Service Life Model Verification for Concrete Pipe Culverts in Ohio

JOHN OWEN HURD

Separate analyses of reinforced concrete pipe durability data collected by the Ohio Department of Transportation were conducted by the Ohio Department of Transportation and another research agency. There was a large discrepancy in the service life predicted for culverts installed in nonacidic sites between the two models. This study was initiated to establish which model was the most accurate. An inventory of older reinforced concrete pipe installations was compiled. The age of many of these culverts approached the very conservative service life predicted by the linear model developed by the other agency. The total number of 196 culverts inspected included 70 culverts installed before 1940, 89 culverts installed from 1940 to 1949, and 37 culverts installed from 1950 to 1969. The culverts were evaluated using a revised, more detailed rating system and predicted service lives extrapolated from the rating and age at the time of inspection. It was found that the linear model significantly underpredicted service life of reinforced concrete pipe for a flow pH range above 4.5 and that the Ohio Department of Transportation model provided a reasonable estimate of projected service life for the entire pH range studied.

In 1982, the Ohio Department of Transportation (ODOT) published a comprehensive research report (*1*) that provided information on the durability of various culvert materials. As part of this report, predictive equations for the service life of reinforced concrete pipe culverts were presented. These equations were developed from data collected in 1972 at 545 concrete pipe culvert sites throughout Ohio. These sites encompassed a wide range of topography and environmental conditions. The condition of the concrete pipe culverts was evaluated by means of the following visual rating system:

1. Excellent—condition of concrete as constructed.
2. Very Good—discoloration but no loss, corrosion, or softening.
3. Good—slight loss of mortar leaving aggregate exposed.
4. Fair—moderate loss of mortar and aggregate, slight softening of concrete.
5. Poor—significant loss of mortar and aggregate, complete loss of invert, concrete in softened condition.

It is readily apparent that the comparative times required for deterioration between progressive ratings were not equal. For the purpose of analysis, however, arbitrary linear numerical values of 0 to 4 were assigned to the visual ratings. The predictive equations for concrete culvert rating derived from the analysis were for pH less than 7.0

$$\text{Rating} = \frac{10\ (\text{age}^{0.13}(\text{slope})^{0.11}}{(\text{pH})^{1.20}}\left(1 - \frac{\text{sed}}{\text{rise}}\right)^{0.76} \tag{1}$$

and for pH greater than or equal to 7,

$$\text{Rating} = \frac{K(\text{age})^{0.17}(\text{slope})^{0.054}}{(\text{velocity rating})^{0.088}} \tag{2}$$

where

sed = sediment depth in inches,
rise = pipe rise in inches,
slope = pipe slope in percent,
age = culvert age in years,
velocity rating = 1 for rapid, 2 for moderate, 3 for slow, 9 for nil, and
K = 0.9 for nonabrasive flow, 1.2 for abrasive flow.

These equations accounted for the nonlinearity in the time of deterioration between successive ratings by the power on the variable age. The fact that this power of approximately ⅙ to ⅐ is so much less than 1 (power = 1 indicating a linear relationship between rating and age) is indicative of the extreme nonlinearity of the time required for progressive deterioration between successive ratings. The comparative times of deterioration for the various ratings are illustrated in Figure 1. This nonlinearity of the rating system was discussed in detail in the 1982 ODOT report (*1*).

Conservative predictive equations for concrete pipe service life were obtained by setting the numerical rating value equal to 3.5 (between fair and poor) and solving Equations 1 and 2 for age. The resulting service life equations were for pH less than 7.0,

$$\text{Service life} = \frac{[0.349(\text{pH})^{1.2}]^{7.76}}{(\text{slope})^{0.82}}\left(1 - \frac{\text{sed}}{\text{rise}}\right)^{-5.912} \tag{3}$$

and for pH greater than or equal to 7.0,

$$\text{Service life} = \left(\frac{3.5}{K}\right)^{5.9}\frac{(\text{velocity rating})^{0.52}}{(\text{slope})^{0.31}} \tag{4}$$

Because of the rather crude and biased rating system used, questions were raised regarding the possible conservatism of the predictive equations for the acidic pH range. The greatest concern was based on the observation that the fair and poor ratings covered too wide a range of actual material condition ranging from moderate mortar loss to complete loss of invert.

Ohio Department of Transportation, 25 S. Front Street, Columbus, Ohio 43215.

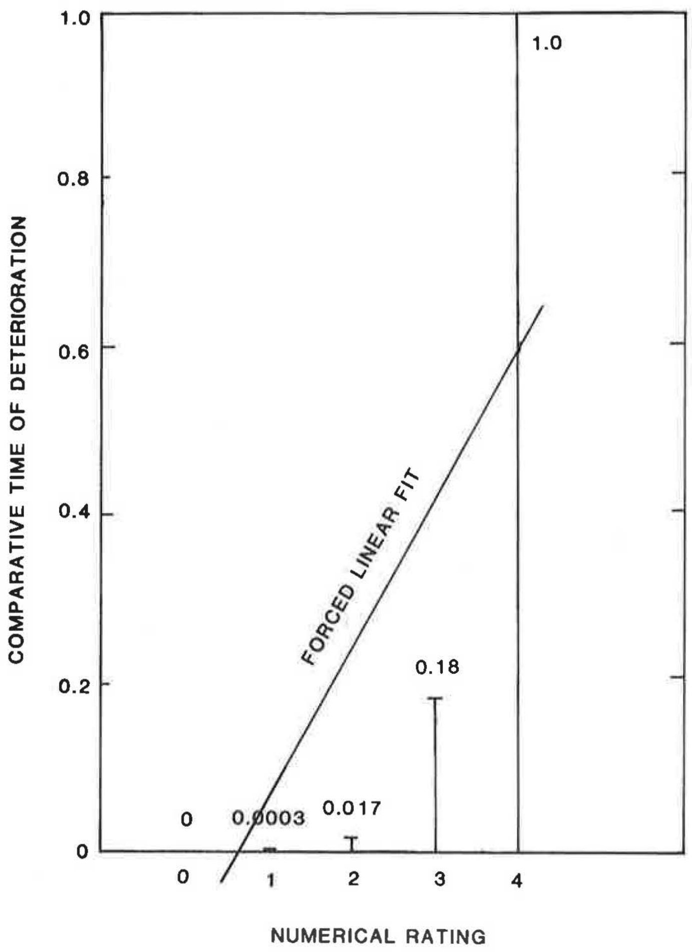

FIGURE 1 Comparative times of deterioration for concrete pipe ratings, ODOT/L&D/82-1.

Pipe with moderate mortar loss could have several decades of useful service still remaining, whereas complete loss of invert would require repair or replacement.

Because of these concerns, a follow-up study (*2*) of culverts at acidic flow sites was conducted in 1984. The original data set for acidic flow was expanded to include additional sites. The sites from the previous work were included with an additional 12 years of service. It should be noted that no culvert rated fair or poor from the initial study had been replaced and all were functioning well with no structural distress at the time of the follow-up study. Except for one culvert installed on an 18 percent slope with a flow pH equal to 3.0, no culverts were observed with complete loss of invert in either the initial or the follow-up study. Otherwise, the worst condition observed was deterioration through the inner reinforcing mesh. This represents about a 1-in. thickness of concrete loss.

The more refined rating system described in Transportation Research Record 1008 (*2*) was used to evaluate the culverts in 1984 as follows:

0 As manufactured,
10 Slight loss of mortar, aggregate exposed,
20 Moderate loss of mortar, aggregate exposed,
30 Significant loss of mortar, slight aggregate loss,
50 Moderate aggregate loss,
60 Significant aggregate loss,
70 Severe aggregate loss,
80 Reinforcing exposed at a few places,
90 Reinforcing exposed throughout the pipe, and
100 Reinforcing gone.

This rating system represented a definite improvement over the 1972 rating system, described earlier in this paper, for two reasons. First, ratings above 95 more accurately describe a pipe with loss of reinforcing that could adversely affect the structural integrity of the pipe. This rating could be defined conservatively as the rating at which end of service life occurs. However, as shown in Figure 2, substantial wall thickness would still remain protecting the pipe foundation from erosion. Second, the number of ratings for culverts with greater degrees of deterioration was expanded.

This 1984 rating system attempted to provide an equal number of ratings for all stages of deterioration. The power of age in the resulting equation for concrete pipe rating indicates a closer approximation of equal times of deterioration between successive numerical ratings.

$$\text{Rating} = \frac{6.5\,(\text{age})^{0.55}(\text{rise})^{1.08}(\text{slope})^{0.23}}{(\text{pH})^{3.08}}\left(1 - \frac{\text{sed}}{\text{rise}}\right)^{1.46} \tag{5}$$

The power on age has been increased from approximately ⅙ to more than ½. However, even with the refined 1984 rating

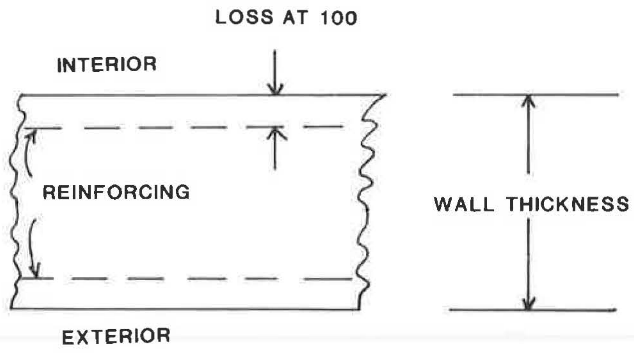

FIGURE 2 Reinforced concrete pipe wall diagram.

system, a true linear relationship between numerical rating and age was not obtained. The comparative times of deterioration for the various ratings are shown in Figure 3. Use of a linear model would result in conservative service life predictions even if the 1984 rating system were used.

A service life equation for concrete pipe at acidic flow sites was obtained by setting rating equal to 95 and solving for age. This equation,

$$\text{Service life} = \frac{123.5(\text{pH})^{5.55}}{(\text{rise})^{1.94}(\text{slope})^{0.42}}\left(1 - \frac{\text{sed}}{\text{rise}}\right)^{-2.64} \qquad (6)$$

gave results that compared closely with Equation 3. The range of service life obtained from Equations 4 and 6 are plotted versus pH for various combinations of concrete pipe size, slope, and so on, in Figure 4 for mild, average, and severe conditions. For this plot, sediment depth is set equal to 0, which is a worst-case condition but desirable from a hydraulic design standpoint. It may seem extremely pretentious to extrapolate approximately 50 to 60 years' worth of data out to a four-figure service life for a mild condition. However, the plot indicates the magnitude of service life that could occur for certain installations. There have been documented histories of extremely long service life for concrete pipe at installations throughout the world (*3*).

In 1986, a separate analysis (*4*) of the initial ODOT 1972 data was conducted by others. No field observations were made and no additional data from other states or the ODOT 1985 report were included. Straight-line linear regression analysis of numerical values arbitrarily assigned to ODOT

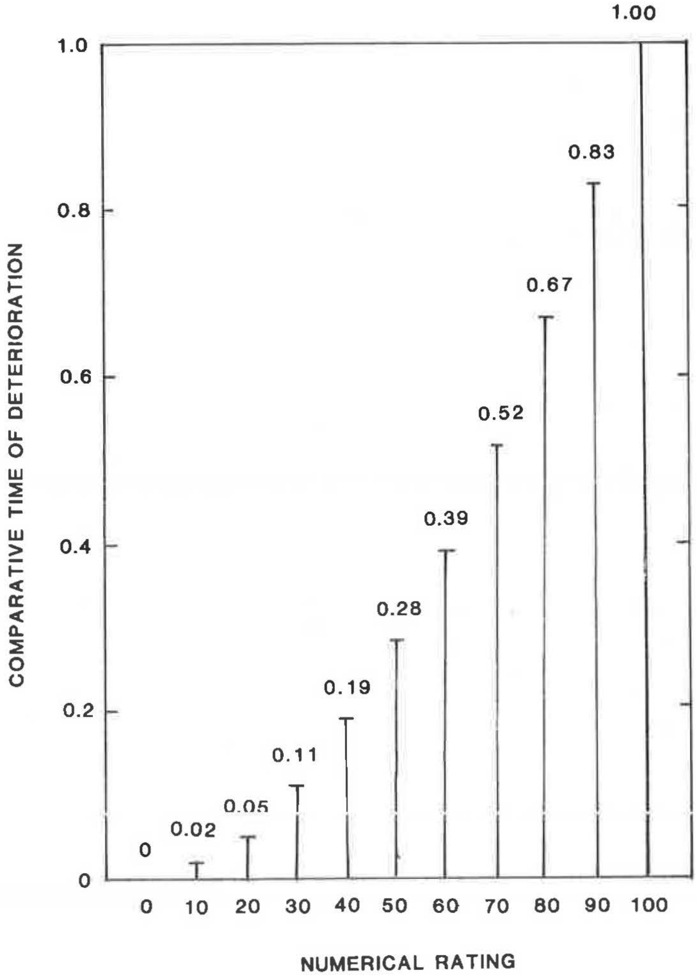

FIGURE 3 Comparative times of deterioration for concrete pipe ratings (*2*).

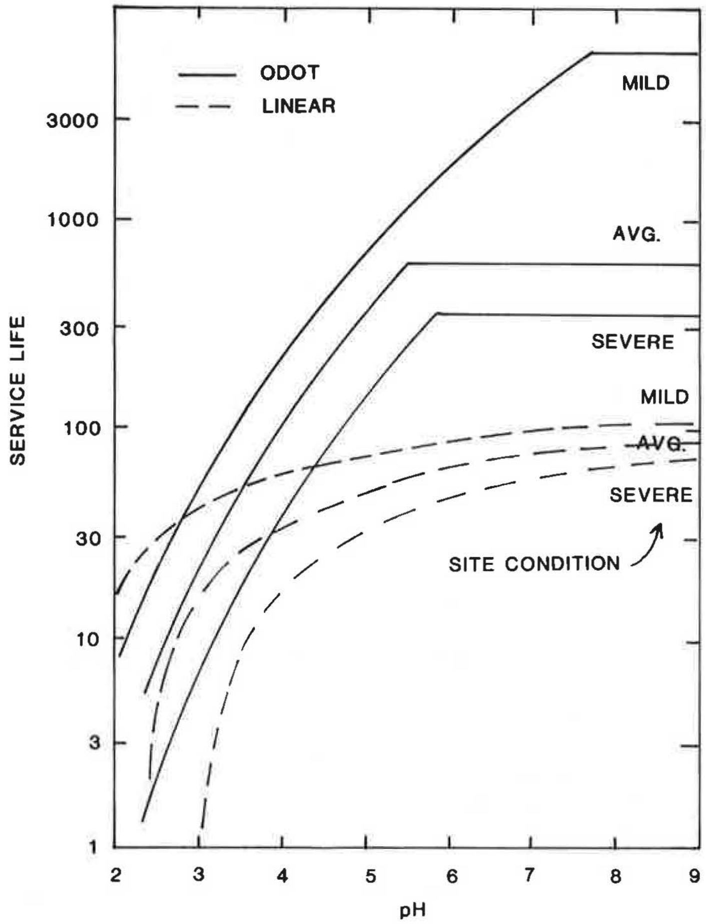

FIGURE 4 Ohio concrete pipe service life models.

ratings versus age and other independent variables were used to develop a predictive linear model for culvert rating.

The problems involved with using a straight linear relationship between arbitrarily assigned numerical ratings and age were explained in detail by both ODOT in previous reports (*1*) and by Stratfull (*5*) in reviewing work by others using a rating system similar to the 1972 ODOT rating system. Any attempt to force a linear regression relationship between age and the arbitrary numerical values assigned to the 1972 ODOT ratings will produce biased service life equations even if the regression statistics, R^2 and standard error, appear reasonable. In the case of the 1972 ODOT rating system, the time required to reach a poor condition would be seriously underpredicted. This can be seen by observing the forced linear regression fit for comparative time of deterioration versus rating in Figure 1. This line is representative of a data set with an equal amount of culverts in each rating. The underestimate would be even more pronounced for a data set dominated by excellent to good ratings, as the 1972 ODOT data set was. In fact, a linear model could have a higher R^2 value than a nonlinear model because of the bias of the data set.

The range of service life (obtained in a way similar to that for the log-linear model) for the linear model for various combinations of pipe size, slope, and so on, is plotted in Figure 4 for mild, average, and severe conditions. There is not much difference between the two models in the extremely acidic range. However, there is clearly a large discrepancy between the ODOT and linear models for slightly acidic to high pH sites. The much lower service life predicted by the linear model for nonacidic sites is contrary to observations made by numerous past researchers (6, 7).

Because of the large difference between the two models based on the same data, this study was initiated to establish which model was more accurate.

SITE SELECTION

In order to evaluate the two predictive models, an inventory of all older reinforced concrete pipe installations over 42-in. diameter or rise was compiled. The 42-in.-diameter cutoff was selected as in the previous studies because this was the smallest-size pipe that could be conveniently inspected by field personnel. The fact that the sizes of pipe inspected were more likely to have dry weather flow would lead to conservative estimates of service life for smaller pipe. This inventory consisted of 495 culverts installed before 1950, of which 173 were installed before 1940. Older culverts were selected to provide a data base population of culverts with ages approaching the very conservative service life predicted by the linear model. This inventory is representative of all precast reinforced concrete pipe culverts installed during that time period, because ODOT has no record of having replaced an in-service precast reinforced concrete pipe culvert because of invert durability problems.

The intention was to observe the condition of these culverts, which were approaching the service life predicted by the linear model, to determine whether they had reached or were approaching the end of useful service life. If not, a service life for each culvert would be projected based on condition and age at the time of inspection. This projected service life would be compared with that predicted by the ODOT and linear models. It was believed that evaluation of old pipe performance could be used to predict performance of newer installations. Manufacturing methods have been improved in the past 50 years, resulting in greater concrete density. However, the basic material and reinforcing cover requirements have remained similar (8–10).

The 1972 sites used in the data analysis for the 1982 ODOT report (*1*) and the linear model report were not deleted from the inventory because 15 years had passed since they had been inspected. The 1984 sites used in the data analysis for the 1985 ODOT follow-up report (*2*) for acidic sites were not deleted from the inventory because the 1985 report had practically exhausted the population of acidic sites. Without these sites, there would have been almost no acidic sites with which to make comparisons. The 1984 data from acidic sites with installation dates since 1950 were also used to expand the data base for the acidic pH range. This was consistent with the inventory selection criterion of culvert age approaching predicted service life, because predicted service life in the acidic pH range is much less than it is for the nonacidic range.

The initial intention of this study was to inspect as many culverts as possible that were installed before 1940 and a selected number of culverts installed from 1940 to 1949 to assure geographic coverage of the state. Selection of culverts installed in the early 1940s rather than those from the late 1940s was preferred in order to keep the data set as old as possible. The total number of culverts inspected for this study was 196. These included 70 culverts installed before 1940, 89 culverts installed from 1940 to 1949, and 37 acidic-site culverts installed from 1950 to 1969. None of the culverts rated fair or poor in the 1982 report (1972 inspection) that were inspected for this study had been replaced. All were still functioning satisfactorily without signs of structural distress. The locations of the culverts inspected are shown on Figure 5. Although not every county in the state was covered, adequate coverage of areas of the state with common environmental conditions was attained.

In addition to those culverts inspected, 33 sites were visited where reinforced concrete pipe culvert of the age indicated was not found. It appeared that there had never been culverts at 22 of these sites, or the roadway had been built much later and that an inventory coding error in the installation date had been made. At the other 11 sites where culvert replacement had occurred, district personnel were questioned and records checked. In no case had the original culvert (if constructed of reinforced concrete) been replaced because of problems with invert deterioration. In each case, the reinforced concrete pipe culvert removed was salvaged for later use.

DATA COLLECTED

Based on the results of previous research, the data collected in each site were limited to the following:

1. Age of the culvert in years based on the inventory installation date and verified by manufacturers' marks where possible;

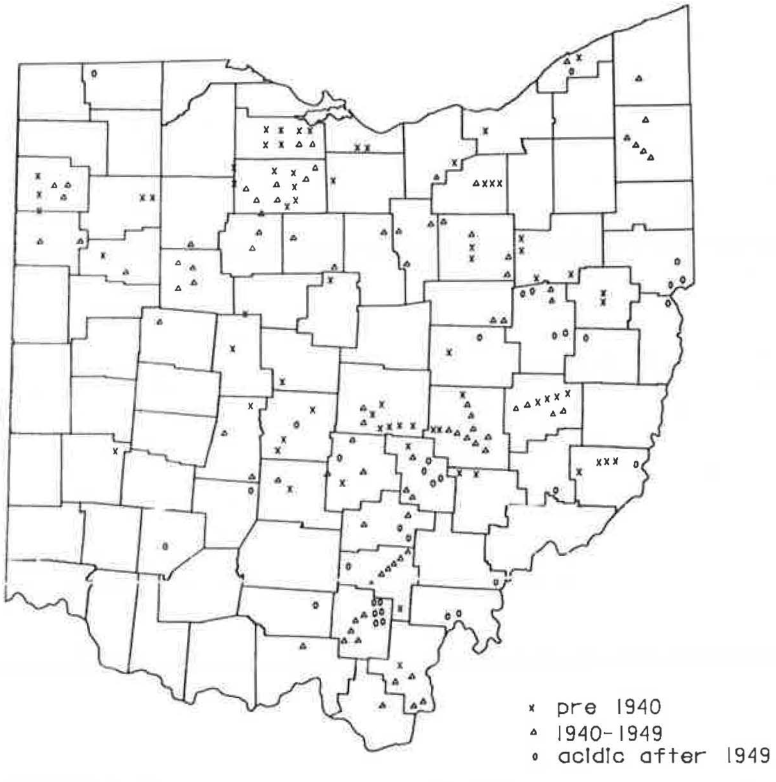

FIGURE 5 Concrete pipe culverts inspected, 1987.

2. Culvert pipe diameter or rise in inches;
3. Flow depth in inches;
4. Flow velocity rating (rapid, moderate, slow, and standing or dry);
5. Sediment depth in inches;
6. Largest frequently occurring bed load particle size in inches;
7. Flow pH;
8. Culvert pipe slope expressed as a percentage; and
9. Culvert pipe rating (*2*) of the culvert invert (shown previously in this paper).

The 1984 ODOT rating system was used to evaluate culvert performance for several reasons. It provides a larger number of ratings for invert conditions approaching that condition defined at end of service life. It comes much closer to representing a linear deterioration rate between successive ratings, demonstrated by Figures 1 and 3. Therefore, projections (either linear or log-linear) of service life based on existing rating and age are less apt to be grossly over- or underpredicted. It specifically defines a culvert condition rating (95 to 100) that can be conservatively used as useful service life (i.e., in cases in which repair should be considered). This rating system is independent of the 1972 ODOT rating system used to evaluate culverts for development of the service life models in the pH range with the greatest discrepancy between models. In general, the condition of the culvert invert was consistent throughout the culvert length and the rating given each culvert was representative of average culvert invert condition.

The data collected is summarized in Table 1 by rating, age range, and pH range. It should be noted that several culverts rated fair or poor on the previous study were reevaluated using revised ratings. Most of those culverts rated fair or poor in 1972 except for extremely acidic sites (pH less than 4.5), were rated between 25 and 65. The age range for these ratings is less than half way to the end of useful service life, as shown in Figure 3. A few culverts had been rated fair or poor because of concrete loss along the haunches caused by shear slabbing, a structural problem caused by improper installation under high fills and unrelated to invert durability. A few others had been rated fair or poor because of concrete spalling on parts of a few pipe sections resulting from lack of adequate cover over reinforcing steel. Although this condition is related to pipe durability, it should not occur with adequate inspection. Inadequate cover over reinforcing steel can be discovered during visual inspection of pipe sections and those sections rejected.

It can be seen from the table that the only culverts, a total of 16, showing serious invert deterioration (rating 75 or greater) are those carrying extremely acidic flow. In fact, only one culvert carrying nonacidic flow showed even moderate deterioration. This particular pipe appeared to have been home made and not in conformance with standard specifications used at the listed time of its manufacture. Wooden form marks were observed, butt joints had been used, the size of large aggregate greatly exceeded allowable limits, and very low cement content mortar appeared to have been used. At the time of inspection, no culvert rated between 90 and 100 showed any structural distress caused by loss of reinforcing steel. In all, 148 (75+ percent) of the 196 culverts whose ages were approaching that service life predicted by the linear model were rated 20 or lower. These ratings represent only surface mortar loss without any aggregate loss, insignificant deterioration compared with that required for end of service life. Twenty-one other culverts (11 percent of the sample) were rated from 25 to 40, experiencing only slight aggregate loss at worst. If the linear model gave accurate estimates of the defined service life, more than 50 percent of the culverts

TABLE 1 SUMMARY OF DATA FROM CULVERTS INSPECTED

Culvert Rating	Age Range	pH Range	No. of Culverts
5, 10	≥50	≥7.0	22
		4.5–6.9	0
		<4.5	0
	40–49	≥7.0	45
		4.5–6.9	4
		<4.5	0
	30–39	≥7.0	18
		4.5–6.9	7
		<4.5	0
	<30	≥7.0	1
		4.5–6.9	8
		<4.5	1
15, 20	≥50	≥7.0	8
		4.5–6.9	2
		<4.5	0
	40–49	≥7.0	12
		4.5–6.9	7
		≥7.0	0
	30–39	≥7.0	4
		4.5–6.9	4
		<4.5	0
	<30	≥7.0	0
		4.5–6.9	3
		<4.5	2
25, 30, 35, 40	≥50	≥7.0	9
		4.5–6.9	0
		<4.5	0
	40–49	≥7.0	4
		4.5–6.9	2
		<4.5	1
	30–39	≥7.0	0
		4.5–6.9	1
		<4.5	1
	<30	≥7.0	0
		4.5–6.9	0
		<4.5	3
45, 50, 55, 60, 65, 70	≥50	≥7.0	0
		4.5–6.9	1
		<4.5	0
	40–49	≥7.0	1
		4.5–6.9	1
		<4.5	1
	30–39	≥7.0	0
		4.5–6.9	1
		<4.5	1
	<30	≥7.0	0
		4.5–6.9	1
		<4.5	3
75, 80, 85, 90, 95, 100	≥50	≥7.0	0
		4.5–6.9	0
		<4.5	0
	40–49	≥7.0	0
		4.5–6.9	1
		<4.5	2
	30–39	≥7.0	0
		4.5–6.9	0
		<4.5	2
	<30	≥7.0	0
		4.5–6.9	0
		<4.5	11

observed should have been rated 70 or greater. This is definitely not the case.

SERVICE LIFE MODEL VERIFICATION

Because it was apparent from these observations that the linear model significantly underpredicted defined service life for concrete pipe, projected service lives for the culverts inspected in this study would have to be developed to compare with the service lives predicted by the ODOT and linear models. The projected service lives of culverts inspected were estimated by both linear and log-linear extrapolation of the culvert age and rating at the time of inspection.

The direct linear extrapolation of culvert age and ratings to project service life is in conformance with the linear model assumption that the actual times required for deterioration between successive arbitrary numerical ratings are equal throughout the range of ratings. Thus, for each culvert

$$\frac{\text{Rating @ Age 2}}{\text{Rating @ Age 1}} = \frac{\text{Age 2}}{\text{Age 1}}\text{, or} \tag{7}$$

$$\frac{\text{100 (i.e., the rating @ end of service life)}}{\text{Rating @ inspection}} = \frac{\text{Service life}}{\text{Age @ inspection}} \tag{8}$$

As stated previously in discussion of the more refined 1984 rating system, this method of extrapolation will result in very conservative estimates of projected service life.

The log-linear extrapolation of culvert age and rating to project service life is in conformance with the assumption made in the ODOT power equation model that the actual times required for deterioration between successive arbitrary ratings increase, as shown in Figure 3. This increase is related to the power of age in Equation 5 as follows:

$$\frac{\text{Rating @ Age 2}}{\text{Rating @ Age 1}} = \frac{(\text{Age 2})^{0.55}}{(\text{Age 1})^{0.55}}\text{, or} \tag{9}$$

$$\frac{(\text{Rating @ Age 2})^{1.82}}{(\text{Rating @ Age 1})^{1.82}} = \frac{\text{Age 2}}{\text{Age 1}}\text{, or} \tag{10}$$

$$\left(\frac{\text{100, i.e., rating @ end of service life}}{\text{rating @ inspection}}\right)^{1.82} = \frac{\text{Service life}}{\text{Age @ inspection}} \tag{11}$$

This method of extrapolation will result in an average estimate of projected service life.

Because both the linear and ODOT log-linear models recognized that increased sediment depths prolonged service life, the projected service lives for the culverts inspected that contained sediment were reduced by an amount equal to that

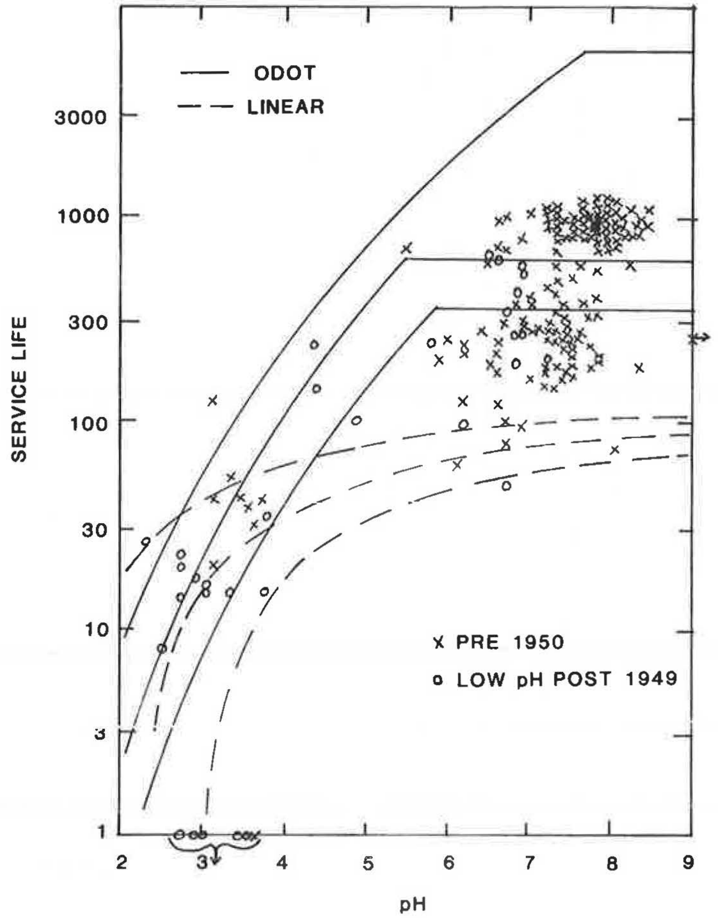

FIGURE 6 Linear projected service life for inspected culverts.

increase in service life attributed to the presence of sediment equal to that observed at the site for each model. The linear projected service life was reduced by subtracting nine times the sediment depth in inches. Although this produces an extreme percentage reduction for short service life at extremely acidic sites, it was applied throughout the range of data for the sake of consistency. The log-linear projected service life was reduced by multiplication by the factor

$$\left(1 - \frac{\text{sed}}{\text{rise}}\right)^{-2.64}$$

from Equation 6.

The sediment-adjusted linear-projected (Equation 8) service lives for the culverts inspected were plotted with the ODOT and with the linear model curves on Figure 6. Even using the conservative linear extrapolation that conforms to the linear theory, only 4 points above a pH of 4.5 fall within the linear model envelope. Approximately 60 percent of the points above a pH of 4.5 fall within the ODOT curves and the rest between the two models. It is demonstrated that the linear model does not represent defined service life but a conservative lower bound. The sediment-adjusted log-linear projected (Equation 11) service lives are plotted in Figure 7. Using the log-linear extrapolation, only 2 points above a pH of 4.5 fall within the linear model envelope. All but a total of 11 points fall within or above the ODOT envelope. It is therefore obvious that the ODOT service life models more accurately estimate the projected service lives for old, in situ reinforced concrete pipe culverts than does the linear model.

CONCLUSIONS

1. ODOT has no record of ever having replaced a reinforced concrete pipe culvert because of invert durability.
2. Both ODOT and linear reinforced concrete pipe service life models reasonably predict service life for concrete pipe installed in extremely acidic environments (pH less than 4.5). The linear model is slightly conservative toward the higher end of this range.
3. The linear reinforced concrete pipe service life model seriously underestimates concrete pipe service life for the pH range 4.5 and above.
4. The ODOT reinforced concrete pipe service life model provides an accurate estimate of concrete pipe service life that conforms well to projected service life of existing older concrete pipe culvert installations.

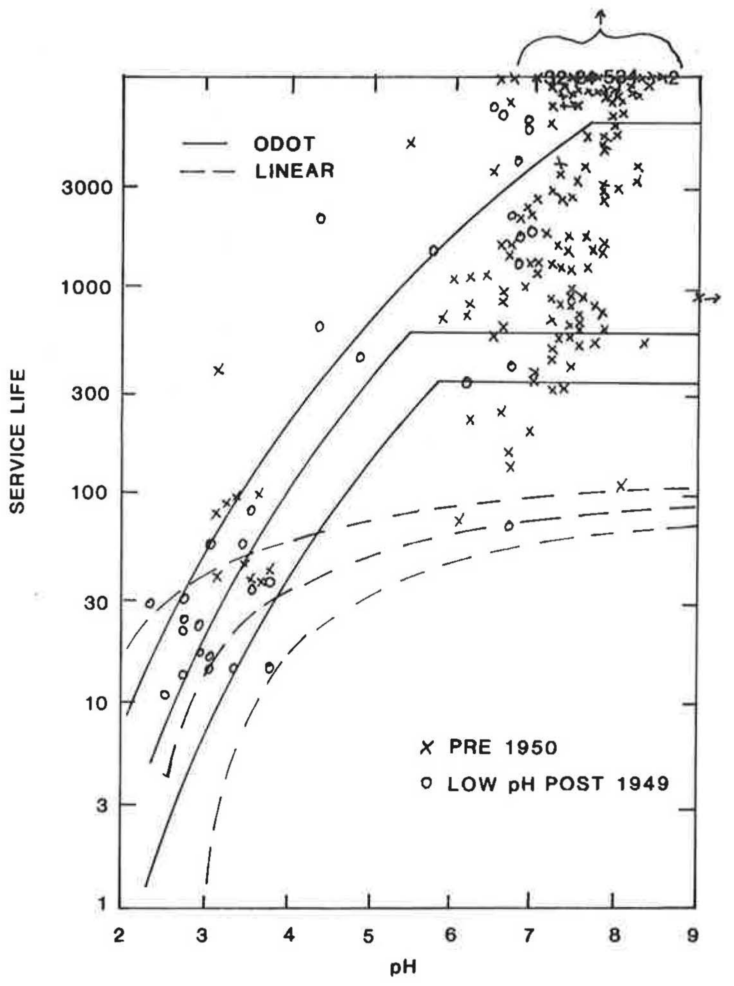

FIGURE 7 Log-linear projected service life for inspected culverts.

5. The ODOT model provides a reasonable estimate of reinforced concrete pipe life expectancy that can be used in life cycle cost analysis. However, the actual average service life of concrete pipe in a pH environment of 6.0 and above is indeterminate at this time because no pipes in this range have had invert deterioration close to that defined as useful service life.

RECOMMENDATIONS

1. The ODOT model should be used in life cycle cost analysis to estimate service life for concrete pipe in culvert installations.
2. The ODOT revised rating system, as given in Transportation Research Record 1008 (*2*), provides an adequate method to evaluate concrete pipe culverts in future studies until an improved rating system is developed.
3. The linear model could be used to estimate a lower bound for concrete pipe service life. If this lower bound value is used in life cycle cost analysis, lower bound service lives must be used for all other materials.
4. Site inspections should be performed at each culvert site to gather data for estimating the service lives of various candidate materials in life cycle cost analysis. This can easily be done during preliminary site surveys.

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DISCUSSION

FABIAN C. HADIPRIONO, RICHARD L. LAREW, AND BENJAMIN LAWU

Department of Civil Engineering, Ohio State University, Columbus, Ohio 43210.

In the paper, Hurd demonstrates the development of prediction equations for determining the service life of concrete pipe culverts in Ohio. Unfortunately, his paper is erroneous both technically and conceptually.

FATAL CONCEPTUAL ERROR IN SERVICE LIFE PREDICTION

Given Hurd's equation, the estimated pH of the flow, the slope, and the rise of a culvert, an engineer can easily calculate the service life of a culvert. We regret that it is not possible to predict the age of concrete pipe culverts using his equations.

When estimating the parameters for his Equation 5, the regression method used by Hurd assumes that the log of age is independent of the log of sediment depth, the log of rise, the log of pH, and the log of slope. Hurd solves Equation 5 to find an equation for predicting age. Using the age prediction equation, he sets rate = 95 to obtain his Equation 6.

This is a fatal error because in Equation 6 the age of concrete pipe culverts is given as a function of the four variables: sediment depth, rise, pH, and slope. But age cannot depend on these variables in Equation 6 and at the same time be independent of these variables in Equation 5. His service life equation must not be used for predicting a particular culvert, and therefore should be rejected.

RESULTS CANNOT BE REPLICATED

Using Hurd's data for pH less than 7, we tried to replicate his method to obtain his Equation 5 for predicting the pipe rate. However, we are unable to obtain the same results for the parameters of this equation. Our parameter estimates of Equation 5 are compared with Hurd's estimates in the following table:

Parameter Descriptions	*Our Estimates*	*Hurd's Estimates*
Constant or intercept	7.798	6.50
Exponent of age	0.576	0.55
Exponent of rise	0.957	1.08
Exponent of slope	0.173	0.23
Exponent of (1 − sediment/rise)	1.659	1.46
Exponent of pH	−2.885	−3.08

Furthermore, we are unable to reproduce Hurd's Figure 7 (Log-linear projected service life for inspected culverts). Using

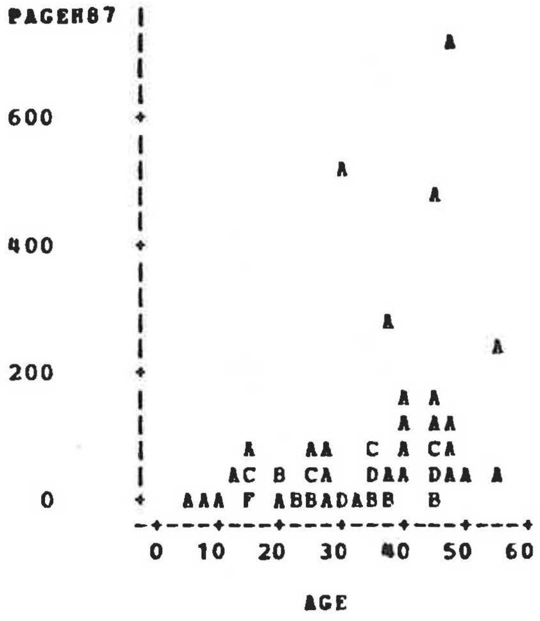

FIGURE 8 Observed sediment depths and rates.

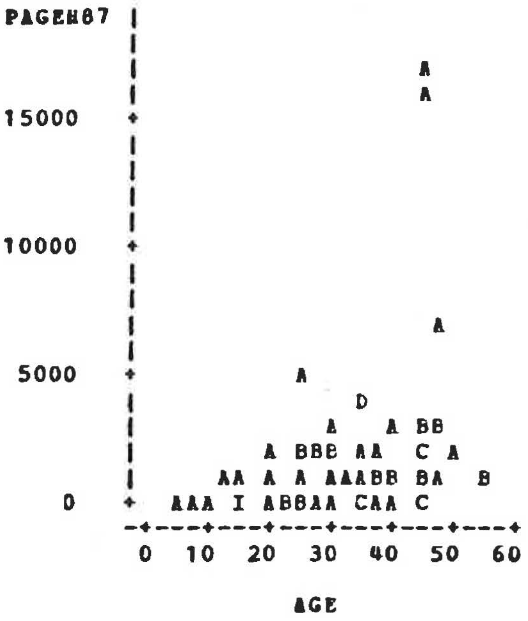

FIGURE 10 Observed sediment depths, rates equal to 95.

his equation for pH values of less than 7, we do not get the same picture. Because he does not find an equation for pH values greater than 7, we have no idea how he plots the service lives in this pH range.

UNACCEPTABLE PREDICTION EQUATION

Replicating Hurd's Equation 6 but using our parameters from the table shown in the preceding section of this discussion, we substituted the observed ratings and sediment depths to plot the relation between the predicted age and the age of the culverts. This relation (PAGEH87 versus Age) for pH less than 7 is shown in Figure 8. Here it can be seen that, despite the fact that none of the culverts in the data set are more than 60 years old, according to Hurd's approach many of these culverts would be predicted to be several hundred years old (about 30 percent of the predicted ages are more than the oldest culverts in the sample). Shown in Figure 9 is the same relation but for sediment depths set to 0 and ratings set to 95. Note that Hurd uses 95 to indicate the terminal condition of the culverts. The results show that the predictions range up to nearly 3,500 years. We also tried to use Hurd's Equation 6 but this results in even larger and unacceptable predicted

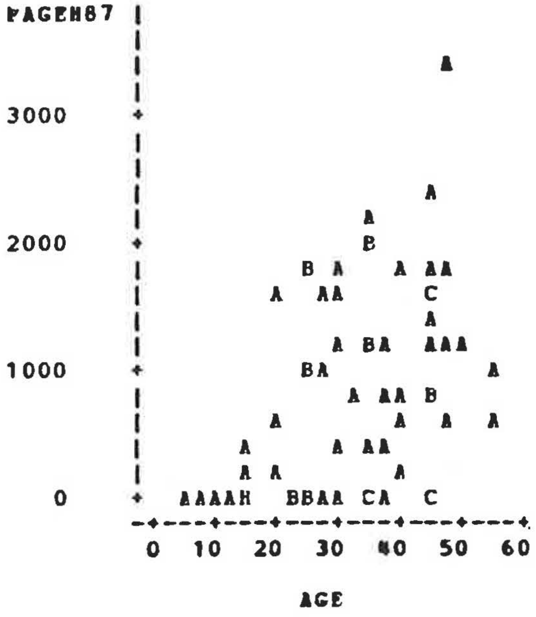

FIGURE 9 Sediment depths equal to 0 and rates equal to 95.

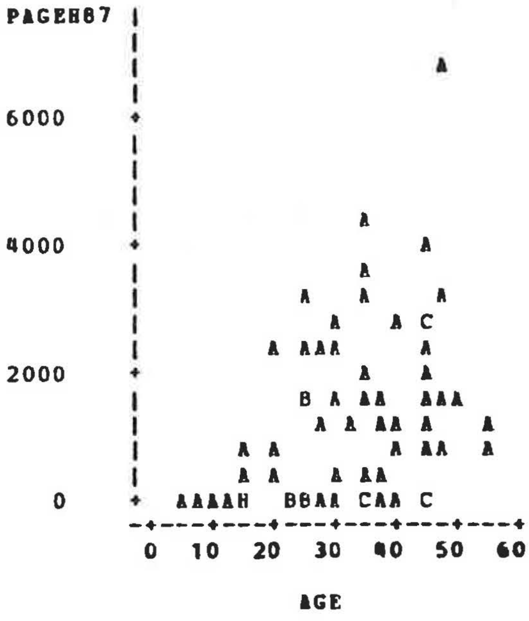

FIGURE 11 Sediment depths equal to 0 and rates equal to 95 (Hurd's Equation 6).

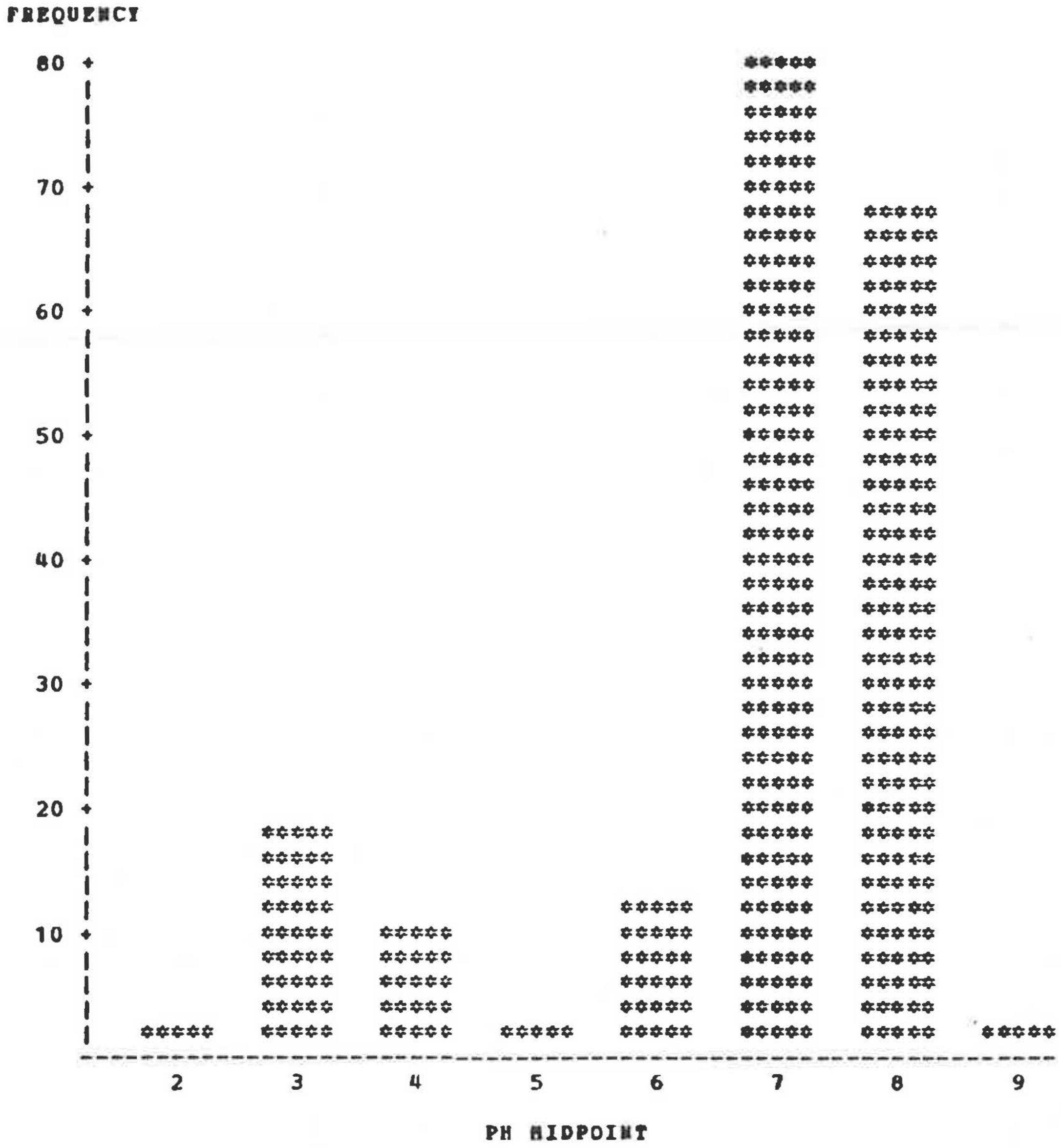

FIGURE 12 Frequency bar chart of pH values.

ages. Predicted ages using observed sediment depths and rate equal to 95 are shown in Figure 10. Sediment depths equal to 0 and rate equal to 95 are used in Figure 11. We reject these predictions.

SAMPLE DATA NOT REPRESENTATIVE

We suspect that another problem in this study is that the sample data are not representative of culverts in Ohio. A binodal sample distribution of pH values of the observations is shown in Figure 12. We expect a continuous uninodal distribution. The relation of age and pH values of the samples are shown in Figure 13, indicating a "boxing" of ages above pH = 7, as well as the lack of observations in the pH = 6 region.

To reduce the variability of prediction errors, we believe that more information is needed about each culvert. This has been addressed in our recent paper (*1*).

REFERENCE

1. F. C. Hadipriono, R. E. Larew, and O-H. Lee. Service Life Assessment of Concrete Pipe Culverts. *Journal of Hydraulic Engineering*, ASCE, Vol. 114, No. 2, 1988, pp. 209–220.

AUTHOR'S CLOSURE

Although the author believes that the commentary presented by the discussants from Ohio State University is not applicable to this paper, he will nonetheless briefly address their concerns.

First, the discussants imply that Equation 6 is not a true valid statistical regression equation. However, nowhere in this

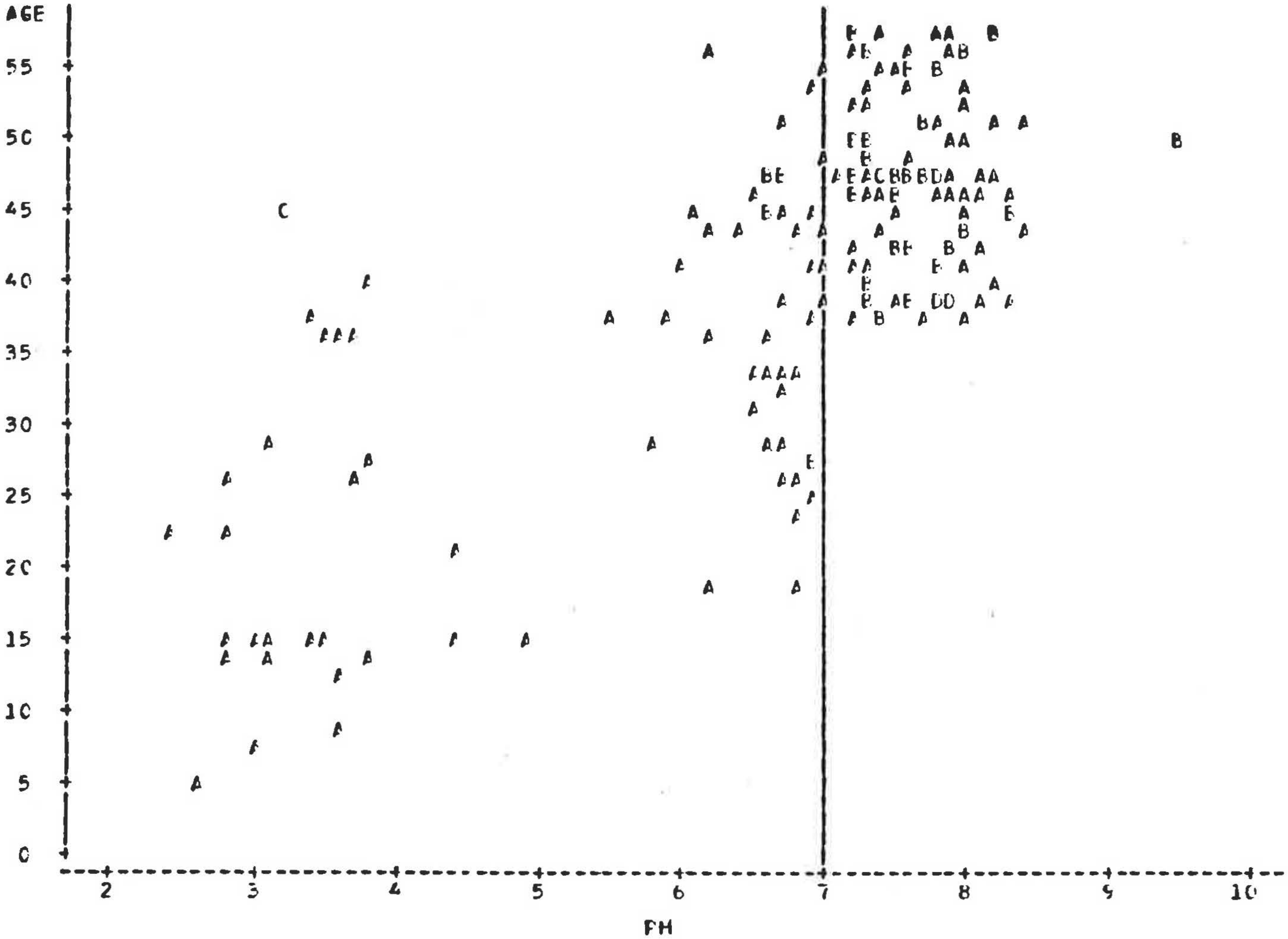

FIGURE 13 Plot of age versus pH.

report or the author's other referenced work was it ever implied that Equation 6 is a statistical regression equation that would produce true average service life for a given set of site conditions. To determine a true average service life for a given set of site conditions, it would be necessary to wait for all concrete culverts installed at sites with those conditions to deteriorate to a specified failure condition, which would not be practical. However, some method of estimating concrete pipe service life is required so that it can be compared with the various available estimates of corrugated metal pipe service life.

Equation 6 is simply a mathematical expression for the mathematical mechanics necessary to produce an estimated median service life value for a given set of environmental conditions. That method is to extrapolate a median deterioration rate from a statistical regression equation containing age and environmental parameters out to a specific failure value and to determine the age required to obtain that value for that set of environmental conditions.

This method is consistent with that used by ODOT to estimate median service life for corrugated metal pipe using the models in "The Ohio Culvert Durability Study" (*1*). These particular models were under review by representatives of the National Corrugated Steel Pipe Association for more than a year before publication without any comment being issued by the Association. The method is also consistent with the methods used to establish the corrugated metal pipe median service life curves from the California report, which is endorsed by the National Corrugated Steel Pipe Association and the American Iron and Steel Institute. In "Durability Study of Concrete Pipe Culverts; Service Life Assessment," Hadipriono indicates that the linear model can be used to estimate median service life by the same methodology ["The service life is determined by obtaining age from Equation 7, given PRate = 4.5 in." (*4, p. 36*)].

Second, the discussants claim that they cannot replicate the results. The author does not know why unless there have been transcription errors made in the half dozen or so transcriptions of the data since it was entered in ODOT's computer program. If transcription errors were caused by the action of ODOT, the author apologizes. However, the original coded data set, program, and printout are available at ODOT. To demon-

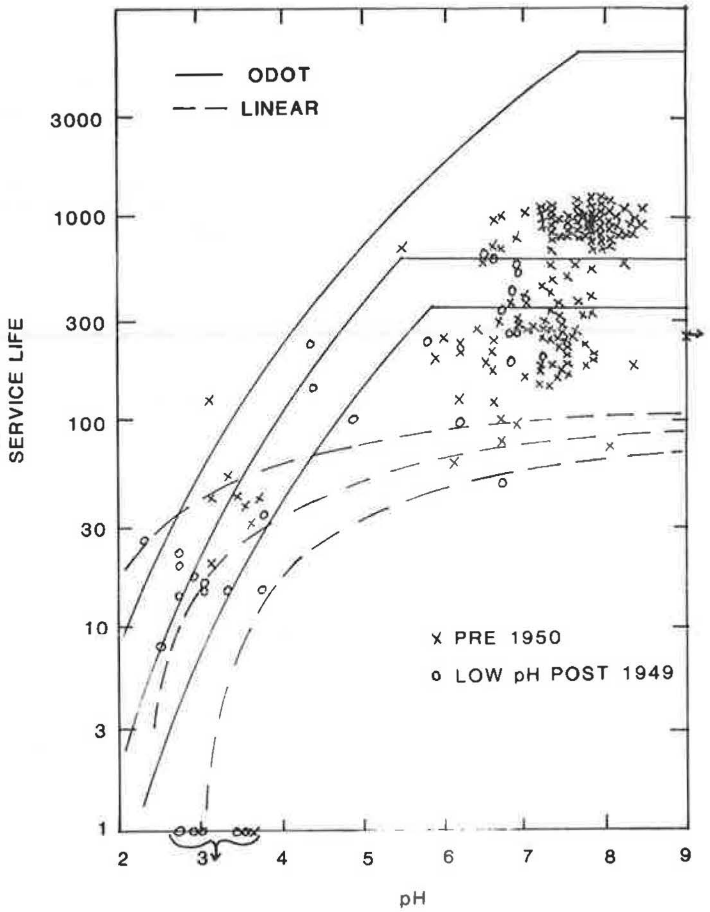

FIGURE 14 Linear projected visual fit service life for inspected culverts.

strate that end results are reproducible, one need only observe the median service life curves in Figures 1 and 3 of Transportation Research Record 1008 (*2*). Here two models developed with different data sets and rating systems produce similar curves. They diverge somewhat at the higher pH values. However, it should be noted that the ODOT service life curves (see Figure 4) cut off this model at higher pH values.

Third, the discussants back calculate estimated values of age using values of rating and other independent variables of the data set to show that the same values of age are not obtained and a large scatter exists outside the original age range of the data. Back calculation to obtain estimated values of any independent variable in any regression equation will produce values outside the original range of values of that independent variable. This is true of both linear and log-linear models. Although log-linear models will tend to produce some rather large outliers from back calculations, median values obtained should still be accurate. Back calculation of the discussants' linear regression model to estimate age will produce negative values of this variable. Back calculation to estimate pH values in the linear model [that uses the log (pH) as an independent variable] produces pH values 2 to 3 units different from actual, which are 100 to 1,000 times more acidic. These results are certainly no less reasonable.

Fourth, the discussants question whether the data sets used in the reports are representative of field conditions in Ohio. This seems presumptuous, because they have never conducted field inspections of any of the culverts used for the data sets. When field data is to be collected, what is there is what is collected, and the researcher does not have the liberty of sitting in an office creating a data set with a perfect distribution of all independent variables.

It appears that the underlying current of all Ohio State University's work in this case is to try to show that because true mean service life values cannot be obtained, life cycle cost analysis or other service life comparisons cannot be made. If that is true, then the designer must specify a minimum guaranteed (bonded) service life for each type of material specified. This service life should be based on the length of time the culvert is to serve drainage needs and not merely the life of the roadway until rehabilitation is needed.

What the discussants have actually done is to take the time to attack a previous work of the author without providing any evidence refuting the logic and findings of this report. That

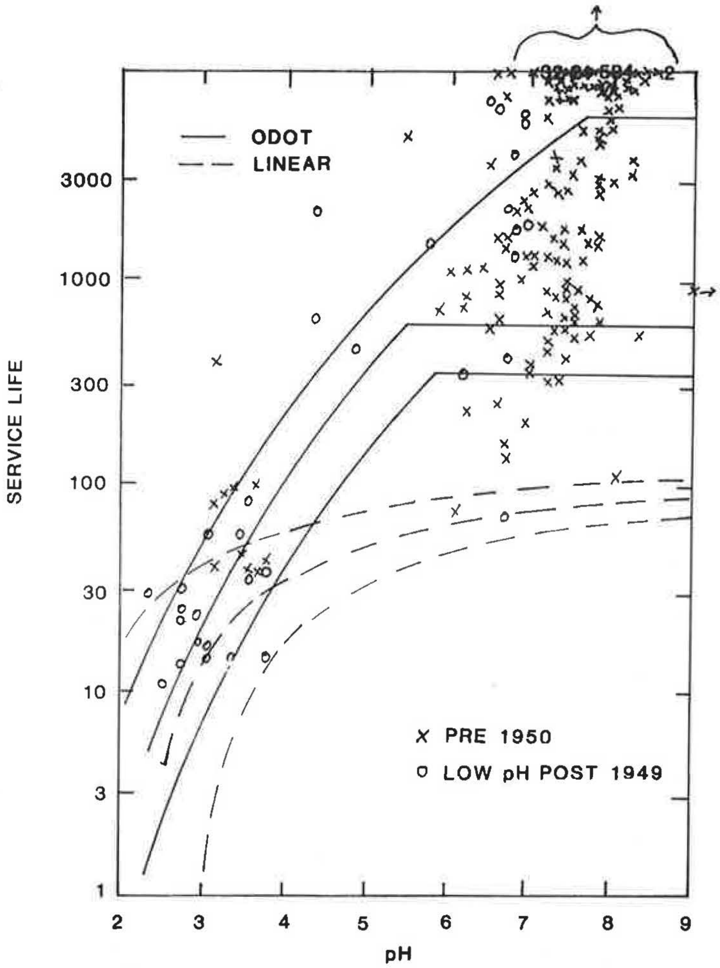

FIGURE 15 Log-linear projected visual fit service life for inspected culverts.

finding is that the data collected at the oldest concrete pipe culvert sites in Ohio clearly indicate that median service life values calculated by using the Ohio State University linear model are gross underestimates.

If the reader does not trust either regression model, the reader may use visual line fitting of a median line on Figure 6 to provide a very conservative estimate of median concrete pipe service life for all conditions (see Figure 14). This is based on the discussants' erroneous assumption of a linear relation of age to the deterioration rating. This was shown in the paper to be extremely conservative. A less conservative estimate could be obtained using Figure 7 (see Figure 15).

Publication of this paper sponsored by Committee on Culverts and Hydraulic Structures.

Culvert Durability Rating Systems

JOHN M. KURDZIEL

The culvert condition rating systems used in durability studies conducted by various private, state, and federal agencies are reviewed in this paper. The rating scales used in these studies were analyzed and compared. A new material durability rating system for both metal and concrete pipe is proposed based on these comparisons. The rating scale corresponds to the one used by the National Bridge Inventory and Inspection Program. The new system will ensure that all types of culvert materials are uniformly rated in every study and will promote the development of a comprehensive data base on the durability of each product material.

The durability of culverts has been studied at great length over the past four decades. Many states at one time or another have conducted at least one study of metal or concrete culverts. Unfortunately, most results have been inconclusive or controversial. Site conditions have an significant effect on how long a facility will last. Product materials react differently in various environments because of inherent strengths and weaknesses. Pipe manufacturers, federal, state, and local government agencies, and consultants all have different opinions on the expected service life of culvert materials and the effects of site conditions.

Durability studies conducted to date have not used a common rating system, instead most have developed their own. This does not present any particular problem to the agency conducting the study but does create problems of correlating information from various studies into a comprehensive assessment of a particular product's qualities and durability in different environments.

Information and ratings from one study seldom correspond directly with those of another, resulting in conflicting data and possible misinterpretation of the information. The answer to these problems is a standard rating system for inspecting and evaluating the condition of the various types of culvert products. A standard rating system would ensure that all culverts were rated identically, end the guess work of correlating studies, eliminate the time and effort of developing rating systems, and eventually provide a comprehensive data base on the durability of each product material. With a standard rating system, various studies could be analyzed to provide guidance on product service lives.

Evaluated in this paper are current state and federal culvert durability rating systems and clarifications are developed to facilitate the use of the Federal Highway Administration (FHWA) *Culvert Inspection Manual* (*1*).

FHWA *CULVERT INSPECTION MANUAL*

The Federal Highway Administration presents standard guidelines in their *Culvert Inspection Manual* (*1*). This publication is a stand-alone supplement to the *Bridge Inspector's Training Manual 70* (*2*). The manual is a unique and valuable tool in that it is the first publication to interrelate reporting procedures, rating systems, and component evaluations. The primary objective of the manual is to provide information that will enable users to do the following tasks:

1. Properly inspect an existing culvert,
2. Evaluate structural adequacy,
3. Evaluate hydraulic adequacy and recognize potential flood hazards,
4. Rate the condition of the culvert,
5. Document the findings of a culvert inspection,
6. Recognize and document traffic safety conditions, and
7. Recommend corrective actions.

To meet these objectives, recommendations are made in the manual for procedures for conducting, reporting, and documenting a culvert inspection, and guidelines for inspecting and rating specific hydraulic and structural culvert components are also provided. Major culvert components, such as shape, joints, seams, footings, and material conditions for metal pipe, and alignment, joint, material, and footing conditions for concrete pipe are described and evaluated to assist the inspector in identifying common types of culvert distress and recognizing their significance. Detailed provisions and guidelines are provided for each type of metal and concrete pipe configuration (Tables 1 and 2).

Recommended in this paper are changes in the assessment and rating of material durability conditions for metal and concrete pipe to improve inspection procedures and evaluation of data. Although distress conditions of both materials are presented in the manual in a systematic and well-structured way, a greater degree of detail is necessary in the condition descriptions to ensure that unique characteristics and features are associated with each rating number in order to eliminate subjective interpretation by an inspector.

Slight modifications to the culvert rating system will be based on the information contained in the durability studies from the various states analyzed. The proposed rating of material evaluations, based on the system used in the *Bridge Inspectors Training Manual 70* (*2*), is as follows:

American Pipe Association, 8320 Old Courthouse Road., Vienna, Va. 22180.

Rating	*Description*
9	New condition.
8	Good condition–no repairs necessary.
7	Generally good condition–potential exists for maintenance
6	Fair condition–potential exists for major maintenance.
5	Generally fair condition–potential exists for minor rehabilitation.
4	Marginal condition–potential exists for major rehabilitation.
3	Poor condition–repair or rehabilitation required immediately.
2	Critical condition–the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete.
1	Critical condition–facility is closed. Study should determine the feasibility for repair.
0	Critical condition–facility is closed and is beyond repair.

RATING SYSTEMS

Culvert rating systems included in available state durability reports and federal agency publications, as well as pertinent Transportation Research Board papers, were examined. A list of the 151 references resulting from the literature search is available from the author. Discussion in this paper is limited to those studies that reflect current practices in each region of the country (Figure 1).

There are a number of methods used for analyzing culvert durability. Studies based on percent of metal or concrete loss provide documentation on the actual pipe wall thickness and the rate of deterioration, but may not present an accurate assessment of the culvert's overall condition. Concrete and metal loss cannot be rated in a linear fashion. Once abrasion and corrosion forces start to pit the surface of the metal, the area exposed to corrosion is increased and the rate of metal loss accelerates. Ratings of 20 to 30 percent metal loss do not portray the actual severity of the installation's condition (Table 3). A culvert with its zinc coating lost, metal heavily corroded and pitted, and a quarter of its thickness gone was not considered indicative of a facility in good condition by any of the other studies examined. Similarly, if 50 percent of a concrete pipe wall had deteriorated, it could represent a much more serious problem than a linear rating would indicate. A rating system should take these effects into consideration.

TABLE 1 FEDERAL HIGHWAY ADMINISTRATION'S CULVERT INSPECTION RATING GUIDELINES FOR CORRUGATED METAL CULVERT BARRELS (*1*)

Rating Guidelines for Round or Vertical Elongated Corrugated Metal Pipe Barrels

Rating	Condition
9	● New Condition
8	● *Shape*: good, smooth curvature in barrel - *Horizontal*: within 10 percent of design ● *Seams and Joints*: tight, no openings ● *Metal*: - *Aluminum*: superficial corrosion, slight pitting - *Steel*: superficial rust, no pitting
7	● *Shape*: generally good, top half of pipe smooth but minor flattening of bottom - *Horizontal Diameter*: within 10 percent of design ● *Seams or Joints*: minor cracking at a few bolt holes, minor joint or seam openings, potential for backfill infiltration ● *Metal*: - *Aluminum*: moderate corrosion, no attack of core alloy - *Steel*: moderate rust, slight pitting
6	● *Shape*: fair, top half has smooth curvature but bottom half has flattened significantly - *Horizontal Diameter*: within 10 percent of design. ● *Seams or Joints*: minor cracking at bolts is prevalent in one seam in lower half of pipe. Evidence of backfill infiltration through seams or joints. ● *Metal*: - *Aluminum*: significant corrosion, minor attack of core alloy - *Steel*: fairly heavy rust, moderate pitting
5	● *Shape*: generally fair, significant distortion at isolated locations in top half and extreme flattening of invert - *Horizontal Diameter*: 10 percent to 15 percent greater than design ● *Seams or Joints*: moderate cracking at bolt holes along one seam near bottom of pipe, deflection of pipe caused by backfill infiltration through seams or joints. ● *Metal*: - *Aluminum*: significant corrosion, moderate attack of core alloy - *Steel*: scattered heavy rust, deep pitting
4	● *Shape*: marginal significant distortion throughout length of pipe, lower third may be kinked - *Horizontal Diameter*: 10 percent to 15 percent greater than design ● *Seams or Joints*: Moderate cracking at bolt holes on one seam near top of pipe, deflection caused by loss of backfill through open joints ● *Metal*: - *Aluminum*: extensive corrosion, significant attack of core alloy - *Steel*: extensive heavy rust, deep pitting
3	● *Shape*: poor with extreme deflection at isolated locations, flattening of crown, crown radius 20 to 30 feet - *Horizontal Diameter*: in excess if 15 percent greater than design ● 3 in. long cracks at bolt holes on one seam ● *Metal*: - *Aluminum*: extensive corrosion, attack of core alloy, scattered perforations - *Steel*: extensive heavy rust, deep pitting, scattered perforations
2	● *Shape*: critical, extreme distortion and deflection throughout pipe, flattening of crown, crown radius over 30 feet - *Horizontal Diameter*: More than 20 percent greater than design ● *Seams*: plate cracked from bolt to bolt on one seam ● *Metal*: - *Aluminum*: extensive perforations due to corrosion - *Steel*: extensive perforations due to rust
1	● *Shape*: partially collapsed with crown in reverse curve ● Seams: failed ● *Road*: closed to traffic
0	● *Pipe*: totally failed ● *Road*: closed to traffic

NOTE: See Coding Guide for description of Rating Scale. As a starting point, select the lowest rating that matches actual conditions.

TABLE 2 FEDERAL HIGHWAY ADMINISTRATION'S CULVERT INSPECTION RATING GUIDELINES FOR CONCRETE CULVERT BARRELS (*1*)

Rating Guidelines for Precast Concrete Pipe Culvert Barrels

Rating	Condition
9	• New condition
8	• *Alignment*: good, no settlement or misalignment • *Joints*: tight with no defects apparent • *Concrete*: no cracking, spalling, or scaling present; surface in good condition
7	• *Alignment*: generally good; minor misalignment at joints; no settlement • *Joints*: minor openings, possible infiltration/exfiltration • *Concrete*: minor hairline cracking at isolated locations; slight spalling or scaling present on invert
6	• *Alignment*: fair, minor misalignment and settlement at isolated locations • *Joints*: minor backfill infiltration due to slight opening at joints; minor cracking or spalling at joints allowing exfiltration • *Concrete*: extensive hairline cracks, some with minor delaminations or spalling; invert scaling less than 0.25 in. deep or small spalls present.
5	• *Alignment*: generally fair; minor misalignment or settlement throughout pipe; possible piping • *Joints*: open and allowing backfill to infiltrate; significant cracking or joint spalling • *Concrete*: cracking open greater than 0.12 in. with moderate delamination and moderate spalling exposing reinforcing steel at isolated locations; large areas of invert with surface scaling or spalls greater than 0.25 in. deep
4	• *Alignment*: marginal; significant settlement and misalignment of pipe; evidence of piping; end sections dislocated about to drop off • *Joints*: differential movement and separation of joints, significant infiltration or exfiltration at joints • *Concrete*: cracks open more than 0.12 in. with efflorescence and spalling at numerous locations; spalls have exposed rebars which are heavily corroded; extensive surface scaling on invert greater than 0.5 in.
3	• *Alignment*: poor with significant ponding of water due to sagging or misalignment pipes; end section drop off has occurred • *Joints*: significant openings, dislocated joints in several locations exposing fill materials; infiltration or exfiltration causing misalignment of pipe and settlement or depressions in roadway. • *Concrete*: extensive cracking, spalling, and minor slabbing; invert scaling has exposed reinforcing steel
2	• *Alignment*: critical; culvert not functioning due to alignment problems throughout • *Concrete*: severe slabbing has occurrerd in culvert wall, invert concrete completely deteriorated in isolated locations
1	• *Culvert*: partially collapsed • *Road*: closed to traffic
0	• *Culvert*: total failure of culvert and fill • *Road*: closed to traffic

NOTE: See Coding Guide for description of Rating Scale. As a starting point, select the lowest rating that matches actual conditions.

FIGURE 1 Location of study reports, indicated by shaded areas.

TABLE 3 CALIFORNIA STATE RATING SYSTEM (*3*)

Rating	Metal Loss (%)	Water	Splash	Air I (inside)	Air O (outside)	Soil	Abrasion
0	0						
1	10						
2	20						
3	30						
4	40	Designates metal loss in the culvert due to the various corrosion components.					
5	50						
6	60						
7	70						
8	80						
9	90						
10	100						

In some studies, sample coupons from field installations were used to determine the metal thickness and were the main basis on which the condition of the facility was rated (Table 4). A major problem with ratings systems based on coupons is the lack of correlation between coupons and field ratings. Coupons may not include perforations, or coating blisters, or thickness loss that may otherwise be observed in field inspections.

Rating systems based on visual observations are more subjective than the precise techniques used for measuring the pipe wall thickness, however they are more indicative of a culvert's overall performance. Visual condition ratings should be based on the worst area observed in the culvert because this will be the most likely point of failure. A uniform rating system should, therefore, be based on visual ratings with detailed descriptions of the culvert's conditions and should include measurements where appropriate.

The first step in developing a comprehensive durability rating system is to examine available studies, analyze the rating systems, and prepare a rating table that most closely reflects the conditions considered by the majority. On the surface this may appear to be a straightforward task, but most studies have a unique goal that is reflected in the rating table. Rating tables also vary in evaluation of condition ratings. What one study considers a poor rating may be a fair or critical rating for another. The range of ratings may also be restricted by the numbering system used. More broad numbering systems provide more latitude in rating a structure but they may, however, prove to be cumbersome if too large. A 0 to 100 scale, although allowing the rater more room for assessment than a 1 to 5 scale, is meaningless to the rater and reviewer if evaluations are other than increments of 10. A scale of 1 to 10 seems to provide the best compromise between maximum flexibility in rating and maintenance of a distinct significance in each number.

Although a scale based on 10 allows easy conversion of many studies and direct correlation to percentages, it does not correspond to the most widely used and accepted rating scale based on 9, which is used in the National Bridge Inspection Program. By using the bridge program's 0 to 9 scale, culvert inspections will follow a national program already in force. The use of an established rating system would make adoption and use of culvert guidelines easier, because no changes to the current bridge system would be necessary and inspectors would already be familiar with the rating scale. A common system would help promote more culvert reviews and result in larger data bases on pipe products.

METAL CONDITION RATING SYSTEMS

The condition rating scales for corrugated metal pipe from the various state studies are presented in Table 5. There is no distinction made between steel and aluminum in the tables because, regardless of actual durability characteristics, the distress conditions are essentially identical. All state rating scales have been adjusted to conform to the 0 to 9 scale. For comparison purposes, the studies were arranged on the scale according to their original condition guidelines. State condition ratings for metal culverts were similar in the top values of 9 and 8. Once a metal culvert had deteriorated past superficial rust, there was little agreement on the rating, and most studies did not show a uniform systematic progression of deterioration. Rating conditions jumped dramatically from "pinpoint rust" to "heavy pitting rust," with very little, if any, guidance given to evaluate conditions between these extremes. Rating descriptions were also not quantitative. Describing a condition as simply "moderate signs of deterioration" does not adequately explain the condition. Specific degrees of deterioration should be listed such as depth of rust, degree of pitting, and amount of thinning of the metal.

The severity placed on the first sign of perforation was somewhat uniform and represented a critical rating: 1 or 0,

TABLE 4 COUPON RATINGS SYSTEMS

Rating Scale	Idaho (*4*)[a] Metal	Colorado (*5*)[b] Metal	Concrete
5	Like new	No visible corrosion	No apparent change except slight staining
4	Dull: age weathered to the point all zinc luster gone	Light salt deposit or rusting, blistering near edges	Light pitting and/or salt deposits
3	Pinpoint rust: evidence of rust in very small areas	Mild salt deposit or rusting, blistering near edges	Moderate loss of surface mortar and salt accumulation
2	Scale rust: large areas of rust wherein scale can be seen	Extensive rusting and formation of blisters	Moderate loss of aggregate
1	Pitting: rusted to the extent base metal is pitted	Severe corrosion or rusting	Extensive aggregate loss, swelling and/or warping of coupon
0		Very severe rusting or loss of adhesion of protective coating	Total failure of coupon

[a] From field installations, used reverse scale in report.

[b] Based on coupons exposed to environmental conditions.

TABLE 5 STUDIES ON METAL CONDITION RATINGS

RATING	FLORIDA (6)	KANSAS (7)	CALIFORNIA (LA COUNTY) (8)	LOUISIANA (9)	MAINE (10)	MICHIGAN (11)	MINNESOTA (12)	MISSISSIPPI (13)
9		No corrosion - Galvanizing intact.	No corrosion.	No signs of deterioration.	Approaching Original Condition (Galvanizing intact)			
8	Galvanizing intact.		Superficial corrosion. Discoloration of surface, red or black scale lightly adhering to surface.			Galvanizing intact	Spelter entirely intact	Spelter entirely intact
7		Superficial rust (edges and bolt heads) - No pitting; weathered to point all zinc luster gone.	Slight corrosion. Some loss of zinc coating, thin flaking and shallow pitting of surface	Very slight signs of deterioration and pitting	Superficial Rust (no pitting)			
6	(+) Galvanizing partly gone, some surface rust.					(+) Galvanizing partly gone, some rust	(+) General pinpoint rust	(+) Spelter just gone and thin rust beginning to form in places, no abrasion and no pitting.
5		Moderate rust - Rust flakes tight, minor pitting.	Moderate corrosion. Deep pitting of surface	Moderate signs of deterioration and pitting	Moderate Rust (minor pitting).			
4	(+) Galvanizing gone. Significant metal loss (about 25%).					Galvanizing gone, significant metal loss.	Heavy pitting rust.	Complete loss of spelter and considerable loss of metal in invert. Pitting and some abrasion.
3		(+) Fairly heaving rusting - Rust flakes tight, moderate pitting, but metal is sound.	Heavy corrosion. Build-up of laminations of rust scale.		(+) Fairly Heavy Rust (moderate pitting, metal sound).			
2	Deep pitting, heavy metal loss, first perforation visual or under blows of spike (at least 50% metal loss).			Extreme signs of deterioration and pitting.		Deep pitting, heavy metal loss, metal can be perforated with a sharp metal probe.	Heavy pitting rust and loss of metal in invert.	Decided pitting and abrasion. Heavy loss of metal in invert.
1	Complete metal loss in about 1/2 area of maximum corrosion in invert.	(+) Heavy rusting - Rust flakes easily removed - Deep pitting into base metal.	Heavy corrosion. Beginning to perforate.		(+) Heavy Rust (deep pitting and some perforation).		Start of perforations.	Metal corroded and abraded through invert in small spots. Very heavy rust and deep pitting in general over invert.
0	Metal gone, full width of area of maximum corrosion.	Heavy rust - Deep pitting and unsound or perforated areas. Unsound areas easily perforated with pick end of geologist hammer.	Perforated.	Signs of complete deterioration, and the pipe is no longer useful as a drainage tool.	Unsound Areas (extensive perforation to bottom completely deteriorated).	Metal perforated.	Entire invert gone.	Entire invert gone.

(+) Indicates intermediate rating - condition may also correspond to the next highest rating.
* National Corrugated Steel Pipe Association.

in all cases. The exact uniform and represented a critical rating: 1 or 0, in all cases. The exact point of failure, however, varied for each study. Some considered this point to be the first perforation, others considered it the deterioration of the entire invert or the collapse of the facility.

Each study concentrated on a unique durability feature, with most increasing the number of rating descriptions as the facility neared failure. One notable exception was the Ohio report. The upper half of the ratings are very distinct and clear for conditions representing "excellent" to "fair" facilities. The "poor" rating, however, constitutes one condition description and dominates the entire lower half of its rating system. There is a great deal of deterioration that must take place for a facility to go from a "fair" condition, which constitutes heavy rust and scale with no penetration, to a "poor" condition, which has the invert gone. The poor rating in this case is too large to be of benefit to an evaluator interested in the lower range of conditions approaching failure. The Ohio report, however, recognized the limitations of the rating system used. The predictive equations developed were based solely on measured metal loss.

The use of the broad "poor" category was reasonable in this case because they were not concentrating on predicting failure by means of evaluating metal ratings but only on identifying those installations that were considered in poor condition. The Ohio report is noteworthy because it illustrates the importance of understanding the concentration and scope of the study before reviewing its data.

The Ohio study also highlights another problem with ratings systems that are skewed heavily in one direction. Reviewers of a rating scale may assume that there is a linear relationship for each of the rated conditions. In the case of the Ohio report and many other studies, this observation would lead to estimation of deterioration to failure sooner than it would actually occur. Care must be taken to review the rating scale and conditions before using and comparing data from a particular study.

The proposed metal rating system in Table 6 provides a detailed and unique description for each rating from new to failure. Incorporated in this table are all changes and additions to the metal rating descriptions in the FHWA *Culvert Inspection Manual* (*1*). The intent was to provide a rating system that is easy to understand and has logical increments of deterioration. Major conditional features identified include galvanizing, level of rust, depth of pitting, metal thinning, and degree of perforations. The ratings in the state studies were adjusted to reflect the facility condition ratings described in the bridge rating scale. The effect was the consolidation of

TABLE 5 *continued*

RATING	OHIO (14)	OKLAHOMA (15)	OREGON (16)	TENNESSEE (17)	WASHINGTON (18)	NCSPA (19)
9	Condition as constructed, no apparent loss of galvanizing (Excellent).	Culvert shows absence of only minor amounts of thin rust coatings present as spots or patches of less than one inch diameters. Spelter intact, even in the invert area. Geology Hammer: hard blows will not penetrate (Excellent).	Zinc like new.		Spelter like new	
8	Discoloration but no scaling or corrosion (Very Good).		Zinc dull to very dull.	Spelter entirely intact	Spelter dull to very dull	Spelter intact - spangles visible
7	Slight to and scale, pitting just started, isolated spots of moderate corrosion (Good).	Thin continuous coatings of rust in invert area. Spelter absent in invert area. Some small blisters (scale) occasionally present. Geology Hammer Hard blow will not penetrate (Good)	Pinpoint rust spots, zinc entirely gone		Pinpoint rust spots, spelter entirely gone	
6	Moderate to heavy scale and rust, no geologist's hammer penetration, no perforation (Fair).		Light rust film, shallow pitting	(+) General pinpoint rust	Light rust film, shallow pitting	(+) General pinpoint rust
5		Thick and scaling rust coatings, pitting of culvert surface noticeable. Geology Hammer Penetrates with 2-3 hard blows in same area (Fair)	Rust or pits not halfway through core metal		Rust or pits not halfway through core metal.	
4				Heavy pitting rust.		(+) Heavy pitting rust.
3		Scaling pronounced, pitting of metal surface obvious and widespread. Geology Hammer Perforates with one moderate blow (Poor).	Rust or pits halfway through core metal.		Rust or pits halfway through core metal.	
2	Penetration with geologist's hammer, perforation, loss of invert (Poor).		Rust or pits over halfway through core metal.	Heavy pitting rust and loss of metal in invert.	Rust or pits three-quarters through core metal.	Rust scaling loose.
1		(+) Severe scaling, pitting progresses to perforation. Holes may be any size. The rating of (Pf) will be used until such deterioration has taken place in order to cause failure (Perforation).	Few holes through metal.	Start of perforation.	Few holes through metal.	First small perforation.
0		Culvert is bent, warped, sagged, broken, etc., to such an extent as to cause the culvert not to function as intended (Failure).	Large area of metal gone.	Entire invert gone.	Large areas of metal gone.	Perforations large or beginning to connect so small strip removed.

(+) Indicates intermediate rating - condition may also correspond to the next highest rating.
* National Corrugated Steel Pipe Association.

TABLE 6 METAL CONDITION RATINGS

Rating	Condition	Description
9	Excellent	New condition, galvanizing intact, no corrosion.
8	Very good	Discoloration of surface, galvanizing partially gone.
7	Good	Superficial or pinpoint rust spots, no pitting.
6	Fair	Moderate rust, rust flakes tight, shallow pitting of surface galvanizing gone.
5	Fair—marginal	Heavy rust and scale, moderate pitting and slight thinning of core metal.
4	Marginal	Extensive heavy rust, thick and scaling rust coatings, deep pitting and significant metal loss (approximately 25 percent).
3	Poor	Rust and pitting halfway through core metal (some deflection or penetration when struck with pick or geology hammer).
2	Very poor	Extreme deterioration and pitting, three quarters of core metal gone, first perforations.
1	Critical	Extensive or large perforations.
0	Failure	Invert completely deteriorated, culvert beginning to bend, warp or sag, collapse of the culvert is imminent.

some of the less significant upper ratings and an expansion of the ratings of the more critical factors. The degree of perforations now span over three ratings instead of one or two, as was the case in many of the state scales. They are still considered poor or critical items, but now correspond closer to the depth of rust and pitting, and thinning of the metal.

CONCRETE COALITION RATING SYSTEMS

The concrete condition rating scales from the state studies are illustrated in Table 7. One observation immediately apparent upon reviewing the table is the lack of reports. There have been very few studies on the durability of concrete pipe. Durability problems are rare with highway concrete culverts, and normally the only problem encountered is concrete loss in the invert resulting from acidic effluents such as those in mine drainage areas. The state of Ohio has conducted the most studies on concrete culverts, with concentration on the effects of acid environments on the pipe.

The conditional rating scales for concrete pipe were similar, considering the small data base available for analysis. Deterioration concentrated on the degree of scaling and softness of the concrete. In all but one case, deterioration was described in a distinct and systematic progression. Failure was uniformly

TABLE 7 STUDIES ON CONCRETE CONDITION RATINGS

RATING	KANSAS (7)	MAINE (10)	MISSISSIPPI (13)	OHIO (I) (14)	OHIO (II) (20)
9	Intact - no deterioration.	Approaching original condition.		Condition of concrete as constructed (Excellent)	As manufactured.
8			No weathering or disintegration and no softening from acid or alkali or other causes	Discoloration but no loss corrosion, or softening (Very Good)	Slight loss of mortar, aggregate not exposed.
7	Light scaling - 0-1/8" in depth.	Discoloration, slight (scaling) of mortar, no softening of concrete		Slight loss of mortar leaving aggregate exposed (Good)	Moderate loss of mortar, aggregate exposed.
6			(+) Some weathering or (scaling) and disintegration. Slight erosion of invert	Moderate loss of mortar and aggregate, slight softening of concrete (Fair).	Significant loss of mortar around aggregate.
5	Medium scaling - 1/8"-1/4" depth.	Slight scaling of smaller aggregate, no softening			Significant loss of mortar, slight aggregle loss.
4			(+) Decided disintegration or erosion in invert. General weathering and (scaling). Softening due to alkali or acid.		Moderate aggregate loss (part of first layer).
3	(+) Heavy scaling - Scaling over 1/4" depth.	(+) Moderate (scaling) (loss of mortar and aggregate minor amounts of softening).			Aggregate loss (all of first layer into second layer).
2			(+) Decided disintegration throughout the pipe. Considerable weathering and (scaling). Softening due to alkali or acid.	Significant loss of mortar and aggregates, complete loss of invert, concrete in softened condition (Poor).	Reinforcing exposed at a few places.
1	(+) Heavy scaling - Exposed mesh or rust showing on surface.	(+) Extensive (scaling) of mortar and aggregate plus softening of concrete.	Extreme disintegration and (scaling). Material very soft due to acid or alkali.		Reinforcing exposed throughout pipe.
0	Heavy scaling - Total thickness of pipe deteriorated.	Invert completely deteriorated.	Disintegration through pipe. Reinforcing exposed.		Reinforcing gone.

(+) Indicates intermediate rating - condition may also correspond to the next highest rating.

considered to be complete disintegration of the invert at a rating of 0.

Table 7 contains two Ohio studies and is a good example of the differences between rating systems. The first, Ohio (I), was developed from the same study as the metal rating system. The rating systems were consistent for both metal and concrete in that there was a strong concentration on the conditional ratings for the upper range of the scale and only one for the lower half. A follow-up study, Ohio (II), conducted 3 years later, provided a much more detailed rating system for concrete pipe. Unfortunately, this study did not cover metal pipe and, therefore, no comparable rating scale is available. This scale proved to be one of the most comprehensive rating systems found for concrete pipe.

The proposed concrete rating system in Table 8 provides a detailed and unique description for each rating from new to failure. Changes and additions to the concrete rating descriptions in the FHWA *Culvert Inspection Manual* (*1*) are shown in bold type. The rating system provides logical and progressive increments of deterioration for mortar and aggregate scaling, concrete hardness, and reinforcement condition. As in the case of the metal rating scale, the conditional ratings in the state studies had to be modified and consolidated to conform to the facility condition rating system used in the bridge inspection program.

One major change that was made to the concrete rating scale was the addition of a new intermediate rating condition. Most rating scales reviewed went from first exposure of reinforcing to total deterioration of the invert in one step. This increment is too large for one rating step. Considering concrete pipe's inherent strength from its reinforcing and wall thickness, and that the 1-in. cover of concrete over the reinforcement is protective rather than structural, a condition rating inserted between the two existing evaluations seems appropriate. The intermediate rating condition will be classified as a 2 rating and described as "invert scaling below first layer of reinforcing, 50 percent loss of wall thickness at invert, concrete very soft."

Analytically, the inclusion of an intermediate concrete rating is supported by the rating equations contained in the Ohio (I) and Ohio (II) reports. In both studies, the major variable in the log-linear rating equations was age. The Ohio (I) age function, $\text{age}^{0.17}$, was definitely not linear as the rating scale indicated. The updated rating evaluations in the Ohio (II)

TABLE 8 CONCRETE CONDITIONAL RATINGS

Rating	Condition	Description
9	Excellent	New condition.
8	Very good	*Discoloration of concrete*, no cracking, spalling, scaling *or softening of concrete* present, surface in good condition.
7	Good	Minor hairline cracking at isolated locations, slight spalling, *light scaling (0 to 1/8 in. in depth) on invert, slight loss of mortar, aggregate not exposed, no softening of concrete.*
6	Fair	Extensive hairline cracks, some with minor delaminations or spalling, *moderate loss of mortar around aggregate, invert scaling 1/8 to 1/4 in. deep.*
5	Fair—marginal	Cracking open greater than 0.12 in. with moderate delamination and moderate spalling exposing reinforcing steel at isolated locations, large areas of invert with spalls greater than 0.25 in. deep, *significant loss of mortar and slight loss of smaller aggregates due to surface scaling (1/4 to 1/2 in. depth).*
4	Marginal	Cracks open more than 0.12 in. with effluence and spalling at numerous locations, spalls have exposed rebars that are heavily corroded, *heavy invert surface scaling greater than 1/2 in., moderate aggregate loss, concrete softening.*
3	Poor	Extensive cracking, spalling, and minor slabbing, invert scaling has exposed reinforcing steel *at isolated locations, moderate amount of concrete softening.*
2	Very poor	Severe slabbing has occurred in culvert wall, *invert scaling below first layer of reinforcing, 50 percent loss of wall thickness at invert, concrete very soft.*
1	Critical	*Holes through in concrete at isolated locations, 75 percent loss of wall thickness at invert, reinforcing exposed throughout invert.*
0	Failure	*Invert completely deteriorated, reinforcing steel gone, collapse of the culvert is imminent.*

NOTE: Condition descriptions in italic reflect additions to those contained in the FHWA Culvert Inspection Manual (*1*).

report, however, presented a more linear approach using an age function, $\text{age}^{0.55}$. An examination of the Ohio data and rating systems indicates that as the length of service life of the concrete pipe in these studies increases, there will be an expansion of ratings within the "marginal" to "poor" range and a consolidation of the "fair" ratings. These conditions would necessitate an increase in the age function of the Ohio equation. The proposed scale broadens the number of "poor" ratings for concrete pipe, increasing the Ohio age exponential to a value closer to 1 or a linear relationship. The incorporation of this condition corresponds to the trend apparent in the Ohio data and allows for an equitable direct comparison between metal and concrete ratings.

SUMMARY

The proposed condition rating systems for metal and concrete pipe provide an orderly progression for determining durability conditions in a culvert. Detailed descriptions of the levels of material distress present unique characteristics and features for each rating number. The development of the systems based on the operational evaluations used under the bridge rating scale permits the two systems to be directly compared. The severity of the conditions in a metal culvert can now be related directly to those for a concrete culvert with the same rating. It also allows for cross comparison with bridge structures, an option that is becoming more important as the number of inspections of bridge length culverts increases.

RECOMMENDATIONS

There should be state and federal programs for inspection of all culverts based on the FHWA *Culvert Inspection Manual* (*1*). The assessment and rating of material durability evaluations for culverts should be revised to eliminate subjective interpretation, thereby creating a uniform evaluation system.

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