Section, 1988.

This report provides results of a continued examination in-service performance of forty-four culverts in Wisconsin dating from 1962 to 1981, including galvanized steel, aluminum, aluminized steel, epoxy-bonded steel, and polymeric-coated steel. Information regarding data collected and aluminum culvert performance is summarized below.

- Some galvanized steel pipe had perforations and appeared to be the most susceptible to corrosion out of the galvanized steel, aluminum, aluminized steel, epoxy-bonded steel, and polymeric-coated steel pipe types in the study. One of seven aluminized steel pipes also showed evidence of corrosion, and three of four epoxy-bonded steel pipes had debonded epoxy likely from abrasion by ice. Three of seventeen aluminum pipes had evidence of pitting or loss of surface cladding, but no pitting or perforation of the core alloy. Bituminous coatings showed poor performance. Polymeric-coated steel pipes appeared to perform well.
- Soil and water test data from tests at sites in 1981 are included in the appendix.
- For the aluminum culverts, the least evidence of corrosion came at sites with flowing water; the few sites with pitting of cladding were occasionally dry, and the pitting may have been from a reaction between the cladding and soil.
- All sites are described in detail, with soil and water chemical test results, and with photos. Many of the aluminum culvert sites were experimental installations, with various other types of culverts installed either in parallel runs or with changes in culvert composition along the culvert length.
- For example, on p. 23, a site in Kewaunee County included 24 in. diameter corrugated steel and corrugated aluminum culvert pipes within several hundred feet of each other, plus a 30 in. diameter Black Klad corrugated steel pipe draining a swampy area with high corrosion potential and presence of anaerobic sulfate reducing bacteria at the site. The Black Klad steel pipe was performing the best, followed by the aluminum pipe with some

loss of cladding at the invert where soil had washed into the pipe, followed by the corrugated steel pipe, which had some pitting.

- In summary, two sites with both corrugated steel and corrugated aluminum culverts on State Highway 29 in Clark and Cipppewa Counties demonstrated aluminum is much more resistant to in-service corrosion than steel. Although “recently” (1981) installed, the sites along State Highway 80 in Juneau and Wood Counties, which is the area with the greatest corrosion potential of all sites in the study, show that the aluminum culvert pipe and polymeric-coated steel culvert pipe show the best performance thus far in their service life; although the aluminum pipe has lost cladding at the invert where soil washed into the pipe, there is no section loss in the core. Polymeric-coated steel pipe, while performing well to date, has only been installed at a few sites and for a short time to date.

3.3 Patenaude, R., Correspondence Memorandum to District Engineers, “Corrosion of Aluminum Drainage Structures,” 26 July 1993.

This memo was prompted by the collapse of a 24 in. diameter corrugated aluminum culvert pipe in late May 1993 on State Highway 54 west of Port Edwards in southern Wood County. The culvert was made from Kaiser 14 ga aluminum alloy 3004, installed in 1969, and the corroded area was covered with a white corrosion product. The culvert had about 1 ft of cover, including fill and pavement. The ends and invert of the collapsed pipe were in good condition, and the crown near midlength was perforated and had greatly reduced thickness. Additional notes from the memorandum are below:

- Periodic field inspections of exposed ends of aluminum drainage structures to date had shown nothing more serious than superficial pitting of the inverts of some pipes; however, advanced corrosion of older aluminum structures has been found at the midlength crown in several structures upon closer inspection following the collapse of the above structure.

- Two 8 ga Kaiser alloy 5052 7 by 12 ft aluminum plate arches on State Highway 54, near the failed pipe, were found to have local perforations up to 2 in. across at the crown near midlength, with white oxidation running down the inside. The structures were installed in 1969 with about 18 in. of cover. A 2 by 6 ft area of backfill was removed from the travel lane over the top of one of the structures and samples of aluminum, and soil were taken for testing. There was a layer, approximately 0.25 in. thick, of white powdery corrosion product on the outside (soil side) surface of the arch.

- Samples of aluminum from the aluminum plate arch examined under scanning electron microscope showed the presence of heavy metal ions such as copper and iron, plus chloride ions; field observations showed a 3 by 3 in. through-wall hole at the location below where a piece of scrap iron had been included in the soil backfill. Soil samples taken from the backfill above the aluminum plate arch were found to be slightly alkaline and to have chloride concentrations between 148.5 and 274.5 ppm; natural soil in Wisconsin not exposed to fertilizer, road salt, or other sources of chlorides generally have a chloride ion concentration between 10 and 20 ppm.

- Of ten aluminum drainage structures examined on State Highway 82 west of Mauston in southwestern Juneau County, nine were in an advanced state of deterioration at the crown, particularly near the center of the pavement. There were typically perforations with white precipitate found. These structures were covered with cracked flexible pavement; the amount of pavement cracking appeared to correlate well with the severity of corrosion. Pavement cracking seemed to have a better correlation with severity of corrosion than the depth of soil cover.

- The wide geographic distribution of aluminum culvert sites exhibiting corrosion and deterioration of the crown of the structures near midlength indicates the corrosion is not related to composition of soil. Having the inverts of the structures below the flow lines of many pipes indicates that the corrosion is not related to chemistry of the water flowing through the pipes.

- The field evidence indicates that the corrosion is most prevalent on more heavily traveled and heavily salted roads, and apparently correlates well with more extensive pavement cracking, and less with depth of soil cover over the structures.

- Collapse of the top of a structure is much more serious than through-wall corrosion of the invert; therefore, the memo recommends use of aluminum culverts be restricted on heavily salted roads unless some type of coating becomes available to protect the outer surface of the structures from road salt.

3.4 Patenaude, R., "Experimental Culvert Pipe, STH 80, Juneau and Wood Counties, Wisconsin, Final Report," WisDOT Research Study # WI 80-02, 03, 04, Wisconsin Department of Transportation Bureau of Highway Construction, Soil and Foundation Engineering Unit, November 2003.

The report discusses the findings from the installation and monitoring of four experimental culvert pipes installed at three sites in central Wisconsin (see earlier reports) that had been in service since 1981.

- In comparing the performance of four culvert types, the report identifies the following trends: 1) Polymeric-coated steel galvanized steel pipes appeared to perform the best, with none of the pipes exhibiting perforation and removal of the coating being localized to exposed rivet heads and section ends. 2) Epoxy-bonded steel pipes did not perforate but had considerable coating loss with some advanced corrosion at joints. 3) Aluminized steel pipes had localized perforation and pitting of the steel cores and inverts at locations of organic material; the coating appeared degraded in some cases. 4) Aluminum pipes exhibited the most severe distress and corrosion of the four types examined with several having thinning, perforation, and failures at the crown, likely from the presence of road-deicing salts; the aluminum pipes, however, appeared immune to corrosion in the natural environment.

- At the time of the report, aluminum culverts with protective coverings over the top were being installed in Wisconsin, but their locations were not noted in the report.

- Soil and water chemistry data from several sites, including historical data back as far as 1975, is presented along with field observations.
- The white precipitate forming on one of the aluminum culverts was examined and found to be aluminum oxide, suggesting the road salt may act as a catalyst and increase the electrical conductivity of the soil adjacent to the pipe.

4. USAGE OF DEICING CHEMICALS ON WISCONSIN HIGHWAYS

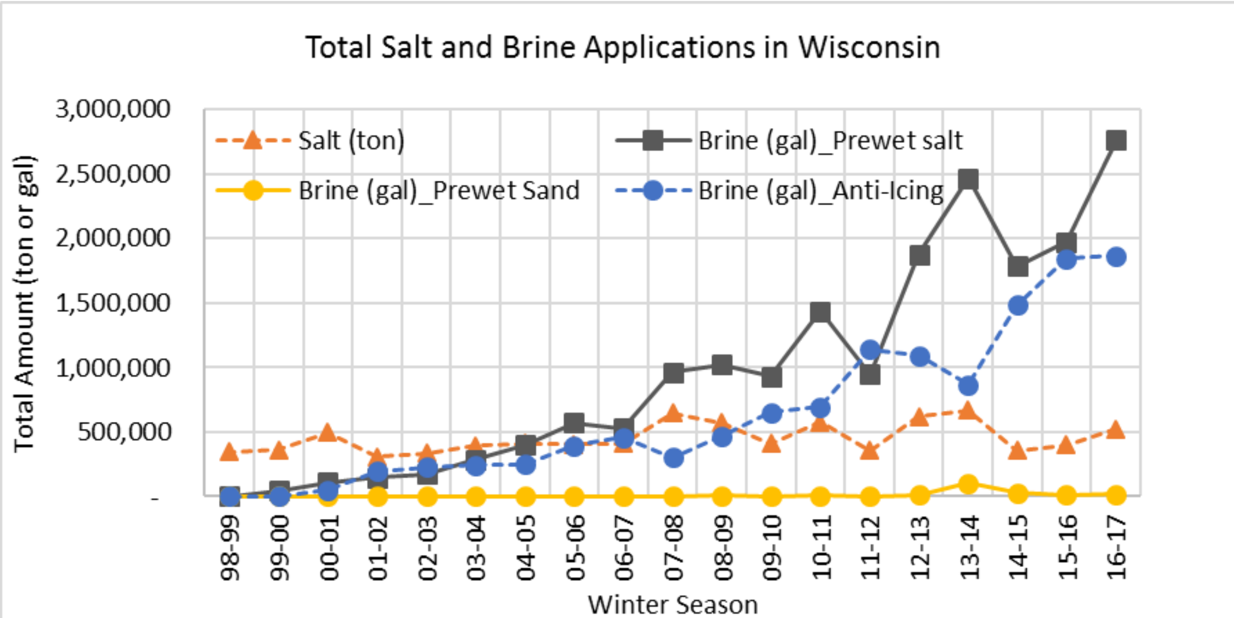
We reviewed a midterm meeting presentation for WHRP Project 0092-17-03, "Evaluation of the Effects of Deicers on Concrete Durability," by Dr. Danny Xiao, dated 20 October 2017. We also had a follow-up call with Dr. Xiao where we reviewed most of his presentation and discussed both our research project and his, and reviewed the final report for the project (Xiao, D., S. Owsus-Ababio, and R. Schmitt, "Evaluation of the Effects of Deicers on Concrete Durability," Final Report to WHRP Project No. 0092-17-03, June 2018).

Notes from review of the presentation and conference call are as follows:

- Dr. Xiao's research project is primarily focused on concrete durability and the effect of chemical deicers on concrete, so his information is not focused on issues that may relate to metal culverts, and some of it may not be directly applicable.
- Dr. Xiao administered a survey of cities and counties in Wisconsin related to their use of deicing chemicals, and has reviewed data in the Wisconsin DOT Storm Report and Automated Vehicle Location (AVL) winter operation databases.
    - For the city and county survey, he received responses from nine cities and forty-four counties. Of the fifty-three respondents, fifty use sodium chloride for deicing, and forty-four use it for anti-icing, followed by calcium chloride (ten for deicing and four for anti-icing) and Beet55 beet juice (nine for deicing, six for anti-icing). Available but less used chemicals include magnesium chloride, potassium acetate, standard beet juice, and proprietary products such as GeoMelt, FreezeGuard, AMP, IceBan M80, M90, ThawRox, M95, and SuperBlend.
    - Application rates of the products in the above paragraph are highly variable, depending on weather conditions, but they are within the Wisconsin DOT Winter Maintenance Guidelines. Application rates for deicing are typically in the 200 to 400 lb per lane-mile range per winter event, although usage varies from 50 to 600 lb per lane-mile for deicing. The typical application rate for anti-icing is between 20 and 50 gal per lane-mile per winter event. Cumulatively, each lane mile of roadway in each winter received an average of 13.78 ton of NaCl, 0.31 ton of $CaCl_2$, and 0.16 ton of $MgCl_2$ according to Storm Report. According to the AVL database, cumulative totals for salt were 9.9 tons and 39.3 gal of salt brine.
    - When asked what factors lead to a jurisdiction's choice in material, respondents rated the material's effectiveness as the top factor (thirty of the fifty-five respondents) followed by temperature and precipitation from weather forecast, cost, availability, wind speed from weather forecasts, environmental concerns, and other. It does not appear that maintenance concerns and durability of

structures influence any jurisdiction's material selection choices, although it is unclear whether reliable, quantifiable information is available regarding each material's effects on maintenance and durability of structures.

- When asked whether specific distresses associated with roads can be attributed to application of deicing and/or anti-icing materials, eleven respondents reported issues with bridge joints and/or bridge decks, and one of those eleven respondents noted premature degradation of storm drain piping.
- Regarding state DOT routes, Dr. Xiao noted that all highway maintenance, including interstates, is performed by counties, and that the counties are not required to enter data into the Storm Report and AVL databases, described further below. They are also not required to carry AVL systems on trucks, therefore only 55% of the roadway system is represented in the AVL database.
- **Overview of Storm Report:** Information is manually entered by the county engineer; data ranges from 1998 to 2017 and covers all counties of Wisconsin.; There are 89,050 records in database; data includes snow depth; total amount of deicers used in a county; time of a storm and the crew operation; deicer types, including salt, salt brine, $CaCl_2$, $MgCl_2$; sand prewetting; anti-icing; and others.
- **Overview of AVL:** Database is automatically populated from AVL/GPS sensors; data ranges from 2010 to 2017, but only from about 55% of state highway system. There are 6,239 total records in database; data includes the quantities of deicers used in a winter operation segment (typically tons/lane-mile/year). Deicer types are entered by the driver as liquid $CaCl_2$, salt, brine, or sand; can be "unspecified" if omitted, or "unrecognized" if, say, the driver misspells one of the choices.
- Per the plot below, while salt usage has remained steady over the last two decades, brine usage has increased by several (two to three) orders of magnitude. Of the liquid brine materials used, salt brine, $CaCl_2$, Freeze Guard ($MgCl_2$), and Beet 55 beet juice account for more than 98% of brine usage, and salt brine alone accounts for between 92% and 95% of usage, depending on whether usage is for prewetting salt or sand, or for anti-icing.



- There are maps in the presentation that show county-by-county use of the top four materials. Slide 23 shows salt application on the state highway system where AVL data is available (route by route on a highway map, with color codes corresponding to relative salt volumes).
- Chemical compositions and concentrations for the deicers listed above (including the proprietary chemicals) are presented on Slide 17 of the interim summary and in the final report appendices based on safety data sheet contents.
- The final report indicates that prewetting and anti-icing have been proven to increase the effectiveness of deicing operations and reduce the overall amount of salt application.
- Traditionally, rock salt (sodium chloride) has been the primary deicing chemical used on Wisconsin roadways. Two recent changes to deicer usage in Wisconsin include 1) usage of a variety of new chemicals including calcium chloride, magnesium chloride, and beet juice, and 2) the introduction of anti-icing. Anti-icing operations apply high-concentration liquid solutions of deicers to dry pavement ahead of winter weather events. Application of anti-icing solutions can be much more detrimental to structures below since the wet solution is applied to dry pavement before precipitation, rather than to wet, potentially saturated surfaces after precipitation starts.
- During winter 2016-2017, WisDOT used 526,199 tons of salt, 2,783,720 gal of salt brine for prewetting, and 1,865,565 gal of salt brine for anti-icing to 34,620 lane-miles of roadways. For that winter, salt use was 32% higher than the previous year, and sand use was 38% less than the average of the five previous winters. Of the seventy-two counties in Wisconsin, sixty-six were equipped to perform anti-icing operations.

5. ALUMINUM MATERIAL INFORMATION INCLUDING MATERIAL AND PRODUCT STANDARDS, ALUMINUM ALLOY DESIGNATIONS, AND CORROSION MECHANISMS

5.1 Aluminum Association Website, *The Aluminum Association,* Arlington, VA, http://aluminum.org/resources/industry-standards/aluminum-alloys-101, viewed on 16 October 2017.

We reviewed information on the Aluminum Association website related to aluminum alloy composition and use summarized below:

- Aluminum alloys are chemical compositions where other elements are added to molten aluminum to enhance properties such as strength. Other elements include iron, silicon, copper, magnesium, manganese, and zinc, which can be combined, and can make up as much as 15% of the alloy by weight. In addition to strength, properties affected by adding other elements include density, workability, electrical conductivity, and corrosion resistance.

- Aluminum alloys can be made stronger through heat treatment or cold working, depending on the alloy. Alloys are designated by series, where the first digit identifies the principle alloying element and the other three digits generally are used to identify the alloy in the alloy registration table (alloys in the 2XXX through 8XXX series with a second digit of “0” are the original alloys in their groups and the final two digits are used to identify modifications to the original alloy chemistry; there may also be a letter appended to the four digit numerical designation; see, “International Designation System for Wrought Aluminum and Wrought Aluminum Alloys,” 15 December 1970, revised June 2014). Information on different series of aluminum alloys is summarized in the table below.

- The current designation system was established in 1954, and agreed upon internationally in 1970. In 1954, there were 75 designations; more than 530 designations are currently registered (and some have been retired).

- The aluminum association maintains the database, “International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys,” also referred to as the “Teal Sheets.” The 38-page Teal Sheets include an internationally recognized set of registered designations and chemical composition limits for aluminum alloys. The document includes historical information such as “inactive original alloys” and redesignations, when alloys were historically reclassified to the modern standard designations and the dates when they were reclassified. The “Teal Sheets” are reviewed in Section 5.5 below.

- As described in other references below, typical alloys used for aluminum pipe and culvert materials include alloy 3004 clad with alloy 7072 for aluminum pipe, and alloy 5052 (unclad) for aluminum structural plate.

Table of Series of Aluminum Alloys

Series	Primary Alloying Elements	Heat Treatable?	Attributes	Typical Uses and/or Other Comments
1XXX	None; ≥ 99% pure Al	N/A	Corrosion resistant, workable, high thermal and electrical conductivity.	Power grid transmission lines; 1350 is used in electrical applications; 1100 is used for food packaging.
2XXX	Copper	Yes	High strength and toughness, not as atmospherically corrosion resistant as other alloys.	Typically painted or clad with other alloys such as 6XXX series for atmospheric exposure corrosion resistance; 2024 is widely used in aircraft.
3XXX	Manganese	No	3003 is popular as a general purpose alloy with moderate strength and good workability.	Only a small percentage of manganese can be effectively added to Al; magnesium is often also added; 3003 is used in heat exchangers and cooking utensils; 3004 and its modifications are used in beverage cans.
4XXX	Silicon	No	Silicon is added to lower the melting point without producing brittleness.	4XXX series typically used in welding wire and brazing alloys; 4043 is widely used for welding 6XXX series alloys for structural and automotive applications.
5XXX	Magnesium	No	Moderate to high strength, good weldability and resistance to corrosion in the marine environment.	Building and construction; storage tanks; pressure vessels; marine applications; 5052 is used in electronics; 5083 in marine applications; anodized 5005 sheet in architectural applications; 5182 for the aluminum beverage can lid.
6XXX	Silicon and Magnesium	Yes	Highly formable, weldable, moderately high strength, excellent corrosion resistance.	Architectural and structural applications; 6061 is used for truck and marine frames; iPhone 6 was made from this series.
7XXX	Zinc	Yes with Magnesium	Very high strength if it includes magnesium, which allows for heat treating.	Other elements such as copper and chromium may be added in small quantities; 7050 and 7075 are widely used in aircraft; Apple watch was 7XXX.
8XXX	Others	N/A		

5.2 AASHTO Aluminum Pipe and Corrugated Plate Standards

5.2.1 AASHTO M 196-16, "Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains," American Association of State Highway and Transportation Officials, Washington, DC, 2016.

- AASHTO M 196-16, Standard Specification for Corrugated Aluminum Pipe for Sewers and Drains [32], is the AASHTO product standard for corrugated aluminum pipe. In the specification, its ASTM analog is listed as ASTM B745. The AASHTO specification covers corrugated aluminum pipe for use in storm water drainage, underdrains, culverts, and other similar uses. The specification references AASHTO M 197 for the aluminum alloy sheet from which the pipe is to be fabricated. The specification allows steel, stainless steel, or aluminum alloy fasteners, with the aluminum alloy bolts specified to be fabricated from alloy 6061-T4.

5.2.2 AASHTO M 197-06 (2016), "Standard Specification for Aluminum Alloy Sheet for Corrugated Aluminum Pipe," American Association of State Highway and Transportation Officials, Washington, DC, 2016.

- AASHTO M 197-06 (2016), Standard Specification for Aluminum Alloy Sheet for Corrugated Aluminum Pipe [33], is the AASHTO specification for the corrugated aluminum from which corrugated pipes are produced. The ASTM analog is listed as ASTM B744. It specifies aluminum alloy sheets or coils to conform to the applicable requirements of ASTM B209 [14] for alclad alloy 3004-H34 for annular pipe an alclad alloy 3004-H32 for helical pipe. Table 2 of the specification identifies chemical composition limits for the aluminum alloy 3004 core and aluminum alloy 7072 cladding, where the composition limits are identical to those provided in Table 2 above. The specification requires the nominal cladding thickness on each side shall be 5% of the total composite thickness of the sheet. We also reviewed the 1982 version of the standard and see the material requirements were for alclad alloy 3004-H34 in accordance with the then-current version of ASTM B209.

5.2.3 AASHTO M 219-92 (2017), "Standard Specification for Corrugated Aluminum Alloy Structural Plate for Field-Bolted Pipe, Pipe Arches, and Arches," American Association of State Highway and Transportation Officials, Washington, DC, 2017.

- AASHTO M 219-92 (2017), Standard Specification for Corrugated Aluminum Alloy Structural Plate for Field-Bolted Pipe, Pipe Arches, and Arches [34], is the AASHTO product standard for corrugated aluminum structural plate. The ASTM analog is listed as ASTM B746. The AASHTO specification covers corrugated aluminum alloy structural plate used in the construction of pipe, pipe arches, arches, underpasses, and special shapes for field assembly generally used for drainage purposes, pedestrian and vehicular underpasses, and utility tunnels. The specification requires the flat plate material used to fabricate structural plates conform to the requirements of ASTM B 209 [*14*] and be fabricated from aluminum alloy 5052-H141. Structural stiffeners shall be fabricated from aluminum alloys 6061-T6 or 6063-T6 conforming to ASTM B 221. Fasteners may be steel with zinc coating, stainless steel, or aluminum. If fabricated from aluminum, the fasteners shall be made from aluminum alloy 6061-T6 in accordance with ASTM F 468. We also reviewed the 1982 version of the standard and see the material requirements were for aluminum alloy 5052-H141 in accordance with the then-current version of ASTM B209. AASHTO M 219-82 provides a chemical composition limit table with composition limits that match those of Table 2 for alloy 5052.

5.3 "Corrosion Resistance of Aluminum and Aluminum Alloys," Metals Handbook Desk Edition, Second Edition, p. 499-505, Edited by J.R. Davis, ASM International, Russell Township, OH, 1998.

ASM International is the world's largest and most established materials information society. The Metals Handbook Desk Edition is an internationally recognized and utilized compilation of information from metallurgical technical experts. It has a chapter dedicated to aluminum and aluminum alloys, including a subsection on corrosion resistance, from which relevant information is presented in the bullets below.

- It identifies aluminum and its alloys as having good corrosion resistance in natural atmospheres, fresh waters, seawater, many soils, many chemicals and their solutions, and most foods. It attributes this resistance to the "very thin, compact, and adherent film of aluminum oxide on the metal surface." When a fresh surface is created, the film reforms rapidly and grows to a stable thickness. When formed in air at ambient temperatures, the film is about 5 nm thick and increases in the presence of water and at higher temperatures. It notes the oxide is soluble in alkaline solutions and strong acids, while being stable over a pH range of 4.0 to 9.0.

- It identifies different types of corrosion and various interactions with induced or imposed stresses, and the surface may become unattractive from pitting, although there may be no effect on durability or function. However, other corrosion phenomena, such as stress-corrosion cracking, localized severe corrosion due to heavy metal ions in solutions, stray electrical currents, or galvanic couples with more anodic metals can be quite damaging.

- **Regarding alloy composition and corrosion tendencies**, it notes copper is the element that has the greatest effect on corrosion resistance because copper "replates from solution as minute metallic particles forming highly active corrosion couples. The effects are apparent at copper contents exceeding a few tenths of one percent." The 7xxx alloys without copper have high general corrosion resistance, and the 7xxx alloys that have more than 1% copper are generally less resistant to corrosion (see the table in Section 5.5 for common culvert alloy compositions). It notes the 3xxx alloys as generally among those having the greatest corrosion resistance, as well as the 5xxx series alloys, which are the best alloys for marine environments. In a table of wrought aluminum alloys, 3004 and 5052 are both listed as having an "A" rating for general corrosion resistance and for stress corrosion cracking resistance. Alloy 7072 (used for cladding of aluminum pipes with a core of 3004 alloy) is not listed in the table.

- It presents plots of average (loss by weight of specimen) and maximum (measurement of pit depth) depths of attack for alloys 1100, 3003, and 3004 (the average of all three alloys are plotted) for seacoast and industrial environments, with a maximum depth of attack corresponding to 0.010 in. with 30 yrs exposure in a seacoast environment.

- **Regarding forms of corrosion**, it notes, "most corrosion in service is localized in one way or another. When the oxide film is insoluble in the corroding medium, corrosion is localized at weak spots in the film, which can result from microstructural features such as the presence of microconstituents. Local cells are formed by such nonuniformities in the metal as well as environmental nonuniformities, such as those created by differential aeration cells or by heavy metals plated out on the surface."

- **Regarding pitting corrosion**, it notes, "Pitting is the most common form of localized corrosion and frequently is difficult to associate with specific metallographic features. Pit shape can vary from shallow depressions to cylindrical or roughly hemispherical cavities," and the shapes distinguish pitting from intergranular or exfoliation corrosion. It notes 5xxx series alloys have the lowest pitting probabilities among commercial alloys, followed by 3xxx series.

- **Regarding intergranular corrosion**, it identifies intergranular corrosion as "a selective attack of grain boundaries. The mechanism is electrochemical, resulting from local cell action in the boundaries. Microconstituents precipitated in grain boundaries have a corrosion potential differing from that of adjacent solid solution and transition precipitate structure and form cells with it. In alloys of the 5xxx and 7xxx groups, the precipitates (Al_8Mg_5, $MgZn_2$, and $Al_2Mg_3Zn_3$) are anodic to the matrix." Susceptibility to intergranular corrosion "depends on the extent of intergranular precipitation, which is controlled by fabricating or heat treating parameters." It identifies intergranular corrosion as being involved with stress corrosion cracking.

- **Regarding stray current corrosion**, aluminum may be corroded in an area of anodic reaction in proportion to a current when an electric current is conducted from aluminum to an environment such as water, soil, or concrete. At low current densities, the corrosion may be in the form of pitting. In soil, this can occur where aluminum is close to other buried metal systems protected by impressed current cathodic protection systems, where ground current can leak onto a buried aluminum structure at one point, then off at another point (where the corrosion occurs) through a low-resistance path between the aluminum structure and the structure being protected. The handbook identifies common bonding (connection by wire) of all nearby buried metal systems as the usual way to avoid such attack.

- **Regarding deposition corrosion**, the handbook identifies it as a special form of galvanic corrosion that causes pitting when particles of a more-cathodic metal plate out of solution on the aluminum surface, setting up local galvanic cells. Copper, lead, mercury, nickel, and tin are aggressive to aluminum, particularly in acidic solutions, but have low solubility in alkaline solutions.

- **Regarding stress-corrosion cracking (SCC)**, this cracking is identified as the "time-dependent cracking under the combined influence of sustained tensile stress and a corrosive environment." SCC is characteristically intergranular in nature and has been experienced only in higher strength alloys and tempers of the 2xxx, 7xxx, and 5xxx types (with more than 3% Mg) and of 6xxx type with excess silicon. However, no SCC problems were encountered in service with 3xxx alloys, or 5xxx alloys with 3% Mg or less (alloy 5052, used for structural plate, has up to 2.8% Mg). SCC can occur in humid air, and, where it can occur, it is accelerated in chloride-containing environments, and is possible in susceptible alloy/temper combinations even at low stresses. There is also orientation-dependence; high stresses are generally required when the stress is parallel to the longitudinal (direction of rolling) or long-transverse direction (perpendicular to the direction of rolling). SCC is possible with low stresses when stress is in the short-transverse direction, identified as perpendicular to the surfaces of plate.

- **Regarding corrosion fatigue**, the handbook notes, "fatigue strengths of aluminum alloys are lower in such corrosive environments as seawater and other salt solutions than in air, especially when evaluated by low-stress, long-duration tests. Such corrosive environments produce smaller reductions in fatigue strength in the more corrosion-resistant alloys, such as the 5xxx and 6xxx series, than in the less resistant alloys, such as 2xxx and 7xxx series. Like SCC, corrosion fatigue requires the presence of water. In contrast to SCC, however, corrosion fatigue is not appreciably affected by test direction, because the fracture that results from this type of attack is predominantly transgranular."

- Regarding other types of corrosion, such as exfoliation corrosion and galvanic corrosion, the typical alloys used for culverts (3004 clad with 7072, and 5052 for structural plate), do not appear to be particularly susceptible to exfoliation corrosion, and, in natural environments that include saline solutions, zinc and magnesium are anodic to aluminum and lend protection, although magnesium can cause corrosion of aluminum in severe marine environments from an alkaline reaction. Copper, copper alloys, brass, bronze, and monel (nickle-copper alloy) are the most harmful for galvanic corrosion of aluminum, followed by carbon steel in saline environments. Filiform corrosion is not applicable to uncoated aluminum, and the type of corrosion of aluminum structures observed in Wisconsin is not local to joints or seams; therefore, we do not thoroughly review crevice corrosion. The handbook identifies hydrogen embrittlement as a possible mechanism for aluminum deterioration; however, this was a relatively new phenomenon at the time of the handbook, and more-recent information is reviewed in ASM International's "Stress-Corrosion Cracking – Materials Performance and Evaluation," Second Ed., Edited by R.H. Jones, 2017 (reviewed below).

5.4 Melchers, R.E., "Time Dependent Development of Aluminum Pitting Corrosion," *Advances in Materials Science and Engineering*, Vol. 2015, Article 215712, Hindawi Publishing Corporation, Cairo, Egypt, 30 April 2015.

The abstract of this article states, "Aluminum alloys have excellent corrosion resistance to a wide variety of exposure conditions. Usually they corrode by pitting rather than by uniform corrosion. For infrastructure applications long-term corrosion behaviour is of interest. The relatively limited long-term pitting data that is available shows that maximum and average pit depths do not follow the power law function as conventionally assumed but tend to follow a bimodal trend with exposure time. This is consistent with the bimodal trends observed previously for corrosion mass loss of aluminum alloys. Most likely it is the result of the accumulation of corrosion products over the pit mouths, leading to the gradual development of localized anoxic conditions within pits. In turn this permits the development within the pits of anoxic autocatalytic conditions, consistent with established theory for pitting corrosion of aluminum. It also is consistent with observations of hydrogen evolution from pits. The implications of this for practical applications are discussed."

Specific information of interest to our research is presented in the bullets below:

- The paper notes that conventional corrosion studies commonly use a power law to estimate the corrosion level with time, although the quantitative data available is typically based on short-term exposures such as a few hours, days, or weeks. Applying a power law to estimate corrosion behavior of an aluminum structure subjected to a corrosive environment for long-term service, however, may not be appropriate, since, for example, pitting corrosion and atmospheric (widespread, uniform) corrosion are not the same phenomenon, and extrapolation of the shorter-term test data does not match trends shown in longer-term exposure studies.

- Other metals such as low carbon steels, weathering steels, and cast iron tend to exhibit a bimodal corrosion behavior, which has a relatively high rate of early corrosion that eventually slows. The bimodal model has a scientific basis and recognizes that the mechanics of corrosion can change as corrosion progresses.

- Figure 1 from the paper, reproduced here, identifies four phases for the bimodal model, with the model resulting in a relatively constant long-term corrosion rate.

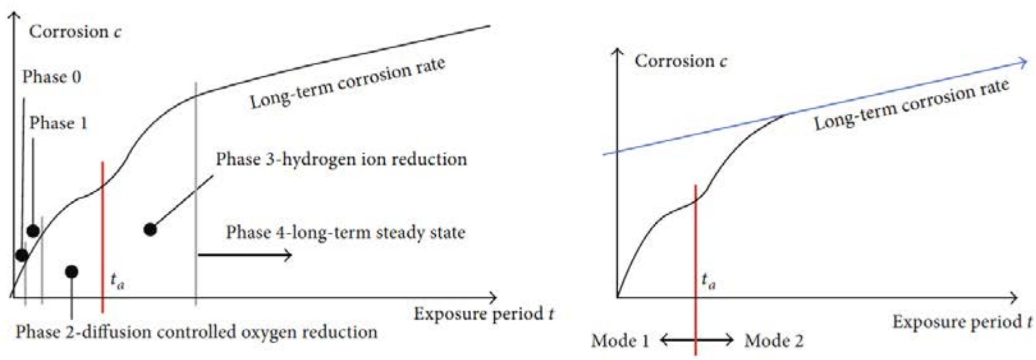


FIGURE 1: Schematic bimodal model for long-term corrosion loss and pit depth in marine environments showing brief descriptions for each of the phases involved and the linear idealization for long-term corrosion. The change from mode 1 with predominantly oxic corrosion conditions to mode 2 with predominantly anoxic conditions occurs at t_a.

- The author notes that there is not a wide body of data available of longer-term pitting corrosion behavior, as previous studies were typically designed and geared toward confirming power-law-type behavior; for example, with readings taken at intervals that work well for power-law but may obscure other intermediate behavior. They examine a variety of previously compiled test results while noting some data caveats, such as the data not necessarily capturing depths of a single pit with time, but rather the deepest pit on a given specimen at the time of measurement (likely different pits measured at different times, and different studies used different measurement techniques).

- The pitting corrosion phenomenon in aluminum includes the following steps:

  1. Aluminum oxide formation in the presence of water or moisture.
  2. When chlorides are present, a variety of aluminum-chloride byproducts form that are considered highly acidic.
  3. Corrosion topography becomes more nonuniform and nonhomogeneous, and as a result, the corrosion products become more nonuniform and nonhomogeneous.
  4. Local regions with low oxygen levels develop with differential aeration cells. This is an oxygen reduction reaction.

  These steps establish conditions for initiation of crevice and pitting corrosion, and may be considered what occurs in the bimodal model for $t < t_a$, which is Mode 1.

  5. Further corrosion likely occurs under localized anoxic conditions, with the cathodic reaction changing to the dissociation of water, which releases gaseous hydrogen. $AlCl_2$ is produced. This is consistent with other references that have

identified hydrogen evolving from aluminum pits and being identified as from the pitting process as opposed to other possible sources. The hydrogen ion reduction phase occurs at the beginning of Mode 2, then slows after larger molecular corrosion products effuse and displace the small, lightweight hydrogen. It is likely outward effusion and perhaps diffusion of $AlCl_2$ will become the long-term corrosion rate limiting behavior, or by processes such as steady state metal ion diffusion.

- The bimodal parameters and influences in the early stage are different than from those in the longer stages.

- The author also notes that aside from some “very specialized” cases involving algae, microbial corrosion of aluminum has not been observed.

- Maximum pit depth data from 20 yr exposure in a marine environment with bimodal curves fit for alloys 1050, 3003, and 5052 is presented in the paper’s Figure 6, reproduced here.

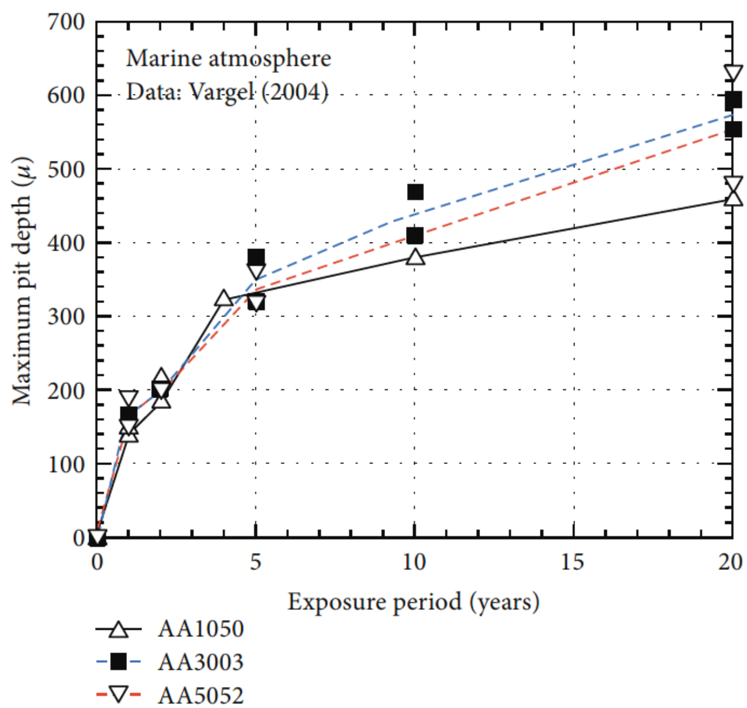


FIGURE 6: Data for maximum pit depth of aluminium alloys AA1050, AA3003, and AA5052 exposed in unspecified marine atmospheres for up to 20 years. The trends for maximum pit depth are shown and are bimodal. The changeover to mode 2 occurs at about 2-year exposure. Data from Vargel [4].

- The authors note that longer-term data tends to follow their bimodal model, but for short-term exposures, the early part of the bimodal model (Phases 0 and 1 in Figure 1a) is similar to the classical power law provided the period of exposure is much less than t_a, which marks the transition between Modes 1 and 2. If certain shorter-term laboratory studies were not of sufficient duration to capture the long-term trends, behavior may have been misidentified as consistent with power laws when actual longer-term behavior may have been consistent with the bimodal model.

5.5 NACE SP0169-2013, "Standard Practice – Control of External Corrosion on Underground or Submerged Metallic Piping Systems," *National Association of Corrosion Engineers (NACE) International,* Houston, TX, 2013.

We reviewed information presented in this Standard Practice related to corrosion of buried aluminum pipelines and identified the following relevant information:

- The Foreword identifies the standard as presenting "methods and practices for achieving effective control of external corrosion on underground or submerged metallic piping systems. These methods and practices are also applicable to many other underground or submerged metallic structures." It includes information on accepted methods and practices for external corrosion control of aluminum piping systems. Information presented in the practice is applicable to new piping systems, existing coated piping systems, and existing uncoated piping systems.

- In Section 3, Determination of Need for External Corrosion Control, it suggests the following information be gathered about the environment (electrolyte) surrounding the piping system (Para. 3.2.2.1.b): "resistivity, pH, and chemical and microbial composition of the soil. Redox potential tests may also be used to a limited extent. Once the nature of the environment has been determined, the probability of corrosiveness is estimated by reference to actual corrosion experience on similar metallic structures, when environmental conditions are similar. Consideration of possible environmental changes such as those that might result from irrigation, spillage of corrosive substances, pollution, and seasonal changes in water table and soil moisture content should be included in such a study."

- The standard provides detailed information on methods to provide electrical isolation of pipelines from various external sources such as pipe hangars, appurtenant structures, stray currents, etc. It also references several types of coatings and coating standards for external coatings for steel and iron pipes.

- Section 6, Criterial and Other Considerations for Cathodic Protection, Subsection 6.2, Criteria, Subsection 6.2.2 Criteria for Aluminum Piping, notes, "Aluminum can suffer from corrosion under high pH conditions, and application of cathodic protection tends to increase the pH at the metal surface. Aluminum can experience corrosion in alkaline or acidic environments (pH > 8.5 and pH < 4) according to the Pourbaix diagrams. The specific ranges depend on the specific electrolyte and alloy being tested." The Pourbaix diagrams are referenced as, M. Pourbaix, "Atlas of Electrochemical Equilibria in Aqueous Solutions," *NACE*, Houston, TX, 1974.

5.6 Registration Record Series Teal Sheets, "International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys," The Aluminum Association, Arlington, VA, January 2015.

The "Teal Sheets" provide chemical composition limits for registered aluminum alloys. The alloys and their composition limits are internationally recognized by signatories to the Declaration of Accord, which includes twenty-two nations plus two European organizations. Chemical compositions for the three primary aluminum alloys used in aluminum culvert manufacturing, 3004 (core alloy in corrugated aluminum pipe that comprises 90% of the thickness), 5052 (aluminum structural plate), and 7072 (cladding over alloy 3004 in corrugated pipe, about 5% of overall thickness on the inner and on the outer surfaces) are reproduced in the table below.

Aluminum Alloy Compositions for the Three Primary Alloys Used for Culverts (Reproduced from the Aluminum Association Teal Sheets)

Element	Alloy Designation and Composition[1]		
	3004	5052	7072
Silicon (Si)	0.30	0.25	–
Iron (Fe)	0.7	0.40	–
Copper (Cu)	0.25	0.10	0.10
Magnesium (Mn)	1.0-1.5	0.10	0.10
Manganese (Mg)	0.8-1.3	2.2 – 2.8	0.10
Chromium (Cr)	–	0.15 – 0.35	–
Zinc (Zn)	0.25	0.10	0.8 – 1.3
Total Silicon and Iron (Si+Fe)	–	–	0.7
Others – Each, Maximum	0.05	0.05	0.5
Others – Total	0.15	0.15	0.15

1. Compositions given are a % maximum by weight unless shown as a range.

5.7 "Stress-Corrosion Cracking – Materials Performance and Evaluation," Second Edition, Edited by R.H. Jones, ASM International, Materials Park, OH, 2017.

This reference, also by ASM International, was reviewed particularly for information on aluminum stress corrosion cracking and aluminum hydrogen embrittlement following our review of the ASM Metals Handbook Desk Edition (1998) above. Relevant information from this reference not covered elsewhere in this literature review is presented in the bullets below:

- **Regarding stress-corrosion cracking susceptibility**, the reference notes, "only aluminum alloys that contain appreciable amounts of soluble alloying elements, primarily copper, magnesium, silicon, and zinc, are susceptible to SCC. For most commercial alloys, tempers have been developed that provide a high degree of immunity to SCC in most environments."

- **Regarding hydrogen-induced cracking**, the reference notes, "For many years it was thought that hydrogen uptake was extremely slow in aluminum alloys and therefore played little to no role in their crack growth or embrittlement. The explanation was that the native oxide was very thermodynamically stable and adherent so that hydrogen uptake was highly impeded. However, more recently it has been shown that hydrogen uptake in pure aluminum and aluminum alloys does occur in most aqueous and wet hydrogen environments, but not dry hydrogen environments."

It continues, "Three hydrogen-induced cracking mechanisms associated with cracking of metals also are supported for hydrogen-induced cracking of aluminum alloys. These are hydrogen-induced decohesion (HEDE), hydrogen-enhanced localized plasticity (HELP), and hydriding." "At this time, arguments for HELP and HEDE are both viable explanations for crack growth of aluminum alloys, but there is no evidence for the presence of hydrides in aluminum alloys."

5.8 Szklarska-Smialowska, Z., "Pitting and Crevice Corrosion," NACE International Press, Houston, TX, 2005.

This book is a reference published by NACE as an update to a 1986 book devoted to pitting and crevice corrosion. The 1986 book was published after 60 yrs of studies. In the following 20 yrs, the introduction notes, "the interest in localized corrosion has increased significantly as a result of scrutinizing the damage by localized corrosion of many engineering materials in different branches of industries. A large number of publications have appeared with new data, better explaining the localized corrosion phenomena, thanks to work of many worldwide researchers. Pitting and crevice corrosion takes place almost exclusively in metals that are in the passive state and possess good resistance to uniform corrosion."

- Chapter 1, Characteristics of Pitting Potentials, provides the following information on pitting potential, E_p, and repassivation potential, E_r, which are mentioned in review of subsequent chapters, below:

    - Pitting potential, E_p, is listed with a variety of definitions, one being "the applied potential necessary to maintain a salt film in a small open pit," and another being "the potential at which the composition of the solution within the pit's precursor is such that the passive film is locally unstable and cannot repassivate." In older literature, it was considered the potential below which pits do not nucleate and above which stable pits are growing, though subsequent research has shown that there is not a hard cutoff point.
    - Repassivation potential, E_r, was formerly defined as the potential below which stable pits cannot initiate and above which already nucleated pits can grow. It is now considered the potential below which no metastable and stable pitting occurs and above which metastable pits can form and already nucleated pits can grow.

- Chapter 3, Pit Morphology in Various Metals and Alloys, has the following information regarding aluminum pit growth, particularly in the presence of environments with NaCl:

    - For pure aluminum, pit growth susceptibility differs on each of the three crystallographic orientations in the presence of NaCl, therefore there may be orientation-dependence for pit growth.
    - Images are provided showing pit growth in pure aluminum in aqueous 0.1M NaCl + 0.3M $NaNO_3$ solution when subjected to a constant potential of $0.8V_{sce}$ for 2 hr, 4 hr, and 6 hr, reproduced below. This identifies that even pure aluminum can be subject to pitting when subjected to the right solution and electrical potential.

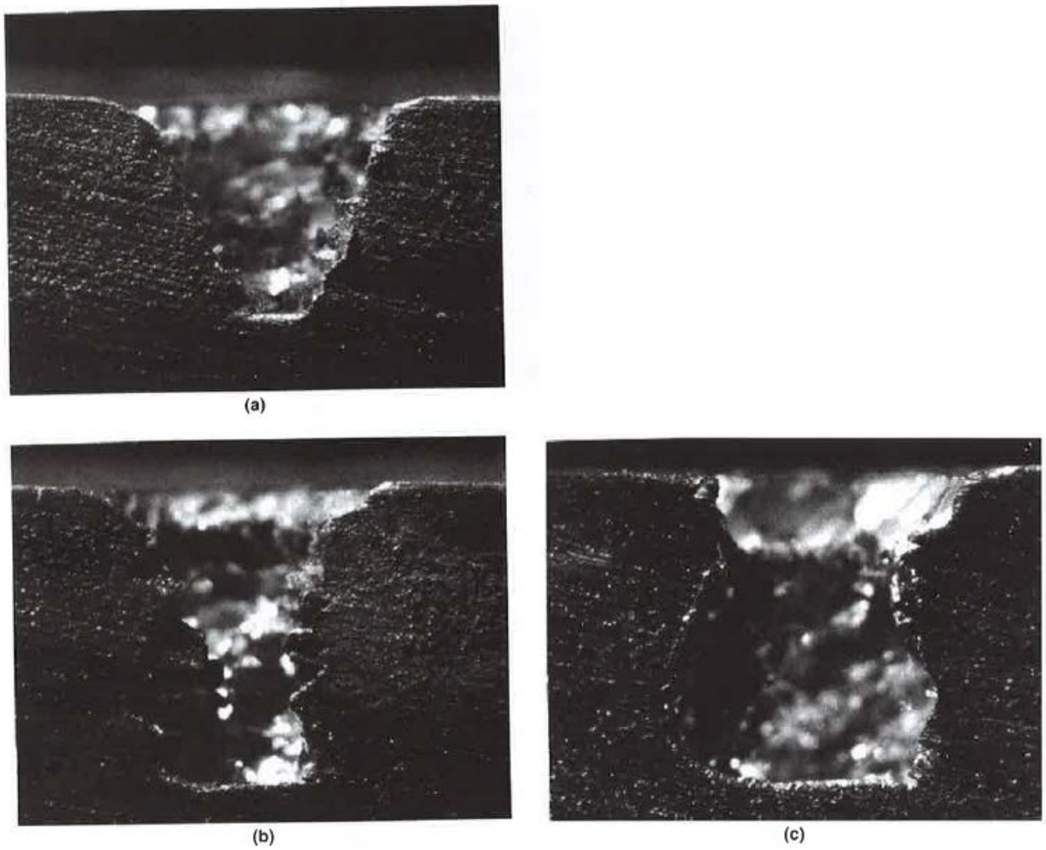


FIGURE 3.11 Cross-sectional views of the grown artificial pits of pure Al subjected to a constant anodic potential of 0.8 V_{SCE} in aqueous 0.1 M NaCl + 0.3 M $NaNO_3$ solution for (a) 2 h, (b) 4 h, and (c) 6 h. *Source*: S. I. Pyun, K. H. Na, W. J. Lee, J. J. Park, *Corrosion*, 56 (2000): p. 1015.

- Chapter 6, Criteria for Pitting Development, provides the following relevant information on development of aluminum corrosion pits in the presence of salt:
    - For general metallic pit development, “analysis of the pit’s content disclosed very concentrated chlorides of dissolved metal cations and very low pH. A salt film also was found at the bottom of the pits, and the pits are usually covered by remnant of passive film together with some metal and corrosion products. All these factors influence the pit development.”
    - The chapter lists the following dependencies for stable pit growth: 1) alloy composition, 2) the composition and the concentration of the solution within the pit, 3) a presence of salt at the pit bottom, 4) the concentration of aggressive and nonaggressive substances in the bulk solution outside the pit, and 5) temperature. “The chemical and physical properties of the passive film formed within pit during repassivation and especially a pit cover, also plays an important role.”

- It notes, "while several researchers argue that a salt film is necessary, others have shown that a critical level of chloride concentration, below the saturation concentration with respect to the metal salt, is sufficient for pit propagation."
- Several studies have shown that aluminum pit growth can be stabilized (i.e., pit growth continues at a constant rate) with or without a salt film, provided the pit environment is concentrated enough to avoid repassivation; however, others argued that "a critical concentration of solution is needed to form a salt film on the metal surface to prevent growth of the passive film." One study of an artificial aluminum pit in $AlCl_3$ solution identified "that a continuous aluminum chloride film will form with an aluminum chloride concentration greater than 80% of saturation at high anodic potentials." Another study identified "that the critical current density is associated with the maintenance of a critical concentration of cation in the pit on aluminum thin films. The critical cation concentration is 1.5M or 48% of the saturation concentration of a salt." All studies point toward the conclusion that "the critical concentration of the pit electrolyte was independent of the pit size but dependent on the applied potential." Also, data presented "show that if the critical concentration of the solution in the pit can be maintained and will not change in time, the pit will grow without salt film in the pit."
- Section 6.4, Salt Film in Aluminum and Titanium Base Alloy Pits, states, "it is well documented that within aluminum pits a salt layer exists, if not during pit nucleation and the first stadium of pit growth, then during a later period of pit growth. In the literature two different types of pit's salt are mentioned: Aluminum chloride ($AlCl_3$) and aluminum oxychlorides $Al(OH)_2Cl$ and $Al(OH)Cl_2$." Depending on the precise salts and chemical reaction, the pH locally within a pit can be as low as 1.
- This section continues, "according to Hagyar and Williams the following sequence of reactions occurs in a pit: ionization of the bare surface of Al occurs rapidly and Al^{3+} undergoes hydrolysis very rapidly, aluminum hydroxide reacts with chloride producing $Al(OH)Cl^+$ and then with water producing acidic conditions $Al(OH)Cl^+ + H_2O \Leftrightarrow Al(OH)_2Cl + H^+$." It also notes that 15% to 20% of the current is consumed for hydrogen evolution reaction within the pits.
- Section 6.5, Role of Pit Cover, notes, "many authors found that pits are covered by a layer suggested to be the remnant of a passive film over the pit mouth. It seems that this cover consists of the remnant of passive film and metal and sometimes corrosion products. There is general agreement that the pit cover is an important factor for stabilizing pit growth…The pit cover acts as a physical barrier against the current flow and diffusion that helps to maintain a concentrated aggressive environment inside the pit." The section continues, "a strong, resistant cover facilitates pit stability, while a weak or stressed cover hinders it." The term pit stability generally refers to stable, continuous pit, and when pits become unstable, they repassivate.
- Section 6.8, pH in Aluminum Pit Solution, states, "the pH of the solution measured in pure Al pits was found to be between 3 and 4 by using a freezing method when the pH of the bulk solution was 11." It continues, "if it is assumed that a saturated solution of $AlCl_3$ is present in the pits, pH values even lower than those given above might be expected because the pH of the saturated solution of $AlCl_3$ is -0.3." A study is referenced where the change in pH and Cl^- ion concentration within artificial pits on aluminum in natural seawater resulted in a pH change from

5 to 2.5 after 100 hrs of exposure with an increase in chloride anions also detected. It also notes from this study that the "pit bottom indicates a selective dissolution along certain crystallographic planes."

- Section 6.10, Gas Evolution From Pits, notes that gas evolution has "been observed from occluded cells" on aluminum. "This indicates that the surface of the corroding metal is at a potential negative to that of hydrogen evolution. In fact, Al undergoes pitting in chloride solutions at potentials more negative than the H^+/H_2 equilibrium potential."
- Section 6.11, Blisters in Aluminum, notes, "it is well known that during pit development on aluminum gaseous hydrogen is forming. Because the aluminum pits are covered by an oxide film," accumulation of hydrogen in the pit while covered by the oxide film results in the formation of a blister than eventually cracks. The section notes that Natishan and McCafferty identify four steps in the growth and rupture of such blisters: 1) the early appearance of a blister, 2) the formation of a primary crack in the oxide film, 3) metal dissolution and hydrogen production at the oxide/metal interface, and 4) rupture of the blister. By applying fracture mechanics to a thin membrane, Natishan and McCafferty derived an equation that describes the critical stress and pressure necessary to rupture a blister, with the stress being about 14,700 psi with a corresponding internal pressure of hydrogen within the blister of about 22 psi.

- Chapter 9, The Interaction of Chloride Ions with a Passive Film, provides the following relevant information on aluminum pitting corrosion, particularly in a buried environment:

  - It notes that chlorides play an essential role in localized corrosion, particularly of passive metals, while there is still much unknown and of considerable debate in the exact nature of this phenomenon.
  - It identifies two fundamental problems that are not yet understood: 1) why the attack of a passive metal is local in a chloride solution, and 2) what is the interaction of chloride anions with a passive oxide film. It goes on to note, "The precise role of Cl^- in promoting or inducing pitting is not well understood. For example, it is still not clear whether the Cl^- causes the local breakdown of the passive film or whether the Cl^- interferes with the repassivation process after the film has broken down or it takes part in both processes."
  - It continues, "All researchers agree that the first step in pitting corrosion is the adsorption of chloride anions on the passive film. However, only a few papers have dealt with this problem. Berzins et al. measured the adsorption isotherms on corroding Al using Cl^{36} as a radioactive tracer. The amount of chloride adsorbed was found to be a function of the chloride concentration and time," and it gives an equation for the relationship. It then notes, "Chloride adsorption was primarily localized on the corroding pit sites." Adsorption of chloride ions on the passive film was found to increase with the potential, and the addition of nitrate or sulfate delayed but did not prevent chloride uptake. Conclusions included that a corroding aluminum surface has a variety of adsorption sites with different adsorption properties but only a minority of the sites are active for pitting corrosion. Results suggest there is no threshold for the chloride concentration below which pitting will not occur, and that the presence of an inhibitor will delay but not prevent the onset of pitting.

  - In Section 9.4, Aluminum, information is presented particularly related to the interaction of chloride ions with the aluminum oxide passive film. Maitra and Verink studied chloride uptake by polarized aluminum in 0.1M NaCl solution with polarization potential below the pitting potential. They reported that the amount of chloride increased with increasing polarization time, and that chloride was present in the oxide film, with greater concentration at the oxide surface and no evidence of chloride at the oxide/metal interface.
  - Other research by Natishan et al. identified chloride in the passive film of pure aluminum at potentials below the pitting potential.
  - Other research by Yu et al. studied the ingress of chloride into aluminum prior to pitting corrosion on samples of 99.9995% pure aluminum in 0.1M NaCl solution at different potentials below the pitting potential. Chloride was found to be present as an adsorbed species at the surface and as an incorporated species within the film. Conclusions included that chloride migrated from the solution/aluminum oxide interface into the passive film prior to pit initiation.
  - In the concluding paragraph of the chapter, the author notes, "Often in the literature the pitting mechanism is considered assuming the local adsorption of chloride on the passive metal, forming soluble complexes with the metal cations (from the oxide), thinning the passive layer until the aggressive solution reaches the metal and ultimately producing the pits. There is no sound proof for supporting this mechanism. The results of chloride incorporation measurements on the thickness of the passive film are not consistent; and rather thickening of the film but not thinning was reported. Taking into consideration the observation of the nucleation of pits on aluminum and stainless steels at the metal/metal oxide interface, the mechanical breakdown models on pitting seem the most probable."

- Chapter 12, Temperature, does not identify a correlation between likelihood of aluminum pitting corrosion and the temperature ranges expected in an outdoor environment in Wisconsin.

- Chapter 14, Pitting of Aluminum, Copper, Titanium, Zinc, and Other Metals and Alloys, provides the following relevant information on aluminum pitting corrosion, particularly in a buried environment:

  - Many intermetallic particles can be found in aluminum alloys, and their compositions and distribution are extremely dependent on the alloy's thermal treatment.
  - Pitting potential was found to increase with increasing copper content, although the highest pitting potential was limited by the solubility of copper in aluminum. Some of this behavior can be age and hardness dependent; for intermediate levels of aging, $CuAl_2$ particles become depleted of Cu, and these zones are locally attacked.
  - The addition of magnesium, manganese, or silicon to aluminum does not significantly affect the pitting potential of the alloy when it is immersed in synthetic seawater. The presence of a small amount of tin in pure aluminum decreases the pitting potential in a sodium chloride solution. Zinc added to aluminum at a concentration higher than 1% reduces pitting potential, E_p, in aluminum and decreases the repassivation potential, E_r, as well.

  - Regarding decreased resistance of pitting of aluminum-zinc alloy in comparison to pure aluminum can be explained by single-activator atoms with the connectivity of a surface oxide monolayer on the aluminum surface which catalyzes the dissolution of aluminum atoms.
  - Silicon increases the pitting potential of aluminum in a chloride solution.

- Chapter 15, Microcrystalline and Amorphous Alloys, notes, "In the past decade, there have been several efforts to produce "stainless" aluminum with high resistance to localized corrosion in chloride solutions… Alloying of aluminum with transition metals to supersaturated solution concentrations exceeding equilibrium solubilities has been successful for improving localized corrosion resistance." Pitting resistance of aluminum can be improved by alloying with tungsten, tantalum, molybdenum, chromium, niobium, and titanium. Two schools of thought prevail on how these alloys improve the pitting resistance: 1) modification of the passive film structure and chemistry that hinders chloride penetration, or 2) the alloying elements exert their influence at the active pits rather than on the passive film, such as by having low solubility in acidic solutions and reducing "the ability of the micropits to maintain the critical environment necessary for growth."

- Chapter 17, Inhibitors, identifies some of the processes and conditions that can be favorable or unfavorable to the initiation of pitting corrosion. Some relevant points are identified below.

  - Since it is not easy to stop the development of an already nucleated pit, the main effort in identifying an effective pitting inhibitor must be directed toward inhibiting the pit nucleation process.
  - In most cases, the properties of the passive film play a dominant role in inhibition of pits. "To prevent or significantly delay pit nucleation, the inhibitor should make the passive film more protective. This can be done by changing the structure and composition of the passive film; reducing the quantity of imperfections in the film; and diminishing the access of aggressive anions to the film by covering it with an adsorbed species." It also notes that if bare metal were to become exposed, the inhibitor should heal the defective site.
  - Section 17.1, The Role of Adsorption in Pitting and Inhibition of Pitting, notes that pitting occurs when halogen ions (mainly Cl^-) are in contact with a passive metal. When exposed to water, a dissociative adsorption of water on the oxide film occurs and leads to the formation of a hydrolated surface layer. The concentration of OH^- on the surface equals that of H^+ at a pH of zero charge. The adsorption of Cl^- does not occur if the pH is greater than the pH of zero charge; however, if the pH is less than the pH of zero charge, Cl^- and other negatively charged anions can be adsorbed. The pH of zero charge for aluminum oxide is 9.1.
  - The section also identifies that research shows there is a critical ratio of inhibitive to aggressive anion concentration above which no pitting will occur. Rudd and Scully identified the following order of efficiencies of pitting inhibitors for aluminum in 0.8M NaCl at pH = 8: nitrate > phosphate > citrate > tartrate > benzoate > acetate. It is believed phosphates and benzoates act as blocking inhibitors by forming insoluble precipitates.

- Section 17.2, Temperature, identifies that temperature plays a role in the effectiveness of corrosion inhibitors by affecting the kinetics of metal dissolution and oxide film formation and influencing the processed of adsorption and desorption. The effectiveness of an inhibitor can increase, decrease, or not change with temperature changes; however, most studies have been focused on evaluating effectiveness of inhibitors at temperatures much greater than those encountered outdoors in Wisconsin.
- Section 17.4, Inorganic Inhibitors, Subsection 17.4.1 Chromate, states, "The most studied and the most important inhibitors for aluminum and iron alloys are chromates." Studies of the effect of CrO_4^{2-} ions as corrosion inhibitors for aluminum show that the chromates inhibit action by blocking the incorporation of Cl^- into the oxide film, likely by supplying oxygen atoms that displace Cl^- from the metal/oxide interface. However, the effectiveness of chromate as an inhibitor decreases with a decrease in pH, and it may not function well for inhibition of pitting in aluminum if there is an acidic pH.
- The rest of Chapter 17 gives results of various studies of different inorganic and organic inhibitors for several different base metals (stainless steels, iron, some aluminum) in various solutions. Performance is mixed depending on pH, solution concentration, and other variables. One common conclusion is that regardless of the inhibitor, once pits nucleate, pit growth is very difficult to stop (especially given the protective skin offered by the passive film over the pit); therefore, the only way to keep pitting corrosion from occurring is to prevent it from the very beginning, before pits have a chance to form.

- Chapter 19, Pits as the Sites for Stress Corrosion Cracks Nucleation, identifies that stress corrosion cracking has been observed to nucleate from corrosion pits on a variety of metals including aluminum and aluminum alloys. Section 19.4, Pits as the Sites of Intergranular Corrosion in Nonferrous Metals and Alloys, identifies multiple aluminum alloys have a reduced fatigue life in the presence of chlorides. In aluminum alloy 6056, SiMg particles were found to be the nucleation sites for pits, which subsequently become reactive and partially dissolved during immersion in NaCl solution. In the concluding paragraphs to the chapter, the following is noted:

    - It is generally accepted that "different types of localized attack in chloride solutions such as crevice corrosion, pitting, intergranular corrosion, stress corrosion cracking, and corrosion fatigue have several features in common. They occur in passive metals and initiate in some weak sites, in aluminum on intermetallic particles or the alloy matrix around the particles. All aluminum alloys in unstressed conditions are attacked by pitting and crevice corrosion in solutions containing chloride ions. The pits (crevices) not only damage the metals, but in the presence of mechanical stresses can act as sites for the initiation of stress corrosion or fatigue cracks… The transition from one type of localized corrosion to another (from pitting to SCC) is a result of the formation of different surface films, when the environmental conditions undergo changes."

5.9 Chu, W-Y., C-M Hsiao, and J-W Wang., “Stress Corrosion Cracking of an Aluminum Alloy under Compressive Stress,” *Metallurgical Transactions A*, Vol. 16A, No. 9, The Metallurgical Society of AIME, Warrendale, PA, 1985.

This paper describes experimental and analytical procedures to investigate stress corrosion cracking (SCC) of 7075 aluminum alloy under compressive stress using a modified wedge opening loading (WOL) specimen. For the experimental component, the alloy was in an aqueous solution of 3.5% NaCl. Results from the experiment showed that SCC could occur if an applied compressive displacement was larger than a critical value. The threshold stress intensity nucleating SCC from the notch under the compressive applied stress was 27.6 MPa-$m^{1/2}$, and the corresponding value under tension stress was 8.3 MPa-$m^{1/2}$. Fracture surfaces for SCC under compression stress were quite different than those from tensile stress; tensile stress fracture surfaces were intergranular and compression stress fractures were quasi-cleavage with a parallel striation pattern. Key information from the study is summarized in the bullets below:

- SCC typically is considered to occur where there is enrichment of hydrogen; however, the paper identifies that this enrichment cannot occur in a region of compressive stress; therefore, many expect that compressive stress would not induce SCC. However, compressive stress can cause slip or creep and thin film rupture, which can allow an anodic dissolution process to occur in freshly exposed metal that allows a crack to propagate.

- Previous research has shown compressive stress can induce SCC in 304 stainless steel.

- Linear elastic fracture mechanics were used to show the stress field near the tip of the notch was compressive. This was confirmed qualitatively by photoelastic experiments and quantitatively by finite element analysis. Fracture surfaces were examined and found to be consistent with observations and expectations from previous work with SCC under compressive stress in the 304 stainless steel. Fracture surfaces from specimens under tensile stress showed notable differences from those of the compression stress specimens.

- The incubation period for SCC under compressive stress is ten times longer than that under tensile stress for the same stress intensity factor, and the threshold stress intensity factor to initiate SCC under compressive stress is four times that for SCC initiation under tensile stress. Therefore, aluminum under compressive stress can be subject to SCC when exposed to high magnitude compressive stresses over a long period of time.

6. INFORMATION AND POLICIES FROM THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS AND U.S. FEDERAL HIGHWAY ADMINISTRATION

We reviewed information related to culvert selection and aluminum culvert use and performance from the American Association of State Highway and Transportation Officials (AASHTO) and U.S. Federal Highway Administration (FHWA).

6.1 "AASHTO Drainage Manual, 2014 First Edition," American Association of State Highway and Transportation Officials, Washington, DC, 2014.

The preface to this manual identifies the Technical Committee on Hydrology and Hydraulics (TCHH) as the producers of this manual, as a method to assist the Standing Committee on Highways, Subcommittee on Design, in developing guidelines and in formulating policy. The intent of the manual is to provide transportation agencies with guidelines for establishing state-specific policy and procedures for the design of highway drainage facilities.

Note that the New York State DOT Highway Design Manual, Chapter 8, references Chapter 9, Culverts, of the AASHTO Model Drainage Manual (2005). The 2005 Model Drainage Manual was superseded in 2014 by the first edition of the AASHTO Drainage Manual, and Culverts appear in Chapter 11. We did not review the 2005 manual, expecting the 2014 version to include more complete and up-to-date information.

- Chapter 11, Culverts, Section 11.2, General Considerations, identifies, "Only the hydraulic aspect of the design of the culvert and the choice of culvert materials will be discussed in this chapter," and "the choice of the culvert materials should consider the desired service life of the culvert and the site conditions affecting this service life. These include abrasion, corrosion, structural (height of fill) factors, and replacement cost commensurate with the risk at the site."

- Chapter 11, Culverts, Section 11.4, Design Features, Subsection 11.4.1, Culvert Shape and Material Selection, identifies material selection should be based on a comparison of the total cost of alternative materials over the design life of the structure, which is dependent upon the following: (1) durability (service life), (2) structural strength, (3) hydraulic roughness, (4) constructability, (5) initial/replacement cost, (6) bedding conditions, (7) passage of fish and aquatic organisms, (8) abrasion and corrosion resistance, and (9) watertightness requirements. It identifies corrugated aluminum pipe (and pipe arches), corrugated aluminum structural plate pipe, and corrugated aluminum structural plate structures of various shapes on a list of over a dozen common culvert shapes and materials.

6.2 "AASHTO Highway Drainage Guidelines, Fourth Edition," American Association of State Highway and Transportation Officials, Washington, DC, 2007.

This document was prepared by the Task Force on Hydrology and Hydraulics, under the Highway Subcommittee on Design, under the Standing Committee on Highways, to provide states guidelines covering major topics on highway hydraulic design. The foreword identifies the Guidelines as intended to provide an overview, discussion, and design philosophy for each of the covered topics while keeping technical information to a minimum by making reference to other technical publications such as the AASHTO Model Drainage Manual, which contains recommended design policy, criteria, procedures, aids, and example problems.

We review relevant portions of the 2007 edition of these Guidelines here, as referenced in the New York State DOT Highway Design Manual (the NYSDOT Manual Chapter 8 references Chapter 4 of these Guidelines). Information relevant to use and durability of aluminum culverts is provided below.

- Chapter 4, Hydraulic Design of Culverts, Section 4.4, Culvert Type, Subsection 4.4.2, Materials, has the following relevant information:

    - "The selection of the material for a culvert is dependent upon several variables (e.g., durability, structural strength, roughness, bedding conditions, abrasion and corrosion resistance, water tightness)." It lists corrugated aluminum as one of nine culvert materials used.
    - "Water and soil environment, construction practices, availability of materials and costs vary considerably depending on location; therefore, listing criteria for selecting culvert material appears to be impracticable as a general guideline. Discussions on the use of certain materials from the durability and hydraulic standpoint are given in Sections 4.5, 4.6, and 4.10."
    - Regarding economics of culvert material selection it states, "The most economical culvert is one which has the lowest total annual cost over the design life of the structure. The initial cost should not be the only basis for culvert material selection. Replacement costs and traffic delay are usually the primary factors in selecting a material that has a long service life. If two or more culvert materials are equally acceptable for use at a site, including hydraulic performance and annual costs for a given life expectancy, consideration should be given to material selection by the contractor."

- Section 4.5, Hydraulic Design, covers issues related to cross-section of culverts, geometry of culvert ends, and flow characteristics. There is no information relevant to our research.

- Section 4.6, Special Hydraulic Considerations, covers issues such as culvert anchorage, joints, piping, cavitation, tidal considerations, etc. There is no information relevant to our research.

- Section 4.10 Service Life, has the following information relevant to culvert material selection, and in particular for aluminum as a culvert material:

    - "Commonly used culvert materials are durable at most locations, but some soil and water environments are hostile and service life must be a consideration in material selection and culvert design. Conditions that affect the service life of culvert materials are corrosion, abrasion, and freezing and thawing action. Measures to increase service life are sometimes costly, and the total annual cost should be considered when designs are prepared."
    - "For a more detailed discussion on service life and durability, see the *Highway Drainage Guidelines*, Chapter 14."
    - The Section includes subsections on Abrasion (4.10.1), which presents general information already covered in more detail in other references in this literature review, and Corrosion (4.10.2). The subsection on corrosion notes environmental conditions that are generally considered to contribute to corrosion of metal culvert pipe are acidic and alkaline conditions in the soil and water and the electrical conductivity of the soil. It also notes the frequency and duration of flows transporting bed loads contribute to corrosion through causing abrasion or other damage to protective coatings.

- Regarding use of aluminum culverts in saltwater environments, the subsection notes that saltwater, depending on the salt concentration, will corrode aluminum, although aluminum culverts are fairly resistant to corrosion in typical saltwater environments. It notes coated aluminum may be considered in alkaline environments or where other metals (e.g., iron, copper) or their salts are present. Experience has not been good with metals in organic muck in estuarine environments.
- Regarding protecting metal culverts from corrosion, the Guidelines identify bituminous fiber-bonded coating or mill-applied thermoplastic coatings as typical, although states have had mixed reviews of their potential increase in service life vs. cost effectiveness. Non-fiber-bonded bituminous coatings may not be successful in hostile environments because of insufficient bond to the metal and potential damage to the coatings during handling and placing. The Guidelines identify mill-applied thermoplastic coatings as superior to bituminous coatings in abrasion resistance, and, perhaps in corrosive environments, though they only have a short track record as of the writing.
- The guidelines identify NCHRP Synthesis Report 50 (1978) and FHWA Report FHWA-FLP-91-006, *Durability of Special Coatings for Corrugated Steel Pipe* (1991) as having guidelines for selection of durable materials and protective measures for various corrosive environments.

- Additional cited references (Section 14.15) that we will consider for review include (1) *AASHTO Maintenance Manual* (1999); (2) Beaton, J.L., and R.F. Stratful, "Field Test for Estimating Service Life of Corrugated Metal Pipe," *Highway Research Board Proceedings*, Volume 41, Highway Research Board, Washington, DC, 1962, 255–272; (3) Haviland, J.E., P.J. Bellair, and V.D. Morrell, *Highway Research Report Number 242: Durability of Corrugated Metal Culverts*, Highway Research Board, Washington, DC, 1968, 41–66; (4) Lowe, T.A., and A.H. Koeph, "Corrosion Performance of Aluminum Culvert," *Highway Research Record No. 56*, Highway Research Board, Washington, DC, 1964, 98–115; (5) Nordin, E.F., and R.F. Stratful, "A Preliminary Study of Aluminum as a Culvert Material," *Highway Research Record No. 95*, Highway Research Board, Washington, DC, 1965, 1–70; (6) Peterson, D.E., *Evaluation of Aluminum Alloy for Use in Utah's Highways*, Utah State Department of Highways, 1973.

- Chapter 14, Culvert Inspection, Material Selection, and Rehabilitation Guideline, has the following relevant information:

  - Section 14.1, Introduction, identifies the purpose of the chapter as "to discuss the various processes that can lead to culvert failure and the factors to be considered in selecting an appropriate repair or rehabilitative strategy." "In addition, this chapter will present information to help designers select culvert materials that have the greatest potential to attain the necessary design service life, given a variety of site conditions and constraints."
  - Section 14.3, Factors Influencing Service Life, identifies design service life as being "typically defined as the period of service without a need for major repairs. Highway drainage structures are usually designed with the goal of providing some pre-selected minimum number of years of service life (that may vary based upon roadway classification or type of drainage structure). For corrugated metal

pipes, this will normally be the period in years from installation until deterioration reaches the point of either perforation or any point on the culvert or some specified percent of metal loss (see Section 14.4.1.2.1 for details)." "It is important to recognize that culverts are not assumed to be at or near the point of collapse at the end of their design service life. Rather, it is the period of little to no rehabilitative maintenance."

- Regarding estimation of service life, Section 14.3 continues, "the ability of designers to accurately estimate service life has proven to be difficult at best and, in some cases, totally inadequate. This difficulty can be traced to the variety of conditions that are typically considered in attempting to evaluate exactly how long a culvert will resist the forces of nature. Some of the influences that must be included in any estimation of service life are (from NCHRP Synthesis 254 by Gabriel (1998)): (1) hydrogen ion concentration (pH) of the surrounding soil and water; (2) soil resistivity, chloride and sulfate concentrations in the soil; (3) size, shape, hardness, and volume of bedload; (4) volume, velocity, and frequency of streamflow in the culvert; (5) material characteristics of the culvert; (6) anticipated chances in the watershed upstream of the culvert (such as development, industry, mining, or logging); and (7) possible effects of severe climates." It does not make reference to chemical deicing salt usage in colder climates being a contributor to decreased service life.
- It identifies other issues such as debris damage, erosion from major storms, improper manufacture or handling, and improper installation or backfilling as other items that may be the cause of rehabilitation, but are not accounted for in estimating service life.
- It notes again that the "best tool for estimating service life is still to look at the site in question and investigate existing drainage facilities. Unless upstream discharges have been altered to include new hostile factors, investigations that show a particular pipe product has successfully met or exceeded its design service life in a like environment will give the designer more useful information than any other service life analysis." Also, an existing culvert that has shown minor deterioration over a lesser period of years may indicate compatibility of attaining or surpassing the design service life.
- Subsection 14.3.1, Corrosion, identifies corrosion basics and corrosion chemical processes, similar to those that have been described in other literature reviewed herein. Regarding corrosion mechanisms, the discussion is focused on soil (in situ soil or imported backfill) and water chemistry, without consideration of deicing salts as a contributor to corrosion potential. Section 14.4.2 is identified as a reference for more information on protective coatings.
- Subsection 14.3.1.1, Hydrogen Ion Concentration (pH), notes, "studies performed in various states have been inconclusive in determining the exact role pH plays in corrosion. The presence of oxygen at the metal surface is necessary for the corrosion to occur and is independent of pH. However, at the very least, a pH reading that is either highly acidic or alkaline is indicative of heightened potential for corrosion." It identifies areas that have received high rainfall over many centuries as likely to be acidic from the runoff and percolation leaching soluble salts, resulting in the soil becoming acidic. Arid areas are more likely to be alkaline due to "soluble salts contained in groundwater being drawn to the surface through capillary action and then concentrating after evaporation occurs."

- Subsection 14.3.1.2, Soil Resistivity, notes that soil resistivity is the ability of a soil to conduct electrical current and that it is affected by the nature and concentration of dissolved salts, temperature, moisture content, compactness, and presence of inert materials such as stones and gravel. The greater the resistivity of the soil, the less capability the soil is of conducting electrical current and the potential for corrosion is lower. Resistivity values of about 5,000 Ω-cm are considered to present limited corrosion potential. Resistivities between 1,000 and 3,000 Ω-cm will usually require some level of pipe protection, depending on the pH level (e.g., if pH < 5, protection may be needed for a resistivity less than 3,000 Ω-cm; however, if pH > 6.5, enhanced pipe protection may not be needed unless resistivity is below 1,500 Ω-cm). The subsection lists typical resistivity values for common soils and liquids such as seawater (25 Ω-cm), clays (750 to 2,000 Ω-cm), loams (3,000 to 10,000 Ω-cm), and granular soils, that may have resistivities much higher than loams.
- Subsection 14.3.1.3, Chlorides, notes that dissolved salts containing chloride ions can be present in soil or water surrounding a culvert, and may also be of a concern in coastal locations or near brackish water sources. "In most instances, corrosive potential is increased as the negative chloride ion decreases the resistivity of the soil and/or water and destroys the protective film on anodic areas. Chlorides, as with most of the more common corrosive elements, primarily attack unprotected metal culverts and the reinforcing steel in concrete culverts if concrete cover is inadequate, cracked, or highly permeable."
- Subsection 14.3.1.4, Sulfates, mentions they can be naturally occurring in soil or a result of manmade activities such as from mine waste. It notes that high concentrations can lower pH and thus be a concern for metal culverts; however, sulfates may be of a greater concern to concrete structures, though concrete mixes can be modified to mitigate the results of sulfate exposure.
- Subsections 14.3.4.5, Industrial Effluents, and 14.3.1.6, Stray Electrical Current, identify these items as potential sources of increased rates of corrosion. Industrial effluents are typically regulated, though tailings from mining operations, livestock operations, or illegal connections from residential or commercial lots may result in higher corrosion rates. Similarly, stray electrical current from electrified rail lines, high tension transmission lines, and cathodically protected structures, such as gas transmission mains, may contribute to corrosion; metal pipes would typically be protected in such areas by applying protective coatings.
- Subsection 14.3.2, Abrasion, mainly presents information covered elsewhere in this literature review, particularly, the California abrasion study and assessment. One interesting note is that "Designers should not use peak flow rate velocities in service life calculations. Most research is done using the assumption of constant velocity, which is not compatible with most actual situations. It is much more reasonable and appropriate to use the velocity generated from a two- to five-year event when considering velocity effects."
- Subsection 14.3.3, Loss of Structural Integrity, provides information on joint separation, misalignment, deflection, seam defects, and other serviceability concerns, none of which is related specifically to aluminum culverts or their durability.

- Section 14.4, Material Selection and Estimating Service Life, Subsection 14.4.1, Culvert Materials, Subsection 14.4.1.2, Corrugated Metal Pipe, Subsection 14.4.1.2.2, Corrugated Aluminum Pipe, states the following:

  > "When installed within acceptable pH and soil resistivity ranges, (typically 4.0 to 9.0 and > 500 Ω-cm, respectively, but designers should check with their local agency as there is substantial agency variation), aluminum pipe (AASHTO M 196) can provide a significant advantage over plain, galvanized steel pipe from a corrosion standpoint. It is therefore possible to use aluminum pipe in lieu of a thicker walled or coated (and thus more expensive) steel pipe.
  > "Because aluminum is softer than steel, it is more susceptible to the effects of abrasion. This is particularly true for higher velocity flows that produce a scraping action, as opposed to lower velocity flows that allow the bedload to roll over the culvert surface. Where high-velocity flows (4.5 m/s (15 ft/s) or greater) carrying a bedload are prevalent, use of aluminum should be carefully evaluated. As with all metal pipes, invert loss is caused by a combination of abrasion and corrosion and, thus, the severity of both conditions must be considered."

- Subsection 14.4.2, Protective Coatings, provides guidance on protective coatings, mainly for steel culvert pipe, while noting that recent advances have led to coatings that have adequate bonding and wearability characteristics that make them attractive for abrasion resistance. It notes that selection of an appropriate coating will require consideration of the pH and resistivity ranges to be encountered, both on the soil and water sides of the culvert, and the potential for abrasion. It notes that "soil side protection of culverts will often provide up to 25 years of additional service life where conditions are not unduly severe." It also notes that any applied coating is only as good as its bond with the base culvert material; a clean application process is essential if the coating material is to provide the expected level of protection. It has five subsections describing various methods of coating, including Subsection 14.4.2.4, Polymeric Sheet Coating; however, none of these subsections describes coating to isolate the soil side of the structure from deicing salts that may leach through pavement and backfill. There is also no section on membrane protection for this issue.

6.3 U.S. Department of Transportation, Federal Highway Administration, "Hydraulic Design of Highway Culverts, Third Edition," *Hydraulic Design Series Number 5, Publication No. FHWA-HIF-12-026*, prepared by J.D. Schall, P.L. Thompson, S.M. Zerges, R.T. Kilgore, and J.L. Morris, April 2012.

- Chapter 1, Introduction, Section 1.1, General, identifies the purpose of the publication as providing information for the planning and hydraulic design of culverts.

- Chapter 1, Introduction, Section 1.3, Overview of Culverts, Subsection 1.3.2, Materials, has general culvert material identification without much elaboration. Several different types of culvert materials are simply introduced without a discussion of each, or pros and cons.

- Chapter 2, Design Considerations, Section 2.3, Site Assessments, Subsection 2.3.4, Culvert Durability, mainly gets into identification and discussion of abrasion and corrosion, which are covered more thoroughly in other references reviewed in this literature review. This subsection identifies a few references about culvert abrasion and corrosion that may warrant review as follows: (1) The Culvert Assessment and Decision-Making Procedures Manual (FHWA Report FHWA-CFL/TD-10-005); (2) Chapter 14, Culvert Inspection and Rehabilitation of the AASHTO Highway Drainage Guidelines (2007); and (3) Caltrans research as reported by DeCou and Davies (2007). These three references are reviewed elsewhere in this literature review.

6.4 U.S. Department of Transportation, Federal Lands Highway, "Culvert Assessment and Decision-Making Procedures Manual," *Publication No. FHWA-CFL/TD-10-005*, prepared by J.H. Hunt, S.M. Zerges, B.C. Roberts, and B. Bergendahl, September 2010.

- Chapter 1, Introduction, includes the following explanation, "This procedures manual is intended to aid users in implementing a fully integrated culvert assessment and decision-making tool that provides guidance for selecting replacement or rehabilitation alternatives."

- The manual presents culvert inspection procedures and rating forms for inspection of culverts on Federal Lands Highways and presents flow charts for action based on inspection findings. It is primarily used for selecting replacement or rehabilitation methods following inspection of existing culverts. Related to abrasion or corrosion of corrugated metal culverts (there is no differentiation between steel and aluminum), additional investigation is required that could lead to remedial action if the culvert condition has deteriorated to Poor or Critical within a 5 yr or shorter period. Flow charts are provided to determine effective means of remediation, and cost data from past Federal Lands Highway rehabilitation projects is provided to estimate costs of various rehabilitation methods. There was no further relevant information to our research.

6.5 U.S. Department of Transportation, Federal Lands Highway (FLH), "Project Development and Design Manual (PDDM)," Preface (December 2014), and Chapter 7 – Hydrology and Hydraulics (December 2012), U.S. Federal Highway Administration.

- The Preface identifies the PDDM as providing "current policies and guidance for the interdisciplinary project development and design related activities performed by FLH Divisions and their consultants. It also serves as a guide for administrators, public officials and others, both within and outside FLH, who are responsible for advancing projects through the project development process." The preface refers to the PDDM as a policy and best practices interactive web-based document.

- Section 7.3, Roadway Hydraulics, Subsection 7.3.6 Alternative Pipe Materials provides information presented in the bullets below:

    - It is FLH policy to specify alternative drainage pipe materials on all projects where feasible and to comply with the provisions of 23 CFR 635.411.

- "All suitable pipe materials, including reinforced concrete, steel, aluminum, and plastic will be considered as alternatives for all new cross culverts and storm drain pipes on FLH projects. Not all pipe materials are appropriate or applicable for all storm drain applications. The design of alternative drainage pipe materials should consider functionally equivalent performance in three areas: structural capacity, durability and service life, and hydraulic capacity. The service life and hydraulic capacity issues are addressed in this section."
- "The two primary causes of early failure in drainage pipe materials are corrosion and abrasion. Corrosion gradually wears away at the pipe walls by chemical action, and can occur from both the soil and water sides of the pipe. Abrasion wears away at the interior pipe wall by friction from suspended or bed-load sediment."
- Corrosion. Representative pH and resistivity determinations are required in order to specify pipe materials capable of providing a maintenance-free service life. Samples are taken in accordance with the procedures described in AASHTO T 288 and T 289. Samples should be taken from both the soil and water side environments to ensure that the most severe environmental conditions are selected for determining the service life of the drainage pipe. Soil samples should be representative of backfill material anticipated at the drainage site. Avoid taking water samples during flood flows or for two days following flood flows to ensure more typical readings.
- Abrasion. An estimate of the potential for abrasion is required in order to determine the need for invert protection. Four levels of abrasion are referred to in this guidance and the following guidelines are established for each level:

    Level 1: Nonabrasive conditions exist in areas of no bed load and very low velocities. This is the condition assumed for the soil side of drainage pipes.

    Level 2: Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 ft/sec [1.5 m/sec] or less.

    Level 3: Moderate abrasive conditions exist in areas of moderate bed loads of sand and gravel and velocities between 5 ft/sec and 15 ft/sec [1.5 m/sec and 4.5 m/sec].

    Level 4: Severe abrasive conditions exist in areas of heavy bed loads of sand, gravel, and rock and velocities exceeding 15 ft/sec [4.5 m/sec].

- Abrasion levels are intended as guidance to help the engineer consider the impacts of bed-load wear on the invert of pipe materials. Sampling of the streambed materials is not required, but visual examination and documentation of the size of the materials in the stream bed and the average slope of the channel will give the designer guidance on the expected level of abrasion. Where existing culverts are in place in the same drainage, the conditions of inverts should also be used as guidance. The expected stream velocity should be based upon a typical flow (i.e., 2 yr flow and less) and not a 10 or 50 yr design flood.

- Section 7.3.6.3.6 Aluminum Alloy Pipe. Aluminum alloy pipe (AASHTO M 196M) will typically be specified as an alternative when environmental conditions permit. The appropriate minimum structural metal thickness is determined from approved FLH fill height tables. Within the following limits of corrosion and abrasion, aluminum alloy pipe can be assumed to have a service life of 50 yrs. Additional service life may be achieved where required by abrasion with the addition of protective coatings or additional metal thickness as discussed below:

    - Corrosion: An aluminum alloy should be allowed if the pH is between 4 and 9 and the resistivity is greater than 500 Ω-cm. An aluminum alloy alternative can also be considered for use in salt and brackish environments when embedded in granular, free draining material.
    - Abrasion: On installations in nonabrasive and low-abrasive environments, abrasion protection is not required. On installations in moderately abrasive environments, the thickness should be increased by one standard metal thickness or invert protection should be used. Invert protection may consist of bituminous coating and invert paving with bituminous concrete or portland cement concrete, installation of metal plates or rails, or velocity reduction structures. On installation in severe abrasive environments, the thickness of metal should be increased by one standard metal pipe thickness from that determined for low-abrasive conditions and invert protection should be provided. Invert protection may consist of installation of metal plates or rails or velocity reduction structures.

- PDDM Section 7.3.6.1 References lists Caltrans Chapter 850 of the California Department of Transportation Highway Design Manual.

6.6 U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway, Standard Drawings Section 602, “Pipe Culverts,” and Section 603, “Structural Plate Culverts,” June 2005.

- The Section 602 drawings provide fill height tables and installation details for a variety of culverts including aluminum round pipes and aluminum pipe arches. The installation sections on Standard Drawing 602-3 shows the extents of bedding and backfill materials for various installation types (trench, embankment, others) and references Standard Specifications Section 704 for bedding and backfill requirements. There is no membrane or other means of providing protection from roadway deicing salts, nor reference to such practices.

- The Section 603 drawings provide fill height tables for a variety of structural plate structures including aluminum structural plate pipe culverts and aluminum structural plate pipe arch culverts. The Section 603 drawings do not provide installation details.

6.7 U.S. Department of Transportation, Office of Federal Lands Highway, "Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects," FP-14, Division 200 Earthwork, Division 600 – Incidental Construction, and Division 700 – Materials, 2014.

- Section 602, Culverts and Drains, Subsection 602.02, Material, requires metal pipe materials conform to Section 707.
- Subsection 602.03, General, requires excavation and backfilling to be in accordance with Section 209.
- Subsection 602.05, Laying Metal Pipe, requires that when aluminum alloys come in contact with other metals, coat the contacting surfaces with asphalt mastic or a preapproved impregnated caulking compound. Subsection 602.02 requires asphalt mastic material conform to Subsection 702.04.
- Section 603, Structural Plate Structures, Subsection 603.02, Material, requires aluminum-alloy structural plate structures conform to Subsection 707.06.
- Subsection 603.03, General, requires excavation and backfilling to be in accordance with Section 209.
- Subsection 603.04, Erecting, requires, where aluminum alloys come in contact with other types of metal, coat the contacting surfaces according to Subsection 602.05.
- Section 704, Soil, provides requirements for bedding and backfill materials for culverts mainly by gradation requirements and AASHTO M 145 classifications.
- Section 707, Metal Pipe, Subsection 707.03, Aluminum-Alloy Corrugated Pipe, requires the pipe conform to AASHTO M 196. Subsection 707.06, Aluminum-Alloy Structural Plate Structures, requires the structures and fasteners conform to AASHTO M 219. Subsection 707.12, Aluminum-Alloy Spiral Rib Pipe, requires the pipe conform to AASHTO M 196 Types IR and IIR.
- Section 209, Structure Excavation and Backfill, provides lift and compaction requirements for placement of bedding and backfill for culverts. There is no reference to protecting the structures from deicing salts through use of a membrane or other means in the backfill envelope.

6.8 U.S. Government Publishing Office, Code of Federal Regulations, "23 CFR 635.411, Title 23: Highways," Part 635 Construction and Maintenance, Subpart D General Material Requirements, Section 411 Material or Product Selection, 28 January 2013.

(f) State transportation departments (State DOTs) shall have the autonomy to determine culvert and storm sewer material types to be included in the construction of a project on a Federal-aid highway.

7. REVIEW OF INFORMATION AND POLICIES FROM OTHER STATE DOTs

We reviewed information related to culvert selection and aluminum culvert use and performance from the California Department of Transportation, which performed the generally used basis for assessing culvert abrasion, and five other state departments of transportation including Maine DOT, Michigan DOT, Minnesota DOT, New York State DOT, and Ohio DOT. We also reviewed Virginia DOT road and bridge standard drawings for allowable pipe types for culverts and storm sewers, as recommended by the Virginia DOT respondent to our aluminum culvert stakeholder survey.

7.1 Review of Information from California Department of Transportation

California Department of Transportation abrasion and durability research laid the groundwork for what many states and federal agencies rely on for classifying abrasive sites and for performance of various culvert types in abrasive environments.

7.1.1 California Department of Transportation, Division of Engineering Services, Materials Engineering and Testing Services, Corrosion and Structural Concrete Field Investigation Branch, "Corrosion Guidelines," Version 2.1, 2015.

This document contains a set of guidelines for use of certain materials in Caltrans projects. The guidelines are not a standard, specification, or regulation. The bullet below identifies sites where aluminum culvert use is acceptable.

- Section 10.2, Culvert Material, provides information based on criteria presented in Chapter 850 of the Caltrans Highway Design Manual, and identifies aluminum pipe as allowed for a "50-year maintenance-free service life" at sites where the soil, backfill, and drainage water have a minimum resistivity greater than 1,500 Ω-cm and pH between 5.5 and 10.

7.1.2 California Department of Transportation, Division of Design, "Caltrans Highway Design Manual," Chapter 850 – Physical Standards, Section 855.2 Abrasion, 2009 (updated in 2014).

The document provides the following information relevant to this research:

- Abrasion is 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. For example, at independent sites with a similar velocity range, bed loads consisting of small and round particles will have a lower abrasion potential than those with large and angular particles, such as shattered or crushed rocks. Given different sites with similar flow velocities and particle size, studies have shown the angularity and/or volume of the material may have a significant impact to the abrasion potential of the site. Likewise, two sites with similar site characteristics, but different hydrologic characteristics, i.e., volume, duration and frequency of stream flow in the culvert, will probably also have different abrasion levels.

- Sampling of the streambed materials generally is not necessary, but visual examination and documentation of the size, shape and volume of abrasive materials in the streambed and estimating the average stream slope will provide the designer data needed to determine the expected level of abrasion.

- The descriptions of abrasion levels in Table 855.2A are intended to serve as general guidance only, and not all of the criteria listed for a particular abrasion level need to be present to justify defining a site at that level. For example, the use of one of the three lower abrasion levels in lieu of one of the upper three abrasion levels is encouraged where there are minor bed load volumes, regardless of the gradation.

- The six abrasion levels from Caltrans Table 855.2A and any related use or restriction of aluminum culverts is reproduced in Table 1 below:

Table 1 – Abrasion Levels based on Bedload and Flow Characteristics Related to Aluminum Culvert Use Adapted from Caltrans Table 855.2A

Level	Bed Load Description	Flow Velocity	Notes Related to Aluminum Culvert Use
1	Bed loads of silts and clays or clear water with virtually no abrasive bed load.	No velocity limitation.	All pipe materials listed in Table 857.2 allowed; no abrasive resistant protective coatings needed for metal pipe.
2	Moderate bed loads of sand or gravel.	1 to 5 ft/sec[1]	Generally no restriction. Polymeric or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structure requirements is inadequate for abrasion potential.
3	Moderate bed load volumes of sands, gravels, and small cobbles.	> 5 to 8 ft/sec[1]	Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential.
4	Moderate bed load volumes of angular sands, gravels, and/or small cobbles/rocks.[2]	> 8 to 12 ft/sec	Aluminum pipe not recommended. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
5	Moderate bed load volumes of angular sands and gravel or rock.[2]	> 12 to 15 ft/sec	Aluminum pipe not allowed. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
6a	Moderate bed load volumes of angular sands and gravel or rock.[2]	> 15 to 20 ft/sec	Aluminum pipe not allowed. None of the abrasion resistant coatings listed in Table 855.2C is recommended even for steel pipe. Lining alternatives include specific polymeric liners or cementitious liners/invert pavement with conditions. For new/replacement structures, consider "bottomless" structures.
6b	Heavy bed load volumes of angular sands and gravel or rock.[2]	> 12 ft/sec	

1. If bed load volumes are minimal, a 50% increase in velocity is permitted.
2. For minor bed load volumes, use Level 3.

- Structural metal plate pipe and pipe arches provide a viable option for 60 in. or larger diameter pipes in abrasive environments because increased thickness can be specified for the lower 90° or invert plates. Pipe arches, which have a relatively larger invert area than circular pipe, generally will provide a lower abrasion potential from bedload being less concentrated.

- Under similar conditions, aluminum culverts will abrade 1.5 to 3 times faster than steel culverts, therefore aluminum culverts are not recommended where abrasive materials are present, and where flow velocities would encourage abrasion to occur. Culvert flow velocities that frequently exceed 5 ft/sec where abrasive materials are present should be carefully evaluated prior to selecting aluminum as an allowable alternate. In a corrosive environment, aluminum may display less abrasive wear than steel depending on the volume, velocity, size, shape, hardness, and rock impact energy of the bed load. However, if it is deemed necessary to place aluminum pipe in abrasion Levels 4 through 6, contact the State Highway Drainage Design Headquarters Office for assistance.

- Table 855.2B provides velocities and flow depths necessary to move various bed materials, and is copied here for reference.

Table 855.2B
Bed Materials Moved by Various Flow Depths and Velocities

Bed Material	Grain Dimensions (inches)	Approximate Nonscour Velocities (feet per second) Mean Depth (feet)			
		1.3	3.3	6.6	9.8
Boulders	more than 10	15.1	16.7	19.0	20.3
Large cobbles	10 – 5	11.8	13.4	15.4	16.4
Small cobbles	5 – 2.5	7.5	8.9	10.2	11.2
Very coarse gravel	2.5 – 1.25	5.2	6.2	7.2	8.2
Coarse gravel	1.25 – 0.63	4.1	4.7	5.4	6.1
Medium gravel	0.63 – 0.31	3.3	3.7	4.1	4.6
Fine gravel	0.31 – 0.16	2.6	3.0	3.3	3.8
Very fine gravel	0.16 – 0.079	2.2	2.5	2.8	3.1
Very coarse sand	0.079 – 0.039	1.8	2.1	2.4	2.7
Coarse sand	0.039 – 0.020	1.5	1.8	2.1	2.3
Medium sand	0.020 – 0.010	1.2	1.5	1.8	2.0
Fine sand	0.010 – 0.005	0.98	1.3	1.6	1.8
Compact cohesive soils					
Heavy sandy loam		3.3	3.9	4.6	4.9
Light		3.1	3.9	4.6	4.9
Loess soils in the conditions of finished settlement		2.6	3.3	3.9	4.3

Notes:

(1) Bed materials may move if velocities are higher than the nonscour velocities.

(2) Mean depth is calculated by dividing the cross-sectional area of the waterway by the top width of the water surface. If the waterway can be subdivided into a main channel and an overbank area, the mean depths of the channel and the overbank should be calculated separately. For example, if the size of moving material in the main channel is desired, the mean depth of the main channel is calculated by dividing the cross-sectional area of the main channel by the top width of the main channel.

- Table 855.2F is a guide for minimum material thickness of abrasive-resistant invert protection to achieve a 50 yr “maintenance free” service life and is reproduced here.

Table 855.2F

Guide for Minimum Material Thickness of Abrasive Resistant Invert Protection to Achieve 50 Years of Maintenance-Free Service Life

Abrasion Level & Flow Velocity (ft/s)	Channel Materials	Concrete (4) (in)	Steel Pipe & Plate (in)	Aluminum Pipe & Plate (in)	PVC (in)	HDPE (in)	CIPP (in)	Calcium Aluminate Abrasion Resistant Concrete (5) (in)	Mortar (5)	
									Calcium Aluminate (in)	Geopolymer (in)
Level 4 > 8 – ≤ 12	Abrasive	2 – 4	0.052	0.075 – 0.164	0.1	0.125 – 0.25	0.1 – 0.3	(6)	1-2	2-4
Level 5 > 12 – ≤ 15	Abrasive	4 – 13	0.052 – 0.18	(2)	0.1 – 0.35	0.25 – 0.875	0.3 – 0.70	3(6)	2-5	4-13
Level 6 > 12 – ≤ 20	Abrasive & Heavy bedloads	(1)	0.109 – 0.5	(2)	0.25 – 1.0(3)	0.625 – 2.5	0.5 – 2	3 – 5	5-8	(1)

Notes:

(1) For flow velocity > 12 ft/s ≤ 14 ft/s use 9" – 15". For > 14 ft/s use CRSP or other abrasion resistant layer special design with, or in lieu of concrete or geopolymer mortar.

(2) Not recommended without invert protection.

(3) PVC liners not recommended when freezing conditions are often encountered and cobbles and rocks are present.

(4) Values shown based on RCP abrasion test results. See Table 855.2E. Results may differ from concrete specified under 15-6.04 for invert paving which must have a minimum compressive strength of 6,000 psi at 28 days and 1 ½-inch maximum grading.

(5) See Authorized Materials List for Cementitious Pipeliners and Concrete Invert Paving: http://www.dot.ca.gov/hq/esc/approved_products_list/
Standard Mortar (Section 51-1.02F of the Standard Specifications) not recommended for Abrasion Level 4 or higher.

(6) Minimum thickness recommended is 3". Not practical or economically viable for Level 4. Consider calcium aluminate mortar or standard concrete (Section 90 of the Standard Specifications) for lower range of Level 5.

7.2 Review of Maine DOT Literature

We reviewed the MaineDOT Bridge Design Guide, Construction Manual, Standard Specs, and Highway Design Guide. We did not locate any MaineDOT standard drawings related to installation or backfill of corrugated metal pipes or culverts for review.

7.2.1 Maine Department of Transportation, "Bridge Design Guide," MaineDOT Bridge Program, August 2003 with updates to March 2017, prepared by Guertin Elkerton & Associates for Maine Department of Transportation, 2017.

- 1 General, 1.1 Introduction, states in part, "This document is intended to provide guidance to those performing design for the Bridge Program of the Maine Department of Transportation (MaineDOT). It should provide clarity to the design thought process, and serves as a supplement to the applicable AASHTO standards."

- 8 Buried Structures, 8.1 General, 8.1.1 Design, states in part, "A buried structure should be considered for any relatively short span crossing, if such a structure is hydraulically adequate for the site. These bridges of minor spans may be full culverts with a bottom or three sided structures founded on footings…All metal buried structures in tidal waters should be aluminum. In inland waters, steel is preferred due to lower initial cost, although aluminum should be used if the existing steel structure is being replaced after less than 50 years of service."

- 8.1.2 Construction Practices, states in part, "Standard Specification Section 509 – Structural Plate Pipes, Pipe Arches, Arches, and Metals Box Culverts describes requirements for lift thickness and balanced lift placement. However, construction requirements controlling compaction of the soil envelope and bedding material are not currently in the Standard Specifications, so compaction requirements must be specified by a special provision of a note on the plans. See the Geotechnical Designer for the appropriate compaction specification."

- 8.2 Structural Plate Pipes and Pipe Arches, 8.2.4 Structural Plate Pipes and Pipe Arches Design Tables, states in part, "These tables specify structural plate thickness requirements for a given structure size, corner radius, and corner radius pressure up to a maximum fill height of 30 feet. Additional metal thickness to resist abrasion and corrosion has been included in these tables.

  All steel plates below ordinary high water should be specified two available plate thicknesses heavier than those shown in the tables. In stream crossings where corrosion or abrasion is known to be severe on metal pipes, consideration should be given to providing further increases in thickness over that indicated in the tables.

  The plate thickness for aluminum structural plate structures should be specified on the contract documents as shown in the tables. If reinforcing ribs are required for the structure, they should be designed by the manufacturer. The thickness of the plates for design should be the thickness stated on the plans minus 0.055 inches. Refer to Appendix D standard Notes."

Commentary to this section includes the basis of the original design that led to the allowable fill heights and identifies that “the metal thickness shown in the steel pipe tables was derived by providing an additional 0.060 [in.] to the minimum design requirements, from the computer input, and rounding up to the nearest available plate thickness. This provides a reserve thickness for abrasion and corrosion losses in addition to the added thickness for plates below ordinary high water. The metal thickness shown in the aluminum pipe tables was derived by providing an additional 0.055 [in.] to the minimum design requirements, from the computer output, and rounding up to the nearest available plate thickness. This provides a reserve thickness for abrasion and corrosion losses and provides additional stiffness for handling.”

Cover height tables are provided for Aluminum Structural Plate Pipes (Table 8-4) and Aluminum Structural Plate Pipe Arches (Table 8-5).

- 8.3 Boxes, 8.3.1 Design, 8.3.2 Metal Structural Plate Box Culvert (Steel or Aluminum), states in part, “Generally, an aluminum structural plate box culvert is preferred over steel due to the uncertainty of the long term durability of the steel frame, and the potential for catastrophic failure when deterioration occurs…The shell plate thickness should equal the plate thickness recommended by the manufacturer plus 0.055 inches or 0.060 inches for aluminum or steel structures, respectively. If reinforcing ribs are required for the structure, they should be designed by the manufacturer. The thickness of the plates for design should be the thickness stated on the plans minus 0.055 inches or 0.060 inches for aluminum or steel structures, respectively. Refer to Appendix D Standard Notes Structural Plate Structures.”

- Similar information is provided in Section 8.4 Three-Sided Structures and Arches, although there is not language about preferring aluminum over steel. Table 8-8 provides a fill height table for aluminum structural plate arches.

- Appendix A Bridge Nomenclature, A.1 Terminology, A.1.7 Structures, defines box culvert as, “A buried structure, typically of aluminum plates or concrete, with a generally rectangular shaped opening.”

- Appendix D Standard Notes, D.12 Standard Notes Structural Plate Structures includes standard notes for the plans, such as how to specify dimensions of a structural plate pipe and structural plate pipe arch. There is no information specifically related to durability or protection of these structures from deicing salts etc.

7.2.2 Maine Department of Transportation, Bureau of Project Development, “State of Maine Department of Transportation Construction Manual, Revision of June 2003,” April 1, 2003.

The introductory sections of the manual do not state its scope or applicability. In reading the section content, summarized below, it seems to pertain to internal guidance for MaineDOT construction office personnel, including required actions by inspectors.

- Division 600, Section 603 Pipe Culverts and Storm Drains lists references including Standard Specifications Section 603 Pipe Culverts and Storm Drains and Section 707 Metal Pipe. The section identifies the requirements for the MaineDOT inspector for acceptance and installation of pipe. There is no information specific to construction practices or other items related to the durability of corrugated aluminum buried structures.

7.2.3 Maine Department of Transportation, Bureau of Project Development, "State of Maine Department of Transportation Standard Specifications, November 2014 Edition," 2014.

- Section 603 Pipe Culverts and Storm Drains, 603.01 Description, states in part, "This work shall consist of constructing or reconstructing pipe culverts and storm drains, in accordance with these specifications, the Standard Detail plans, and in reasonably close conformity with the lines and grades shown on the plans or established. The word 'pipe' in these specifications shall include both round pipe and pipe arches."

- 603.02 Materials references Section 707.06 for Corrugated Aluminum Alloy Pipe & Pipe Arches.

- The rest of Section 603 provides the construction requirements for pipe and culverts, which generally follow similarly to those of other states. Noteworthy here is that flexible circular culvert pipe 48 in. in diameter and larger are to be shop strutted with the vertical diameter increased by 3% to 5%, and the struts are removed after backfill. Pipe trenches are generally backfilled in accordance with Section 206.03 with some additional requirements provided in Section 603.08 Backfilling Culverts and Storm Drains; however, none of the information in Section 603.08 is specific to aluminum culverts or their durability.

- Section 206 Structural Excavation, 206.03 Backfilling, gives general backfill requirements for structure backfill including lift heights, etc., that are applicable to buried structures and pipes. It specifically excludes backfill for structural plate units and requires they be backfilled in accordance with Section 509 Structural Plate Pipes, Pipe Arches, Arches, and Metal Box Culverts.

- Section 509 Structural Plate Pipes, Pipe Arches, Arches, and Metal Box Culverts includes assembly and installation requirements for structural plate structures, including those made from aluminum structural plate; however, there are no special requirements related to durability of these structures or protection from deicing salts. The section references Section 707.14 for Aluminum Alloy Structural Plate Pipe, Pipe Arches, Arches, Box Culverts, and Fastener materials.

- Section 707 Metallic Pipe, 707.06 Corrugated Aluminum Alloy Pipe and Pipe Arches states, "This pipe and special fittings such as elbows, tees, and wyes shall conform to the requirements of AASHTO M196/M 196M Type I, IR, or II. Special sections, such as elbows and metal end sections, shall be of the thickness called for on the plans and shall conform to the applicable requirements of AASHTO M 196/M 196M. Aluminum sheet shall conform to the requirements of AASHTO M197/M 197M."

- Section 707 Metallic Pipe, 707.14 Aluminum Alloy Structural Plate Pipe, Pipe Arches, Arches, Box Culverts, and Fasteners states, “Plates for this pipe shall conform to the requirements of AASHTO M 219/M 219M. Bolts and nuts shall conform to the requirements of ASTM F 468M alloy 6061-T6 and F467 alloy 6061-T6.”

7.2.4 Maine Department of Transportation, Highway Program, “Highway Design Guide, February 2015 Edition,” Chapter Twelve, *Drainage Design*, January 2015.

- Much of the document is related to hydraulic design of culverts. Within Section 12-4 Culverts, 12-4.01 Physical Characteristics, the document identifies two options for pipe culvert materials, the first of which is Option I, which allows any of the following to be used: (a) corrugated steel, metallic (zinc or aluminum) coated pipe, (b) reinforced concrete pipe, or (c) any metal pipe allowed under Option III. Option III is the second option (there is no reference to or definition of Option II), which allows any of the following to be used: (a) fiber-bonded corrugated steel pipe, (b) corrugated aluminum alloy pipe, (c) PVC pipe of certain diameters, (d) polymer-precoated galvanized corrugated steel pipe, or (e) reinforced concrete pipe.

- Section 12-4.01 lists aluminum alloy pipe exclusively as recommended for use in salt water areas, while recommending Option I pipes specifically for use under driveways, reinforced concrete pipe under guardrails and at other locations at the designer’s discretion that may include deep fill areas and high-use roads, flexible pipes (any type other than reinforced concrete) where soils may be susceptible to settlement, and to generally use Option III pipe types at sites where the other criteria above do not apply.

- Section 12-4.01 recommends round pipe wherever possible, although pipe arches or elliptical pipes may be used where there are clearance problems, etc., and identifies the Bridge Design Division as being responsible for the design of box culverts.

- The section then provides tables of minimum wall thickness for various types of pipe and corrugation geometry. Section 12-4.02 provides tables of minimum and maximum heights of fill for various types of culverts or culvert materials, corrugation geometries, wall thickness, and structure geometries (e.g., for pipe arches, etc.); the design basis for the fill height tables is not identified, other than to note certain pipe types and fill height tables as applicable to HS-20 live load with a specified compaction level (such as “85% or greater compaction” for aluminum pipe with 2-2/3 in. by 1/2 in. corrugations); the live load and compaction are not typically specified for other culvert types.

7.3 Review of Michigan DOT (MDOT) Literature

We reviewed the MDOT Drainage Manual, MDOT Road Design Manual, MDOT Standard Specifications for Construction, and MDOT Road & Bridge Standard Plans.

7.3.1 Michigan Department of Transportation and Tetra Tech MPS, “Drainage Manual,” January 2006.

- Chapter 5, Culverts, 5.3.1 Introduction, states in part, “Select a culvert which best integrates engineering, economic, and environmental considerations. The chosen culvert shall meet the selected structural and hydraulic criteria and shall be based on: construction and maintenance costs, risk of failure or property damage, traffic safety, environmental or aesthetic considerations, political or nuisance considerations, and land use requirements."

- 5.3.2 Culvert Policy, 5.3.2.1 Culvert Pipe Class Designation, states, "Culvert pipe classes are used to designate the pipe's strength and its load-carrying properties. Culvert pipes are designated by class. The height of fill over the top of culvert pipe determines the class [of] pipe to be used. See the current MDOT Standard Specifications for Construction."

- 5.3.2.2, Culvert Usage Guidelines, states in part, "All pipe culverts will be specified by class and diameter, e.g. Culv, Cl A, 24-inch. The design life for culverts will be 50 years, except driveway culverts will be 25 years."

  For culverts with diameter ≥ 30 in., the material type (roughness coef.) must be accounted for in the hydraulic analysis, and the designer must perform a hydraulic analysis for all available pipe materials in the class.

  The section acknowledges a specific material may be required exclusively or a material may be determined inappropriate for a particular location. Required materials should be specified in the pay item, and prohibited materials should be identified by note on the plans. "When a specific material is prohibited and its exclusion is not covered in the Standard Specifications, a note to the file must be written to describe the basis for exclusion." The exception to this rule is where existing culverts are extended. The section also states, "Multiple culverts (parallel) should be avoided," and, "Culverts should be regularly inspected and maintained."

- 5.3.4, Culvert Design Considerations, mainly identifies hydraulic considerations for culverts and specifies minimum diameters based on type of traffic such as 24 in. for Interstates, 18 in. for trunklines other than Interstates, 12 in. for driveway culverts, and to "use arch or oval shapes only if required by hydraulic limitations, site characteristics, structural criteria, or environmental criteria."

- 5.3.7, Bedding and Filling Around Pipe Culverts, requires, "The bedding and filling around
  pipe culverts shall be done according to Standard Plan R-82-Series upon which the Culvert Class-Depth-Usage Table is based. For further discussion on bedding and filling, see RDM, Chapter 4, Section 4.05.12."

- Chapter 6 Bridges is strictly related to hydraulic openings below bridges and does not provide information about structure types, such as buried bridges, or materials or design of larger span culverts or bridges. A bridge is classified as a structure with a centerline span of 20 ft or more.

- Chapter 7 Road Storm Drainage Systems provides introductory terms, recommendations, and a procedure for hydraulic design of roadway storm drainage systems without getting into specific information on materials or channel/culvert type (other than open vs. closed channels).

7.3.2 Michigan Department of Transportation, Bureau of Development, Design Division, "Road Design Manual," not dated, downloaded from https://mdotcf.state.mi.us/public/design/files/englishroadmanual/englishrdm.zip on 26 December 2017.

- Chapter 4 Drainage gives some very basic general information in the beginning, then provides requirements specific to storm sewers and roadway culverts. For roadway culverts, requirements include pipe or culvert length quantities being in commercially available lengths, methods to estimate peak flows, requirements for soil boring if the diameter is ≥ 60 in. or a box culvert has an opening ≥ 4 ft by 4 ft.

- Section 4.05.12, referenced from Drainage Manual Section 5.3.7 above, identifies concrete pipe installation types, including Positive Projecting Embankment, Trench Installation, Negative Projecting Embankment, and Induced Trench. There is no information specific to metal culverts. There is no further information in Chapter 4 related to metal culverts of their installation.

- Chapter 11 Specifications and Special Provisions includes general information and definitions related to the Standard Specifications for Construction and Special Provisions, including introducing the term Frequently Used Special Provisions, but without introducing any specific provisions.

7.3.3 Michigan Department of Transportation, Bureau of Development, Design Division, "2012 Standard Specifications for Construction," 1 April 2011.

- On p. 3 of the manual PDF, the Standard Specs identify several MDOT publications that are included by reference as if they were repeated in their entirety. The Drainage Manual and Road Design Manual are not referenced. The one referenced document that may be particularly relevant to metal culverts would be the Road and Bridge Standard Plans.

- Division 4 Drainage Features, Section 401 Pipe Culverts, includes Table 401-1 Pipe Alternates for Culvert Classes. Corrugated and Spiral Ribbed Aluminum Alloy Pipe is allowed for all of the same cases as steel pipe, which includes Culvert Classes A through F, except Class E. For Class E culverts, where the culvert is beneath the "influence of proposed pavement" and the depth of cover is 3 ft or less, only reinforced concrete pipes are allowed. Culvert pipe materials are required to be in accordance with Section 909.

- Section 401.03, Construction, in two locations (C.3. and J.) specifies to not use dissimilar types of base metal (steel or aluminum alloy) or dissimilar types of coatings on steel (zinc or aluminum) in a single run of pipe. Backfill for all types of pipe except corrugated plastic is specified in the same manner (there is no particular specification section referenced for backfilling), and there is no requirement particular to steel or aluminum pipes with regard to protecting them from deicing salts.

- Section 402, Storm Sewers, specifies storm sewer pipe to be in accordance with Section 909. Storm sewer pipes are divided into five classes in Table 402-1. Corrugated

Aluminum Alloy pipe is allowed for Classes A through D (it is not allowed for Class E, which is similar to the restriction for regular culvert pipe, where the cover for Class E ranges from 0 to 3 ft). Allowable diameters for aluminum spiral ribbed pipe are 12 to 66 in., and for helically corrugated (2-2/3 in. by 1/2 in.) the allowable diameters are 12 to 18 in. There is no special requirement related to installation or backfill of corrugated aluminum storm sewer pipe and its durability.

- Section 909, Drainage Products, requires pipe materials shown in Tables 401-1 and 402-1 to be used for culverts or sewers. Galvanized corrugated steel or aluminum structural plates are to be provided as required, and corrugated aluminum structural plates are required to meet "ASTM B790 or Section 12 of the AASHTO LRFD Bridge Specifications." Galvanized corrugated steel structural plate is required to meet AASHTO M167; the aluminum analog is not referenced, only ASTM B790 (ASTM structural design method for aluminum pipe and structural plate structures) and AASHTO Section 12 are, both of which relate to design.

- Section 909.05, Metal Pipe Products, requires minimum or required wall thickness to be determined from Tables 909-6, 909-7 through 909-17, and 909-20. Table 909-19 provides gage equivalents for specified nominal thicknesses.

- Section 909.05B provides the minimum requirements for corrugated aluminum alloy pipe, which requires corrugated aluminum alloy pipe to meet AASHTO M 196, except that it be fabricated from aluminum sheet with the nominal thickness specified in Tables 909-12,
909-13, 909-14, 909-15, 909-16, and 909-17. If directed by the Engineer, use only Type IA and Type IIA corrugated aluminum alloy pipe.

- For aluminum pipe, Table 909-6 gives reference to Table 909-12 for driveway culverts and downspouts with 25 yr service life, Table 909-13 for culverts with 50 yr service life, and Table 909-14 for sewers with 70 yr service life; for aluminum spiral ribbed pipe, it gives reference to Tables 909-15, 909-16, and 909-17 for the same types of structures and service lives. Table 909-12 provides minimum wall thickness for 2-2/3 by 1/2 in. and 3 by 1 in. corrugations for ranges of diameters and cover heights. Tables 909-13 through 909-17 give minimum wall thickness for different Classes (A, B, C, D, E, or F) of pipe based on ranges of diameter and corrugation type, independent of cover height.

- We reviewed the errata to the 2012 Standard Specifications (dated through 1 August 2017, Document No. 12SS-001-14) and found no changes that were relevant to corrugated metal culverts and their durability.

- We reviewed the 2012 Recommended Special Provisions, Division 4 Drainage Features, and Division 9 Materials (https://mdotjboss.state.mi.us/SpecProv/specProvHome.htm) and found no recommended Special Provision related to aluminum culvert and aluminum culvert durability.

7.3.4 Michigan Department of Transportation, Bureau of Development, Design Division, "Road & Bridge Standard Plans," 22 August 2017.

- We reviewed Standard Drawing R-82-D, "Bedding and Filling Around Pipe Culverts" (Sheets 1 and 2), and found no specific requirements relevant to metal culvert durability. We also reviewed Standard Drawing R-83-C, "Utility Trenches" (Sheets 1 to 5) and similarly found no requirements relevant to metal culvert durability.

7.4 Review of Minnesota DOT (MnDOT) Literature

We reviewed the MnDOT Drainage Manual, MnDOT Technical Memorandum No. 14-04-B-02 regarding requirements for use of metal box culverts, and MnDOT Standard Specs. We did not locate any MnDOT standard drawings related to installation or backfill of corrugated metal pipes or culverts for review.

7.4.1 File, "Aluminum Culverts.xlsx," provided by Paul Rowencamp, Bridge Standards Engineer, of the Minnesota Department of Transportation Office of Bridges and Structures, in response to our Aluminum Culvert Stakeholder Survey, file provided on 22 May 2018.

- The file provides an inventory of 16 aluminum culverts, identified as aluminum box culverts, with spans ranging from 10 ft-11 in. to 23 ft-2 in., and installation dates from 1980 to 2012. One structure is owned by a city, two are within the State DOT right of way, and thirteen are owned by counties (six total counties represented, of which, St. Louis county has four). All structures are listed as single-span structures, and barrel lengths range from 26 to 72 ft. Inspection or condition data were not included.

7.4.2 Minnesota Department of Transportation, Office of Bridges and Structures, "Drainage Manual," 30 August 2000.

- Chapter 2, Materials and Structural Design, Section 2.2, Factors Influencing Service Life, states, "Design service life is typically defined as the period of service without a need for major repairs. Highway drainage structures are usually designed with the goal of providing some pre-selected minimum number of years of service life. For corrugated metal pipes, this will normally be the period in years from installation until deterioration reaches the point of perforation of any point on the culvert…It is important to recognize that culverts are not assumed to be at or near the point of collapse at the end of their design service life. Rather, it is the period of little to no rehabilitative maintenance."

- Section 2.2 continues, "Some of the factors that affect service life are: hydrogen-ion concentration (pH) of the surrounding soil and water; soli resistivity, chloride, and sulfate concentrations in the soil; size, shape, hardness, and volume of bedload; volume, velocity, and frequency of streamflow in the culvert; material characteristics of the culvert; and anticipated changes in the watershed upstream of the culvert (such as development, industry, mining, or logging)."

- Section 2.2.1, Corrosion, states, "Corrosion is the destruction of pipe material by chemical action. Most commonly, corrosion attacks metal culverts, or the reinforcement in concrete pipe, as the process of returning metals to their native state of oxides or salts…In order for corrosion to occur, an electrolytic corrosion cell must be formed. This requires the presence of water, or some other liquid to act as an electrolyte, as well as materials acting as an anode, cathode, and conductor. As electrons move from the anode to the cathode, metal ions are released into the solution, with characteristic pitting at the anode. The culvert will typically serve as both the anode and the cathode. Corrosion can affect the inside or outside surface of a pipe, or both. The potential for corrosion to occur, and the rate at which it will progress, is variable and dependent upon a variety of factors."

- Section 2.2.1 Corrosion, Soil Resistivity, states, "Resistivity of soil is a measure of the soil's ability to conduct electrical current. It is affected primarily by the nature and concentration of dissolved salts, as well as the temperature, moisture content, compactness, and the presence of inert materials such as stones and gravel…Resistivity values in excess of about 5,000 ohm-cm are considered to present limited corrosion potential. Resistivities below the range of 1,000 to 3,000 ohm-cm will usually require some level of pipe protection, depending upon the corresponding pH level (e.g. if pH < 5.0, enhanced pipe protection may be needed for resistivities below 3,000 ohm-cm; if pH > 6.5, enhanced pipe protection may not be needed unless resistivities are below 1,500 ohm-cm). As a comparative measure, resistivity of seawater is in the range of 25 ohm-cm, clay soils range from approximately 750-2,000 ohm-cm, and loams from 3,000-10,000 ohm-cm. Soils of a more granular nature exhibit even higher resistivities."

- Section 2.2.1 Corrosion, Chlorides, states, "Dissolved salts containing chloride ions can be present in the soil or water surrounding a culvert. Dissolved salts can enhance culvert durability if their presence decreases oxygen solubility, but in most instances corrosive potential is increased as the negative chloride ion decreases the resistivity of the soil and/or water and destroys the protective film of anodic areas. Chlorides, as with most of the more common corrosive elements, primarily attack unprotected metal culverts and the reinforcing steel in concrete culverts if concrete cover is inadequate, cracked, or highly permeable."

- Section 2.2.1 Corrosion, Sulfates, states, "Although high concentrations can lower pH and be of concern to metal culverts, sulfates are typically more damaging to concrete."

- Section 2.2.2 Abrasion, Bedload, states, "By far, bedload is the leading cause of abrasion. Critical factors in evaluation of the abrasive potential of bedload material are the size, shape, and hardness of the bedload material, and the velocity and frequency of flow in the culvert. Generally, flow velocities less than 5 ft/sec are not considered to be abrasive, even if bedload material is present. Velocities in excess of 15 ft/sec which carry bedload, are considered to be very abrasive and some modifications to protect the culvert should be considered."

- Section 2.3 Pipe Durability, states, "The Department is presently doing a statewide condition survey of centerline culverts. It is planned to correlate the results of the survey with information regarding soil and water properties including pH and resistivity measurements to develop a revised policy regarding the use of metal culverts. Until that study is completed the usage criteria for prefabricated corrugated galvanized culverts that was previously in the Drainage Manual will remain in effect and are given in Table 2.1 and Figure 2.1." Figure 2.1 divides the state into four major soil zones without providing guidance on the characteristics of each zone or what differentiates their borders. Prefabricated corrugated galvanized steel culverts (PCGSC) and structural plate culverts are allowed in any zone if the structure is in a "dry" environment, where the structure drains out after rainfall or snow melt. PCGSC are not allowed in Zones 1 or 3 in wet conditions (where there is standing or flowing water practically the entire year), are allowed in Zone 4 in wet conditions, and are allowed in Zone 3 in wet conditions if it is not an acidic environment. Structural plate culverts are allowed in all zones in all conditions, but are restricted for use in Zones 1 to 3 with wet conditions to areas that are not a swamp or to areas where the soil or water does not have a pH of 6.5 of less.

- Section 2.3 provides the California chart (Caltrans Test Method 642-C) as guidance for determining average life of galvanized pipe and the use of increased steel thickness or protective coatings. It also recommends a paved invert "be considered for metal pipes if abrasion is considered to be a concern."

- Section 2.4 Material Types for Drainage Facilities, states, "Following is the policy for selecting material types for culverts, storm drains, and tile." Section 2.4.1 Culvert Materials, "Pipe for culverts shall be selected on the basis of the type which best fulfills all of the engineering requirements for a specific installation. Factors to be considered in fulfilling the engineering requirements should be hydraulic performance, structural stability, serviceability, and economy. The culvert design sheet shall provide documentation for each pipe installation indicating the engineering considerations which dictate the specific type of pipe."

- Section 2.4.1 continues, "If, for engineering reasons, the use of corrugated metal pipe is necessary in areas that have been detrimental to this type of pipe, the designer must take proper precautions such as increasing the thickness of the base metal or providing a protective coating to assure required serviceability. Pipes for centerline culverts shall be selected on the basis of engineering analysis which [sic] result in the most favorable combination of hydraulic performance, structural stability, serviceability, and economy."

- Section 2.4.2 Storm Drain Material, states, "Reinforced concrete pipe will normally be required for all storm drains. Corrugated polyethylene pipe may be allowed as an alternate to reinforced concrete pipe for 12 in. to 36 in. diameter pipes." Metal pipes are not referenced in the section.

- Section 2.5.3 Metal Pipe Load Tables provides fill height tables for a variety of metal pipe, and a description of the required installation conditions, such as the consideration of "AASHTO HS25 wheel loading"; minimum cover height is measured from top of pipe to top of rigid pavement; or bottom of flexible pavement; and other specific considerations for pipe arches. Tables 2.16 to 2.21 provide minimum and maximum fill heights for 2-2/3 in. by 1/2 in. corrugated aluminum round pipe, 3 in. by 1 in corrugated aluminum round pipe 3/4 in. by 3/4 in. by 7 in. aluminum spiral rib pipe, 2-2/3 in. by 1/2 in. corrugated aluminum pipe arch, 3 in. by 1 in. corrugated aluminum pipe arch, and 3/4 in. by 3/4 in. by 7-1/2 in. aluminum spiral rib pipe arch, respectively.

- Chapter 5, Culvert, 5.1 Introduction, states, "This chapter provides design procedures for the hydraulic design of highway culverts which are based on the Federal Highway Administration (FHWA) Hydraulic Design Series No. 5 (HDS-5), *Hydraulic Design of Highway Culverts* (FHWA, 1985). Section 5.1.1 Definition, states, "a culvert is defined as a structure sized hydraulically to convey surface water runoff under a highway, railroad, or other embankment. Culverts are structures distinguished from bridges by being covered with an embankment and generally composed of a structural material around the entire perimeter with some exceptions such as a MN/DOT Arch which may utilize the natural streambed and appropriate erosion protection as the bottom," and "classified as a bridge when horizontal opening width is 10 feet or greater measured perpendicular to the roadway centerline, however, the structure is analyzed using procedures defined in this chapter."

- Section 5.4 provides a design procedure for culverts and flow chart for items that need to be considered in implementing the design. The design procedure is mainly related to hydraulic design. Note that structural design is "by fill height table" as given above.

- There is not structural design procedure for culverts in Chapter 5, although there are some considerations, such as minimum yield strengths and safety factors for different limit states given alongside the fill height tables. These seem to indicate what was considered in developing the fill height tables through whatever design method was originally used, as there is no particular design method referenced other than to rely on the given fill height tables.

7.4.3 Minnesota Department of Transportation, "Standard Specifications for Construction 2018 Edition," 9 June 2017.

- Section 2501, Pipe Culverts, Subsection 2501.2 Materials, lists allowable types of pipe and structural plate and includes corrugated aluminum pipe (per Section 3225) and corrugated aluminum structural plate (per Section 3233).

- Per Section 2501.3, Construction Requirements, excavation and backfill for pipes and culverts are to be in accordance with the plans and Section 2451 Structure Excavations and Backfills with compaction in accordance with Section 2105 Excavation and Embankment. Section 2501.3 and Sections 2451 and 2105 do not contain any special requirements related to aluminum or other corrugated metal pipe, such as requirements for installation of protective membranes, etc., to protect the structures from deicing salts.

- Section 3225, Corrugated Aluminum Pipe, has the following relevant requirements: "Provide pipe meeting the requirements of AASHTO M196 and the following: A. Physical Properties, The Contractor may provide pipe in the least thickness of metal listed for a specified diameter, unless otherwise shown on the plans or special provisions." Other additional requirements are to supply aprons and coupling bands that meet M 196, and that identification, sampling, and testing be in accordance with M 196. Basically, MnDOT relies on AASHTO M 196.

- Section 3233, Aluminum Alloy Structural Plate for Pipe, Pipe-Arches, and Arches, has the following relevant requirements: "Provide structural plates, accessories, and fasteners meeting the requirements of AASHTO M219 and the following: A. Fabrication, Provide the plate thickness, pipe shape, sheet fabrication details, and assembly bolting as shown on the plans, B. Workmanship and Finish, The Engineer will reject individual plates or shipments of plates with the following defects," and the defects listed include plates without careful and finished workmanship; plates with ragged edges, dents, or bends; incorrect shapes or plates with illegible or improper markings; and plates with unevenly lined or spaced bolt holes. The sampling or testing additional requirements (Section 3233.3) are blank, indicating that M 219 is valid. Basically, MnDOT relies on AASHTO M 219.

- Section 3352, Signs, Delineators, and Markers, Subsection 3352.2 Requirements, A.1 Base Material for Sign Panels, Delineators, and Markers, A.1.a Sheet Aluminum, requires, "Provide sheet aluminum for sign panels, delineators, and markers meeting the requirements of ASTM B209M for Alloy 5052-H38 or Alloy 6061-T6." Alloys 5052-H38 and 6061-T6 are specifically referenced for road signs in Minnesota.

7.4.4 Minnesota Department of Transportation Technical Memorandum No. 14-04-B-02, "Requirements for Use of Metal Box Culverts," 13 May 2014.

- The memo supersedes Technical Memorandum 08-16-B-04: Requirements for the Use of Metal Box Culverts, and "shall remain in effect until May 13, 2019 or until this information is modified or included in the MnDOT Standard Specification for Construction, or whichever comes first. The guidelines in this Technical Memorandum are effective immediately."

- The purpose of the memo is to allow a road authority the option to specify metal box shape culverts "as a bid alternate to other approved structures detailed as a box culvert or other special structures."

- Guidelines and requirements include that the design be in accordance with the AASHTO LRFD Bridge Design Specifications (AASHTO LRFD) with some modifications that include the following: 17.0 ft max. span and 8.0 ft max. rise, single-barrel structures only, average daily traffic ≤ 400, soil borings are required with evaluation of bearing capacity and electrochemical properties, frost action is considered and designed for, scour is considered and designed for, fill heights range from 2 to 5 ft, the structure either have a full-width integral bottom or be on properly designed concrete foundations that meet the MnDOT provisions for scour of three-sided bridge footings, a manufacturer's representative be on site during installation of the metal box culvert and backfilling, skews greater than 15° must utilize cast-in-place reinforced concrete headwalls, materials and construction procedures meet the current provisions of the MnDOT Standard Specifications for Construction and the AASHTO LRFD Bridge Construction Specifications, construction specifications be provided that describe any additional backfilling requirements beyond those required by AASHTO and the MnDOT Standard Specs along with the limits of backfilling requirements, and that final construction plans and design computations be prepared and certified by a qualified Professional Engineer licensed in Minnesota.

7.5 Review of New York State DOT (NYSDOT) Literature

We reviewed individual chapters of the NYSDOT Highway Design Manual, relevant standard drawings, and relevant standard specifications.

As referenced by the NYSDOT Highway Design Manual, we reviewed Chapter 4 of the AASHTO Highway Drainage Guidelines, the AASHTO Drainage Manual (supersedes the AASHTO Model Drainage Manual), and FHWA Hydraulic Design Series No. 5. These documents are all reviewed above.

We also reviewed the 1984 report on metal loss rates of steel and aluminum culverts in New York by Bellair and Ewing; the review of this document is included below.

7.5.1 New York State Department of Transportation, Engineering Division, "Highway Design Manual" Chapter 8, Revision 87, 1 May 2016, and Chapter 19, Revision 63, 19 May 2011.

The NYSDOT Highway Design Manual is available online through links to individual chapters with additional referenced files such as appendices or other appurtenant documents at https://www.dot.ny.gov/divisions/engineering/design/dqab/hdm. We reviewed Chapter 8 Highway Drainage, and Chapter 19 Reinforced Concrete Box Culverts and Similar Structures, and their appurtenant files, summarized as follows.

- Section 8.6 Culverts identifies culverts as generally open-ended closed conduits such as pipe or open conduits such as arches. It identifies any single structure with a span greater than 20 ft as a bridge, which requires different procedures of coordination and design. It identifies culverts as being discussed in greater detail in Chapter 4, Hydraulic Design of Highway Culverts, of the AASHTO Highway Drainage Guidelines; Chapter 9, Culverts, of the AASHTO Model Drainage Manual; and FHWA Hydraulic Design Series No. 5, *Hydraulic Design of Highway Culverts*. These references are reviewed earlier in this literature review (note that the AASHTO Model Drainage Manual has since been superseded by the new AASHTO Drainage Manual (2014 edition), which is reviewed earlier in this literature review).

- Section 8.6.2, Pipe Design Criteria, states in part, "Acceptable culvert materials are steel (see note below), reinforced concrete, aluminum, polyethylene, and polypropylene. The design criteria for these materials consist of design life, anticipated service life, structural criteria, and economics."

- The note referenced in the bullet above states, "Note: Steel shall not be specified for culverts installed to act as equalizer channels or at other locations such as canals where the water level is expected to remain relatively constant. The near constant water levels result in localized metal loss rates in excess of those anticipated (refer to Section 8.6.2.2), and these water levels usually are at a location – on the sidewalls – where the stress levels are higher than at the invert."

- Section 8.6.2 continues, "The material specified shall be the most economical which satisfies all the pipe criteria (design life, anticipated service life, and structural criteria) in addition to meeting the hydraulic criteria (allowable headwater, etc.). Refer to section 8.6.2.4 for further discussion regarding selection of the final culvert material."

- Section 8.6.2.1, Design Life, defines culvert design life as the "number of years of in-service performance which the pipe is desired to provide," and it takes into consideration the initial cost of the pipe, its installation, and backfill; cost to rehabilitate or replace; disruption to traffic during rehabilitation or replacement once an installation reaches the end of its design life. Table 8-5 identifies driveway pipes as requiring a 20 yr design life, significant locations as requiring 70 yr design life, and other location as requiring 50 yr design life. Significant locations include interstate and/or other freeways, natural watercourses or channels, location with 15 ft or greater fill depth, locations with high traffic volumes, and locations where long detours would be required if there was a failure.

- Section 8.6.2.2 Anticipated Service Life defines the anticipated service life of a culvert as "the number of years it is anticipated the culvert pipe material will perform as originally designed or intended." Steel service life is based on assuming 2 or 4 mils/yr of section loss along the invert or flow line; locations with 4 mils/yr are identified Table 8-6. In normal conditions, the anticipated service life for aluminum, concrete, polyethylene, and polypropylene is 70 yrs. However, where there are high velocities and potentially abrasive bed loads, or high concentrations of industrial waste are present or suspected, 70 yrs should not be expected for aluminum.

- Below Table 8-7, which gives service life in years for steel culverts based on gauge and whether it is a Zone 1 (2 mils/yr) location or Zone 2 (4 yrs/location), Note 2, which is generally applicable to the table, states, "Use caution in designing culverts on grades steeper than 6±% carrying potentially abrasive bed loads. Do not rely on polymer coating alone to increase the service life in abrasive conditions. Use fully paved pipe or paved invert. In very severe conditions, consider use of concrete or polyethylene. Aluminum is not recommended due to the potentially abrasive bed load."

- Section 8.6.2.3 Structural Criteria, Subsection A. Height of Fill Tables, identifies the fill height tables in Appendix A to be used to obtain the thinnest gage steel or aluminum, or lowest class of concrete pipe required for the site. Tables 8-28 to 8-33 are listed for various types of aluminum pipe or pipe arches, or aluminum structural plate pipe or pipe arches.

- Subsection B, Bedding Conditions and Installation Methods calls out Standard Sheets 203-004 and 203-05 for concrete, steel, and aluminum pipe installations. Standard Sheet 203-05 is also applicable to smooth interior corrugated polyethylene pipe.

- Section 8.6.7 Rehabilitation of Culverts and Storm Drains, Subsection 8.6.7.1 General, Subsection 8.6.7.1.A. Structural Paving of the Invert with Portland Concrete [sic] Cement (PCC), states, in part, "This is an excellent rehabilitation methodology when the culvert has maintained its original shape, even if it exhibits considerable invert deterioration. Structural invert paving should be the predominant choice for rehabilitating large diameter arches and culverts, where using a new pipe lining method is cost prohibitive…Design details on structural invert paving along with extended guidance can be found in Section 8.6.7.6."

- Section 8.6.7.6.A.1, Structural Paving of the Invert with Portland Cement Concrete (PCC), recommends that it be applied where the pipe is of sufficient size (48 in. diameter or larger), that the paving extend beyond the area of significant corrosion loss so that reinforcement can be attached to sound metal on both sides of the invert, and that for culverts and arches spanning up to 6 ft, welded wire fabric reinforcement (WWFR) be embedded in a 4 in. thick layer of concrete measured over the corrugation crests. The WWFR should be attached by welding directly to the corrugations or by stainless steel anchors. Rebars are recommended for reinforcement of structures spanning between 6 and 10 ft, and the paving thickness is to be between 6 and 8 in., depending on the span with a minimum concrete cover of 2 in.; shear transfer is accomplished by welding shear studs onto the culvert, and rebars are wire tied to the studs. There is also information in Subsection 8.6.7.6.A.2 for lining with shotcrete.

- Chapter 19, Reinforced Concrete Box Culverts and Similar Structures, provides information and requirements for reinforced concrete box culverts and three-sided precast concrete culverts. However, in Section 19.2, Selection Criteria, it notes, "The most appropriate type of short-span structure must be determined by the designer. The basic choices are a corrugated metal structure, concrete box culvert, concrete frame or arch, and a short-span bridge." It also notes, "Information on corrugated metal structures (steel and aluminum) is available in Chapter 8 of this manual. Corrugated metal structures may be more cost efficient and should be considered when there will be no major risk of corrosion such as an arch on pedestal walls where there is infrequent water contact with the metal portion of the structure. Acceptable crossing features are railroad tracks or bicycle and equestrian paths."

7.5.2 New York State Department of Transportation, Engineering Division, Office of Design, "New York State Standard Sheets," 1 January 2018, Drawing No. 203-05, *Installation Details for Corrugated and Structural Plate Pipe, Pipe Arches and Plastic Pipe*, Approved 22 April 2016.

This standard drawing shows installation details for corrugated metal and structural plate pipes, pipe arches, and plastic pipes. There is no reference to special coatings or membranes in the backfill envelope to protect metal pipes or culverts from deicing salts.

7.5.3 New York State Department of Transportation, Engineering Division, "Standard Specifications," 1 May 2018.

- Section 603, Culverts and Storm Drains, has the following information relevant to corrugated aluminum pipes and plate structures:

    - Subsection 603-2, Materials, references Section 207 for Geotextile, Section 707-13 for corrugated aluminum pipe, and Section 707-14 for Corrugated Aluminum Structural Plate Pipe for Pipe and Pipe-Arches.
    - Subsection 603-3, Construction Details, 603-3.02, Laying Pipe, *E. Corrugated Structural Plate Pipe and Pipe Arches*, requires joints to be covered "with a

geotextile conforming to Geotextile Underdrain from the Department's Materials Bureau Approved List. Extend the covering a minimum of 12 inches beyond each side of the joint for its entire length. A minimum of 12 inches is required for any longitudinal lap."

- Subsection 603-3.03, Bedding and Backfilling Pipe, reads, "Apply the standards of Section 203, *Select Granular Fill*, and the appropriate NYSDOT Standard Sheets. Select Granular Fill used to backfill around aluminum or aluminum coated pipes will be free of Portland cement unless the pipe sections are thoroughly coated with Zinc Chromate Primer, Section 708-04, or an equivalent alternative as approved by the Materials Bureau. 100% of Select Granular Fill used around Type IR and IIR corrugated aluminum pipe must pass a 2 inch sieve."

- Section 707, Metal Pipe, has the following information relevant to corrugated aluminum pipes and plate structures:

  - Subsection 707-13, Corrugated Aluminum Pipe, identifies its scope as covering corrugated aluminum pipe intended for use in construction of culverts and drainage systems, and classified as Types I, IA, IR, II, IIR, and III. The different types are related to corrugation geometries/wall construction, pipe vs. pipe arch, and for perforations and otherwise have no bearing on our research. The section references AASHTO M 196M for material requirements, with one modification to rib dimensions.
  - Subsection 707-14, Corrugated Aluminum Structural Plate for Pipe and Pipe Arches, identifies its scope as covering corrugated aluminum structural plates for use in the construction of pipe and pipe arches. For material requirements, it requires plate, nuts, and bolts to conform to AASHTO M 219.

- Section 203, Excavation and Embankment, Subsection 203-3, Construction Details, Subsection 203-3.06, Select Granular Fill, does not identify any special precautions for placement of backfill around metal pipes and generally refers to the Standard Drawings.

- Section 207, Geosynthetics, has three types listed in Subsection 207-1, Description, which are Geotextiles, Geomembranes, and Prefabricated Composite Drains for Structures. There is no specific reference to use of these materials over pipes or culverts.

7.6 Review of Ohio DOT (ODOT) Literature

We reviewed the ODOT Standard Specs, Location and Design Manual Volume 2 Drainage Design, the ODOT culvert design process flow chart, and the ODOT On-Line Bridge Maintenance Manual. We did not locate any ODOT standard drawings related to installation or backfill of corrugated metal pipes or culverts.

7.6.1 Ohio Department of Transportation, Division of Construction Management, "Construction and Material Specifications," 1 January 2016.

- Standard Specification Section 611, Pipe Culverts, Sewers, Drains, and Drainage Structures has the following requirements relevant to corrugated aluminum culverts:

- 611.02, Materials, includes "Conduit shown in the plans is designed for hydraulic capacity and durability only. Furnish conduit that meets the performance requirements of this specification and meets the durability and hydraulic capacity specified in the plans." It then references the material specification in Section 707 for every applicable material for each type of conduit (Types A through F) and other incidental drainage structures.
- 611.03, Definitions, includes the following relevant definitions:

  "**Conduit**. Includes pipe, culverts, sewers, and drains. Conduits are classified as Type A, B, C, D, E, and F."
  "**Corrugated Metal Conduit**. Includes all conduit made from corrugated steel or corrugated aluminum. Either material may also have coatings. This includes all of the following types of materials: 707.01, 707.02, 707.03, 707.04, 707.05, 707.07, 707.11, 707.12, 707.13, 707.14, 707.15, 707.17, **707.21**, **707.22**, **707.23**, **707.24**, and **707.25**." Bold emphasis added by SGH to identify specification sections for aluminum materials.
  "**Design Service Life**. The average usable life of a conduit or structure."

- 611.09, Exterior Coatings and Membrane Waterproofing, includes the following information relevant to corrugated aluminum:

  "Apply exterior coatings and membrane waterproofing as specified below. Protect the exterior coatings and membrane waterproofing from damage during placing of the bedding, backfill, and embankment."
  "B. For structural plate metal structures and corrugated metal box culverts (707.03, 707.15, 707.23, and 707.25), apply waterproofing by one of the following methods.

  1. Coat the exterior of the conduit above the limits of the bedding and within the limits of backfill. Ensure that all plate seams and bolts are thoroughly sealed. Furnish coating material and apply it according to AASHTO M243. Allow asphalt mastic material to dry 48 hours and tar base material to dry 28 hours before placing the conduit backfill. Rib stiffeners do not need to be coated.
  2. Construct buried liner waterproofing membrane protection in the fill according to the manufacturer's recommendations. The buried liner waterproofing membrane protection must be a continuous sheet placed over the conduit and extend at least 10 feet (3.3m) outside of the paved shoulder and for the width of the trench. Seams constructed in the field are not acceptable."

- 611.11, Field Paving of New or Existing Conduit, requires field paving the bottom of the conduit with concrete as shown on the plans. At least 4 ft of cover is required, or that the top of the subgrade is reached prior to field paving, and if paving is placed prior to completion of backfill, gaps between the conduit and concrete are to be cleaned then filled with a bituminous material conforming to Section 705.04. Paving is to be reinforced with 2 x 2 W0.9 x W0.9 galvanized welded wire fabric, or comparable, to a width 4 in. less than the finished paving. Use galvanized chairs to support the mesh, and attach the mesh to the conduit at the edges and center at points not greater than 4 ft apart along the flow line of the culvert. Repair damage to zinc coating caused by placement or tack welding using wire brushing and application of zinc-rich paint. “For aluminum structural plate, securely fasten the mesh to the circumferential seam bolts with galvanized tie wire.” While the section references attachment of steel reinforcement to aluminum structural plate bolts, we do not see reference to isolating aluminum from the concrete used for the invert pavement.

“Construct paving so that it is 3 inches thick measured from the top of the corrugations of the conduit to a height equal to 1/3 of the rise. Maintain the position of the mesh while placing concrete. After placing the concrete, strike it off with a template to produce the proper radius, and finish with a float to produce a smooth finish. Cure the concrete according to 451.11.”

- 611.12, Performance Inspection, requires inspection of all Type A, B, and C conduits with lengths greater than 20 ft and slopes of 25% or less. Performance inspections are not required for Types D, E, and F conduits, or for projects where all conduits are Type C and conduit plan quantities are less than 100 ft with less than 16 ft maximum fill height. Inspections are generally to be performed between thirty and ninety days after reaching finished grade. Remote inspection is required for round conduits up to 36 in. in diameter; from 36 up to 48 in. diameters, manual or remote inspection may be performed; for 48 in. and greater diameter and for all noncircular conduits, manual inspection is required.

    - Section 705.04 Hot Applied Joint Sealer, referenced for filling gaps between invert pavement and corrugations in Section 611.11, states in its entirety, “Furnish hot applied joint sealer conforming to ASTM D6690, Type II. Use this material as the primer for Type 3 membrane.”
    - Sections 707.21, 707.22, 707.23, 707.24, and 707.25 provide requirements for various types of corrugated aluminum pipe and corrugated aluminum structural plate. Corrugated aluminum pipe is generally required to conform to AASHTO M 196. Corrugated aluminum structural plate and fasteners are generally required to conform to AASHTO M 219. Corrugated aluminum box culverts are required to conform to ASTM B864 and be supplied by pre-approved manufacturers with calculations and shop drawings.

7.6.2 Ohio Department of Transportation, Office of Hydraulic Engineering, “Location and Design Manual, Volume Two Drainage Design” July 2017.

- Section 1000 Drainage Design Criteria, Subsection 1002 Pipe Criteria, 1002.1 Introduction, states, “The Departments Pipe Criteria governs the determination of the size and type of pipe specified or permitted…” and “Deviations from this Pipe Criteria concerning type of pipe or pipe placement must be based on sound engineering judgement and/or life cycle cost analysis. Deviations involving the specification of only one type of pipe material where special conditions prevail must include sound engineering judgement such as:” and examples relevant to corrugated metal include the following: “where a larger corrugated pipe would require a higher pavement grade to satisfy minimum cover requirements or require more cells than a rigid alternate; where a metal pipe arch would be required as an alternate to a round rigid pipe; site conditions prevented the existing conduit material to meet design service life and verification that the existing conduit material had been correctly designed to ODOT durability design needs to be documented; if a structure type study is performed and the cost analysis indicates a lower cost. The use of a single material type is subject to the approval of the OHE."

- 1002.2 General Requirements, 1002.2.1 Pipe Materials, states, "The type of pipe materials listed under the various conduit types in Section 611.02 of the Construction and Material Specifications are considered equal within their size, structural, and material durability limitations."

- 1002.2.2, Conduit Durability and Service Life, requires field measurement of pH of the normal stream flow in the field. If flow is not present, Figures 1002-2 and 1002-3 are to be used. The stream bed is to be classified as abrasive or non-abrasive by observation, where abrasive conditions are defined as "the presence of granular material with a stream gradient or flow sufficient to cause movement of the material. Granular material is defined as material the size of pea gravel or larger. Assign an abrasion level to the stream on a scale of 1-6 according to the below descriptions. Use Level 1 if non-abrasive."

  Figure 1002-2 is a map of Ohio with average pH values by county, with a range of 5.1 for Hocking County (south-central/southeast OH) to 8.3 or above in north-central and southwest Ohio. Figure 1002-3 is a map of Ohio with contour plots of pH for individual culverts that ranges from < 4.5 to ≤ 8.5.

- The abrasion scale of Section 1002.2.2 is as follows:

  > "Level 1: Bedloads of silts and clays or clean water with virtually no abrasive bed load. Non-Abrasive Material.
  > Level 2: Moderate bed loads of sand or gravel.
  > Level 3: Moderate bed load volumes of sand, gravels, and small cobbles.
  > Level 4: Moderate bed load volumes of angular sands, gravels, and cobbles/rocks.
  > Level 5: Moderate bed load volumes of angular sands and gravel or rock.
  > Level 6: Moderate bed load volumes of angular sands and gravel or rock OR Heavy bed load volumes of angular sands and gravel or rock."

- Section 1002.2.2 requires durability design to be performed using the OHE Durability Design spreadsheet available at http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Additionsl%20Resources/Pages/default.aspx. It states that the "tabulations in the Durability Design spreadsheet are based on the Assessment of ODOT's Conduit Service Life Prediction Methodology research report (FHWA/OH-2016/16). Additional abrasion level information and abrasion level site photos are available in the reference data tab of the Durability Design spreadsheet."

  We reviewed this spreadsheet and see it allows users to evaluate whether input environmental conditions (pH, abrasion level) will result in the desired service life (50 or 75 yrs) for a given culvert material and thickness, and whether coatings and/or invert pavement will help achieve the required service life, if needed. Six photos are provided to give a visual example of each of the six abrasion levels based on bedload type and volume.

- Section 1002.2.2 also requires to "Ensure the pH and abrasiveness determination is included in the plans in accordance to L&D, Volume 3. If it is that future flow conditions will be more corrosive or abrasive than existing conditions, specify protection that is greater than what is currently required. Submit documentation of the known future flow condition and the proposed additional protection." Volume 3 of the Location and Design Manual is titled "Highway Plans."

- Section 1002.2.4, Special Shapes, identifies several shapes of conduit including corrugated metal arch or pipe arches that are "generally limited for use under shallow cover installations or extremely low or restrictive headwater control otherwise requiring multiple circular conduits to satisfy allowable headwater conditions. Generally elliptical concrete and corrugated metal pipe arch of the required size to satisfy hydraulic conditions are to be shown on the plan. Special shaped conduits may be provided to conform to the cross-sectional geometry of sensitive streams identified in the environmental documentation. Where corrugated metal and structural plate pipe arches are specified or permitted, a foundation investigation shall be submitted as required by Section 1008.1.5."

- Section 1002.3, Conduit Types, 1002.3.1 Type A Conduits, states, "Type A conduits shall be designated for soil-tight, sealed-joint open-ended cross drains under pavements and paved shoulders…For culverts under freeways or high fills (16 feet), the size shall be increased one pipe size over the required size to allow for future repair. Ensure the pipe is only upsized once. All hydraulically adequate pipe alternates which provide the required service life shall be shown on the plans and listed in the pertinent pay item. In the applicable size ranges, alternates should include, vitrified clay, concrete, plastic, corrugated steel, and corrugated aluminum. For corrugated metal pipe, the corrugation profile which requires the thinnest metal shall be listed. Where durability requires increased thickness of the corrugated steel alternate, the 1-inch corrugation profile should be specified for pipe diameters over 48 inches. For the steel corrugation profile specified, all combinations of thickness and protection providing the required service life shall be specified…Furnish all Type A conduits under State and Federal routes with a minimum service life of 50 years. Use a service life of 75 years at sites that have one of the following characteristics: (1) Fill height ≥ 16 feet (measured from flowline to finished grade), (2) Freeways, (3) Structures defined as a Bridge." Ohio requires 75 yr service life for important or deep structures, and requires durability evaluation to ensure that service life is met.

- 1002.3.2 Type B Conduits, states, "Type B conduits shall be designated for soil-tight, sealed joint sewers under pavements, paved shoulders, and commercial or industrial drives…The design service life for all Type B conduit is 75 years. Use a minimum abrasion level equal to 2 when performing durability design." Ohio requires 75 yr service life for important structures including those under commercial or industrial drives, and requires increased durability resistance even if abrasion is not anticipated to impact design life.

- Section 1008 Conduit Design Criteria, Subsection 1008.1 Corrugated and Spiral Rib Steel and Aluminum Pipes, and Corrugated Steel and Aluminum Pipe Arches, provides the following design criteria relevant to aluminum culvert installations and their durability:

    - 1008.1.1, Material Durability, “The Criteria outlined in Section 1002.2.2 specifying types of protective coatings and/or extra metal thickness shall be followed.”
    - 1008.1.2, Designation and Thickness, “The corrugation profile and required metal thickness for structural strength is furnished by the Manufacturer in accordance to Construction and Material Specifications Handbook (CMS) Item 611.”
    - 1008.1.4, Height of Cover, “See General Notes for Figures 1008-1 through 1008-6 and 1008-15 through 1008-19 for minimum height of cover.”
    - 1008.1.5, Foundation Reports, “Conduct an investigation of the supporting foundation material to estimate the bearing capacity of the material and determine that no settlement will occur. A foundation investigation is required for all proposed metal pipe installations with 100 feet of fill or more and all pipe arch installations. Submit the foundation report with the Stage 1 review. Refer to section 1008.9 for information on foundation types.”

- 1008.4, Corrugated Steel and Aluminum Box Culverts and Corrugated Steel Long Span Culverts, provides the following requirements relevant to aluminum culvert installations and their durability:

    - 1008.4.1, Designation and Thickness, requires the corrugation profile and metal thickness to be in accordance with the “AASHTO LRFD Bridge Design Specifications design methodologies” and that “Structural strength design is furnished by the Manufacturer in accordance to Construction and Material Specifications Handbook (CMS) Item 611.” Skews are typically limited to ≤ 15°.
    - 1008.4.2, Height of Cover, requires minimum cover of 18 in., and that corrugated steel and aluminum culverts with rib stiffeners shall be provided adequate cover so that the stiffeners are completely located within the subgrade.
    - 1008.4.3, Foundation Reports, requires an investigation of the foundation conditions and bearing capacity estimate to be submitted with Stage 1 review.

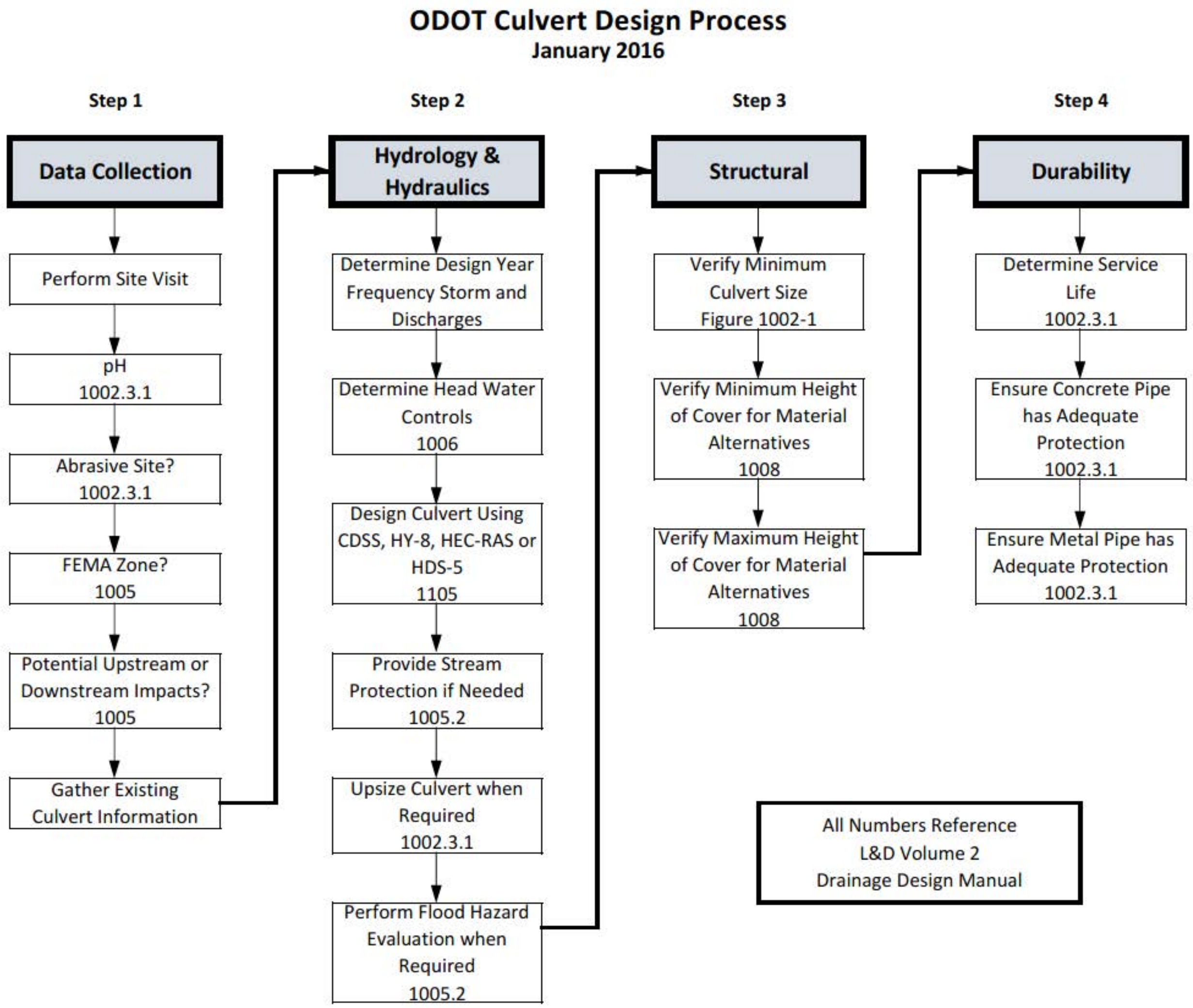
- 1008.9, Arch or Flat Slab Top Culvert Foundations, provides requirements for foundations of any three-sided and flat-topped culvert. The main requirements are to ensure that scour is adequately considered and that an accurate cost analysis is performed. Deep foundations are to be in accordance with the requirements of the Bridge Design Manual; spread footings are to be in accordance with the requirements of the Office of Geotechnical Engineering. Keyways are required.

- 1008.11 Waterproofing Membrane requires an external waterproofing membrane be applied to the external side of all precast reinforced concrete box culverts, three-sided flat-topped culverts, arch culverts, and round sections. The membrane is to be Item 512 Waterproofing, Type 2 along the vertical sides, and Types 2 or 3 across the top; Type 3 is to be used if pavement is to be used directly on top of the structure. A minimum overlap of 12 in. is required between the top and vertical membranes.

- Section 1105, Roadway Culverts, Subsection 1105.1 General, states, "A culvert generally carries a natural stream under the highway embankment…Check the design with a single-cell round pipe as a first choice. In cases where required cover or discharge precludes a round pipe, select a shape that reduces the vertical requirements while maintaining the hydraulic capacity. Check the design with the following shapes in order of minimum cost to increasing cost: single-cell elliptical concrete, metal pipe-arch, prefabricated box culvert or three-sided structure." Round pipe is the least expensive, then elliptical concrete, then metal pipe arch, followed by a culvert or three-sided structure.

7.6.3 Ohio Department of Transportation, "Culvert Design Process Flow Chart," January 2016.

We reviewed the ODOT Culvert Design Process Flow Chart downloaded from http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Additionsl%20Resources/Pages/default.aspx and reproduced below. Numerical references in the flow chart refer to sections in the Location & Design Manual, Volume Two Drainage Design, reviewed above.



7.6.4 Ohio Department of Transportation, "On-Line Bridge Maintenance Manual – Preventative Maintenance/Repair Guidelines for Bridges and Culverts," web document available at http://www.dot.state.oh.us/Divisions/Engineering/Structures/bridge%20operations%20and%20maintenance/PreventiveMaintenanceManual/Pages/default.aspx, viewed 28 December 2017.

- On the culvert topic page, aluminum plate box culverts are identified as having been introduced in Ohio in the mid-1980s with spans ranging from 10 to 18 ft. The website is not dated but states, "not many problems have been reported with these structures to date."

- On the culvert repair page, the manual recommends invert paving for culverts where there is existing bottom corrosion from abrasion or chemical action. The repair identifies invert pavement as costing approximately \$100/lf and providing an estimated 20 yr life extension compared to culvert replacement at an estimated \$1,200/lf with an estimated service life of 35 yrs.

7.6.5 Ohio Department of Transportation, Office of Structural Engineering and ODOT District Offices, "Ohio Department of Transportation Culvert Management Manual," revised October 2017.

- The goal of the manual is to provide guidelines for the inventory and inspection of conduits and structures with a span less than 10 ft that are not inspected according to the ODOT Manual of Bridge Inspection.

- We did not review it in detail as part of this policy-focused literature review, but identify that it may have procedures, forms, and other information that may be of use for planning the site inspection portion of this research project.

7.7 Review of Virginia DOT References Recommended Following Stakeholder Survey

We reviewed the below standard drawings as recommended by John Schuler, Program Manager, Virginia DOT Materials Division, in response to our Aluminum Culvert Stakeholder Survey. As noted by Mr. Schuler, Virginia DOT performed updates to their pipe material selection standards in 2015 while including pipe manufacturer industry review and input from representatives of the corrugated metal, corrugated plastic, and reinforced concrete pipe industries.

7.7.1 Virginia Department of Transportation, "2016 Road and Bridge Standards," Standard Drawings 107.20 to 107.22, *Allowable Pipe Criteria for Culvert and Storm Sewers*, November 2015.

- Drawing 107.20 provides a table (Table A) of allowable types of pipe for culvert applications. Corrugated aluminum alloy pipe and corrugated aluminum alloy structural plate pipe are allowed for all applications in all locations in the state; however, they are subject to site-specific environmental (pH, resistivity, and flow velocity) limitations indicated in Table C of Drawing 107.21, and subject to meeting minimum gage requirements in Table D of Drawing 107.22., Aluminum, is included as noted above for usage in both higher functional class (HFC, principal arterial, minor arterial, collector roads, and roads with ADT greater than 4,000, which all require 75 yr design life) and lower functional class (LFC, rural and urban local roads and streets including those with ADT less than or equal to 4,000) roadways.

- Drawing 107.21 provides a table (Table A1) of allowable types of pipe for storm sewer applications. The only type of aluminum structure identified in the table is aluminum spiral rib pipe, which is allowed for LFC roadways, but not HFC roadways, while subject to the same environmental and minimum gage requirements as those identified in Table A for culverts.

- Drawing 107.21 also provides Table C, which includes site-specific environmental limitations for use of each type of culvert material. Aluminum is allowed where the pH of soil and water range from 4.0 to 9.0, where resistivity of soil is greater than 1,500 Ω-cm, and where the maximum flow velocity based on a 10 yr design discharge is 5 ft per second if an abrasive bed load is present or anticipated.

- Drawing 107.22 provides tables of required metal gage thickness after abrasion considerations. Minimum gage requirements for aluminum, aluminum-coated steel (Type 2), and polymer-coated steel are the same, and are given based on site pH and in situ soil resistivity. Two tables are provided, one for 50 yr design life, and one for 75 yrs. Note 2 on the drawing indicates that Level 2 abrasion is the maximum abrasion level allowed for several metal pipe types, including aluminum. FHWA abrasion levels are referenced.

8. ALUMINUM CULVERT MANUFACTURER LITERATURE

8.1 Big R Bridge, "Dur-A-Span Aluminum Structural Plate Product Guide," Big R Bridge, The AIL Group of Companies, Greely, CO, 2008.

- "Dur-A-Span is made from the strongest non-heat treatable alloy in common use – alloy 5052. Additional hardware made from alloys 6061 and 6063 also have a proven history of excellent corrosion resistance even in salt water environments."

- Structures may be assembled with hot-dip galvanized steel bolts that meet ASTM A449 specifications. Aluminum fasteners meeting ASTM F468 alloy 6061-T6 and stainless steel fasteners meeting ASTM F593 Alloy Groups 1, 2, or 3 are also available.

- A 75 yr maintenance free design life is referenced without mention of abrasion or installation measures such as membranes integral with the backfill for use in locations subject to deicing salts.

8.2 Contech Engineered Solutions, "Corrugated Metal Pipe Design Guide," Contech Engineered Solutions LLC, a Quikrete Company, OH, 2017.

- "The durability and service life of a drainage pipe installation is directly related to the environmental conditions encountered at the site and the type of materials and coatings from which the culvert is fabricated. Two principle causes of reduced service life in drainage pipe materials are corrosion and abrasion."

- "Service life can be affected by the corrosive action of the backfill in contact with the outside of a drainage pipe or more commonly by the corrosive and abrasive action of the flow in the invert of a drainage pipe."

- The manual recommends aluminum alloy for use where soil and water pH range from 5 to 9 and where the minimum resistivity is 500 Ω-cm. The manual includes FHWA Abrasion Guidelines with Abrasion Levels 1 to 4, which are the same as referenced in the US FHWA PDDM, above, with flow velocities based on a 2 yr storm event.

- Table 3 provides a range of structure gages that relate to design service life based on abrasion level. For aluminum alloy culverts, the minimum gage to meet design service life between 25 and 100 yrs at Abrasion Level 1 and 2 sites is 16 ga. The minimum required gage to meet 25 to 100 yr design service life requirements at Abrasion Level 3 and 4 sites is 14 ga, with velocity reduction structures required at the invert for Abrasion Level 4 sites.

- Reference specifications for aluminum alloy pipe and pipe arches are AASHTO M 197 for the material and AASHTO M 196 for the pipe products.

- The manual provides installation guidance and references Section 26 of the AASHTO LRFD Bridge Construction Specifications, the installation manual of the National Corrugated Steel Pipe Association, and specifically ASTM B788 for aluminum pipe installations.

8.3 Contech Engineered Solutions, "Structural Plate Design Guide," 6th Ed., Contech Engineered Solutions LLC, West Chester, OH, 2017.

- In general, a pipe with a full invert or pipe with a buried invert is preferable in terms of cost versus an arch because of the elimination of concrete footings. However, many regulations require natural, undisturbed stream bottoms. In this case, an arch on footings is typically less expensive than a traditional bridge.

- If flow is to be particularly abrasive, the designer should consider a natural invert (arch or buried invert), heavier invert plates, an aluminum structure, or applying a paved invert.

- Where there is particularly corrosive effluent, an arch on elevated footing walls (pedestal walls) may be the best solution.

- In terms of design life, corrosion, and abrasion, many recommendations are provided that are similar to those referenced above in the Contech Corrugated Metal Pipe Design Guide.

- The natural aluminum oxide layer has been shown in field and laboratory observation to be stable in an environment with pH between 4 and 9 with resistivity greater than 500 Ω-cm. Within this range, corrosion rates are minimal and prediction of service life is a matter of assigning a pit rate based on laboratory testing. Conservatively, a pit rate based on 0.001 in./yr may be used.

- In tidal brackish and saltwater environments, aluminum structural plate will perform well if backfilled with free-draining material. The pH and resistivity requirements outlined previously must also be met. Seawater normally exhibits a pH from 7.5 to 8.0 and resistivity < 100 Ω-cm, but given the neutral pH and a free draining backfill, aluminum structural plate still performs well.

- "The designer should not underestimate the abrasive action of sand transported in sustained flows. When flow velocities reach approximately 5 to 6 ft/sec, sand and gravels can become mobile or suspended."

- Upstream stilling basins that allow abrasive particles to settle or drop out prior to entering the structure can be very effective in extending the service life.

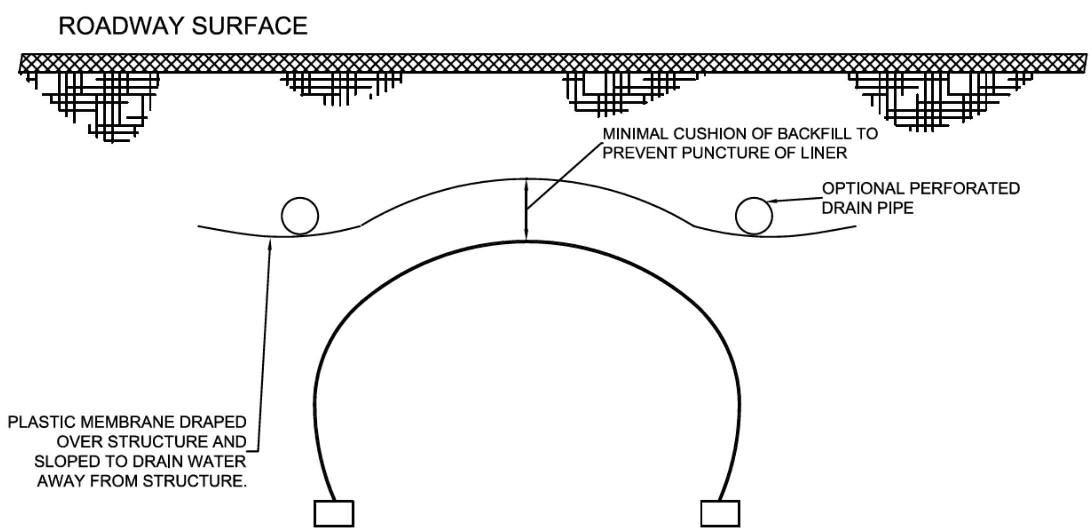
- "Velocity and abrasiveness may be present at a particular site. However, if the flow necessary to carry the bedload occurs only a few times during the life of the structure, abrasion may not be a concern. The designer should refer to the 2 or 5 year event velocity and then use this to decide if abrasion is a valid concern."

- Aluminum may lose its oxide layer from abrasion, but it will reform during low flow conditions, therefore limiting corrosion. "This is not meant to suggest that aluminum structural plate should be used in heavily abrasive environments. However, its performance can be expected to be superior to galvanized steel."

- At nonabrasive, low abrasive, or moderately abrasive sites, no additional protection is necessary for aluminum structural plate. At severely abrasive sites, increase the thickness of the material by one standard thickness and add a concrete paved invert.

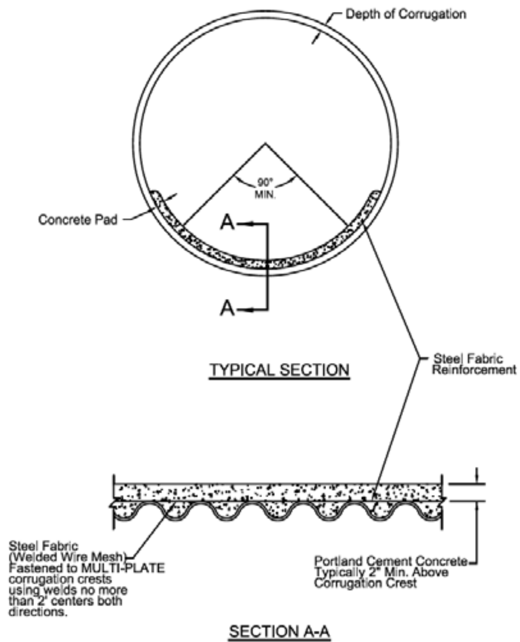
- Metals with a substantial difference in electrical potential should be insulated from each other. Electrical potential may be established by referring to the electromotive scale. The only significant concern with regard to structural plate is the use of "black" steel in conjunction with aluminum. Back steel should not be in contact with aluminum. Hot-dipped galvanized steel is compatible with aluminum structural plate.

- The potential for use of deicing salts on roadway surfaces above structural plate must be addressed during the design phase. Calcium chloride and magnesium chloride as well as other deicing materials can cause corrosion of galvanized steel and aluminum. It is recommended that the designer consider the use of either an asphalt coating on the exterior of the structure or a polymeric membrane over the structure. In addition, impermeable clay layers above the select backfill have been used to shed water from the crown of the structure. Sketches showing membrane installation for protection from deicing salts and recommended details for paved invert installation are pasted below.



OPTIONAL MEMBRANE PROTECTION
FROM DE-ICING SALTS

Membrane Protection of Structure from Deicing Salts from Contech Structural Plate Design Manual



Paved Invert Detail from Contech Structural Plate Design Manual.

- Reference specifications for aluminum structural plate material are AASHTO M 219 and ASTM B746. For aluminum box culverts, AASHTO M 219 and ASTM B864 are referenced. ASTM B789 is referenced along with the AASHTO LRFD Bridge Construction Specifications, Section 26, for installation. Plates are fabricated from an aluminum alloy with material properties that conform to AASHTO M 219 and ASTM B209. ASTM F467 and F468 are referenced for aluminum fasteners, and A307 or A449 for steel fasteners. Design is specified in accordance with ASTM B790.

8.4 Lane Enterprises, "Aluminum Drainage Products Brochure," Lane Enterprises, Inc., Camp Hill, PA, 1998.

- "The core material for aluminum drainage products is alloy 3004. It is highly corrosion resistant. Corrosion resistance is further improved by cladding each surface of the core with alloy 7072. This alloy, which totals 10% of the total sheet thickness, contains 1% zinc and provides galvanic protection to the 3004 alloy core."

- Fill height tables are provided based on Alclad Alloy 3004-H34 with minimum yield strength of 24.0 ksi and a minimum tensile strength of 31.0 ksi.

- AASHTO M 196 and ASTM B745 are referenced for corrugated aluminum pipe for sewers and drains. AASHTO M 197 and ASTM B744 are referenced as the material specification for aluminum alloy sheet for use in corrugated aluminum pipe.

8.5 Lane Enterprises, "Corrugated Metal Pipe Technical Guide," Lane Enterprises, Inc., Camp Hill, PA, 2012.

- This document has very similar information to the Contech Corrugated Metal Pipe Design Guide and Contech Structural Plate Design Guide. New and/or different information relative to the Contech guides is presented in the bullets herein.
- Corrugated aluminum alloy pipe provides a minimum 75 yr service life in the recommended environment with pH of 4 to 9 and resistivity greater than 500 Ω-cm. "Aluminum drainage products are especially appropriate for brackish and seawater (35 Ohm-cm) environments when the pipe is backfilled with a clean, free draining granular material."
- Fill height tables are provided for corrugated aluminum alloy pipe based on Alclad Alloy 3004-H32 with minimum yield strength of 20 ksi and a minimum tensile strength of 27 ksi.
- Installation requirements are presented in the guide, but there is no mention of using membranes to protect metal structures from deicing salts (filter fabric is referenced, but for controlling migration of fines).

9. RESEARCH REPORTS AND OTHER PUBLICAITONS RELATED TO BURIED ALUMINUM STRUCTURES

9.1 Bellair, P.J., and J.P. Ewing, "Metal-Loss Rates of Uncoated Steel and Aluminum Culverts in New York," Final Report FHWA/NY/RR-84/115, Final Report for NY State DOT Research Project 29-1 in cooperation with the U.S. Federal Highway Administration, New York State Department of Transportation, Engineering Research and Development Bureau, 1984.

- The report describes laboratory evaluation of three techniques to determine metal loss on coupons extracted from corrugated metal pipe, a field evaluation of thirty pipes to determine the sample size and locations necessary to characterize metal loss, results from a statewide survey of 190 galvanized steel and 35 aluminum culverts in New York, and a plan for implementation of the results of the study.
- An initial study of durability of metal pipe culverts for the environmental conditions encountered in New York State was undertaken starting in 1964. Initial findings were gathered in 1967 with follow up in 1968; however, there were discrepancies in the data and a new plan was developed as part of the 1984 work to accomplish three goals: (1) establish a method to determine metal loss rates from a single location within a pipe, (2) determine the number and location of coupons necessary to characterize metal loss within a single pipe, and (3) to determine long-term annual rates of metal loss from corrosion and/or abrasion of galvanized steel and aluminum pipes in New York State.
- The study identified a pointed (pin) micrometer as a reasonably accurate method to estimate metal loss on 1 in. diameter sections of pipe.

- The study identified a stratified random sample of eight locations to provide a reasonable level of accuracy to determine metal losses in a single pipe for large-scale surveys of culvert condition. The stratified random sample was to be taken from locations selected along a single straight line visually identified as the “worst condition” line on the culvert (typically at the invert or flow line), and that the eight be stratified to obtain two cores from each position on the corrugations (upstream face, crest, downstream face, and valley). A table of random numbers was used to select the sampling locations throughout the length of the culvert; if the randomly selected location was a point of perforation, the metal loss equivalent to the original thickness was noted. Original metal thickness was determined based on measurement of another location, typically at the top of the pipe, in an uncorroded area.

- Thickness measurements were performed on35 uncoated aluminum culverts, of which 3 were in service for up to 5 yrs, 7 in service for 6 to 10 yrs, and 25 in service for 11 to 15 yrs. The thirty-five culverts were mostly located in town and county rights of way. None of the culverts showed a loss rate greater than 1 mil/yr.

- Based on the results of the study, a metal loss rate of 0.5 mil/yr was selected to determine the expected life of the culvert as the point at which the invert or flow line would be completely removed if the metal loss rate occurred uniformly throughout the culvert’s length. For a 70 yr design life, a 35 mil metal thickness would be required. The report’s conclusion notes that the 35 mil thickness is substantially less than would be required for structural integrity; therefore, no special durability considerations are required for aluminum.

- One item interesting to note about the similar survey of the 190 galvanized steel culverts in New York State (7% of which had been in service for less than 11 yrs, 62% for 11 to 20 yrs, 25% for 21 to 40 yrs, and 5% for 41 to 50 yrs) is that on the soil-side, only some galvanizing loss and light rusting was observed (no heavy pitting was observed), indicating that soil-side corrosion was not a significant problem for galvanized steel culverts in New York.

9.2 DeCou, G., and P. Davies, “Evaluation of Abrasion Resistance of Pipe and Pipe Lining Materials,” Final Report FHWA/CA/TL – CA01-0173 EA 680442, Caltrans Department of Transportation, Office of Highway Drainage Design, 2007.

- The report presents the findings from a 5 yr long project evaluating pipe material resistance to abrasion at a site known to have abrasive flow conditions. The objective of the report was to evaluate various pipe and pipe liner products for their relative resistance to abrasion at a real-world abrasive site, as existing info at the time was laboratory based and inadequate in terms of specific results and the materials covered.

- The test site was chosen as a 180 in. diameter structural steel plate pipe undergoing replacement as the original structure was chronically perforated in the 1 ga invert after less than 20 yrs of service. Two 12 in. by 12 in. test panels were made for each material being tested with a 24 in. radius (i.e., for a 48 in. diameter pipe) and were attached to a concrete apron at the outfall of the culvert. The panels were visually inspected and their thickness was measured at nine points, both on an annual basis following each year's rainy season.

- A total of eighteen materials were tested ranging from reinforced concrete pipe and other cementitious materials to various plastics and corrugated metal pipes, with and without various coatings, and included an aluminum spiral rib pipe.

- Results showed the aluminum panels abraded approximately two to three times faster than steel (steel results includes several different types of coating, with coated steel typically outperforming uncoated steel, but only polyethylene-coated steel pipe was recommended for abrasive sites with flow limited to 14 ft/sec). The report recommends invert protection for corrugated aluminum pipes in abrasive environments.

9.3 Gabriel, L. H. "Service Life of Drainage Pipe," National Cooperative Highway Research Program, Synthesis 254, 1998.

- Corrosion of refined metals is a return to native states as oxides or salts. Corrosion requires an electrolyte, anode, cathode, and conductor. The electrolyte carries electrons between the anode and the cathode. The anode releases electrons that flow to the cathode through the electrolyte. The conductor completes the electrical circuit.

- Oxygen concentration cells are a major type of corrosion mechanism and commonly develop on buried pipelines and culverts. Pipes are usually placed on compacted or relatively undisturbed soil at the bottom of a trench. Backfill materials are typically more permeable than surrounding soils and provide a shorter pathway to the top of the structure and make the surface more accessible to diffused oxygen. The portion of a culvert under pavement usually has less access to oxygen than other parts of the culvert, such as under unpaved shoulders.

- For metal culverts, the electrolyte can be soil moisture or groundwater. The anode and cathode can be oxygen-starved and oxygen-rich air pockets, respectively, along the length of the culvert. If the midlength of pipe is below pavement, the soil will get less oxygen access, than at the exposed end of the pipe. The conductor can be the metal culvert. The corrosion would be accelerated where moist soil contains chloride ions. In this situation, corrosion will occur at the top of the culvert, with the most aggressive corrosion occurring near the pavement edges.

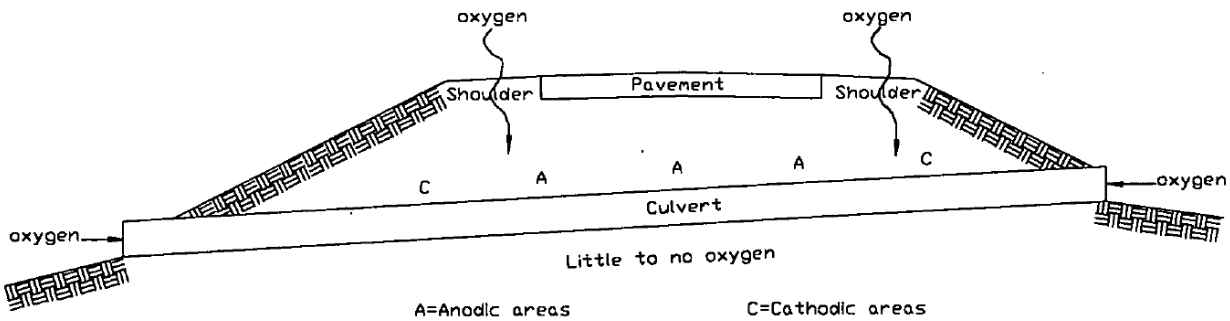


FIGURE 1 Oxidation corrosion cells in pavement drainage structures (after 2).

- Corrosion is accelerated by aggressive ions such as chlorides and sulfides.

- Where corrosion proceeds at the same rate over the metallic surface, it is called uniform or general corrosion. Where corrosion occurs at discrete sites, such as pitting corrosion or crevice corrosion, it is called localized corrosion.

- Localized corrosion such as pitting may occur where there is oxygen concentration cells and aggressive ions; crevice corrosion will occur where there is a restricted pathway for oxygen diffusion (such as where there may be overlapping plates; oxygen concentration cells accelerate corrosion, and corrosion products such as magnetite in the case of steel, may compound the process by galvanic effects); stress corrosion and cracking occurs where there is a combination of other corrosion potential such as above, plus tensile stress, including residual tensile stress; microbiologic corrosion occurs where conditions are favorable, such as steel culverts with low oxygen and anaerobic sulfate reducing bacteria present.

- If a culvert is cathodically protected to inhibit general corrosion, stress corrosion is more likely to occur as it may lead to an accumulation of alkali salts on the surface of the pipe.

- Aluminum pipe has a very thin (2E-7 in.) natural coating of protective aluminum oxide that is unreactive and prevents corrosion. If the coating is nicked, the exposed surface of the underlying aluminum corrodes, quickly forming a new protective film.

- Heavy metal ions (e.g., copper, iron) in backfill increase the electrochemical corrosion potential of aluminum.

- Abrasion, a consequence of heavy bed loads and high velocities, can lead to accelerated corrosion and further degradation by removing protective coatings and passivating films, if present.

- Aluminum is corrosive in strong acids with pH < 4 and in strong, caustic solutions. In aerated environments, a protective scale forms.

- The simplest criterion for estimating the corrosivity of a soil to metals is by measuring soil resistivity, which depends largely on the nature and amount of dissolved salts in the soil, but is also dependent on temperature, moisture content, soil compactness, and presence of larger, inert particles of stones and gravel.

- Allowable resistivity and pH ranges vary by state, and field performance results have varied. Most states limit pH to between 4 and 9, and have lower limits of resistivity around 1,000 Ω-cm, but some states allow as low as 500 Ω-cm (Nevada) or higher limits such as 1,500 Ω-cm in CA, LA, PA. Mississippi requires > 10,000 Ω-cm for 50 yr design life, or > 1,500 Ohm-cm for 25 yr design life. Wyoming also limits soluble sulfates to 0.125%.

- Aluminum culvert specifications include AASHTO M 179, M 196, and M 219, co-listed as ASTM C4, B745M, and B746M, respectively.

- For alloy 3004, the alloy is typically sandwiched between outer layers (outer cladding layer is typically 5% of final thickness) of aluminum zinc alloy 7072. Abrasion, therefore, may erode the outer cladding allowing for exposure of the inner, more corrosion susceptible alloy. Also, the relative softness of aluminum compared to steel, makes abrasion more of a concern for aluminum than steel.

- There is a DOT survey in an appendix where 49/50 states responded.

9.4 Hartemink, A., "Soils Maps of Wisconsin," *Geoderma* 189-90, 2012.

- Reviews soil maps of Wisconsin from 1882, 1926, 1976, and 1993. Sample ratio in most-recent survey of 1:710,000, covering entire state. Soils primarily classified as loamy or silty.

- Matches general description of state soils from USDA NRCS (via county surveys) as silt, loam, and hydric.

9.5 Haviland, J.E., P.J. Bellair, V.D. Morrell, "Durability of Corrugated Metal Culverts," Research Report 66-5, Physical Research Project 291, New York State Department of Transportation, Bureau of Physical Research, 1967.

This report is the precursor to the 1984 Bellair and Ewing report, "Metal-Loss Rates of Uncoated Steel and Aluminum Culverts in New York," reviewed above.

The purpose of the report states, "In the absence of any previous systematic study of corrugated metal culvert durability in New York State, this investigation was initiated to provide highway designers with reliable data on corrosion/erosion rates of corrugated aluminum and galvanized steel culverts under the environmental conditions encountered in this state." Two studies were performed under the project: (1) a survey of 792 bituminous coated and uncoated galvanized steel culverts (complete at the time of the report), and (2) periodic evaluations of steel culverts and uncoated alclad aluminum culverts that were exposed to similar conditions at twenty-one locations throughout New York State (the study was ongoing at the time of the report). The aluminum culverts studied in the report were installed by local agencies between 1961 and 1964 and compared with steel culverts in the same or adjacent waterways.

Findings relevant to the corrosion and durability of the aluminum culverts are presented in the bullets below; as the 1984 Bellair and Ewing report provides more comprehensive results of longer-term performance, only a few items of note are provided below:

- At the twenty-one culvert sites, water pH ranged from 6.2 to 8.8, and other chemical analyses of the water identified a preponderance of soft water (low calcium carbonate concentration), and frequent occurrence in solution of ions of iron, ammonia, and nitrate. The report notes that seasonal fluctuations were also noticed, such as with soil pH at a given site that ranged from 5.2 to 8.4 during a twenty-month period, and another site that had soft water at one period and hard water at another period.

- The thirty-four aluminum culverts studied were in excellent condition and exhibited no metal loss at the times of inspection. Regarding durability, the culverts frequently had a dull white surface film accompanied by slight pitting that the report identified as characteristic of atmospheric weathering, and that the pits were occasionally close enough that they created an etched appearance, but penetration was slight.

- The study gave favorable conclusions on the overall performance of aluminum culverts in New York State.

9.6 Hurd, J.O., and S. Sargand, "Field Performance of Corrugated Metal Box Culverts," *Transportation Research Record*, Issue 1191, Transportation Research Board, Washington DC, 1988, 39–45.

- Thirty-nine corrugated aluminum and 10 corrugated steel box culverts in Ohio were inspected and evaluated, all of which had 7 yrs or less time in service. One 6 yr old aluminum culvert had very minor pitting at the invert but the steel bolts and aluminum plates did not show signs of corrosion. Much of the paper is devoted to observed shapes of the structure and the deviations from specified shape.

- The paper notes that Ohio DOT used sodium chloride for winter deicing of roads, that there was seepage through the bolted seams on many structures, and that the amount of deposits and corrosion were always greatest beneath the edge of the pavement. A potential crown corrosion problem exists on shallow buried structures, although increased cover height (varying from 1.25 to 5.7 ft) did not reduce the severity of seepage or corrosion.

9.7 Jacobs, K. M., "Durability of Drainage Structures," *Transportation Research Record*, Issue 1001, Transportation Research Board, Washington DC, 1984, 14–20.

- Evaluation of steel, aluminum, and concrete culverts for durability. Includes actual installations and test installations. Based in Maine.

- Clad-aluminum alloy pipe used for 20 yrs in Maine. Located in tidal waters (corrosive). Sample Size 44, cores or field measurements taken on 85% indicate average metal loss of 0.0002 in. with standard deviation of 0.0004 in. (not sure if this is a rate or total); next sentence states corrosion rates may be accelerating with time based on comparison to data from a 1976 study. Section loss measured indicates perforation at over 100 yrs for

16 ga using even the conservative metal loss data. Good durability shown in fresh and salt water, pH normal, resistivity greater than 10,000 Ω-cm (standard backfill practice requires granular fill).

- Aluminum Alloy Structural Plate Culvert Pipes: Three in salt water (15, 12, and 3 yrs old), one in fresh water (11 yrs old). Good performance, limited details provided.

- Conclusion that aluminum-alloy and aluminum structural plate have best service life, only type that should be used in salt water. Study mentions excessive deflections observed, which is the most serious observation for aluminum culverts in the study.

9.8 Lowe, T.A., and A.H. Koeph, "Corrosion Performance of Aluminum Culvert," *Highway Research Record No. 56*, Highway Research Board, Washington, DC, 1964, 98–115.

This paper was referenced in the AASHTO Highway Drainage Guidelines and was written by Mr. Lowe, of the Department of Metallurgical Research, and Mr. Koepf, the Field Engineering Manager, both of Kaiser Aluminum, an aluminum producer.

- The abstract states, "This paper discusses corrosion characteristics of aluminum and how these characteristics might be affected by burial in soil. The influences of various types of soil on aluminum are discussed in the light of experience gained through monitored culvert installations including a compendium of field performance with aluminum culvert and an appraisal of the overall performance of the product."

- The paper identifies more than 20,000 installations of aluminum culverts have been made since the product was introduced 4 yrs prior.

- Regarding aluminum oxide protective film, the paper identifies it as forming instantaneously on a bare aluminum surface when oxygen is present, and that it is tough and does not break away as the metal is distorted, formed, or subjected to temperature or humidity variations. The oxide is identified as inert to a range of chemical environments within a pH range of 4 to 9, is a good electrical insulating material, immediately reforms if damaged mechanically or corroded, and "should the film be disrupted as the result of corrosion, the corrosion products that collect at the point of attack tend to stifle further corrosion reaction by providing an effective barrier between the metal surface and the aggressive environment."

- **Regarding cladding**, the paper notes that corrosion attack of aluminum usually occurs at highly localized points that are believed to represent defects in the oxide film that become more vulnerable to penetration by aggressive ions; adding a layer of cladding with a layer of a more electronegative alloy provides galvanic protection to the core. Where there is no cladding, the small areas become the anodes of the corrosion cells, which tend to penetrate into the metal rather than cause general removal of metal over large areas. The idea behind the cladding is to spread the corrosion attack laterally over the clad layer rather than into the core. It notes that even if the alloy 7072 cladding were to "be completely removed, the 3004 core alloy of culvert sheet possesses a high order of corrosion resistance."

- Table 2 of the paper, pasted below, sows the potential of various common aluminum alloys. Discussion below Table 2 notes that alloy 7072 is sufficiently anodic to provide protection to all of the alloys listed in the table.

TABLE 2

TYPICAL VALUES[a]

Alloy	Potential (v)
1100	0.84
2024-T4	0.69
3003	0.83
3004	0.84
5052	0.86
5086	0.88
6061-T6	0.83
7072	0.96

[a]In aqueous solution containing 57 gm/liter NaCl and 3 gm/liter H_2O_2 at 25C, using a 0.1 N calomel reference electrode.

- Under the heading, “Resistance to Chemical Attack,” the paper states, “Experience with salt water exposure and experience gained during this evaluation indicate that aluminum can serve satisfactorily in saline environments. However, it is possible for corrosion of aluminum culvert stock to proceed at significant rates in the presence of chlorides under anaerobic conditions. This should not be construed to indicate problems with aluminum due to anaerobic bacteria such as sulfate reducers. There is considerable information attesting its compatibility in the acid hydrogen sulfide environments caused by these bacteria.” It continues, “The organic acids usually associated with peat do not cause corrosion of aluminum. In addition to the installations shown under ‘peat’ and ‘ground-water podzol’ in Table 5, aluminum has provided nine years of satisfactory performance for buried irrigation lines in a Grayland, Wash. bog.”

- There is a discussion of abrasion and erosion, much of which is covered more thoroughly by other references reviewed in this literature review.

9.9 Lowe, T.A., R.H. Vaterlaus, R.L. Lindberg, and L.R. Lawrence, "Corrosion Evaluation of Aluminum Culvert Based on Field Performance," *Highway Research Record 262*, Highway Research Board, Washington, DC, 1969, pp. 56–68.

This paper presents the results of field evaluation of the performance of 965 aluminum culverts with an average in-service history of 4.7 yrs, with about 20% having been in service for six or more years. Of the 965 culverts, samples were taken from 583 and evaluated in a laboratory. Two of the authors were with Kaiser Aluminum, and two were with Reynolds Metals; they credit the Aluminum Association with having undertaken the nationwide culvert inspection program described in the paper. Relevant points from the paper are provided below:

- Under the heading "The Nature of Aluminum Corrosion," the paper identifies detailed discussion of aluminum corrosion a beyond the scope of the paper while making reference to the following references: (1) Goddard, H.P., W.B. Hepson, M.R. Bothwell, and R.L. Kane, "The Corrosion of Light Metals," Chapters 1 and 2, John Wiley and Sons, 1967, and (2) Van Horn, K.R., "Aluminum," Vol. 1,1967, 209–238, 257–276.

- Regarding pitting corrosion, the paper states, "Certain elements present as purposeful additions or as impurities are believed to affect the structure of the oxide film. In other words, we have point-site imperfections in the protective film. When attack occurs at these imperfections, the imperfection is enveloped by aluminum oxide resulting from corrosion of the metal substrate, or it is displaced by the oxide. The resulting build-up of oxide protects the underlying metal, and attack is effectively arrested. This and similar processes occurring as the result of other mechanisms accounts for the localized attack, or pitting, associated with the corrosion of aluminum." It identifies the pitting as being "self-stopping" with reference to the Goddard, et al. (1967) reference above, and to *ASTM Technical Publication 175*, "Symposium on Atmospheric Corrosion of Non-Ferrous Metals," 1955, 21–44.

- During the field inspection program, visual inspection of the culverts was performed, and the culverts were rated on a scale of A (excellent) to E (very poor), with the criteria for an "E" rating being perforation of the metal. The inspector took soil and water samples where available. The inspector removed a series of 1 in. diameter samples from the culverts from the invert, waterline, and in some cases, the top of the culvert for examination in the laboratory; the paper notes the coupons as having been taken from locations on the culvert where the most severe attack was observed. The paper provides the below table identifying environmental data at sites with culverts that had "D" and "E" ratings; a "D" rating was representative of culverts with coupons that showed attack but not perforation of the core alloy, generally accompanied by extensive surface corrosion.

TABLE 5
EVIRONMENTAL DATA ON SITES PRODUCING D AND E RATINGS

Sample No.	Location	Water		Soil		Time in Service	Rating
		pH	Resistivity	pH	Min. Resistivity		
67-042	North of Maine Prairie Road, Salano, Calif.	6.9	1700	7.7	1330	5.0	D
67-180	Sweetwater Bridge, National City, Calif.	6.5	35	7.7	10.1	5.8	D
68-415	Severin Road, Port Charlotte, Fla.	6.2	35	6.7	–	6.0	E
68-449	Highway 17, Brunswick, Ga.	6.8	97	7.6	165	7.0	D
68-001	California 17, Santa Cruz County, Calif.	3.1	1440	5.4	1345	5.5	E
68-458	County Road No. 4, Meigs County, Ohio	4.5	45310	4.1	3524	8.0	D
68-461	County Road No. 33, Steudal, Pike County, Ind.	3.4	185	4.8	810	6.0	E
68-471	West of Coe, Pike County, Ind.	2.2	115	2.9	230	5.0	D

- Of culverts studied in the field investigation, 11 of the 965 culverts were in Wisconsin, all of which were sampled, and 6 of which were in the “six or more years of service life” category. None of these appears to be in the “D” to “E” rating category based on the above table.

- The paper includes some further discussion on estimates of service life for clad aluminum, typically assuming the cladding acts as a large array anode, and is not corroded by pitting corrosion.

9.10 Maher, M., “Service Life of Culverts.” National Cooperative Highway Research Program, Synthesis 474, 2015.

- Corrosion is electrochemical degradation (loss of section or coating). Current flows from an anode to a cathode via an electrolyte and conductor, causing degradation at the anode. Corrosion can affect the inside or outside of a pipe, and is a function of pH, resistivity, chloride and sulfate concentration, soil moisture, and other factors such as dissolved gasses and bacterial activity.

- The primary methods of corrosion protection are increased wall thickness to account for a certain level of corrosion, protective coatings that form a barrier between aggressive environments and corrosion-susceptible materials, and cathodic protection systems that force corrosion to occur in a separate sacrificial, replaceable anode.

- pH is a measure of the acidity or alkalinity of a solution through the concentration of hydronium ions. pH between 5.5 and 8.5 is generally not detrimental. pH between 0 and 5.5 (acidic) or 8.5 and 14 (alkaline/basic) have increased corrosion potential. Soil can become acidic due to high rainfall removing soluble salts, mining sites, or geologic conditions (e.g., limestone, marshes). Soil can become alkaline in arid areas as evaporation removes water and increases the concentration of soluble salts.

- Resistivity is a measure of a soils ability to conduct current. It is a function of soluble-salt concentration, temperature, moisture, compaction, and soil chemistry. A high resistivity indicates a soil less capable of conducting current and inducing corrosion. Resistivity greater than 2,000 to 5,000 Ω-cm generally limits corrosion. For resistivity lower than 1,000 to 3,000 Ω-cm, corrosion is a concern. Brackish or seawater and clay, loam, and organic soils typically have resistivity values in this range.

9.11 McKeel, W.T., "A Comparative Study of Aluminum and Steel Culverts," *Culvert Studies Progress Report No. 4*, Document No. VHRC 70-R38, Virginia Highway Research Council, Charlottesville, VA, 1971.

This research presents a comparison of performance of steel and aluminum culverts at six sites throughout Virginia. Five sites were studied starting in 1961, and the sixth site was added in 1967. The report identifies its purpose as providing the Virginia Department of Highways a recommendation on the use of aluminum culverts based on comparison of aluminum and steel culvert performance at six secondary highway sites throughout Virginia chosen to provide a wide range of exposure conditions. Evaluation included periodic visual inspections and "rough chemical analyses" of the water flow at each location. Specific information on the culverts in the study and their performance include the following:

- Culvert diameters ranged from 18 to 48 in.; the aluminum culverts were not coated; steel culverts at three of the sites were bituminous coated; the water flows at each site were described as mountain stream, pasture runoff, acidic water, brackish water (two sites), and swamp.

- At one of the brackish sites, the aluminum had widespread corrosion of the cladding after 5 yrs of service, and the corrosion appeared to be confined to the cladding, with no observed evidence of pitting of the exposed core metal. The performance of the aluminum culvert was considered equal or superior to the steel culvert at that site.

- At the site with acidic water, which is believed to have been contaminated by sulfurous waste from nearby strip mining, resulting in a water pH as low as 3.2, the invert of the aluminum pipe was severely pitted after 1 yr of service and completely removed by corrosion in 2 yrs. The study noted the bituminous coated steel pipe was performing relatively well where the coating was intact, but, with some areas of coating loss, it was inevitable corrosion would proceed from the exposed edges.

- In the discussion, the paper notes aluminum pipes performed comparably or better than steel pipes for a variety of soil and water conditions, which represent much of the typical environment found in Virginia. It references similar findings for 965 culverts studied by the Aluminum Association (Lowe, et al., 1969) and identifies the Virginia study has similar conclusions to those from the New York State study by Haviland, et al. (1968).

- The failure of the aluminum culvert at the acidic site resulted in a recommendation that that the absolute lower limit of pH be 4.0 at a site for use of uncoated aluminum culverts.

9.12 Meacham, D.G., J.O. Hurd, and W.W. Shisler, "Ohio Culvert Durability Study," Report No. ODOT/L&D/82-1, Ohio Department of Transportation, 1982.

- The study involved field investigation of the in-service performance of 1,616 culverts in all eighty-eight counties of Ohio, and others in Kentucky and Indiana.

- The scope includes concrete pipe and galvanized corrugated steel pipe, and identifies that the text uses corrugated metal pipe (CMP) and corrugated steel pipe (CSP) interchangeably. The scope identifies ODOT as having a limited number of aluminum pipes in their inventory, but does not present any results of their performance.

9.13 Molinas, A., and A. Mommandi, "Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials," Report No. CDOT-2009-11, Colorado Department of Transportation, 2009.

- The report reviews policies and procedures for selection and service life of culverts are reviewed from Arizona (1996), Florida (1999), California (2003), Montana (2003), New Mexico (2004), and the then-current Colorado Corrosion Resistance Guidelines.

- The Colorado Department of Transportation made field measurements at twenty-one sites, including soil and water samples. Three sites had aluminum culverts, all installed in 1980, and all with severe corrosion after 26 yrs of service.

- Two of the aluminum sites had no water readily available for pH testing, the third site had water pH of 8.3. Soil pH values at all three sites ranged between 6 and 8. The average soil resistivity at the three sites was approximately 4,000, 9,000, and 750 ohm-cm. Chloride and sulfate concentrations were high.

- High chloride and sulfate concentrations were stated as the reason for the corrosion of the aluminum culverts. The one site with little damage after 26 yrs of service had low chloride concentrations.

9.14 National Cooperative Highway Research Program, "Synthesis of Highway Practice 50: Durability of Drainage Pipe," Transportation Research Board, National Research Council, Washington, DC, 1978.

The foreword notes, "This synthesis will be of special interest and usefulness to design and materials engineers and others seeking information on corrosion and abrasion of drainage pipe. Durability guidelines are presented to permit selection of appropriate pipe materials for given design conditions." We reviewed Chapters 2 (Theory and Mechanisms), 3 (Pipe Materials), and 4 (Pipe Protective Measures) of the synthesis and present relevant information from those chapters below.

- Chapter 2, Theory and Mechanisms, presents information on corrosion theory and mechanisms, most of which is also identified and covered in NCHRP Synthesis 254 by Gabriel, reviewed above. The chapter identifies "water and the chemicals that have reacted with, become dissolved in, or been transported by the water" as the main corrosion medium affecting drainage facilities. It also states, "Although most chemical elements and their compounds are present in soils, only a limited number exert an important influence on corrosion," with reference given to National Bureau of Standards Circular 579 by Romanoff (1957). A figure showing a buried roadway culvert, oxygen paths, and anodic and cathodic area distribution along the length of the culvert, as shown in Synthesis 254, is presented.

- Chapter 3, Pipe Materials, identifies clad-aluminum alloy pipe as becoming available for highway use in 1960. It identifies four references of studies by industry and eleven references of studies by prospective users regarding research on aluminum and field evaluations of its use. It states, "Aluminum is suitable for use in neutral and mildly acidic environments, but not in most strongly acidic environments. Aluminum does perform well in organic acid environments, however. As pH increases into the alkaline range, corrosion resistance of aluminum normally decreases." It goes into ranges of allowable pH and laboratory soil resistivity as identified by industry and several states at the time. It goes on to state, "The presence of heavy metals (copper, iron, etc.) in bedding or backfill of aluminum pipe increases the possibility of corrosion. Although several states have soils that contain copper, only one state has identified a problem that could be attributed to heavy metals in backfill material. The pipe at the problem location is still in service." It goes on to talk about abrasion, which includes similar information to that covered in this literature review from other sources.

- Chapter 4, Pipe Protective Measures, identifies several types of coatings for various types of pipe, including metallic coatings, which can be classified as anodic (sacrificial) or cathodic (nonsacrificial); in this area, it identifies aluminum as a coating for steel, though there is not much discussion of its performance or of coated aluminum. In a separate paragraph, it discusses aluminum cladding. In clad aluminum, it identifies it as "a sandwich with an inner core of aluminum-magnesium-manganese alloy 3004 between two layers of aluminum-zinc alloy 7072 'cladding,' which is anodic or sacrificial to the core material. All three layers of the sandwich are bonded metallurgically during the rolling operation, with each outer cladding layer constituting 5 percent of the final sheet thickness. Under corrosion attack, the cladding is galvanically expended, protecting the core material until large areas of cladding are gone." It identifies cladding as being sensitive to abrasion.

9.15 Peterson, D.E., "Evaluation of aluminum Alloy Pipe for Use in Utah's Highways," Utah State Department of Highways, July 1973.

The abstract identifies the report as presenting "information on the use and performance of aluminum alloy culvert pipe and aluminum alloy structural plate pipe. It includes the results of experimental sections and of a test site for pipe materials located in a very hostile environment in Utah. The results of a nationwide survey on the use of aluminum alloy pipe is also included," along with literature review, and new criteria for use of aluminum alloy pipe in Utah are recommended. Information relevant to the durability performance of aluminum pipe is presented in the bullets below.

- Utah allowed aluminum alloy pipe as an alternate to galvanized steel at the option of the contractor for several years prior to the research. Two projects were constructed at the time of the report (one in 1964 and one in 1969) where aluminum alloy pipe had been used on the above basis; the 1964 project used 4,100 ft of aluminum pipe (the amount in the other project was not provided). Aluminum pipes were also installed at three test sites with varying environmental conditions between 1962 and 1967.

- Two pipes from one of the test sites examined after 11 yrs of service showed little to no evidence of corrosion; the soil at one of the sites had a pH of 8.1 and resistivity of 3,000 Ω-cm; the soil at the other site had a pH of 8.1 and resistivity of 900 Ω-cm.

- At another site, a 48 in. diameter aluminum alloy pipe was placed inside an existing pipe (type not reported) in 1963. The site has a high salt content, pH range of 6.6 to 8.2, and resistivity between 17.9 and 55.4 Ω-cm. Periodic observations from Materials Laboratory personnel described the pipe as having generally good performance.

- A field test site for pipe materials was established at a location with soil pH of 9.6 and resistivity of 280 Ω-cm, where the soil was wet year-round. The aluminum pipe at the test site showed favorable performance after 7 yrs in ground, with no pitting in the cladding.

- The report presents results from a survey of the fifty state DOTs and the District of Columbia (fifty of fifty responded), and the author notes there was a general lack of experience with minimal usage of aluminum nationwide, although forty-four of fifty allowed its use for pipe culverts (five of the forty-four indicated it had yet to be used in their jurisdiction). Illinois, Oregon, and Pennsylvania were the states that had used it most (approximately 10%). For structural plate pipe, twenty-five of fifty do not allow use of aluminum structural plate, thirteen agencies had used it, and only Vermont and Washington had reported using it more than 1% (VT = 4% and WA = 10%). Many agencies had no criteria to evaluate locations where aluminum alloy would be allowed. Missouri identified aluminum pipes as having had short service lives (4.5 to 5.5 yrs) when installed with pH between 2.9 and 3.1.

- The report recommended allowing the use of bare aluminum alloy pipe where the pH of soil or water is between 4.5 and 9, and where the soil resistivity is not less than 1,000 Ω-cm.

9.16 Romanoff, Melvin, "Underground Corrosion," United States Department of Commerce, National Bureau of Standards Circular 579, April 1957.

This circular appears to be the seminal research on underground corrosion of buried metals and is referenced in a variety of work. It is probably one of the most comprehensive studies of underground corrosion ever performed and includes information on corrosion of buried aluminum.

The abstract states the following, "The Circular is a final report on the studies of underground corrosion conducted by the National Bureau of Standards from 1910 to 1955. Up to 1922, the studies were confined to corrosion due to stray-current electrolysis and its mitigation. After it became apparent that serious corrosion occurred in soils under conditions that precluded stray-currents as an explanation, a field burial program was initiated in order to obtain information pertaining to the effect of soil properties on the corrosion of metals. More than 36,500 specimens, representing 333 varieties of ferrous, nonferrous, and protective coating materials, were exposed in 128 test locations throughout the United States. During this time the electrical and electrochemical aspects of underground corrosion have been continuously studied in the laboratory. Results from both field and laboratory investigations are presented." Information relevant to soil characteristics and environmental corrosion of buried aluminum from this study is provided below.

- In Figure 1, the study presents a map of eight major soil groupings in the U.S. (after Marbut, 1935), referred to as the "Great Soil Groups," and includes dots locating the buried metal corrosion test sites that were part of the study. The eight soil groupings are referenced in several other pieces of literature reviewed in the current work. Note that Wisconsin has two groups: Group I podsol soils to the north, and Group II gray-brown podsolic soils to the south. These soil groups are also found in Ohio (only Group II), Maine, Michigan, Minnesota, and New York, which were the other states whose specifications were reviewed above.

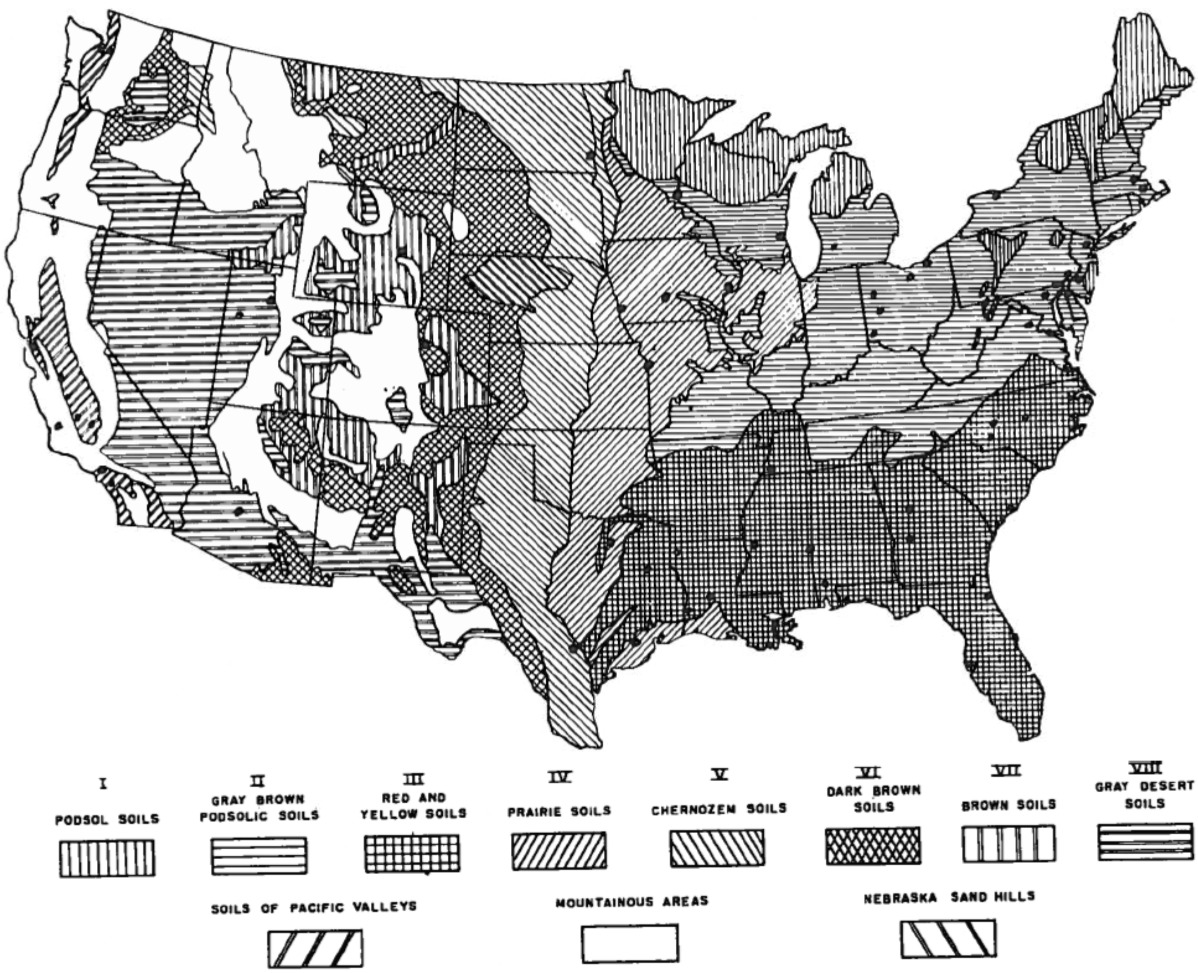


FIGURE 1. *Soil groups of the United States. Marbut [60].*
The dots show the location of the National Bureau of Standards test sites.

- Per Table 1 of the Circular, Group I podsol soils tend to have a thin layer of leafy mat followed by a transition through various colors (dark gray to whitish-gray to dark- or coffee-brown) of organic layers until transitioning to a depth at which there is yellowish-brown silicate subsoil; areas with podsolic soils tend to be strongly acidic. Group II gray-brown podsolic soils tend to have a thin surface layer of leaf litter and mild humus, followed by a 2 to 4 in. thick dark-colored layer, followed by 8 to 10 in. of grayish-brown leached horizon, and subsoils that consist of yellowish-brown to light reddish-brown heavier silicate soils.

- Regarding theory of underground corrosion, Romanoff notes, "underground corrosion that has occurred can be explained, but, even today, theory does not permit accurate prediction of the extent of corrosion to be expected to occur and is dangerous unless complete information is available regarding all of the factors present and their individual and interrelated effects." Factors that affect underground corrosion include aeration (oxygen stimulates corrosion; areas with the least oxygen are generally anodic), electrolyte (soil furnishes the electrolyte that carries the current to promote corrosion), electrical factors (variation in electrical potential between two points on the metal), and miscellaneous (combinations of the above effects, or other contributors, such as backfill placement and compaction or bacterial influences, etc.). Electrical factors include any variation homogeneity of the structure and composition of the metal, which can include strains, inclusions, intermetallic compounds, or separate constituents, such as graphite in cast iron. Potential differences as high as 0.9 V have been observed in the laboratory when one portion of a soil in contact with a steel plate was kept moist and thereby was deficient of oxygen in comparison to an adjacent portion of soil that was drier and more permeable to oxygen.

- Study of Aluminum Alloy Specimens Buried for 10 yrs in Five Different Soils:

  - The study included evaluating the corrosion performance of buried three different types of aluminum specimens with the three alloy compositions shown in the table below:

Composition of Aluminum Alloy Samples in Bureau of Reclamation Tests

Element	% Composition by Weight[1]		
	Commercial Aluminum	Aluminum with Manganese	Duralumin
Silicon (Si)	0.3	0.44	0.23
Iron (Fe)	0.33	0.51	0.30
Copper (Cu)	0.09	0.16	4.10
Magnesium (Mn)	0.03	1.12	0.62
Manganese (Mg)	–	–	0.52
Zinc (Zn)	–	0.02	–

1. Compositions given are a % maximum by weight and heading descriptions are how the different alloys were referred to in the study.

  - Results from 10 yrs of burial of 120 total coupons (40 coupons each of "Commercial Aluminum," "Aluminum with Manganese," and "Duralumin"), 6 in. by

2 in. by 0.062 in. thick, from five different soil sites along with similar specimens made from open hearth iron (0.125 in. thickness) and carbon steel with 0.2% copper (0.062 in. thickness) at the same sites are presented in the table below.

- Information describing soil and environmental characteristics at each of the test sites is provided in the second table below.
- Although information in the paper identifies 120 total test specimens (40 from each alloy), it appears, based on the footnote to the results table, that two specimens of each alloy were buried at each site, which corresponds to 10 specimens of each alloy.
- Regarding the study of corrosion of the aluminum specimens, Section 12.4 in the circular notes, “In some soils, duralumin was completely converted to a greenish-white paste. The aluminum alloys were susceptible to intergranular corrosion. In the advanced stages, this type of attach caused ridges and blisters to occur on the surface, beneath which was a white powder on some of the specimens. The unalloyed specimens were the best of the group.” It continues, “None of the thin materials was satisfactory for use unprotected in the corrosive soils to which they were exposed. Great strides have been made during recent years in the development of aluminum alloys which might be more corrosion resistant” than the tested specimens.

Results of National Bureau of Standards Buried Corrosion Tests – Aluminum, Cast Iron, and Steel Coupons[1]

Material	Soil 13 – Hanford Very Fine Sandy Loam, 10.16 yr Exposure		Soil 29 – Muck, 10.08 yr Exposure		Soil 42 – Susquehanna Clay, 10.05 yr Exposure		Soil 43 – Tidal Marsh, 10.73 yr Exposure		Soil 45, Unidentified Alkali Soil, 10.55 yr Exposure	
	Loss in Weight (oz/sq ft)	Max. Pit Depth (mils)	Loss in Weight (oz/sq ft)	Max. Pit Depth (mils)	Loss in Weight (oz/sq ft)	Max. Pit Depth (mils)	Loss in Weight (oz/sq ft)	Max. Pit Depth (mils)	Loss in Weight (oz/sq ft)	Max. Pit Depth (mils)
Commercial Aluminum	0.086	21	D	62+	0.35	62+	0.18	< 6	0.49	46+
Aluminum with Manganese	0.35	45+	0.97[2]	62+	0.20	14	0.22	13	0.33	20
Duralumin	D	D	D	D	1.39	62+	0.15	< 6	0.56[2]	62+
Open-Hearth Cast Iron	9.92	125+	5.86	62	5.61	70	D	125+	D	125+
Steel with 0.2% Copper	D	62+	6.91	56+	5.40	59	D	62+	D	62+

1. "D" designates specimens destroyed by corrosion; "+" designates one or both specimens perforated by corrosion.
2. Data is for single specimen only; the other specimen was destroyed by corrosion.

Soil and Environmental Data at Aluminum Coupon Test Sites

Parameter		Soil 13 – Hanford Loam	Soil 29 – Muck	Soil 42 – Susquehanna Clay	Soil 43 – Tidal Marsh	Soil 45 – Unidentified Alkali
Soil Type		Very Fine, Sandy Loam	Muck	Susquehanna Clay	Tidal Marsh	Unidentified Alkali Soil
Location		Bakersfield, CA	New Orleans, LA	Meridian, MS	Elizabeth, NJ	Casper, WY
Internal Drainage		Fair	Very Poor	Fair	Very Poor	Poor
Soil Resistivity (Ω-cm)		290	1,270	13,700	60	263
Soil pH		9.5	4.2	4.7	3.1	7.4
Composition of Water Extract (mg-eq. per 100 g of soil)	Total Acidity (H+)	A[(1)]	28.1	28.2	36.8	A[(1)]
	Na + K as Na	6.23	2.15	–	45.10	8.15
	Ca	0.09	1.92	–	5.17	3.70
	Mg	0.13	1.55	–	9.45	0.70
	CO_2	0.0	0.00	–	0.00	0.00
	HCO_3	1.12	0.0	–	0.00	0.24
	Cl	1.64	1.69	–	43.30	0.18
	SO_4	3.76	2.30	–	37.00	11.98
Annual Mean Temperature (°F)		64.6	69.3	64.0	52[(2)]	47.2
Annual Mean Precipitation (in.)		5.6	57.4	53.0	43[(2)]	15.3
Soil Chemistry Description		Inorganic, Oxidizing, Alkaline Soil	Organic, Reducing Acid Soil	Inorganic, Oxidizing, Acid Soil	Organic, Reducing Acid Soil	Inorganic, Reducing, Alkaline Soil

1. "A" designates alkaline reaction.
2. Data is from a nearby city.

9.17 Wenzlick, J.D., and J. Albarran-Garcia, "Effectiveness of Metal and Concrete Pipe Currently Installed in Missouri (Phase 2)," Report No. OR 08-014, Missouri Department of Transportation Organizational Results, Jefferson City, MO, January 2008.

The Executive Summary to the report identifies that it includes a review of 125 culvert pipe installed on construction projects installed from 2002 to 2007, plus some older pipe installations, both of which included aluminum alloy pipe installations. All pipes in the study were visually inspected; at certain locations expected to be corrosive environments, soil and water pH readings were taken. It identifies aluminum alloy as the best-rated metal pipe; however, it notes there are only a half-dozen aluminum alloy pipe installations in the state because of their high initial costs. Information on aluminum alloy pipe performance in the study includes the following points:

- Three aluminum alloy pipes installed in 1962 and 1974 showed only a slight discoloration or no corrosion at all. Aluminum alloy pipes rated the best of all metallic pipe, and had seen 33 to 45 yrs of service at the time.
- Based on performance of several types of pipe in the study, the report recommends reinforced concrete pipe remain the sole type in Group A; however, it notes that aluminum alloy pipe (and aluminum-coated steel pipe) could prove with further experience that they could move up into Group A.

9.18 West, A., K. Williams, and P. Carrol, "Performance Guidelines for Buried Aluminum Structural Plates Structures", Report Number 09-2014, Presented at the Transportation Association of Canada Annual Conference & Exhibition, Montreal, QC,2014.

This report was prepared as a supplementary handout during a poster presentation at the 2014 Transportation Association of Canada Annual Conference and Exhibition and was provided to the research team by Kevin Williams of Atlantic Industries Limited when the research team was interviewing Mr. Williams for the stakeholder survey phase of this research project. Points relevant to the WHRP aluminum culvert policy and performance research are as follows:

- The introductory paragraph notes, "Although aluminum structural plate has been in the marketplace for over 50 years, few best practice guidelines exist in the public domain and little detailed information exists in the Canadian Highway Bridge Design Code."
- It identifies aluminum structural plate as being first developed in 1962 and made from alloy 5052-H141.
- It identifies aluminum as unique "in that it protects itself from aggressive environments with a self-healing oxide when exposed to atmosphere or any oxygen carrying environment. The oxide is dense, resists mars and scratches due to its hardness, and adheres well to the underlying aluminum."
- Table 1, reproduced here from the accompanying poster, provides a literature review of environmental parameters and abrasion limitations for aluminum structural plate (alloy 5052-H141) and aluminum pipe (alloy 3004-H32) structures.

Environmental Parameters & Abrasion Limitations

Organization	pH	Resistivity of soil, backfill or effluent Ω-cm	Flow Velocity ft/s (m/s)	Bedload Characteristics & Special Notes
FHWA* & TxDOT*	4 - 9	≥ 500		≥ 25 Ω-cm when backfill is free-draining or saltwater applications
Aluminum Association	4 - 9	≥ 500		≥ Expect good performance in sea water (~ 35 Ω-cm) when surrounding soil is clean
Kaiser Aluminum Corp.*	4 - 9	≥ 1,500	≤ 10 (3.0)	Flows containing large bedload; sandy bedload allows for higher velocities
US Military Specification	4 - 9	—		Even in seawater applications
ODOT*	4.5 - 10	≥ 1,500		
MTO*	4.5 - 9	≥ 200	≤ 5 (1.5)	If buried with free draining backfill material, resistivity is permitted to be as low as 25 Ω-cm; Minor bedloads of sand and gravel
US Army Corps, Crane Materials Int. & Alcan Inc.	4 - 9	—		Recommended against use in non-draining clay-organic soils
FDOT*	5 - 9	≥ 1,000	≤ 8 (2.4)	Moderate bedload volumes of sand and gravels; 1.5 in. (3.8 cm) max
Caltrans*	5.5 - 8.5	≥ 1,500	≤ 5 (1.5)	Abrasive channel materials
Highway Design Manual*	5.5 - 8.5	≥ 1,500	≤ 8 (2.4)	Bedloads of sand, silts or clays regardless of volume

*Note: *Information pertains to aluminum CMP (AA3004-H32) not aluminum structural plate (AA5052-H141). AA5052 is a superior aluminum alloy with respect to hardness, impact and abrasion resistance. Maximum recommended flow velocities and bedload characteristics are based on no metal loss; flow velocity and/or bedload can be greater if abrasion counter measures are considered (i.e. sacrificial thickness added, abrasion plates, invert paving, etc.)*

- Table 2, reproduced here, provides a comparison of mechanical properties of alloy 3004-H32 (aluminum pipe) and alloy 5052-H141 (aluminum structural plate), with reference to the accompanying ASTM standards (ASTM B209 for sheet and plate used to produce aluminum pipe, and ASTM B746 for structural plate).

	Density (g/cm^3)	Hardness (Brinell)	Tensile Strength (MPa)	Yield Strength at 2% Offset (MPa)	Shear Strength (MPa)
AA3004-H32[11]	2.72	52	≥ 190	≥ 145	≥ 120
AA5052-H141[12]	2.68	60	≥ 235	≥ 165	≥ 140

- After presenting alloy composition for alloys 3004 and 5052, the paper notes the 5000-series alloys have a greater percentage of magnesium, which increases strength, hardness, and strain-hardening ability. It notes that the hardness and strength characteristics of alloy 5052 allow aluminum structural plate to better resist impact, wear, and abrasion, when compared to aluminum pipe made from alloy 3004. It also notes that the presence of chromium in alloy 5052 improves the corrosion resistance of the alloy over alloy 3004, which does not have chromium as an alloying element, since the chromium helps form a corrosion-resistant oxide and also contributes to hardness.

- The authors performed field inspections of six aluminum structural plate structures across New Brunswick, Canada, with ages ranging from 10 to 22 yrs, and usages ranging from culverts in residential neighborhoods, highway culverts with concrete baffled inverts to promote fish passage, to tidal flow culverts under the TransCanada Highway. The inspection team rated the culverts in accordance with Item 62, Culverts, of the U.S. FHWA's Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (1995). The six structures were rated 8 or better, with a rating of 8 corresponding to "No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift." Data for the six structures is summarized in a table, including year installed, water chemical properties, and ratings. Of note, the oldest structure, installed in 1992, is a round structure with aluminum invert that had water with the lowest resistivity of 111 Ω-cm and water pH of 7.2, with a structure rating of 8. Aside from one water resistivity measurement of 5,945 Ω-cm, all other sites had water with resistivity greater than 25 kΩ-cm.

- The paper gets into a discussion of service life of aluminum structural plate, indicating it is dependent environmental factors including primarily pH, resistivity, and abrasion, giving reference to a Florida Department of Transportation first perforation corrosion model represented by the following equation:

$$SL = \frac{T_p}{R_{pH} + R_r}$$

Where:
SL = service life; time to first perforation (yrs)
T_p = thickness of plate (in.)
R_{pH} = Corrosion rate for pH (in./yr)
R_r = Corrosion rate for resistivity (in./yr)

The corrosion model is presented in Cerlanek, W.D., and R.G. Powers, "Drainage Culvert Service Life Performance and Estimation," State of Florida Department of Transportation, State Materials Office, Corrosion Research Laboratory, 1993. Tables for the pH and resistivity localized corrosion rates are presented in inches per year of section loss.

- Regarding fasteners, the paper identifies hot-dip galvanized bolts as the preferred fasteners since they offer superior strength and installation benefits over aluminum bolts; however, aluminum bolts, made from an appropriate alloy, are recommended in high chloride (> 250 ppm) environments based on Corrugated Steel Pipe Institute of Canada Technical Bulletin Issue 13, 24 October 2011. It also notes austenitic stainless steel fasteners may be an alternative to aluminum fasteners where higher strengths are needed, citing the commentary to the Canadian Highway Bridge Design Code, CAN/CSA-26-06 (2014).

- Regarding contact with concrete, the paper identifies that aluminum must be [electrically] isolated from contact with concrete if any of the following are true: (1) steel reinforcement is embedded in the concrete, whether electrically connected or not, (2) deicing salts will be applied in the vicinity, (3) calcium chloride is contained in the concrete mix, or (4) the structure is in or near salt water. It cites an Ontario Ministry of Transportation document that identifies two methods of providing electrical isolation: the first being to coat reinforcement with bitumastic material to isolate the dissimilar metals, and the second being to separate aluminum from concrete using nylon, neoprene, or bitumastic materials.

APPENDIX B

Aluminum Culvert Stakeholder Survey

Date: 5 April 2018

From: Jesse L. Beaver (JLBeaver@sgh.com)
Brent J. Bass (BJBass@sgh.com)
Simpson Gumpertz & Heger, Inc.

Subject: Aluminum Culvert Policy and Performance Survey

INTRODUCTION

Simpson Gumpertz & Heger Inc. (SGH) is undertaking research on behalf of the Wisconsin Highway Research Program (WHRP) regarding policy and the performance of aluminum culverts. Wisconsin Department of Transportation (WisDOT) policy prohibits the use of aluminum box culverts and limits corrugated aluminum pipe to locations with ADT < 1,500 and side drains (and only through the use of a project special provision). The reasoning behind the limited use follows failure of an aluminum pipe culvert in the 1990s and subsequent discovery of severe corrosion along the soil side of the crowns of several aluminum culverts, near the centerline of the roadway. SGH's research task is to review current policies, best practices, and the performance of aluminum culverts either to reaffirm the current WisDOT policy or to provide recommendations to update WisDOT policy based on sound engineering and the current state of practice.

As part of the research, we are tasked with performing a stakeholder survey. The WHRP research project number is 0092-17-05, and the project is scheduled for completion at the end of 2018. The results of the survey and policy recommendation will be included in the final report, which will be available from WHRP following the completion of the project.

Please review the following questions in preparation for our call. We will record your answers in the call, and you may also key them into the document below and send the completed survey back to us. We appreciate your willingness to participate in this survey.

SURVEY QUESTIONS

Note: some questions may not be applicable to your work.

1. Describe your position within your agency and division, and the responsibilities of the division for which you work.

2. Are metal pipe/culverts currently allowed in your jurisdiction? Are aluminum pipe/culverts currently allowed in your jurisdiction?

3. Have aluminum and/or metal pipe/culverts been used historically in your jurisdiction?

4. Four-part question as follows:

A. Does your jurisdiction have a policy limiting the use of metal culverts based on site conditions such as site soil resistivity, pH, stream abrasion classification, type of roadway, traffic volume, pipe size, or any other factor related to corrosion or abrasion?
B. Are there specific limits for the use of aluminum pipe/culverts?
C. If yes for 4B, what are the limits?
D. Is your policy located in one of your design manuals or other documents that we can access?

5. Does your agency maintain policies or have any past research related to the use of aluminum pipes/culverts or aluminum used for any other buried applications?

6. Does your agency maintain an inventory of pipe/culverts (records to identify structure by size, material, location, and other characteristic) that would allow identification of aluminum pipe/culverts?

7. Five-part question as follows:

A. Does your agency conduct pipe/culvert inspections? Does your agency maintain pipe/culvert inspection records? If yes, please address the following follow-on questions.
B. Are there inspection records available for aluminum culverts in your jurisdiction?
C. In general, how long have the structures with inspection records been in use and how are they performing?
D. Does the inspection process require checking the condition of the pipe/culvert interior side at the crown of the culvert at mid-length (under the centerline of the roadway), and do the inspection records document this in writing and/or photos?
E. If inspection records are available, can you provide (by email, ftp, etc.) one or two records, preferably from culverts that have been in service for at least 25 yrs?

8. Is there information available about the alloys historically used for aluminum culverts in your jurisdiction? Do current or historical specifications within your jurisdiction for the use of aluminum pipe/culverts specify alloys, coatings, or other product information?

9. Are you aware of any current projects being developed, out to bid, or under construction that will use aluminum pipe/culverts?

10. Does your agency have any special details or requirements (coatings, membranes, minimum fill height, other installation details) to isolate aluminum pipe/culverts from contact with deicing chemicals that may permeate downward through the pavement and soil?

11. Are metal and/or aluminum <u>box culverts</u> allowed in your jurisdiction? Are they used?

12. Are metal and/or aluminum buried bridges (three-sided structures typically founded on reinforced concrete foundations and constructed from structural plate sections bolted together) allowed in your jurisdiction? Are they used?

13. Are you aware of any policy changes or other efforts to disallow or introduce aluminum buried structures in your jurisdiction?

14. What methods are used, if any, to predict aluminum pipe/culvert service life?

15. Have you heard anecdotally of any performance benefits or detrimental performance issues related specifically to aluminum pipe/culverts? If so, please elaborate.

16. Given the scope of this research as you understand it, do you have further information that would be of use to the research team (e.g., relevant technical literature)?

17. Can you recommend additional contacts for this survey from within or outside your agency?

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APPENDIX C

Wisconsin and FHWA Aluminum Culvert Inventory Data

PRESENTATION OF ALUMINUM CULVERT DATA FROM WISDOT HSIS DATABASE

The following pages present twelve figures that summarize data extracted from the Wisconsin DOT Highway Structures Information System (HSIS) database in July 2018. Data are presented for a total of fifty-three aluminum culverts that were identified when the search term "aluminum" was entered into the database. Fifty-five results were returned, but two of the returned structures are specifically identified as galvanized steel, and those two structures have been excluded from the summary. The structures contained in the database are generally built from aluminum structural plate. There are many smaller-diameter corrugated aluminum pipes in service in Wisconsin; however, the smaller pipes are not typically captured in the HSIS inventory.

Note that some culverts have missing data from one or more fields, so histograms do not always have the same total number of culverts.

CORROSION LEVELS IN FIGURES

We viewed photos in the most recent PDF field inspection reports from the HSIS database. We compared the photos to lengths and descriptions of corrosion reported in the inspection reports and assigned levels of corrosion to each culvert as: No Corrosion, Minor Corrosion, or Significant Corrosion. These corrosion levels are identified as:

- **No corrosion (39 of 53 culverts)**: No level of corrosion was noted in the inspection report.

- **Minor corrosion (8 of 53 culverts)**: Includes minor corrosion of bolts, localized/small areas of corrosion on barrel, minimal spread of surface corrosion/staining, etc. Corrosion is not (expected to be) structurally significant at the time of inspection.

- **Significant corrosion (2 of 53 culverts)**: Noted on two culverts with remedial action recommended based on the observed level of corrosion. The two culverts with significant corrosion are two of the lowest-rated culverts in the National Bridge Inventory (NBI).

Low NBI ratings can be based on other system component condition, such as headwall condition, barrel alignment, etc., so it is possible to have a low rating for a culvert with no corrosion, though culverts identified with significant corrosion do have the lowest ratings in this inventory subset.

OVERALL CONCLUSIONS BASED ON FIGURES

- **Geographic Distribution (Figure C.1):** The geographic distribution of culverts with no corrosion, minor corrosion, and significant corrosion appears to be random, with no particular geographic region appearing to have a higher likelihood of corroded aluminum culverts.

- **Span (Figures C.2 and C.3):** The data show small correlation between corrosion level and culvert span. Both culverts with significant corrosion and most culverts with minor corrosion had spans of 13 ft or less, and only two of the twenty-three culverts with spans greater than 13 ft were identified as having corrosion, both of which had minor corrosion.

- **Age (Figures C.4 and C.5):** Older structures generally show more corrosion. The two culverts with the most significant corrosion are in the middle range of ages of culverts from the database (20 to 40 yrs). The data are unclear whether any of the oldest culverts have been rehabilitated or replaced.

- **Fill Depth (Figures C.6 and C.7)**: All culverts in the database have shallow fill depths (60 in. maximum), and all culverts with corrosion noted have fill depths between 14 and 51 in. Note that two culverts are reported as having 0 in. fill depths in the inspection data.

- **Length (Figures C.8 and C.9)**: Reported barrel lengths ranged from 22.7 to 130.5 ft, with an average of 57.7 ft and median of 50.0 ft. Barrel lengths in the 60 to 80 ft range appear to be more likely to have minor or significant corrosion, as shown in Figure C.9. However, it is unclear if barrel length is consistently reported as the length of individual barrels of multi-barrel culverts or the total length of all barrels. Culverts with greater road width do tend to have greater barrel length (both as reported and when normalized by number of barrels), but there is not a clear trend when comparing barrel length or normalized barrel length with fill depth.

- **Average Daily Traffic (ADT, Figure C.10):** The data do not appear to show a significant correlation between corrosion level and ADT. This is surprising, considering the likelihood for increased use of deicing salts and chemicals on roadways with higher ADT.

- **Pavement Cracking (Figures C.11 and C.12):** The data show increased corrosion in culverts where the pavement condition was noted as cracked in culvert inspection reports. The data do not provide pavement history, preventing direct correlation of pavement condition over time with levels of corrosion.

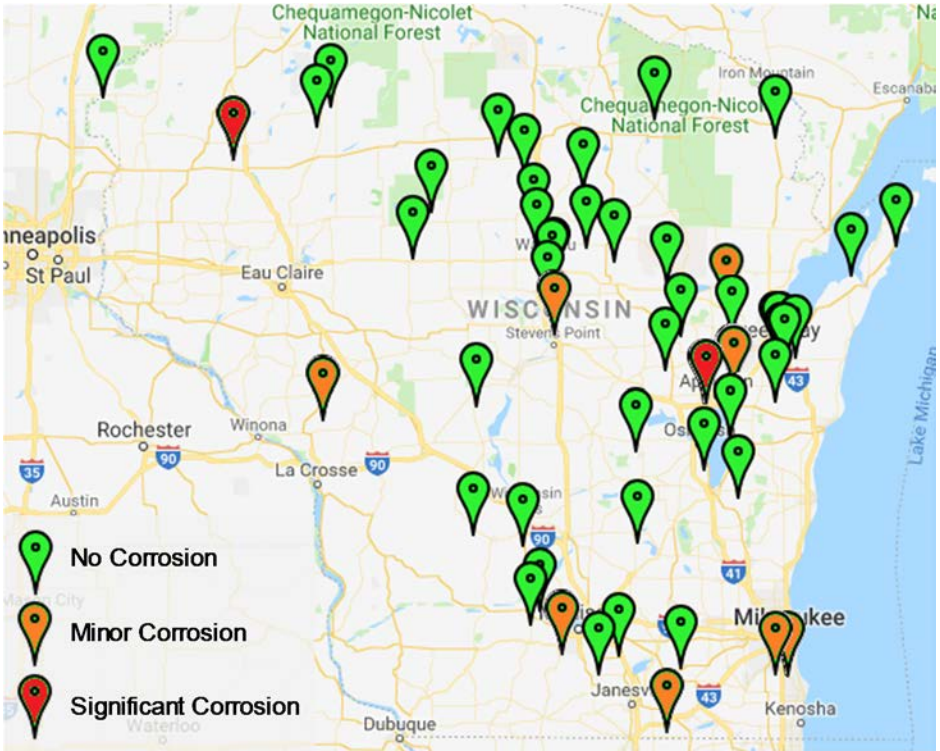


Figure C.1

Geographic distribution of aluminum culverts in Wisconsin HSIS database with corrosion level based on review of most-recent inspection report.

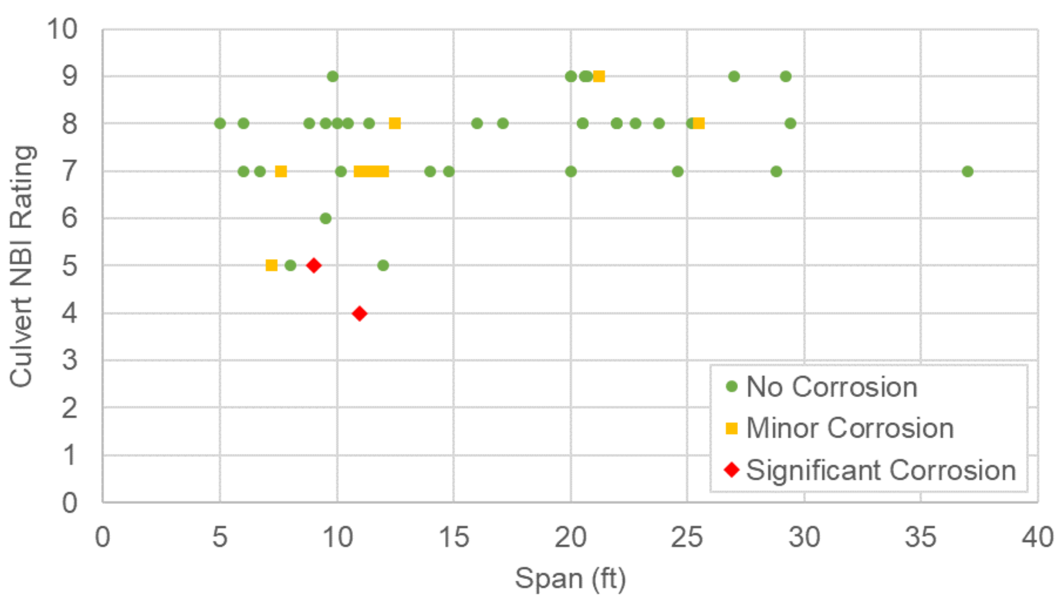


Figure C.2

Culvert NBI rating vs. span with corrosion level based on review of most-recent inspection report.

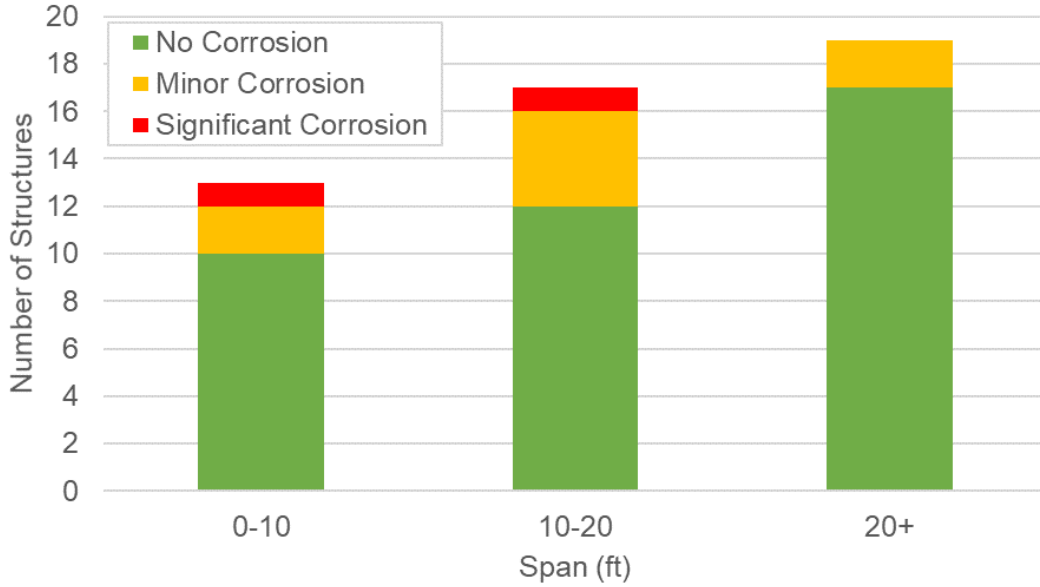


Figure C.3

Histogram of culvert spans with corrosion level based on review of most-recent inspection report.

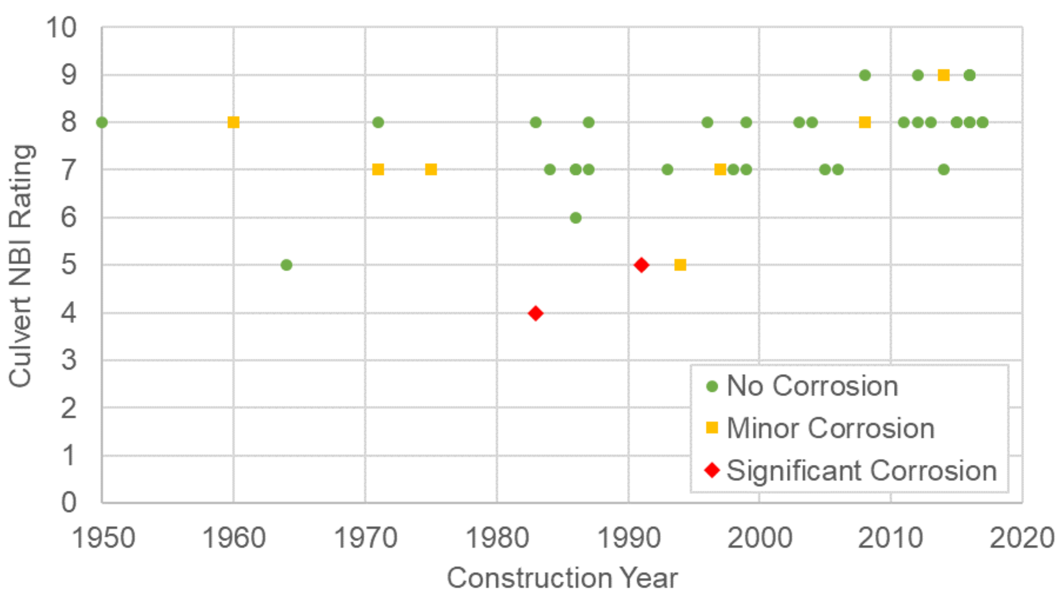


Figure C.4

Culvert NBI rating vs. construction year with corrosion level based on review of most-recent inspection report.

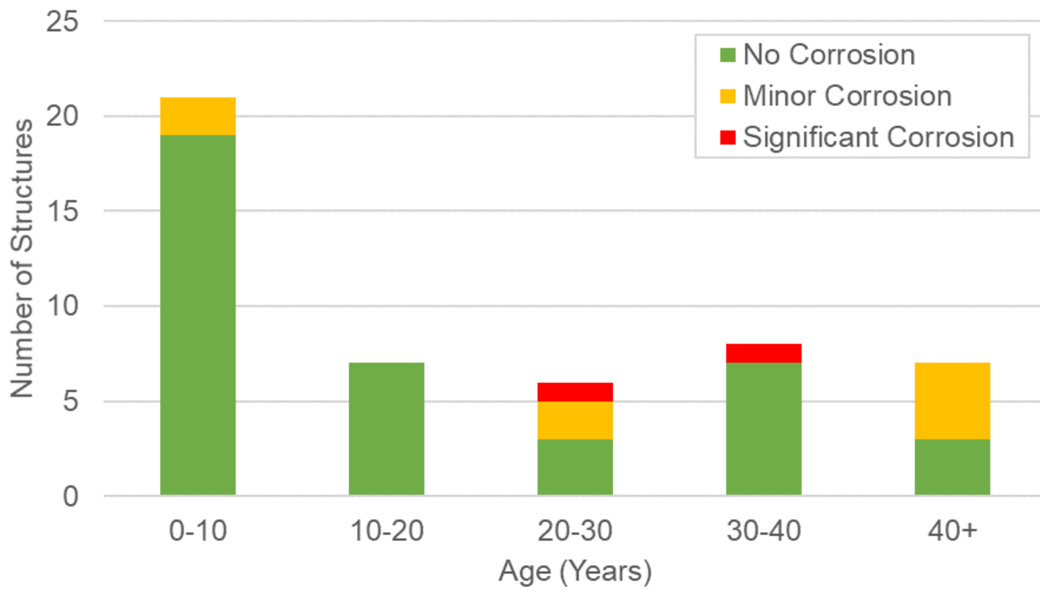


Figure C.5

Histogram of culvert ages with corrosion level based on review of most-recent inspection report.

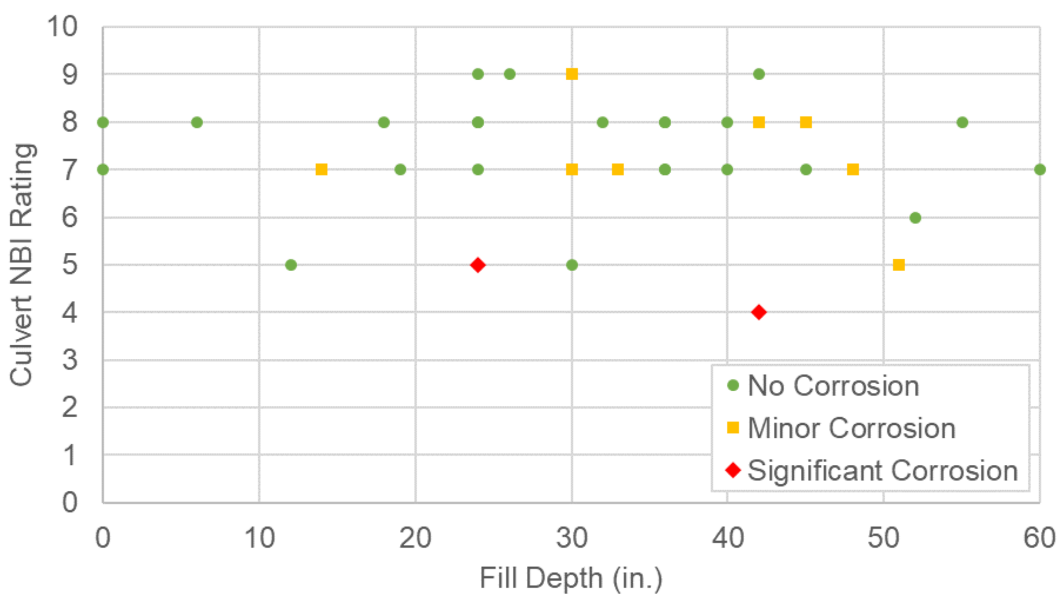


Figure C.6

Culvert NBI rating vs. fill depth with corrosion level based on review of most recent inspection report.

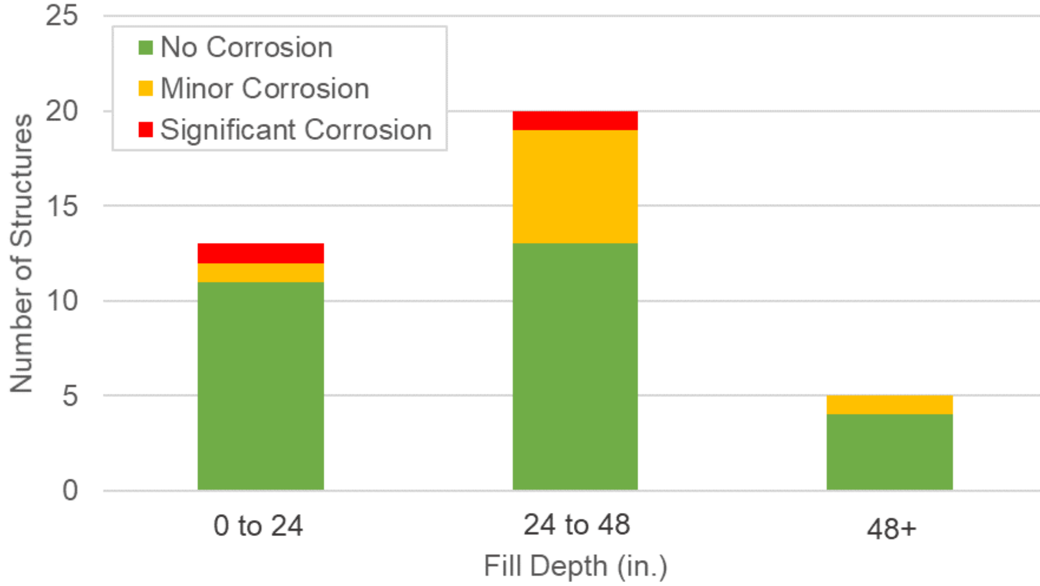


Figure C.7

Histogram of culvert fill depth with corrosion level based on review of most-recent inspection report.

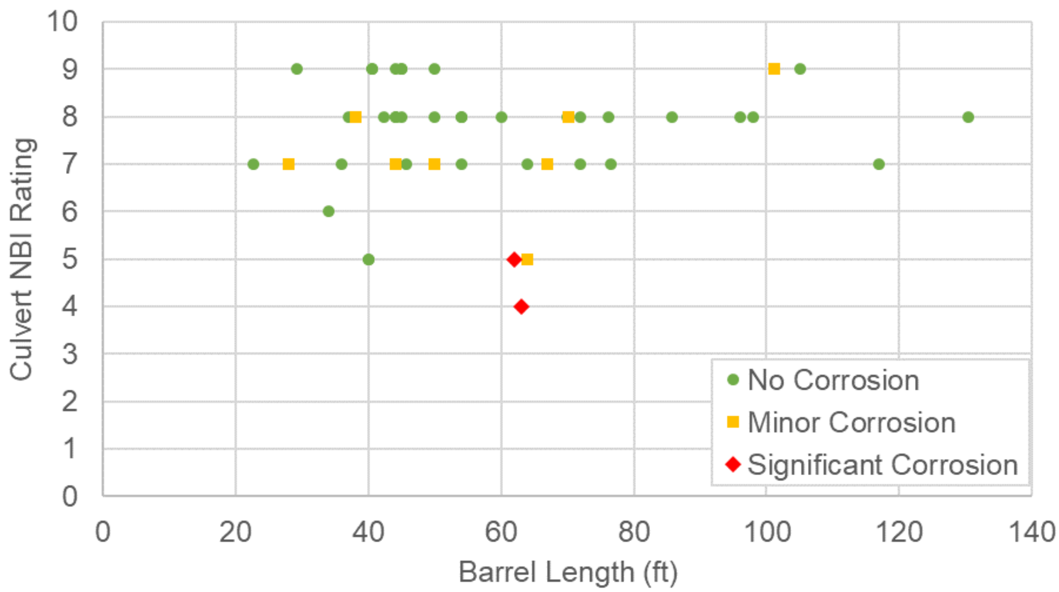


Figure C.8

Culvert NBI rating vs. barrel length with corrosion level based on review of most-recent inspection report.

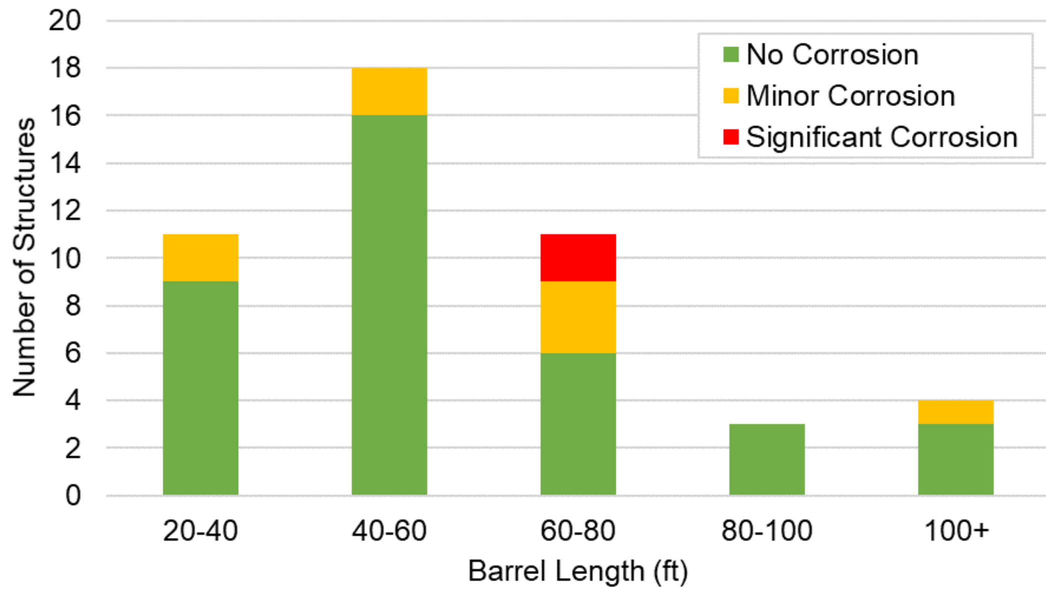


Figure C.9

Histogram of barrel length with corrosion level based on review of most-recent inspection report.

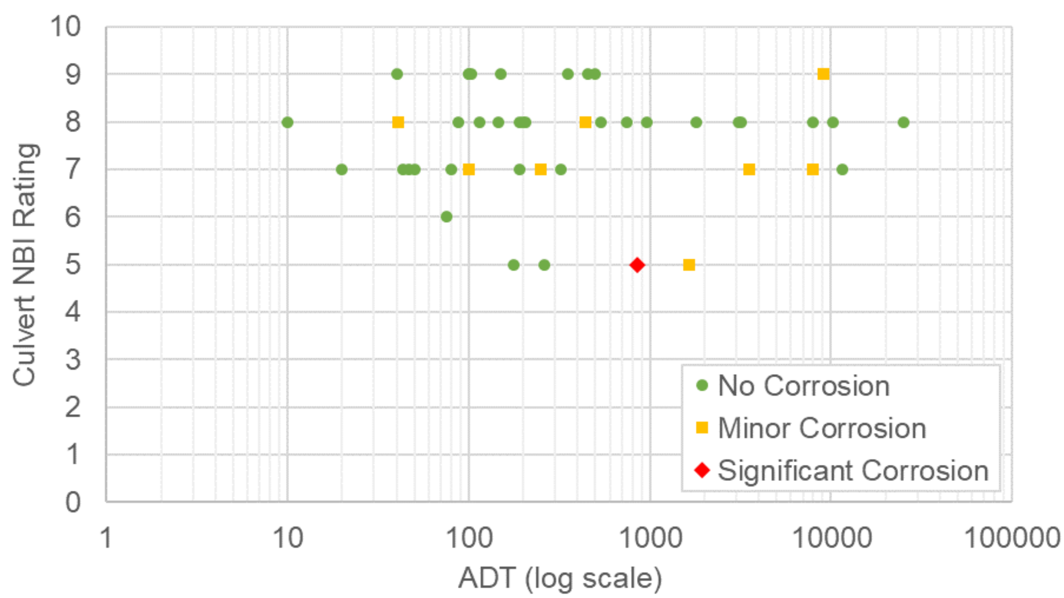


Figure C.10

Culvert NBI rating vs. ADT (log scale) with corrosion level based on review of most-recent inspection report.

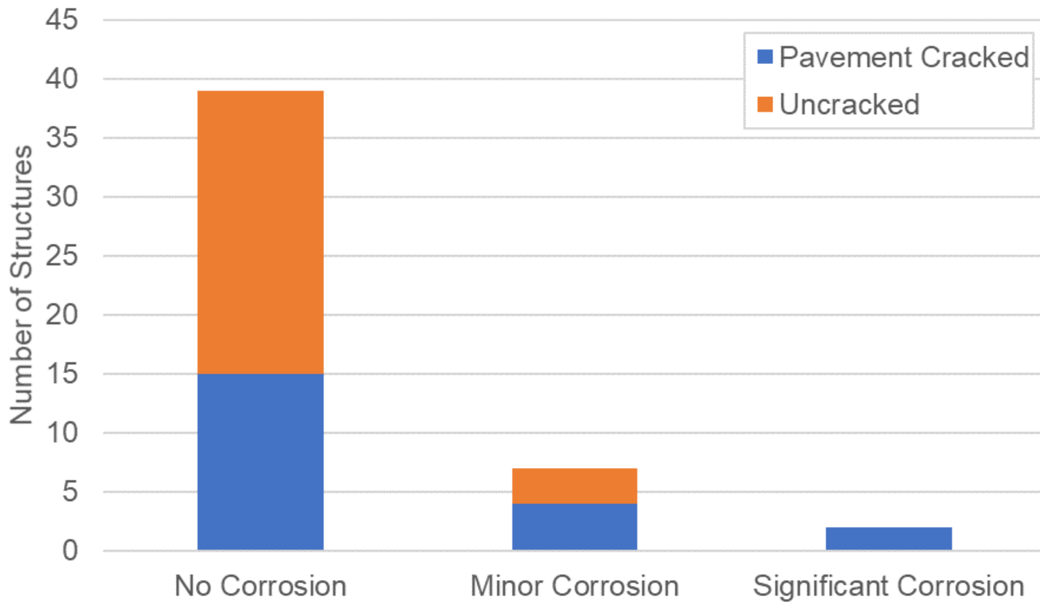


Figure C.11

Histogram of culvert corrosion level and identification of cracked or uncracked pavement both based on review of most-recent inspection report.

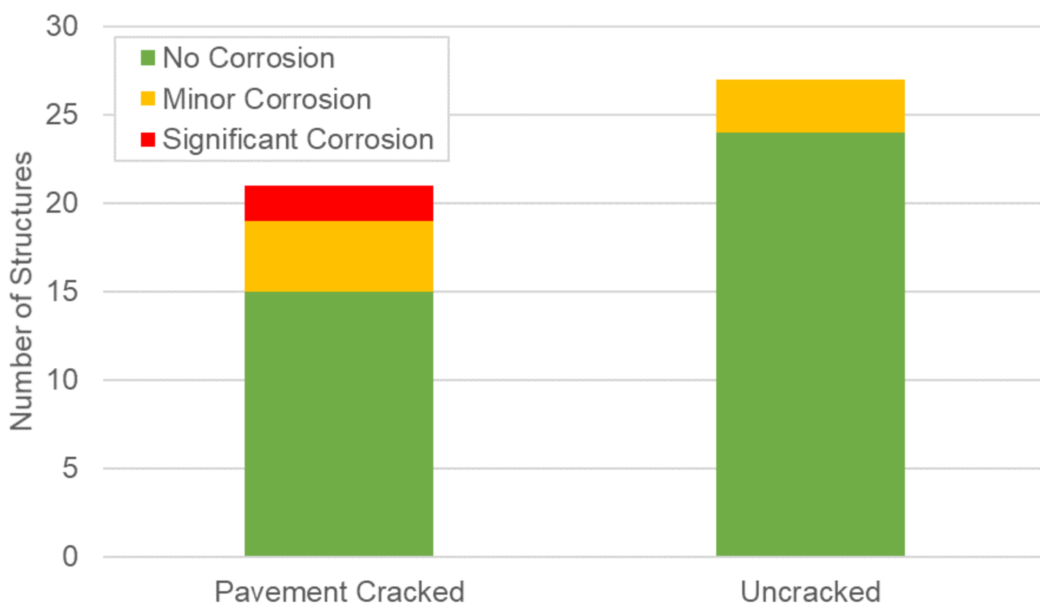


Figure C.12

Histogram of culverts identified with cracked or uncracked pavement with corrosion level based on review of most-recent inspection report.

PRESENTATION OF ALUMINUM CULVERT DATA FROM NORTH-CENTRAL INSPECTIONS

The following pages present seven figures based on North-Central District Inventory (NCI) inspection data provided by Wisconsin DOT in July 2018. Data presented are for a total of 204 aluminum culverts, primarily round, with spans ranging from 1.5 ft to 5 ft.

Note that some culverts have missing data fields, so histograms do not always have the same total number of culverts.

CORROSION RATINGS IN FIGURES

The data provided rate the roadway, cracking, and corrosion condition of each culvert on a scale from 1 – 4, as defined in the Wisconsin DOT Structure Inspection Manual (Part 4 Ancillary Structures, Chapter 3 Small Bridges).

- **Condition State 1**: Good. No corrosion.
- **Condition State 2**: Fair. Minor surface corrosion, light bolt corrosion.
- **Condition State 3**: Poor. More advanced corrosion, significant section loss.
- **Condition State 4**: Severe. Significant corrosion, near complete section loss.

OVERALL CONCLUSIONS BASED ON FIGURES

- **Geographic Distribution (Figure C.13):** The geographic distribution of corroded culverts appears to be random, with no particular geographic region appearing to have a higher likelihood of corroded aluminum culverts.
- **Span (Figure C.14):** Almost all culverts in the NCI data (94%) have a span of 3 ft or less. For this small range of spans, there is no significant correlation between span and level of corrosion. None of the larger spans, greater than 4 ft, are severely corroded, but there are only 9 culverts of this size in the data (4% of total).
- **Fill Depth (Figure C.15):** There does not appear to be a strong correlation between fill depth and corrosion rating.
- **Length (Figure C.16):** There does not appear to be a significant correlation between barrel length and reported corrosion rating. While the 50 to 70 ft range of barrel length has the greatest number of culverts with corrosion ratings of 3 and 4, this range also has the greatest number of culverts with a corrosion rating of 1.
- **Culvert Function (Figure C.17):** The reported function of the culvert (cross culvert or stream) does not have significant correlation with the reported corrosion rating.
- **Pavement Cracking (Figures C.18 and C.19):** There is no significant correlation between roadway rating and corrosion rating. However, culverts with higher corrosion rating are more likely to have higher cracking rating. The discrepancy between roadway rating and cracking rating correlation may be due to other factors considered in roadway rating beyond pavement cracking.

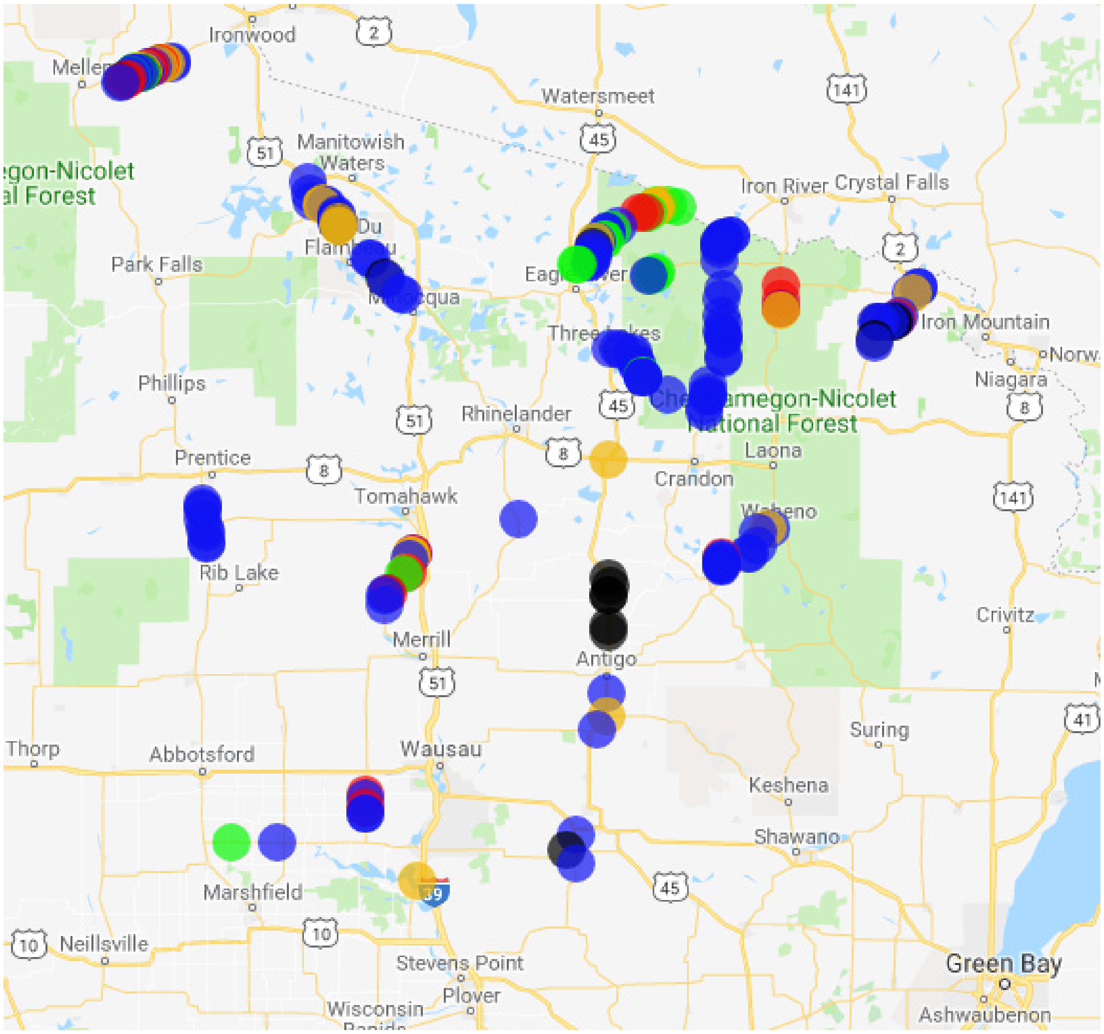


Figure C.13

Geographic distribution of aluminum culverts in Wisconsin NCI data with corrosion ratings of 1 to 4 shown as green, blue, orange, and red, respectively, and culverts with unknown corrosion ratings as black.

Reference: [https://mapmakerapp.com/ .](https://mapmakerapp.com/)

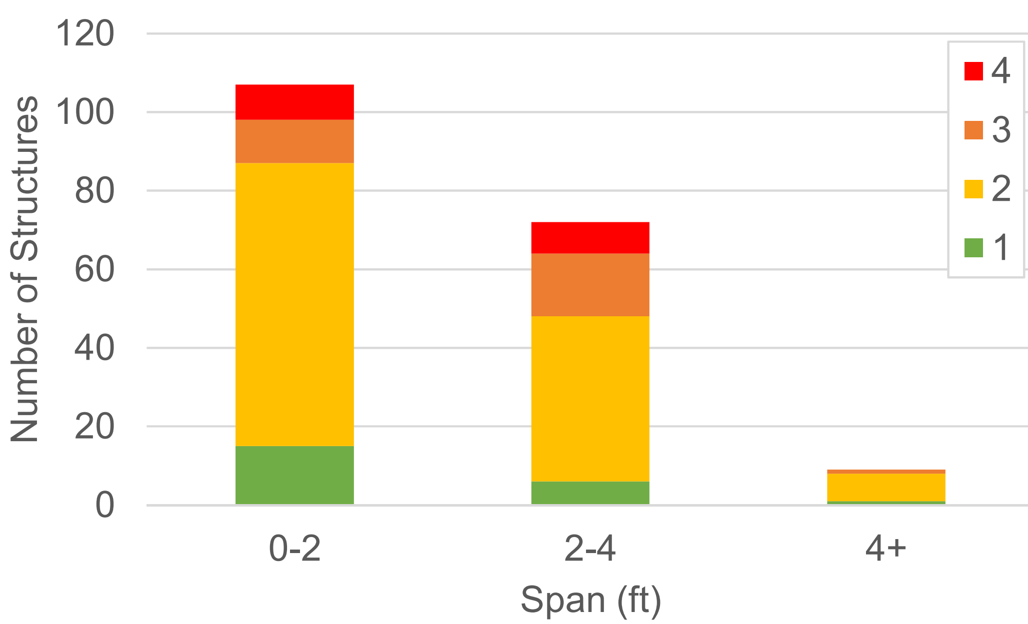


Figure C.14

Histogram of reported culvert span with reported corrosion rating.

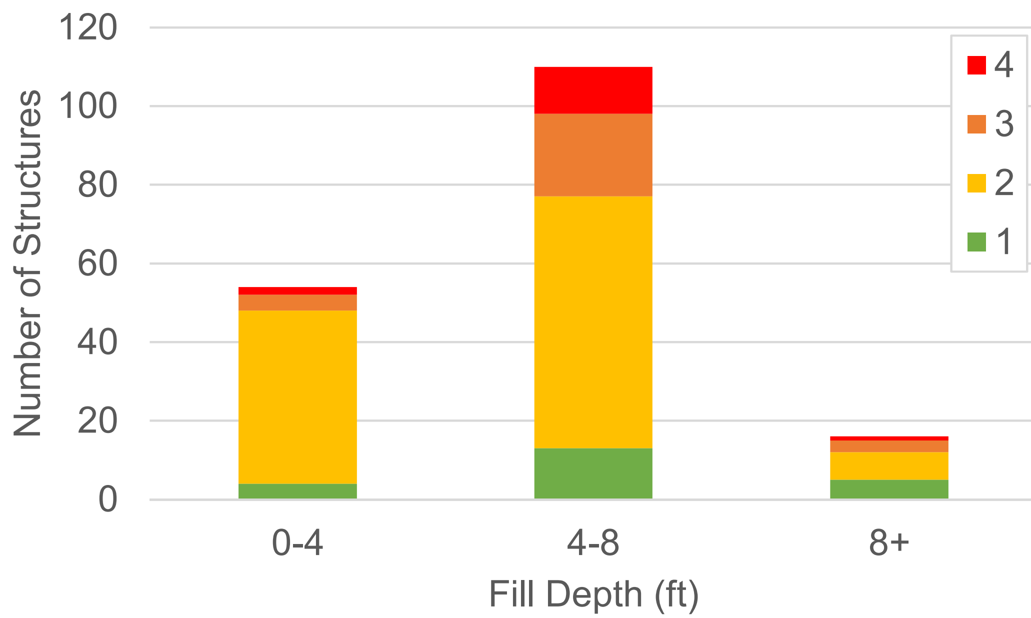


Figure C.15

Histogram of reported fill depth with reported corrosion rating.

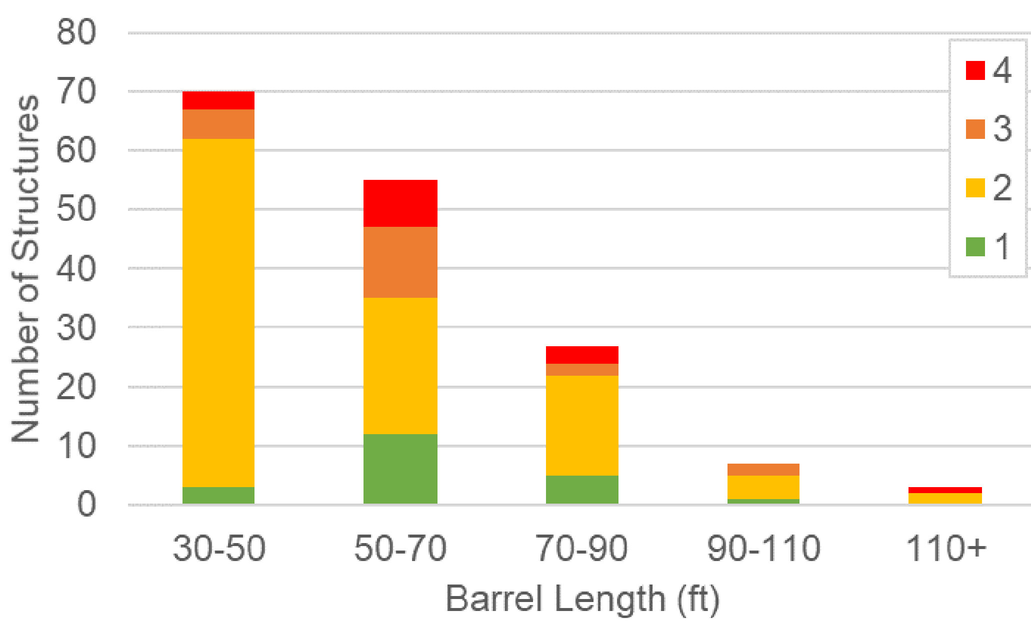


Figure C.16

Histogram of reported pipe length with reported corrosion rating.

Figure C.17

Histogram of reported pipe function with reported corrosion rating.

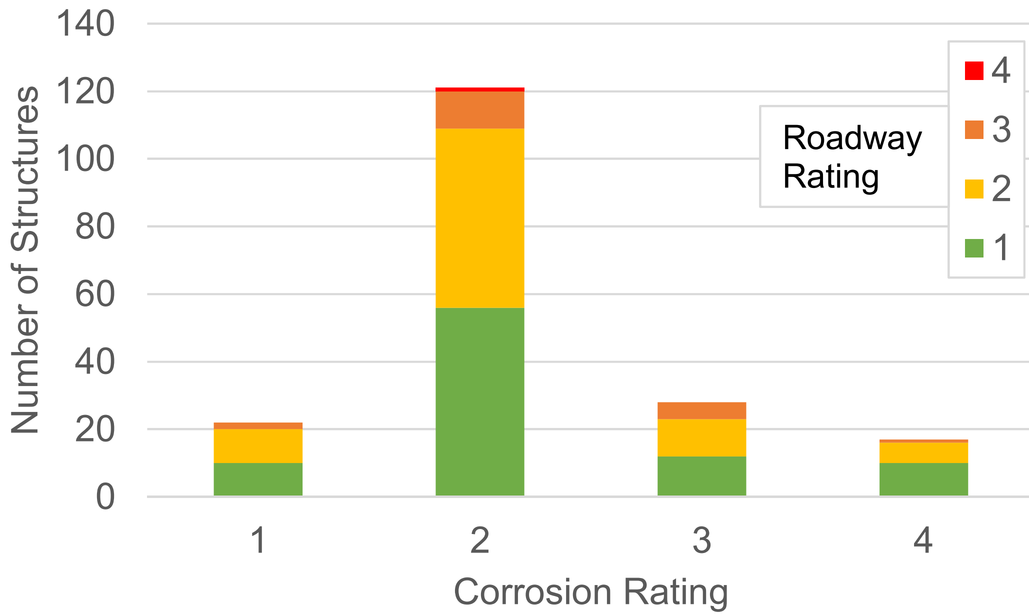


Figure C.18

Histogram of reported roadway and corrosion ratings.

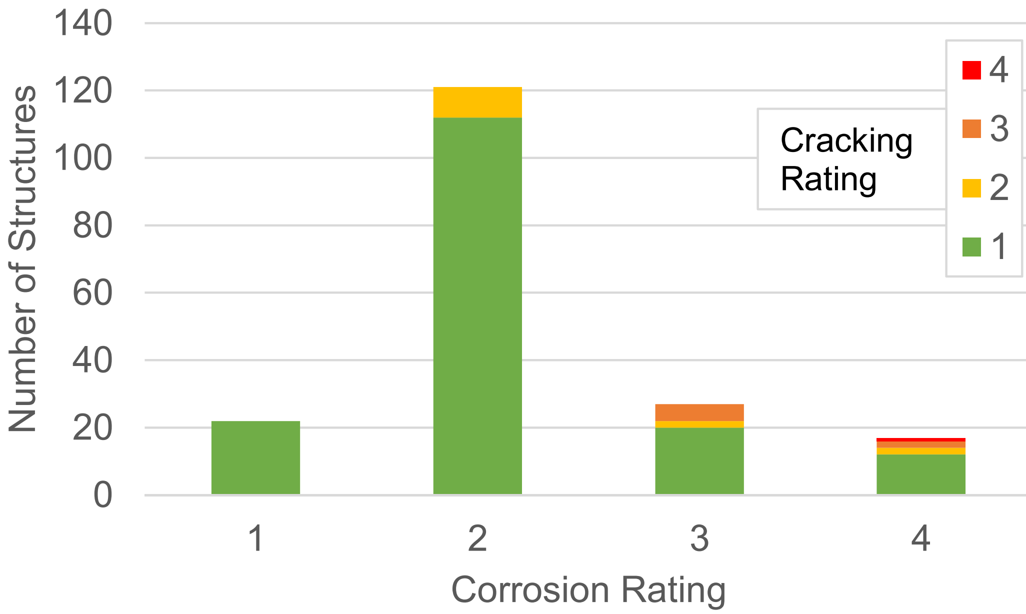


Figure C.19

Histogram of reported cracking and corrosion ratings.

PRESENTATION OF LIKELY ALUMINUM CULVERT DATA FROM LTBP DATABASE

We reviewed data from the FHWA Long-Term Bridge Performance (LTBP) InfoBridge database in October 2018. We focused our review on structures the met the combination of having "Aluminum, Wrought Iron or Cast Iron" populate the "Main Span Material" field in combination with "Culvert" populating the "Main Span Design" field. This combination gives 1,442 results. There was no field that separated aluminum from wrought or cast iron, so the data presented are limited to "aluminum, wrought iron, or cast iron" culverts, with a high likelihood that typical culverts in the database would be made from aluminum and not iron. We hereafter refer to these 1,442 structures as likely aluminum culverts.

The likely aluminum culverts in the database are spread geographically throughout the U.S. and have spans listed with a range from 0 to 22.7 m (0 to 74.5 ft).

We observed some discrepancies in different parts of the LTBP data itself, and with comparison of the LTBP data and data from the HSIS database for structures that appeared in both. Given the above discrepancies, the data and conclusions drawn from the data contained in the LTBP database for these likely aluminum culverts should be taken with some degree of skepticism, although we expect that given the number of structures the major trends should be captured.

The data we reviewed from the LTBP includes "structural evaluation" and "culvert" rating fields, with ratings that range from 1 to 9 and appear analogous to the National Bridge Inventory (NBI) rating system. In the NBI system, a rating of 9 is excellent condition, and a rating of 0 is failed condition. The "structural evaluation" and "culvert" rating data appear identical except that some structures do not have an entry for structural evaluation rating. We base our further analysis on culvert ratings and omit structural evaluation ratings.

Culvert ratings for the 1,442 likely aluminum culverts ranged from 3 to 9, with an average culvert rating of 6.9 and median of 7. Note that culverts may receive a particular rating for a variety of reasons, including corrosion, settlement, holes, wingwall or headwall deficiencies, scour, erosion, or other reasons. Observations specifically related to metal culvert barrels that may result in a particular culvert rating are identified in Table C1. Note that it is impossible to know from the data whether particular culverts received their rating based on barrel distress or corrosion or any of the other numerous factors identified above, as the database does not provide a direct indication of corrosion. The number of culverts versus culvert rating for the 1,442 likely aluminum culverts is plotted in Figure C.20. An LTBP database-generated map with average rating by state is shown in Figure C.21.

Table C1 – Metal Culvert Barrel Distress Observation and Corresponding Culvert Rating

Observed Distress in Metal Culvert Barrel[1]	Corresponding Rating[2]	Rating Description
Metal culverts have extreme distortion and deflection in one section, extensive corrosion, or deep pitting with scattered perforations.	3	Serious Condition
Metal culverts have significant distortion and deflection throughout, extensive corrosion, or deep pitting.	4	Poor Condition
Metal culverts have significant distortion and deflection in one section, significant corrosion, or deep pitting.	5	Fair Condition
Metal culverts have a smooth curvature, nonsymmetrical shape, significant corrosion, or moderate pitting.	6	Satisfactory Condition
Metal culverts have a smooth symmetrical curvature with superficial corrosion and no pitting.	7	Good Condition
No noticeable or noteworthy deficiencies that affect the condition of the culvert. Insignificant scrape marks caused by drift.	8	Very Good Condition
No deficiencies.	9	Excellent Condition

1. From the data presented, it is impossible to know whether metal culvert barrel distress or any other of a variety of factors such as scour or appurtenant deficiencies led to individual culvert ratings given in the data.
2. If metal barrel distress in the first column was observed in a culvert, the culvert's corresponding rating can be found in this column if no other culvert components would have resulted in a more deficient rating.

Given the above information, we group the culverts from the LTBP database as follows:

- **Low Rating (44 of 1,442 culverts):** Culvert rating of 3 to 4, serious to poor condition.
- **Medium Rating (390 of 1,442 culverts):** Culvert rating of 5 to 6, fair to satisfactory condition.
- **Good Rating (564 of 1,442 culverts):** Culvert rating of 7, good condition.
- **High Rating (444 of 1,442 culverts):** Culvert rating of 8 to 9, very good to excellent condition.

The geographic distributions of likely aluminum culverts in the LTBP database with culvert ratings classified as Low (red), Medium (orange), Good (yellow), and High (green) are superimposed based on their latitude and longitude on a equirectangular map of the U.S. is shown in Figure C.22.

The red and orange dots in Figure C.22, representing likely aluminum culverts with Low and Medium culvert rating, respectively, are scattered throughout the U.S. without any obvious correlation.

Although the LTBP database does not provide a direct indication of culvert corrosion, we checked for correlation between culvert rating and various metrics as described below. Overall conclusions from the available LTBP data for likely aluminum culverts include the following:

- **Geographic Distribution (Figures C.21 and C.22)**: The geographic distribution of likely aluminum culverts with Low, Medium, Good, and High Culvert Ratings appears to be random, with no particular geographic region appearing to have a higher likelihood of culvert distress.

- **Span (Figures C.23 and C.24)**: Excluding the fourteen likely aluminum culverts listed with spans of 0 m (0 ft), the remaining spans range from 0.6 to 74.5 ft., with an average of 21.0 ft and median of 22.0 ft. Considering this is a national database with many structures entered into the database because of federal NBI requirements, which require inventory and inspection data for bridge-length structures, it makes sense that the majority of structures are in the 20 to 30 ft span range. The data show no strong correlation between culvert rating and span. On a percentage basis, the distribution of colors in Figure C.23 appears relatively consistent between the four different groups. Figure C.24 does show that culverts with the lowest ratings (culvert rating of 3 or 4) all have spans of about 35 ft or less.

- **Age (Figures C.25 and C.26)**: Ages range from 1 to 118 yrs for these likely aluminum culverts, with an average age of 21.1 yrs and median of 20.0 yrs. Older structures generally show lower ratings, which is evident in both figures.

- **Length (Figures C.27 to C.29)**: Barrel lengths range from 20 to 600 ft, with an average of 30.4 ft and median of 24.9 ft. The proportions of low, medium, good, and high ratings on the histograms in Figures C.27 (lengths up to 60 ft) and C.28 (lengths greater than 60 ft) appear evenly distributed aside from the two structures listed with barrel lengths in the 140 to 180 ft range, which both have a culvert rating of 8. The distribution of culvert ratings by barrel length is shown in Figure C.29.

- **Average Daily Traffic (ADT, Figures C.30 and C.31)**: ADT ranges from 0 to 139,500 vehicles, with an average of 1,547 vehicles and median of 220 vehicles. The data shows that the lowest-rated structures also have relatively low ADT. Figure C.28 provides an adjusted scale limited to a maximum ADT of 10,000; this figure shows that the majority of the culverts with lowest ratings have 2,000 or less vehicles ADT. This is surprising, considering the likelihood for increased use of deicing salts and chemicals on roadways with higher ADT.

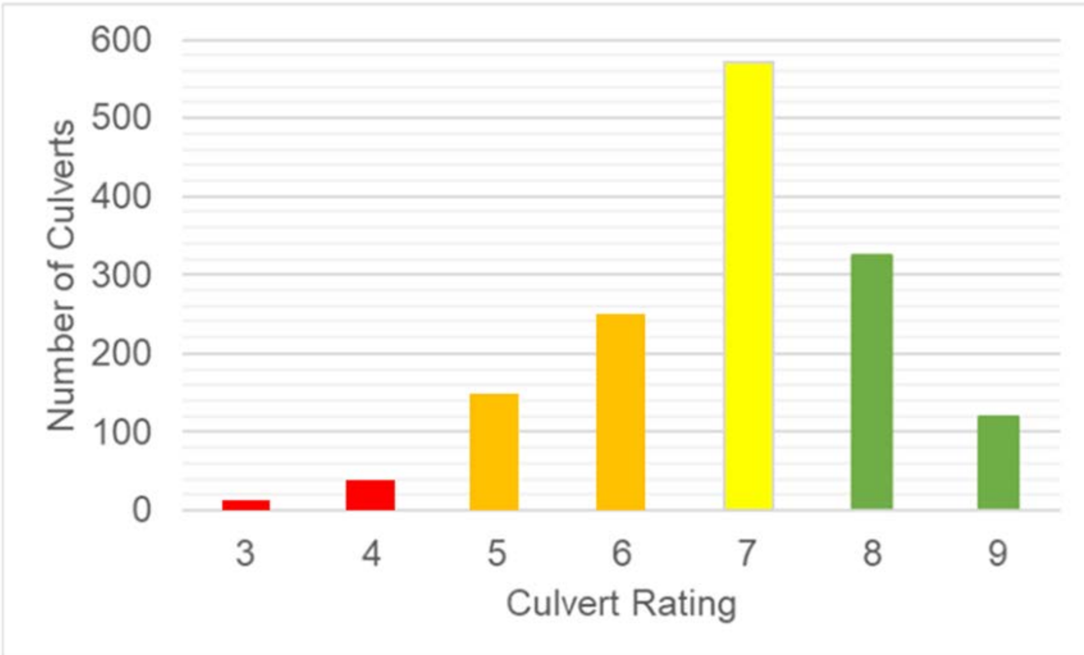


Figure C.20

Number of likely aluminum culverts in LTPB database by culvert rating.

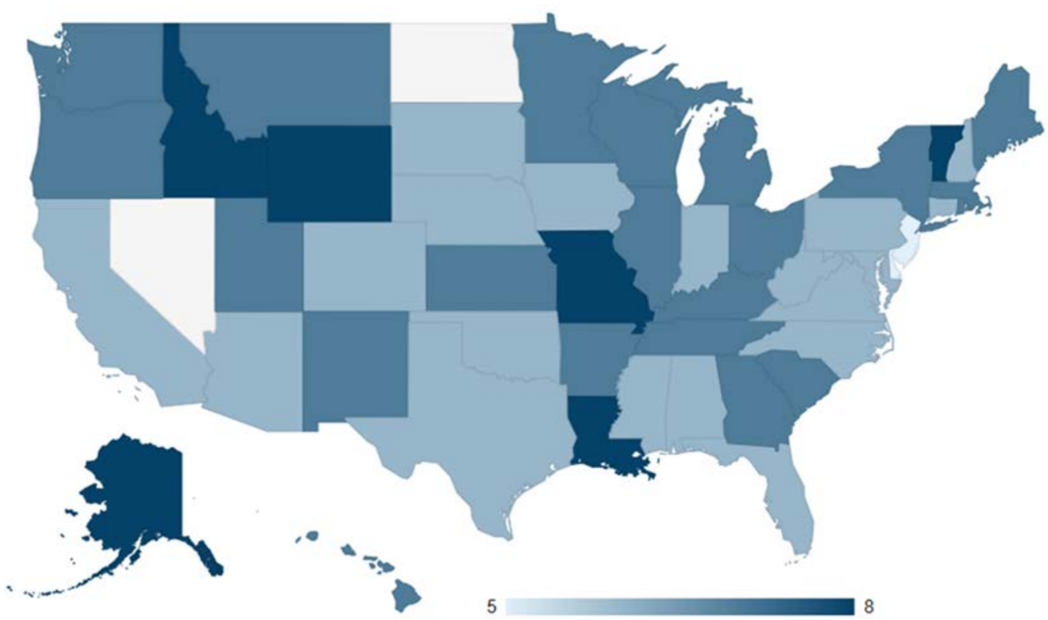


Figure C.21

FHWA LTBP database map for average culvert rating by state of likely aluminum culverts (darker shading is more favorable rating).

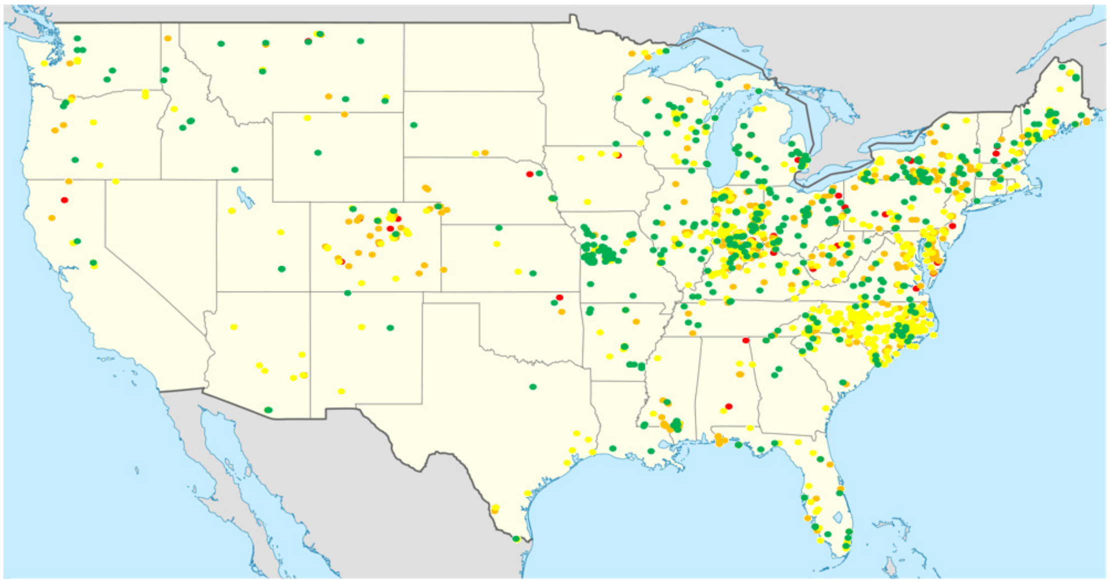


Figure C.22

Geographic distribution of likely aluminum culverts in LTBP database with low, Medium, Good, and High culvert condition ratings.

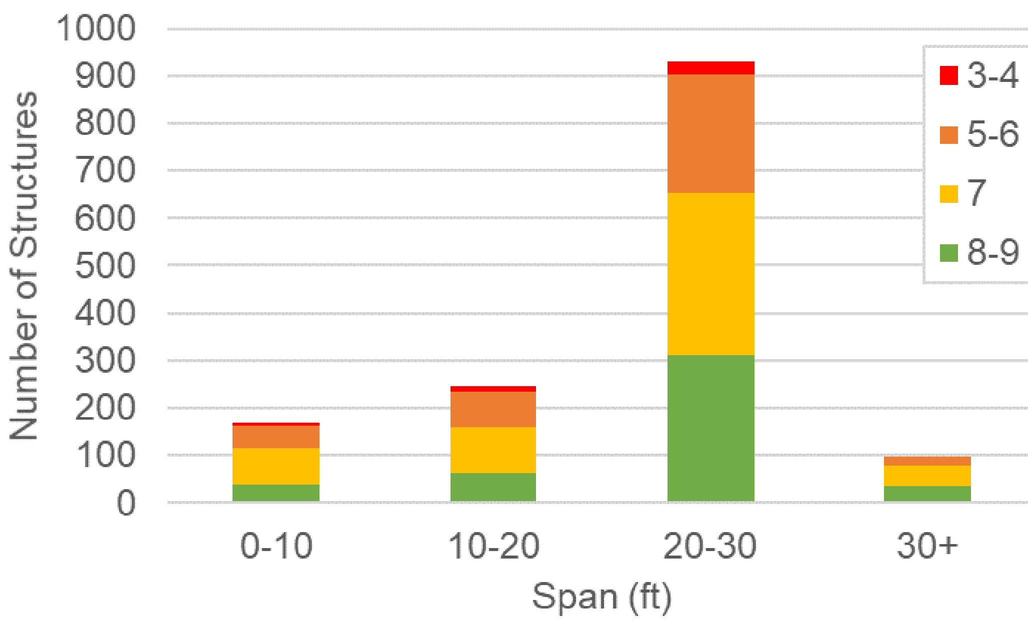


Figure C.23

Histogram of span with culvert rating.

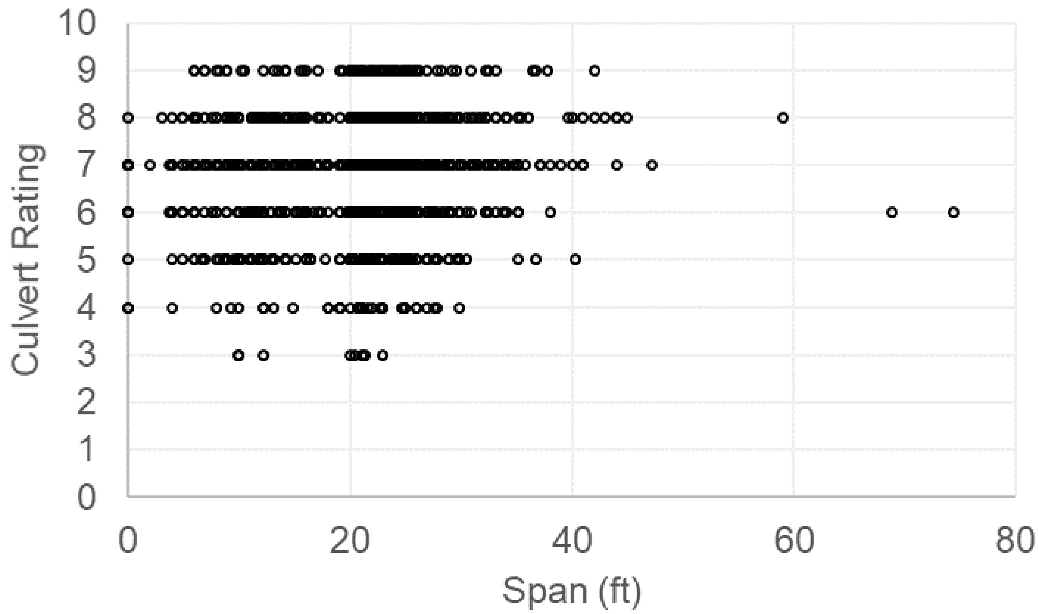


Figure C.24

Culvert Rating vs. Span.

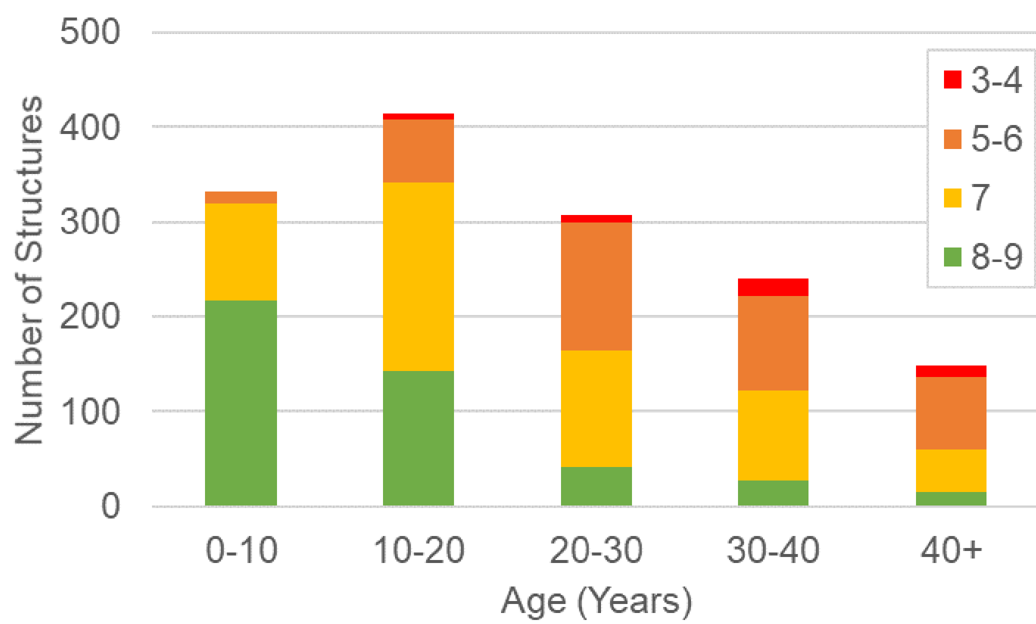


Figure C.25

Histogram of age with culvert rating.

Figure C.26

Culvert rating vs. construction year.

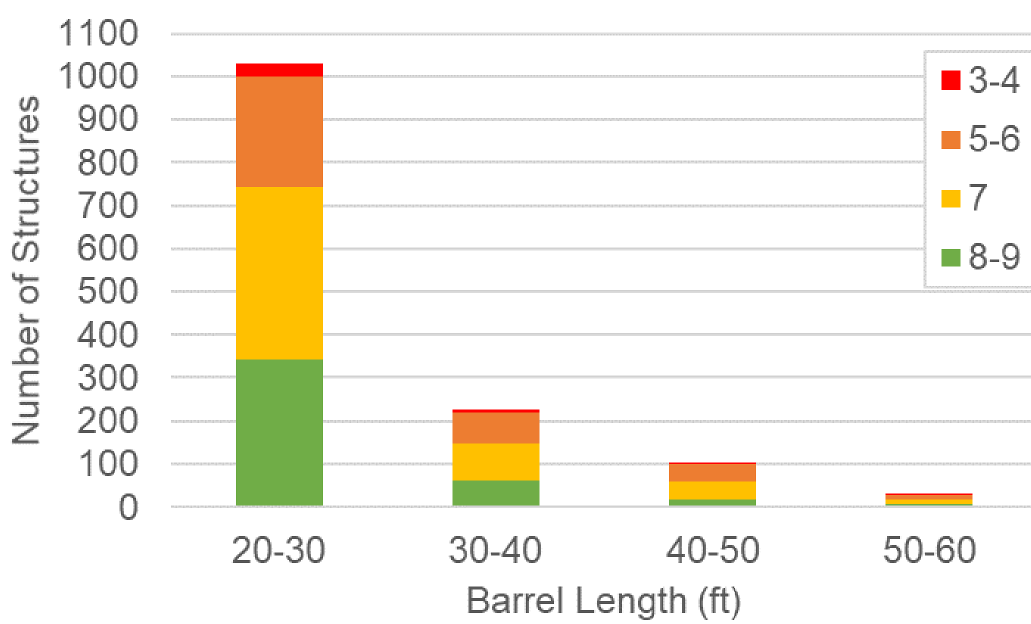


Figure C.27

Histogram of barrel length with culvert rating for barrels up to 60 ft in length.

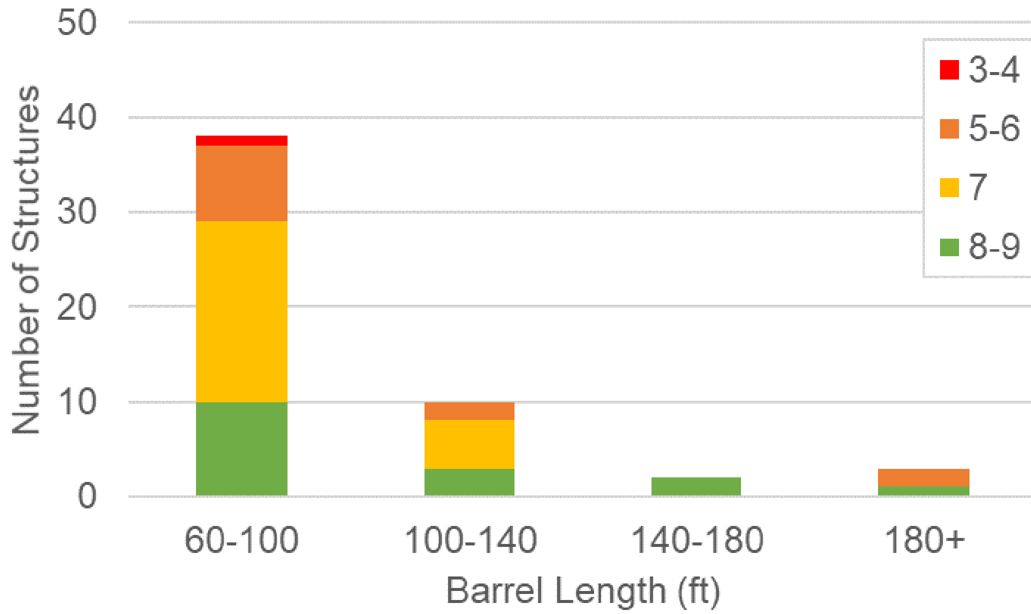


Figure C.28

Histogram of barrel length with culvert rating for barrels greater than 60 ft in length.

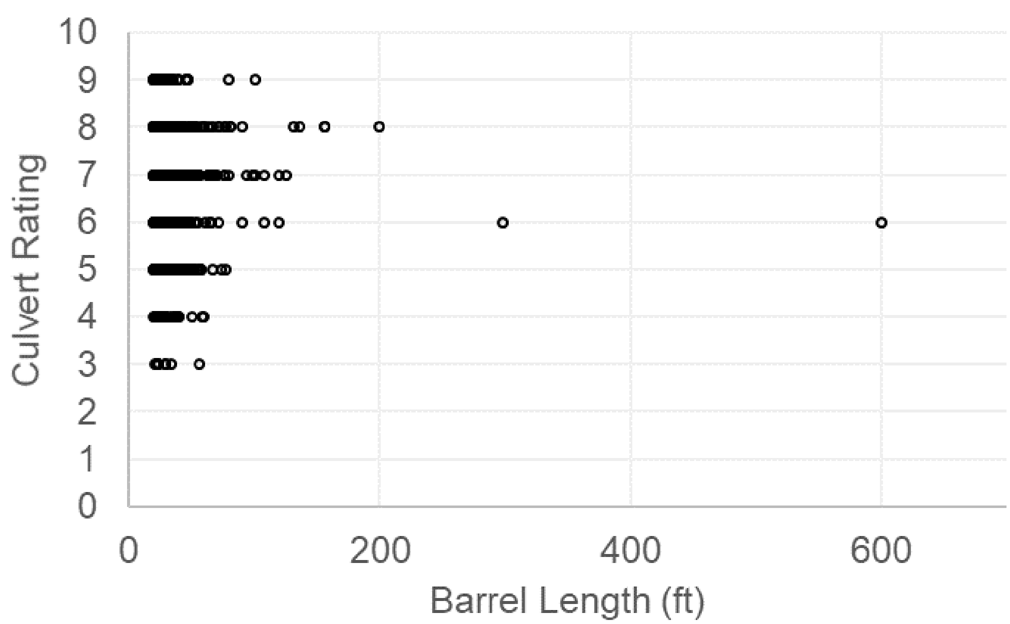


Figure C.29

Culvert rating vs. construction year.

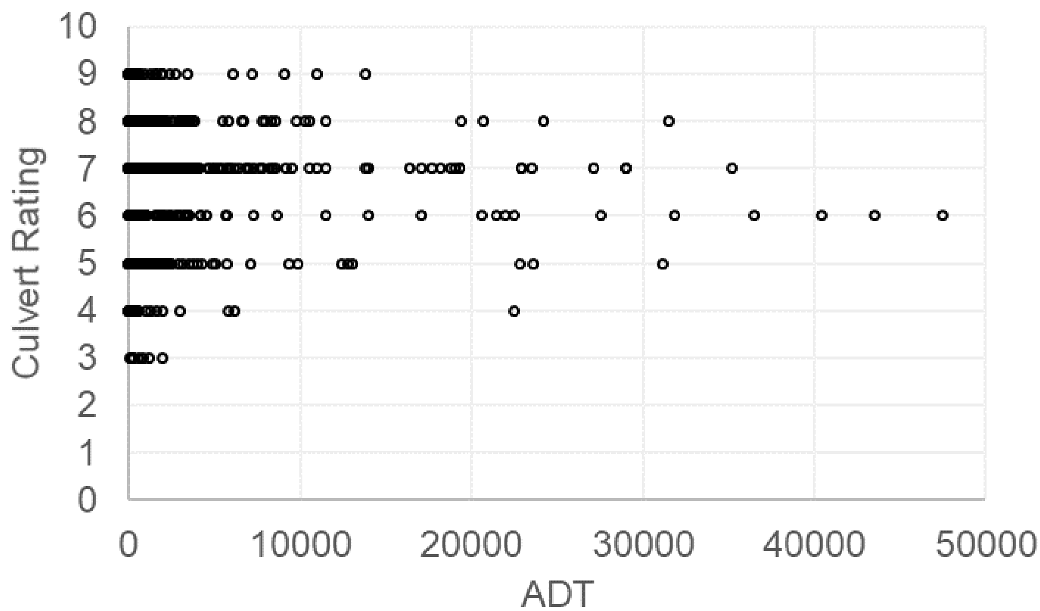


Figure C.30

Culvert rating vs. ADT.

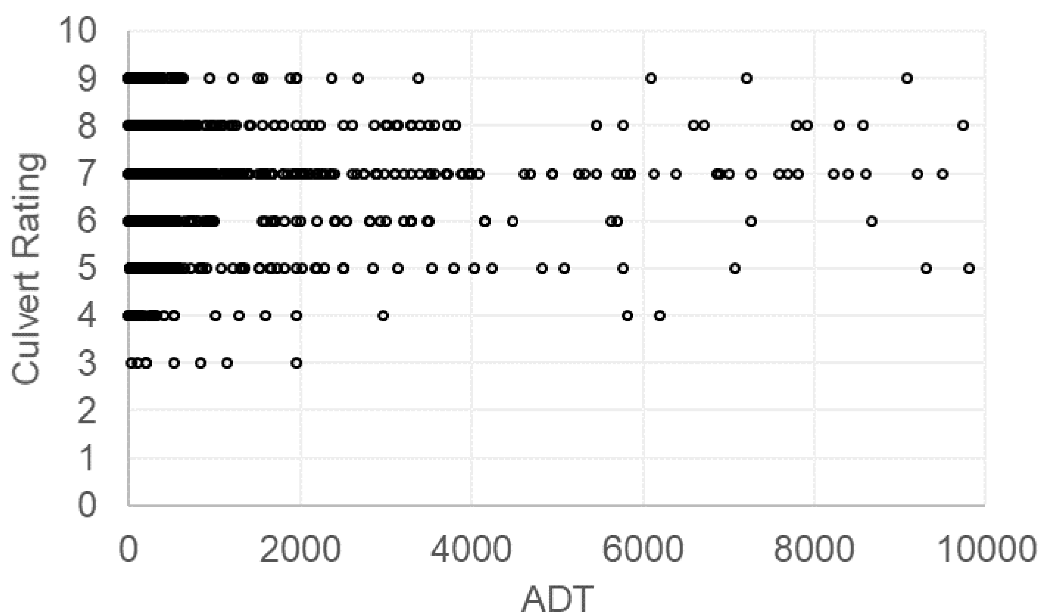


Figure C.31

Culvert rating vs. ADT, horizontal scale limited to 10,000 vehicles ADT.

APPENDIX D

Field Inspection Plan and Results

Inspection Plan

Memorandum

Date: 3 July 2018

To: File

From: Brent J. Bass

Project: 170848.03 – Wisconsin Culvert Field Inspection Plan

Subject: Plan for Field Inspection of Three Aluminum Culverts in Wisconsin

1. REQUIREMENTS FROM WORK PLAN

1.1 Task 3 - Inspection Plan

From our work plan, we will select three primary culverts for inspection and consider two additional as backup in case unforeseen issues prevent access to one or more of the primary culverts.

We will develop a preliminary inspection plan for each of the three primary culverts, including a checklist of steps for systematic inspection with culvert rating criteria and any detailed test methods with proposed locations for each field test. The inspection plan will be based on the new Culvert and Storm Drain System Inspection Manual, which provides recommendations for inspection plans, checklists, and condition rating criteria. Prior to the field work, we will develop site inspection sheets that we will use to record data and measurements while on site.

1.2 Task 4 - Field Inspection

From our work plan we will do the following:

- Perform in-depth inspection to quantify environmental condition at the sites, such as field measurements of water and soil pH, and soil resistivity, and quantify flow characteristics at the time of inspection.

- We will assess the barrel of the structure for section loss, qualitatively overall and quantitatively through ultrasonic thickness (UT) measurements and localized measurements of pitting. Our inspection will include confirmation of UT gage readings by hand measurements with calipers on the culvert end, if accessible.

- We will assess the culverts for abrasion based on FHWA and CALTRANS abrasion classification tables and conduct qualitative assessment of the abrasion loading based on site conditions.

Soil Resistivity. We will measure soil resistivity in the field following the method presented in ASTM D6431 – Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation, to understand soil corrosivity. We will use a four-electrode test apparatus, likely in the Wenner arrangement. The specific location where the tests will be performed at each culvert will be determined in Task 3 following selection of the culverts for inspection; possible locations include in the backfill above the structure (particularly if unpaved), on the embankment between the top of the culvert and the roadway, or along the edge of the streambed upstream or downstream of the structure.

Soil and Ground Water Chemistry. We will collect a small soil sample to perform laboratory tests on the soil and its pore water, such as pH, resistivity, chloride ion content, and sulfate concentration. A detailed chemical testing protocol will be identified in the Task 3 Field Inspection Plan. We will also collect small samples of surface water to perform laboratory chemical analysis, including pH, resistivity, chloride ion concentration, and sulfate concentration.

We will evaluate soil-side corrosion near the ends of the culverts. This will be subject to the ability to safely access the ends of the culverts and temporarily remove a small quantity of cover soil.

We will correlate the in-service performance of these culverts with the environmental conditions and installed aluminum alloy, as input to the final policy guidelines.

We do not anticipate the need for traffic control associated with these inspections and will follow Wisconsin and OSHA requirements for safe culvert access and work on and around highways.

2. INSPECTION PLAN

2.1 Culverts Selected

Table 1 identifies the culverts selected for inspection and their main attributes. Table 2 identifies alternate culverts for inspection should there be a problem encountered in the field with inspecting one of the Table 1 culverts.

Table 1 – Culverts Planned for Inspection

SGH No.	Structure Number (Coordinates)	Descriptive Name	Custodian & Year Built	No. Spans	Cover (ft)	Span (ft)	Rise (ft)	Length (ft)	ADT	Water?	Comments
1	C030048 (45°26'57.1"N, 91°50'50.7"W)	Highway 25 over Drainage	State, 1983	1	3.5	11	7.2	63	NR	Looks dry	2018 inspection reports pitting & perforations; dry bed at time of photos https://goo.gl/maps/NyTNFufAnVN2
2	P580065 (44.943056, 89.146389)	Church Rd over M BR Embarrass River	Town, 1971	3	0.5-1	9.5	NR; pipe arch	44	206	Up to knee	No distress noted; selected for low cover and “good” condition https://goo.gl/maps/4tUkUezixJv
3	190700670 (45°54'33.1"N, 88°16'27.0"W)	Highway 70 over dry stream	State, unknown	1	5	3	3	60	NR	Looks dry	Inspected 20 Nov 2017. Pipe showing signs of corrosion and cracking, recommended for replacement. https://goo.gl/maps/8S6zJ98zZKL2

Table 2 – Alternate Culverts

SGH No.	Structure Number (Coordinates)	Descriptive Name	Custodian & Built Date	No. Spans	Cover (ft)	Span (ft)	Rise (ft)	Length (ft)	ADT	Water?	Comments
4	260770061 (46°20'30.2"N, 90°31'00.4"W)	Highway 77 over Javorsky Creek	State, unknown	2	5	4	4	70	NR	Looks dry	Inspected 4 June 2018, minor corrosion noted at top center. https://goo.gl/maps/cxWzDUtc9xv
5	B070008 (45°45'45.2"N, 92°45'49.8"W)	River Rd over Wood River	Town, 1983	2	9.25	8	8	29.4	146	Up to knee	Inspection reports slight discoloration, embankment is soil, looks like tunnel liner plate
6	P510906 (42.829078, -87.914956)	Seven Mile Rd over BR Root River	Town, 1971	2	4	11	NR; pipe arch	67	3,564		Corrosion/efflorescence at bolts/seams; 2 dents
7	P510913 (42.836456, -87.919792)	7-1/2 Mile Rd over BR Root River	Town, 1960	2	3.75	12.5	NR; pipe arch	70	440		Corrosion/efflorescence at bolts/seams; hazardous/poisonous vegetation noted

2.2 Tests and Measurements to Perform

Detailed checklists and paperwork to document these tests and measurements are provided at the end of this memo. Sample culvert rating forms are also provided. All of this paperwork will be brought to site in a field binder with sufficient pages to document the condition of each culvert.

Span
Length
Shoulder to shoulder width of pavement
Width of unpaved shoulders
Estimate cover
Water depth
Flow rate
Overall photographs
Water pH
Soil pH
Soil resistivity
Abrasion – bed load (review FHWA requirements)
Joint/seam spacing (circumferential and longitudinal)
Vertical and horizontal diameters
Thickness – manual with calipers
Thickness – UT gage
Visual inspection for distress
Quantification of observed distress (dimensions, location, thickness, etc)
Local measurements of pitting
Sample soil
Sample water
Review pavement, embankment, etc
Scour stability
Joints (infiltration/exfiltration, bolts/fasteners)

2.2.1 Chemical Testing Protocol

2.2.1.1 Soil Testing

Collect soil samples from each culvert for lab testing as follows:

- Lab resistivity (AASHTO T288)
- pH (AASHTO T289)
- Sulfate Ion Concentration (AASHTO T290)
- Chloride Ion Concentration (AASHTO T291)

Sample size for all tests is 2,100 g of soil passing a 2 mm sieve, which is about a 5 in. cube based on 120 pcf. GeoTesting recommends approximately 1 gallon zip lock bag per site sample to perform all four tests. Collect 1 soil sample from each culvert site; soil sample should include high percentage of fines.

2.2.1.2 Water Testing

Perform pH measurements of water on site.

Collect stream water and, if possible soil pore/ground water from each site in bottles provided by Rhode Island Analytical Labs (RIAL).

Submit to RIAL for total chloride (Cl^-)and total sulfate (SO_4) contents.

2.2.2 Equipment

The equipment we will bring is listed in Table 3.

Table 3 – Equipment for Culvert Inspections

Item	Quantity
Reflective vests	2
Chest or thigh-high waders	1
Rubber boots	2 pair
Telescoping diameter tool or survey rod	1
Tape measure (25 ft and 100 ft)	1 EA
Laser distance meter	1
Needle point depth gage (measure metal pitting)	1
Crack width card	2
UT gage	1
Calipers	1
Camera	1
Air monitor	1
Four-electrode resistivity probe (rented)	1
Hammer	1
Screw driver (flat)	1
Putty knife/ 5 in 1 tool	1
Small shovel or garden spade	1
Paper pH strips with 1 key	10 strips
Hard hat	2
Safety glasses	2
Cloth rubber palm work gloves	2 pair
Work boots	2 pair
Water sample containers	6 min
Gallon size zip lock bags	10
Sandwich size zip lock bags	10
3 ft digital level	1
Bosch self-leveling laser tool	1
LED flash light	1
Head lamp	2
Rags	6
Large plastic bags	3
Plumb bob	1
Clip board	1
Inspection forms & references	6
Lumber crayons	6
Sharpies	2
Magnets	2
Retractable utility knife	1
Sheet of sand paper	1

2.2.3 Procedure at Each Culvert

Park vehicle safely on side of road, use hazard lights if needed, and don reflective vests and other PPE prior to exiting vehicle.

Confirm GPS location of culvert and any numerical identifiers.

Assess roadway (number of lanes, approach roadway width, approach roadway pavement condition, culvert roadway width, culvert pavement condition, shoulder condition, embankment/headwall condition, barrier condition).

Estimate cover (laser, level, diameter tool).

Assess culvert structure (number of barrels, measure span/length/rise of each, corrugation type/spacing/depth, circumferential joint type/spacing/fastener condition, longitudinal seam type/spacing/fastener condition, foundation type and condition, UT gage thickness measurements, caliper thickness measurements, magnet test, surface damage/corrosion/abrasion, shape, seam condition/alignment/infiltration/exfiltration.

Photographs (elevation view from each end of structure, roadway approaches from both sides, roadway over structure and shoulders, upstream and downstream views of watercourse, headwall/embankment conditions on both sides, typical connections inside structure, typical foundation, representative condition of barrel, items to note in barrel).

Assess culvert for abrasion (bedload classification, flow rate, bedload/sedimentation presence in culvert; bedload classification guide is attached after the flow chart at the end of this memo).

Select location for soil sampling and sample soil.

Select location for water sampling and sample water from stream.

Check for possibility of ground water sampling and sample ground water.

Select location(s) and perform soil resistivity measurements.

2.2.4 Checklists and Forms

2.2.4.1 Inspection Checklist

CULVERT INSPECTION FORM			
Structure No.		Arrival Time	
Confirm GPS Coordinates		Departure Time	
Confirm Numerical Identifier		Weather (condition & temp.)	

Roadway Assessment			
Number of Lanes:		Culvert Roadway Width:	
Approach Roadway Width:		Culvert Pavement Cond:	
Approach Pavement Cond:		Shoulder Condition:	
Upstream Barrier Condition:		U/S Embank/Headwall Cond:	
Downstream Barrier Cond:		D/S Embank/Headwall Cond:	

Estimate Cover			
Upstream Shoulder:		Downstream Shoulder:	
Estimate Roadway Crown, etc:			

Photographs			
Roadway Approach Dir. 1:		Upstream Watercourse:	
Roadway Approach Dir. 2:		Downstream Watercourse:	
Roadway Over Structure:		Typical Barrel Condition:	
Typ. Shoulder/Barrier:		Typical Joint Condition:	
Looking Down U/S Headwall:		Typical Seam Condition:	
Looking Down D/S Headwall:		Typical Foundation:	
Upsream Elevation:		Distress Photos:	
Downstream Elevation:		Other:	

Continued on next page.

Culvert Structure Assessment - Structure No.:			
Number of Barrels:		This Sheet is Applicable to Which Barrel(s)?	
Barrel 1 Identifier:			
Barrel 2 Identifier:			
Barrel 3 Identifier:			
Span (nominal):		Foundation Type:	
Rise (nominal):		Water Depth (U/S):	
Length:		Water Depth (D/S):	
Span (if loc. w/ visual min.):		Rise (if loc. w/ visual min.):	
Rise (at min. span location):		Span (at min. rise location):	
Min. Span Location:		Min. Rise Location:	
Corrugation Type:		For multiple barrels, are corrugations the same in each?	
Corrugation Depth:			
Corrugation Spacing:			
Joint (Circumf. Seam) Type:		Longitudinal Seam Type:	
Joint (Circ. Seam) Spacing:		No. of Long. Seams/Perim:	
Joint (Circ.) Fastener Cond:		Long. Seam Fastener Cond:	
For multiple barrels, are circ seams consistent?			
For multiple barrels, are long seams consistent?			
UT Gage Measurements, Loc 1:		UT Gage Measurements, Loc 4:	
UT Gage Loc 1 Description:		UT Gage Loc 4 Description:	
UT Gage Measurements, Loc 2:		UT Gage Measurements, Loc 5:	
UT Gage Loc 2 Description:		UT Gage Loc 5 Description:	
UT Gage Measurements, Loc 3:		UT Gage Measurements, Loc 6:	
UT Gage Loc 3 Description:		UT Gage Loc 6 Description:	
U/S End Caliper Meas:		D/S End Caliper Meas:	
U/S End Caliper Loc:		D/S End Caliper Loc:	
U/S Soil Resistivity:		U/S Half Cell:	
D/S Soil Resistivity:		D/S Half Cell:	
Other Soil Resistivity:		Other Half Cell:	
Magnet Test Performed?		Water Sample(s) Collected?	
Flow Rate:		Soil Sample(s) Collected?	
Bedload Description and Abrasion Level (see sheet):		GW Sample(s) Collected?	
		Streambed Material in Pipe?	
Soil pH Measurement:		Water pH measurement:	
Identify Any Surface Damage/Corrosion/Abrasion (locations, extents, description):			
Identify Any Joint or Seam Issues such as Damage/Corrosion/ Infiltration/Exfiltration:			

Other Comments:

2.2.4.2 Culvert Rating Form

CULVERT INSPECTION RATING FORM

Structure ID:		Date of Inspection:	
Route & Milepost:		Entry Type:	
Shape / Span:		Inspector:	

APPROACH ROADWAY	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Pavement								
Guardrail								
Shoulders								

EMBANKMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Slope Stability and Embankment Erosion								

CHANNEL ALIGNMENT AND PROTECTION	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Channel Alignment								
Bank Erosion and Scour								
Protection								
Waterway Adequacy								

END TREATMENT AND APPURTNANT STRUCTURES	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Cracking (Concrete)								
Surface Damage Spalling or Delamination (Concrete)								
Deformation and Damage (Metal)								
Corrosion (Metal)								
Scour and Stability								
Settlement/Rotation								

CONCRETE FOOTING AND INVERT SLAB	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Differential Settlement and Movement								
Scour and Stability								
Cracking								
Surface Damage								
Spalling / Delamination / Patches								

Continued on next page.

BARREL ALIGNMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR		RATING:
Barrel Alignment								

CORRUGATED METAL BARREL	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Surface damage								
Corrosion								
Abrasion								
Shape (Closed Shape)								
Shape (Open Bottom)								

SEAMS (CORRUGATED METAL PLATE)	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING:
Infiltration / Exfiltration								
Seam Alignment								
Seam Bolts/Fasteners								
Seam Bolt Holes								

COMMENTS: ______________________________

REVIEWED BY: ______________________ DATE: ______________

For reference, the NCHRP Culvert and Storm Drain System Inspection Manual inspection flow chart is presented on the next page. Relevant pages from the NCHRP Culvert and Storm Drain System Inspection Manual will be included in the field project binder to systematically rate each culvert and component. The CalTrans/FHWA abrasion classification table is provided in Table 4.

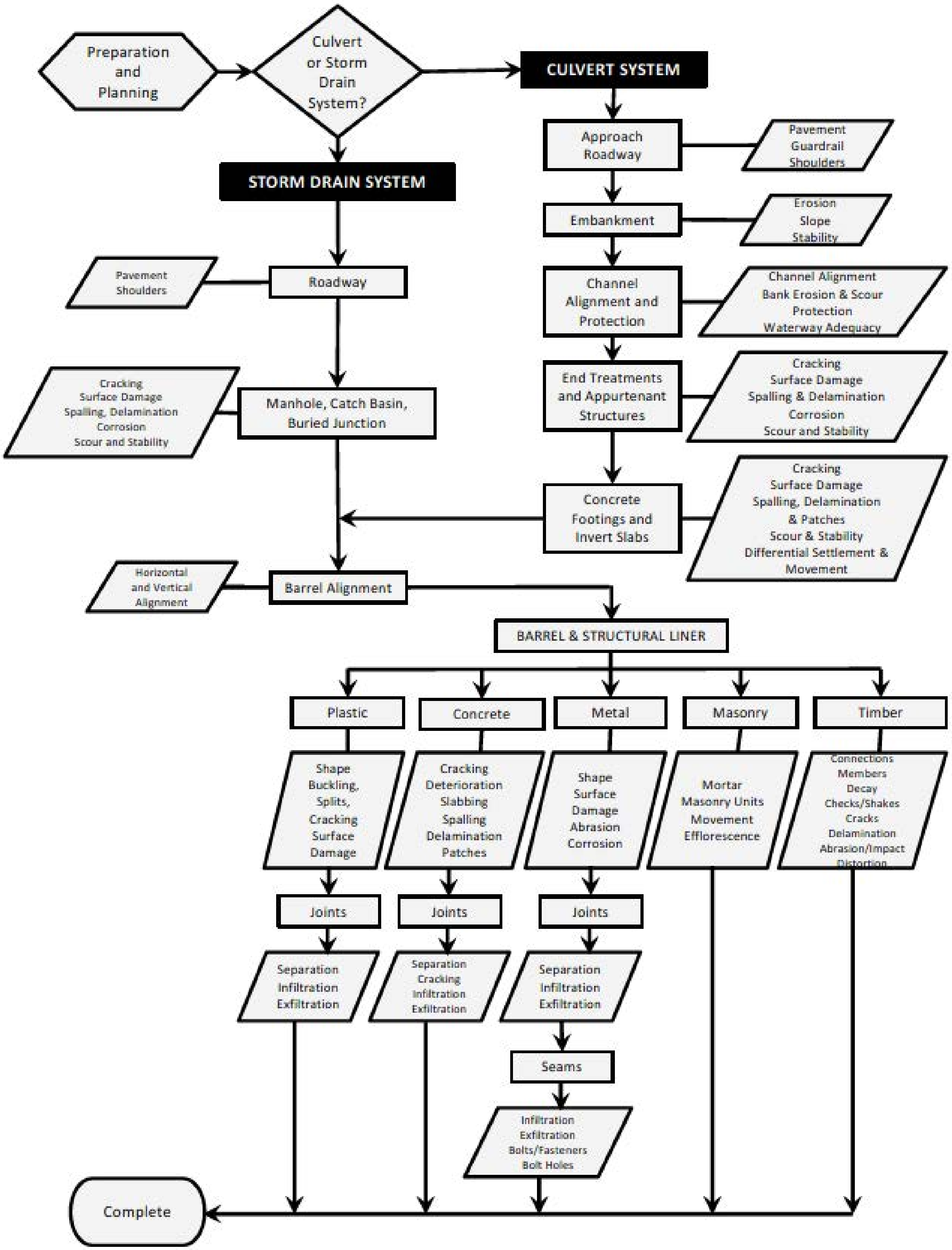

Preparation and Planning
Culvert or Storm Drain System?
CULVERT SYSTEM
STORM DRAIN SYSTEM
Approach Roadway
Pavement Guardrail Shoulders
Embankment
Erosion Slope Stability
Roadway
Pavement Shoulders
Channel Alignment and Protection
Channel Alignment Bank Erosion & Scour Protection Waterway Adequacy
Cracking Surface Damage Spalling, Delamination Corrosion Scour and Stability
Manhole, Catch Basin, Buried Junction
End Treatments and Appurtenant Structures
Cracking Surface Damage Spalling & Delamination Corrosion Scour and Stability
Concrete Footings and Invert Slabs
Cracking Surface Damage Spalling, Delamination & Patches Scour & Stability Differential Settlement & Movement
Horizontal and Vertical Alignment
Barrel Alignment
BARREL & STRUCTURAL LINER
Plastic
Concrete
Metal
Masonry
Timber
Shape Buckling, Splits, Cracking Surface Damage
Cracking Deterioration Slabbing Spalling Delamination Patches
Shape Surface Damage Abrasion Corrosion
Mortar Masonry Units Movement Efflorescence
Connections Members Decay Checks/Shakes Cracks Delamination Abrasion/Impact Distortion
Joints
Joints
Joints
Separation Infiltration Exfiltration
Separation Cracking Infiltration Exfiltration
Separation Infiltration Exfiltration
Seams
Infiltration Exfiltration Bolts/Fasteners Bolt Holes
Complete

Table 4 – Abrasion Levels based on Bedload and Flow Characteristics Related to Aluminum Culvert Use Adapted from Caltrans Table 855.2A

Level	Bedload Description	Flow Velocity	Notes Related to Aluminum Culvert Use
1	Bedloads of silts and clays or clear water with virtually no abrasive bed load.	No velocity limitation.	All pipe materials listed in Table 857.2 allowed; no abrasive resistant protective coatings needed for metal pipe.
2	Moderate bed loads of sand or gravel.	1 to 5 ft/sec(1)	Generally no restriction. Polymeric or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structure requirements is inadequate for abrasion potential.
3	Moderate bed load volumes of sands, gravels and small cobbles.	> 5 to 8 ft/sec(1)	Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential.
4	Moderate bed load volumes of angular sands, gravels, and/or small cobbles/rocks.(2)	> 8 to 12 ft/sec	Aluminum pipe not recommended. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
5	Moderate bed load volumes of angular sands and gravel or rock.(2)	> 12 to 15 ft/sec	Aluminum pipe not allowed. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
6a	Moderate bed load volumes of angular sands and gravel or rock.(2)	> 15 to 20 ft/sec	Aluminum pipe not allowed. None of the abrasion resistant coatings listed in Table 855.2C is recommended even for steel pipe. Lining alternatives include specific polymeric liners or cementitious liners/invert pavement with conditions. For new/replacement structures, consider "bottomless" structures.
6b	Heavy bed load volumes of angular sands and gravel or rock.(2)	> 12 ft/sec	

1. If bed load volumes are minimal, a 50% increase in velocity is permitted.
2. For minor bed load volumes, use Level 3.

- Sampling of the streambed materials generally is not necessary, but visual examination and documentation of the size, shape and volume of abrasive materials in the streambed and estimating the average stream slope will provide the designer data needed to determine the expected level of abrasion.

- The descriptions of abrasion levels in Table 4 are intended to serve as general guidance only, and not all of the criteria listed for a particular abrasion level need to be present to justify defining a site at that level. For example, the use of one of the three lower abrasion levels in lieu of one of the upper three abrasion levels is encouraged where there are minor bedload volumes, regardless of the gradation.

Culvert 1 Inspection Results

CULVERT INSPECTION FORM

Structure No.	C030048	Arrival Time	8: 30 am- July 10-2018
Confirm GPS Coordinates	Confirmed	Departure Time	14:15
Confirm Numerical Identifier	No Identifier	Weather (condition & temp.)	Sunny; Temp.= 80F

Roadway Assessment			
Number of Lanes:	2	Culvert Roadway Width:	30 to 33 ft
Approach Roadway Width:	Same as culvert road width	Culvert Pavement Cond:	Sealed cracks, smooth
Approach Pavement Cond:	Sealed cracked across pvmnt	Shoulder Condition:	Paved, gravel beyond
Upstream Barrier Condition:	No Barrier	U/S Embank/Headwall Cond:	Good, riprap, no erosion
Downstream Barrier Cond:	No Barrier	D/S Embank/Headwall Cond:	Good, no erosion

Estimate Cover			
Upstream Shoulder:	3 ft	Downstream Shoulder:	3 ft
Estimate Roadway Crown, etc:	No more than 6 in. crown at center		

Photographs			
Roadway Approach Dir. 1:	1300; From North (lkg South)	Upstream Watercourse:	1321-1323
Roadway Approach Dir. 2:	1304; From South (lkg North)	Downstream Watercourse:	1424
Roadway Over Structure:	Through #1310	Typical Barrel Condition:	through 1419
Typ. Shoulder/Barrier:	None	Typical Joint Condition:	1425-1426
Looking Down U/S Headwall:	#1317	Typical Seam Condition:	Done
Looking Down D/S Headwall:	#1320	Typical Foundation:	1426
Upstream Elevation:	#1324-1330	Distress Photos:	Done
Downstream Elevation:	1421-1423	Other:	Done

Culvert Structure Assessment - Structure No.: C030048			
Number of Barrels:	1	This Sheet is Applicable to Which Barrel(s)?	N/A
Barrel 1 Identifier:	N/A		
Barrel 2 Identifier:	N/A		
Barrel 3 Identifier:	N/A	Pipe Arch	
Span (nominal):	138 in.	Foundation Type:	Closed Invert
Rise (nominal):	81.5 in.	Water Depth (U/S):	0
Length:	64.5 ft	Water Depth (D/S):	0
Span (if loc. w/ visual min.):	N/A	Rise (if loc. w/ visual min.):	N/A
Rise (at min. span location):	N/A	Span (at min. rise location):	N/A
Min. Span Location:	N/A	Min. Rise Location:	N/A
Corrugation Type:	9 x 2.5 - Str. Plate	For multiple barrels, are corrugations the same in each?	N/A
Corrugation Depth:	2.5 in.		
Corrugation Spacing:	9 in.		
Joint (Circumf. Seam) Type:	Bolted at 9 in.	Longitudinal Seam Type:	Bolted
Joint (Circ. Seam) Spacing:	56 in.	No. of Long. Seams/Perim:	3 seams
Joint (Circ.) Fastener Cond:	Minor corrosion - galv	Long. Seam Fastener Cond:	Galv. Minor corrosion
For multiple barrels, are circ seams consistent?	N/A; Circumf. seams at crown staggering by 1/2 plate length from bottom 2 plates		
For multiple barrels, are long seams consistent?	N/A; All counting of plates/ seams is from bottom plates		
UT Gage Measurements, Loc 1:	0.101 in.	UT Gage Measurements, Loc 4:	0.099
UT Gage Loc 1 Description:	PL-1, 10:00 Mid length	UT Gage Loc 4 Description:	PL-7, 10:00 Mid length
UT Gage Measurements, Loc 2:	0.099	UT Gage Measurements, Loc 5:	0.100
UT Gage Loc 2 Description:	PL-3, 10:00 Mid length	UT Gage Loc 5 Description:	PL-9, 10:00 Mid length
UT Gage Measurements, Loc 3:	0.099	UT Gage Measurements, Loc 6:	0.100
UT Gage Loc 3 Description:	PL-5, 10:00 Mid length	UT Gage Loc 6 Description:	PL-11, 10:00 Mid length
U/S End Caliper Meas:	0.104, 0.100, 0.100, 0.100, 0.099	D/S End Caliper Meas:	0.105, 0.106, 0.106, 0.106, 0.107
U/S End Caliper Loc:	10:00; Cut Edge	D/S End Caliper Loc:	10:00
U/S Soil Resistivity:		U/S Half Cell:	
D/S Soil Resistivity:	See Sheets	D/S Half Cell:	See Sheets
Other Soil Resistivity:		Other Half Cell:	
Magnet Test Performed?	Barrel Not Mag; Fasteners Mag	Water Sample(s) Collected?	PL -9; Invert
Flow Rate:	None	Soil Sample(s) Collected?	D/S; South Bank
Bedload Description and Abrasion Level (see sheet):	Level #4; Based on rocks (no flow)	GW Sample(s) Collected?	No, could not collect
		Streambed Material in Pipe?	3 boulders
Soil pH Measurement:	6 to 7	Water pH measurement:	6
Identify Any Surface Damage/Corrosion/Abrasion (locations, extents, description):	See below		
Identify Any Joint or Seam Issues such as Damage/Corrosion/ Infiltration/Exfiltration:	See below		

Other Comments:

- U/S plate is 5 corrugations long, typical length of plate section is 6 corr.
- 15 total plates long including U/S and D/S. D/S is 2.5 corr.
- From U/S end, 2nd plate, 5th inside crest has bulge/split at 9:00, 1/4 in. separation, 3 in. long
- 4th and 5th plates from U/S end have through wall pitting and efflorescence, approx. 1 in. dimeter pits with 2 in. min clear spacing
- Pitting most prevalent from 8:00 to 9:30 and 1:30 to 4:00, across crown pitting has not progresses to through wall, extends, onto U/S half of 6th plate below springlines.
- 7th plate has 8 pits, 1 is through wall near crown, all at 10:00 to 2:00.
- 8th plate has about 12 pits from 2:00 to 3:30 and about 14 at 9:00.
- 9th plate has increased pitting and staining from 8:00 to 9:30 and 2:30 to 4:00.

- 10th plate has major through wall holes, soil visible, through walls are B/T 9:00 to 10:00 and 2:00 to 3:00, typically at outside crest, 4th outside crest is worst with up to 16 in. circ by 5 in. long at 9:00, two 9 in. by 9 in. at 2:00.
- Three boulders inside PL #10 at 6:30 up to 24 in. by 22 in. by 16 in.
- PL# 11 has corrosion at U/S 4 corr near springlines, diminishing D/S and toward crown/invert.
- PL#12 has white spots/staining near spring lines, approx. 24 total.
- PL#13 has no white spots
- PL # 14 and PL #15 have none.
- Gouge, 6 in. long at last corr at 2:00 removed loose piece as uncorroded sample

CULVERT INSPECTION RATING FORM

Structure ID:	C030048	Date of Inspection:	10-Jul-18
Route & Milepost:	Highway 25	Entry Type:	Manual
Shape / Span:	Pipe Arch	Inspector:	BJBass/ SABorghei

APPROACH ROADWAY	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Pavement		X					
Guardrail						X	
Shoulders		X					

EMBANKMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Slope Stability and Embankment Erosion		X					Riprap at west embankment loose

CHANNEL ALIGNMENT AND PROTECTION	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Channel Alignment		X					
Bank Erosion and Scour	X						
Protection		X					
Waterway Adequacy		X					

END TREATMENT AND APPURTNANT STRUCTURES	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Cracking (Concrete)						X	
Surface Damage Spalling or Delamination (Concrete)						X	
Deformation and Damage (Metal)		X					
Corrosion (Metal)	X						
Scour and Stability		X					
Settlement/Rotation	X						

CONCRETE FOOTING AND INVERT SLAB	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: NR
Differential Settlement and Movement						X	
Scour and Stability						X	
Cracking						X	
Surface Damage						X	
Spalling / Delamination / Patches						X	

BARREL ALIGNMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR		RATING: 1
Barrel Alignment	X							

CORRUGATED METAL BARREL	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 3
Surface damage		X						
Corrosion			X				Through wall holes - repair	
Abrasion	X							
Shape (Closed Shape)		X						
Shape (Open Bottom)								

SEAMS (CORRUGATED METAL PLATE)	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 2
Infiltration / Exfiltration						X		
Seam Alignment	X							
Seam Bolts/Fasteners		X						
Seam Bolt Holes		X						

COMMENTS:

Date:	10-Jul-18		By: BBass; ABorghei			Sheet No.: 1 of 1	
Address:	See Culvert 1 Inspection and Rating Form					GPS:	
Arrival Time:	Time of test 12:00	Departure Time:		Weather (Condition & Temp.):		Sunny - 80F	
Purpose and scope of survey:							
Client:	Wisconsin DOT					Project No	170848.04-INSP
Equipment Model:	4620	Electrode Geometry:	Wenner Electrode Arrangement				
Location and orientation of arrays marked on the site map:	☐						
Comment:							

Soil type:	Sand	Soil moisture:	Almost Dry	Soil color:	Brown
Water table:	Deeper than ground surface				
Soil Description:					

Array No.	Description:
1	Northeast Corner, Looking upstream right side of culvert, 80 in from edge of pavement
2	Southeast corner
3	Southwest corner
4	Northwest
5	Northwest- Edge of farm field, far from the culvert and road, in typical ground

Test No.	Array No.	Horizontal Distance from Culvert Edge (ft)	Electrode Spacing "A" (ft)	Electrode Embedment (in)	Measured Resistance (Ω)	Resistivity (Ω*cm)	Comment and corrections:
1	1	10	7	4.2	2.4	4,560	
2	1	10	7	8.4	2.31	4,417	
3	2	-10	7	4.2	1.8	3,420	
4	3	-10	7	4.2	3.2	6,080	
5	4	10	7	4.2	4.7	8,930	
6	5	> 100 yds	7	4.2	4.51	8,569	
7	5	> 100 yds	7	8.4	4.47	8,547	

Culvert 1 Inspection Photos

Photo 1

View looking north from south of culvert showing overall view and general roadway condition.

Photo 2

View looking across roadway at centerline of culvert in west (upstream) direction. Note sealed pavement crack directly over culvert.

Photo 3

West (upstream) embankment.

Photo 4

East (downstream) embankment.

Photo 5

Elevation at upstream end.

Photo 6

Elevation at downstream end.

Photo 7

Channel and elevation at downstream end.

Photo 8

Overview of inside of culvert looking downstream. Note two areas of pitting and white staining approximately below roadway shoulders.

Photo 9

General condition at invert of culvert.

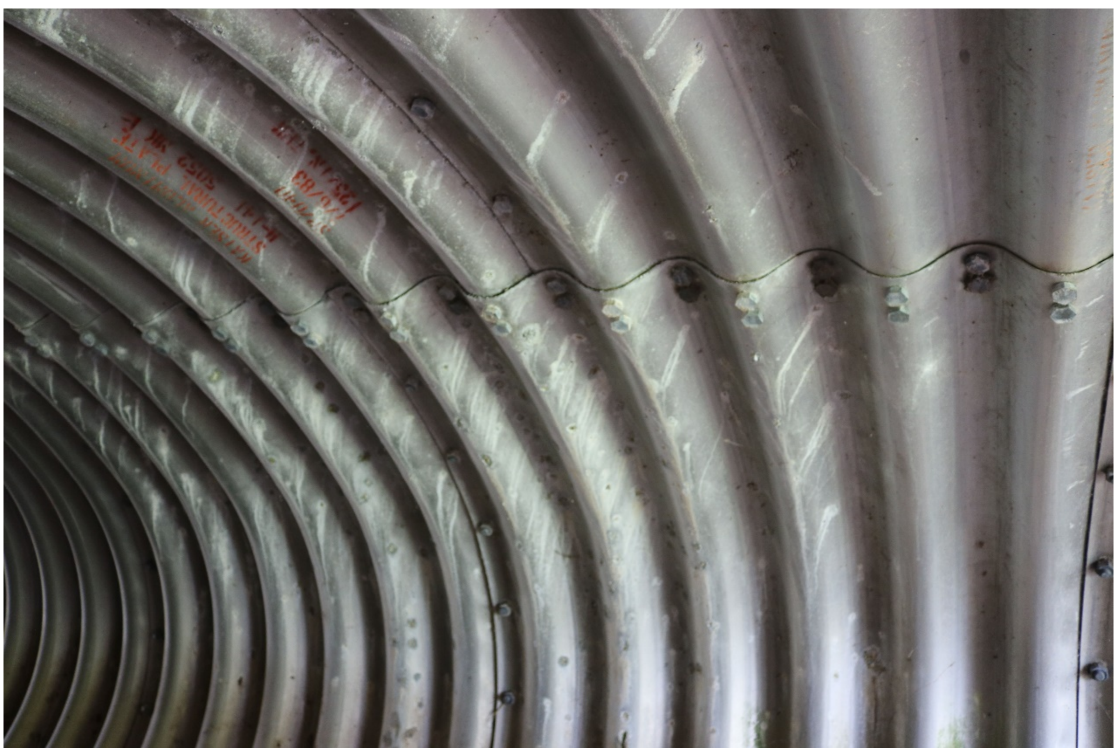


Photo 10

Close-up of one area of corrosion staining and marking on culvert identifying alloy 5052 and 6 July 1983 date.

Photo 11

Close-up view of marking.

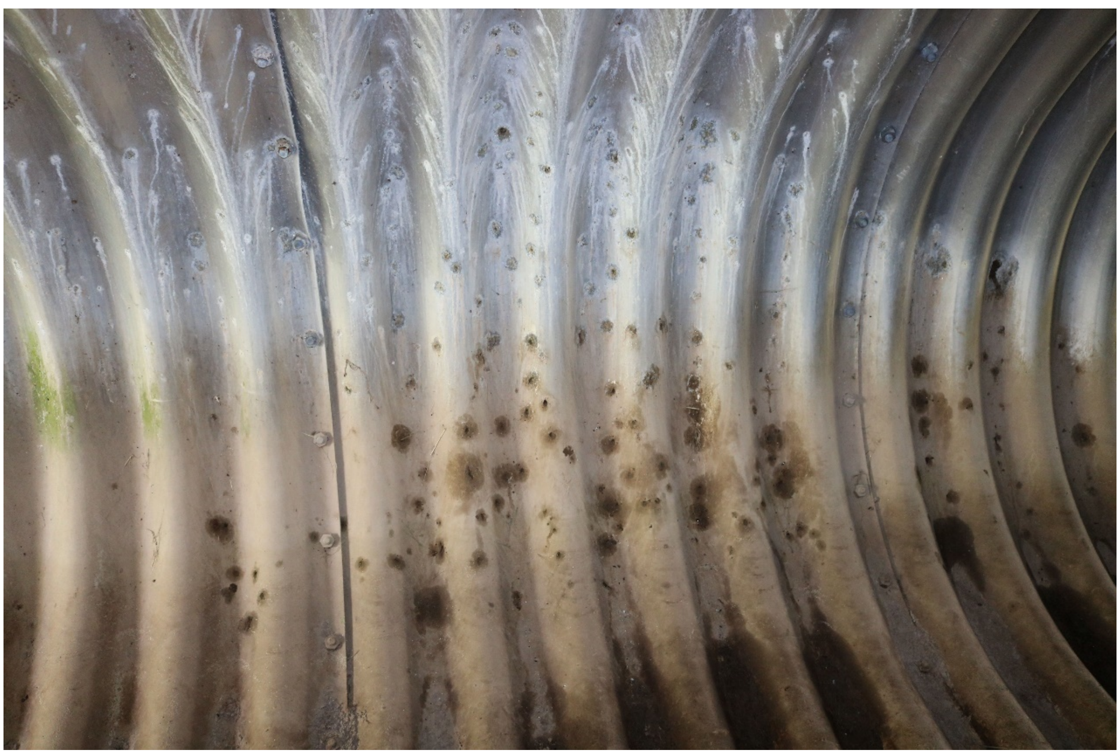


Photo 12

Area of through-wall pitting and corrosion staining at north springline, below west shoulder.

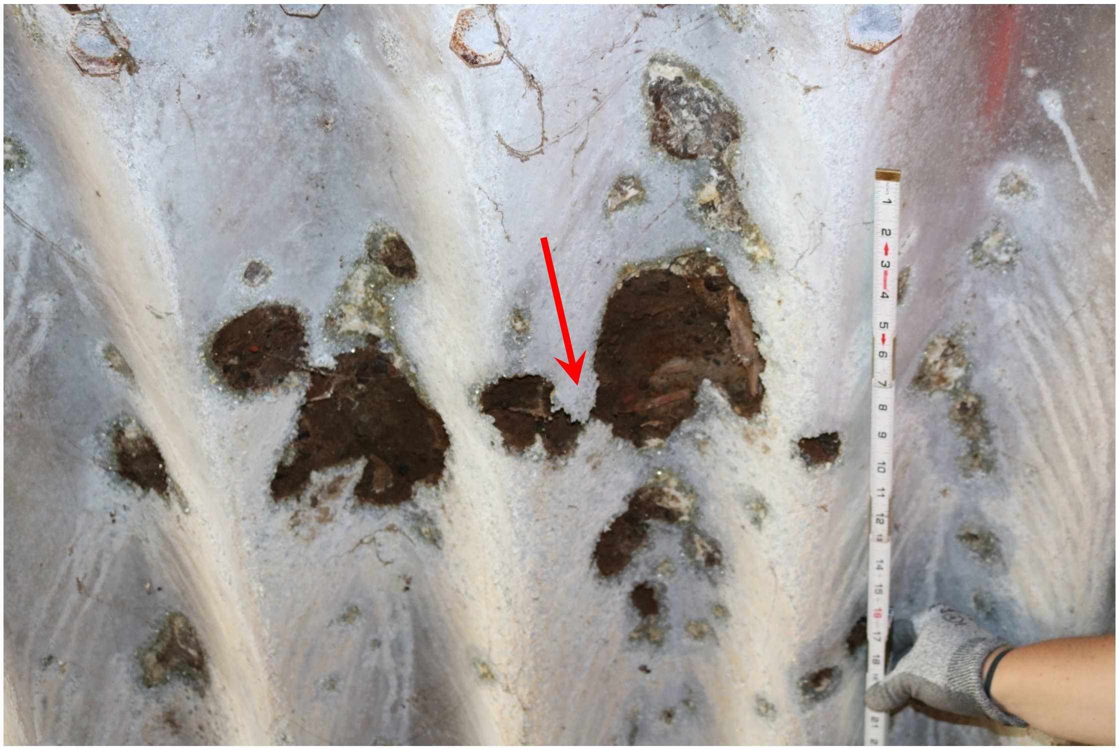


Photo 13

Area of coalesced through-wall pitting with severe corrosion staining and soil visible along north springline below east shoulder. Arrow points to area from which corrosion sample was removed.

Photo 14

Similar location as Photo 13.

Photo 15

Area of coalesced through-wall pitting with severe corrosion staining and soil visible along south springline below east shoulder

Photo 16

General view of corrosion pits working their way from the exterior to the interior of the structure, and surficial corrosion to galvanized steel bolts.

Photo 17

Boulders at invert of culvert.

Photo 18

Close-up view of through-wall pit.

Photo 19

Close-up views of edges of pits with white corrosion products.

Photo 20

Area of previous damage at east end of culvert from which a small sample was removed for laboratory examination of uncorroded aluminum.

Photo 21

Typical soil resistivity test. View is looking southwest, at northeast of culvert.

Culvert 2 Inspection Results

CULVERT INSPECTION FORM

Structure No.	P580065	Arrival Time	11 July 2018, 10:45 AM
Confirm GPS Coordinates	Confirmed	Departure Time	15:45
Confirm Numerical Identifier	None	Weather (condition & temp.)	Partly cloudy, 75F

Roadway Assessment

Number of Lanes:	2 Unmarked	Culvert Roadway Width:	20 ft 6 in.
Approach Roadway Width:	21 ft	Culvert Pavement Cond:	Narrow cross cracks
Approach Pavement Cond:	Minor Rutting + some cracks	Shoulder Condition:	Grass
Upstream Barrier Condition:	Sound but low	U/S Embank/Headwall Cond:	Soil, some erosion
Downstream Barrier Cond:	Sound but low	D/S Embank/Headwall Cond:	Soil, some erosion

Estimate Cover

Upstream Shoulder:	1 ft 3 in. at center	Downstream Shoulder:	9 in. (east pipe)
Estimate Roadway Crown, etc:	Roadway crown is minimal < 3 in.		

Photographs

Roadway Approach Dir. 1:	Looking west to 1582	Upstream Watercourse:	BJB
Roadway Approach Dir. 2:	Looking east 1589-1590	Downstream Watercourse:	BJB
Roadway Over Structure:	1583-1588	Typical Barrel Condition:	BJB
Typ. Shoulder/Barrier:	1591-1594	Typical Joint Condition:	BJB
Looking Down U/S Headwall:	1595-1600	Typical Seam Condition:	BJB
Looking Down D/S Headwall:	1601-1609	Typical Foundation:	BJB
Upstream Elevation:	BJB	Distress Photos:	BJB
Downstream Elevation:	BJB	Other:	BJB

Culvert Structure Assessment - Structure No.: P580065			
Number of Barrels:	3	This Sheet is Applicable to Which Barrel(s)?	All
Barrel 1 Identifier:	West		
Barrel 2 Identifier:	Center		
Barrel 3 Identifier:	East		
Span (nominal):	5 ft 6 in.	Foundation Type:	closed bottom
Rise (nominal):	84.5 in.	Water Depth (U/S):	W= 8 in., C= 13 in., E= 9.5 in.
Length:	44 ft	Water Depth (D/S):	W= 12 in., Ctr= 12 in., E= 11 in.
Span (if loc. w/ visual min.):	N/A	Rise (if loc. w/ visual min.):	N/A
Rise (at min. span location):	N/A	Span (at min. rise location):	N/A
Min. Span Location:	N/A	Min. Rise Location:	N/A
Corrugation Type:	9 by 2.75 in.	For multiple barrels, are corrugations the same in each?	Yes
Corrugation Depth:	~ 2.75 in.		
Corrugation Spacing:	9 in.		
Joint (Circumf. Seam) Type:	Bolted	Longitudinal Seam Type:	Bolted
Joint (Circ. Seam) Spacing:	6 Corrugations = 54 in.	No. of Long. Seams/Perim:	3
Joint (Circ.) Fastener Cond:	Galv, minor corr	Long. Seam Fastener Cond:	Gal, v. minor surf. corr
For multiple barrels, are circ seams consistent?	Yes		
For multiple barrels, are long seams consistent?	Yes		
UT Gage Measurements, Loc 1:	0.149 in.	UT Gage Measurements, Loc 4:	0.149
UT Gage Loc 1 Description:	PL 11, 10:00, Mid Culvert	UT Gage Loc 4 Description:	PL 6, 10:00, Mid Culvert
UT Gage Measurements, Loc 2:	0.149	UT Gage Measurements, Loc 5:	0.150
UT Gage Loc 2 Description:	PL 9, 10:00, Mid Culvert	UT Gage Loc 5 Description:	PL 5, 10:00, Mid Culvert
UT Gage Measurements, Loc 3:	0.148	UT Gage Measurements, Loc 6:	0.150
UT Gage Loc 3 Description:	PL 7, 10:00, Mid Culvert	UT Gage Loc 6 Description:	PL 3, 10:00, Mid Culvert
U/S End Caliper Meas:	0.149, 0.150, 0.151, 0.150, 0.149	D/S End Caliper Meas:	0.148, 0.150, 0.150, 0.149, 0.149
U/S End Caliper Loc:	10:00, CTR Culvert	D/S End Caliper Loc:	10:00 - CTR - Culvert
U/S Soil Resistivity:	See Sheet	U/S Half Cell:	N/A
D/S Soil Resistivity:		D/S Half Cell:	
Other Soil Resistivity:		Other Half Cell:	
Magnet Test Performed?	Yes - Not Mag; Fasteners are	Water Sample(s) Collected?	Yes
Flow Rate:	W= 30 sec, C= 21 Sec, E= 41 sec	Soil Sample(s) Collected?	Yes SE Bank
Bedload Description and Abrasion Level (see sheet):		GW Sample(s) Collected?	No, No GW
		Streambed Material in Pipe?	Yes, See Below
Soil pH Measurement:	No	Water pH measurement:	7
Identify Any Surface Damage/Corrosion/Abrasion (locations, extents, description):	See Below		
Identify Any Joint or Seam Issues such as Damage/Corrosion/ Infiltration/Exfiltration:	See Below		

Other Comments:

- West culvert: upstream end, Plate 1 = 1 corr, then Plate 2 and on are 6 corr standard plates, all circumf. seams staggered.
- Plate count is by west springline, Plate 5 has 3 white stain spots at 2:30 within 8 in. circ distance; structure is 11 plates long.
- PL 11 is 4 corr long. Bed load = Sandy silt/gravel w/ occasional boulders up to 18 in., plates stamped Kaiser aluminum S.P. 5052- H-141 GA.150 710413.
- Center Culv - Seams staggered similar to west and start same way at U/S end, minimal bed material at invert, gravel and up to 8 in. rocks, 11 plates long, D/S end west side = 4 corr, no visible distress
- East is similar to other 2, bed load is mainly silty sand/gravel w/up to 10 in. rocks, PL 5 has 2 areas w/ white staining, 1 at 10:00, 1 at 2:00, PL 7 has 1 at 12:30, 1 at 11:00

CULVERT INSPECTION RATING FORM

Structure ID:	P580065	Date of Inspection:	11-Jul-18
Route & Milepost:	Church Road	Entry Type:	Manual Entry
Shape / Span:	Pipe Arch	Inspector:	BJBass/SABorghei

APPROACH ROADWAY	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Pavement		X					Some cracking/rutting but smooth
Guardrail		X					Low guardrail
Shoulders		X					

EMBANKMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Slope Stability and Embankment Erosion		X					

CHANNEL ALIGNMENT AND PROTECTION	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 2
Channel Alignment		X					
Bank Erosion and Scour	X						
Protection		X					
Waterway Adequacy		X					

END TREATMENT AND APPURTNANT STRUCTURES	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: 1
Cracking (Concrete)						X	
Surface Damage Spalling or Delamination (Concrete)						X	
Deformation and Damage (Metal)	X						
Corrosion (Metal)	X						
Scour and Stability	X						
Settlement/Rotation	X						

CONCRETE FOOTING AND INVERT SLAB	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments: RATING: NR
Differential Settlement and Movement						X	
Scour and Stability						X	
Cracking						X	
Surface Damage						X	
Spalling / Delamination / Patches						X	

BARREL ALIGNMENT

	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR		RATING: 1
Barrel Alignment	X							

CORRUGATED METAL BARREL

	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 2
Surface damage		X						
Corrosion		X					Very minor corrosion spots	
Abrasion	X							
Shape (Closed Shape)	X							
Shape (Open Bottom)						X		

SEAMS (CORRUGATED METAL PLATE)

	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 2
Infiltration / Exfiltration						X		
Seam Alignment	X							
Seam Bolts/Fasteners		X					Very slight surface corrosion	
Seam Bolt Holes	X							

COMMENTS:

Date:	11-Jul-18		By: BBass; ABorghei			Sheet No.: 1 of 1	
Address:	P580065 - See Culvert 2 Inspection and Rating Forms					GPS:	
Test Time:	2:30 PM	Departure Time:		Weather (Condition & Temp.):		Sunny, Hot	
Purpose and scope of survey:							
Client	: Wisconsin DOT					Project No.:	170848.04-INSP
Equipment Model:	4620	Electrode Geometry:	Wenner Electrode Arrangement				
Location and orientation of arrays marked on the site map:							
Comment:							

Soil type:	Sand	Soil moisture:	Almost Dry	Soil color:	Brown
Water table:	It was not measured				
Soil Description:	Sand with some clay				

Calibration was done. The reading was 99.9 omh. The actual resistance is 100 ohm.

Array No.	Description:
1	Northeast
2	Northwest
3	Southwest; 10 ft from burried cables
4	Southeast; 20 ft from burried cables

Test No.	Array No.	Horizontal Distance from Culvert Edge (ft)	Electrode Spacing "A" (ft)	Electrode Embedment (in)	Measured Resistance (Ω)	Resistivity (Ω*cm)	Comment and corrections:
1	1	10	5	3	Fault	High Resistivity. Embedmend of electrodes was increased.	
2	1	10	5	8.4	23.1	31,798	
3	2	-10	5	8.4	23.8	32,762	
4	3	-10	5	8.4	29.1	40,057	10 ft from burried cables.
5	4	10	5	8.4	22.4	30,834	20 ft from burried cables.

Culvert 2 Inspection Photos

Photo 1

View looking southeast showing cross cracking of pavement in vicinity of culvert with shallow ruts. Downstream end of culvert is beyond barrier.

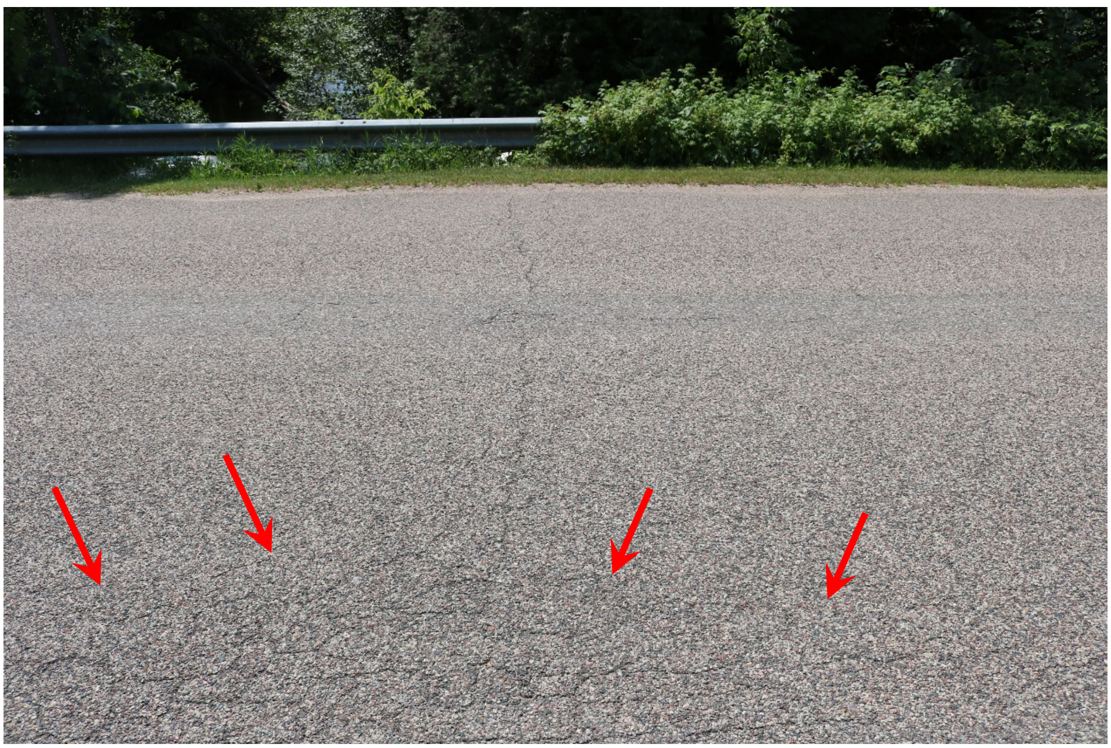


Photo 2

View looking north toward upstream end of culverts showing large cross crack aligned with crown of culvert, and additional alligator-type pavement cracking in foreground (red arrows).

Photo 3

Pavement cross crack in vicinity of culvert.

Photo 4

View looking northeast along upstream embankment.

Photo 5

Looking down north (upstream) embankment.

Photo 6

Looking southeast along downstream embankment.

Photo 7

Looking down south (downstream) embankment.

Photo 8

View looking north at upstream watercourse.

Photo 9

North elevation (looking southeast).

Photo 10

North elevation (looking southeast).

Photo 11

Typical condition along length of culvert looking downstream.

Photo 12

Typical stream flow and bedload during inspection.

Photo 13

Corrugated aluminum structural plate markings: 5052-H-141 Mark A GA .150 Kaiser Aluminum.

Photo 14

Typical shape inside culvert barrels.

Photo 15

Downstream watercourse (looking south).

Photo 16

South elevation (looking north).

Photo 17

White corrosion staining appearing as evidence of pitting in west barrel, Plate 5, at 2:30 clock position.

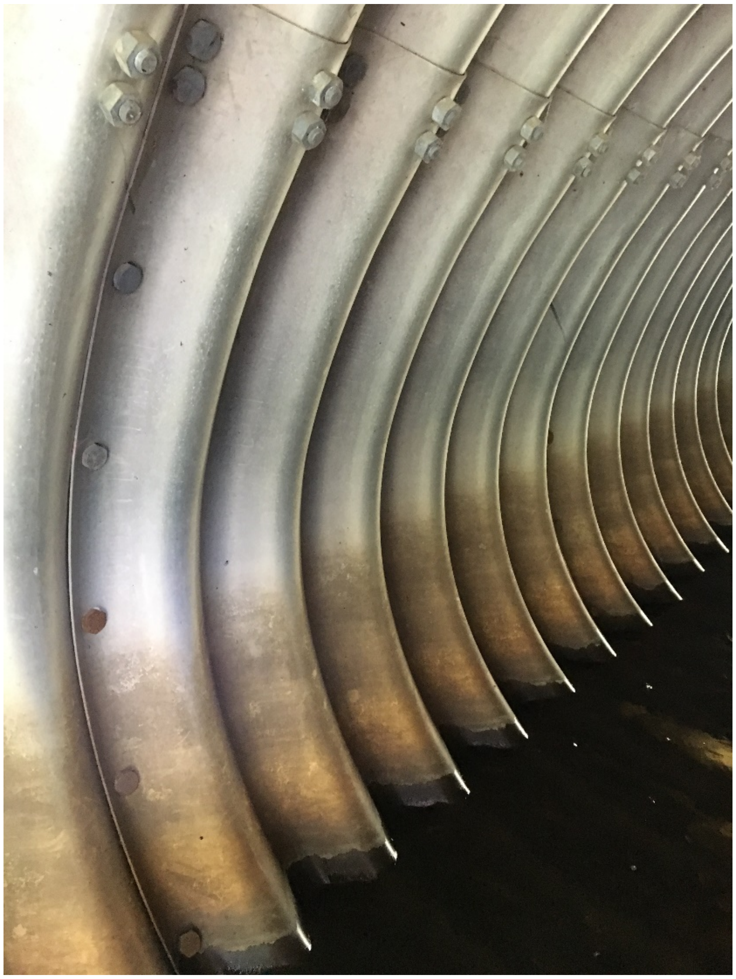


Photo 18

Typical brown staining in lower portion of barrel, and typical fastener condition with minor surface corrosion at high water line fasteners.

Culvert 3 Inspection Results

CULVERT INSPECTION FORM

Structure No.	190700670	Arrival Time	7/12/2018 14:00
Confirm GPS Coordinates	Confirmed	Departure Time	18:00
Confirm Numerical Identifier	None	Weather (condition & temp.)	Cloudy - 70F

Roadway Assessment

Number of Lanes:	2	Culvert Roadway Width:	29.5 ft
Approach Roadway Width:	29.5 ft	Culvert Pavement Cond:	Unsealed cracks
Approach Pavement Cond:	Mostly sealed cracks	Shoulder Condition:	Paved + Unpaved
Upstream Barrier Condition:	None	U/S Embank/Headwall Cond:	Grass
Downstream Barrier Cond:	None	D/S Embank/Headwall Cond:	Grass, erosion

Estimate Cover

Upstream Shoulder:	3 ft	Downstream Shoulder:	3.5 ft
Estimate Roadway Crown, etc:	About 6 in. crown		

Photographs

Roadway Approach Dir. 1:	From west looking east	Upstream Watercourse:	Done
Roadway Approach Dir. 2:	From east looking west	Downstream Watercourse:	Done
Roadway Over Structure:	Done	Typical Barrel Condition:	Done
Typ. Shoulder/Barrier:	Done	Typical Joint Condition:	Done
Looking Down U/S Headwall:	Done	Typical Seam Condition:	Done
Looking Down D/S Headwall:	Done	Typical Foundation:	Done.
Upstream Elevation:	Done	Distress Photos:	Done. No abrasion
Downstream Elevation:	Done	Other:	Done

Culvert Structure Assessment - Structure No.: 190700670			
Number of Barrels:	1	This Sheet is Applicable to Which Barrel(s)?	1 of 1
Barrel 1 Identifier:	N/A		
Barrel 2 Identifier:	N/A		
Barrel 3 Identifier:	N/A		
Span (nominal):	35 in.	Foundation Type:	Closed Pipe
Rise (nominal):	35 in.	Water Depth (U/S):	2.5 in.
Length:	55.5 ft (Approx. from outside)	Water Depth (D/S):	2 in.
Span (if loc. w/ visual min.):	N/A	Rise (if loc. w/ visual min.):	N/A
Rise (at min. span location):	N/A	Span (at min. rise location):	N/A
Min. Span Location:	N/A	Min. Rise Location:	N/A
Corrugation Type:	2.75 by 0.5 in.	For multiple barrels, are corrugations the same in each?	N/A
Corrugation Depth:	0.5 in.		
Corrugation Spacing:	2.75 in.		
Joint (Circumf. Seam) Type:	Ends crimped, mostly riveted plate	Longitudinal Seam Type:	Riveted
Joint (Circ. Seam) Spacing:	24.5 in	No. of Long. Seams/Perim:	N/A
Joint (Circ.) Fastener Cond:	Good	Long. Seam Fastener Cond:	N/A
For multiple barrels, are circ seams consistent?	N/A		
For multiple barrels, are long seams consistent?	N/A		
UT Gage Measurements, Loc 1:	0.107, 0.108, 0.104, 0.111, 0.108	UT Gage Measurements, Loc 4:	N/A
UT Gage Loc 1 Description:	U/S end 12:00	UT Gage Loc 4 Description:	N/A
UT Gage Measurements, Loc 2:	0.103, 0.103, 0.103, 0.100, 0.100	UT Gage Measurements, Loc 5:	N/A
UT Gage Loc 2 Description:	D/S end - 12:00	UT Gage Loc 5 Description:	N/A
UT Gage Measurements, Loc 3:	N/A	UT Gage Measurements, Loc 6:	N/A
UT Gage Loc 3 Description:	N/A	UT Gage Loc 6 Description:	N/A
U/S End Caliper Meas:	0.123, 0.125, 0.124, 0.123, 0.123	D/S End Caliper Meas:	0.110, 0.112, 0.120, 0.125, 0.118
U/S End Caliper Loc:	12:00, Cut end	D/S End Caliper Loc:	12:00, Cut end
U/S Soil Resistivity:	See Sheet	U/S Half Cell:	N/A
D/S Soil Resistivity:	See Sheet	D/S Half Cell:	N/A
Other Soil Resistivity:	See Sheet	Other Half Cell:	N/A
Magnet Test Performed?	Yes	Water Sample(s) Collected?	Yes
Flow Rate:	1.8 sec/ 4ft	Soil Sample(s) Collected?	Yes U/S west
Bedload Description and Abrasion Level (see sheet):		GW Sample(s) Collected?	No
		Streambed Material in Pipe?	1 rock 12 x 3 x 8
Soil pH Measurement:	N/A	Water pH measurement:	6
Identify Any Surface Damage/Corrosion/Abrasion (locations, extents, description):	See comments		
Identify Any Joint or Seam Issues such as Damage/Corrosion/ Infiltration/Exfiltration:	See comments		

Other Comments:
- Seams are 24 or 24.5 in. on center, 1 long seam per ring
- Fasteners are generally in good conditions.
- PL 5 has white sting at long seam. (1st at U/S end)
- PL 6 to 10 have white deposits.
- 4.5 ft from D/S end, 12 in. length of damage.
- Most plates have some white staining, salts.
- Staining more concerted around joints/ seams.
- Not local pitting- Different from other structures inspected.
- End segments may have been added during road widening - they are not riveted and have different corrug

CULVERT INSPECTION RATING FORM

Structure ID:	190700670	Date of Inspection:	12-Jul-18
Route & Milepost:	Highway 70	Entry Type:	Man Entry
Shape / Span:	Pipe, 36 in. Diameter	Inspector:	BJB

APPROACH ROADWAY	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 2
Pavement		X					Some sealed/ unsealed Cracks	
Guardrail						X	No Guardrail	
Shoulders		X					Some sealed/ unsealed Cracks	

EMBANKMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 3
Slope Stability and Embankment Erosion			X				Settlement and erosion	

CHANNEL ALIGNMENT AND PROTECTION	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 2
Channel Alignment		X					Upstream makes bend before entry	
Bank Erosion and Scour		X						
Protection						X		
Waterway Adequacy						X		

END TREATMENT AND APPURTNANT STRUCTURES	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 5
Cracking (Concrete)						X		
Surface Damage Spalling or Delamination (Concrete)						X		
Deformation and Damage (Metal)					X		Steel corroded through at inv. both ends	
Corrosion (Metal)					X			
Scour and Stability		X						
Settlement/Rotation			X				Soil settling around failed ends.	

CONCRETE FOOTING AND INVERT SLAB	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: NR
Differential Settlement and Movement						X		
Scour and Stability						X		
Cracking						X		
Surface Damage						X		
Spalling / Delamination / Patches						X		

BARREL ALIGNMENT	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR		RATING: 2
Barrel Alignment		X					Sags in center of road	

CORRUGATED METAL BARREL	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 3
Surface damage		X					Local damgae at D/S end	
Corrosion			X				White stains througout. No Local pitting	
Abrasion	X						No evidence	
Shape (Closed Shape)		X						
Shape (Open Bottom)						X		

SEAMS (CORRUGATED METAL PLATE)	Good (1)	Fair (2)	Poor (3)	Critical (4)	Failed (5)	NR	Comments:	RATING: 3
Infiltration / Exfiltration			X				White stainning prevalent at seams	
Seam Alignment		X						
Seam Bolts/Fasteners		X						
Seam Bolt Holes		X						

COMMENTS:

Date:	12-Jul-18			By: BBass; ABorghei		Sheet No.: 1 of 1	
Address:	See Culvert 3 Forms - Hwy 70 between Florence and Hwy 101					GPS:	
Arrival Time:	14:00	Departure Time:	6:00	Weather (Condition & Temp.):		Sunny, 80F	
Purpose and scope of survey:							
Client:	Wisconsin DOT					Project No	170848.04-INSP
Equipment Model:	4620	Electrode Geometry:		Wenner Electrode Arrangement			
Location and orientation of arrays marked on the site map:				yes			
Comment:	Calibration was done. 100 ohm was read. The actual resistance is 100 ohm.						

Soil type:	Sandy with silt & clay	Soil moisture:	Moist	Soil color:	Brown
Water table:	Water table was not measured				
Soil Description:					

Array No.	Description:
1	Southwest
2	Southeast
3	Northeast
4	Northwest

Test No.	Array No.	Horizontal Distance from Edge of Culvert(ft)	Electrode Spacing “A” (ft)	Electrode Embedment (in)	Measured Resistance (Ω)	Resistivity (Ω*cm)	Comment and corrections:
1	1	10	5	8.4	6.11	8,411	
2	2	-10	5	8.4	9.03	12,430	
3	3	-10	5	8.4	10.51	14,467	
4	4	10	5	8.4	10.65	14,660	

Culvert 3 Inspection Photos

Photo 1

View looking north (downstream) across roadway above culvert. Note unsealed cross crack aligned with culvert (culvert is aligned with white spray paint and culvert marker in distance).

Photo 2

View looking east along south (upstream) embankment.

Photo 3

View looking south down upstream embankment.

Photo 4

Looking down south (upstream) embankment. Note galvanized end structure, which is corroded through at invert.

Photo 5

Upstream channel.

Photo 6

South elevation (looking north). Note corroded invert of galvanized steel end structure.

Photo 7

View looking downstream (north) through culvert.

Photo 8

Typical riveted seam with circumferential seams at 24 in. on center, and one longitudinal seam per ring. Some white corrosion staining visible at seams.

Photo 9

View looking downstream inside culvert showing typical circumferential seams with white staining.

Photo 10

Longitudinal seam, higher portion is lapped over lower portion in photo, and lower portion has evidence of white corrosion products and surficial section loss. Rivets appear to be in good condition at top. Culvert Section 5, approx. 10 ft from upstream end.

Photo 11

Similar location and view to Photo 10.

Photo 12

White corrosion staining at longitudinal seam with some surface irregularities/ pitting.

Photo 13

Downstream watercourse (looking north).

Photo 14

Damage at crown, 1 ft long, near downstream end. Note: Ends of culvert are spiral with crimped seams and appear to have been added on, perhaps with roadway widening; the visible damage is in the end section.

Photo 15

Close up of crown damage near downstream end of culvert.

Photo 16

North elevation (looking south/upstream). Note galvanized steel end structure corroded through.

Photo 17

Looking downstream down south embankment. Some erosion visible upstream of end structure.

Photo 18

View looking west along north shoulder.

APPENDIX E

Laboratory Test Results

Client:	Simpson Gumpertz & Heger, Inc.
Project Name:	WI DOT Culvert Research
Project Location:	WI
GTX #:	308509
Test Date:	08/06/18
Tested By:	jbr
Checked By:	emm

pH by AASHTO T 289

Boring ID	Sample ID	Depth, ft	Description	pH
---	Culvert 1	---	Moist, red silt	6.27
---	Culvert 2	---	Moist, dark brown silt	5.33
---	Culvert 3	---	Moist, dark brown silt	6.33

Notes:

Client:	Simpson Gumpertz & Heger, Inc.
Project Name:	WI DOT Culvert Research
Project Location:	WI
GTX #:	308509
Test Date:	08/06/18
Tested By:	jbr
Checked By:	emm

Minimum Laboratory Soil Resistivity by AASHTO T 288

Boring ID	Sample ID	Depth, ft.	Sample Description	Minimum Soil Resistivity, ohm-cm
---	Culvert 1	---	Moist, red silt	5,682
---	Culvert 2	---	Moist, dark brown silt	2,270
---	Culvert 3	---	Moist, dark brown silt	12,396

Comments: Test Equipment: Nilsson Model 400 Soil Resistance Meter, MC Miller Soil Box
Test conducted in standard laboratory atmosphere: 68-73 F

PO Box 572455 / Salt Lake City UT 84157-2455 / USA
TEL +1 801 262 2448 · FAX +1 801 262 9870 · www.TEi-TS.com

GEOTESTING EXPRESS INCORPORATED
125 NAGOG PARK
ACTON MA 01720-3451
USA

Analysis No.	TS-A1807530
Report Date	28 July 2018
Date Sampled	25 July 2018
Date Received	26 July 2018
Where Sampled	Acton, MA USA
Sampled By	Client

This is to attest that we have examined: Soil for Project Name: WI DOT Culvert Research; Location: WI; Job Number: GTX-308509

When examined to the applicable requirements of:

AASHTO T-291-13	“Standard Method of Test for Determining Water-Soluble Chloride Ion Content in Soil” Method A
AASHTO T-290-16	“Standard Method of Test for Determining Water-Soluble Sulfate Ion Content in Soil”

Results:

AASHTO T-291 - Chloride (Soluble) Method A

Sample	Results		Detection Limit
	ppm (mg/kg)	%[1]	
Culvert 1	<10.	<0.0010	
Culvert 2	<10.	<0.0010	10.
Culvert 3	<10.	<0.0010	

NOTE: [1]Percent by weight as received

Testing Services Analytical Laboratory
3455 South 500 West
Salt Lake City, UT 84115-4234 USA
TEL: +1 801 262 2448
FAX: +1 801 262 9870

CERTIFICATE OF ANALYSIS

AASHTO T-290 – Sulfates (Soluble)

Sample	Results		Detection Limit
	ppm (mg/kg)	%[1]	
Culvert 1	24.	0.0024	10.
Culvert 2	34.	0.0034	
Culvert 3	60.	0.0060	

NOTE: [1]Percent by weight as received

END OF ANALYSIS

USEPA Laboratory ID UT00930

Merrill Gee P.E. – Engineer in Charge

R.I. ANALYTICAL
Specialists in Environmental Services

LABORATORY REPORT

Simpson, Gumpertz & Heger Inc.
Attn: Mr. Brent Bass
41 Seyon Street
Building 1 Suite 500
Waltham, MA 02453

Date Received: 7/24/2018
Date Reported: 7/31/2018
P.O. Number

Work Order #: 1807-15709

Project Name: PROJECT #170848.04, WISCONSIN DOT CULVERT RESEARCH

Enclosed are the analytical results and Chain of Custody for your project referenced above. The sample(s) were analyzed by our Warwick, RI laboratory unless noted otherwise. When applicable, indication of sample analysis at our Hudson, MA laboratory and/or subcontracted results are noted and subcontracted reports are enclosed in their entirety.

All samples were analyzed within the established guidelines of US EPA approved methods with all requirements met, unless otherwise noted at the end of a given sample's analytical results or in a case narrative.

The Detection Limit is defined as the lowest level that can be reliably achieved during routine laboratory conditions.

These results only pertain to the samples submitted for this Work Order # and this report shall not be reproduced except in its entirety.

We certify that the following results are true and accurate to the best of our knowledge. If you have questions or need further assistance, please contact our Customer Service Department.

Approved by:

Paul Perrotti
President

Laboratory Certification Numbers (as applicable to sample's origin state):

Warwick RI * RI LAI00033, MA M-RI015, CT PH-0508, ME RI00015, NH 2070, NY 11726
Hudson MA * M-MA1117, RI LAO00319

R.I. Analytical Laboratories, Inc.

Laboratory Report

Simpson, Gumpertz & Heger Inc.

Work Order #: 1807-15709

Project Name: PROJECT #170848.04, WISCONSIN DOT CULVERT RESEARCH

Sample Number: 001
Sample Description: CULVERT 1
Sample Type : GRAB
Sample Date / Time : 7/10/2018 @ 11:18

PARAMETER	SAMPLE RESULTS	DET. LIMIT	UNITS	METHOD	DATE/TIME ANALYZED		ANALYST
Chloride	65	5.0	mg/l	EPA 300.0	7/25/2018	18:02	HHC
Sulfate	10	5.0	mg/l	EPA 300.0	7/25/2018	18:02	HHC

Sample Number: 002
Sample Description: CULVERT 2
Sample Type : GRAB
Sample Date / Time : 7/11/2018 @ 14:00

PARAMETER	SAMPLE RESULTS	DET. LIMIT	UNITS	METHOD	DATE/TIME ANALYZED		ANALYST
Chloride	12	5.0	mg/l	EPA 300.0	7/25/2018	18:16	HHC
Sulfate	6.8	5.0	mg/l	EPA 300.0	7/25/2018	18:16	HHC

Sample Number: 003
Sample Description: CULVERT 3
Sample Type : GRAB
Sample Date / Time : 7/12/2018 @ 14:45

PARAMETER	SAMPLE RESULTS	DET. LIMIT	UNITS	METHOD	DATE/TIME ANALYZED		ANALYST
Chloride	<5.0	5.0	mg/l	EPA 300.0	7/25/2018	18:31	HHC
Sulfate	<5.0	5.0	mg/l	EPA 300.0	7/25/2018	18:31	HHC

APPENDIX F

WisDOT Employee Training Slides

WHRP 0092-17-05 ALUMINUM CULVERT POLICY RESEARCH

Project Summary and Training Slides for WisDOT Personnel

Jesse L. Beaver and Brent J. Bass
Simpson Gumpertz & Heger Inc., Waltham, MA
February 2019

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

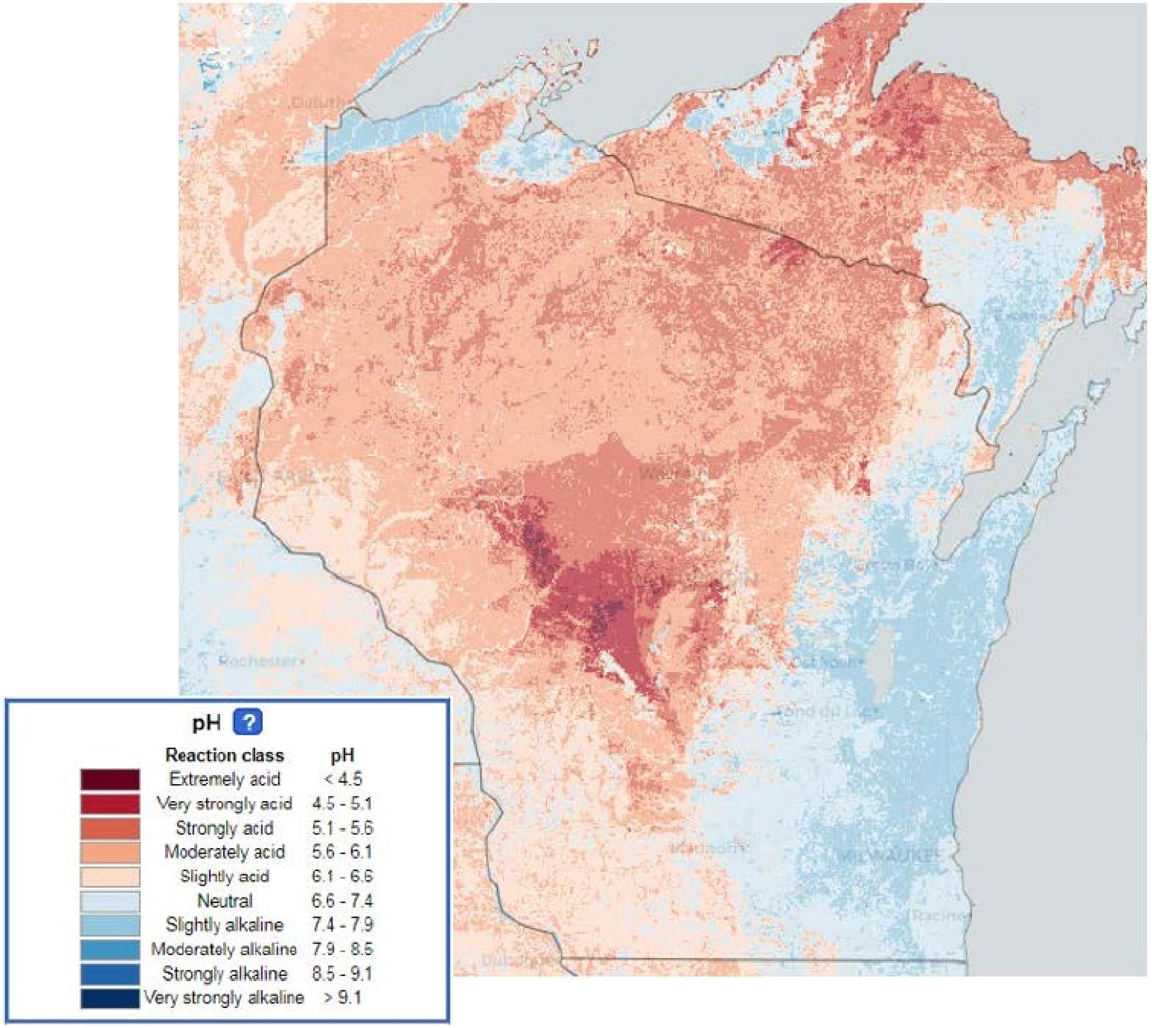
Outline

- Expected Aluminum Culvert Performance and Corrosion Concerns
- Detail and Requirements for Isolation Membrane
- Overall Summary of Research Project WHRP 0092-17-05
- Proposed Updates to WisDOT Literature

EXPECTED ALUMINUM CULVERT PERFORMANCE AND CORROSION CONCERNS

Expected Aluminum Culvert Performance in Wisconsin

- Aluminum culverts are expected to perform well in the natural Wisconsin environment at sites that meet the following:
  - Soil and water pH between 4.5 and 9
  - Soil and water resistivity > 500 Ω-cm
  - Abrasion Level 1 to 3 (non- to low-abrasion site)
- These criteria cover most of WI and will result in aluminum culverts with high resistance to general corrosion
  - Soil and water sample laboratory testing is recommended for new culvert sites, and all new culvert sites should be evaluated for abrasion based on established Caltrans/FHWA methods
- Aluminum culverts will, however, develop localized pitting corrosion if concentrated chlorides are allowed to contact them and dry on the aluminum surface



Abrasion Evaluation for Aluminum Culverts

- Classify a site as Abrasion Level 1 to 6 based on bed load and flow velocity from a 2 to 5 yr flood
- Bed load evaluation by visual examination (no lab tests)
- Table at right adapted to aluminum culverts from Caltrans Highway Drainage Manual
  - Caltrans HDM includes additional information for other culvert materials
- A second table is provided in the HDM to link bed load materials/particle sizes, water depths, and non-scour velocities

Level	Bed Load Description	Flow Velocity	Notes Related to Aluminum Culvert Use
1	Bed loads of silts and clays or clear water with virtually no abrasive bed load.	No velocity limitation.	All standard pipe materials allowed; no abrasive-resistant protective coatings needed for metal pipe.
2	Moderate bed loads of sand or gravel.	1 to 5 ft/sec[1]	Generally no restriction. Polymeric or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential.
3	Moderate bed load volumes of sands, gravels, and small cobbles.	> 5 to 8 ft/sec[1]	Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential.
4	Moderate bed load volumes of angular sands, gravels, and/or small cobbles/rocks.[2]	> 8 to 12 ft/sec	Aluminum pipe not recommended. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
5	Moderate bed load volumes of angular sands and gravel or rock.[2]	> 12 to 15 ft/sec	Aluminum pipe not allowed. Lining alternatives include various polymeric liners or cementitious liners/invert pavement.
6a	Moderate bed load volumes of angular sands and gravel or rock.[2]	> 15 to 20 ft/sec	Aluminum pipe not allowed. Abrasion-resistant coatings over steel pipe are not expected to provide acceptable service life. Lining alternatives include specific polymeric liners or cementitious liners/invert pavement with conditions. For new/replacement structures, consider "bottomless" structures.
6b	Heavy bed load volumes of angular sands and gravel or rock.[2]	> 12 ft/sec	

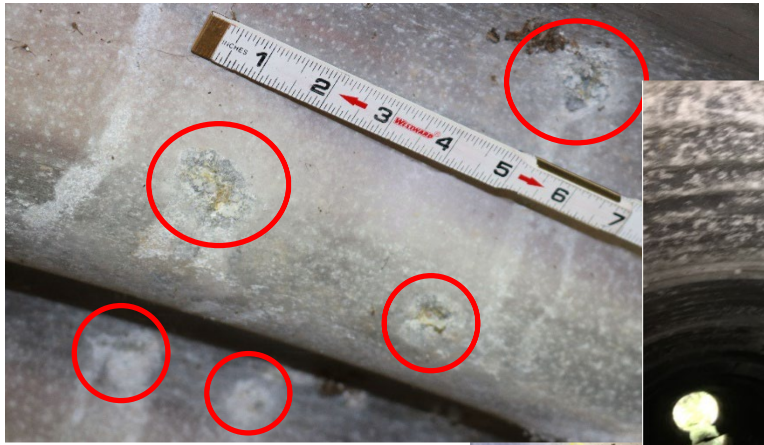
1. If bed load volumes are minimal, a 50% increase in velocity is permitted.
2. For minor bed load volumes, use Level 3.

OK

NR

Aluminum Culvert Pitting Corrosion

- Aluminum will corrode by pitting corrosion when exposed to concentrated chlorides.
- Research found a correlation between likelihood of corrosion, prevalence of cracked pavement, and increased culvert age.
- No obvious correlation between likelihood of corrosion and ADT, fill depth, or culvert length.
- Once pits form, they do not stop and will continue to drill their way through the aluminum.



Wisconsin Usage of Chloride-Based Road Treatments

- Usage of chloride-based deicing salts has been steady.
- Usage of chloride-based anti-icing brine has increased.
- Even newer treatments, such as Beet 55 (beet juice), are used as additives to chloride-based salts or brines and the solutions will still be aggressive to aluminum.

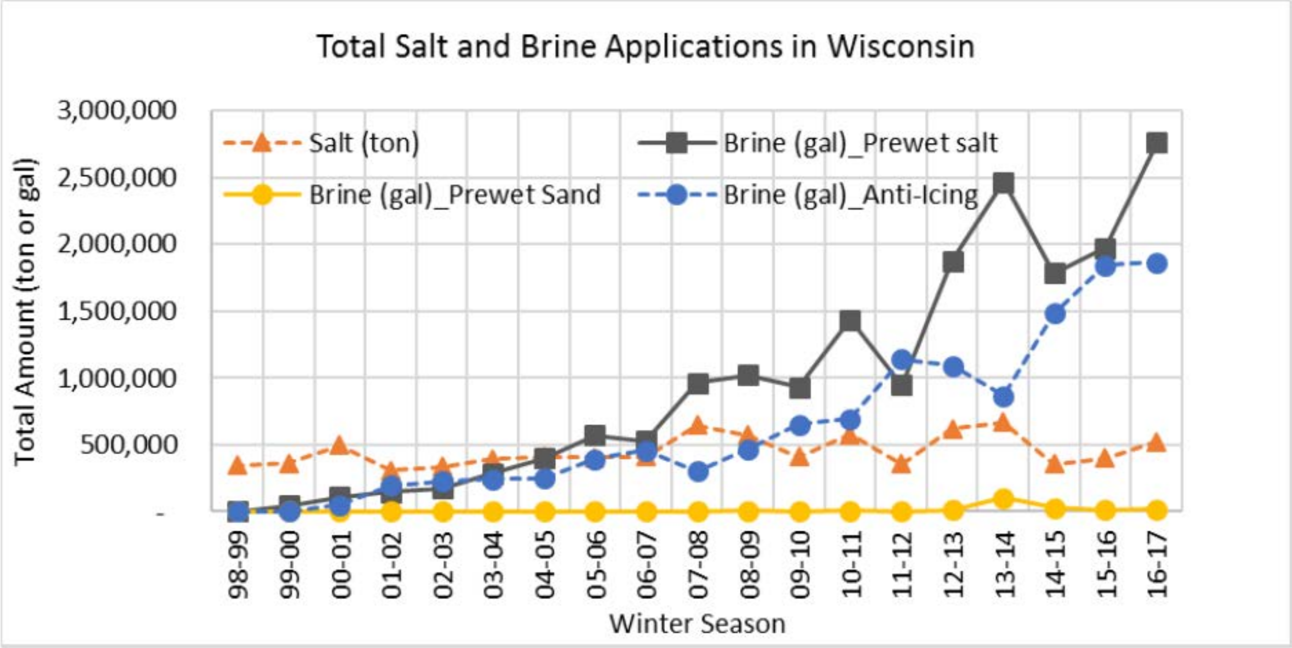
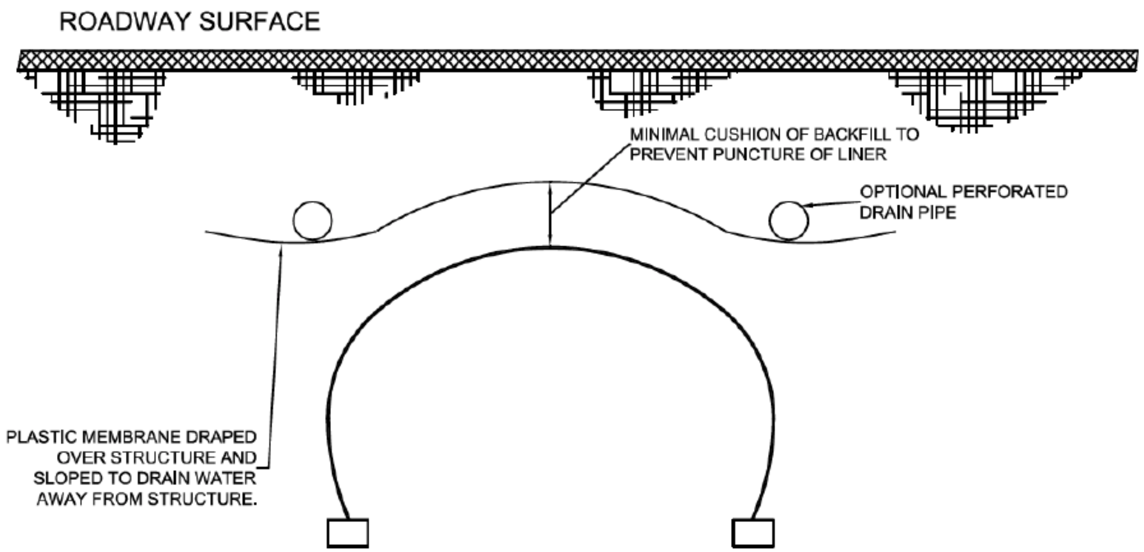


Figure Reference: WHRP Project 0092-17-03

DETAIL AND REQUIREMENTS FOR ISOLATION MEMBRANE

Backfill Isolation Membrane – Concept

- Detail at right conceptually shows a backfill isolation membrane detail from a metal culvert manufacturer.
- Membrane should be extended at least for the trench width and for 10 ft from the edge of pavement or to the end of culvert.
- Backfill below the membrane should have limited chloride content; best practice is for the backfill in contact with the culvert to be free-draining.



Backfill Isolation Membrane – Specification

- Currently, there is no consensus specification for the membrane itself
- Ohio DOT requires a membrane but the referenced material specs are for sheet waterproofing (precast concrete culvert joints)
  - Per Standard Specifications:
    - Min. thickness = 0.06 in. (ASTM D1777)
    - 300% min. elongation (ASTM D412 Die C)
    - 40 lb min. puncture resistance (ASTM E154)
  - Per Construction Specs:
    - Continuous sheet extending at least 10 ft outside of paved shoulder and for trench width
    - No field-constructed seams
- State specifications for membrane protection of MSE wall steel reinforcement generally point to a variety of ASTM specifications – see right as example from NH DOT

From NH DOT MSE wall special provisions
(other nearby states have similar requirements):

Property	Test Method	Property Requirements
Thickness [mil (mm)]	ASTM D 1593	30 (0.75) ± 5% min.
Specific Gravity	ASTM D 792	1.20 min.
Dimensional Stability (% change)	ASTM D1204	5 max.
Tensile Strength [pounds per square inch (kPa)]	ASTM D 882	2300 (16,000) min.
Tear Resistance [pounds (N)]	ASTM D 1004 Die C	8 (35) min.
Low Temperature Brittleness [°F (°C)]	ASTM D 1790	-20 (-30) min.
Resistance to Soil Burial (% strength retained)	ASTM D 3083	95 min.
Hydrostatic Resistance [pounds per square inch (kPa)]	ASTM D 751 Method A	75 (520) min.

RESEARCH PROJECT WHRP 0092-17-05
OVERALL SUMMARY

Overall Summary of WHRP 0092-17-05 Findings

- Aluminum culverts are very resistant to general corrosion if installed at sites with soil and water pH between 4.5 and 9 and resistivity > 500 Ω-cm.
  - Testing can be done in a laboratory on samples collected from a new culvert site.
- All culvert sites can be evaluated for abrasion resistance according to established Caltrans/FHWA methods from visual examination of bed load and flow velocity based on 2 to 5 yr event.
  - Aluminum culverts should provide acceptable performance for Abrasion Level 1 to 3 sites.
- Once environmental conditions are met, aluminum culverts will provide a minimum service life of 50 to 75 yrs when not influenced by other corrosion mechanisms, such as contact with chloride-based roadway deicing salts.
- Fill height tables established by culvert design in accordance with the AASHTO LRFD Bridge Design Specifications (and WisDOT modifications) provide a comparable level of safety among culvert types; there is no technical basis for ADT restrictions based on culvert material.
- The most economical method to protect aluminum culverts from chloride-based deicing salts that can migrate though soil fill, unpaved shoulders, and cracked pavement is through inclusion of an impermeable isolation membrane in the backfill above the structure and limiting the chloride content of the backfill under the membrane. Also, consider specifying this backfill as free-draining.

PROPOSED UPDATES TO WISDOT LITERATURE

Proposed Updates to WisDOT Bridge Manual

- Update Chapter 36 to identify other types of box culverts other than “reinforced concrete closed rigid frames” and remove the prohibition on aluminum box culverts. Identify aluminum structural plate structures as acceptable closed and three-sided culverts when designed in accordance with the AASHTO LRFD Bridge Design Specifications. Identify requirements for isolating aluminum box culverts from chloride-based deicing salts by use of an impermeable isolation membrane, testing and limiting chloride content below such membranes, and consider specification of free-draining backfill in this area.
- Update Chapter 9 to include aluminum as a culvert material.

Proposed Updates to WisDOT FDM

- Proposed Facilities Development Manual (FDM) updates include the following for Chapter 13-1-15 Culvert Material Selection Standard:
  - Update Section 15.2 to include corrugated aluminum in Classes III-A, III-B, and any other applicable class. Remove restriction on culvert materials other than reinforced concrete for sites with ADT greater than 7,000 unless sound engineering judgment and explanation are provided. Consider updating culvert material selection to use a similar process as the Ohio DOT culvert design process flow chart. Indicate that environmental conditions at aluminum culvert sites must meet pH, resistivity, and abrasion requirements and that an impermeable isolation membrane must be installed above the top of structure and below pavement, with a limit on the chloride ion content of the backfill below the membrane, and consider specification of this backfill as free-draining.
  - Update Table 15.2 to allow corrugated aluminum culvert pipe with diameters up to 60 in., corrugated aluminum arch pipes, and corrugated aluminum structural plate structures, including arches, closed-bottom culverts, and box culverts, to have similar ADT restrictions to other flexible culverts, and make reference to the environmental limitations and isolation membrane notes in the bullet above.

Proposed Updates to WisDOT FDM

- Proposed FDM updates for Chapter 13-1-15 Culvert Material Selection Standard (continued):
  - Update Section 15.4 to include pH and resistivity testing of soil and water samples collected from all new culvert sites, update the note on aluminum culvert restrictions to make the ADT limitation in line with other flexible culverts, and add description of environmental limits and impermeable membrane with low-chloride-content backfill below the membrane as described on the previous slide, consider specification of free-draining backfill below the membrane. Add a sentence noting that new culvert sites should be evaluated for abrasion. Aluminum shall only be used at sites with Abrasion Levels 1 to 3.
  - Update Section 15.5 to include abrasion classification for all culvert sites based on Caltrans and FHWA guidelines and include relevant information to assess culvert sites. Abrasion classification should be based on a visual survey of bedload material with flow velocity based on a 2 to 5 yr flow event.
  - Update Section 15.6 and Table 15.3 to ease the restrictions on aluminum culvert use based on ADT, and update with reference to the updated versions of Sections 15.2 and 15.4, described above.

Proposed Updates to WisDOT FDM

- Proposed FDM updates for Chapter 13-1-25 Fill Height Tables:
  - Update text in Section 25.2 to note that all fill height tables should be based on design in accordance with AASHTO LRFD Bridge Design Specifications. Consider potential fill height increase for aluminum culverts with free-draining granular backfill, and perhaps compaction of this backfill.
  - Update fill height table Attachments 25.2, 25.6, 25.7, and 25.8 for corrugated aluminum pipe and corrugated aluminum structural plate structures of standard shapes. Consider anticipated abrasion section losses over the design life when developing minimum thickness requirements and fill height tables; ensure that other metallic structures are similarly designed including appropriate anticipated corrosion and abrasion section losses.

Proposed Updates to WisDOT Standard Specs

- Proposed updates to the WisDOT Standard Specifications for Highway and Structure Construction include the following:
  - Update Table 520-1 to include aluminum as an allowable culvert material for applicable classes of culvert pipe defined in updates to FDM 13-1-15 Section 15.2.
  - Update Section 520.3 to identify where the impermeable isolation membrane should go within the backfill envelope, and require that the membrane be sloped away from the structure, extending down the embankment for at least 10 ft from pavement or to the end of the culvert, and at least equal to the trench width. Update the section to require backfill below the membrane to have limited chloride content, and consider specification of free-draining backfill in this area.
  - Either develop a material and product specification or a performance-based specification for impermeable backfill membranes and include it in a new section in the Standard Specs, with reference from Section 520.3, or add the information directly to Section 520.3 if that is the only location the membrane would be used.
  - Update Sections 525 and 527 to include notes that backfill between the isolation membrane and structure must be tested for chloride ion concentration and have a concentration less than 100 ppm. Give reference to a WisDOT standard method to measure chloride ion content of backfill soils. Consider specification of the backfill in this area as free-draining.