a value of 1.0. In reality, this point can only be estimated rather crudely. Another argument could be made that many culverts with inverts completely removed are still in service. From a structural standpoint, however, those installations are at best unstable.

For design purposes, New York has established a theoretical end point. It is when the culvert invert or flow line would be completely removed if the design metal loss (2 or 4 mils per year) occurred uniformly throughout the length of the culvert.

The following example will demonstrate the design procedure. Assume that hydraulically and structurally an installation in Zone 1 requires a 48-in.-diameter, 14-gauge steel pipe. Using a metal-loss rate of 2 mils per year for a design life of 50 years would require a minimum 100-mil metal thickness. Because 14-gauge pipe has a nominal 79-mil thickness, it does not satisfy the durability requirement. Therefore, either a 12-gauge pipe (109 mils) must be used or a protective coating of suitable durability must be applied to the 14-gauge pipe.

Aluminum Culverts

The design concepts applied to steel culverts also apply to aluminum culverts; that is, a design metal-loss rate and an end point in the life of the culvert should be established. Based on the results of this study, a metal-loss rate of 0.5 mils per year was selected. This value would be exceeded about 10 percent of the time. The same theoretical end point can be applied to aluminum as steel; that is, the point at which the invert or flow line would be completely removed if the design metal loss (0.5 mil) occurred uniformly throughout the length of the culvert.

In practice, application of these criteria to aluminum culverts is quite simple. Based on the maximum 70-year design life, only a 35-mil metal thickness would be required. This is substantially below the minimum thickness necessary for structural integrity, and thus no special durability considerations are required.

ACKNOWLEDGMENT

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[Authors' note: Readers interested in a more detailed account of this research should request Research Report 115, "Metal-Loss Rates of Uncoated Steel and Aluminum Culverts in New York," available without charge from the Engineering Research and Development Bureau, New York State Department of Transportation, Albany, N.Y. 12232.]

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Bacterial Corrosion of Steel Culvert Pipe in Wisconsin

ROBERT PATENAUDE

ABSTRACT

An ongoing project to investigate culvert corrosion in Wisconsin has indicated that anaerobic sulfate-reducing bacteria were a contributing factor in the corrosion of galvanized steel culvert pipe at 31 percent of the culvert sites examined since 1972. Two corrosion products and two environments of corrosion are characteristic of bacterial corrosion. One association is oxidation scale, which is related to bacteria active in organic, poorly drained soils of near-neutral pH. The other is nodular oxidation, which is related to bacterial colonies on the pipe surface associated with a water source of nutrients and characterized by local perforations of the invert, particularly along the flow lines. In this paper field tests are discussed and a description of the occurrences is given.

A continuing program to investigate culvert corrosion has been in effect in Wisconsin since 1965 and has involved the examination of approximately 500 culvert sites. This program was initiated by using equipment and procedures described in California Test Method 643-B (1,2). This is a system for predicting culvert pipe corrosion rates based on pH and electrical resistivity values of soil and water at a culvert site. Higher corrosion rates are associated with lower values of pH and resistivity. Predicted times to perforation of culvert pipe afforded by the

California test method were compared with observed corrosion rates inferred from pipe gauge and date of manufacture provided by tags on the pipes (before 1960). As more sites were examined, it developed that the better correlation between predicted and observed corrosion rates occurred at sites where the actual corrosion rates were relatively high and the pH values were low. But at many sites of near-neutral pH, the actual corrosion rates were often much greater than the predicted corrosion rates. A literature search was begun for other possible sources of corrosion, and references were noted concerning the corrosive effect of anaerobic sulfate-reducing bacteria in soil (3-9).

SOIL-RELATED BACTERIAL CORROSION

The contribution of bacteria to corrosion was first recognized by Dutch scientists in the 1930s, and since that time work has been done in England and the United States to further identify the process. Several strains of anaerobic sulfate-reducing bacteria use hydrogen in their metabolism of sulfate to sulfide and in so doing maintain an electrical potential between anodic and cathodic portions of steel pipe, thereby perpetuating a corrosive environment. These bacteria are most commonly active in poorly drained organic soil or near-neutral pH, usually between pH 5.5 and 8. Active anaerobic sulfate-reducing bacteria are associated with oxidation-reduction (redox) potentials in the soil, which commonly range from +200 to -200 millivolts, and a field test for their presence is a measurement of the redox potential of the soil.

A further field test for the presence of these bacteria is a test for the presence of sulfide in the soil. Sulfide only occurs naturally in soil as a result of bacterial activity. Dilute (0.1N) HCl is added to a soil sample and lead acetate paper is used as an indicator. If sulfide is present in the soil, the action of the acid generates hydrogen sulfide; this results in darkening of the test strip by the formation of lead sulfide.

Many culvert sites that have high observed corrosion rates and low predicted corrosion rates based on pH and resistivity values were reexamined and were found to give positive indications of bacterial corrosion, with soils characterized by low redox values and positive tests for sulfide. Performing the redox and sulfide tests became routine, in addition to performing pH and resistivity tests of soil and water, in the course of all subsequent culvert corrosion investigations beginning after 1972. Anaerobic sulfate-reducing bacteria were observed to be active at the greatest number of culvert sites in spring and early summer, when the soil was becoming warmed and was also more commonly water saturated.

The most common corrosion product found to be associated with active sulfate-reducing bacteria in the soil is scale on the pipe invert. This scale is similar in appearance to corrosion scale that develops in acid or low resistivity environments or both. This corrosion product is reported to be black by researchers who have studied the corrosion products on buried samples, but in the case of culvert pipes the corrosion products are usually exposed to more aerated conditions, and the scale soon becomes rust colored.

Results of the hydrogen sulfide test depend somewhat on the time that the acid remains in contact with the soil. The procedure followed in Wisconsin is to allow 12 to 15 min for the reaction to proceed. Results are subjective and are classified as negative, weakly positive, moderately positive, positive, and strongly positive. The strength of the reaction is dependent on a number of factors, including the amount of organic material in the soil, the amount of time that the soil has been in a reducing environment so that sulfide can accumulate, and the activity level of the bacteria. Low redox values can also result from several conditions and can be related to the action of denitrifying bacteria and iron- and manganese-reducing bacteria, but the lower redox values have been found to be commonly associated with active anaerobic sulfate-reducing bacteria.

The effect of anaerobic bacteria appears to be greater in clayey and silty soils that have low electrical resistance, whereas similar redox values in higher resistance soils appear to be associated with less dramatic shortening of time to pipe perforation. In spite of the imprecision involved, a tentative chart that relates redox and electrical resistivity values to a correction to the predicted times to perforation by the California method is shown in Figure 1. This chart is used for soils that have provided a positive test for sulfide using dilute HCl and lead acetate paper. The chart is empirical and is based on field observation, and additional studies will probably indicate a continuing need for modification to the chart.

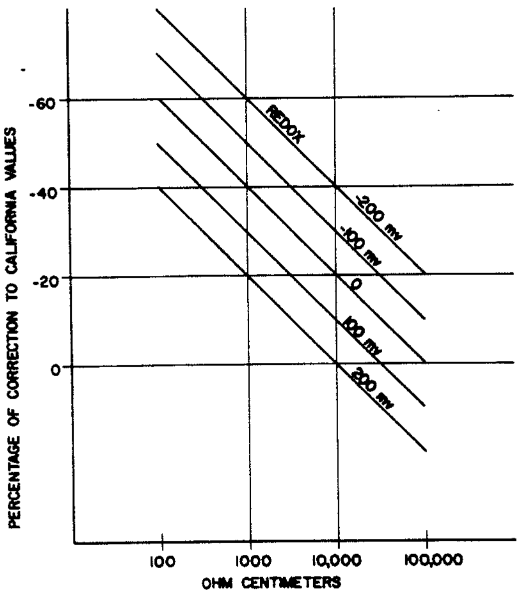

FIGURE 1 Redox correction to California method for sites with positive sulfide test.

Where anaerobic sulfate-reducing bacteria are active in the soil at the site of a steel culvert pipe, the potential for corrosion may be reduced by removing the organic soil and by surrounding the pipe with at least a foot of crushed limestone or clean sand. The use of geotextiles may help prevent mixing of the fill with natural soil. This should extend the service life of steel culvert pipe at sites where these bacteria are active in the soil, as indicated by redox values and H_2S tests.

WATER-RELATED BACTERIAL CORROSION

With the recognition of the corrosive effect of sulfate-reducing bacteria in the soil, it was thought that the cause of corrosion at most sites that have high corrosion rates was understood. However, in 1979 culvert sites on several projects were examined where culvert pipes up to 12 gauge in thickness had perforated in less than 18 years. These were at sites where tests for pH, electrical resistivity, and bacterial activity in the soil had indicated low corrosion rates. One common characteristic of these sites was the presence of nodular oxidation products on the water-covered inverts of the pipes.

Previously, culvert pipes that had these rust lumps had occasionally been observed at other sites about the state, but generally the occurrences had been few in number and had not been associated with high corrosion rates. Culvert pipes that have nodules also commonly have discrete perforations in the invert, often concentrated along the flow lines. The metal surface beneath the nodules is commonly pitted, and when active nodules are first removed from a pipe surface the underlying pitted surface is bright and shiny. In time the pits beneath the nodules penetrate the pipe, thus creating the perforations. Samples of nodules were taken to the University of Wisconsin Bacteriology Department and were identified microscopically as bacterial colonies (see Figure 2).

FIGURE 2 Nodular oxidation generated by anaerobic sulfate-reducing bacteria colonies on surface of plate arch, about one-third scale (water level in pipe recently lowered).

Samples of nodules were also taken to the University of Wisconsin Metallurgy Department, and a chemical test for a bacterial origin of the nodules was suggested. This consisted of a nutrient broth known as Baar's solution, which turns black because of the formation of iron sulfide when anaerobic sulfate-reducing bacterial are present. Strongly positive results of this test indicated the presence of these bacteria in the nodules. In addition, samples of scale from pipes at sites of low redox potential and positive sulfide tests of the soil were also put in Baar's solution, with positive results also confirming the presence of the bacteria in these corrosion products.

Nodules are commonly about the size of finger tips, but have been observed as large as half a golf ball. The nodules become active in early spring when meltwater begins to flow. When first active, the nodules are grayish-green, but after a few days they become oxidized to rust brown. During periods of low or fluctuating water levels the nodules become softened, and when the next period of high water flow occurs the softened nodules are often flushed from the pipe, thereby removing obvious traces of their presence. A positive test for H_2S is obtained when firm nodules are placed in dilute HCl. The same test on softened, oxidized nodules provides negative results, probably because the sulfide is quickly oxidized when the nodules are exposed to air.

Apparently, nodular corrosion results from the activity of sulfate-reducing bacteria, which are independent of the soil and which obtain nutrient from the water at the culvert site. This type of corrosion has been observed at sites of standing water, and also in better-drained areas where the soil would generally be too well aerated to support anaerobic bacteria, but where running water is present in the pipe a significant part of the year. Two general types of localities have been noted where nodular bacterial corrosion has been most common. One is at sites of perennial streams that drain marshes or shallow lakes that have a large amount of bottom vegetative growth. These kinds of sites tend to be randomly distributed about most of Wisconsin. The other type of occurrence can involve a number of culverts in a local area where more of the drainage may consist of surface runoff and will therefore be more intermittent than drainage of the first group. The source of sulfate at these latter localities might be related to local geology or to industry. Nodular bacterial colonies have been observed at sites where sulfur in the water ranged from 1 to 30 parts per million (ppm). Development of the nodules does not appear to correlate directly with the sulfur content of the water, and it appears that other factors may be involved. In addition to culvert pipe, nodular corrosion has been observed at a dam on the Yellow River in central Wisconsin, which resulted in perforation of the corrugated steel gates. Nodules were also observed on cans, railroad spikes, and tie plates discarded in a small stream.

Currently, there is no predictive method that will indicate a potential for nodular bacterial corrosion of galvanized steel pipe associated with water at a culvert site, nor is there a suggestion regarding prevention of this problem.

RESULTS OF FIELD TESTING

Since 1972 tests for sulfide in the soil have been positive at 95 of 418 culvert sites where this test was run. Sulfide tests were not run at some well-drained sites that have granular soil devoid of organic material. In addition, nodular bacterial corrosion has been observed at 35 of 418 sites, with the result that anaerobic sulfate-reducing bacteria, either of a soil or a water origin, would be a factor in corrosion at 31 percent of the culvert sites tested for the presence of bacteria since 1972. Current experience indicates that almost all corrosion of galvanized steel pipe that has been noted in Wisconsin can be related singly or in combination to low pH, high electrical conductivity, or bacterial activity at a culvert site.

It has also been observed that the presence of these bacteria has no effect on concrete or aluminum pipe. Tests for the presence of sulfide in the soil were run at sites of 14 aluminum culvert pipes, both experimental sites and sites of corroded and replaced galvanized steel pipe. Eight of these sites gave positive tests for the presence of anaerobic sulfate-reducing bacteria. In addition, tests for sulfide were run at the sites of 38 concrete pipes and concrete boxes with corrugated steel culvert pipe extensions, of which 21 tests were positive. There was no indication of any corrosive effect on either the aluminum or concrete at these sites, nor have the nodular bacterial colonies been observed on aluminum or concrete.

CONCLUSIONS

Examination of culvert pipe in Wisconsin has indicated that bacterial activity, both soil and water related, is a significant cause of corrosion of galvanized steel culvert pipe in Wisconsin. The examination also noted that corrosion at most culvert sites can be related singly or in combination to bacterial activity, low pH, and low electrical resistivity of soil or water or both at a culvert site.

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Galvalume Corrugated Steel Pipe: A Performance Summary

A. J. STAVROS

ABSTRACT

Laboratory and field tests have been used to characterize the performance of Galvalume corrugated steel pipe. Galvalume, galvanized, and aluminum-coated Type 2 sheet were subjected to laboratory tests designed to measure corrosion resistance in salt spray (ASTM B 117), cyclic standing water, and full immersion. Abrasion resistance and asphalt adhesion were also tested. In all tests Galvalume sheet demonstrated the best relative performance. Results of field tests that compared nearly 1,000 ft each of Galvalume and galvanized corrugated steel pipe at 16 sites in the northeastern United States substantiated the laboratory predictions. After 9 to 9.5 years, the Galvalume inverts and intermittently wet zones inside the pipe, where service is most severe, were overall in much better condition than those of the galvanized pipes.

Aluminum-zinc (Al-Zn) alloys have been developed into a hot-dip coating for steel that provides superior corrosion resistance. A 55 percent Al-Zn coated sheet is available in the United States from Bethlehem Steel and other companies under the trade name Galvalume. Worldwide, the annual production capacity for 55 percent Al-Zn coated sheet exceeds 2 million tons.

Galvalume sheet has become a growing factor in the preengineered metal building, appliance, agriculture, and automotive markets. Its phenomenal success in these markets is due to the significant improvement in atmospheric corrosion resistance when compared with standard galvanized sheet.

Based on 13-year exposure test results of sheet samples in severe marine, marine, industrial, and rural atmospheres, 55 percent Al-Zn coating is 2 to 4 times more durable than a galvanized coating of the same thickness [see Figure 1 (1)].

Corrugated steel pipe is another traditionally galvanized product that can benefit from Galvalume sheet. In order to develop meaningful performance behavior, Bethlehem, in cooperation with nine state highway agencies, established field trials for full-sized Galvalume corrugated steel pipe. Subsequently, a number of laboratory tests were conducted to supplement the field trial data. The results of these