Durability of Corrugated Metal Culverts

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To provide data on corrosion and abrasion rates for corrugated pipe, two surveys were conducted—one for steel culverts with 2 to 35 yr of service, and another comparing aluminum and steel culverts installed for up to 4 yr in similar environments. Uncoated steel culverts are performing satisfactorily, being unaffected by properties of normal soil and water, but with significantly greater durability when bituminous coated or coated/paved. Uncoated aluminum culverts are proving durable, indicating no need for such protection. Abrasion was found to be of minor influence. A statistical method for estimating metal loss, and a design procedure are presented.[1]

•EACH year, vast quantities of corrugated metal pipe culvert are used in the nation's highways. The cost of these installations represents a substantial portion of the highway dollar. This has stimulated numerous studies to determine optimum size and gage for given installations, based on hydraulic and structural requirements. These studies have provided sufficient data to design the given installations with reasonable assurance that they will carry anticipated flow and support structural loads imposed. By contrast, culvert durability or life expectancy is an important design aspect that has received less attention.

Life expectancy of corrugated metal pipe is governed by the rate of metal loss due to corrosion and/or erosion. If sufficient metal is removed, the culvert becomes structurally unstable and failure ultimately occurs. Rate of metal loss, however, is difficult to predict. One of the most reliable means available to the designer is to examine existing culverts in the same stream channel where a new culvert will be placed. A practical alternative is to evaluate the performance of a large number of installations of various ages in different environments, as a basis for developing design criteria.

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 separate studies were conducted to accomplish this objective. One was a single, comprehensive, statewide survey of 792 bituminous coated and uncoated galvanized steel culverts installed between 1930 and 1963. The other, still under way, consists of periodic evaluations of coated and uncoated galvanized steel and uncoated alclad aluminum culverts exposed to similar conditions at 21 locations throughout the State. (For the remainder of this report the terms "steel culverts" and "aluminum culverts" will indicate corrugated galvanized steel culverts and corrugated alclad aluminum culverts, respectively.) This phase is referred to here as the comparison survey, in contrast to

[1]Extensive data appendixes on culvert locations and field surveys are omitted because of space limitations. They are available (Research Report 66-5) from the Bureau of Physical Research, New York State Department of Transportation, Albany, New York 12226.

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the steel culvert survey. Since the Department only recently (1964) permitted use of aluminum culverts in State highway construction, the latter investigation is based mainly on culverts installed by other public and private users since 1961. In view of the short period that these culverts have been in use, their performance cannot be conclusively evaluated at this time. It is planned, therefore, to continue periodic observations and tests for several years, and to include other comparative installations in future construction.

An important aspect of this investigation involved comprehensive review of available literature (to June 1966) on the subject of culvert durability. Because of widespread interest in this subject and numerous inquiries received concerning findings of other investigators, each reference reviewed has been summarized in Appendix A. No attempt has been made to compare the results of these studies, the intent being to present a concise transcript of only the authors' results and conclusions.

EVALUATION PROCEDURES

Testing Program

Both surveys included series of on-site tests to identify environmental conditions considered likely to influence culvert durability. In the case of the steel culvert survey, the large number of sites visited necessitated limiting actual measurements to pH and electrical resistivity determinations, other tests being qualitative, estimated, or restricted to the comparison survey. Details of the procedures and equipment used are given in Appendix B. It is important to note that all tests in soil were performed on culvert backfill material only, and those in water in the stream channel near or within the culvert.

Hydrogen-Ion Concentration (pH)—In chemistry, one criterion used to classify fluids is the pH concept; that is, the amount of free hydrogen ions present in a unit volume. On a standard numerical scale, a pH of 7.0 represents the chemically neutral condition of pure water. Values less than 7.0 denote an acid condition (with the degree of acidity increasing with decreasing pH), while values greater than 7.0 correspond to increasing alkalinity.

This concept is applicable in studies of metal culvert durability in that most drainage structures carry water contaminated with certain naturally occurring chemicals, industrial wastes, or other pollutants. If the solution is sufficiently acidic or alkaline, as measured by the pH, corrosion may be accelerated. Some investigators (1, 2, 3, 4) have reported a strong association between pH and rate of corrosion, while others (5, 6) have found no apparent relationship.

Hardness and Saturation—Water containing an excessive amount of calcium carbonate is said to be "hard." When the quantity of this compound present in a solution exceeds the amount necessary to produce saturation, generally considered to be more than 180 parts per million, the excess settles out and forms a coating on the surface it contacts. In the case of steel culverts, this coating helps to retard corrosion. On the other hand, calcium carbonate is usually aggressive toward aluminum, and under certain conditions can accelerate corrosion.

Chemical Tests—Qualitative chemical tests were performed on water and soil samples to determine the presence or absence of the following ions: sulfides, sulfites, sulfates, chlorides, nitrates, ammonia, ferrous iron, and ferric iron.

Electrical Resistivity—Corrosion is an electrochemical process involving flow of minute electrical currents between points on a metal having different electrical potentials. In culverts, current flows through the surrounding soil and water in seeking the path of least resistance. Since the magnitude of the current is governed by Ohm's law ($E = IR$), a small resistance (R) will be accompanied by a large flow of current (I) for a given potential (E) and a corresponding high rate of electrochemical corrosion. Aggressive electrochemical corrosion is generally associated with soil-water systems having a resistivity less than about 1000 to 1200 ohm-cm.

Electrical Potential—Theoretically, the electrochemical current associated with corrosion can be calculated if the electrical resistance and potential difference are known. It should then be possible to relate current flow to rate of corrosion as expressed by the amount of metal lost.

Flow Velocity—Knowledge of stream velocity is essential in evaluating culvert metal loss resulting from abrasion by material carried in the stream. Sediment-laden streams flowing at velocities of about 8 fps or more are generally considered aggressive from the standpoint of abrasion. The quantity, type, shape, and grain size distribution of sediments are also important, but obtaining this information requires a substantial effort when a large number of installations are studied. In this investigation, therefore, classification of sediments was based on visual examination at each site.

Inspection

Each culvert was inspected throughout its entire length (minimum diameter was 24 in.). Culverts containing deposits were cleaned at various points along the invert to permit metal inspection and sampling. Pertinent information recorded included general condition of the culvert, percent bituminous coating removed (where used), and estimated average metal loss. Physical and environmental conditions recorded in relative or qualitative terms included: inlet channel and culvert grades, velocity and apparent regularity of flow, general nature of the bed load in terms of potential abrasiveness, accumulation of sediment in the invert, land use, and topography.

Metal loss was determined by visual examination accompanied by soundings made with a geologist's hammer. Removed metal was estimated to the nearest 5 percent of original thickness and prorated on the basis of area affected to determine average metal loss for the entire culvert. The reliability of this method was established early in the investigation by comparing the estimates with actual measurements of 1-in. diam samples cored from 67 culverts. Samples were carefully cleaned in the laboratory and their thickness compared to the standard gage size specified in the construction contract. As a further check, sample thickness was also compared to average thickness of several areas of the culvert where no metal loss had occurred. When analyzed statistically, the data indicated a favorable degree of linear correlation ($r = 0.73$ at the 95 percent confidence level) between estimated and measured thickness.

Metal loss reported for each culvert refers to the longitudinal section containing the most severe distress over the entire length, exclusive of the first few feet at each end. For culverts carrying continuous flow, this section corresponded to the zone between high and low water lines, while for culverts with intermittent flow it usually was the portion of invert containing the lowest point on the culvert cross-section. This approach is considered more realistic than the "first perforation" concept used by some investigators, because it recognizes that service life does not terminate upon initial perforation. This was clearly demonstrated by the fact that no case of structural failure was encountered in the surveys, although perforation was observed in a few older installations.

STEEL CULVERT SURVEY

Selection of Culverts

This survey involved examinations of steel culverts in three basic classes or groups: 111 uncoated, 238 bituminous coated, and 443 bituminous coated/paved. When inspected in 1965, the culverts in each of these three groups ranged in age from 2 to 35 yr. Additionally, distribution of each group provided representation in major geographic areas of the State and, hence, included all physiographic provinces. Figure 1 shows locations of 159 construction contracts containing the culverts inspected. In terms of original metal thickness, the installations ranged from No. 1 gage (0.2690 in.) structural plate pipe down to No. 16 gage (0.0598 in.) fabricated metal pipe. Eighty-one percent (642 culverts) were within the narrow inclusive range of No. 14 gage (0.0747 in.) to No. 10 gage (0.1345 in.).

Environment

Evaluation of environmental conditions at each of the 792 sites included pH and electrical resistivity measurements of soil and water, a qualitative determination of saturation with respect to calcium carbonate, and an estimate of flow velocity. In addition,

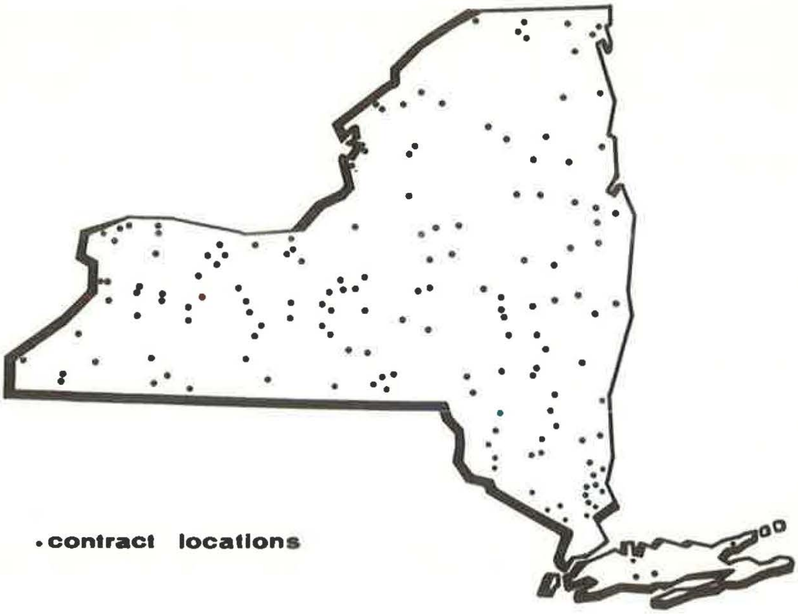

Figure 1. Locations of contracts included in statewide survey of steel culverts of various ages.

various physical features were described in general terms. Because the volume of data collected is too large to include in this report, only a summary is given here.

Hydrogen-Ion Concentration (pH)—Because of sustained drought over the entire State, only 299 culverts contained water. Moreover, difficulties were experienced with the pH meter, so that only 152 were tested. However, these were widely distributed and in-

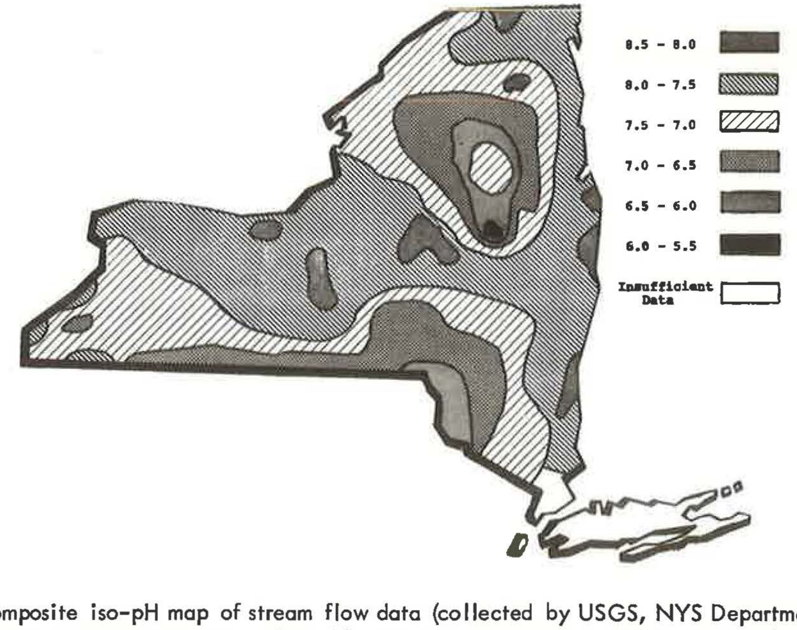

Figure 2. Composite iso-pH map of stream flow data (collected by USGS, NYS Department of Commerce, NYS Department of Health, and NYS Department of Transportation).

cluded mountainous, agricultural, wooded, industrial, and swampy areas. Under these varied conditions, pH was found to range within the narrow limits of 6.2 to 9.0. The majority of culverts (142) contained water with pH's of 7.0 to 8.9, while the extreme values each occurred only once. These results agree remarkably with similar tests conducted independently in small streams throughout the State by the New York State Departments of Health and Commerce, and the U. S. Geological Survey (7, 8). Data from all sources have been combined to form a composite iso-pH map of New York (Fig. 2), excluding the southernmost area where insufficient data were available.

It should be stressed that the distribution shown only distinguishes areas of generally similar pH, and is not applicable for precise determinations at specific locations. This is especially true when considering a culvert installation immediately adjacent to a chemically deleterious effluent, where proximity to the point of discharge, the volume of discharge, etc., will determine pH of the combined fluids carried by the culvert. However, the fact that no highly aggressive conditions were recorded, even though some culverts were as close as 20 ft from the discharge point of industrial effluent, suggests that dilution may occur rapidly.

The pH of soil surrounding each culvert was measured at 787 installations. Values varied from a minimum of 3.8 (one site) to a maximum of 9.4 (one site), with 728 sites (92 percent) between 6.0 and 8.9. There was no apparent relationship between pH of soil and water at each site.

Electrical Resistivity—Water resistivities were established in all 299 culverts containing water, the values ranging from a minimum of 50 ohm-cm at two sites to a maximum of 30,000+ ohm-cm in numerous cases. Significantly, only 8 sites (2.6 percent) were less than 1000 ohm-cm, while 263 sites (88 percent) were more than 2000 ohm-cm.

A similar range of resistivities was encountered in soil. Of the 792 sites tested, only 10 had values less than 1000 ohm-cm, and 744 sites (94 percent) were greater than 2000 ohm-cm. In general, resistivity of the soil and water at each site was of essentially the same magnitude. This narrow range for soil probably resulted from use of select granular backfill.

Electrical Potential—A series of electrical potential measurements were made at selected locations where electrical resistivity had been determined. However, the results were erratic and the test was abandoned early in the survey in favor of a polarization technique, not reported here, which when fully developed may yield reliable corrosion current values directly.

Saturation—Calcium carbonate saturation was qualitatively determined at 148 sites. About the same numbers were found to be saturated and unsaturated—76 and 72, respectively. Their distribution was fairly uniform throughout the State, without apparent correlation to limestone or dolomitic rock formations.

Flow Velocity—Water velocity was estimated at 291 sites and designated moderate (5.0-7.9 fps), slow (2.0-4.9 fps), or stagnant (less than 2.0 fps). The corresponding numbers of sites in each category were 7,113, and 171, respectively. No instance of rapid flow (greater than 8.0 fps) was noted, possibly because of the statewide drought.

Other Factors—The distribution of culverts by various other classifications was as follows:

Flow: continuous 289, intermittent 502
Inlet grade: steep 64, moderate 190, flat 537
Culvert grade: steep 24, moderate 134, flat 633
Invert: sediments 375, no sediments 416
Topography: mountainous 87, flat 199, rolling 446
Land use: industrial 3, residential 17, open field 48,
agricultural 114, wooded 141, combinations 473.

Condition of Culverts

A wide range of performance was encountered in all three classes of steel culvert. Many new and old installations exhibited essentially no metal loss; others in each category showed localized perforation. Complete loss of invert was found for one uncoated culvert (26 yr old) and one coated culvert (31 yr old). However, no case of structural failure was found.

In general, culvert extremities were more distressed than interior portions. This was attributed to the combined effects of hydraulic end conditions, to exposure to the elements—particularly the sun's rays and changes in ambient temperature, and to other factors having considerably less influence on interior sections of pipe. Because the extreme ends were judged to play a minor part in the overall integrity of an installation, they were not included in the estimate of average metal loss.

An important finding of this survey is that metal loss associated with corrosion originates on the culvert's interior surface and progresses toward the exterior surface. This was borne out by the 67 specimens cored from old and young pipe, with and without coating/paving, and from crown areas as well as inverts. The exteriors of 38 specimens had the galvanizing or bituminous coating intact, and 17 others exhibited negligible corrosion. The remaining 12 specimens showed various stages of corrosion; however, these were sampled from portions of uncoated pipe adjacent to leaking joints and in heavily corroded sections of invert which were almost completely penetrated from the inside. It was also found that with few minor exceptions, progressive corrosion was confined to the area below the waterline. Some corrosion was noted above, but even in older culverts penetration was shallow. Collectively, these facts provide information valuable in helping to resolve the long-standing question concerning the distribution of corrosion in metal culverts.

With regard to causes of the recorded metal loss, the results suggest that abrasion is a minor contributor. There was little evidence of polishing, damage to fasteners, concentrated wear on the upstream side of corrugations, or other typical characteristics of abraded surfaces. This is consistent with the range of estimated stream velocities and with the magnitudes of metal loss. This interpretation is further supported by results of a linear regression analysis of coating loss vs age. The average time required to remove 50 percent of the portion of bituminous coatings below the waterline was 12 yr for coated culverts, and 35 yr (projected) for the coated/paved culverts.

It is appropriate to mention that the condition of a culvert can be grossly underrated when based solely on a cursory visual observation excluding soundings and careful examination. Often, what appears to be severe corrosion, as evidenced by widespread discoloration and pitting, proves to be typical surface corrosion which is progressing at a normal pace. A case in point is a No. 5 gage structural plate pipe which discharges a stream into the Hinkley Reservoir in Herkimer County. Installed about 1950, this culvert was reported as severely corroded after 15 yr of service, and the Department was concerned that it would require replacement long before its anticipated useful life was reached. Careful visual inspection indicated that nearly the entire interior surface was rusted (the pipe is completely inundated when the reservoir is full), and the invert covered with numerous tubercular corrosion products. In spite of this discouraging appearance, metal loss in the most severely corroded areas was found to be between 20 and 40 percent of the original thickness, and only 15 percent on average, or 1 percent per year of service. The balance of the cross-section had essentially no metal loss. It was concluded that the culvert was in far better condition than its appearance indicated.

Analysis

The data were analyzed statistically with an electronic computer to determine the relationship, if any, between culvert performance and environmental conditions. Average metal loss was used as the measure of performance so that the three classes of steel culverts (uncoated, coated, coated/paved) could be compared directly. This made it possible to evaluate effectiveness of the bituminous coatings in retarding metal loss.

Regression Analysis—Complete data were obtained for 146 installations which included all three classes of culverts but were evaluated as a common group. These were evaluated initially by a regression analysis. The pH and electrical resistivity of the soil and water, and the age of each culvert were treated as independent variables. Metal loss, expressed as a rate in inches per year (ipy), was the dependent variable.

By applying a stepwise regression technique in which the independent variables were successively eliminated from the analysis, the relative influence of each variable on metal loss was established. From this analysis, culvert age was determined to be the only statistically significant factor.

To determine whether the analysis was influenced by interaction of other variables, the procedure was refined by grouping the data in various ways. For example, the culverts were grouped into five geographic areas and a multiple regression analysis was performed for each area. Other groupings evaluated included: land use (agricultural, industrial, wooded, etc.), topography, relative stream velocity, saturation with respect to calcium carbonate, presence or absence of sediment in the culvert, and presence or absence of a bituminous coating. As before, the only statistically meaningful correlation among the five variables was between average metal loss and age, the degree of association being about the same for the coated and uncoated classifications.

These results suggested that a simple linear correlation between cumulative metal loss and the corresponding age of all culverts inspected in each class might provide a useful comparison. Figure 3 illustrates this relationship for uncoated, coated, and coated/paved culverts. The wide range in metal loss is immediately apparent. Many culverts in each category had no metal loss at ages through 30 to 35 yr, while others exhibited appreciable loss in much shorter periods. Such variations emphasize the importance of evaluating a statistically large sample to provide a satisfactory representation of the culvert population.

A condition that could not be explained is the abrupt increases in the upper limits of metal loss corresponding to the 10 to 15-yr and 25 to 30-yr age intervals. These occur in all three categories, but are most pronounced for the coated culverts. Since the affected culverts are located in widely separated areas, unusual environmental conditions, such as floods and specific suppliers, were ruled out as possible causes. Inquiries among fabricators established that no apparent changes had occurred in the quality or composition of the sheet steel and bituminous materials supplied during these periods (1935-1940 and 1950-1955). Because the number of culverts with abnormally high metal loss is only 7 percent of the coated installations, and considerably less for the uncoated and coated/paved pipes, their effect on this analysis is not significant.

In Figure 3, the straight lines represent the best fit of the data based on a least-squares linear regression analysis. These lines denote the average relationship between total metal loss and age, and provide a useful means of comparing relative performance of the three classes of steel culvert. Referring to the coefficient of the "X" term in the equations of the lines, uncoated culverts exhibited an average metal loss of 0.00137 ipy, compared to 0.00085 ipy for coated pipes (or 62 percent as much), and 0.00029 ipy for coated/paved culverts (or only 21 percent as much). Stated another way, on the average, the rates of metal loss are in the ratios of 4.7:2.9:1.0 for uncoated, coated, and coated/paved pipe, respectively. This clearly demonstrates the long-term effectiveness of bituminous coatings, particularly the coated/paved combination. Other supporting evidence is the progressive reduction in maximum metal loss recorded (uncoated = 0.134 in., coated = 0.094 in., coated/paved = 0.054 in.), accompanied by an overall decrease in disperson of the data. Due to the large number of culverts having little or no metal loss, the data points are not normally distributed, in the statistical sense, about the regression lines. Consequently, the standard error of estimate and the correlation coefficient are not applicable. A more rational method of predicting probable metal loss for design purposes is presented later.

There is ample evidence in the literature to support the finding that the corrosion rate of steel is not influenced by pH over the range of values measured in this survey. For example, Uhlig (6) states: "Within the range of about pH 4 to 10, the corrosion rate is independent of pH, and depends only on how rapidly oxygen diffuses to the metal surface.... Oxygen concentration, temperature and velocity of the water alone determine the reaction rate. These facts are important because practically all natural waters fall within the pH range 4 to 10. This means that whether a high or low carbon steel, or similarly a low alloy steel (e.g., 1 to 2 percent Ni, Mn or Cr) or wrought iron, or cast iron, or cold-rolled mild steel are exposed to fresh or sea water, the observed corrosion rates in a given environment are all essentially the same...."

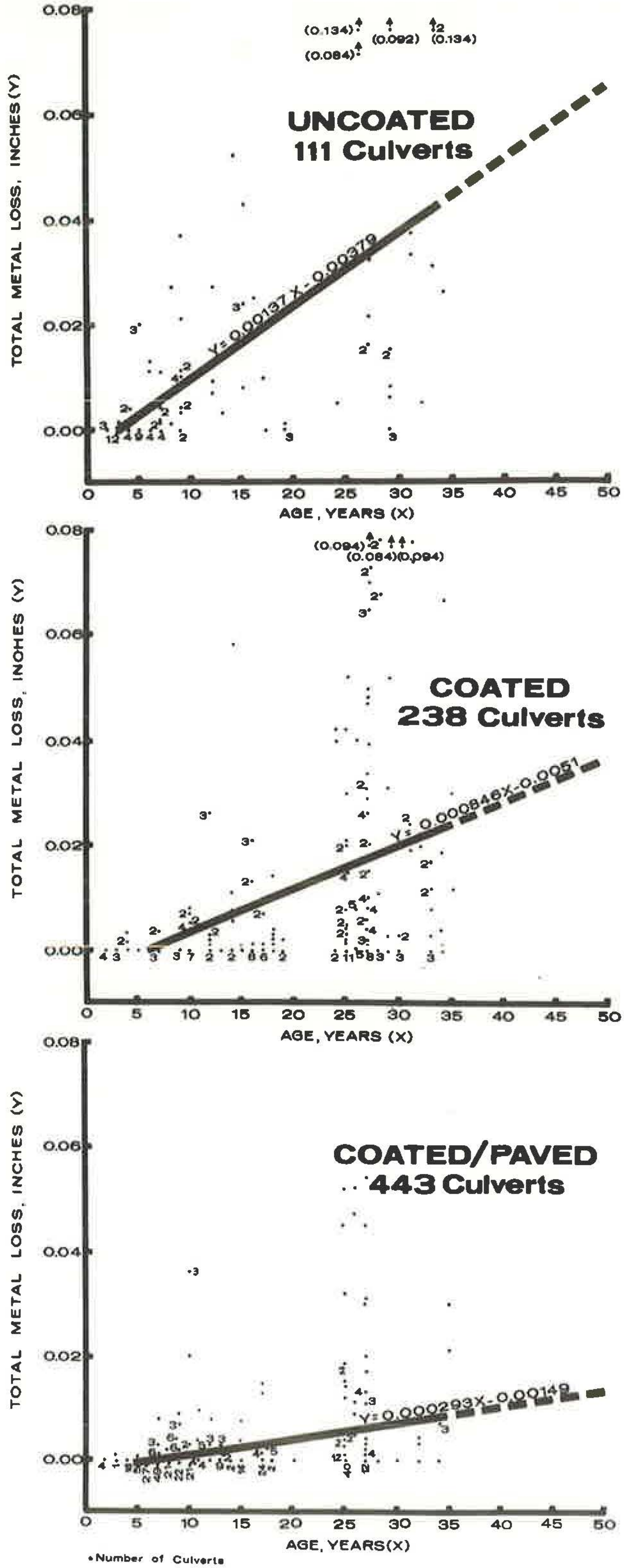

Figure 3. Metal loss with age.

In light of this information, it is appropriate to compare the performance of the uncoated culverts with typical corrosion in other contexts. Reported corrosion rates of steel cover a broad range, depending on specific chemical environment, composition of steel, temperature, etc. However, average values for steel exposed for long periods to quiet natural waters, to salt water, and to industrial atmospheres are most often quoted between the narrow limits of about 0.001 and 0.005 ipy. Much higher values are encountered in moderate to swift flowing waters. In comparison, 86 percent of the uncoated culverts developed less than 0.002 ipy loss, and the maximum rate recorded was 0.005 ipy for the one culvert with a completely removed invert.

Culverts, then, have performed quite satisfactorily from the standpoint of "normal" corrosion. The relatively small rates of loss suggest that galvanizing effectively retarded corrosion during early years of exposure. Equally significant, the results also indicate that mechanical abrasion played a minor part, and that the recorded metal loss is primarily due to corrosion. As previously noted, this was substantiated, in part, by the absence of evidence of abrasion in all but a few of the culverts, and by the durability of the bituminous coatings.

Another consideration in evaluating performance is the percent of original metal thickness removed, since this provides a measure for estimating service life of existing installations. For uncoated culverts less than 10 yr old, metal loss averaged 3 percent, and the maximum recorded was 23 percent. Corresponding values in the 10 to 24-yr group were 10 and 50 percent, respectively. The oldest group of uncoated culverts (those 25 yr and older) averaged 29 percent metal loss and included the one with 100 percent invert loss. Significantly, about 70 percent of this group lost less than

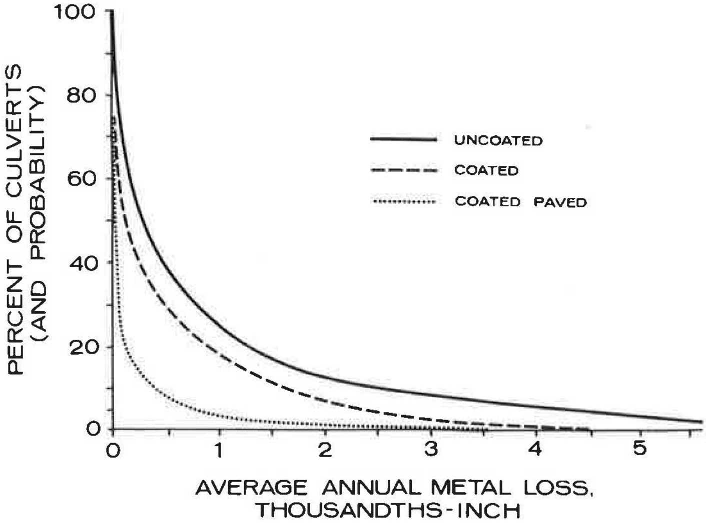

Figure 4. Distribution of average metal loss for galvanized steel culverts.

half their original thickness. This indicates that over 40 yr of service can be expected for most existing uncoated culverts.

Bituminous-coated culverts performed better. For example, 73 culverts comprising the 10 to 24-yr group developed an average 6 percent metal loss. The 138 pipes in the group 25 yr or older averaged 18 percent loss, with 70 percent missing less than one-quarter of their original thickness. Therefore, service life of 50 yr or more can be anticipated for most existing coated culverts. A comparable analysis of the coated/paved culverts indicates that they can be expected to provide satisfactory service beyond the practical limits of design life.

A note of caution is essential here. During the 33-yr period represented by these culverts, design procedures incorporated large safety factors to compensate for lack of accurate information concerning load distribution. The thick metal resulting from this conservative approach provided a substantial margin for loss from corrosion/erosion. In large measure, this fact accounts for the longevity of the culverts inspected. However, research has recently made possible dramatic reductions in safety factors, permitting use of thinner gages than would previously have been allowed for similar structural design conditions. In some instances, reductions in metal thickness of as much as 40 percent have resulted. It is important to realize, therefore, that future culverts must be selected on the basis of both structural and durability requirements.

Frequency Distribution—From the standpoint of design, the regression analysis does not accurately define the mathematical association between metal loss and age. Stated in statistical language, the variations in metal loss are only partially explained by the corresponding variations in age. (A much higher degree of correlation probably would be obtained if it were possible to include the environmental variables mentioned previously: namely, the temperature, oxygen concentration, and velocity of the water. However, a series of repetitive measurements would be required at frequent intervals over a long period for accurate description of these variables. Moreover, available methods for determining oxygen concentration in the field are, at best, approximate.) However, when viewed in the form of a cumulative frequency distribution of rate of metal loss, the association is more meaningful.

Figure 4 shows the idealized frequency distribution for the three classes of steel culverts. Each curve was constructed by plotting the percentage of culverts (ordinate), regardless of age, that equaled or exceeded successively greater average rates of metal loss (abscissa). The resulting graphs were then adjusted slightly to fit a continuous curve, with the general equation $y = e^{-fx}$ representative of the entire population of culverts.

The advantage of this type of presentation is that every result is embodied in the curves and, therefore, statistical interpretations can be referenced to all culverts in each class. For example, the large number of coated/paved culverts that exhibited no metal loss, on average, is reflected in the steep slope of the corresponding curve down to about the 15 percent level. The superior performance of this class of pipe, compared to the uncoated and coated culverts, is also apparent.

An important characteristic of the frequency distribution is that it provides a direct means of estimating probability of occurrence of a selected rate of metal loss. To illustrate, 10 percent of uncoated culverts had a metal loss equaling or exceeding about 0.0025 ipy. One can predict, therefore, that 10 percent (1 of 10, 10 of 100, etc.) of future culvert installations exposed to the same range of environmental conditions will exhibit this rate of loss. Conversely, 90 percent will show lower losses. Such predictions are, of course, only as reliable as the data from which they are derived. Accordingly, site conditions differing from those encountered in this survey would require special consideration. For example, even though little evidence of severe abrasion is found, a site may be selected where excessive bed load abrasion is anticipated. Two cases where such abrasion is suspected are described in the comparison survey. In other instances, indications of corrosion associated with sedimentation were noted, but no valid correlations could be established. Except for these unusual situations, the curves in Figure 4 provide the Department with a more rational basis for estimating the life expectancy of steel culverts than has been available.

Design Considerations

Once the hydraulic requirements of a proposed culvert have been satisfied, structural adequacy and durability must be considered in arriving at the final design. These factors determine the combinations of gage thickness and class of culvert required to insure acceptable performance. The structural aspects of culvert design are extremely complex and will not be discussed here, except to note that they are incorporated in the Department's current design criteria for fabricated and multi-plate culverts. With regard to durability, the primary points to be resolved are how to estimate the amount of metal loss for a specified design life, and how to translate the result into required gage thickness.

Estimating Metal Loss—Because the rate of metal loss at a particular site is dependent upon environmental conditions not readily measurable, the designer must exercise engineering judgment in selecting an appropriate value. Primarily, he must decide on the degree of reliability of his estimate required by the function and relative importance of the proposed culvert. Driveway pipe, for instance, serves light traffic, is relatively easy to replace when necessary, and would not present a serious problem if actual metal loss occasionally exceeded the amount estimated. Therefore a design rate corresponding to the 40 to 30 percent probability range in Figure 4 might be appropriate. On the other hand, a culvert for a primary or Interstate highway serves heavy traffic, is frequently installed under high embankments, and is expected to have a long service life with minimum maintenance. Here, a small allowable risk is indicated and, therefore, a probability of 10 percent or less would be in order.

It should be clear that whatever probability (level of risk) is chosen, the value indicates the percentage of culverts that are expected to equal or exceed the corresponding rate of metal loss. A 5 percent probability, for example, means that 5 of every 100 uncoated culverts, or any other equivalent proportion, will lose metal at a rate of 0.0042 ipy or more. For coated and coated/paved pipe, corresponding rates are 0.0023 and 0.0008 ipy, respectively. It follows that the lower the probability, the smaller is the risk of a culvert exceeding the predicted rate. Once the design rate is selected, multiplication by the design life, in years, gives the estimated total metal loss.

Required Gage—Having tentatively selected a culvert fulfilling the structural requirements, the designer must consider the effects of the estimated metal loss. It can be argued that crucial periods in the life of a culvert occur during installation as a result of handling and construction operations, and during its early years of service when the soil cover is adjusting to the weight of the embankment and other loads. Because of uncertainties concerning actual stresses induced during these periods, current structural design procedures provide for factors of safety varying from about 2.0 for buckling stresses to about 4.0 for deflection and seam strength. Since it has been demonstrated that little metal is lost during the early years, these required safety margins are essentially upheld over this period.

It is logical, however, to question whether the entire initial thickness of metal is necessary when the design life of the culvert is approached. The fact that no structural failures were noted in this investigation, even where the entire invert was removed, suggests that something less than the original thickness is needed to insure lifelong structural integrity. This idea is not new. In fact, some engineers have claimed that once the structure of the soil surrounding a culvert is fully developed and attains static equilibrium, most of the load is carried by the soil, and the culvert primarily provides containment. While such a design assumption would entail substantial risk, a compromise providing a measure of safety but also recognizing the load-carrying contribution of the soil seems appropriate.

A suggested approach is to require a design safety factor of 1.0 when the culvert attains its design life, and is scheduled for replacement. Thus, the difference between the initial thickness required for full structural support and the reduced final thickness corresponding to a safety factor of 1.0 would be available for corrosion/erosion. Actually, the real safety factor would be greater than 1.0 because of the safety margins inherent in allowable working stresses, and the fact that metal loss occurs within a limited portion of the culvert cross-section. If this difference equals or is less than the predicted metal loss, the selected gage will be adequate. If sufficient metal is not available, then a heavier gage would be necessary. The likelihood of this occurring, of course, is greatest for uncoated culverts because of their relatively high rates of metal loss. On the other hand, only a small percentage of coated/paved pipe would probably require an increase in metal thickness.

In summary, design of corrugated galvanized steel culverts should consider durability as well as structural adequacy. Once a culvert has been tentatively selected on the basis of the Department's current structural design criteria, it should be examined for potential corrosion/erosion as follows:

1. Assign a metal loss probability value commensurate with the intended use of the culvert, and select the corresponding design rate from Figure 4.
2. Compute estimated total metal loss as the product of design rate and design life.
3. Establish the thickness required to provide the minimum safety factor acceptable at the end of the design life. A safety factor of 1.0 is suggested.
4. If the sum of 2 and 3 equals or is less than the gage of the pipe selected, the design is acceptable.
5. If the sum of 2 and 3 is greater than the gage of the pipe selected, a deficiency of metal is indicated and a greater thickness is required.

Illustrative Example—The following example is applicable only to steel culverts. This example is intended to demonstrate the suggested procedure for estimating metal loss. Accordingly, values believed to be reasonable have been assumed to illustrate the concepts involved. In practice, the Department's structural design criteria should be used to determine the required thicknesses.

Assume that a 48-in. round, corrugated, galvanized steel culvert is required for cross-drainage beneath an embankment for a secondary highway. Structural considerations require an initial wall thickness of 0.1644 in. (No. 8 gage), and a final thickness of 0.038 in. after 30 yr, to provide a minimum safety factor of 1.0. Environmental conditions typical of those described are anticipated.

1. The class of highway and the 30-yr culvert design life define a medium-risk situation. An appropriate probability value of 15 percent is chosen for this example.
2. Select the corresponding rates of metal loss from Figure 4, and compute the estimated total metal loss:

uncoated = 0.0017 ipy × 30 yr = 0.051 in.
coated = 0.0012 ipy × 30 yr = 0.036 in.
coated/paved = 0.0002 ipy × 30 yr = 0.006 in.

3. Initial thickness required to insure a residuum of 0.038 in. at the end of 30 yr:

uncoated = 0.051 in. + 0.038 in. = 0.089 in. < 0.1644 in. ok
coated = 0.036 in. + 0.038 in. = 0.074 in. < 0.1644 in. ok
coated/paved = 0.006 in. + 0.038 in. = 0.044 in. < 0.1644 in. ok

In this example, structural requirements during installation control the design. The No. 8 gage required will also provide ample thickness for total metal loss estimated for all three classes of pipe. While an uncoated culvert would be the obvious choice in this case, final selection should be based on economic considerations in light of all the culverts included in a construction contract.

In practice, situations will occur where estimated metal loss for an uncoated pipe will exceed the amount furnished for structural requirements, while the same pipe coated or coated/paved will be satisfactory. An example would be an Interstate installation with a design life of 40 yr. Here, a low-risk probability of 5 percent would be appropriate. The corresponding estimated total metal loss would be 0.176 in. for an uncoated pipe, 0.092 in. if coated, and 0.028 in. if coated/paved. Applying these values to the illustrative example, the No. 8 gage would not provide sufficient thickness for an uncoated culvert. Therefore, the designer would have to decide between a coated or coated/paved No. 8 gage fabricated pipe, or a heavier gage uncoated multi-plate pipe.

COMPARISON SURVEY

The intent of this portion of the investigation was to evaluate the long-term durability of aluminum and steel culverts similarly exposed to the environmental conditions found in New York. However, because aluminum culverts were not specified in State construction until 1964, their performance cannot be rated conclusively for several more years. As an interim measure, some aluminum culverts installed by other agencies

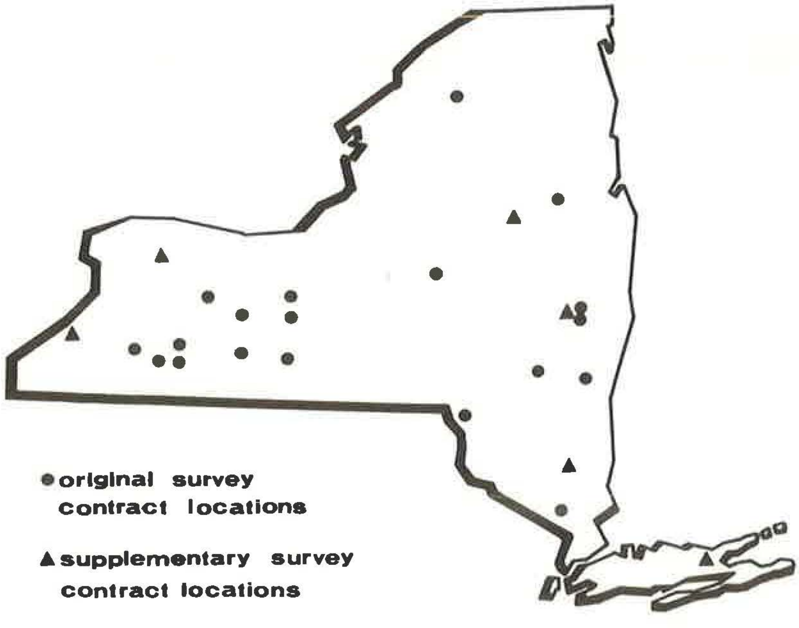

Figure 5. Locations of aluminum and steel culverts of similar ages.

between 1961 and 1964 were examined and compared with steel culverts in the same or adjacent waterways.

It was not always possible to select sites providing identical exposure for both types of culverts. Moreover, a few of the steel culverts are considerably older than their aluminum counterparts, and at two locations no steel pipes were available for comparison. Therefore, the results reported are preliminary, pending an evaluation of side-by-side installations in recent and future State construction. To date, 6 contracts have been negotiated which contain 26 culverts for this study. The performance of these and subsequent test installations will be evaluated in a future report.

Selection of Culverts

Twenty-one sites containing 34 aluminum and 26 steel culverts were selected. Their distribution is shown in Figure 5. Every condition included in the steel culvert survey is also represented here, except an industrial waste environment.

All aluminum pipes are uncoated, since no bituminous-coated culverts installed prior to 1965 could be identified. This apparently reflects the widespread interest in uncoated aluminum culverts that accompanied their introduction in 1959. By contrast, 4 of the steel culverts are bituminous coated/paved, 4 bituminous-coated, and 18 uncoated. Gage sizes of the aluminum pipes range from No. 8 (0.1644 in.) to No. 14 (0.0747 in.), while the steel pipes vary between No. 3 (0.2391 in.) to No. 16 (0.0598 in.). The No. 12 gage (0.1046 in.) is the most common size for both types.

Environment

Beginning in June 1964, essentially every culvert was inspected monthly for nine consecutive months, excluding December 1964 and January and February 1965, because of snow and ice conditions. During each inspection, the environmental tests discussed at the beginning of this report were performed, and metal loss was estimated visually by the procedure described. The only exceptions were velocity measurements, which were made during the anticipated period of peak flows—March, April and May 1965. At the end of the 1-yr program, 90 cored samples of 1-in. diam were removed (71 from the aluminum culverts and 19 from the steel culverts) and measured for actual metal loss.

With a few minor exceptions, the pH, electrical resistivity, and stream velocity results of the two surveys were in agreement. For example, water pH values among the comparison sites ranged from 6.2 to 8.8. This compares closely with the 6.2 to 9.0 range recorded for the steel culvert survey. On the other hand, only 30 percent of the comparison sites were classified as being saturated with respect to calcium carbonate, against 51 percent of the steel culvert survey sites. However, this difference is academic in light of the absence of correlation between this environmental variable and metal loss, as previously discussed. Two other tests, for hardness and chemical properties, were performed at the comparison sites. The results indicate a preponderance of soft water (low calcium carbonate concentration), and the frequent occurrence in solution of ions of iron (Fe^{+3}), ammonia $(NH_4)^{+1}$, and nitrate $(NO_3)^{-1}$. An important point illustrated by the field survey results is that individual environmental conditions at a site can vary appreciably, probably reflecting the effects of seasonal changes and the limitations inherent in testing procedures. Typical of such fluctuations are the soil pH values at one site which varied from 5.2 to 8.4 during the 12-month period, and water hardness at another which ranged from 126 to 214 ppm (soft and hard, respectively).

Performance of Aluminum Culverts

Without exception, the 34 aluminum culverts were in excellent condition and exhibited no measurable metal loss. In most culverts, changes in the original silver-like appearance were evident, but were judged insignificant from the standpoint of durability. A common surface phenomenon was staining of the area in contact with stream flow. Typically, the discoloration gave a dark, reddish-brown appearance much like that of rusted steel. Another frequent occurrence was formation of a dull white surface film accompanied by slight pitting, which is characteristic of atmospheric weathering. Occasionally, the pits were so closely spaced as to create an etched appearance, but penetration was slight. A few culverts in areas of greater potential abrasion displayed mild scratches and peening.

The good performance of these culverts can be logically explained. No chemically deleterious condition was encountered in the statewide survey of steel culvert performance. Also, the magnitude of long-term metal loss for those culverts was characteristic of "typical" corrosion, with oxygen concentration, velocity, and temperature the principal environmental variables involved. Since environments encountered were similar in both surveys, the same three factors would also apply to aluminum culverts. The range of temperatures and velocities encountered is not aggressive, but within normal limits, so that little corrosion would be expected.

Future evaluations will determine the validity of this reasoning. Performance to date, however, suggests that bituminous coatings are unnecessary for aluminum culverts, except in unusually aggressive chemical or abrasive environments. Results of other aluminum culvert investigations (1, 5, 9, 10, 11), under similar exposure conditions, support this interpretation.

Performance of Steel Culverts

The steel culverts in the comparison survey mirrored performance of steel culverts in the statewide survey. Average metal loss varied from none to appreciable amounts, without any apparent influence by environmental conditions. However, no case of local perforation was encountered. As before, loss of metal was confined to the inside surface below the waterline. Uncoated inverts typically had a dark central area bordered by a light-brown zone. This condition was generally associated with slow-moving stream flow carrying little or no granular material. Where higher velocities and/or granular bedloads were recorded, evidence of abrasion was sometimes noted.

Table 1 gives estimated average metal loss for the three classes of steel culverts. Because these are very young installations (except Nos. 2-2 and 22-2), the results do not necessarily suggest future performance trends. For this reason, the results should not be expected to agree with Figure 4, which is heavily weighted by culverts that are considerably older. In support of this point, it is interesting to note that the two old culverts just cited, both of which are uncoated, exhibited corrosion rates compatible with Figure 4.

Among uncoated culverts, two showed exceptionally high losses. At Site 3-1, a loss of 0.0343 in. was recorded. This represents a 25 percent reduction in original thickness in only 3 yr. The corresponding rate is 0.0114 ipy, or approximately two times the highest rate encountered in the steel culvert survey under apparently similar exposure. The invert is uniformly corroded and shows little evidence of abrasion. The culvert at Site 21-2 is similarly corroded and has lost 0.0168 in. thickness in 3 yr, or about 12 percent at the rate of 0.0056 ipy. This corresponds closely with the highest rate recorded in the steel culvert survey. The performance of these culverts is difficult to explain. Their appearance indicates that corrosion is primarily responsible. A possible explanation suggested by the field survey data is that metal loss is periodically accelerated by abrasion during transient peak flows, exposing fresh surfaces to corrosion. It is reasonable to suppose that these culverts would have developed appreciably less metal loss had they

TABLE 1

ESTIMATED AVERAGE METAL LOSS FOR STEEL CULVERTS

Site	Age (yr)	Total Loss (in.)	Rate (ipy)
(a) Uncoated			
1-4	1	0.0002	0.0002
2-2	31	0.0613	0.0020
3-1	3	0.0343*	0.0114
4-7	2	0.0034	0.0017
7-2	4	0.0050	0.0013
9-1	unknown	0.0101*	–
12-2	2	0.0028	0.0014
15-1	unknown	0.0034	–
17-4	2	0	0
17-5	2	0	0
17-6	2	0*	0
18-2	4	0*	0
19-2	2	0*	0
21-1	4	0.0131	0.0033
21-2	3	0.0168	0.0056
21-4	3	0.0105	0.0035
22-2	28	0.0034	0.0001
(b) Coated			
6-2	3	0.0034	0.0011
8-1	unknown	0.0183	–
14-5	unknown	0.0112*	–
20-2	2	0.0002	0.0001
(c) Coated/Paved			
1-1	3	0.0004	0.0001
1-2	4	0.0004	0.0001
10-3	3	0.0026	0.0009

*Based on cored samples.

been bituminous coated/paved. Both surveys demonstrated the effectiveness of such protection.

CONCLUSIONS

Results of the statewide survey of corrugated steel culverts in service 2 to 35 yr indicate the following:

1. Uncoated culverts have performed satisfactorily from the standpoint of durability. Approximately 70 percent of those in service 25 yr or longer have lost less than one-half of their original thickness. The large majority of existing uncoated culverts can therefore be expected to provide total service of at least 40 yr.
2. Protective bituminous coatings have reduced metal loss significantly, coating/paving being appreciably more effective than coating alone.
3. Metal loss does not correlate with pH, electrical resistivity, chemical concentration, or other soil and water properties, within the limits usually encountered in New York.
4. Metal loss is primarily associated with normal corrosion, abrasion playing but a small part.
5. Culverts should be designed to satisfy durability requirements, in view of the thinner gages permitted by current structural design practices. A suggested design procedure for uncoated, coated, and coated/paved culverts is outlined in this report.

Results of the comparison survey of corrugated aluminum and steel culverts under essentially similar exposures from 1 to 4 yr warrant the following tentative conclusions:

1. Uncoated aluminum culverts exhibited no measurable metal loss. This indicates that protective bituminous coatings are not required, except where severe chemical or abrasive conditions exist.
2. Uncoated and bituminous-coated steel culverts in the comparison survey essentially duplicated the performance of steel culverts in the statewide survey.

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This paper has also been published, with extensive data appendixes on culvert locations and field survey data on the steel and aluminum comparison sites, as Research Report 66-5, available from the Bureau of Physical Research, New York State Department of Transportation, Albany, New York 12226.

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Appendix A

SUMMARY OF CORRUGATED METAL PIPE DURABILITY STUDIES BY OTHER INVESTIGATORS

ALCLAD ALUMINUM

Approximately 9 yr ago (1959), the aluminum industry introduced corrugated aluminum culverts. Because they seemed to offer desirable engineering features, many agencies began using them immediately. Agencies of such states as Virginia and California initiated formal research programs to compare service histories of aluminum and galvanized steel culverts. Reports by Virginia (1, 9, 10) and California (11), together with Lowe and Koepf's nationwide summary of aluminum culvert performance (5) comprise the currently available literature (June 1966) on durability of aluminum culverts. The results of each of these studies are summarized in the following:

Virginia (1962-1965)

Initiated in 1961, the Virginia study includes five comparison sites where aluminum and steel culverts were installed side by side. The five sites were selected to represent different environmental conditions as follows: (a) abrasive flow, (b) wet-dry (fresh water), (c) high acid flow, (d) wet-dry (brackish water), and (e) swampy condition.

None of the aluminum culverts were bituminous coated, but the steel culverts at the high acid flow, wet-dry (brackish water), and swampy sites were bituminous coated.

After 3 yr of service the following observations were made:

1. The aluminum and steel culverts were performing equally well at the abrasive flow, wet-dry (fresh water), and swampy sites.
2. At the high acid flow site (pH 3.2 to 4.6 at times), the invert of the aluminum pipe had been almost completely removed. Severe rusting was observed on portions of the steel pipe where the bituminous coating had been removed, although the metal was not perforated.
3. Pitting of the aluminum cladding material had occurred at the wet-dry (brackish water) site, but no pitting of the base metal was observed. The steel pipe had rusted at the ends where the bituminous coating had been removed.

Other than concluding that bituminous-coated steel would be preferred to uncoated aluminum at the high acid flow site, no recommendations were made concerning future use of aluminum culverts in the State. Additional sites were recommended, particularly in areas having pH values between 4.0 and 6.0.

California (1965)

California's study, initiated in 1961, consisted of an evaluation of seven comparison sites and one site where only aluminum was installed. Also, laboratory corrosion and abrasion tests were conducted. The sites were moderately severe to severe from the standpoint of corrosion or abrasion, and all culverts were uncoated. Three were subjected to acid flow, two to abrasion, and three to soils with low electrical resistivities.

Both the steel and aluminum culverts at the acid flow sites (pH 2.7 to 3.7) performed poorly. The culverts perforated or were expected to perforate in less than 3 yr. At the site where steel was not represented, the aluminum culvert perforated at 0.83 yr. Aluminum and steel culverts both perforated at 0.56 yr at another site. At the third site the aluminum perforated at 0.33 yr while the steel was predicted to perforate in 2.3 yr.

The calculated stream velocity at one abrasion site was 10 to 14 fps, while at the second site it was about twice as fast. The predicted times to perforation for the steel and aluminum culverts at the less severe site were 41 and 3.6 yr, respectively. At the more severe abrasion site the times to perforation were 1.3 and 0.14 yr, respectively. It was concluded that for all practical purposes no commonly used culvert coating or material would offer a maintenance-free service life at the highly abrasive site.

Culverts in the remaining sites were located in soils having low minimum electrical resistivities. Estimated years to perforation at these sites for the steel and aluminum, respectively, were 49 and 12 yr for resistivities of 620 to 973 ohm-cm, 24 and 34 yr for 39 ohm-cm, and 8.0 and 8.8 yr for 6.5 ohm-cm.

On the basis of this investigation, the authors estimated that under favorable conditions aluminum culverts may have a service life up to 25 yr. However, this conclusion was subject to revision pending further field experience.

Lowe and Koepf (1964)

Approximately 500 aluminum culvert installations were reviewed in 1963, and 68 uncoated culverts were selected as typical sites. These sites, ranging in age from 0.4 to 3.6 yr, were inspected and evaluated. Several samples were taken from various culverts, and pH and soil resistivity measurements were made at most sites.

On the basis of the field observations and metallographic analyses of the samples, several tentative conclusions were drawn, as follows:

1. Aluminum culverts are resistant to attack by soils of the Great Soil groups comprising almost all soil in the United States.
2. The corrosivity of a soil to aluminum roughly follows its structural rating; that is, corrosion possibilities increase as the structural desirability of the soil decreases. Exceptions are peat and associated groups which are good-draining, highly organic materials. In these soils aluminum is performing well.
3. Aluminum corrodes severely in acid soils and acid runoffs having a pH of 4.0 or lower. Bare aluminum, therefore, is not recommended in these instances.
4. The use of aluminum culvert should be limited to runoff velocities below 10 fps if a heavy, rock-laden bed load is anticipated. Higher velocities are permissible if the bed load is primarily sand.

GALVANIZED STEEL

At one time or another, practically every state has found it necessary to investigate the durability of various culvert materials in relation to corrosion. Some that have conducted a culvert study include Georgia (12[2]), Tennessee (13[2], 14[2]), Virginia (14[2], 15[2]), California (2, 16[2]), West Virginia (17[2], 18), Idaho (19), Kentucky (13), North Carolina (20, 21) and Alabama (24). Summaries of their reports follow, including items issued through June 1966.

Georgia (1926-1928)

Approximately 3,300 in-service culverts ranging in age from 5 to 12 yr were rated both materially and structurally in the survey. Life expectancies were estimated by a method adapted from a system originally developed by California, which credits a maximum rating of 90 percent to apparently perfect culverts over 4 or 5 yr old, and 0 percent rating to all failures. Intermediate ratings were based upon the judgment of the inspector.

The calculations were empirically formulized and are included here as a point of interest:

$$F = L + \frac{H - L}{K}$$

[2]These reports have been summarized previously in a report published by Kentucky (13). These summaries were extracted either wholly or partially for inclusion in this report.

where

F = final rating, or percentage worth of the structure at time of inspection;
H = higher rating, whether material or structural;
L = lower rating, whether material or structural; and
K = a somewhat arbitrary constant.

From the final ratings, the annual rate of deterioration was calculated by

$$U = \frac{100 - F}{A}$$

where

U = unit deterioration (per year);
A = age at time of rating; and
F = final rating.

Lite expectancy, (E) was then obtained by

$$E = \frac{100}{U}$$

In one respect, structural adequacy of a culvert pipe at any age is related to the amount of material deterioration that has taken place. Structural conditions such as faulted joints, cracks, and silting are not necessarily the result of material deterioration, but may reflect some fundamental disadvantage of the type of culvert, or even poor construction and maintenance practices. In these equations, all these contributing influences are more or less averaged together in a single numerical rating. Such a rating may indicate overall condition of a culvert, but fails to credit any cause to the condition.

As a result of the survey, corrugated metal culverts were discontinued in certain parts of southern Georgia, due to their rapid deterioration under acid conditions. The actual data on life expectancies are rather difficult to summarize. As a notable observation, there were a surprising number of failures in what were originally considered permanent installations. A number of installations rated in 1926 were re-rated in 1928, and the average expectancies, particularly for vitrified clay, were somewhat higher. This indicates that the rating system probably gave conservative results.

A third investigation was begun in 1930, and was expected to include about 4,000 installations; however, it is not known whether the work was ever completed or the results reported.

Tennessee (1925-1927) (1941)

Although the Tennessee report, prepared by E. W. Bauman in 1928, is not available, the work has been summarized by Slack (13) and Crum (14) in published reports. It seems that the Tennessee investigation preceded the Georgia survey by almost a year, and some of those early developments were incorporated into the plans for the Georgia survey. A total of 2,924 culverts of all types commonly used in Tennessee were included in the inspection. Quoting Slack's summary:

> It was early seen that all culverts ultimately failed structurally but that two distinct paths of deterioration led to final failure. The corrugated metal or flexible type usually, but not always deteriorated more rapidly materially than it did structurally. The rigid type, including vitrified clay and concrete pipe, usually but not always deteriorated more rapidly structurally than materially.

Virginia (ca. 1925) (1946)

An original report by Shreve Clark, then Engineer of Tests in Virginia, is not available. Crum's summary of the report (14) is quoted:

> The outstanding result of the Virginia culvert investigation was the elimination of the use of corrugated metal culverts in Tidewater Virginia east of the "Fall" line. It was found that on account of the brackish waters in the tidal area, the lives of these culverts were too short to justify their use in comparison with other types.
>
> North and west of the "Fall" line no appreciable difference in the service of vitrified clay, concrete, or corrugated metal pipe was found, and these types are therefore on a parity for construction in this region.
>
> In 1946, performance of bituminous-coated metal pipe was studied in the Tidewater area (15). Whereas, the average life of plain galvanized metal pipe in the area had been on the order of 10 yr, bituminous-coated pipe already in service 10 yr at the time of the survey appeared capable of giving many additional years of service.

California (1925-1927) (1929-1930)

No report on the original 1925-1927 survey in California was ever compiled for distribution. According to a summary of the unpublished work, prepared in July 1950 by T. E. Stanton, then Materials and Research Engineer, the 1926-1927 survey failed to furnish conclusive data concerning comparative merits of different base metals, and that report was held confidential. As an outgrowth of the inconclusive status, a long-term (20 yr) performance tests on a variety of corrugated metals was started in 1929-1930. At the conclusion of the 20-yr period (in 1950), there were still no outstanding differences in corrosion resistance for any of the base metals. Some of the conclusions from the earlier survey, as cited in Stanton's summary, are also of interest:

> The average indicated life of corrugated metal culverts in California, in fresh water and with intermittent flow, based on observations of 2500 such structures, is about eighty years.
>
> Deterioration in corrugated metal culverts is due almost exclusively to corrosion, is preventable in many cases, and may be greatly reduced in others.
>
> Spelter alone does not provide sufficient protection against corrosion, except under most favorable conditions of exposure, and bituminous and other protective coatings are usually desirable even where spelter is used.
>
> Under favorable conditions of exposure the value of corrugated metal culverts...may be only 25 to 75% of the value of permanent structures. Economic considerations should control under these circumstances, as in all others, and the selection of some type not affected by these destructive conditions may thus be found desirable.

According to Stanton, the 1950 California Specifications permitted the use of five kinds of base material as in Table 1 of AASHO Standard Specification M36-47. Under severe scouring or other adverse conditions, bituminous coated/paved pipe is specified.

California (1953-1954)

In 1959, the California Division of Highways reported (2) on findings of a corrosion survey conducted in 1953-1954, involving 7,000 corrugated metal culverts located in the northwest district (District 1). The results of this survey indicated that the corrosion rate of metal culverts was variable, depending on environment, with certain factors exerting greater influence than others. By using information from the first study and supplementing it with data from different types of watersheds located in various parts of the State, it was found that the major factors influencing corrosion rate were the pH and electrical resistivity of the soil and water. A further study was conducted for estimating service life of corrugated metal culverts. The findings are summarized as follows:

1. The life of metal culverts depends primarily on the presence of moisture and the chemicals contained in the watershed.
2. The chemical environment of a specific culvert site is directly influenced by the soil, vegetation, rainfall, and drainage characteristics of the watershed, and by the regularity and volume of the flow. The chemical environment of a watershed affects the pH and electrical resistivity of the runoff.
3. A method was developed which provides a relatively accurate estimate of the corrosion rate of galvanized metal based on pH resistivity values of the soil and water.
4. Bituminous coatings were found on the average to add 6 yr to the life of CMP culverts. The actual added life varied from zero in areas of continuous flow carrying heavy debris to over 20 yr in arid areas of intermittent runoff.

All the investigations indicated that the time to perforation of a galvanized corrugated steel culvert can be extended by means of a protective coating.

West Virginia (1928-1929) (1931)

In 1934, the State Road Commission of West Virginia, in cooperation with West Virginia University, published a report (17) of a culvert survey made in 1931. The author, W. S. Downs, described the situation as follows:

> A major portion of the State's area contains valuable coal deposits consisting of numerous seams which differ somewhat in the mineral content. Many such coal deposits are being operated or have been operated. In either event the oxidizing effect of the air in contact with the workings causes the drainage water from the mines to be highly impregnated with mineral salts. Most of them show an acid reaction due to the sulfur and iron (free sulfur and sulfur in combination with iron, never iron alone) in the coal so that the effect upon metal or even upon concrete cannot be ignored. Under such conditions, it is necessary to exercise discretion in the selection of the culvert type. In certain localities it may be advisable to reject the use of a culvert type which under different conditions has proven highly economical.

Approximately the same system of evaluation as in Georgia, Tennessee, and California was used in the West Virginia survey except that the structural factor was not averaged with the material factor. The lower rating was simply used to calculate life expectancy. The culverts ranged in age from 3 to 12 yr. The statistical results of the survey (in part) were as follows:

Corrugated Metal Culvert Type	Culverts Observed	Avg. Expected Service Life (yr)
General	1277	27
Plain	832	22
Paved invert	445	49

Quoting again:

> It is conclusively shown that mine drainage which possesses a low pH value

> (highly acid) will rapidly disintegrate the invert of any exposed metal pipe.... As a general rule, however, this survey shows values ranging from 6 to as low as 2.7. The survey further shows that pipe deterioration (concrete and metal) increases as the pH value of the water decreases.

In 1928 and 1929, West Virginia also attempted to resolve the base metal problem (18). A series of test sections of various metal pipes were installed in a flume carrying highly acid mine water. Though the report on this work too has been held in confidence for some 20 yr, test conditions were very similar to those at the Kentucky test installation at Morton's Gap. In those tests, bare metal in contact with the acid water lasted only 86 days, and there was little difference observed in the life of the different base metals. (At Morton's Gap, the plain galvanized metal sections did not last quite that long.)

North Carolina (1945) 1954) (1964)

In 1945, an inspection and survey was made of bituminous-coated, corrugated metal pipe culverts installed in eight sections of the Blue Ridge Parkway in North Carolina. The culverts had then been in service 4 to 9 yr. Three types of bituminous-coated pipe were used:

1. Asphalt-coated/paved galvanized metal pipe.
2. Asbestos-bonded metal pipe with asphalt coating/paving.
3. Galvanized metal pipe with asphalt coating/paving reinforced with a metal plate invert.

The summary of the data obtained in the inspection pointed out the following:

1. In general, the most severe deterioration of the asphalt coating/paving occurred at the outlet end of the culverts.
2. The amount of water flow did not seem to bear any consistent relation to the degree of deterioration occurring in the coating/paving.
3. The slope of the pipe had little influence upon deterioration of the asphalt coating/paving.
4. The asphalt coating on the outside of the pipe usually exhibited a checked pattern of cracking and was found to have very little adhesion to the metal.
5. The metal-reinforced type of paved invert showed the greatest amount of deterioration under service conditions.
6. The culverts in which asbestos-bonded metal was used appeared to have greatest resistance to deterioation. Although some coating was lost, the asbestos sheet appeared to give added protection to the metal.
7. The better condition of the asphalt coating in one section as compared with another seems to indicate that the coating's durability depends considerably upon the type of asphalt used.

In 1954, an inspection of plain galvanized pipe was conducted on another section of the Blue Ridge Parkway. These culverts had been in service for 18 yr and were generally in good condition. The corrosion noted was not considered serious and no pitting was observed. Most corrosion occurred in culverts where debris could accumulate, and most severely along the line at the surface of the debris where the deposit was damp and exposed to the air. All outside exposed metal was in excellent condition.

During April and May 1964, the bituminous coated/paved culverts inspected in 1945 and the plain galvanized culverts inspected in 1954 were again observed (after 23 to 28 yr of service). A partial summary of these observations was as follows:

1. Environmental conditions in the various sections were approximately the same, without adverse soil or water characteristics that would accelerate corrosion.
2. Uncoated metal pipe showed appreciably more corrosion than coated pipe. Coated pipe that lost the coating early in service showed approximately the same amount of corrosion as uncoated pipe.

3. The asphalt-coated/paved pipe that retained the coating/pavinghad good resistance to corrosion.

4. The asbestos-bonded, asphalt-coated pipe was in excellent condition. There was essentially no loss of coating or corrosion of metal.

Kentucky (1949-1952)

In 1949, the Kentucky Department of Highways initiated a survey of existing culvert installations. Reports were published in 1950 and 1952. The following conclusions were stated:

1. Sulfur-bearing natural deposits such as shales and coals are the foremost sources of severely corrosive drainage waters of any consequence in the State.

2. Drainage waters within the coal fields vary from mild to extreme acidity, but the majority of waters carried by highway drainage culverts are only mildy acid or not acid at all.

3. Severely acid waters occur only within the coal fields, but mild acidity may occur at shale outcroppings or along deeply entrenched stream valleys.

4. Uncoated galvanized metal pipe has no resistance to corrosion by acid waters and is vulnerable to corrosive deterioration even under mild conditions. Under non-acid conditions, the life expectancy may range from 10 to 100 yr depending on the exposure. Because of this, metal pipe should be regarded as: (a) of no value where there is acid water; (b) unsuitable for use in non-acid water where flow is moderate and where the installation is designed for long life; and (c) suitable for use in non-acid water where the installation is designed for limited life or where the ease of replacement justifies the risk of early failure.

5. Bituminous-coated metal pipe is resistant to acid corrosion as long as the coating insulates the metal from contact with acids. On the basis of information available from other sources, a bituminous coating properly applied should have an anticipated service period of at least 15 yr. The service life of coated pipe in acid waters should be comparable with the life of the coating, and in non-acid waters the service life should range upward from 15 yr depending on site conditions.

6. Vitrified clay pipe is the only culvert material now in use that is totally inert to corrosion by even the most severe drainage waters. Its use as a lining material affords promising possibilities where conditions of high acidity are known to exist.

Alabama (1960-1964)

During the summer of 1960, it was discovered that two perforated metal pipes on I-65-2, near Jemison had been excessively damaged along the flow line by natural elements. This deterioration, or corrosion, of pipe culverts in certain areas of the State is not unusual, but the fact that these pipes had been destroyed in less than 8 months was.

Tests showed that the pH of water passing through these structures was about 2.5, and the nearby soil was so acid in places that no vegetation would grow. As a result, a statewide survey was conducted to establish the distribution of pH and electrical resistivity, and thereby identify geographic areas that are potentially deleterious to metal culverts. The following conclusions were reached:

1. Measuring the pH of surface water throughout an area is a fast, relatively inexpensive means of identifying locations that may affect the performance life of highway drainage structures.

2. The accuracy of an iso-pH map depends on taking a sufficiently large number of readings, in enough locations, to insure thorough coverage.

3. In areas of questionable pH values a check sampling program should be conducted. This is necessary to confirm the presence of organic compounds originating from pollution and agricultural products.

4. Separate test programs and maps should be made seasonally during heavy and light rainfall. A third map should be constructed as a check against the season producing the most aggressive condition.

5. The variable nature of in-place pH values taken in surface water will result in a general pH trend; that is, iso-pH lines are not conclusive, but averages, and should be considered as such.

Idaho (1957-1965)

In November 1957, the Idaho Department of Highways, together with the Armco Metal Products Co., inspected metal culverts to determine life expectancy of metal culvert pipe and to provide standards for selecting the type of pipe to be used under specific environments. The conclusions were as follows:

1. Performance of galvanized corrugated metal pipe in service indicates life expectancies as follows: (a) desert, 40 to 60 yr or more; (b) cultivated; 30 to 60 yr or more; (c) timbered, 25 to 60 yr or more; and (d) pasture, 30 to 50 yr.
2. The only installations indicating a service life less than 40 yr are in areas characterized as cultivated, timbered, or pasture.

It was recommended that the California test be used as a guide to determining service life, and where predicted life is less than 40 yr that asphalt coating be used.

Appendix B

TESTING METHODS AND EQUIPMENT

Hydrogen Ion Concentration (pH)

A Beckman Model 180 pocket pH meter was used to test samples of soil and water placed in clean half-pint jars. Soil samples were diluted, one-to-one, with distilled water; water samples were tested without dilution. Initially, all tests were made at each culvert site; however, this was time-consuming and the final procedure followed was to perform all tests at the end of each day. Early attempts to delay testing until the samples were returned to the laboratory were discontinued when the pH was found to change significantly after about 12 hr.

Hardness and Saturation

Water hardness, expressed as parts per million (ppm) of calcium carbonate ($CaCO_3$), was measured with a portable titrating unit manufactured by Calgon, Inc. Saturation of the water with respect to calcium carbonate was determined by measuring the pH of the water, and then adding calcium carbonate and observing the resulting change in pH. If the pH became more basic (increased), the water was considered unsaturated. If it remained the same or became more acid (decreased), the water was considered saturated.

Chemical Tests

Soil samples were diluted with distilled water in a one-to-one ratio and stirred to dissolve the soluble salts in the soil. The water was then tested to determine whether the ions previously mentioned were present. Water samples were tested as sampled without dilution.

Electrical Resistivity

Soil and water resistivities were measured with an M-Scope Resistivity Meter manufactured by Fisher Research Laboratories, Inc. The meter has an upper limit of 30,000 ohm-cm. This single probe device was used in preference to the multiple probe types commonly used in pipeline work, because it appeared to provide a more precise determination of resistivity of backfill material directly adjacent to the culverts. In addition, it is a simple matter to determine water resistivity with this device.

Measurements of soil resistivity were made by driving a steel rod into the backfill as close to the pipe as possible, removing the rod, and then placing the resistivity probe in the hole. After twisting the probe to insure good contact with the soil, the resistivity was recorded as the in-place resistivity. To obtain an estimate of the minimum resistivity possible, distilled water was then poured into the hole and another reading made. This procedure was continued by adding increments of water and repeating the test until the resistivity maintained a constant low value or began to increase. The lowest value obtained was recorded as the minimum resistivity of the soil. Measurements of in-place and minimum resistivities of the soil were made at several points adjacent to each culvert. Where conditions permitted, measurements were taken adjacent to the pipe at its center line, flow line, invert, and 1 ft below the invert.

Water resistivities were determined by placing the probe in the stream at several points near the culvert. When more than one value of resistivity was measured, the lowest value was recorded.

Electrical Potential

Electrical potentials between the culvert and soil, and between the culvert and water, were measured using a Leeds and Northrup millivolt potentiometer. Lead wires from the potentiometer were connected to the culvert and to a reference electrode placed either in the soil or water. A copper rod was used as the reference electrode for all soil measurements and for water measurements during the early period of testing. Later, a copper-copper sulphate reference electrode was used for water and soil measurements in place of the copper rod.

Culvert-to-soil measurements were made two ways—one with the copper rod placed in the soil near the crown (top) of the culvert, and the other with the copper rod placed near the invert (bottom) of the culvert. Culvert-to-water measurements were made with the reference electrode (either the copper rod or copper-copper sulfate electrode) in the stream.

Flow Velocity

Where the velocity of water flowing through the culverts was calculated, the time for either a ping-pong ball or a dye to travel the measured distance between the inlet and outlet of the pipe was recorded.

Discussion

A. VAN KAMPEN, Director of Engineering, American Concrete Pipe Association—We have reviewed the report on which the presentation was based, and agree fully with the intent that the design of metal culverts should be based not only on structural requirements, but should include considerations of durability. Since durability depends on corrosion and abrasion, we feel that the statement "abrasion was found to be of minor influence" is misleading. The data presented in the comparison survey, Table E-1 of the original report (see footnote 1), show a maximum velocity of 8.0 fps, with only 7 locations having a velocity exceeding 5.0 fps. With the lack of any higher velocity, we are not surprised that abrasion was found to be of minor influence and agree with the authors that this may well have been caused by the draught in the northeastern United States, as was the large number of dry culverts (299 out of 792) observed during the study. There is a lack of correlation between slopes of the culverts and the observed velocities. We agree with the authors that the scatter of data, when plotting the age of the culverts versus metal loss, is such that the data are not normally distributed and feel that a conclusion on the comparative age of uncoated, coated and paved culverts should not be based on such an abnormal distribution.

We fully agree with the authors that a note of caution is essential in predicting the anticipated life of culverts. As stated in the report, the expected life of 40 years for uncoated culverts and 50 years for coated culverts, is based on existing installations which incorporated large safety factors in their original design. The present trend in design toward thinner gages, based on current structural theories, will reduce these safety factors and result in reduced life expectancy, unless this reduction is taken into account during the design of the culverts.

We generally agree with the conclusions in the report, but would like to point out that the expected service of the culverts is based on the larger safety factors used in the original design.

The lack of correlation between metal loss and pH is limited to the range encountered in New York and differs from experiences in other states. In concluding that abrasion plays but a small part, we feel such a conclusion can only be based on the low flow velocities observed. Additional observations with higher velocities, are required before such a far-reaching conclusion can be made.

JOHN E. HAVILAND, PETER J. BELLAIR, and VINCENT D. MORRELL, Closure—We appreciate Mr. Van Kampen's discussing our paper. He has done an excellent job of summarizing some of the limitations we have placed on our data.

His emphasis on the role of abrasion in metal loss is valid, when evidence of abrasive damage exists. He is also correct in noting that our measurements indicated low velocities of flow. However, the two points must remain separate.

Our conclusion that abrasion plays a small part in overall corrosion was based on the absence of abrasion-related damage to coatings, fasteners, and corrugations. It was not based on measured velocity. It would be presumptuous, indeed, to relate drought velocities to the potential for abrasive damage. However, if structures with as much as 30 yr of service exhibit no evidence of abrasion damage, we feel it reasonable to assume that the potential for such damage is very low. Further verification of the minor influence of abrasion is the fact that all our rates of metal loss are less than reported values for atmospheric and still water exposure.

The water velocity measurements to which Mr. Van Kampen refers (Table E-1) are not included in this printing, but are available (see footnote 1). These measurements, to some extent, reflect the extended drought in New York; nevertheless, they should be regarded as reasonable indicators. They were made randomly for several years, at all times of the year when the structures were accessible. Further, recent measurements after the drought ended have not exceeded the reported values. Their low magnitude, in comparison with theoretical values, may be explained by the fact that none of these structures was found to be flowing more than 10 percent full when inspected. Indeed, none showed evidence of ever flowing much more than half full. Theoretically, such low flows coupled with a hydraulically inefficient square end condition would produce low velocities in short culverts, just as we found.

Mr. Van Kampen's comment that our conclusions are relevant only to New York State is a reiteration of our own warning. We are concerned that our conclusions may lull designers into a false sense of security. Such an error would be dangerous. Our findings are generally valid for the State, but there may well be undetected, isolated locations where highly deleterious conditions exist. Such a possibility is conceivable whenever sampling is substituted for a total inspection, regardless of sample size. Thus, we feel our findings provide the designer with a good basis for determining probable life of a new structure, but only when he is sure its environment is similar to the State in general—we do not relieve him of responsibility to assure himself that it is similar.