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Field Performance of Concrete and Corrugated Steel Pipe Culverts and Bituminous Protection of Corrugated Steel Pipe Culverts

JOHN OWN HURD

ABSTRACT

In this paper information is provided regarding the durability of concrete pipe, galvanized corrugated steel pipe (6 x 2-in. and 2.67 x 0.5-in. corrugations), and bituminous protection (AASHTO M 190, Types A, B, and C) of corrugated steel pipe used for culverts in Ohio. Detailed analyses were performed to evaluate the effects of various environmental factors on the durability of these materials. None of the environmental parameters studied had a significant effect on the performance of the bituminous protection. Loss of adherence to the pipe was the major cause of deterioration of the material. The average lives of bituminous coating and coating with invert paving were 3.16 and 18.71 years, respectively. Water pH and abrasiveness of flow were the only environmental parameters to have a significant effect on the deterioration rate of corrugated steel pipe. Below a value of 7.0, water pH had a significant effect on concrete pipe performance. Predictive equations and graphs are presented that can be used to estimate service lives of concrete and corrugated steel pipe culverts. Information is provided regarding the geographic location of various ranges of environmental parameters found to have a significant effect on culvert durability.

Material durability is an important factor in the determination of what type of pipe is selected at specific culvert sites. Before 1971 no accurate method of predicting the service life of culvert pipe materials in Ohio was available. Pipe selection was based on the experience and subjective judgment of the designer.

Published reports on the durability of culverts in other states were reviewed (1-9). It was noted that the effects various environmental parameters had on culvert durability varied widely among the results reported by the different states. Because of these varied results and because environmental conditions in Ohio were unlike those in any of these other states, the Ohio Department of Transportation (ODOT) decided to evaluate culvert pipe durability in Ohio.

In the fall of 1971 ODOT began a comprehensive and continuing program to evaluate the field performance of various types of pipe and pipe protection used for culverts in Ohio. The major part of this program to date involved an extensive field investigation and statistical analyses of data to evaluate the performance of concrete pipe, galvanized corrugated steel pipe, and conventional bituminous protection (AASHTO M 190 Types A, B, and C) for corrugated steel pipe. An earlier report (10) published by ODOT provides a detailed description of the data collection and analyses. A summary of the results obtained from that work are reported in this paper.

FIELD INSPECTION

A total of 531 concrete pipe culverts, 386 structural plate pipe (SPP) culverts, and 624 corrugated steel pipe (CSP) culverts were inspected between 1972 and 1975. Of the 624 CSPs, 127 were bituminous coated (AASHTO M 190 Type A) and 302 were bituminous coated with paved inverts (AASHTO M 190 Types B and C). These culverts were nearly all 42 in. or larger in size. This minimum size was determined from trial studies to be the smallest a person could work in without undue difficulty. It is also a size where there will normally be dry weather flow at the site.

The selected culvert sites were located throughout the state to assure a complete geographic coverage of all environmental regions of Ohio. The total sample of 1,541 culverts represents approximately 20 percent of the total number of culverts in the state of 42-in. size and greater.

The following data pertinent to culvert durability were collected at each site:

1. Pipe size, material type, and pipe wall thickness;
2. Type of pipe protection;
3. Depth and velocity of dry weather flow;
4. Presence of abrasive material and apparent effect;
5. Amount and type of sediment or debris or both;
6. pH of water, streambed, and embankment;
7. Electric resistivity of water, streambed, and embankment;
8. Description of protection and protection rating (based on amount of protection lost);
9. Description of base pipe and base pipe rating (based on amount of rust and scale for metal pipe and on amount of mortar and aggregate loss for concrete pipe);
10. Qualitative chemical tests (at selected sites); and
11. Metal cores (at selected sites).

The following is a list of concensus observations made by study teams throughout the data-collection phase. They were subjective opinions because no in-depth statistical analyses had been performed at that time.

1. Visual rating systems were generally a good practical method of classifying the condition of culverts.
2. The two main factors that affect pipe durability were low water pH and abrasive bed load. Electric resistivity did not appear important.
3. Nearly all durability problems were limited to the lower half of the pipe interior.
4. Bituminous coating without invert paving is of little value.
5. Bituminous coating with invert paving does extend the life of corrugated steel culverts.
6. Adherence problems were the main cause of loss of bituminous protection. Dry weather flow overtopping the coating-paving interface aggravated that situation.

PERFORMANCE OF BITUMINOUS PROTECTION OF CSP

Initial statistical analyses of data for CSP indicated that there was a significant difference in the performance of pipe with and without bituminous protection. It was decided to develop a method to estimate the service life of the protection rather than considering it as part of the protection and pipe system. Bituminous coating (AASHTO M 190 Type A) and bituminous coating with invert paving (AASHTO M 190 Types B and C) were analyzed separately. From this point on the two will be referred to as "coated" and "coated and paved," respectively. Because only the lower halves of the culverts were rated, no distinction was made between culverts where coating was applied only to the bottom half of the pipe and those where coating was applied to the entire pipe.

Results of stepwise regression performed on data for coated culverts indicated that age was the only independent variable tested that had a significant effect on protection rating. However, the multiple correlation coefficient of the regression equation was only 0.38. Considering this and the qualitative nature of the numerical values assigned to the ratings, any attempt to predict the protection rating for an individual coated culvert as a function of age would be highly questionable.

To estimate the life of bituminous coating, the method chosen employed a relation in which the percentage of bituminous-coated culverts without poor rated coatings could be described as a function of age. The method assumed that the useful life of the protection had ceased when rated poor. Because of the small number of coated culverts inspected of any one age, the percentage of coated culverts not having a poor protection rating was calculated for 5-year intervals. These values are plotted at the midpoint of each interval in Figure 1.

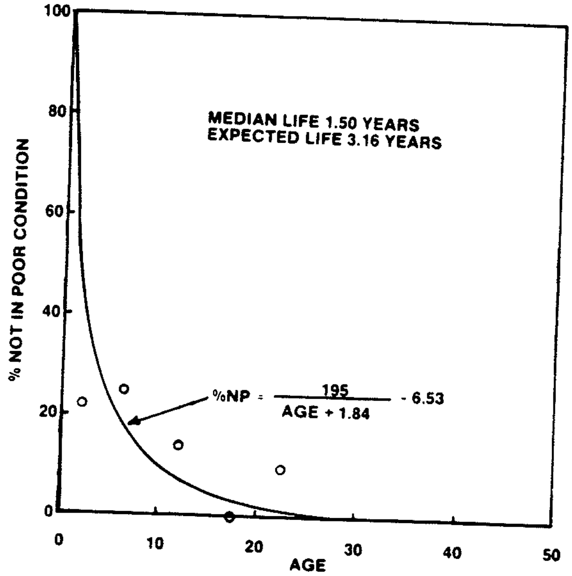

FIGURE 1 Percentage of bituminous-coated culverts with protection not rated poor.

The equation used to fit the points plotted in Figure 1 is

$$\% \text{ Not Poor} = [195/(1.84 + \text{age})] - 6.53 \qquad (1)$$

The correlation coefficient between actual and predicted values of % Not Poor, including end points, was 0.97 in this case. The average life of bituminous coating was calculated to be 3.16 years, and the median life was 1.50 years.

The results of stepwise regression performed on the data for coated and paved culverts indicated age had the largest effect on protection rating. The multiple correlation coefficient comparing actual values of protection rating with those predicted by using age alone was 0.48. Flow depth and sediment depth also had a small effect on protection rating. When the sum of the two increased, the rating became worse. This concurs with the field observations that coating and paving performed much better for those culverts where the low or dry weather flow had been contained in the paved portion of the pipe.

Although the multiple correlation coefficient for the regression equation for coating and paving was slightly better than that for coating, predicting protection rating for an individual culvert as a function of age and sediment depth plus flow depth would still be questionable. Therefore, to estimate the life of bituminous coating and paving, the same method was employed as that for coating alone. The percentage of coated and paved culverts without a poor protection rating was calculated for each year up to 17 years of age, and at 5-year intervals thereafter. These values are shown in Figure 2. The equation used to fit the points plotted in Figure 2 is

$$\text{\% Not Poor} = [3{,}000/(15.55 + \text{age})] - 45.77 \qquad (2)$$

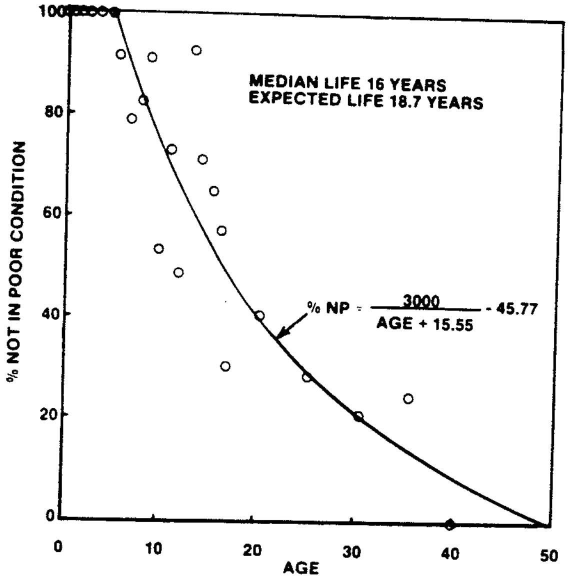

FIGURE 2 Percentage of bituminous-coated-and-paved culverts with protection not rated poor.

A plot of this equation is shown in Figure 2. Actual to predicted % Not Poor for age had a multiple correlation coefficient of 0.912. The average life of bituminous coating and paving was calculated to be 18.71 years for any field condition.

The sample of coated and paved culverts was then divided into two groups: those where it appeared that substantial overtopping had occurred and those where the dry weather flow had remained primarily within the paved portion of the culvert. The percentage of culverts without poor protection rating was determined for the same age breakdown as in the total sample for each group. These are shown plotted in Figure 3. The curves shown in Figure 3 were fit to each group by eye. However, the expected (average) lives obtained from these curves, 12 years for those with overtopping and 25 years for those without, illustrates the detrimental effect of dry weather flow depth exceeding the paved portion of the culvert.

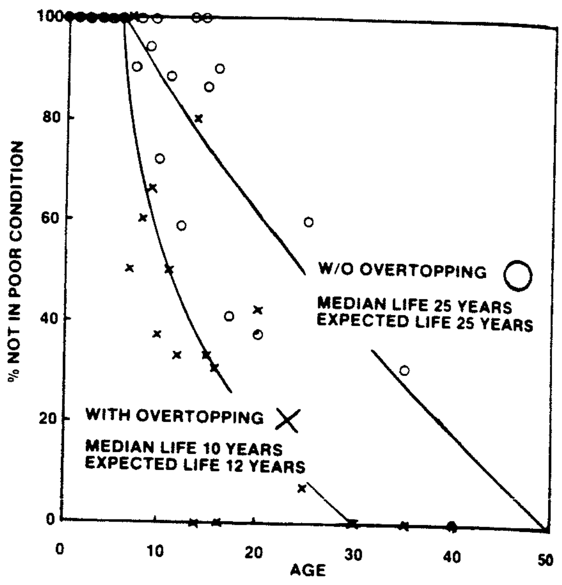

FIGURE 3 Percentage of bituminous-coated-and-paved culverts with protection not rated poor (overtopping considered).

PERFORMANCE OF GALVANIZED CSP

This study considered two types of galvanized steel conduits: corrugated (2.67 x 0.5-in.) steel pipe and pipe-arches and structural plate corrugated (6 x 2-in.) steel pipe and pipe-arches, hereafter noted as CSP and SPP, respectively. From the total number of CSPs and SPPs inspected, a sample was obtained for analysis of measured metal loss. A breakdown of the culverts selected for the measured metal-loss analysis, based on pipe type and metal ratings, is given in Table 1.

TABLE 1 Culverts Selected for Metal-Loss Analysis

	Corrugated Steel Pipe		Structural Plate Pipe	
Rating	Total Inspected	Metal-Loss Analysis	Total Inspected	Metal-Loss Analysis
Excellent and very good	104[a]	36	210	32
Good and fair	226	72	164	34
Poor	110	60	12	9

[a] This figure includes only those culverts where metal was exposed, thus excluding those culverts where the protection was still intact. The total excellent and very good CSPs was 287.

The effects of the independent variables on metal loss and metal rating were analyzed by various statistical methods. Those variables that exhibited consistent significant effects on the durability of corrugated steel culverts were age, water pH, abrasion, and pipe protection. It should be noted that water pH and abrasiveness of flow were the only environmental parameters affecting CSP deterioration, just as noted by the field crews. In the predictive equations for metal loss, the effect of protection was accounted for by subtracting protection life from the age of the culvert. Therefore, the variable age referred to in the following equations is actually the years that metal has been exposed.

Numerous predictive metal-loss (ML) equations were developed by using the variables age, water pH, and abrasion for various combinations of CSP and SPP. The resulting four equations that best fit the data are as follows: for CSP without abrasion:

$$ML = 7{,}210\ (\text{age})^{1.0164}/(\text{pH})^{4.3076} \qquad (3)$$

for CSP with abrasion:

$$ML = 5{,}040\ (\text{age})^{1.4569}/(\text{pH})^{4.4691} \qquad (4)$$

for SPP without abrasion:

$$ML = 4{,}995{,}000\ (\text{age})^{0.8427}/(\text{pH})^{8.0583} \qquad (5)$$

and for SPP with abrasion:

$$ML = 18{,}300\ (\text{age})^{1.602}/(\text{pH})^{5.44446} \qquad (6)$$

The regression statistics for the four equations are given in Table 2. These equations are plotted in Figures 4 and 5. It should be noted that for nonabrasive conditions the performance of SPP is significantly better than that of CSP. The reason for this could be due in part to the superior zinc coating on SPP compared with that on CSP.

TABLE 2 Statistics of Log-Linear Form of Metal-Loss Equations

Equation	For	R	SD	2(SD)
3	CSP without abrasion	0.700	0.605	1.210
4	CSP with abrasion	0.804	0.474	0.948
5	SPP without abrasion	0.694	0.583	1.166
6	SPP with abrasion	0.815	0.447	0.894

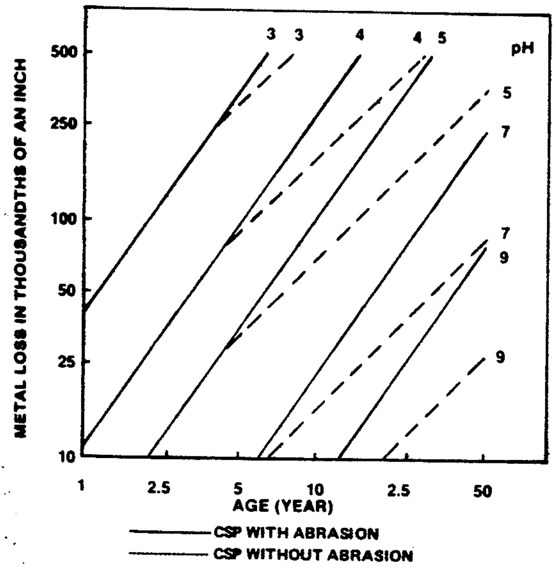

FIGURE 4 Predicted metal loss for CSP culverts.

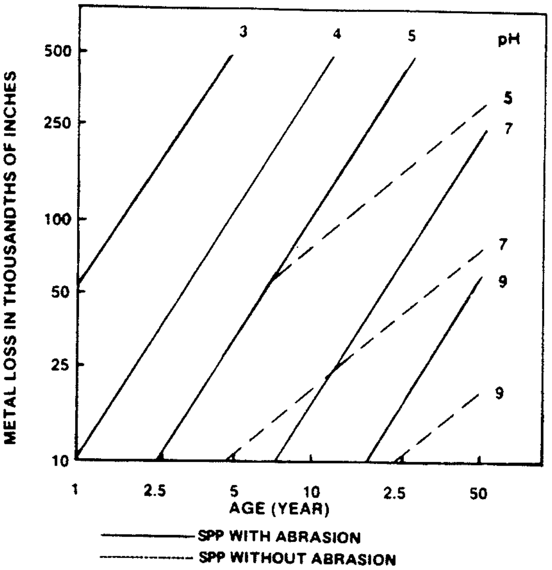

FIGURE 5 Predicted metal loss for SPP culverts.

PERFORMANCE OF CONCRETE PIPE

The concrete culvert field ratings were analyzed to determine the durability of concrete culverts exposed to various environments. The concrete ratings are based directly on concrete loss as opposed to indications such as rust and scale, which were used to determine metal ratings.

The analyses indicated that the performance of the concrete culverts differed for two environmental groups based on ranges of water pH. The first group consisted of those culverts with water pH equal to or greater than 7.0. For this group water pH did not affect the condition of the culverts (concrete ratings) for the range studied (7.0 to 9.5). Those variables that have a significant effect on concrete rating for this pH group, in order of importance, are age, pipe slope, flow velocity, and abrasion. The multiple correlation coefficient for the regression equation developed was too small (R = 0.45) to use the results to predict pipe performance of an individual culvert. However, for a worst-case condition, the model predicted a service life well in excess of the age range of culverts in the study.

The second group contained those culverts with water pH less than 7.0. The variables that have a significant effect on concrete rating for this group, in order of significance, are water pH, pipe slope, sediment depth, and age. Two equations were developed that best fit the data:

$$\text{Concrete rating} = [9.999\ (\text{age})^{0.134}\ (\text{slope})^{0.103}] \div \{(\text{pH})^{1.205} \times [1 + (\text{sed/rise})]^{1.1573}\} \qquad (7)$$

$$\text{Concrete rating} = [10.015\ (\text{age})^{0.129}\ (\text{slope})^{0.106}] \div \{(\text{pH})^{1.204} \times [1 - (\text{sed/rise})]^{0.762}\} \qquad (8)$$

Both had multiple correlation coefficients and standard deviations of 0.82 and 0.33, respectively. Setting the concrete rating equal 3.5 as a factor of safety to account for some of the deviation of concrete rating, the two equations were reduced to

$$\text{Years to poor} = [0.350\ (\text{pH})^{1.205}/(\text{slope})^{0.767}]^{7.457} \times [1 + (\text{sed/rise})]^{8.630} \qquad (9)$$

and

$$\text{Years to poor} = [0.349\ (\text{pH})^{1.204}/(\text{slope})^{0.824}]^{7.758} \times [1 - (\text{sed/rise})]^{-5.912} \qquad (10)$$

respectively. These equations are plotted in Figures 6 and 7, respectively, with the sediment term (sediment depth divided by rise of pipe) set equal to zero, because in general sediment cannot be accurately predicted nor is it desired hydraulically.

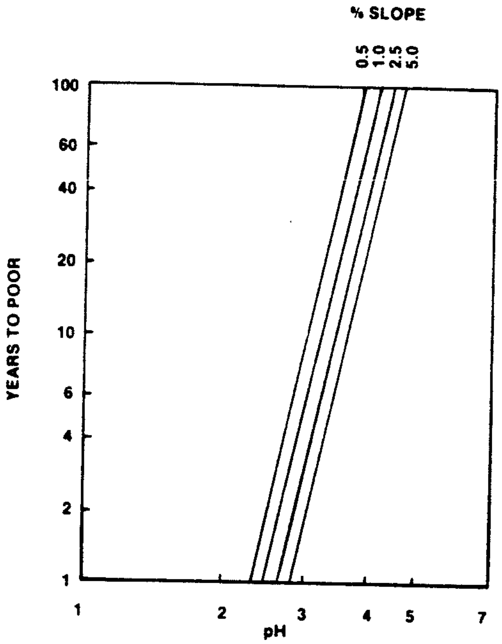

FIGURE 6 Plot of Equation 9 for concrete pipe culvert life.

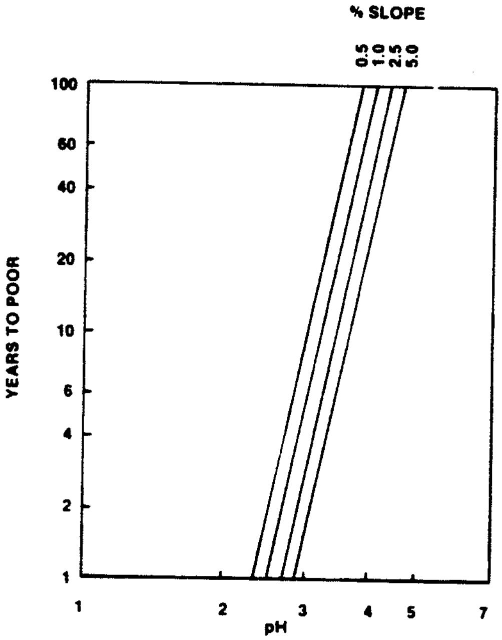

FIGURE 7 Plot of Equation 10 for concrete pipe culvert life.

ENVIRONMENTAL FACTORS

The locations of abrasive culvert sites were compared with various geologic features of the state. There was only one noticeable relation between the location of abrasive culvert sites and bedrock, peat, topography, or parent material. In general, glacial till and residuum were abrasive and lake-laid deposits were nonabrasive. Except for the northwest area of the state (lake-laid deposits), Ohio soils can provide abrasive material if the stream gradient exists to carry it.

Water pH contours were compared with various geologic features of the state. Water pH related little to bedrock, peat, topography, or parent material, except for the fact that nearly all values below neutral occur within residual soil areas. The strongest relation is that between the very low water pH range (less than 5.5) and areas of coal mining. All low water pH values occur in areas where there has been coal mining, which cover approximately 17 percent of the area in the state.

The qualitative chemical tests performed at selected sites only enhanced the other conclusions and produced no significant results. Therefore, these are not recommended for use in further studies because the cost is excessive compared with the results obtained.

CONCLUSIONS

1. Because of its limited average service life (3.16 years), bituminous coating of CSP culverts (AASHTO M 190 Type A) appears to be of little value in Ohio.
2. Bituminous coating with invert paving (AASHTO M 190 Types B and C) extends the life of corrugated steel culverts for an average of 12 or more years, depending on local conditions. An increase in the height of paving would extend the average service life.
3. The main cause of loss of bituminous protection is loss of adherence rather than erosion of the material.
4. Water pH and abrasiveness of flow are the only environmental factors that have a significant effect on the deterioration rate of CSP in Ohio.
5. For high pH ($\geq$7.0) nonabrasive sites, SPP performance was significantly better than that of conventional CSP.
6. At values less than 7.0, water pH has a significant effect on the durability of concrete pipe. Between values of 7.0 and 9.5, water pH does not have a significant effect on the durability of concrete pipe.

ACKNOWLEDGMENTS

The work was funded by the Ohio Department of Transportation. The researchers for this project were assisted by many members of ODOT and other organizations. Although lack of space prevents a detailed listing of all who provided assistance, their efforts are nonetheless greatly appreciated.

Discussion

Carl M. Hirsch[*]

A review of Hurd's pipe inspection data indicated that his two similar graphs for predicting concrete pipe life (Figures 6 and 7) are based on data too sparse and too scattered to permit life prediction with any accuracy by his chosen technique.

DATA REVIEW

Of the total of 545 concrete pipes surveyed, only 72 pipes were in waters with measured pH values less than 7.0, and only 31 of the 72 pipes were within or near the pH/slope ranges shown in Figures 6 and 7 (pH = 2.2 to 4.5, slope = 0.5 to 5.0 percent). Of these 31 pipes, 10 had fully protective acid-resistant vitreous clay liners. One of the remaining 21 pipes was a high-rated pipe that was far too young (4 years) to be useful in predicting life. Of the remaining 20 possibly useful pipes, 5 had no reported slope and could not have been used to construct the graphs in their present form.

Of the remaining 15 pipes, 6 are rated poor, 8 are rated fair, and 1 is rated good. The 6 poor rated pipes reached the poor condition after short exposure times, ranging from 4 to 16 years, and thus do not support graph predictions of outstanding performance. Five of the six were exposed at low pH (2.4 to 3.2) and deteriorated rapidly. The sixth pipe was at a higher pH of 3.8 and a slope of 0.4 percent, and its performance clearly contradicted graph predictions of outstanding life. This pipe reached the poor condition in only 16 years, whereas the graphs predict it should have required close to 200 years to do so. One of the pipes with no reported slope exposed at pH 3.8 was in the poor condition after 13 years. Thus, among pipes already at the poor condition and with no errors of extrapolation or visual rating, there is no support for and some contradiction of graph predictions of outstanding life.

The eight fair-rated pipes included five that reached this condition within short exposure periods of 4 to 14 years, and thus do not support any graph predictions of outstanding life. Hurd describes the fair condition as moderate loss of mortar and aggregate (10); to reach this condition in such short times indicates deterioration rates are high. Two of the five pipes were exposed at low pH (2.6 and 3.0) and reached the fair condition within only 5 and 8 years. The remaining three were exposed at pH values of 3.6, 3.6, and 4.6; had slopes of 0.12, 0.15, and 0.70 percent; and have reached the fair condition within only 9, 12, and 4 years, respectively. The graphs suggest that times needed to reach the poor condition are about 250, 250, and 400 years, respectively, but this is contradicted by the short times involved in reaching the fair condition. One pipe with no reported slope and exposed at pH 3.7 reached the fair condition within only 5 years, despite some bituminous coating protection.

The final three fair rated pipes and the one good rated pipe do show evidence of substantially better performance than the others. As will be discussed later, all four are associated with factors that mitigate the detrimental effect of acidity.

DATA INTERPRETATION

Hurd has followed the common technique for this type of study, which is to look for the best perceived mean or average trend in the data as a whole. He has tried to improve the technique and predict life by noting the average overall effect of pH while accounting for inconsistencies in this effect with slope difference. The problems with this approach can be seen by plotting the pipes on the graphs using various reasonable estimates of time to poor for fair rated pipes (2 to 4 times present age). As shown in Figure 8, the effect of pH is highly inconsistent because large life variations are observed at a given pH, and slope differences do not begin to account for the inconsistency. There is no pattern of correlation between actual and theoretical slopes, and most actual slopes contradict theoretical values, some by a factor of more than 10 times.

Actually, the data are so sparse and scattered that the average overall effect of pH on life is uncertain, and a line such as CD can represent this effect as well as Hurd's four slope-range lines (see note 3 in Figure 8). Hurd's lines, which are indicative of a much larger pH effect, have accuracy problems, as can be seen by looking at the pipes in groupings. For example, six poor rated pipes all reached the poor condition in similar times (11 to 16 years), despite large differences in acidity (pH range = 2.4 to 3.8, which is an acid concentration variation of about 25 times). Also, four fair rated pipes all reached the fair condition at about the same time (4 to 5 years), despite large differences in acidity (pH range = 2.6 to 4.6, which is an acid concentration variation of about 100 times). Obviously, for these 10 pipes the effect of pH on life was small, and any attempt to predict life by using Hurd's large assumed effect of pH will give large errors. Even if the average overall effect of pH was known accurately, the data are so scattered that the life of many nonaverage pipes could not be predicted reasonably well.

AN ALTERNATE DATA INTERPRETATION

Obviously other factors besides pH and slope greatly influence concrete pipe performance in acidic water, and these factors must somehow be accounted for if the sparse data are to reveal any performance trends. One such factor is water stagnancy, which greatly mitigates the effect of acidity by minimizing the amount of acid contacting a pipe invert at a given pH over a given time. It also promotes formation of a soft-matter layer that partly restricts acid access to unattacked material (11). Slow water flow mitigates acidity because it minimizes compound erosion and acidity effects. Invert sediment is beneficial, as Hurd has noted (10), possibly because of localized stagnancy under sediment. An important factor is a streambed pH that is much higher than the water pH because this indicates that the water is not really as acidic as it appears. A low water pH should be accompanied by a low streambed pH, which was normally the case, but two of the best performing pipes had streambed pH values near 7.0, and pH accuracy is highly suspect there.

The data imply extreme importance of acid-miti-

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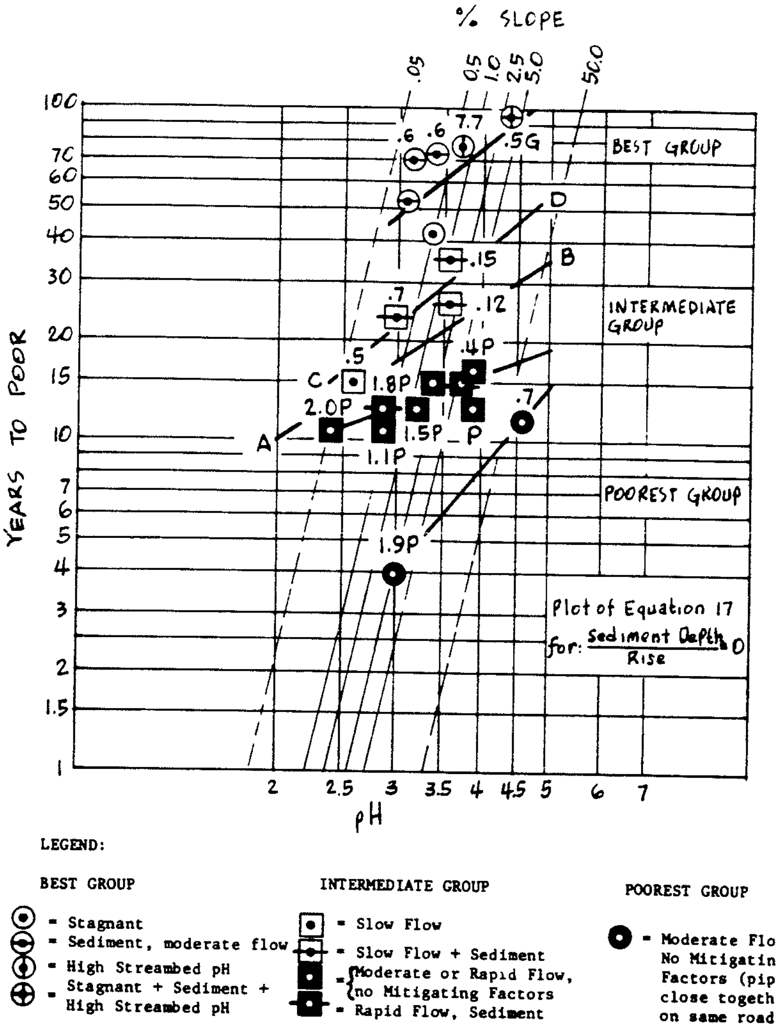

1\. NOTE: IN THE ABOVE GRAPH FAIR-RATED PIPES ARE GIVEN AN ESTIMATED TIME TO POOR OF 3X PRESENT AGE. ONE GOOD-RATED ONE IS GIVEN ABOUT 5X AGE. ONE RATED VERY GOOD AFTER 4 YEARS CANNOT BE ESTIMATED REASONABLY WELL.

2\. NOTE: ACTUAL SLOPE IS NOTED BESIDE EACH OF 15 DATA POINTS. PIPES RATED POOR OR GOOD AT PRESENT AGE HAVE P OR G AFTER SLOPE (ALL OTHERS ARE FAIR).

3\. NOTE: IT IS MORE EVIDENT THAT CD CAN BE THE AVERAGE pH EFFECT BY SEEING THAT THE DATA HORIZONTAL SPREAD IS ARTIFICIALLY COMPRESSED BY THE GRAPHING OF THE LOG OF pH (LOG OF LOG OF ACID CONCENTRATION) VS. THE LOG OF TIME.

FIGURE 8 Plot of best, intermediate, and poor groups.

gating factors in predicting pipe life. For example, in the critical portion of the graph pH range greater than 4.0, there are just 2 pipes, and one at pH 4.4 that is rated good after 21 years benefitted from three acid-mitigating factors (stagnancy, sediment, and streambed pH of 6.7). The other pipe at pH 4.6 is rated fair after only 4 years and had no known mitigating factors (moderate flow, no sediment, and streambed pH value of 4.4). If the data are treated equitably, the obvious conclusion is that concrete pipe deteriorates rapidly at pH 4.6 in the absence of acid-mitigating factors.

The data must be handled in some fashion such that the influence of pH with and without beneficial acid-mitigating factors is denoted. The only logical way to do so is to permit the data to separate into groups of benefitted and unbenefitted pipes to the extent possible. There appear to be three or four distinct groups that separate rather well along the lines of their degree of association with mitigating factors. As shown in Figure 8, there is a group of 6 best performing pipes near the top of the graph and a small group of 2 poorest performing ones near the bottom, and a larger intermediate group of 12. In the best group, mitigating factors are consistent, whereas in the poorest group they are absent. In the intermediate group they are neither consistent nor absent. The intermediate group does separate further into a better performing upper group of four with consistent mitigating factors and a poorer performing lower group of eight with essentially no mitigating factors. The best and the upper-intermediate groups have nearly all cases of invert sediment, all cases of stagnant and slow-flowing water, and also all cases of high streambed pH. In every group concrete pipe life is far shorter than Hurd's graphs suggest. Line AB represents average behavior in the intermediate group (most typical group).

OTHER PIPES EXPOSED BELOW pH 7.0

There were only two other pipes exposed below pH 5.9, and one had a protective clay liner whereas the other, which was a good rated one at pH 5.5, benefitted from invert sediment, slow flow, and high streambed pH (7.3). There are 34 pipes in the pH 5.9 to 6.9 range that have no clay liners and are more than 5 years old. Any perceived behavior trend among these pipes should never be used to help establish a behavior trend within the graph pH limits because the effect of pH can change drastically over such a wide pH range (2.2 to 6.9). Furthermore, there is evidence that complicating mitigating factors are important in the 5.9 to 6.9 pH range also, because 6 pipes that performed rather poorly had inconsistent mitigating factors, whereas 28 good performing pipes had rather consistent ones.

Author's Closure

In the first part of Hirsch's discussion of this paper he questions the analyses of the low pH (less than 7.0) concrete culvert data set based on the following general factors:

1. The use of subjective visual concrete ratings to describe concrete pipe performance,
2. The use of data to develop Equations 7 and 8 that is "too scant and too disparate" to make a meaningful predictive equation, and
3. Scatter in the data about the predictive equation plot.

Because of the limited discussion of site selection, data collection, and data analyses in the paper, these are valid concerns and will be addressed later in the closure.

The remainder of the discussion, however, does not appear to directly address the preceding three concerns. It appears to me to be more an attempt to show how and why certain small subsets of the data set do not exactly fit the best-fit statistical regression equation, and to draw inferences on concrete pipe performance from these subsets. The subsets are developed based on combinations of ratings and the broad subjective term acid-mitigating factors, which refers to some variables that were found to have no statistically significant effect on the performance of concrete pipe.

It appears to be inconsistent with the general concerns previously given to draw inferences from data sets that are subsets of a data set referred to as "too scant" using "subjective" terms to describe how each subset is consistent within itself. Therefore, I will not address the specific evaluation of data in Hirsch's discussion in this closure, but only address the three main concerns cited previously.

1. The visual concrete rating system used to describe the performance of concrete pipes was subjective. However, it was based directly on the loss of concrete, with each successive rating clearly indicating more deterioration, as noted in the following table:

Rating	Description
Excellent	Condition of concrete as constructed
Very good	Discoloration but no loss, corrosion, or softening
Good	Slight loss of mortar, leaving aggregate exposed
Fair	Moderate loss of mortar and aggregate; slight softening of concrete
Poor	Significant loss of mortar and aggregate; complete loss of invert; concrete in softened condition

Although borderline cases might have been rated to one side or another by different inspectors, it is unlikely that a good culvert would be rated fair or a fair culvert rated poor or vice versa. Moreover, it would be extremely unlikely for a good culvert to be rated poor or vice versa. Therefore, I believe the visual rating system used is a valid descriptor of concrete pipe performance, and therefore the predictive equations based on the visual ratings are also valid.

2. The data used to develop Equations 7 and 8 are given in Table 3. The data set is composed of 45 sites from which all vitrified lined concrete pipes were excluded. A data set of 45 points used to develop a regression equation with only 4 independent variables is certainly not scant. The total low pH concrete pipe data set was expanded from the initial randomly selected concrete pipe data set to include all low pH unprotected concrete pipe on the state highway system. This was done to ensure as large a data set as possible. I grant that the use of field data does not allow for perfect experimental design that eliminates all possible statistical confounding effects of independent variables. However, the data in Table 3 do give a fairly broad range of various combinations of the independent variables.

3. Scatter about the best-fit regression equation is a fact of life in statistical analysis. Not all points fit the line. If they did, statistical analysis would be unnecessary. Equations 7 and 8 are the best-fit statistical regression equations that

TABLE 3 Low pH Concrete Pipe Data

Rating	Age (yr)	pH	Slope (%)	Sediment	Rise	Sediment ÷ Rise
Very good	36	6.6	0.02	3	42	0.071
	33	6.2	0.80	18	48	0.375
	33	6.8	1.00	13	42	0.310
	32	6.3	0.46	6	48	0.125
	24	5.9	0.10	0	48	0.000
	24	6.1	0.41	6	48	0.125
	22	6.6	0.32	1	54	0.019
	22	6.7	1.50	8	48	0.167
	19	6.0	1.50	0	42	0.000
	17	6.4	1.50	0	42	0.000
	15	6.9	0.60	4	60	0.067
	14	6.7	0.50	4	72	0.056
	12	6.8	0.01	8	72	0.111
	7	6.6	1.40	0	48	0.000
	3	6.3	0.97	0	48	0.000
	3	6.4	0.80	18	42	0.429
	3	6.7	1.30	0	60	0.000
	3	4.4	0.70	6	48	0.125
Good	42	6.8	11.50	6	60	0.100
	39	6.5	2.90	0	48	0.000
	33	6.8	2.60	0	48	0.000
	33	6.8	2.00	4	48	0.083
	32	6.4	2.78	1	48	0.021
	26	6.8	3.73	0	48	0.000
	26	5.5	2.96	2	42	0.048
	22	6.4	2.30	2	84	0.029
	21	4.4	0.50	2	60	0.033
	7	6.4	0.90	0	66	0.000
Fair	44	6.4	2.00	6	48	0.125
	26	3.7	7.70	0	42	0.000
	24	3.4	0.60	18	60	0.300
	24	3.2	0.60	4	60	0.067
	21	6.8	1.37	0	66	0.000
	17	6.8	1.07	0	60	0.000
	8	3.6	0.12	6	96	0.063
	7	3.0	0.70	12	58	0.209
	4	2.6	0.50	0	42	0.000
	3	4.6	0.70	0	42	0.000
Poor	24	3.5	2.70	0	60	0.000
	15	3.8	0.40	0	60	0.000
	14	3.2	1.50	0	72	0.000
	14	2.8	1.80	0	42	0.000
	11	2.8	1.10	0	54	0.000
	10	2.4	2.00	0	42	0.000
	3	3.0	1.90	1	42	0.024

describe the concrete ratings as a function of all statistically significant, independent variables. The regression statistics for these equations (R^2 = 68 percent and standard deviation = 0.33) are considered satisfactory for use of the equations to predict concrete pipe performance at other sites. The fact that specific data points do not exactly fit the equation is more likely caused by the range in values of environmental variables at each site with time rather than the exclusion of variables whose effect was not statistically significant from the predictive equations.

Although not all specific points may exactly fit Figures 6 and 7, it is believed that the figures basically represent concrete pipe performance as observed in the field by ODOT engineers both before and during the ODOT culvert durability study. That is, in Ohio, except at sites with very acidic coal-mine-effected flows (pH approximately 4.0 or less), unprotected concrete pipe provides adequate service life. For acidic flow sites, protection is recommended.

For a more complete description of site selection, data collection, and data analyses, the readers are referred to the work by Meacham et al. (10).

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