Culvert Asset Management Practices and Deterioration Modeling

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Drainage infrastructure systems and culverts constitute an important portion of highway assets that require routine inspections, maintenance, and timely repair and renewal. Variations in structural characteristics (i.e., material type, shape, and dimension), environmental exposure, and wide geospatial distribution of these infrastructure assets accompanied with strict budget restrictions pose significant challenges for transportation agency officials. Deterioration models constitute one of the most essential components of any infrastructure asset management strategy; these models provide insight on the significant factors that affect infrastructure condition states and expected behavior of infrastructure assets under different conditions. The objectives of this study are to provide a review of previous studies on factors that affect culvert performance and durability and those on culvert asset management, to present current practices of transportation agencies with regard to management of culverts, and, last, to present development of a preliminary deterioration model that will allow decision makers to identify significant factors that affect deterioration of metal culverts and prioritize inspection procedures. The preliminary deterioration model presented in this study is developed by employing binary logistic regression with a forward stepwise variable selection method on data obtained from the Ohio Department of Transportation.

Roadway infrastructure in the United States expanded at a remarkable rate in the 20th century. Today, drainage infrastructure systems (culverts, storm sewers, outfalls, and related drainage elements) represent an important portion of the assets of state departments of transportation (DOTs)—assets that require routine inspection, maintenance, and timely repair and renewal. Any failure associated with these systems may present challenges for DOTs because of costly emergency replacement projects or potentially high indirect costs associated with the lost time and economic burdens faced by highway users.

Traditionally, preservation of the visible infrastructure elements, such as pavements and bridges, has been a higher priority for transportation agencies and researchers in comparison with the buried drainage infrastructure. Several theories, models, and framework and management plans have been developed to track, inspect, maintain, and repair the surface infrastructure. However, the invisible critical components such as culverts have been neglected (*1*). In most cases, the location and condition of these highway elements are noticed when a major problem occurs that affects the visible elements, such as settlement or complete failure of a roadway. However, deterioration of culverts and other drainage components is an emerging problem for transportation agencies. Variations in structural characteristics (e.g., material type, shape, and dimensions), wide geospatial distribution and variations in environmental exposure, and increasing budget restrictions further complicate effective management of these assets. Therefore, drainage infrastructure systems need special attention in terms of development and application of proactive and preventive asset management strategies.

One of the most important steps in establishing any infrastructure asset management strategy is development of deterioration models that will assist in describing the expected behavior of infrastructure assets. By analyzing available databases, transportation agency officials should be able to identify critical infrastructure assets and take necessary actions in a timely manner to repair, rehabilitate, or replace these assets before failure occurs.

The objectives of this study are to provide a review of previous studies on factors that affect culvert performance and durability and on culvert asset management, to present current practices of transportation agencies with regard to management of culverts, and last, to develop a preliminary deterioration model that will allow decision makers to identify significant factors that affect deterioration of metal culverts and prioritize inspection procedures. In order to accomplish the last objective, inventory and inspection data sets for galvanized and unprotected circular metal culverts were obtained from District 4 of the Ohio Department of Transportation (DOT). Binary logistic regression with a forward stepwise selection method was employed to identify significant variables. The resultant model is expected to assist agency officials in prioritizing inspection procedures for circular metal culverts.

FACTORS AFFECTING CULVERTS

Factors affecting culvert performance and durability have been studied by several researchers. In these studies, various types of culverts were examined under different environmental conditions. Previous studies provide important insight in terms of understanding the behavior of culverts. In this section, results of some of the studies are presented that focus on the factors that affect the two dominant culvert types, namely, metal (steel) and concrete culverts.

Metal Culverts

Metal has been the preferred material for a large number of culvert applications as a result of the wide selection range in terms of shape and size and flexibility associated with their design procedures.

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Some of the advantages and disadvantages of corrugated metal culverts are as follows (*2*):

- They are relatively easy to ship because of their light weight.
- They come in a large variety of shapes and sizes.
- The thickness of the sheets and also the corrugations can be selected from a wide range in order to obtain the required strength.
- Installation and assembly of metal culverts are relatively easy compared with heavier material types.
- Corrugation roughness decreases the rate of flow unless the culvert has a smooth interior.
- Presence of sand, rocks, or both, in a high-velocity stream may cause loss of pipe material as a result of abrasion.
- Sensitivity to soil or water pH or soil and water resistivity makes them susceptible to corrosion.
- Backfill operations must be handled with care because of the importance of soil support for load-bearing purposes.

Bednar indicated that the most important factors affecting durability of galvanized steel pipes are water pH, dissolved solids present in the flow, hardness and alkalinity of the flow, water velocity, temperature, and time of water contact (*3*). Also in this study, water-side corrosion was stated to be more aggressive than soil-side corrosion.

According to the statistical analysis conducted by Meacham et al., the age of the culvert, which was defined as the length of time (in years) until the metal itself is exposed to the flow, is the most significant factor that affects metal loss (*4*). Other significant parameters were the pH of water and abrasion. The acidity of the flow was shown to have a negative impact on culvert condition. Abrasion was found to be detrimental for flows with high pH. It was also indicated that pipe slope had a small but significant impact on metal loss for corrugated metal pipes.

Mitchell et al. determined that the maximum service life of metal culverts is 60 to 65 years and they showed that the type of the culvert (corrugated metal pipe versus structural steel plate), pH of the flow, abrasiveness, flow velocity, age, and rise are significant parameters that affect the culvert rating (*5*). Perforations at the invert and the flow line, scour at the inlet and outlet, and concrete headwall movement were the most frequently encountered problems in this study. The invert region was found to be more sensitive to material deterioration compared with other regions. However, crown corrosion due to the seepage of groundwater that contains road salts can also be observed for some metal culverts (*6*).

Degler et al. inspected structural plate corrugated metal pipe structures that feature the pipe-arch configuration (*7*). The durability of the corrugated metal structures was determined to be affected by the age of the structure and the presence of highly abrasive streams with low pH values located in the southeastern portions of Ohio. The most frequently encountered modes of failure were found to be corrosion and pitting of the multiplate structure and seepage and corrosion of the bolted joints.

Apart from abrasion and corrosion, corrugated metal pipes may also be affected by backfill operations. Improper choice of backfill material, presence of groundwater, level of compaction, and the type of compaction equipment used may have significant effects on the structural performance of corrugated metal pipes. Sehn and Duncan investigated the causes of excessive deformations that led to the replacement of a newly installed corrugated metal culvert (*8*). In this study, silty soil was found to be significantly affected by the vibratory loading during compaction of the backfill. The strains were determined to be much higher because of vibratory loading.

Concrete Culverts

Being more rigid compared with metal and steel culverts, concrete culverts are generally more resistant to backfill loading, corrosion, and abrasion. The advantages of concrete culverts are as follows (*2*):

- There is a wide range of sizes and shapes.
- The thickness and strength of the concrete and the amount and configuration of the reinforcement also vary in a wide range; thus the design can be customized appropriately for a specific site.
- They exhibit resistance to corrosion and abrasion in normal installations.
- The flow faces less resistance in comparison with that in corrugated pipes because of the presence of a smoother interior surface.
- Rigidity makes these culverts better in resisting loads during compaction.

The disadvantages of concrete culverts are as follows:

- They are heavier in weight compared with metals, which may result in higher shipping costs.
- Installation or casting may be more difficult and time-consuming compared with that for metals.

According to Bealey, service conditions that feature the presence of abrasion and erosion, sulfate soils, chlorides and acids, and freeze–thaw are the most important factors that affect the durability of concrete culverts, whereas for precast concrete culverts acid attack constitutes the only potentially significant harmful impact (*9*).

According to Meacham et al., concrete culverts exhibit different behaviors with respect to different pH levels of the water (*4*). For flows with a pH value that is equal to or larger than 7, the age of the culvert was determined to be a significant variable along with slope, flow velocity, and abrasion, which had significant but minor effects on the culvert rating. For flows with a pH value less than 7 (acidic flow), pH was determined to be the factor with the highest significant effect. As the acidity increased (lower pH values), the concrete rating was found to decrease. For concrete culverts that convey flows with pH levels lower than 4.5, application of protection was suggested. Other significant variables were determined to be pipe slope, sediment depth (positive), and age (negative).

Mitchell et al. determined the service life for concrete culverts as 70 to 80 years (*5*). Age, pH, and abrasiveness were found to be the significant factors that had an impact on the culvert rating. Headwall deterioration, deterioration in the crown region of the top slab and inlet end and transverse shear cracks on abutment walls were the most common problems encountered during the inspection of concrete culverts.

Hurd investigated the performance of 133 precast reinforced-concrete box culverts in Ohio (*10*). According to the results, all of the culvert inverts were in excellent condition; however, nine exhibited deterioration on the top slab of the end sections. This type of deterioration was estimated to be caused in part by the exposure of these sections to roadway deicing salts. It was suggested that to protect these sections, a surface sealer should be placed on the exterior side of the top slabs for culverts that are located at a depth of less than 3 ft (0.914 m).

Soil conditions adjacent to the concrete pipes can trigger structural problems. Heger and Selig conducted two case studies in which severe distresses were observed during the installation of two rigid pipes (*11*). According to this study, the presence of soft soil adjacent to pipes under high fills can cause increased earth loads on these structures. It was suggested that soft soils should be removed from each side of the culvert for a distance of at least one diameter.

CULVERT ASSET MANAGEMENT

A majority of transportation authorities have effective management systems for visible transportation assets such as bridges and pavements. Culverts, however, are generally neglected, with an "out of sight, out of mind" philosophy (*1*). According to a survey that was conducted for NCHRP, 27 of 37 DOTs did not have guidelines for pipe assessment, 34 of 36 DOTs did not have guidelines for repair methods, 35 of 36 DOTs did not have guidelines for rehabilitation methods, and only 19% of the overall respondents were reported as using the pipe assessment data in their management systems (*12*).

In another survey Mitchell et al. reported that 24 DOTs of 40 had an inspection policy for highway culverts, whereas 30 DOTs of 40 did not have a culvert inspection manual and only 23 of 40 DOTs were using a computer database for the highway culverts in their state (*5*). In a survey conducted by Markow, it was determined that from the responses collected from a total of 30 agencies, more than 80% immediately corrected suddenly failed culverts, whereas only 20% had a preventive scheduled maintenance approach (*13*).

These three recent surveys demonstrate that there is a lack of nationwide recognition regarding the importance of culvert management procedures. DOTs are generally reactive rather than proactive, which most of the time results in significant impacts on society, the agency, and the environment.

In one of the earliest studies, Kurt and McNichol developed a computer program to rank culverts (*14*). Four ranking formulas were generated that established the link between the culvert parameters and user and agency costs with respect to load capacity, hydraulic capacity, width deficiency, and maintenance of the culvert. Some of the parameters used in this study were posted weight (in tons), average daily traffic, relative width (in feet), detour length, flood detour length, flood days per year, average cost per day per flood, and maintenance costs per year. Posted weight, flood days per year, average cost per day per flood, and yearly maintenance costs were based on assumptions.

FHWA developed the culvert management system (CMS) software in 2001 (*15*). The CMS was designed to help transportation agencies inventory and monitor their culvert assets. Five modules were developed: inventory, condition, work needs, work funding, and schedule. The CMS essentially allows transportation agencies to store the information needed to manage their culverts in a systematic way; however, it is limited in terms of providing assistance to the user for prioritizing the culverts and assigning the required treatment methods. The software program requires the user to enter the type of maintenance or renewal to be performed for each culvert and ranks these treatments by priority on the basis of the factors assigned by the user. According to the results of a survey published in 2002, none of the responding agencies indicated that they used this software program (*12*). However, a more recent study published by FHWA in 2007 indicated that the Shelby County Highway Department in Alabama incorporated FHWA's CMS software in their culvert asset management procedures (*16*).

Cahoon et al. investigated the significant factors that affect the overall condition ratings and the decision-making process for repair or replacement of 460 culverts located in 11 regions of Montana (*17*). In this study, the authors generated a condition rating form that included 33 parameters and a general overall rating. An ordered probit model was employed to analyze the collected data and a *t*-test was employed to identify the significant factors. According to the results, the following nine factors were determined to be significant in estimating the overall condition rating: age, scour at outlet, evidence of major failure, degree of corrosion, worn-away invert, sedimentation, physical blockage, joint separation, and physical damage.

In a study conducted for the Utah DOT, an inventory and inspection software program, Utah Culvert Database, was developed (*18*). The inspection procedure was divided into two main components: waterway (hydraulic) and barrel (structural) performance. A condition rating within a range of 0 to 9 was selected for each component. The lesser of the two components was multiplied by an "importance modifier," and the resultant value was used to assign the culvert into one of three zones: no further action required other than placing a note in the inspection report, notify superiors regarding the condition of the culvert, and notify superiors as soon as possible both verbally and in a written format. The importance modifier was designed to reduce or increase the condition rating score depending on the roadway class, culvert drain type (main, edge, lateral, or slope), and culvert span.

Meegoda et al. (*19*) presented a classification method generated in a previous study (*20*) that features a scale of 1 to 4 to describe the condition states of corrugated steel culvert pipes in New Jersey with respect to the severity of corrosion. The authors provided recommendations regarding selection of appropriate rehabilitation and replacement methods by considering the condition state, size, and length of the culvert. Meegoda et al. generated three survival probability curves to portray the deterioration of corrugated steel culverts with condition states of 1, 2, and 3 respectively (*20*). Meegoda et al. used these curves to estimate the remaining service life for culverts in Condition State 1, 2, or 3, which was defined as the number of years left until a survival probability of 0.35 is reached (*19*). As a decision rule, it was proposed to compare the combined cost of repair, rehabilitation, or replacement and current value of a culvert with the value of the culvert after the selected action was performed. Survival probability curves were also used to estimate the probability of failure for culverts with known age values but unknown condition states. The decision rule for this case suggested comparing cost of failure with the cost of repair or rehabilitation. Recently, Meegoda et al. developed a culvert information management system, which includes a reliability analysis component and a financial optimization component (*21*). In this study, the authors used a scale of 1 to 5 to describe condition states of corrugated steel culverts. The reliability analysis employed a Weibull distribution to model the survival probability.

Masada et al. (*22*) performed field inspections at 25 metal culvert sites based on the procedures provided in the Ohio DOT's 2003 *Culvert Management Manual* (*23*) and also based on a second set of rules that were proposed by the researchers. According to the results, the Ohio DOT's inspection procedures were found to be sound. A risk assessment method was also generated on the basis of the ratio of soil cover to culvert rise. It was proposed to lower the overall culvert rating by 15% if the ratio of height of cover to rise was below 2.5 and to lower the overall culvert rating by 10% if the ratio of height of cover to rise was larger than 2.5 but less than 5.

FHWA published a case study that described the efforts of three state agencies (Maryland State Highway Administration, Minnesota DOT, and Alabama DOT) and a local agency (Shelby County Highway Department, in Alabama) with regard to implementation of culvert management systems (*16*). This study highlighted the risk-based management approach followed by the Maryland State Highway Administration, use of Pontis and HYDINFRA by the Minnesota DOT, and implementation of FHWA's CMS program and a prioritization module by the Shelby County Highway Department.

Gharaibeh et al. developed an asset management framework based on a geographic information system for stormwater drainage structures of El Paso, Texas (*24*). The framework consisted of three modules: inventory, documents, and condition assessment. The inventory module was developed to store various structural attributes and geographical information associated with drainage structures. The documents module was developed to store electronic design files, as-built records, reports, and other important documents. The condition assessment module was developed to store inspection photographs, information regarding structural condition state, and hydraulic analysis of each drainage element. The culvert condition rating system developed in this study featured a scale of 1 to 5 for evaluation of various items such as alignment and shape of the culvert; condition of the pavement, headwalls, wing walls, upstream and downstream channel protection; and so forth. Hydraulic analysis was performed by using the HY-8 software program developed by FHWA. Thus, the geographic information system–based asset management framework developed in this study allowed engineers to examine the hydraulic capacity of drainage structures along with the structural condition ratings.

CURRENT CULVERT ASSET MANAGEMENT

A survey of transportation agencies was conducted with the objective of understanding the current development and implementation of culvert asset management practices in the United States and Canada. Transportation agencies in all 50 states and 10 provinces were contacted to select the respondents on the basis of their positions in the agency, experience, and work area. An invitation along with an electronic format of the survey was sent to all the participants. The responses were stored and monitored on a server. Detailed information regarding the questionnaire survey and the responses can be found in the report by Najafi et al. (*25*).

Responses were examined on the basis of the extent of information supplied, and responses that provided little to no information were not considered. The resultant data set consisted of 26 responses. One of the state agencies submitted a separate response for culverts that have an opening of less than 36 ft^2 and one for other culverts. These two responses are considered as originating from different respondents. Some of the outcomes of the survey are as follows:

- Approximately 42% of the respondents (11 of 26) indicated that they did not have a standard set of inventory guidelines for culverts. Four of these respondents indicated that they were in the development phase of generating an inventory guideline.
- Approximately 62% of the respondents (16 of 26) indicated that they had a standard set of inspection guidelines for culverts. Two participants did not provide a response for this question, whereas seven respondents (approximately 27%) indicated that they did not have a standard set of inspection guidelines and one respondent indicated that the DOT was in the development phase of generating inspection guidelines.
- Approximately 42% of the respondents (11 of 26) indicated that they had a computer database for culverts. Five participants did not provide a response for this question, whereas six respondents (approximately 23%) indicated that they did not have a computer database for culverts and four respondents indicated that they were in the development phase of generating a computer database.
- Approximately 8% of the respondents (2 of 26) indicated that they had a model or formula to predict the remaining service life of culverts. Three participants did not provide a response for this question, whereas 18 respondents (approximately 69%) indicated that they did not have a model or formula to predict the remaining service life of culverts and three respondents indicated that they were in the development phase of generating such a model.
- Approximately 12% of the respondents (3 of 26) indicated that they had a decision support system for selection of a repair or renewal method for culverts. Four participants did not provide a response for this question, whereas 18 respondents (approximately 69%) indicated that they did not have a decision support system for selection of a repair or renewal method for culverts and one respondent indicated that the DOT was in the development phase of generating a decision support system.
- When the participants were asked about the most commonly inspected items for metal and concrete culverts, 19 participants of 26 provided a response. The most commonly inspected areas for metal culverts were corrosion (all 19 participants), deflection (all 19 respondents), and joint failures (18 of 19 respondents). The most commonly inspected areas for concrete culverts were cracking (all 19 respondents), joint failures (18 of 19 respondents), hydraulic capacity (15 of 19 respondents), and corrosion (15 of 19 respondents).
- When the participants were asked about the important factors that affected decision-making procedures regarding whether a culvert needed to be renewed, 24 participants of 26 provided a response. The factors listed were presence of structural problems (23 of 24 respondents), presence of hydraulic problems (21 of 24 respondents), and material degradation (18 of 24 respondents). Inspection results were considered by 15 of 24 respondents and age of the culvert was considered by 10 respondents of 24 as a part of decision-making procedures.
- When the participants were asked about the most commonly used repair methods, 24 participants of 26 provided a response. Most commonly used repair methods included point repairs (9 of 24 respondents) and grouting (8 of 24 respondents).
- When the participants were asked about the most commonly used renewal method, 24 participants of 26 provided a response. The most commonly used renewal method from cured-in-place pipe, slip-lining, and pipe bursting was slip-lining (10 of 24 respondents). Cured-in-place pipe was used by 3 of 24 respondents.

PRELIMINARY DETERIORATION MODEL FOR CIRCULAR METAL CULVERTS

From the results of the survey and literature review, it is evident that transportation agencies are in need of deterioration models that make the best use of the available data in order to prioritize culvert inspection, repair, or both. However, lack of well-defined and standardized inventory and inspection guidelines and recording procedures limits the accuracy and power of deterioration models. In this section binary logistic regression is used in the development of a deterioration model that can predict the probability that a circular metal culvert will reach a condition state that will require repair.

Binary Logistic Regression

Binary logistic regression is a statistical method that can be used to investigate the relationship between a set of independent variables and a dichotomous dependent variable. The general form of the binary logistic regression is as follows (*26*):

$$\log\left(\frac{P\left(Y=1\middle|X_1, X_2, \ldots, X_p\right)}{1-P\left(Y=1\middle|X_1, X_2, \ldots, X_p\right)}\right)=\alpha+\beta_1 X_1+\beta_2 X_2+\cdots+\beta_p X_p \qquad (1)$$

where

Y = dichotomous dependent variable,
$X_1, \ldots, X_p$ = independent variables,
α = intercept term, and
$\beta_1, \ldots, \beta_p$ = logistic regression coefficients.

The values of the intercept term and the regression coefficient for each independent variable are estimated by the maximum likelihood estimation method.

Application of binary logistic regression in infrastructure deterioration modeling requires recoding the condition states into a binary scale. The grouping is made on the basis of the actual meaning of the condition states. As an example, if for a researcher the point of interest is the failure of a particular infrastructure type, the grouping may be made such that highly deteriorated condition states indicate the failure and the remaining states indicate the nonfailure mode. In this study the point of interest was to determine the probability that a metal culvert needs repair.

Development of Model and Results

The preliminary deterioration model for metal culverts was developed on the basis of the information obtained from the Ohio DOT, District 4. The data set on which binary logistic regression was applied contained a total of 99 records. The independent variables used in this study are the following:

- Age (years). Time difference between installation of the pipe and inspection;
- Span (inches). Diameter of the culvert pipe;
- Slope (%). Vertical displacement of the pipe section per horizontal displacement; and
- Protection type. Galvanized or unprotected.

The dependent variable to be studied was determined on the basis of the item "general" in the Ohio DOT's *Culvert Management Manual* (*23*) since this inspection item is considered to be the one that most closely reflects the structural deterioration of the culvert. The manual requires inspectors to rate the condition of the culvert within a range of 9 (best) to 0 (worst). Detailed descriptions of each rating can be found in the Ohio DOT *Culvert Management Manual* (*23*). In this study, culverts with a rating of 6 or worse were considered to be in need of repair; hence, these culverts were grouped and assigned a value of 1 for the dependent variable. The remaining culverts were assigned a value of 0.

In order to determine the significant variables, the forward stepwise variable selection method with a likelihood-ratio removal criterion was employed. Details of the variable selection algorithm can be found elsewhere (*27*). In this method, first the most significant variable is identified and evaluated for incorporation into the model. If this particular variable satisfies the significance level requirement (0.05 in this study), the variable is entered into the model. In the second step, the model developed in Step 1 is used as the base model and significance values of each of the remaining variables for entry are determined. The most significant variable is evaluated for incorporation into the model developed in Step 1. If the variable satisfies the significance level requirement, the variable is added into the model. Before the next step, variables entered into the regression equation are evaluated for their significance levels by using the likelihood ratio test. If all variables are significant at the specified significance level (0.10 in this study) based on the likelihood ratio test, the next step starts. If the significance value for a variable exceeds the predetermined significance level, the term is removed from the equation and the regression model is reevaluated to determine if any additional terms should be removed from the model. The algorithm continues until eliminations result in a previously evaluated model or none of the variables meet entry or removal criteria (*27*).

TABLE 1 Binary Logistic Regression Output

Variable	Coefficient	Significance	exp (Coefficient)	95% CI for exp (β_1) and exp (β_2)
Intercept	$-2.040 = \alpha$	.05	0.130	NA
Age	$0.083 = \beta_1$	.001	1.087	(1.034, 1.141)
Span	$-0.022 = \beta_2$	.013	0.978	(0.961, 0.995)

NOTE: NA = not available; CI = confidence interval; exp = exponent.

Table 1 summarizes the output of the binary logistic regression analysis. According to the analysis, slope and protection type were not significant after age and span were entered into the regression equation. According to the values provided in Table 1, a unit increase in age results in an 8.7% increase in the odds (the ratio of probability of occurrence of an event to the probability of nonoccurrence of an event) that a culvert will require repairing and a unit increase in span results in a 2.2% decrease in the odds that a culvert will require repairing.

Traditionally, span value has been used to identify critical culvert pipes with higher consequences of failure. However, from the findings of this study it can be concluded that the span of a culvert pipe also has an impact on its deterioration profile. It can be speculated that the reason for a large culvert pipe to have a lower probability of having a condition state that requires repairing in comparison with a smaller culvert pipe that has the same age can be due to the potentially higher quality standards followed during construction of larger culvert pipes. It can also be speculated that smaller culverts may have less contingency to increases in flows and are more vulnerable to the changes in the landscape profile in their close proximity. Inadequate hydraulic capacity in these cases may lead to flooding and eventually to loss of soil support around the culvert pipe.

The overall percentage of correct predictions is 68.7%. The resulting classification is as follows:

Observed Condition State	*Estimated Condition State*		*Percent Correct*
	0	*1*	
0	19	21	47.5
1	10	49	83.1

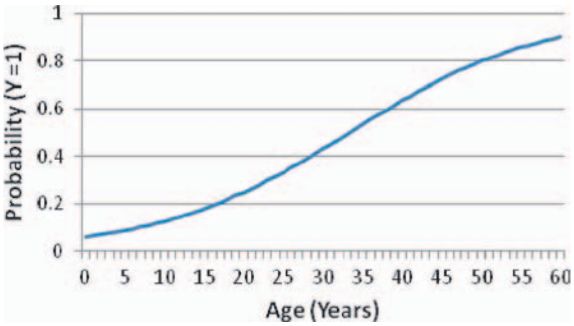

FIGURE 1 Probability curve for 32-in. metal culvert.

Probability curves that represent the probability of a culvert pipe to require repairing with respect to time can be generated by using the following equation:

$$P(Y=1)=\frac{\exp(-2.040+0.083\times \text{age}-0.022\times \text{span})}{[1+\exp(-2.040+0.083\times \text{age}-0.022\times \text{span})]} \quad (2)$$

Figure 1 is provided as an example to demonstrate the shape of the probability curve for a circular metal culvert pipe that has a span of 32 in. According to Figure 1, for a circular metal culvert with a span of 32 in., the probability of having a condition state that requires repair becomes higher than the probability of having a condition state that does not require repairing once it reaches 34 years of age.

CONCLUSIONS

Since the majority of culverts and drainage infrastructure systems in the United States either have aged beyond their design lives or are approaching the end of their design lives, it is anticipated that development of effective culvert asset management practices will be one of the significant components of transportation asset management in the near future. From the findings of this study, it can be concluded that there is a lack of nationwide recognition regarding the importance of culvert management procedures. Large numbers of culverts and wide variations associated with their structural properties and environmental operating conditions cause major complications in effective management of these important roadway structures. In order to make well-informed decisions regarding inspection and repair of culverts, agencies need to develop systematic inventory and inspection procedures and enforce the execution of data collection activities based on these procedures. Lack of well-defined and standardized inventory and inspection guidelines and recording procedures limits the accuracy and power of data analysis. Even though the condition states of culverts are generally reported in ordinal scales, given the limitations associated with the available data sets, this study demonstrated that binary logistic regression may provide a suitable solution for deterioration modeling purposes until more comprehensive data sets are created.

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