CORROSION OF GALVANIZED METAL CULVERTS

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Corrosion is a major factor in the life expectancy of metal culvert structures. Corrosion resistance, therefore, is of special interest to the user of galvanized culverts. A thorough investigation was conducted on 287 galvanized culverts located on the 56-mile (90-km) route of I-75 in the Upper Peninsula of Michigan. The service life of the culverts inspected ranged from 10 to 14 years. Visual observations and electrical tests were made at the culvert site to define the degree of corrosiveness. Water and soil were sampled and chemically analyzed to determine their relationship to or influence on deterioration. Significant corrosive attack was noted in 39 culverts. Test results revealed that major deterioration was occurring from the exterior (soil side) of the culvert. Exposure conditions found to cause excessive deterioration in uncoated galvanized culverts are dissimilar soil contacts, presence of organic soils, and differentials in aeration and soil moisture. Sulfates and chlorides were contributing factors to the excessive culvert deterioration as was biological corrosion in the form of sulfate-reducing bacteria.

•AN investigation of the corrosion performance of galvanized metal culverts was initiated by the Michigan Department of State Highways and Transportation in June of 1972 upon discovery of a severely corroded culvert that resulted in a collapsed roadway shoulder. A preliminary inspection along the I-75 route suggested that the deterioration might be widespread; therefore, an investigation was needed to define the scope and magnitude of the problem in Mackinac and Chippewa Counties where galvanized metal culverts were installed and to identify environmental factors influencing culvert durability.

Michigan has culvert installations using many different materials for drainage structures—galvanized steel, concrete, plastic, vitrified clay, and aluminum are all in service. Selection of culvert material is dictated by specific drainage conditions, design requirements, and economic considerations. Along Interstate 75 in Mackinac and Chippewa Counties, corrugated galvanized metal culverts were installed. The lightweight, securely banded, corrugated steel culverts met the necessary design criteria for the soft soil conditions prevailing in that area.

Durability (or service life expectancy) should be a prime consideration in the design of any underground structure. There is a general tendency of designers to look at fluid and strength requirements for drainage structures without establishing service life. The years of service a culvert gives are an important consideration for these essential installations along a heavily traveled highway. Frequent culvert maintenance and periodic replacement create high maintenance expenditures.

Metallic corrosion is a major factor in the life expectancy of metal culvert structures. Corrosion resistance, therefore, is of special interest to the users of galvanized culverts.

In the testing program initiated in this study to evaluate corrosion performance, 287 installations of galvanized culverts in various exposures were reviewed. Analysis

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of the data collected established a relation with aggressive parameters unfavorable to economical culvert life and provided a basis for a more knowledgeable approach to galvanized culvert corrosion.

CORROSION

Corrosion is the deterioration and loss of a metal due to electrochemical attack. The electrical energy needed for a corrosion reaction to occur is supplied from a galvanic cell.

In a basic galvanic corrosion cell (Figure 1) there must exist a potential difference between 2 points that are in electrical contact and immersed in an electrolyte. The electrolyte in underground corrosion refers to the soil moisture or liquid in contact with the metal and includes any other chemicals contained therein. Any 2 areas on a metal surface, known as a cathode and anode, that have a difference in potential (volts) and are within an electrolyte constitute the necessary components for a flow of current. When these conditions exist, current flows from the anode through the electrolyte to the cathode area and then through the metal to complete the circuit. The electrically charged atoms, known as ferrous ions, break away from the anode area. It is here that corrosion (loss of metal ions) occurs. The cathode is the area to which the current flows through the electrolyte and where hydrogen ions from the water are deposited. Any number of corrosion cells may operate on the same piece of metal as a network, each with its own anode and cathode.

The potential difference between the anode and cathode that drives the corrosion reaction can come from various sources. Almost any chemical or physical difference between the anode and cathode areas will support a corrosion cell, whether the difference is in the electrolyte or the metal.

All corrosion cells are associated with a flow of electricity. They operate according to Ohm's Law ($I = E/R$); that is, the amount of current flowing, and hence corrosion, decreases as the resistance of the circuit increases. The amount increases as the potential difference between the anode and cathode increases. Therefore, the rate of corrosion is dependent on the resistance of the electrolyte, which regulates the amount of current flow. Wherever this current leaves the metal and flows through the electrolyte, corrosion will occur.

Various types of corrosion cells are recognized (1). Those associated with culvert corrosion include (a) galvanic composition cells, (b) electrolysis or stray current, (c) biochemical corrosion cells, (d) oxygen concentration cells, and (e) salt concentration cells. The galvanic composition cell is established when dissimilar metals are in mutual contact in an electrolyte. The metal higher in the electromotive series acts as the anode from which current will flow and metal loss will occur. Dissimilarities in composition along the surface of a metal can also create a galvanic cell that supports corrosion. Electrolysis or stray current from improperly grounded dc motors or generators can also cause extensive and rapid corrosion. Biochemical corrosion is attributed to the direct or indirect attack of microscopic bacteria. These bacteria act as another environmental factor that accelerates the process of corrosion. The oxygen-concentration type of corrosion is set up when a metal within an electrolyte has 2 areas on its surface with different concentrations of oxygen. Oxygen content is influenced by many factors, such as the oxygen content of the water, the rate of diffusion, and the permeability of the corrosion products on the metal. High corrosion rates have been observed in oxygen concentration cells. The oxygen-deficient areas become the anodes, and corrosion occurs at these locations. The salt concentration cell is formed when a metal is in contact with an electrolyte in which the salt concentration varies. The area of the metal in the more concentrated solutions becomes the anode and corrodes.

PHYSIOGRAPHY

Study Area

The study was conducted on 56 miles (90 km) of I-75 in Mackinac and Chippewa Counties, as shown in Figure 2. All of the culvert sites inspected are located within the I-75 right-of-way in these 2 counties.

Surface Geology

This area lies in the Great Plains Region, with surface details formed during the Pleistocene Epoch. Most of the study area was covered by the main and post stages of Glacial Lake Algonquin and has a relief of less than 150 ft.

Lake bed deposits associated with Glacial Lake Algonquin are the most extensively mapped geomorphic feature in the study area, forming the surface for 92 percent of the study area. Predominantly sand, silt, and clay, these flat-lying deposits have a high water table and sluggish groundwater movement. Many of these lake-bed deposits are very poorly drained low areas, forming large swamps and wetlands. These swamps, located within the lake-bed deposits, make up 67 percent of the area traversed by I-75 in Mackinac County and 22 percent in Chippewa County.

Bedrock Geology

The study area lies on the northern rim of the Michigan Basin, where the edges of 12 different bedrock formations subcrop between St. Ignace and Sault Ste. Marie (Figure 3). Bedrock is found at or near the surface throughout most of the Mackinac portion of the study. Outcropping occurs primarily in the southern part of the county near St. Ignace, the M-123 interchange, Carp River, and the M-134 interchange. The overlying drift is much thicker in the Chippewa County portion of the study area, and no bedrock outcrops are encountered.

Of the 5 rock formations traversed in Mackinac County only the Salina formation is of particular interest. At or near the surface between M-123 and M-134, this formation is composed of limestone and dolomite interbedded with thin beds of salt, anhydrite, and gypsum. These evaporites greatly influence the soils in this area. The highest concentrations of sulfates and chlorides in the soils were found between M-123 and M-134. The bedrock underlying Chippewa County has a much thicker glacial drift mantle and does not directly influence the soil to the extent that it does in Mackinac County.

Soils

Mackinac and Chippewa Counties lie in the Podzol Soil Region of Michigan. The character of major soil associations existing along the I-75 route is considerably different in each county (Figure 4).

The Mackinac portion of the study area has swampy, poorly drained soils with a high organic content throughout most of its length. Between the Mackinac Bridge and Castle Rock Road the limestone bedrock outcrops or is very near the surface. Any thin discontinuous mantle of soil that does exist in this area is primarily well-drained sands and sandy loams. From Castle Rock Road to the M-134 interchange the soils are generally very poorly drained mucks, peats, sands, and loams. Imperfectly drained to well-drained clays and loams are the third and largest group of soils encountered in the study. These soils are mapped in most of the remaining area from the M-134 interchange through Sault Ste. Marie.

Figure 1. Corrosion cell.

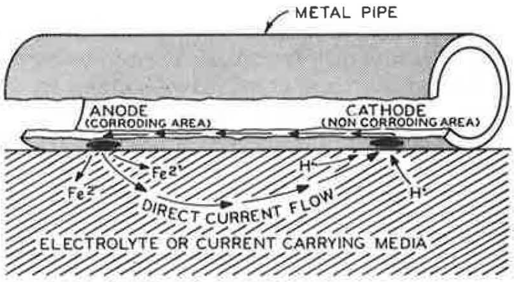


Figure 2. Location of the study area.

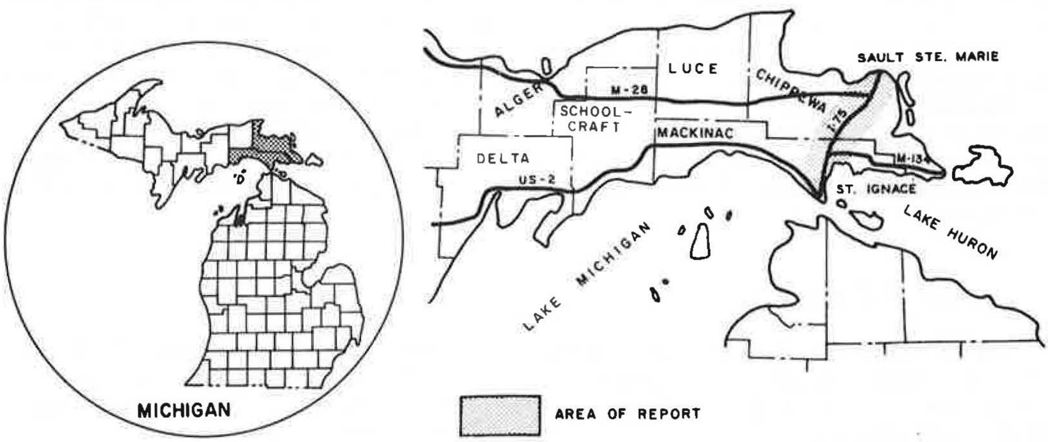


Figure 3. Major rock types.

BED ROCK GEOLOGY		
Dm	Mackinac Breccia	Limestone and Limestone Breccia, Chert, Shale, and Gypsum Blocks
Ss	Salina Formation	Shale, Interbedded with Limestone and Dolomite; Anhydrite; Gypsum; Rock Salt
Se	Engadine Dolomite	Massive, Hard Dolomite Interbedded with Limestone
Sm	Manistique Dolomite	Hard High Calcium Dolomite and Magnesian Limestone
Sbb	Burnt Bluff Limestone	Hard Limestone and Dolomitic Limestone. Some Beds of High Calcium Limestone
Smc	Cataract Group	Thick Bedded Dolomite, Gypsum, Ferrous, Calcareous, and Dolomitic Shale Members Near the Base of the System
OR	Richmond Group	Shale, Limestone, Argillaceous Limestone, and Interbedded Shale and Argillaceous Limestone
OC	Maysville Group	Bituminous and Dolomitic Shale
OT	Trenton Limestone	Limestone, Argillaceous Limestone and Dolomite
OBR	Black River Group	Limestone and Argillaceous Limestone
Oh	Hermansville Group	Sandstone and Dolomite
CLS	Lake Superior Sandstone Group	Sandstone

TESTING PROGRAM

The testing program consisted of a series of on-site determinations as well as laboratory analyses. Electrical resistivity and pH measurements were made at each culvert installation. The large number of sites inspected and the time constraints placed on the study by the urgency of the problem necessitated limiting the number of soil and water samples taken for chemical analysis. All tests made on the soil were performed on soils representative of that in which the culvert was lying; water samples tested were taken from the stream channel within the culvert.

Culvert Visual Examination and Rating

One aim of this study was to establish an inspection method that would provide a systematic procedure for defining the extent of the deterioration on a buried metal culvert. Each culvert was visually inspected and rated on a scale from 90 to 0 as adopted by the National Corrugated Steel Pipe Association (Figure 5). The top, side, and invert were carefully examined and assigned a rating. The lowest value was used to designate a measure of the culvert's service performance. Exterior culvert examination was limited to the top of the end section. Where physically possible, the entire length of the culvert interior was inspected and information recorded as to the general condition and estimated metal loss. Metal loss through corrosion was determined visually, aided with soundings made by a geologist's hammer.

Environmental Evaluation

Various physical and environmental conditions recorded at each site were watershed characteristics; culvert grades; stream rate of flow and direction; high water line; stream load in terms of abrasiveness, quantity, and sedimentation; soil series of the surrounding native soil; and the nature of the culvert bed material.

Electrical Resistivity

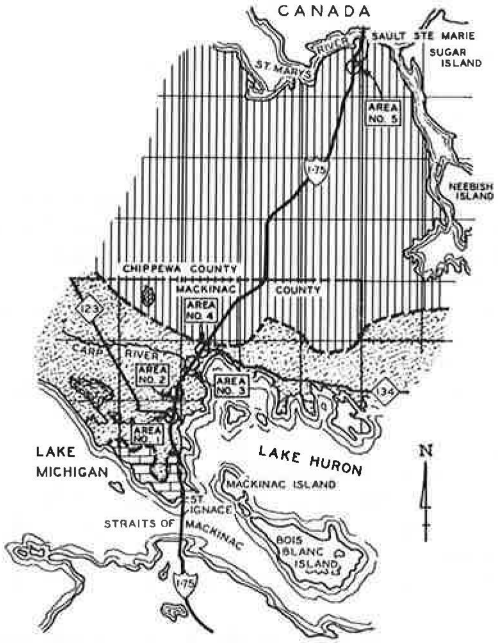
Electrical resistivity has universally been accepted as a rapid field testing method that indicates conduciveness to electrochemical corrosion. Electrical resistance is directly related to the quantity of dissolved salts in the soil and water; the higher the dissolved salt concentration the lower the resistivity. Several soil resistivity measurements using a Keck earth resistivity instrument were made at each culvert site to identify the area of lowest resistivity, which reflects the most corrosive condition. This aggressive area was selected for further testing and sampling.

A "minimum" soil resistivity was also obtained in the field using a soil resistance box and measuring the conductance with a Michi-Mho AC instrument in accordance with the apparatus and procedure developed by Beaton and Stratfull (2). This value of "minimum" resistivity provides a base level to which corrosion can be related.

Spontaneous Potential

An important consideration in any corrosion investigation is the detection of stray electrical currents within the earth. These currents may owe their origin to man-made mechanisms or naturally occurring phenomena and are known to cause rapid metal deterioration. Electrical currents flowing through the earth, regardless of their origin, are associated with potential gradients. A surface measurement of these gradients, called spontaneous potential, has been widely used in geophysical prospecting and is readily adaptable to corrosion analysis. Potentials were measured and a survey of mapped potential values was compiled for background data. Detection of large

Figure 4. General soil survey.



GENERALIZED SOIL CLASSIFICATIONS			
SYMBOL	GENERAL TEXTURAL CLASSIFICATION	GENERAL DRAINAGE CONDITIONS	MAJOR SOIL ASSOCIATION
	Well Drained	Limestone Bedrock Sands and Loams	Moran, St. Ignace, Johns Wood and Alpena
	Poorly Drained	Organic Deposits Sands and Loams	Muck, Peat, Roscommon, Saugatuck, Satago, Bruce and Angelica
	Imperfectly to Well Drained	Clays and Loams With Small Organic Deposits	Ontonagon, Bergland, Pickford, Muck and Peat

FIVE MOST SEVERLY CORROSIVE AREAS
AREA NUMBER 1 - 5 severely deteriorated culverts.
AREA NUMBER 2 - 6 severely deteriorated culverts.
AREA NUMBER 3 - 12 severely deteriorated culverts.
AREA NUMBER 4 - 3 severely deteriorated culverts.
AREA NUMBER 5 - 4 severely deteriorated culverts.

Figure 5. Rating scale for culvert inspection.

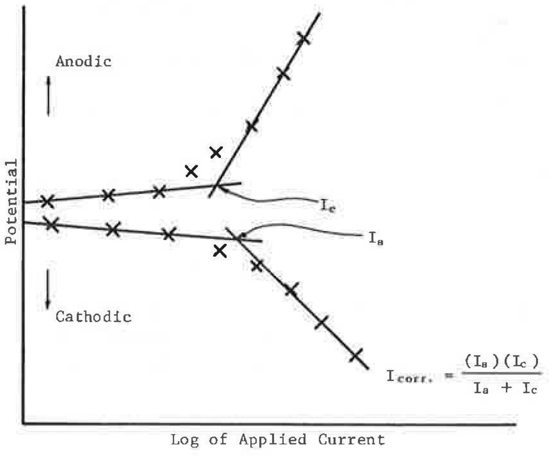
Visual Evaluation

	Rating	Comments
Top	________	______________________
Sides	________	______________________
Invert	________	______________________
Pipe exterior	________	______________________

VISUAL RATING SCALE:

90 Galvanizing intact
75 Galvanizing partly gone, some rust
50 Galvanizing gone, significant metal loss
25 Deep pitting, heavy metal loss, metal can be perforated with a sharp metal probe
0 Metal perforated

Figure 6. Polarization curves.



variances of mapped potentials would expose possible interference currents.

Polarization Test

Every electrochemical cell has an associated electric current that is directly related to the rate of corrosion. The polarization test is a technique used to measure the composite effective value of corrosion current, from which one can estimate corrosion occurring at the time data are obtained. Monitoring changes in electrical potential between the test specimen and soil induced by an impressed current allows a determination of the corrosion current.

By applying external direct currents both cathodically and anodically, the local galvanic action characteristic of the corrosion of buried metals is reduced to zero. A plot of the potentials measured versus the incrementally applied current determines where a change in slope or break occurs. This plot has important significance and is shown in Figure 6. The break in the curves where the two straight-line portions intersect represents the anodic and cathodic current (identified as I_a and I_c respectively) for the galvanic couples on the corroding metal. Pearson (3) from his studies derived an equation (Figure 6) that describes the corrosion current (I_{corr}), and with the use of Faraday's Law the weight of metal loss on a corroding metal surface can be calculated from this current.

The equipment used to measure the polarization voltages was a Sheppard's resistivity apparatus modified to perform according to the polarization circuitry developed by Lindberg (4). In order to more adequately represent the effects of all possible galvanic couples created on a large surface area of a culvert, this test method was conducted in the field.

Hydrogen Ion Concentration

Acidity or alkalinity is one parameter used to describe the aggressiveness of the natural environment. The pH investigations were directed toward determining the acidity and alkalinity of the culvert environment and correlating pH values with conditions that would be corrosive to metal culverts. To ensure representative measurements, all pH values for soil and water were obtained in the field at the culvert sites using portable pH electrometers.

Laboratory Measurements

Qualitative and quantitative chemical analyses were performed on water and soil samples to determine the presence or absence of specific ions. Water samples collected at every installation containing water were analyzed for their content of dissolved solids, chloride, calcium, magnesium, iron, sulfate, and hardness (as calcium carbonate). Total alkalinity was also measured and associated with dissolved solids and calcium in a common test called Langelier's Saturation Index (5).

Soil sample analysis included determination of the soluble quantities of chloride, sulfate, calcium, magnesium, and total iron concentrations.

Several metal samples were obtained from the severely corroded culverts for microscopic inspection. Each culvert sample was examined as to corrosion products and characteristic forms of corrosive action.

STUDY FINDINGS

This study involved the examination of 287 galvanized metal culverts. None of these culverts were bituminous-coated or paved. When inspected the culverts ranged in age from 10 to approximately 14 years. In terms of metal thickness the installations varied

Table 1. Culvert condition from visual evaluation.

Rating[a]	Number of Culverts
90	137
75	84
50	17
25	18
0	21

[a]National Corrugated Steel Pipe Association scale (see Figure 5).

from 16- to 8-gauge. Three basic classes were surveyed: circular corrugated metal pipes, corrugated metal arch pipes, and corrugated metal structural plate culverts. Each culvert structure was fabricated out of copper steel base metal galvanized by a hot-dip process with no less than 2 ounces of coating per square foot.

Records of tested stock reports on the installed galvanized culverts were reviewed to determine the possibility of a common materials factor related to the incidence of corrosion. It was found that a common denominator did not exist.

The field inspection revealed rather large differences in culvert performance in spite of the small differential in the range of culvert ages. All the culverts classified in Table 1 have been in service for an average of 11 years. As seen in the table, 39 culverts classed as 0 or 25 exhibited signs of heavy metal loss. Most of the severely corroded culverts, 30 out of 39, are contained within 5 geographic areas (Figure 4).

Metal samples were obtained from 15 perforated culverts for microscopic inspection. In 12 out of the 15 samples, the greater pit depth was found on the outside of the culvert sample. These observations coupled with the field inspections indicate that, although there is some corrosion activity taking place on the inside of the culverts, the major deterioration is occurring from the exterior, with the soil as the corrosive controlling factor.

Resistivity Results

Soil resistivity measurements taken at 277 culvert sites varied from a minimum of 684 ohm-cm to a maximum of 15 242 ohm-cm. The resistivity ranges and their relationship to corrosion are given in Table 2. At 188 culvert sites, which is 68 percent of total sites tested, the soil resistivities ranged from 684 to 4500 ohm-cm. This low range of resistivity offers little resistance to the flow of corrosion current and may be considered as a highly aggressive environment. It is significant to point out, however, that many culverts in excellent condition were found within this same range.

Water resistivity values obtained at 155 sites varied from a minimum of 311 ohm-cm to a maximum of 19 500 ohm-cm. As seen in Table 2, there were very few culvert sites containing water with resistivities over 4500 ohm-cm. Although this indicates high possibilities for corrosive action on the interior of the culvert, evidence of interior corrosion by runoff water was not established in this study through other tests.

It is apparent that the resistivity by itself does not ensure the occurrence of corrosion; it will, however, identify a potentially corrosive environment for metal culverts.

Electrolysis or Stray Current

An important form of underground corrosion recognized today is electrolysis or stray current corrosion. This corrosion results when direct current emanating from a source external to the buried pipe flows to the pipe and is eventually discharged from the pipe wall.

Examples of external sources of current include improperly grounded electric generators or equipment that can leak currents that travel through a low-resistance soil and support corrosion. Different lithologies in bedrock strata can also generate electrical currents. Potentials on the order of 1700 millivolts have been associated with ore deposits. A common source for stray cur-

Table 2. Relationship of corrosion to resistivity.

Resistivity Range (ohm-cm)	Corrosiveness	Number of Occurrences	
		Soil	Water
0-2000	Severe	100	88
2000-4500	Heavy	88	47
4500-6000	Mild	29	6
6000	Little or none	60	14

rent corrosion is cathodically protected structures installed nearby.

A thorough investigation of the culvert's surrounding area with respect to any neighboring electric current sources was made in the study area. Spontaneous potential measurements were collected at each culvert site for analysis. A comparison of potentials taken at the corrosive sites against those in an area of no corrosion activity was used to distinguish any pipes exposed to interference currents. This analysis reflects no evidence of any culverts influenced by stray currents from an external source. Stray current corrosion is clearly not a factor in the culvert deterioration in this investigation.

pH Results

The pH was measured from May to August in a widely distributed topography consisting of pasture, tilled land, forests, and swamps. The soils classified in this region are of the Great Podsol Group, which is generally acidic. Th pH values of the soils tested at the culvert installations, however, were found to be near neutral. The average for all sites was 6.7, and it varied within a narrow band of 5.9 to 8.5. The surface water runoff at 154 culverts had a pH range of 5.7 to 8.6, with an average of 6.8. It is felt that the neutral soil and water pH measurements observed eliminate the possibility that culvert deterioration in this study area is caused by acidic corrosion.

Statistical Interpretations

Oftentimes a statistical examination will bring forth relationships that could not be seen otherwise. Data compiled on all culverts inspected were analyzed with statistical methods. A multiple linear regression was used to determine the relationship between the culvert's performance and corrosive factors in the culvert's environment. The culvert's performance was denoted by an assigned "rating" of 90 through 0. The variables measured at each culvert installation were then correlated against this visual "rating" that reflects the severity of corrosion.

Variables found to be the best indices of the culvert's service life (performance) are pH, resistivity, chloride, and sulfate. A multiple linear regression on these variables had a correlation of 0.41 with the culvert rating and a standard error of estimate of 31.30. This analysis accounted for only 16 percent of the data variation, suggesting that other factors not included in the regression analysis were largely responsible for the rapidly deteriorating culverts.

Further refinement of the data into special groupings drew attention to a definite relationship existing between deteriorated culverts and near-saturated soil conditions, aeration, and organic content of the soil. These soil parameters appear to play a significant role in the corrosion activity, particularly at the most severely deteriorated culvert sites.

Effect of Soil Factors on Corrosion

A relationship between corrosion and various soil types and characteristics, although difficult to establish, is necessary in the investigation of deteriorating buried metal structures. Potential differences developed at various areas on the surface of a buried metal are a principal factor in the corrosion process. Dissimilar soil types, drainage conditions, aeration, and the presence of organic material were associated with severely corroded culverts and can render a soil aggressive to metal structures.

Although most of the culverts were installed in trenches and backfilled with granular material from local sources, the culvert bed mat was usually the native soil. In many instances, some of the native soil (clays, loams, mucks) was included with backfill material during culvert installation. This condition of including native soils was found to occur primarily at the culvert end sections. The lack of homogeneity in the soils around the culvert can develop a potential difference that is capable of driving current in a corrosion cell. Visual inspections in this study revealed that 14 culverts that incurred heavy localized corrosion at the end sections were in contact with dissimilar soils.

Changes in the environment along the length or circumference of a culvert due to dissimilar soils can cause galvanic cell corrosion. When 2 areas on the surface of a metal culvert have dissimilarities and are joined in electrical contact in the presence of an electrolyte, electricity will flow from the anode to the cathode. In this study, many culverts that showed serious localized deterioration at their inverts were found to be installed on bed mats of clay backfilled with a granular material. Within this environment the portion of the culvert lying in the clay soil acts as an anode from which current is discharged and corrosion occurs.

Corrosion can also be formed by a variation in moisture of the soil around the culvert. A galvanic corrosion cell is created by the higher moisture content near the bottom of the culvert trench. Current flow in this case is from the bottom of the culvert through the soil to the top portion of the pipe. This type of corrosion occurs at the lower portion of the culvert.

Culverts lying in contact with poorly aerated native soils and well-aerated granular backfill are susceptible to corrosion through oxygen concentration cells. The culvert surface surrounded by poorly aerated soils acts as the anode. A cathode develops at that portion of the culvert with higher concentrations of oxygen such as well-aerated backfill or dissolved oxygen carried by flowing surface water. The difference in oxygen concentration induces a current flow from the anode to the cathode, causing metal ions to go into solution and corroding the anodic area of the culvert pipe.

Most of the severely corroded culverts were located within the 5 geographic areas shown in Figure 4. Mapping the native soil types shows that, of the 39 rapidly deteriorating culverts, 22 were in areas of very poorly drained mucks and peats. Poorly drained clays, loams, and sands were found at most of the remaining corrosive sites.

A characteristic of organic deposits and fine-grained soils with small pore spaces is sluggish groundwater movement. Low permeability restricts water movement and therefore limits oxygen diffusion within these soils. Mottled brown, gray, and black soils were encountered within the environment of many deteriorating culverts. This mottling effect is associated with the more poorly drained and less aerated soils. The natural drainage of a soil is an important factor in terms of corrosiveness because of its effect on moisture content, water movement properties, and aeration. A definite correlation between such poorly drained, poorly aerated soils and areas containing deteriorated culverts was established during this study.

Biological Corrosion

Another form of corrosion showing its effects on drainage culverts is biological corrosion. Severe corrosion of buried metal structures has been attributed to the activity of bacterial organisms in an oxygen-free environment.

The theory of the manner in which bacteria stimulate corrosion was proposed by von Wolzogen Kuhr and van der Vlugt (6). The process involves the consumption of hydrogen from the cathodic areas on the surface of steel by microbiological organisms. The main bacteria of concern is Spiro Desulfuricans, which utilizes hydrogen to break down sulfates into sulfides. By preventing a protective hydrogen film from forming (depolarization), current flow continues and hence allows corrosion to proceed unchecked.

Detection of bacterial corrosion is accomplished by noting the nature of the corrosion and characteristic corrosion products. The effect of bacterial corrosion is pitting of steel. In severe corrosive conditions, pits are concentrated close together and fused to produce large corroded areas. Von Wolzogen Kuhr and van der Vlugt (7) state that ferrous sulfide (FeS) was present in the highly corrosive anaerobic soils that they studied. A black, hard crust of FeS is commonly observed over the corroded area of the pipe. Upon removal of the loosely attached corrosion products, a bright metal surface is exposed. Generation of H_2S by treatment of the corrosion products with hydrochloric acid is a positive test for the presence of sulfide and is used to indicate

Table 3. Culvert rating versus corrosion current determined from polarization measurements.

Culvert Rating[a]	Corrosion Current (ma)	Metal Loss (gram/ft²/year)
90	3.25	0.1050
75	4.54	0.0760
50	8.41	0.1787
25	6.09	0.1287
0	11.18	0.2713

[a]National Corrugated Steel Pipe Association scale.

the influence of Spiro Desulfuricans.

The conditions favorable for the growth of sulfate-reducing bacteria are (a) presence of moisture; (b) pH between 5.8 and 8.2; (c) total absence of air; (d) presence of organic matter; and (e) presence of sulfate. Sites with active anaerobic bacteria can be expected in flat, low-lying lands or swamps that maintain a high water table. Poorly drained, heavy-textured soils, such as clays and clay loams, are commonly involved. Peats and mucks rich in mineral and assimilable organic compounds are excellent breeding grounds for sulfate-reducing bacteria.

There is a basis for believing that bacterial corrosion plays an important role in some of the severely corroded culverts encountered in this investigation. Various factors recognized during this study lend support to this concept. Statistical data show that the majority of severely deteriorated culverts were found in anaerobic soils of high sulfates with organics available. In 15 out of 21 cases of severely perforated culverts, the hydrochloric acid test of the corrosion products gave evidence of sulfide. Corrosion products and forms of pitting examined under the microscope reflect those characteristics reported by other investigators as bacterial corrosion. Although the microorganism was not visually identified, its symptoms were detected.

Polarization Voltage Measurements

In that polarization measurements can give an indication of the magnitude of the corrosion activity on the surface of a buried culvert, this test method was intended to determine culvert metal loss in grams per square foot without the need of physically exposing the culvert for visual examination.

Time allowed only a preliminary trial of the polarization test in this study, and therefore the analysis is limited to the collection of measurements and plotting of polarization curves at 46 culvert sites. The corrosion current and calculated metal loss have been compared to the culvert ratings determined through visual inspection, and the results are given in Table 3. A correlation can be seen between the culvert rating and corrosion current. The mean value of the corrosion current, 3.25 ma, for culverts in good condition (90 rating) is relatively lower than the corrosion current, 11.18 ma, found at the perforated culverts (0 rating). A positive relation is not as evident when comparing metal loss per square foot with visual rating. This results from polarization data collected at culverts with large variations in surface areas.

Problems did arise from what appeared to be erroneous values. Several individual measurements obtained at various culvert sites could not realistically be assumed to occur for the duration of a year in view of the culvert's condition. The erratic values of the corrosion current measured at culverts with a 50 rating indicate this. Further definement of equipment and test procedures, therefore, is necessary before meaningful service life determinations can be derived.

CONCLUSIONS

1. Environmental exposures should be a prime consideration in the selection of culvert materials to ensure an economic service life.
2. An inspection of 287 galvanized metal culverts that have been installed for 10 to 14 years revealed 39 that are seriously corroded; 30 of these are confined to 5 limited areas.
3. The establishment of low resistivity determinations at a culvert site will not ensure the occurrence of corrosion; it will, however, identify a potentially corrosive environment.

4. Neutral soil and water pH measurements observed in the study area eliminate the possibility that the culvert deterioration is caused by acidic corrosion.

5. A spontaneous potential test procedure developed to detect stray electrical currents indicates that the deterioration of the buried culverts is not caused by interference currents.

6. The statistical evaluation of all soil and water parameters studied rendered pH, resistivity, chlorides, and sulfates as the best indices to the rate of corrosion. These variables had a correlation coefficient of 0.41 with the visual rating and only accounted for 16 percent of the data variation, suggesting that other factors not included in the regression analysis must be largely responsible for the rapidly deteriorating culverts.

7. Examination of the 5 delineated areas containing rapidly deteriorating culverts in this study reflects the importance of considering the following soil factors in determining the service performance of a metal drainage structure: uniformity of soil backfill, presence of organic materials, differential aeration, and soil moisture differentials.

8. Bacterial action is another factor that plays a role in underground corrosion. The presence of sulfate-reducing bacteria in anaerobic soils containing organic material increases the aggressiveness of the soil by preventing the formation of a protective hydrogen film on a buried corroding culvert.

9. The corrosion current determined from polarization measurements compared favorably with observed corrosion rates. Polarization measurements, as a field test, have merit in describing corrosion activity and can be improved by additional development of technique and equipment.

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