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DEVELOPING A CULVERT INSPECTION MANUAL AND ESTIMATING CULVERTS' DETERIORATION CURVE, INSPECTION FREQUENCY AND SERVICE LIFE FOR UDOT

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DISCLAIMER

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16. Abstract

Culverts are among the most important assets of state transportation departments. As culvert inspection and maintenance are critical to the safe operation of transportation infrastructure systems and preventing injuries, human life losses, and heavy financial losses, they should be inspected and maintained regularly. Several state DOTs and the American Association of State Highway and Transportation Officials (AASHTO) have published culvert inspection and asset management manuals, which vary widely between states. Despite the effectiveness of these guidelines and manuals, different states consider different qualitative and quantitative parameters, which means that they are specific to each state and may not apply to Utah's culverts. To this end, the purpose of this research is to help UDOT develop a comprehensive system of culvert management by producing a Utah culvert management manual. The research's objectives are threefold: (1) develop a comprehensive inspection and asset management manual for culverts in Utah based on specific characteristics, (2) estimate the deterioration curves for UDOT culverts, and (3) predict the frequency and service life of UDOT culverts.

Based on culvert inventories from Colorado, Utah, and Vermont, the final curves were generated using Support Vector Regression (SVR) and Random Forest Regression (RFR) algorithms. Estimating the final deterioration curve for culverts in Utah can be done using the combination of the inventories. After determining the likelihood of failure based on Utah's final culvert deterioration curve, a risk-based prioritization approach was used to determine the frequency of culvert inspections. The final stages of research included generating the final deterioration curve based on the three culvert inventories for Utah's culverts, as well as developing a culvert management manual. In developing the Culvert/Storm Drain Management Manual for Utah, the contents of other states' manuals and federal guidelines for culvert inspection and maintenance were combined and modified for Utah.

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ANN	Artificial Neural Network
CMS	Culvert Management Systems
COF	Consequence of Failure
DOT	Department of Transportation
FEMA	Federal Emergency Management Agency
LOF	Likelihood of Failure
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NCSS	National Cooperative Soil Survey
PACP	Pipeline Assessment and Certification Program
RFR	Random Forest Regression
SSD	Single Shot Detector
SVR	Support Vector Regression
SVM	Support Vector Machine
UDOT	Utah Department of Transportation
WSS	Web Soil Survey

EXECUTIVE SUMMARY

Traditionally, various theories, models, and management systems for inspecting, maintaining, and repairing surface infrastructures, such as bridges and pavements, have been developed. However, critical components that are not visible, such as culverts, have been overlooked despite the fact that their failure has a significant impact on transportation systems. To overcome this issue, many state departments of transportation, including the Utah Department of Transportation (UDOT), plan to develop a customized comprehensive culvert management system (CMS), including a culvert management manual, for their state.

In this regard, UDOT intends to classify culverts as a highly important asset, a tier 1 asset, due to the high number of culverts in Utah and the potential for roadway disruptions and property damage that could result from poorly maintained culverts. Consequently, this research aims to help UDOT in developing a comprehensive CMS by producing the Utah culvert management manual. To achieve this objective, the authors identify the culvert deterioration curves based on the historical data of three states in the US (Utah, Colorado, and Vermont) and then employ them to estimate the culverts' inspection frequency and service life. Machine learning algorithms, including Support Vector Regression (SVR) and Random Forest Regression (RFR), and the risk-based prioritizing approach, were used in the proposed method for determining culvert deterioration curves and inspection frequency, respectively. The proposed solution is supposed to be integrated into the ATOM software, which combines asset and maintenance management for UDOT.

With an accuracy of 71% and 79% for SVR and RFR, the developed models performed well in predicting culvert conditions. The proposed method was tested by scheduling the inspection of 272 culverts in Utah. Based on the results, UDOT could focus on inspecting and maintaining 10% of the culverts instead of inspecting all 272. Following the development of the data-driven approach for scheduling culvert inspections, a draft manual for managing culverts in Utah was developed in the last part of the study. Several culvert inspection and maintenance manuals from other states have been reviewed for the purpose of developing Utah's culvert/storm drain management manual. For the first draft of the manual, we combined the contents of other states' manuals with Utah's rating system for culverts and the data-driven approach. UDOT's maintenance division can enhance and finalize this draft of the manual for use across the state.

INTRODUCTION

1.1 Introduction

Culverts are hydraulic passages built of various materials, either perpendicular or parallel to roads, that connect upstream and downstream areas beneath an embankment while bearing both earth and traffic loads. According to the Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance (FHWA, 2017), the bridge inventory in the United States contains 118,394 culverts. However, the actual number of culverts in the U.S. is much higher than 118,394 since only culverts with a structural width of 20 feet or more are tracked by the National Bridge Inventory (NBI) (Yang, 2011).

Across the United States, culverts play a vital role in the transportation and water management systems. The failure of these assets can have devastating effects on the environment and cause road closures that may lead to traffic delays for travelers (Stoner et al., 2019). In 2015, South Carolina experienced a 1000-year rainfall event, causing major damage to infrastructures, including culverts. Failure of culverts in Richland and Lexington Counties resulted in at least 15 extended road closures (Gassman et al., 2017). Many culverts in the U.S. have deteriorated and are close to the end of their design life. The loss of structural integrity of a culvert can adversely affect the road surface above it by causing surface depression, extensive cracking, or even collapse in extreme cases as can be seen in Figure 1. There are multiple failure mechanisms for these culverts, as shown in Figure 2, and the status of a culvert can be determined by a variety of criteria and parameters, including physical and environmental features. Estimating the deterioration rate of culvert structures to predict their future conditions and increase the service life of these assets is essential (Stoner et al., 2019). Hence, generating deterioration models is critical because they prevent the negative consequences of culvert failure.

The development of deterioration models is one of the essential steps in developing any infrastructure asset management strategy. It can assist in characterizing the expected behavior of infrastructure assets and reveal factors influencing infrastructure condition states. Analyzing available culvert datasets (i.e., inspection datasets) helps transportation agency officials to develop deterioration models for culverts, estimate the inspection frequencies, and identify critical culverts to repair, rehabilitate, or replace quickly before their failure (Salem et al., 2012). Delaying or eliminating proper maintenance is predicted to have a negative impact on the condition and performance of the assets, resulting in a lower level of service, early deterioration, and eventually the need for costly rehabilitation or replacement. Thus, culverts, as critical infrastructures in the transportation system, should have a management plan in each transportation agency, and the first step is to develop culvert deterioration models.

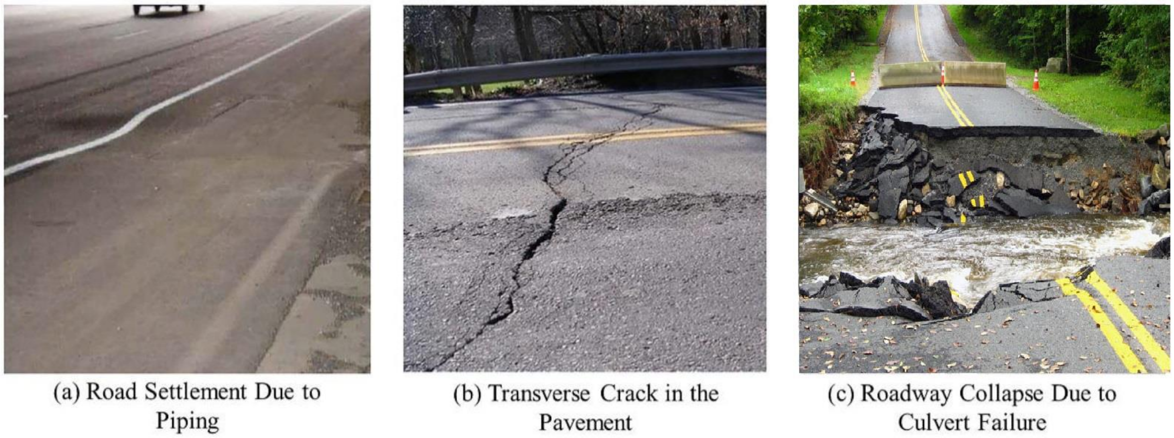


Figure 1- Three examples of culvert failure consequences (Piratla et al., 2019)


(a) Corrosion of Invert (b) Invert Abrasion (c) Joint Separation
(d) Vertical Crack in Culvert Barrel (e) Joint Infiltration (f) Spalling in Concrete Culvert
(g) Wall Damage in Plastic Culverts (h) Piping Beneath a Culvert (i) Outlet Scour

Figure 2- Common culvert defects (Piratla et al., 2019)

1.2 Problem Statement

In the United States, infrastructure systems are in desperate need of maintenance and rehabilitation. With various bonds and public funds, more than a trillion dollars are invested in the nation's mostly aging infrastructure. A large portion of the budget is used to construct new infrastructure or replace old infrastructure. Thus, investing a significant portion of these investments into proactive infrastructure maintenance, rather than waiting and being forced to respond to disruptive events, would be cost-effective in the long term (Meegoda & Zou, 2015). When it comes to a vital civil infrastructure system like culverts, the importance of proactive maintenance management becomes even more pronounced. The significance of proactive maintenance arises from the fact that a component failure in such complex systems typically causes disruptions that can have cascading effects. Those effects result in many inconveniences and major economic effects, which require a huge expenditure to cover the damages caused by such premature failures. For example, according to ePM/OMS reports, the Utah Department of Transportation's (UDOT's) average annual funding for fixing culverts from 2016 through 2020 was $3,902,403. Departments of transportation (DOTs) are typically reactive rather than proactive, which has severe consequences for society, the agency, and the environment.

UDOT has more than 47,000 culverts in its inventory. UDOT is responsible for maintaining these culverts, but there is no comprehensive Culvert Management System (CMS) to monitor their status and plan maintenance activities. There is a risk that poorly maintained culverts will disrupt roadways and damage property, so the objective of the CMS should be a systematic approach for assessing culvert conditions and performing necessary maintenance (Beaver & McGrath, 2005). Unfortunately, UDOT and most state DOTs lack a comprehensive CMS.

Several state DOTs, as well as the American Association of State Highway and Transportation Officials (AASHTO), have published culvert inspection and asset management manuals. However, methods of assessing culvert conditions differ greatly from state to state since different states take various quantitative and qualitative factors into account, such as pipe material/shape/coating, drain type, installation year, and highway importance. Manuals outlining these methods are unique to each state and may not consider Utah culverts' specific environmental and soil conditions.

In summary, UDOT plans to develop a comprehensive CMS to maintain culverts systematically. Regular inspection and maintenance of culverts are very important for the safe operation of transportation infrastructure systems and the prevention of injuries, deaths, and heavy financial losses. No systematic approach has yet been developed to recommend an effective inspection procedure for Utah culverts. As a result, the first step in developing a comprehensive CMS for Utah is to publish a customized version of the culvert management manual for Utah's culverts. To achieve this goal, this study offered a data-driven approach for determining culvert inspection frequencies. The objectives of this study are generating deterioration curves using available datasets of culverts, risk assessment of culvert failure, estimating culvert inspection frequencies, and finally, developing a draft culvert management manual for Utah. To accomplish these objectives, in the next section, we will review the key factors of culvert condition prediction models as well as culvert inspection manuals in the literature. Next, we will go through the machine learning models and risk-based prioritizing approach that were employed in this study. Then, the data collection procedure will be explained. Finally, we will discuss the deliverables and findings of this study.

1.3 Background

In order to implement a data-driven approach for determining culvert inspection frequency, the deterioration curve of culverts must be determined using available historical data. Culvert deterioration curves can predict culverts' conditions based on their characteristics. This section will discuss the characteristics of various culverts along with numerous studies focusing on predicting the culvert condition.

Typical manufacturing materials for culverts in the U.S. are concrete and metal. There are other materials like plastic and masonry, which are rarely used in some regions. In Utah, 75% of culverts are made of corrugated steel, 25% of them are reinforced concrete, and 5% of them are plastic, according to a UTRAC study conducted by UDOT. Other materials like wood, brick, and rock are also present but limited (McGrath & Beaver, 2004). Therefore, most researchers studied the factors affecting the performance and durability of concrete and metal culverts, and the findings of those studies will be discussed below.

A large number of culverts have been built out of metal due to the variety of shapes and sizes of the material, as well as the flexibility associated with the design procedures (Ring, 1984). According to Bednar (1989), pH of water, dissolved particles in the flow, flow hardness and alkalinity, velocity of water, temperature, and period of water contact are the most important features affecting the durability of galvanized steel pipes. Meacham et al. (1982) indicated that before the metal itself is exposed to the flow, the age of the culvert is the most important factor influencing metal loss. The pH of the water, abrasion, and pipe slope were other important factors. Mitchell et al. (2005) reported that metal culverts have a maximum service life of 60 to 65 years, and significant factors that affect the culvert rating include culvert type (corrugated metal pipe versus structural steel plate), flow pH, abrasiveness, the velocity of flow, age, and pipe diameter. Degler et al. (1988) conducted research on structural plate corrugated metal pipe structures featuring the pipe-arch configuration. They claimed that the durability of the corrugated metal structures depended on the structure age and the presence of highly abrasive streams with low pH values located in the southeastern regions of Ohio. Corrosion and pitting of the multiplate structure, as well as seepage and corrosion of the bolted joints, were discovered to be the most often encountered modes of failure.

Concrete culverts have different characteristics than metal ones. Concrete culverts, for example, are more resistant to corrosion and abrasion, as well as being more rigid than metal and steel culverts, which means they can withstand backfill loads better (Ring, 1984). According to Bealey (1984), the most critical factors affecting the durability of concrete culverts are the presence of abrasion and erosion, sulfate soils, acids and chlorides, and freeze-thaw, whereas acid attack is the only factor with a potentially significant harmful impact on precast concrete culverts. In their study on culvert durability, Meacham et al. (1982) discovered that concrete culverts behave differently depending on the pH of the water. For flows with a pH of 7 or above, the age of the culvert was found to be the most important factor, along with slope, flow velocity, and abrasion, which all had substantial but minor effects on the rating of culvert condition. For acidic flows, pH less than 7, pH value of the flows was found to be the most crucial factor. The rate of concrete culvert condition decreased as the acidity increased (lower pH values). In this regard, the application of protection was recommended for concrete culverts that convey flows with pH values less than 4.5. Other than flow pH, the slope of the pipe, sediment depth (positive effect), and age (negative effect) were also identified as important variables. The service life of concrete culverts was estimated to be 70 to 80 years by Mitchell et al. (2005). The most significant characteristics that influenced the culvert condition rating were determined to be age, pH, and abrasiveness. The most common problems identified during the inspection of concrete culverts were deterioration of headwall, deterioration in the crown region of the top slab and inlet end, and transverse shear cracks on abutment walls. Soil conditions around concrete pipelines might cause structural issues. In two case studies conducted by Heger & Selig (1994), considerable distress was noticed during the installation of two rigid pipes. In this study, they found that the presence of soft soil next to pipes under high fills can increase earth loads on these structures. The suggestion made was to remove soft soil on both sides of the culvert for a distance of at least one diameter.

It is clear from the preceding paragraphs that earlier studies recognized key characteristics of each type of culvert. In addition to them, previous culvert condition prediction models used a wide range of input characteristics based on the prediction model type, the type of culvert, and the desired output variables. In one of the earliest studies, Kurt & McNichol (1991) developed a computer program for ranking culverts. They generated four ranking formulas to create a link between culvert characteristics, user, and agency costs. The following criteria were employed in the study: posted weight, average daily traffic, culvert width, detour length, flood detour length, flood days per year, the daily average cost per flood, and yearly maintenance costs. A study conducted by Cahoon et al. (2002) identified the significant factors affecting the overall condition ratings and the decision-making process for the repair or replacement of 460 culverts located in 11 counties of Montana. An ordered probit model was used to evaluate the data in this study, and a t-test was used to find critical features. According to the results, age, scour at outlet, major failure signs, degree of corrosion, worn-away invert, sedimentation, physical blockage, joint separation, and physical damage were the significant features in determining the overall condition rating. Salem et al. (2012) developed a preliminary deterioration model for metal culverts that will assist decision-makers in identifying major elements that affect metal culvert deterioration and prioritizing inspection operations. The initial deterioration model in this study was developed using binary logistic regression and a forward stepwise variable selection method. The Ohio DOT, district 4 provided the data set, which had a total of 99 records. Age, span, slope, and protection type were used as features during the development of the deterioration model. The latest study by Mohammadi et al. (2023) explored the use of machine learning models to predict culvert conditions. They assessed five multiclass classification algorithms, including Decision Tree, k-Nearest Neighbor, Artificial Neural Network, Random Forest, and Support Vector Machine. A dataset of 2555 culverts was used. Culvert conditions were best predicted by Random Forest, according to their results. Furthermore, results showed that age, soil moisture, and soil pH were the three most significant factors for predicting the condition of culverts.

Following the literature review, it can be concluded that the age factor is almost always important in evaluating deterioration and condition estimation models (Colorado Urrea, 2014; Meegoda & Juliano, 2009; Mohammadi et al., 2023). The size and slope of culverts were two other critical physical factors utilized in most models. Depth of cover over the culvert, culvert protection, and thickness of the culvert were also found to be other important physical characteristics. Along with the physical characteristics of culverts, several environmental characteristics related to the site were considered significant. Environmental characteristics such as stream beds abrasion, pH of water, and characteristics of the water source flow were commonly used. Furthermore, the material type of a culvert has a considerable impact on its behavior (Stoner et al., 2019). Due to the wide variety of deterioration modes and potential quantitative defects or condition states, the combination of these features and their relation with the culvert condition is complex. As a result, the findings of each study were directly tied to the culvert characteristics under consideration, which are entirely dependent on their availability.

One of the prediction models for culvert condition estimation is the deterioration curve, and CMS must determine the deterioration curve of culverts as one of its many responsibilities. Also, it should record culvert data, provide a culvert maintenance manual, allocate resources and funds for culvert management, and schedule culvert inspections. Scheduling culvert inspections may seem straightforward, but in the CMS, it is actually of great importance, as most culvert repair and maintenance are dependent on this process. In other words, repairs and maintenance will not be carried out unless the inspector reports a damaged culvert. As a result, culvert inspection requires a combination of skills and experience, as well as a thorough understanding of the types of materials plus the design and installation criteria (Noll & Frascella, 2010). Consequently, only properly trained personnel can conduct culvert inspections onsite. Moreover, full culvert inspections require significant resources due to the large number of culverts currently used in roadway systems. In this regard, several state DOTs have developed guidelines to suggest how frequently culverts should be inspected so that the task of inspecting culverts can be accomplished efficiently (Richie & Beaver, 2017).

The culvert inspection policies used by different state transportation agencies depend on the DOTs own criteria, according to the National Cooperative Highway Research Program (NCHRP) survey (Thompson et al., 2012). Ohio DOT employed a 3-tiered inspection system that was based on culvert condition and culvert span (OhioDOT, 2021). The New York State DOT similarly utilized a tiered approach based on the condition rating of culverts (NYSDOT, 2006). Culverts with spans of more than 10 ft were inspected every 12 to 24 months by the Minnesota DOT, and inspection intervals of more than two years were not permitted (FHWA, 2007). Indiana DOT inspected culverts with a span of less than 48 inches every 4 or 5 years regardless of their condition (Bowers et al., 2014). Maryland DOT’s Bridge Inspection and Remedial Engineering Division (BIRED) inspected culverts every four years; however, this frequency could be increased to two years if the condition justified the increase (FHWA, 2007). As the first draft of the culvert inspection policy, UDOT recommended inspecting a new culvert every ten years, a good culvert every five years, a fair culvert every three years, and a poor culvert every year. These suggested policies for culvert inspection frequencies were fixed for various scenarios or conditions and were not data driven, which means they could not reflect reality. Furthermore, they were mainly based on expert judgments, and some of them just consider culvert condition, which was fine but insufficient.

Recently, DOTs have found that planning culvert inspections solely based on culvert span and condition is not an effective approach, which is why researchers recently developed decision support systems for culvert inspection planning. A decision support system was developed for New Jersey DOT by Meegoda et al. (2017) for assessing drainage infrastructures, estimating maintenance costs, and allocating budget funds for infrastructure. The Integrated Drainage Information, Analysis and Management System (DIAMS) consists of four main modules: uploading data, identifying assets, administrating the system, and providing financial information. Pipes, inlet/outlet structures, outfalls, and manufactured treatment devices were the four distinct asset categories that were examined by the DIAMS. After analyzing collected data and comparing risks of failure with costs of maintenance, DIAMS offered four options for project-level and network-level decisions: inspect, rehab, replace, or do nothing. Piratla et al. (2019) presented an approach for prioritizing culvert maintenance based on failure risk for reinforced concrete pipes and corrugated metal pipes in South Carolina. The weighting of the barrel inspection criteria specified in the SCDOT culvert inspection manual was obtained using an analytical hierarchy process (AHP). As a part of the AHP method, state DOTs were emailed a survey to get the opinions of experts on pair-wise comparisons of seven condition assessment factors of culvert barrels. The seven factors were crack, joint in/exfiltration, bedding voids, corrosion, joint misalignment, and shape deformation. Also, Sousa et al. (2021) developed a framework based on qualitative risk analysis for prioritizing culverts that needed intervention. They calculated a single global risk index based on three partial risk elements: hazards, exposures, and consequences. According to the results of the study, qualitative risk analysis enriched the decision-making for culvert maintenance, even though inspectors' judgment was critical in determining the results. To ensure an effective CMS, a comprehensive risk-based approach is needed to consider all the associated risks in the event of culvert failure.

A risk-based asset management system considers not only the culvert condition but also the costs of potential failure in calculations for determining inspection frequencies. It also quantifies the risk associated with each culvert to help understand the relative importance of the culverts. Using this strategy, culverts can be ranked based on their risk scores to identify the most critical assets for future maintenance. Prioritizing asset maintenance based on the highest failure risk might help to avoid potential asset failures, particularly culvert failures, which can have significant economic, social, and ecological effects. In addition, the overall system condition can be improved by repairing or replacing the most critical assets first, before any serious failure takes place. Typically, calculating an asset's risk of failure entails two steps: (1) determining its likelihood of failure (LOF), and (2) determining its consequence of failure (COF). Once these values have been determined, there are numerous ways for determining the risk of failure, the most commonly utilized is the usage of a risk matrix (Vladeanu & Matthews, 2019).

The likelihood of failure, the first component of a risk analysis framework, can be determined through the deterioration curve, which is the prediction of the asset's future condition rating based on historical condition data. Multiple studies used different statistical models and methodologies to identify the LOF of pipes (culverts); for example, they used regression methods (e.g., Chughtai & Zayed, 2008; Salem et al., 2012; Vladeanu & Koo, 2015), Markov chain models (e.g., Wirahadikusumah et al., 2001; Baik et al., 2006), artificial neural networks (e.g., Najafi & Kulandaivel, 2005), and Bayesian networks (e.g., Anbari et al., 2017).

The consequence of failure is the second component of a risk analysis framework. Due to the high uncertainty and subjectivity involved in calculating both direct and indirect expenses associated with a pipe failure, few papers documented the COF estimating procedure comprehensively. Water Research Foundation's report on the cost of buried assets (Raucher, 2017) points out that current practices emphasize primarily the direct economic costs of asset failure, a factor that may be contributing to the underfunding of buried assets. According to the report, the COF needs to be analyzed not only economically but also socially and environmentally. This is called the triple bottom line (TBL). Several impact factors are considered in the TBL approach as a consequence of a possible failure of an asset, including (1) the utility economic cost; (2) social impacts caused by travel delays, rerouting, service outages, and property damages to customers and the affected community; and (3) environmental impacts such as the loss of land following an unforeseen sewer failure, contamination of groundwater and wildlife habitats, etc. (Vladeanu & Matthews, 2019). The Pipeline Assessment and Certification Program (PACP) methodology gives a guideline for determining the COF of a sewer pipe as part of the risk-based decision-making framework. Diameter of pipe, burial depth, pipe location, relative pipe position in the network, closeness to environmentally sensitive elements, type of customers served, and pipe accessibility are all criteria taken into account when determining the TBL COF of a sewer segment. Each element is assigned a weight depending on its importance to the failure's economic, social, and environmental consequences. The weighted average of all individual criteria is used to obtain the overall COF score of the analyzed segment (NASSCO, 2001). This method, however, is offered just as a basic guideline for calculating COF scores, and utilities are suggested to either expand on or remove criteria from the assessment based on their specific scenario.

1.4 Objectives

As mentioned above, culvert inspection is essential to quantify the potential risks to travelers and public transportation systems in the event of culvert failure. Still, it takes time and resources to inspect all culverts. For instance, UDOT estimated that the cost of the inspection program, using the Region 2 data, which includes 2315 culverts, would be approximately $1.6 million total, or $691 per culvert. Using culvert inspection data, we can predict the condition of culverts instead of inspecting them every few years, which is a more intelligent approach. To this end, this study aims to develop a model that could be used to estimate the deterioration curve of the culverts in Utah based on the available culverts database of several states, including Vermont, Colorado, and Utah. Then, it recommends the inspection frequency using a risk-based approach based on the estimated deterioration curves. In estimating inspection frequencies, a risk-based approach not only considers the culvert condition, but also the costs of potential failure. Risk-based prioritization will enable inspection frequencies to be assigned based on the estimated risk factors for each culvert. As the last part of this study, the Culvert/Storm Drain Management Manual for Utah is developed using federal and state-specific culvert inspection and maintenance guidelines.

The developed system can be integrated into the ATOM software, an enterprise asset management, and maintenance management software that has been integrated into the department's organizational culture. ATOM software will enable UDOT to make informed decisions about investment into each asset class to ensure that its assets are maintained at a high level of service across each region.

1.5 Outline of Report

- Introduction
- Research Methods
- Data Collection
- Results
- Conclusions

2.0 RESEARCH METHODS

The process of modeling and predicting the future condition or performance of an asset item is known as deterioration modeling. Deterioration models are classified as either deterministic or stochastic. Besides, machine learning algorithms can be used to discover relationships between influencing factors (independent variables) and the condition of assets (dependent variable).

In this section, first, we will discuss various deterioration models along with their advantages and disadvantages. Next, we will explain selected machine learning algorithms for deterioration modeling by considering the conditions of Utah culverts. Then, we will introduce a risk-based prioritization approach for finding culvert inspection frequencies. Finally, we will discuss how UDOT's culvert/storm drain management system manual was written.

2.1 Deterministic Models

Deterministic models, which are based on regression analysis of condition data, presume that the deterioration process of an asset is certain. These models rely on an empirical connection between the dependent variable and one or more independent variables. Here, the dependent variable is the condition of culverts, and independent variables are contributing factors, including the age of the culvert, pH of water, slope, soil type, the material of the culvert, etc. Since deterministic models are easy to understand and simple to implement, they are popular among transportation agencies. The advantages of the deterministic model are that it is the simplest approach for predicting the asset's future condition, and it is practical at the network level. However, the model limitations include ignoring uncertainty given the inherent stochastic nature of infrastructure deterioration and being computationally expensive to update the models when new data is available (Srikanth & Arockiasamy, 2020).

2.2 Stochastic Models

In stochastic models, the deterioration process of a culvert is considered as one or more random variables (such as time and condition state of culvert elements) to capture the uncertainty and randomness of the deterioration process. There are two types of stochastic models: state-based models and time-based models. These models provide a more accurate view of risks. As a result, they may be able to assist asset managers in lowering the risks associated with their decisions.

2.2.1 State-Based Models

State-based models are able to model the deterioration process based on the transition probability between two condition states in a discrete period of time. Considering that deterioration is influenced by several measurable variables, including age, Annual Average Daily Traffic (AADT), climate, material, etc., Markov chains have been extensively employed in state-based models. The Markov chain model is a state-based model that is based on two theories: first, it considers asset condition states as a series of discrete states, and second, it incorporates the state transition probabilities for assets when moving from one condition state to the next within a unit of time. These probabilities are derived from expert judgments or, when available, from a mix of expert judgments and maintenance data (Betti, 2010). Markov chain theory has two fundamental properties: memorylessness (just the current state affects the process' future states) and homogeneity (the transition probabilities from one condition to the next remain constant over time).

The Markov chain models have the following advantages. Markov models enable considering uncertainty in their framework, their implementation is straightforward, and they are so practical at the network level. However, these models also have limitations; for instance, transition probabilities are time-independent (homogeneous) (Betti, 2010); Markov chain models only give a qualitative prediction of the asset element's future condition (e.g., excellent, good, fair, poor); and the Markov chain model cannot be utilized to examine the structural reliability in terms of strengths and stresses (Srikanth & Arockiasamy, 2020).

2.2.2 Time-Based Models

Time-based models use distributions such as Weibull and Gamma to characterize the process of deterioration. The random variable of those probability distributions is the duration that an asset, such as a culvert, remains at a particular condition state (Kotze et al., 2015). Weibull models are shown to be more realistic because of using actual scatter in duration data for a certain rating of condition and treating this duration as a random variable by the Weibull-based technique (Agrawal et al., 2008). As an improvement to the Markov model, time-based models were employed to provide an age-dependent failure probability (Thompson et al., 2012). However, these models also have limitations. These models ignore the interaction of different elements regarding structural integrity (Ghodoosi et al., 2014); time-based models have complexity in distribution parameter estimation, particularly in lower condition states where condition data is scarce; time-based models are acceptable to use only if inspection data are available for more than 20 years; otherwise, state-based models are preferred (Mauch & Madanat, 2001).

2.3 Machine Learning Models

Machine learning was first proposed by Arthur Samuel in 1959. Machine learning refers to a computer learning process when it is not explicitly designed (Samuel, 2000). Researchers have been interested in using machine learning to forecast maintenance activities in recent years (Morales et al., 2017). A machine learning technique explores deep inter/intra-correlations and patterns in a dataset with minimum human participation. Machine learning enhances predictive analytics by learning from data rather than using subjective assumptions and simplifications. Numerous machine learning algorithms have been utilized in transportation asset management, such as Support Vector Machine and Artificial Neural Network (ANN) (Wang et al., 2017).

In this research, two machine learning (ML) algorithms are used, including Support Vector Machine (SVM) and Random Forest, to develop culvert deterioration prediction models. Choosing these two algorithms instead of the ANN algorithm was due to the fact that they are less expensive and they do not require a large dataset.

2.3.1 Support Vector Machine for Regression

Support Vector Machines (SVM) are supervised learning models that examine data used for classification and regression analysis in machine learning. As a discriminative classifier, SVMs assign data points to different classes based on an optimal hyperplane determined by the algorithm. With SVM, the objective is to find the optimal hyperplane for data separation that maximizes the margin between data points of different classes (Berwick, 2003). The best separation hyperplane has the same distance between the two classes (positive and negative), as demonstrated in the example of the SVM model in Figure 3 (Burges, 1998). Support vectors are the data points nearest to the hyperplane; in this example, they are the data points on the margin borders.

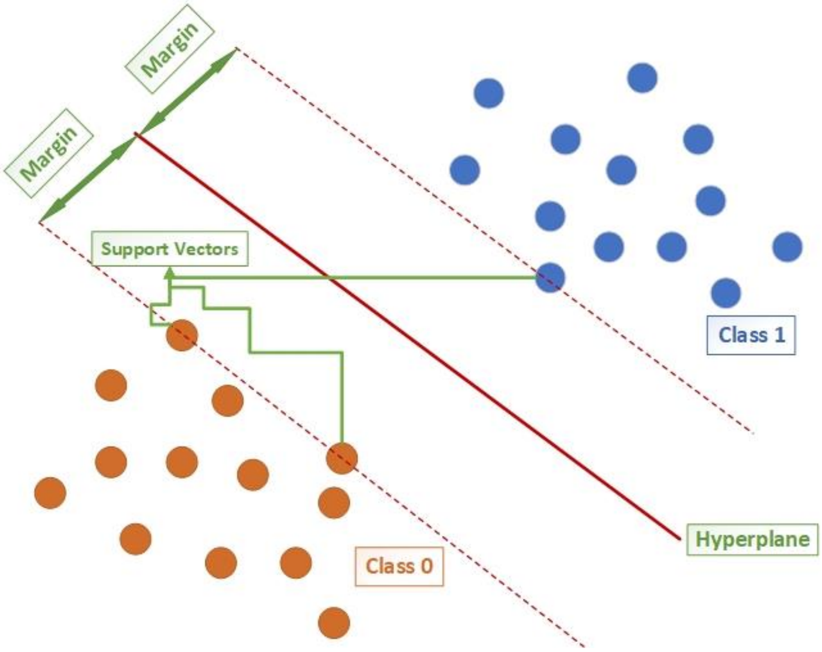


Figure 3- SVM model illustration

In mathematical terms:

For classification of data points $xi \in R^n$ $(i = 1,2,3 \dots n)$ into negative class and positive class labeled as $yi \in \{-1,1\}$. All points closer to the hyperplane may be found as (Salazar et al., 2012):

$$\boldsymbol{W^T X + b} \begin{cases} \geq 1, if\ y_i = 1 \\ \leq -1, if y_i = -1 \end{cases} \quad i = 1,2,3 \dots n$$

Equation 1

Where $\boldsymbol{W}$ and **b** are the weight vector and bias term for the SVM model, respectively.

The distance between the hyperplane and the nearest point of each class is $\frac{1}{||\mathbf{W}||}$ and $\frac{2}{||\mathbf{W}||}$ is the distance between the classes which is equal to the margin. In order to maximize the distance between two groups, the following optimization problem (Equation 2) should be solved (Salazar et al., 2012).

$$\underset{\boldsymbol{W},b}{\text{minimize}} \quad ||\boldsymbol{W}||^2 \quad \text{subject to} \quad y_i\,(\boldsymbol{W}^T\boldsymbol{X} + b) \geq 1 \qquad (i = 1,2,3 \dots n)$$

Equation 2

If the solutions of this optimization problem are $\boldsymbol{W}^*$ and b^*, the hyperplane of the SVM will be defined as follows:

$$D^*(\boldsymbol{X}) = (\boldsymbol{W}^*)^{\boldsymbol{T}} \boldsymbol{X} + b^* = 0$$

Equation 3

It should be mentioned that this hyperplane only applies to data points that are linearly separable in the original space. When the data points are not linearly separable, SVM employs the kernel function, K, to transform the data into a new space that can be separated linearly (Berwick, 2003). Some popular kernel functions are:

- Radial Basis Function (RBF): $K(x, x') = \exp(-\frac{\left\|x-x'\right\|^2}{2a^2})$
- Polynomial function: $K(x, x') = (\mathrm{x} \times \mathrm{x}' + c)^q$
- Sigmoid function: $K(x, x') = \tanh(\mathrm{ax} \times \mathrm{x}' - b)$

The hyperplane, after applying the kernel function, becomes as follows:

$$D^*(\boldsymbol{X}) = (\boldsymbol{W}^*)^{\boldsymbol{T}} \boldsymbol{K(X)} + b^* = 0$$

Equation 4

Several studies have utilized SVM classifiers to develop condition or failure predictor models for various types of infrastructures, such as bearing failures prediction in railways (Li et al., 2014), bridge structures damage prediction (Bao et al., 2013), and pavement failures probability prediction (Schlotjes et al., 2015). These investigations found that SVM could forecast asset quality and failure accurately.

In classification issues, SVMs are well known. However, the application of SVMs in regression is less extensively documented. Support Vector Regression models are the name for these sorts of models (SVR). SVR is a version of SVM which was proposed by Drucker et al. in 1996. A generalization of the classification problem is the regression problem. The introduction of an ε-insensitive region around the function, known as the ε-tube, allows SVM generalization to SVR. The optimization problem is reformulated by this tube to determine the tube that best predicts the continuous-valued function while balancing model complexity and prediction error (Awad & Khanna, 2015).

Training the original SVR means solving following optimization problem (Equation 5):

$$\underset{\boldsymbol{W},b}{\text{minimize}} \quad 0.5\|\boldsymbol{W}\|^2 \quad \text{subject to} \quad |\, y_i - (\boldsymbol{W}^T\boldsymbol{X} + b) \,| \leq \varepsilon \qquad (i = 1,2,3 \ldots n)$$

Equation 5

Where $\boldsymbol{X}$ is a training sample with target value y_i and a threshold parameter ε. All predictions have to be within an ε range from the target label.

2.3.2 Random Forest Regression (RFR)

Random Forest Regression (RFR) is a supervised learning algorithm for classification, regression, and other problems that works by creating a large number of decision trees throughout training. Ensemble learning is a methodology for making more accurate predictions by combining predictions from various machine learning algorithms (Hickey et al., 2022).

For classification tasks, the Random Forest output is the class chosen by the majority of trees. However, the average of the individual tree prediction is returned for regression tasks, as shown in Figure 4. A Random Forest is made up of several random decision trees. The trees have two types of randomization built in. First, each tree is built on a randomly selected original data sample. Second, a subset of features is randomly chosen at each tree node to obtain the optimal split. To this end, random decision forests overcome the problem of decision trees, which is overfitting to their training set (Zhang & Ma, 2012).

The Random Forest algorithm is as follows:

- Draw T bootstrap samples of data
- Draw a subset of available attributes at each split
- Train trees on each sample/attribute set → T trees
- Average prediction of trees on out-of-bag samples

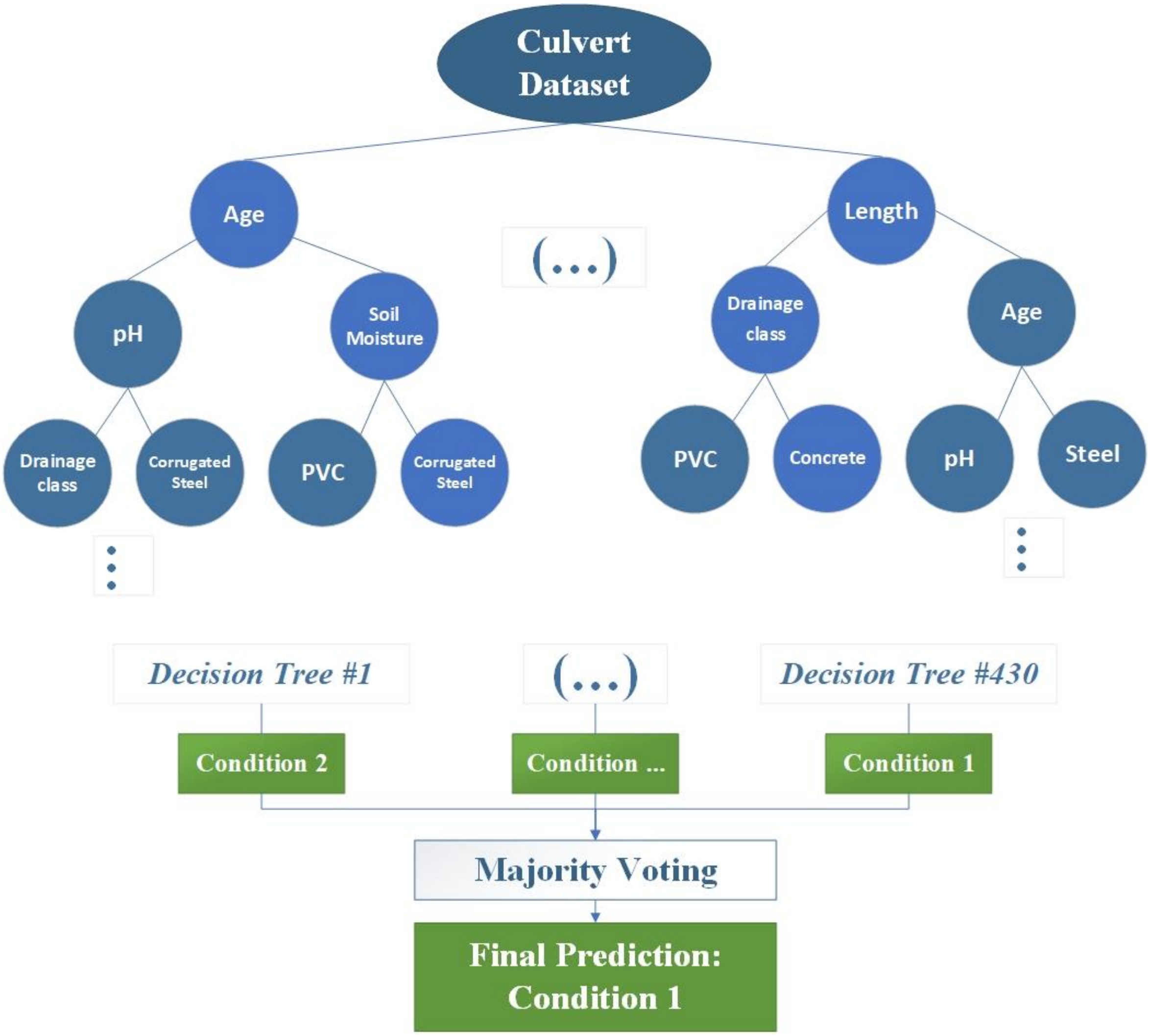


Figure 4-Random Forest structure

2.4 Risk-Based Prioritization

After generating culvert deterioration curves, the next step was using these curves to estimate culvert inspection frequencies. It is common to prioritize asset inspections such as sewers, pipes, pavements, and bridges based on risk factors. Similarly, this study implemented a risk-based prioritization approach to assign culvert inspection frequencies based on the estimated risk factor for each culvert. Risk factor is equal to the multiplication of the likelihood of failure (LOF) by the consequence of the failure (COF) (Equation 6).

$$\boldsymbol{Culvert\ Risk\ Factor} = \boldsymbol{Likelihood\ of\ Failure}(\boldsymbol{LOF}) \times \boldsymbol{Consequence\ of\ Failure}(\boldsymbol{COF})$$

Equation 6

2.4.1 Likelihood of Failure (LOF)

The LOF is directly proportional to the culvert's present condition. Because culverts are increasingly prone to erosion and abrasion as they age, the failure rate increases. The LOF is influenced by several parameters, including culvert material, remaining useful life, repair history, soil type, and inspection rating. Since deterioration curves generated in previous steps consider most of these parameters, they can be used directly to approximate the LOF under different scenarios. Figure 5 describes culvert conditions with a deterioration curve.

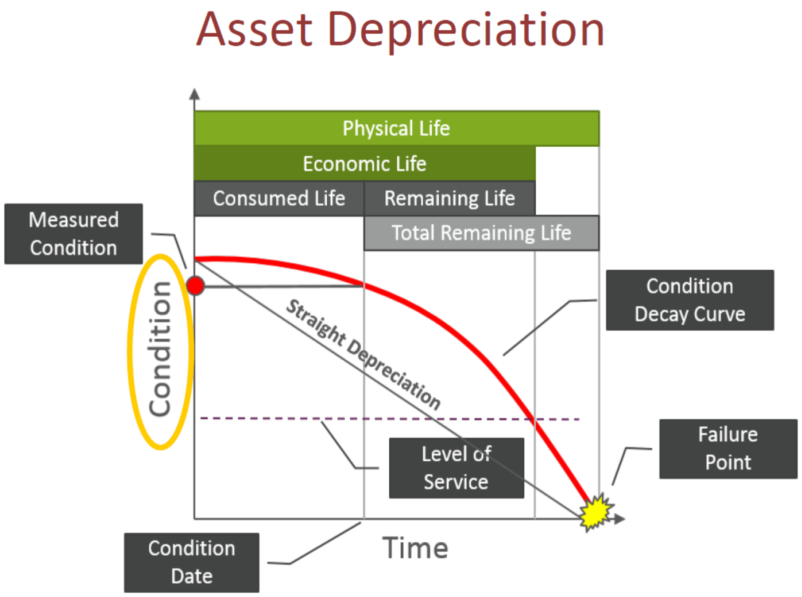


Figure 5-Illustrating culvert condition with deterioration curve (Eubanks, 2017)

Most studies assigned LOFs to condition ratings between 0 and 1, but using other ranges such as 1 to 10 or 1 to 100 is acceptable if the concept is valid. Table 1 shows the LOF that UDOT provided to use for this research.

Table 1-LOFs based on UDOT culvert risk assessment

Condition	LOF
1	0.0029
2	0.00655
3	0.0102
4	0.0138
5	0.01745

2.4.2 Consequence of Failure (COF)

Calculating risk factors implies that identifying culverts with a higher LOF may not be sufficient because inspecting all of them still requires a significant amount of investment. Thus, the COF of the culvert should be analyzed to consider all of the essential factors for prioritizing inspections. For example, a culvert beneath the I-15 highway with a lower LOF may pose greater risks than a culvert beneath a rural road with a higher LOF. COF is linked to the asset types and this study categorized COF into economic and social impacts.

Economic impacts include repair/replacement costs and damages to nearby properties. Some researchers have attempted to quantify the costs using indirect methods because the actual economic impact is composed of many cost items. For example, culverts' physical dimensions (e.g., diameter and length) were used to determine repair or replacement costs. There are many variables affecting the repair costs, but the type and dimensions (length and size) of the culvert are the most important ones. Approximation methods, in addition to historical repair data or published tables in guidelines, were used for calculating the repair cost per length or total repair costs.

In this study, repair costs have been calculated relatively based on the material type and dimensions of the culvert (Equation 7). Table 2 shows the relative weights for the cost per volume of each culvert material. These weights are approximated based on the historical repair data and other available reports. It is worth mentioning that the base repair cost and coefficients may vary depending on where the culvert is located and its condition, and even from one culvert to another culvert. Using these values allows you to compare a culvert's repair costs with those of others and highlight the ones that are most critical. The final risk value doesn't show the exact repair cost of the culvert.

$$\boldsymbol{Repair\ Costs = Cost\ per\ volume\ weight\ \times Volume\ of\ culvert}$$

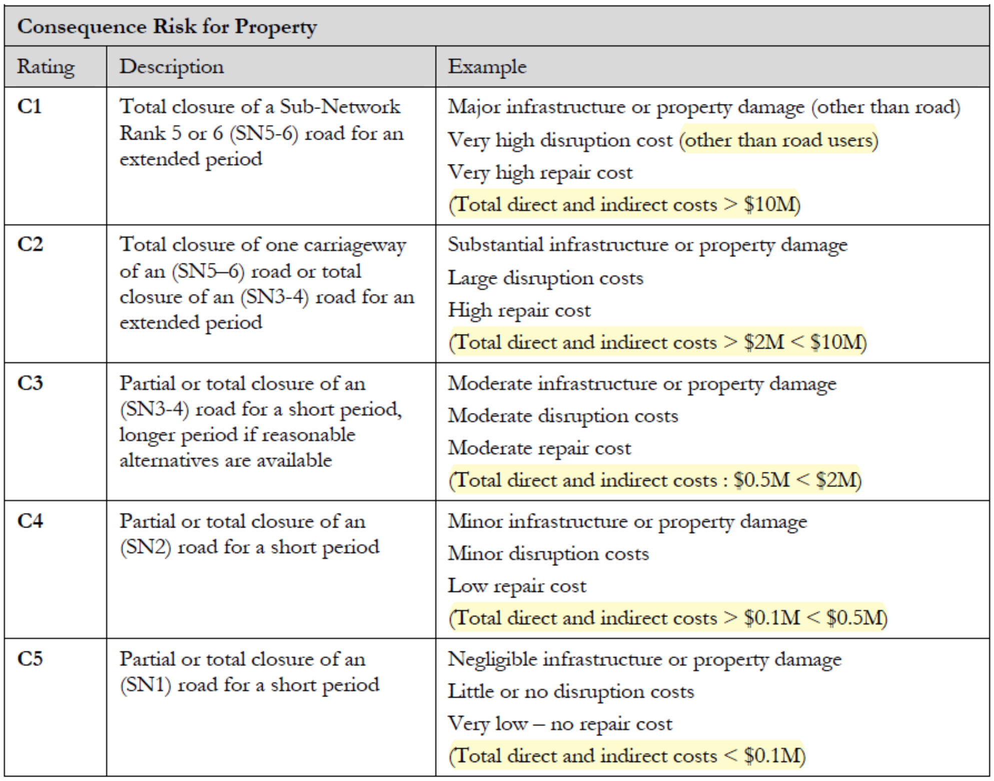
Equation 7

Table 2-Culvert material weight of repair cost

Culvert Type	Cost Per Volume ($/volume) Weight
Reinforced Concrete	1.0
Aluminum	0.4
Corrugated Steel	0.4
Timber	0.4
High Density Polyethylene	0.6
Poly Vinyl Chloride	0.6
Steel Plate	0.8
Unreinforced Concrete	0.8

Also, approximation methods should be used to quantify damage costs to nearby properties. Table 3 shows an example of consequence risk rating for properties and total direct and indirect costs in case of culvert failure. Using this table, we estimated base damage costs to properties is equal to $300,000, but UDOT can update this value later based on real damage costs to properties in Utah. Damage costs to nearby properties may vary based on different factors, including location, condition, etc. To this end we used Equation 8 for calculating direct damage costs to nearby properties. It is important to assign higher weights to culverts on a flood plain/sensitive watershed because their failure can impose higher risks to nearby properties or facilities.

Table 3-Culverts consequence risk rating (Roads and Traffic Authority, 2010)



Consequence Risk for Property		
Rating	Description	Example
C1	Total closure of a Sub-Network Rank 5 or 6 (SN5-6) road for an extended period	Major infrastructure or property damage (other than road) Very high disruption cost (other than road users) Very high repair cost (Total direct and indirect costs > $10M)
C2	Total closure of one carriageway of an (SN5–6) road or total closure of an (SN3-4) road for an extended period	Substantial infrastructure or property damage Large disruption costs High repair cost (Total direct and indirect costs > $2M < $10M)
C3	Partial or total closure of an (SN3-4) road for a short period, longer period if reasonable alternatives are available	Moderate infrastructure or property damage Moderate disruption costs Moderate repair cost (Total direct and indirect costs : $0.5M < $2M)
C4	Partial or total closure of an (SN2) road for a short period	Minor infrastructure or property damage Minor disruption costs Low repair cost (Total direct and indirect costs > $0.1M < $0.5M)
C5	Partial or total closure of an (SN1) road for a short period	Negligible infrastructure or property damage Little or no disruption costs Very low – no repair cost (Total direct and indirect costs < $0.1M)

$$\boldsymbol{Direct\ Damage\ Costs = W1\ \times W2 \times Base\ Damage\ Costs}$$

Equation 8

To calculate W1 and W2, we considered the stream type and Federal Emergency Management Agency (FEMA) flood zones through their assigned weights to approximate the damage to nearby properties in case of culvert failure. Table 4 and Table 5 show these weights, respectively.

Table 4-Weights related to each stream type

Stream type	Weight (W1)
Standing	0.125
Ephemeral	0.25
Intermittent	0.5
Perennial	1

Table 5-Weights related to each flood zone

FEMA Flood Zones		Definition	Weight (W2)
A	A	**1-percent-annual-chance** flood event generally determined using **approximate methodologies**	1
A	AE, A1-A30	**1-percent-annual-chance** flood event determined by **detailed methods**	1
A	AH	**1-percent-annual-chance** shallow flooding, typically areas of **ponding (average depths are between one and three feet)**	1
A	AO	**1-percent-annual-chance** shallow flooding, usually **sheet flow on sloping terrain (average depths are between one and three feet)**	1
A	AR	Decertification of a previously accredited flood protection system	1
A	A99	**1-percent-annual-chance** flood event, but will ultimately be protected (**such as dikes, dams, and levees**)	1
A	V	**1-percent-annual-chance** flood event (**areas along coasts)**	1
A	VE, V1-V30	**1-percent-annual-chance** flood event with additional hazards due to **storm-induced velocity wave action**	1
B	X (Shaded), B	**Moderate flood hazard** between limits of the **1-percent-annual-chance** floodplain and the **0.2-percent-annual-chance** floodplain	0.2
C	X (Unshaded), C	**Minimal flood hazards outside 0.2-percent-annual-chance** floodplain	0.1
D	D	**Possible** but **undetermined flood risk**	0.1

The failure of a culvert causes indirect damage as well as direct damage. Social impacts refer to any impact on people in case of culvert failure. One of the important social impacts is the cost of service loss, mainly the user delay cost. In this study, we derived user delay costs through Equation 9 and based on the following terms:

- Annual Average Daily Traffic (AADT) of the road on which the culvert is being installed;
- Average increase in delay or congestion caused by the installation per car per day ('t' in hours);
- Number of days required to complete the project (d);
- Average rate of person-delay in dollars per hour (C_v= $ per person-hour of delay);

- Average rate of freight-delay in dollars per hour (C_f= $ per freight-hour of delay);
- Percentage of passenger vehicles traffic (V_v= % vehicle passenger traffic);
- Vehicle occupancy factor (V_{of} = persons per vehicle)
- Percentage of truck traffic (V_f = % truck traffic)

$$\textit{Indirect Damage Costs} = \sum_{k=0}^{n} AADT_k \times t_k \times d_k \times (c_{vk} \times v_{vk} \times v_{ofk} + c_{fk} \times v_{fk})$$

Equation 9

It is worth noting that the k factor enables each user delay cost to be assigned to a specific time period of the failure year, even if the factors may vary in the future. Also, the user delay cost should not be taken into account if the culvert is not located beneath a roadway. User delay costs were approximated by assigning the values in Table 6 to the parameters of Equation 9. These values are variable based on the road, AADT, alternative roads available next to the road, and percentage of trucks passing and can be substituted by the actual values which are obtained gradually.

Table 6-Parameters of User Delay Cost

	User Delay Cost Parameters		
These parameters are specific to each culvert location and road conditions	Average Delay per Vehicle	30	min
	Project Days	5	day
These parameters are approximations	Person-Delay Cost	17.18	$/person-hour
	Freight-Delay Cost	50	$/freight-hour
	Percentage of Passenger Vehicles	97	%
	Vehicle Occupancy Factor	1.2	-

Therefore, the total consequence of culvert failure was calculated based on the location of the culvert, as shown in Figure 6.

Figure 6- COF summation flowchart

2.4.3 Risk Matrix

Finally, it was possible to generate the risk matrix after calculating LOF and COF. In Figure 7, one axis shows the LOF of the culvert, and the other axis shows the COF of the culvert. Culverts with higher LOF and COF are given higher priority, while those with lower LOF and COF are given lesser priority. As can be seen in Figure 7, the highest priority assets are red zone, the medium priority assets are orange zone, and the lowest priority assets are green zone.

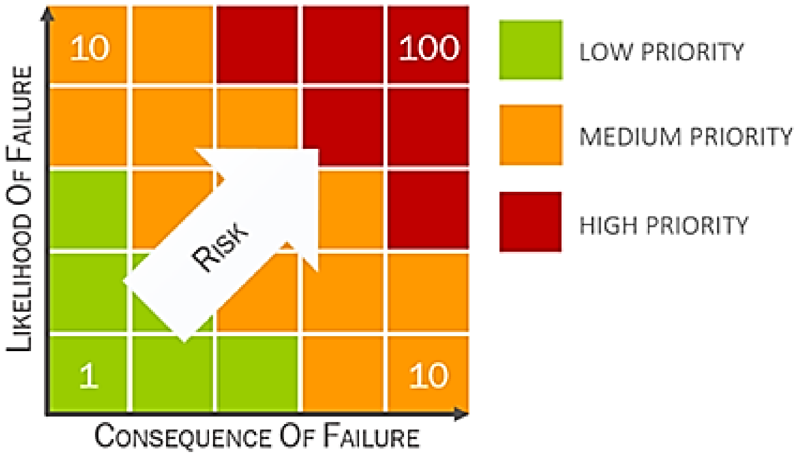
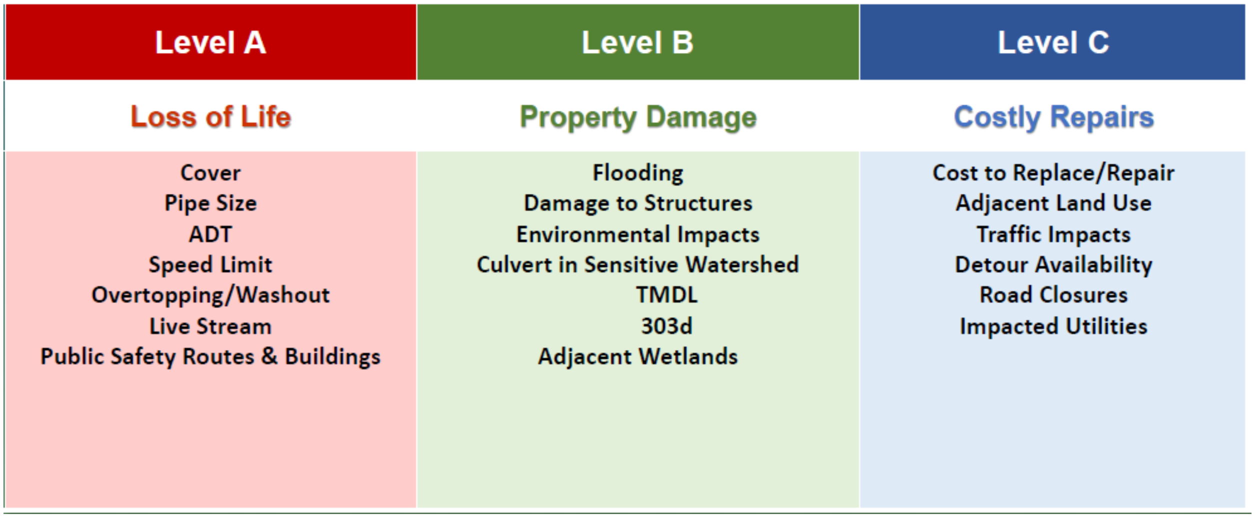


Figure 7-Risk Matrix

According to UDOT, risk can be classified into three qualitative categories based on several factors, and we used these categories in generating the risk matrix. Table 7 shows the categories provided by UDOT.

Table 7-Culvert risk categories provided by UDOT



Level A	Level B	Level C
Loss of Life	Property Damage	Costly Repairs
Cover Pipe Size ADT Speed Limit Overtopping/Washout Live Stream Public Safety Routes & Buildings	Flooding Damage to Structures Environmental Impacts Culvert in Sensitive Watershed TMDL 303d Adjacent Wetlands	Cost to Replace/Repair Adjacent Land Use Traffic Impacts Detour Availability Road Closures Impacted Utilities

The culvert risk factor is equal to the multiplication of LOF by COF, according to Equation 6. Based on the risk factor ranges, different risk categories will be assigned to each culvert. The following ranges were chosen based on the distribution of risk, and the minimum and maximum risk values:

- **No Action**: Risk factor < first quartile (Q1)
- **C**: Q1 ≤ Risk factor < second quartile (Q2)
- **B**: Q2 ≤ Risk factor < third quartile (Q3)
- **A**: Q3 ≤ Risk factor

With each culvert given its respective risk category and condition rating, one could identify the risk level of all culverts according to the generated risk matrix. Risk levels are defined as Level 1 to Level 4 in Figure 8. From level 1 to level 4, the percentage of the criticality of culverts declines, with level 1 being the most critical and level 4 being the least critical.

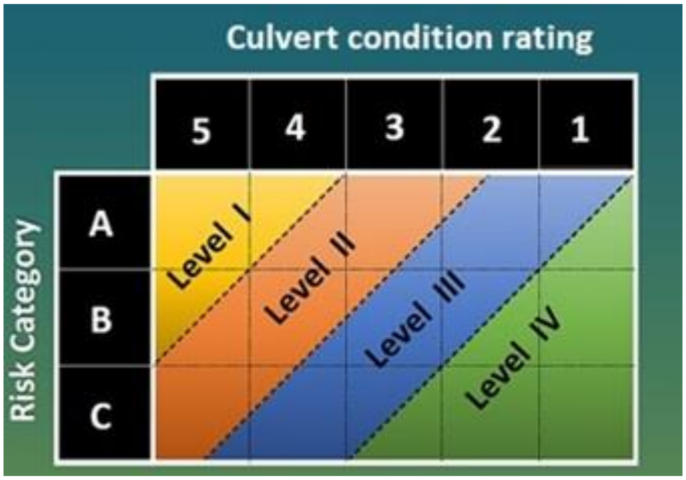


Figure 8-Risk matrix based on the risk factor and culvert condition rating

2.4.4 Inspection Frequency

The last step was assigning inspection frequencies to culverts based on the determined risk level. By considering the draft of the inspection cycle manual from UDOT, culverts in the level 4 zone should be inspected every ten years, level 3 every seven years, level 2 every three years, and level 1 every year. The values of Table 8 are subject to change as UDOT finalizes the total budget required for culvert inspection. Culverts in Level 1 are the critical culverts, and inspecting them annually can save money and prevent higher repair costs.

Table 8-Inspection cycle table

Risk Level	Inspection Frequency (year)
1	1
2	3
3	7
4	10

2.5 Utah's Culvert/Storm Drain Management System Manual Draft

The final task in this study was to develop a manual for managing culverts and storm drains in Utah. For this purpose, we reviewed several federal and state-specific culvert inspection manuals including AASHTO Culvert & Storm Drain System Inspection Guide (AASHTO, 2020), FHWA Culvert Inspection Manual (FHWA, 2007), New York DOT Culvert Inventory and Inspection Manual (NYSDOT, 2006), Ohio DOT Conduit Management Manual (OhioDOT, 2021), Michigan Non-NBI Culvert Structure Inspection Guide (Michigan, 2021), Delaware DOT Bridge Element Inspection Manual (Renman et al., 2021), and New Mexico DOT Culvert Asset Management System: Best Practices (Villwock-Witte et al., 2016). Besides these culvert inspection manuals, the Rehabilitation of Culverts and Buried Storm Drain Pipes from NCHRP (Sezen, 2022) was also reviewed as a culvert maintenance guide. After reviewing these manuals, we figured out that they may have different layouts or chapters but they mostly cover the same concepts and provide the necessary content for the draft of Utah's Culvert/Storm Drain Management Manual.

The most common chapters among the inspection manuals were Inventory Guideline, Inspector Characteristics, Inspection Procedures, and Rating System. According to the format of the manuals, they had other chapters besides the ones mentioned, which we did not use as separate chapters in UDOT's manual. In addition to culvert inspection, culvert maintenance is also a part of culvert management. Since we developed a management system manual for UDOT, we should include a chapter about maintaining culverts and storm drains. As a result, we proposed the following outline for the Utah Culvert/Storm Drain Management System Manual based on the manuals that we reviewed:

- Chapter 1: INTRODUCTION
- Chapter 2: INVENTORY
- Chapter 3: THE INSPECTOR
- Chapter 4: INSPECTION
- Chapter 5: PERFORMANCE MEASURES and MAINTENANCE RATINGS
- Chapter 6: MAINTENANCE
- Chapter 7: GLOSSARY
- Chapter 8: REFERENCES

This manual for culverts and storm drains was drafted by combining all of these manuals to provide a Utah-specific manual. Chapter 1 of the manual introduces the topic of culvert and storm drain system inspections, provides a basic introduction to the manual sections, highlights the need for standardized inspection, and presents the objectives and intended audience of the manual. Chapter 2 introduces standard features recorded in the culvert inventory system to provide a comprehensive inventory database for culverts. Chapter 3 discusses the inspector's duties and qualifications, the equipment required for inspections, and the safety measures necessary during the inspections. Chapter 4 covers the preparation and planning of inspections, the inspection sequence for routine inspections, types of entry, inspection frequency calculation, and recording inspections. An entire section of this chapter is dedicated to the data-driven inspection method we proposed. Chapter 5 provides quantitative criteria for rating the condition of culverts and storm drain system components based on UDOT pipe defect rating sheets. Chapter 6 explains common culvert repair and rehabilitation methods, and discusses the capital improvement program. Chapter 7 contains an alphabetical list of terms or words relating to culverts with explanations. Documents used in the production of this manual are listed in Chapter 8.

2.6 Summary

In order to predict the deterioration of culverts based on physical and environmental features, two types of machine learning algorithms were developed, including SVR and RFR. Figure 9 depicts the process of generating deterioration curves based on available data for the states of Utah, Vermont, and Colorado. These culvert deterioration curves were used to determine inspection frequencies using a risk-based prioritization approach.

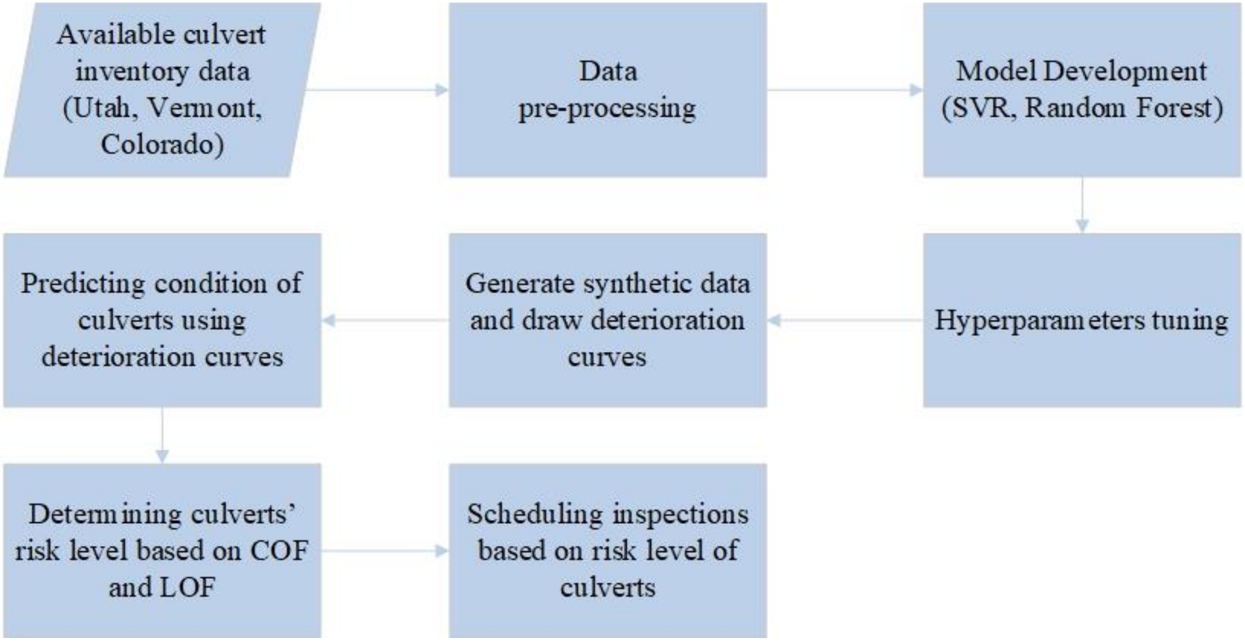


Figure 9-Flowchart of the approach used for culvert inspection

3.0 DATA COLLECTION

3.1 Overview

Collecting necessary input data is the first step toward developing any robust machine learning model. This study employed three datasets to determine the deterioration of culverts. UDOT provided Colorado and Utah culvert inventories. However, Vermont culvert inventory was obtained from the Vermont Agency of Transportation. One of the limitations of these datasets was that they did not include soil data. Therefore, we downloaded soil data from the Web Soil Survey database. Furthermore, these datasets needed to be pre-processed before they could be used in the Utah culvert management system. We used available packages in python to fill missing values in the dataset or remove the outliers.

3.2 Specifications

3.2.1 Soil Data

According to the literature, soil chemical properties, soil erosion factors, soil physical properties, and soil-related water features could all have an influence on the culvert deterioration curve. The Web Soil Survey (WSS) website offers soil data and information generated by the National Cooperative Soil Survey (NCSS). The latitude and longitude of culverts were utilized to identify soil properties associated with each culvert and add them to the dataset, as shown in Figure 10.

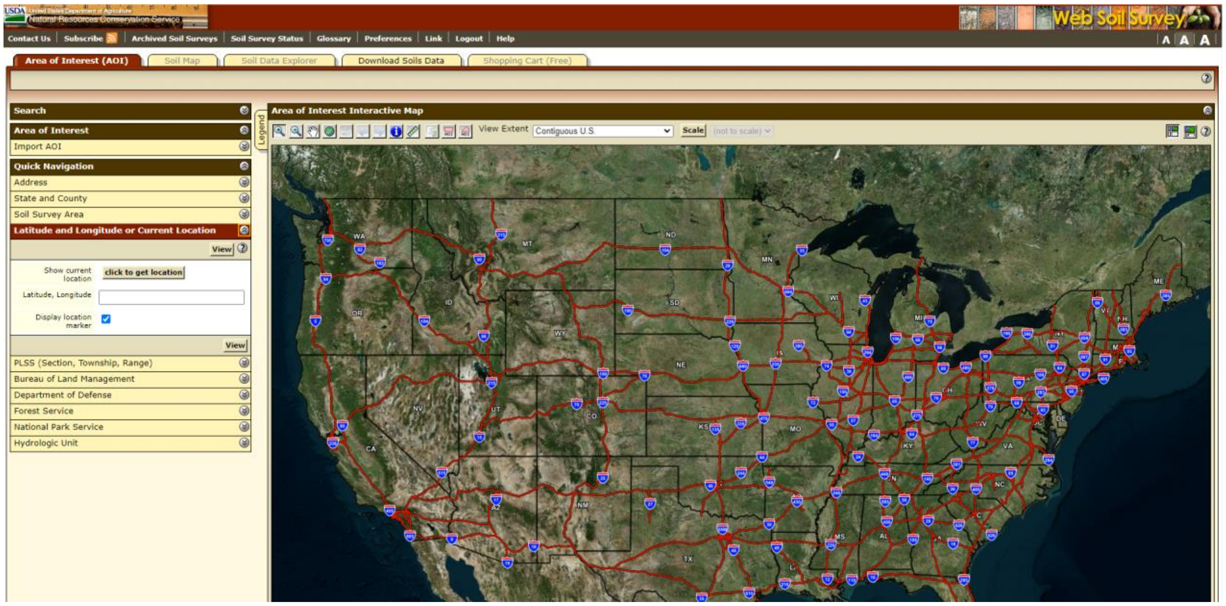


Figure 10-Web Soil Survey website

The process of obtaining data from unstructured or poorly structured data (e.g., website) sources for further data processing is known as data extraction (Laender et al., 2002). Data extraction was not possible since the WSS website is too complicated and old, as well as authorization was necessary. Thus, for almost 2000 culverts, all of the soil attributes were manually collected from this website. The following are the final soil attributes and their definition obtained from the WSS website (*Web Soil Survey*, n.d.). It is worth noting that the effects of these features on steel and concrete culverts are not the same.

- Soil Drainage Class: "Drainage class (natural)" refers to the frequency and duration of wet periods under conditions similar to those under which the soil formed.
- Soil pH: Soil reaction is a measure of acidity or alkalinity.
- Soil Moisture: Soil moisture is assumed to be equal to the water content-15 bar, which is the amount of soil water retained at a tension of 15 bars, expressed as a volumetric percentage of the whole soil material.
- Soil Electrical Conductivity (EC): Electrical conductivity is a measure of the concentration of water-soluble salts in soils.
- Soil Surface Texture: Soil texture, or how the soil looks and feels, is determined by the size and proportion of the particles (clay, silt, and sand) that make up the mineral

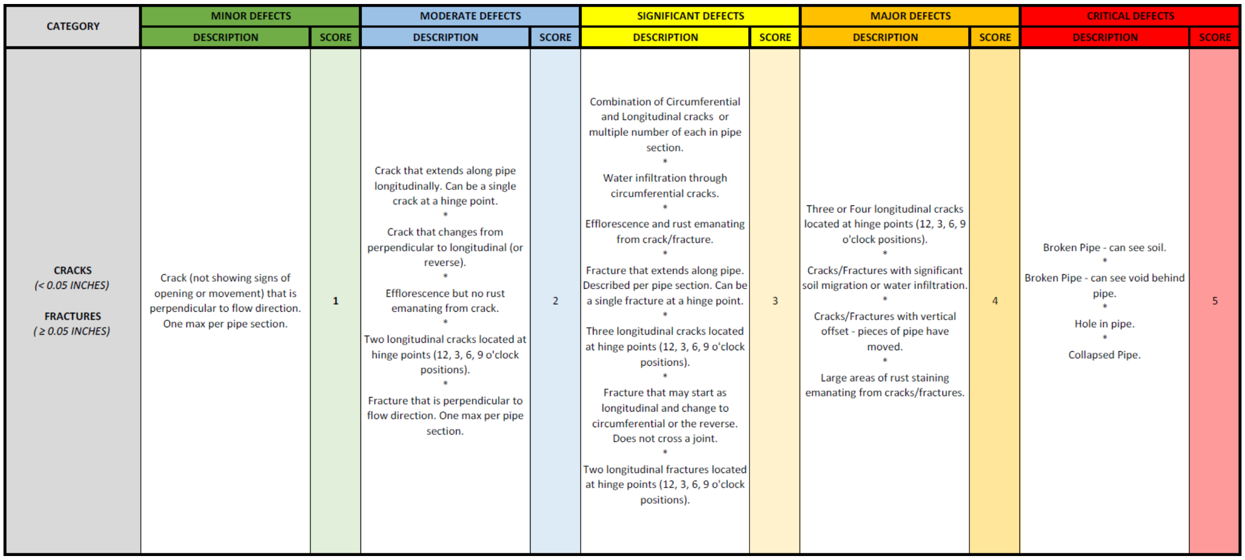
fraction. There are 12 United States Department of Agriculture (USDA) textural classes (e.g., sandy loam, silty clay).

- Corrosion of Concrete: "Risk of corrosion" pertains to potential soil-induced electrochemical or chemical action that corrodes or weakens the concrete.
- Corrosion of Steel: "Risk of corrosion" pertains to potential soil-induced electrochemical or chemical action that corrodes or weakens uncoated steel.
- Soil Flooding Frequency: Flooding is the temporary inundation of an area caused by overflowing streams, runoff from adjacent slopes, or tides. Frequency is expressed as none, very rare, rare, occasional, frequent, and very frequent.

3.2.2 Data Modification

In order to establish the deterioration curve of culverts in Utah, further modifications to these datasets were also required. UDOT proposed a 5-point rating system for culverts which is different from the Colorado and Vermont rating systems. Table 9 illustrates an example of the Utah rating system for concrete culverts. Furthermore, all pipe defect rating sheets developed by UDOT can be viewed in APPENDIX A: UDOT Pipe Defect Rating Sheets.

Table 9-UDOT rating system for concrete culverts



CATEGORY	MINOR DEFECTS		MODERATE DEFECTS		SIGNIFICANT DEFECTS		MAJOR DEFECTS		CRITICAL DEFECTS	
	DESCRIPTION	SCORE	DESCRIPTION	SCORE	DESCRIPTION	SCORE	DESCRIPTION	SCORE	DESCRIPTION	SCORE
CRACKS *(< 0.05 INCHES)* **FRACTURES** *(≥ 0.05 INCHES)*	Crack (not showing signs of opening or movement) that is perpendicular to flow direction. One max per pipe section.	1	Crack that extends along pipe longitudinally. Can be a single crack at a hinge point. * Crack that changes from perpendicular to longitudinal (or reverse). * Efflorescence but no rust emanating from crack. * Two longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions). * Fracture that is perpendicular to flow direction. One max per pipe section.	2	Combination of Circumferential and Longitudinal cracks or multiple number of each in pipe section. * Water infiltration through circumferential cracks. * Efflorescence and rust emanating from crack/fracture. * Fracture that extends along pipe. Described per pipe section. Can be a single fracture at a hinge point. * Three longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions). * Fracture that may start as longitudinal and change to circumferential or the reverse. Does not cross a joint. * Two longitudinal fractures located at hinge points (12, 3, 6, 9 o'clock positions).	3	Three or Four longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions). * Cracks/Fractures with significant soil migration or water infiltration. * Cracks/Fractures with vertical offset - pieces of pipe have moved. * Large areas of rust staining emanating from cracks/fractures.	4	Broken Pipe - can see soil. * Broken Pipe - can see void behind pipe. * Hole in pipe. * Collapsed Pipe.	5

Table 10 shows the proposed method for adjusting the rating systems. Also, deterioration curves are adjusted based on the updated rating system as the dataset labels.

Table 10-Rating conversion table

Vermont	Utah		Colorado
Excellent	1	Minor Defects	9
			8
Good	2	Moderate Defects	7
Fair			
Poor	3	Significant Defects	6
Critical	4	Major Defects	5
Urgent	5	Critical Defects	4
			3
			2
Closed			1
			0

3.3 Summary

This research aims to detect culvert deterioration curves by using two machine learning algorithms and based on culvert inventories of three states in the United States. Collecting accurate input data is the first step in developing a machine learning algorithm. In total, three datasets were utilized in this study, two of which were provided by UDOT, and another one was collected by the researcher. Also, soil features, for instance, soil pH and soil flooding frequency, were manually added to all three datasets separately. Since each dataset had its own rating system, modifications had to be made before feeding data into machine learning algorithms in order to generate culvert deterioration curves of the same rating scale and ultimately find the final deterioration curve for the culverts of Utah. In the next section, we will discuss the results of the machine learning algorithms that were applied to the collected data.

4.0 RESULTS

4.1 Overview

Following the steps outlined in the preceding sections, machine learning models were developed to identify various deterioration curves using culvert inventories from Colorado, Vermont, and Utah. As a first step, we generated deterioration curves for Utah, Colorado, and Vermont culverts separately. Following that, we aggregated the three inventories and generated deterioration curves based on the aggregated data. The inspection frequencies for Utah culverts were then determined using the outputs of the final model.

4.2 Deterioration Models

4.2.1 Utah Dataset

UDOT provided a dataset including Utah culvert information. After preprocessing, the final dataset included 272 rows and 49 columns (features). The following Figures are the deterioration curves generated by the SVR and RFR models. Our method for evaluating the performance of the model used a 90%-10% split of data, which means splitting the dataset into training (90% of data) and testing (10% of data) sets. The Utah culvert dataset's developed RFR, and SVR models yielded 80% and 62% accuracy in predicting culvert conditions based on specified features such as soil data and age, respectively. For determining accuracy, we utilized R-squared (R2), a statistical metric that quantifies the proportion of a dependent variable's variation that is explained by an independent variable.

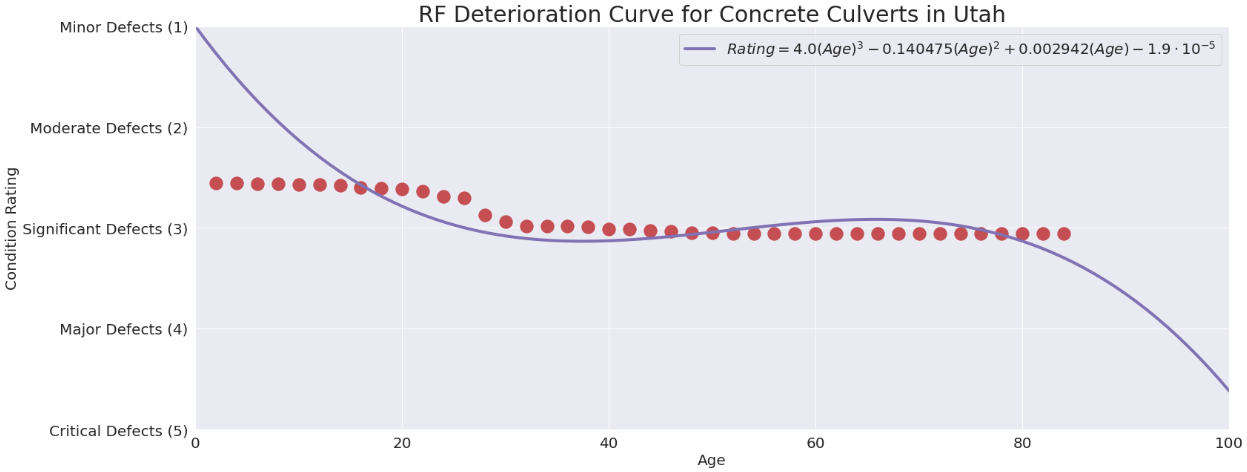


Figure 11-Deterioration curve with Random Forest for concrete culverts in Utah

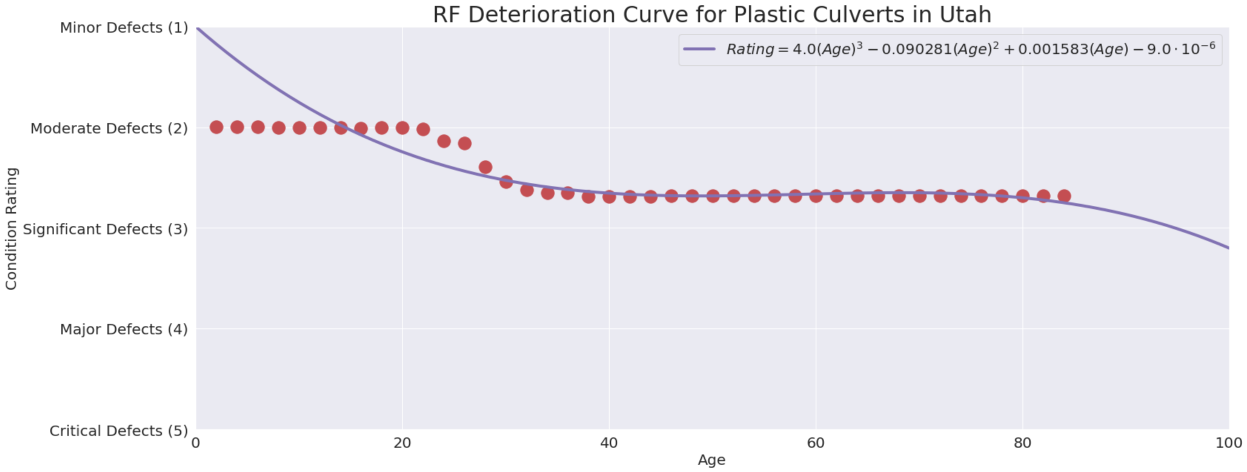


Figure 12-Deterioration curve with Random Forest for plastic culverts in Utah

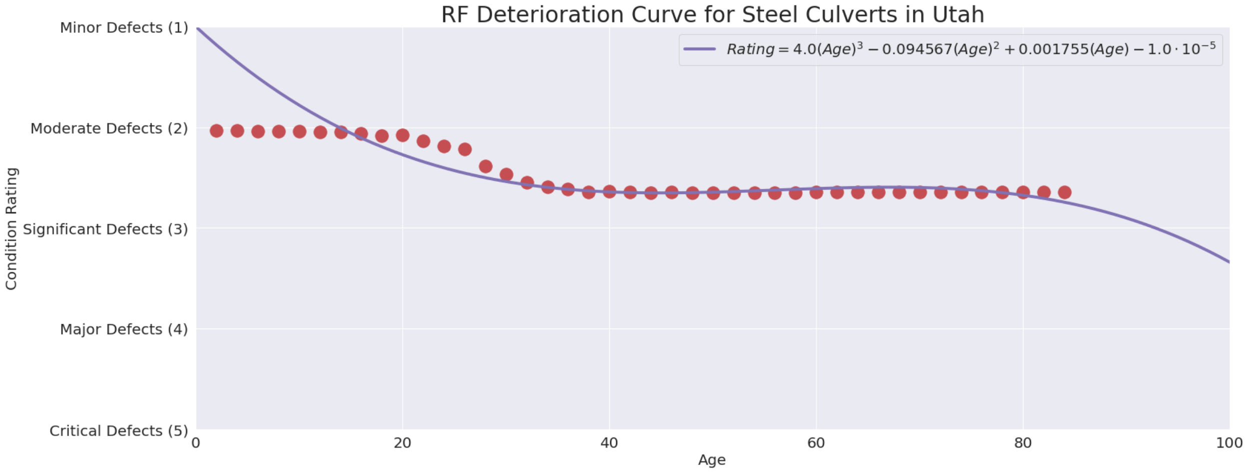


Figure 13-Deterioration curve with Random Forest for steel culverts in Utah

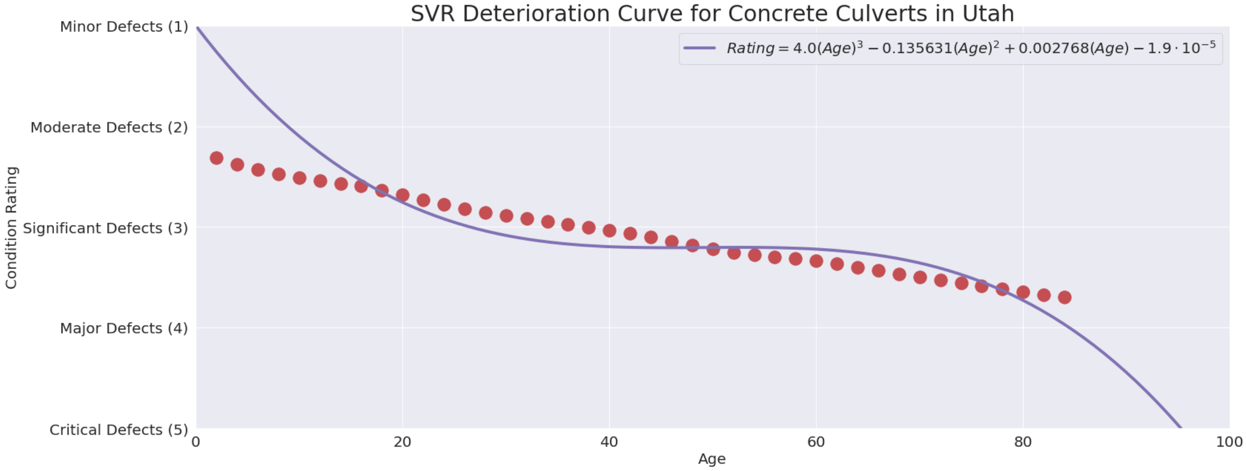


Figure 14-Deterioration curve with SVR for concrete culverts in Utah

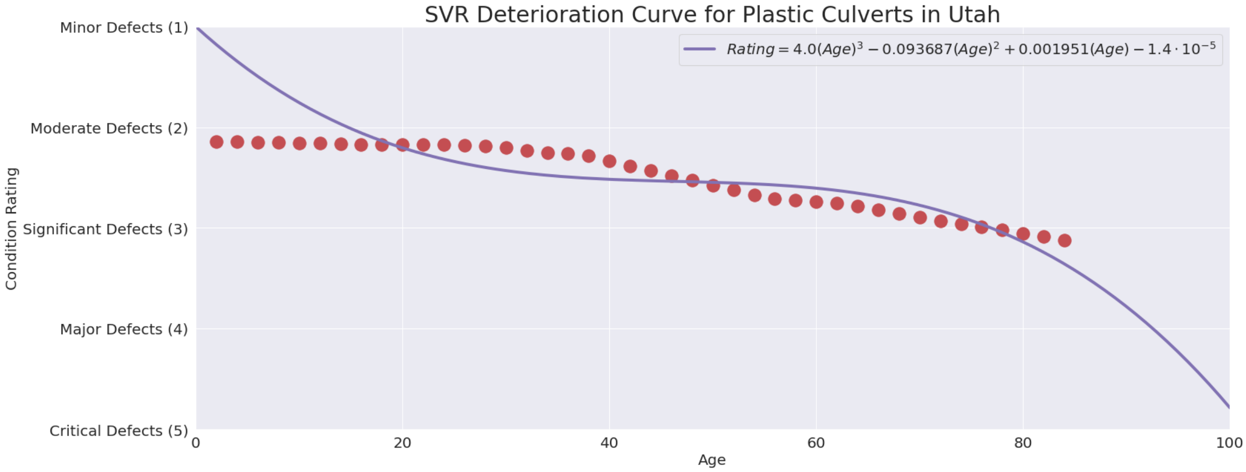


Figure 15-Deterioration curve with SVR for plastic culverts in Utah

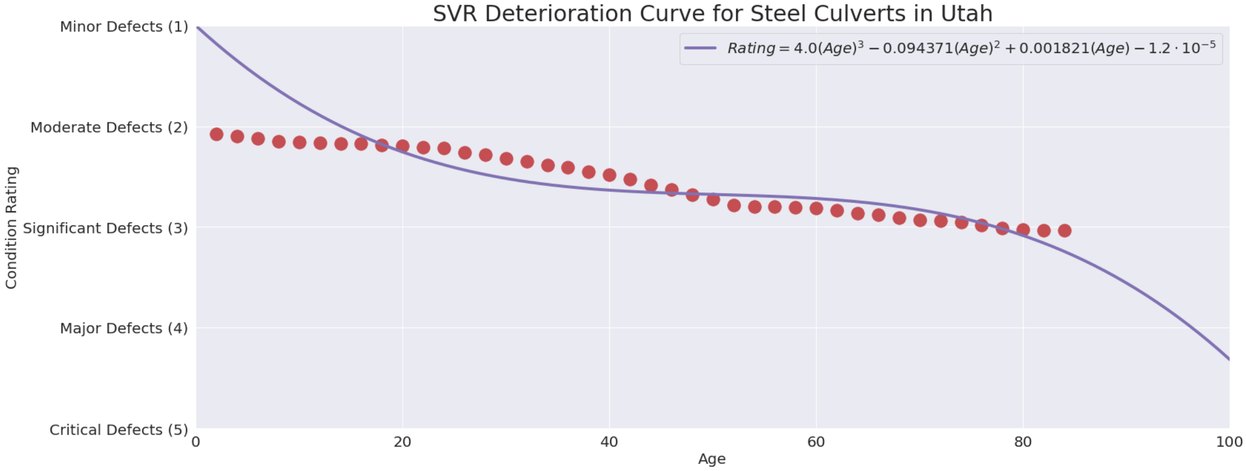


Figure 16-Deterioration curve with SVR for steel culverts in Utah

4.2.2 Colorado Dataset

UDOT provided Colorado culvert inventory information in two different datasets that we merged in order to produce a comprehensive dataset of Colorado culverts. After preprocessing, the resulting dataset included 813 rows and 25 columns (features). The deterioration curves generated by the SVR and RFR models for steel and concrete culverts are shown individually in the figures below. In predicting culvert conditions based on specified features such as soil data and age, the RFR and SVR models developed for Colorado culverts achieved 81% and 61% accuracy, respectively.

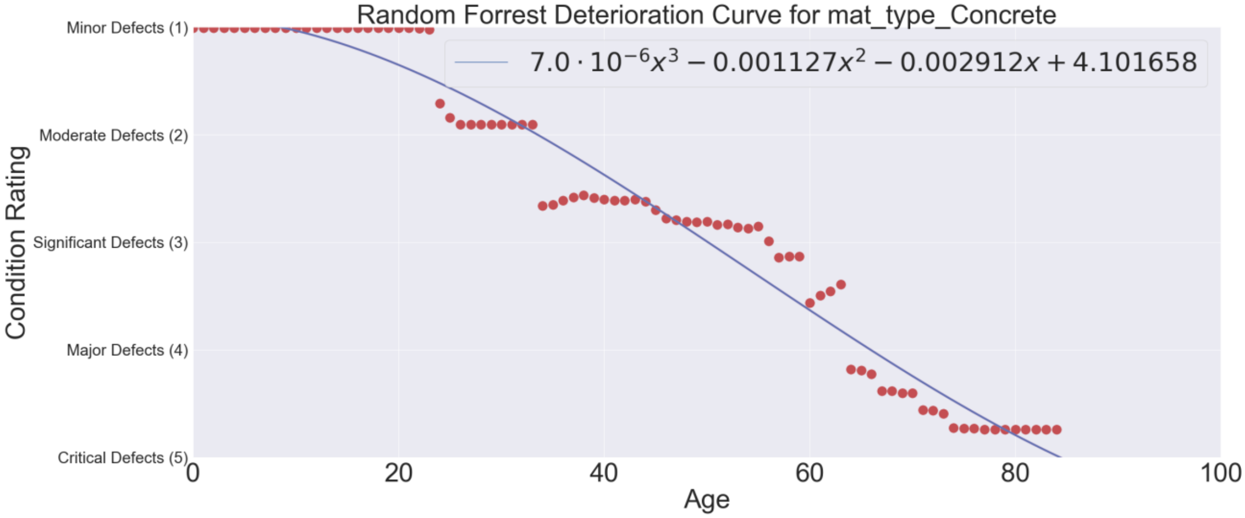


Figure 17-Deterioration curve with Random Forest for concrete culverts in Colorado

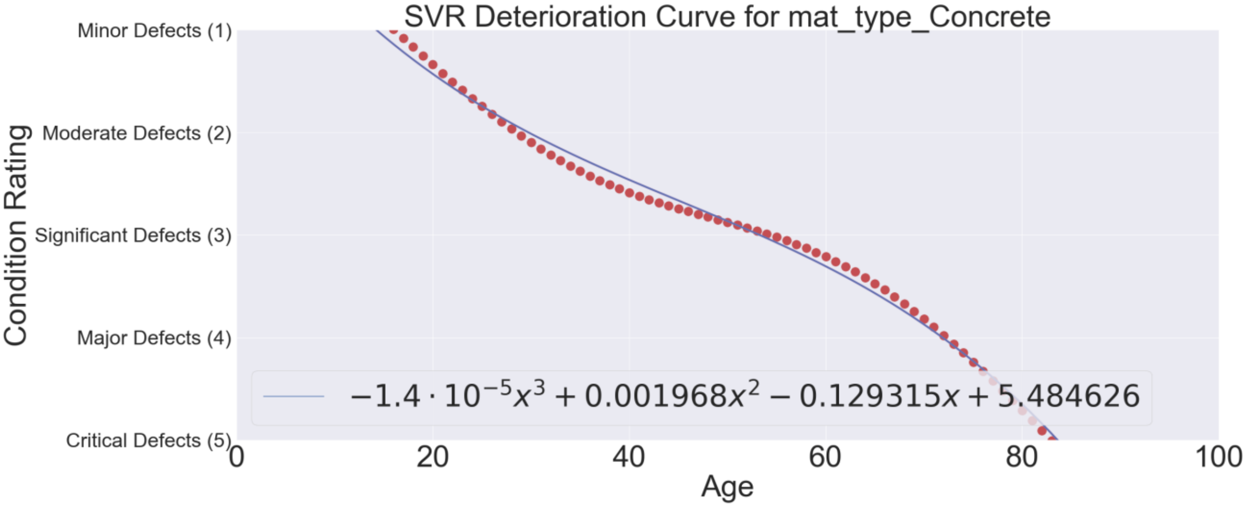


Figure 18-Deterioration curve with SVR for concrete culverts in Colorado

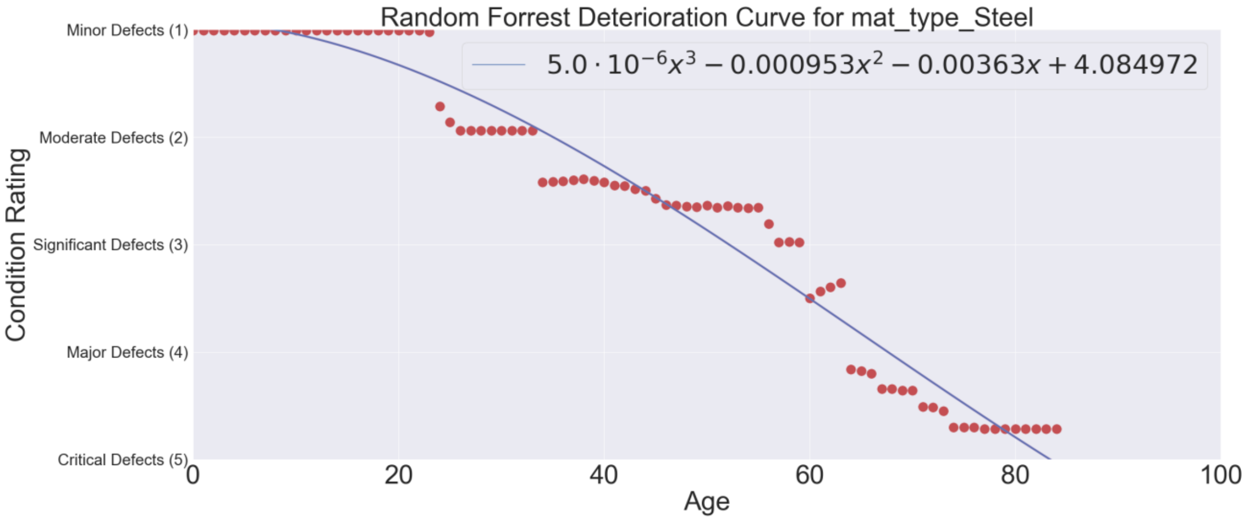


Figure 19-Deterioration curve with Random Forest for steel culverts in Colorado

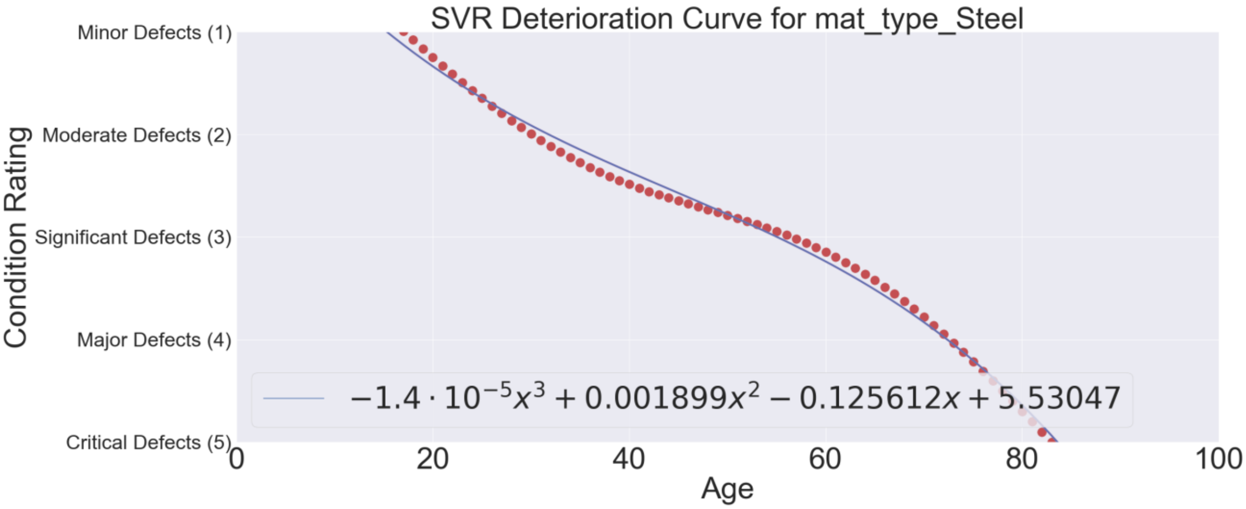


Figure 20-Deterioration curve with SVR for steel culverts in Colorado

4.2.3 Vermont Dataset

We collected the Vermont culvert dataset from the Vermont Agency of Transportation database. It had 107524 rows and 39 columns (features) when it was initially collected. After filtering and preprocessing the data, only 1130 rows and 24 columns (features) remained. The following are the deterioration curves that the SVR and RFR models generated. The RFR and SVR models developed for Vermont culverts achieved 71% and 60% accuracy, respectively, in predicting culvert conditions. (Road Importance = RI)

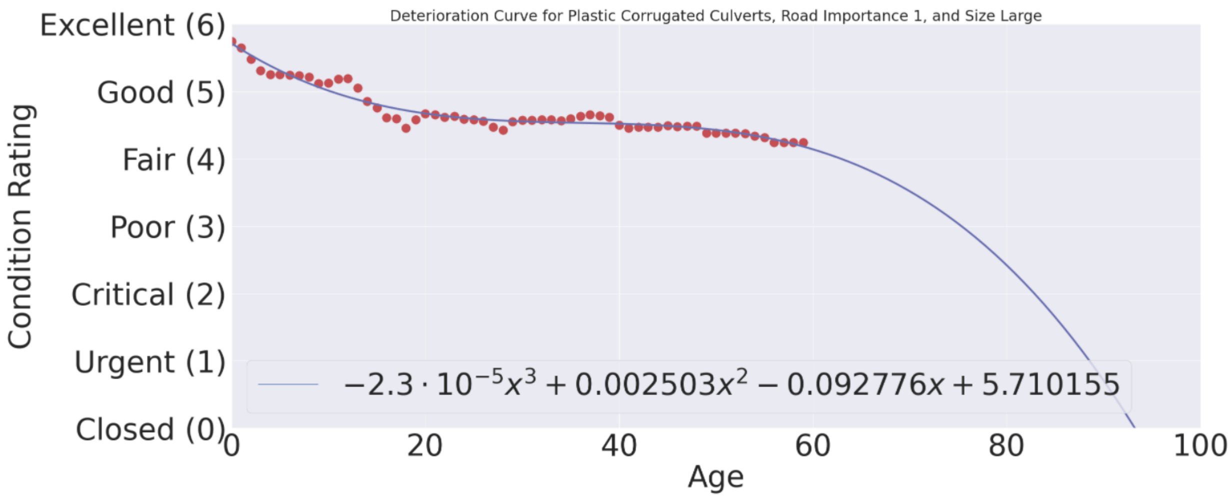


Figure 21-Deterioration curve for plastic corrugated culverts with Random Forest RI = 1

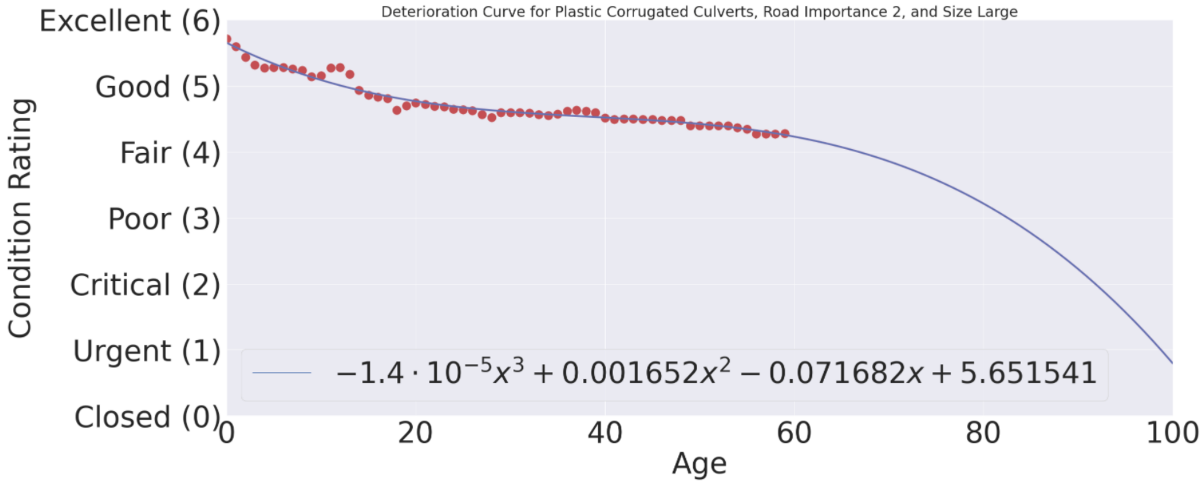


Figure 22-Deterioration curve for plastic corrugated culverts with Random Forest, RI = 2

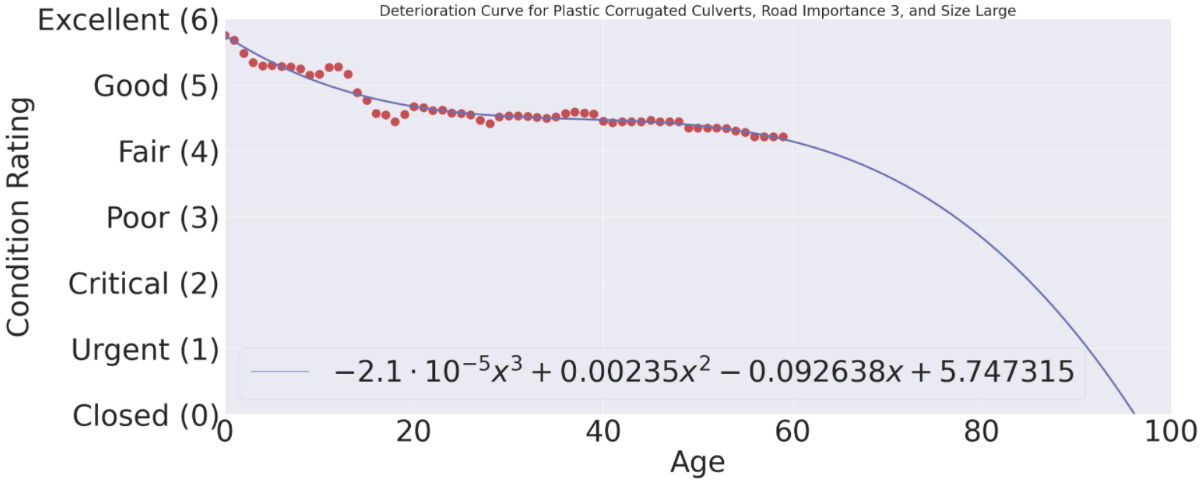


Figure 23-Deterioration curve for plastic corrugated culverts with Random Forest, RI = 3

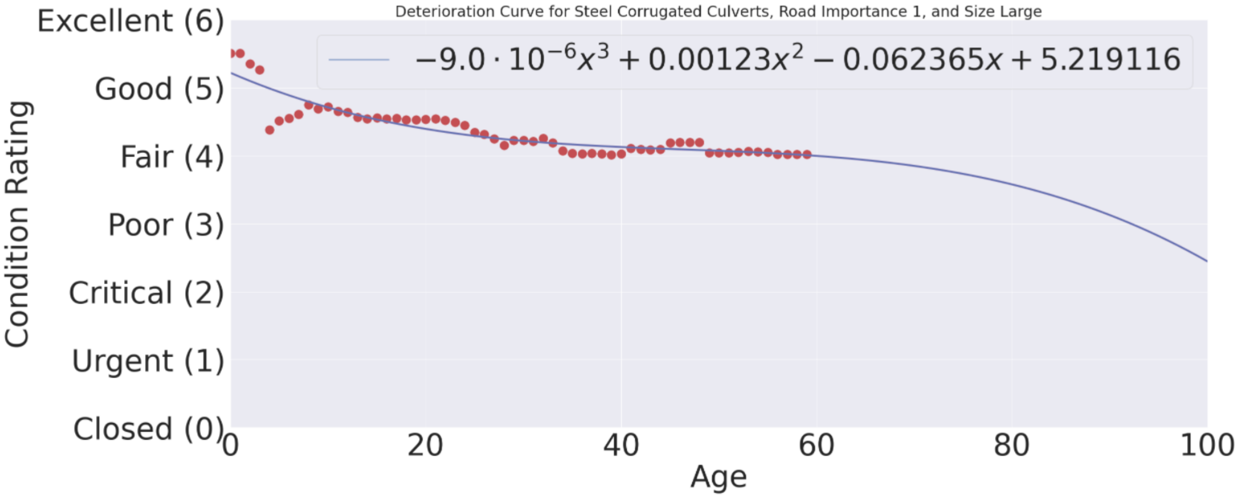


Figure 24-Deterioration curve for steel corrugated culverts with Random Forest, RI = 1

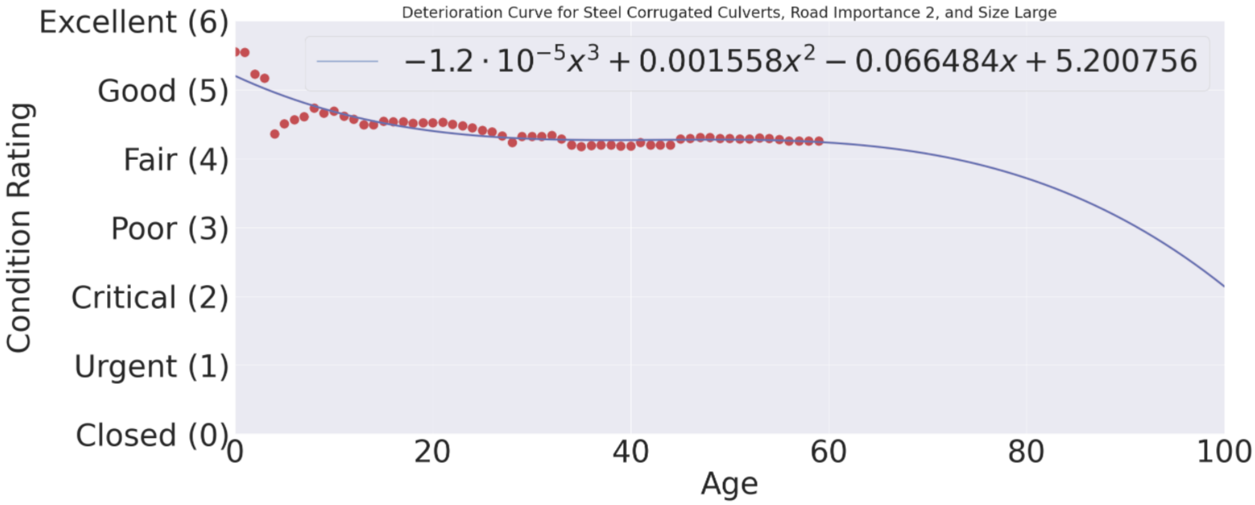


Figure 25-Deterioration curve for steel corrugated culverts with Random Forest, RI = 2

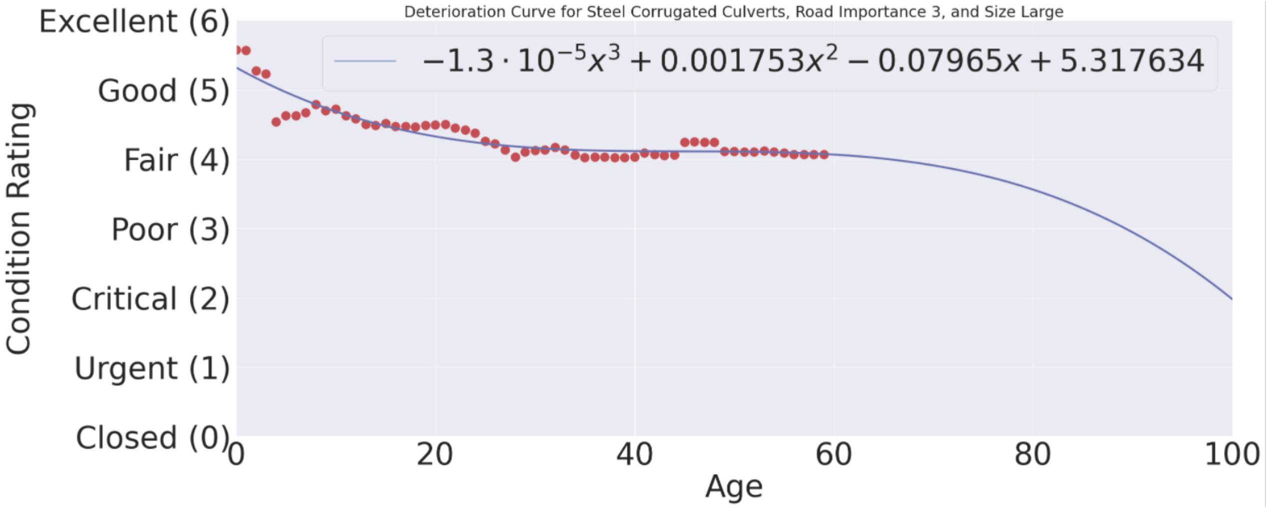


Figure 26-Deterioration curve for steel corrugated culverts with Random Forest, RI = 3

4.2.4 Three Datasets Together

Utah's culvert inventory was supplemented with two culvert inventories from Colorado and Vermont. In order to make data from two other inventories similar to Utah's culvert inventory, the data was preprocessed. As a result, we had a dataset similar to Utah's culvert inventory in terms of culvert features, but with more rows of data. After preprocessing, 2070 rows were included in the final dataset. Here are the deterioration curves generated by the SVR and RFR models for various culvert materials, including concrete, plastic, and steel. The RFR and SVR models developed for this dataset achieved 79% and 71% accuracy, respectively.

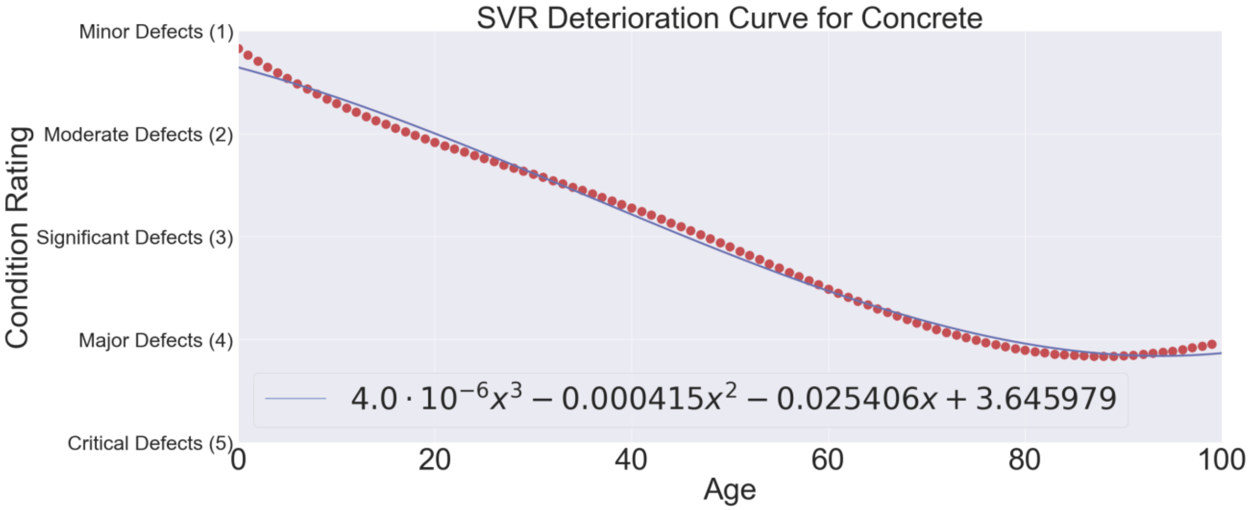


Figure 27-Deterioration curve for concrete culverts with SVR

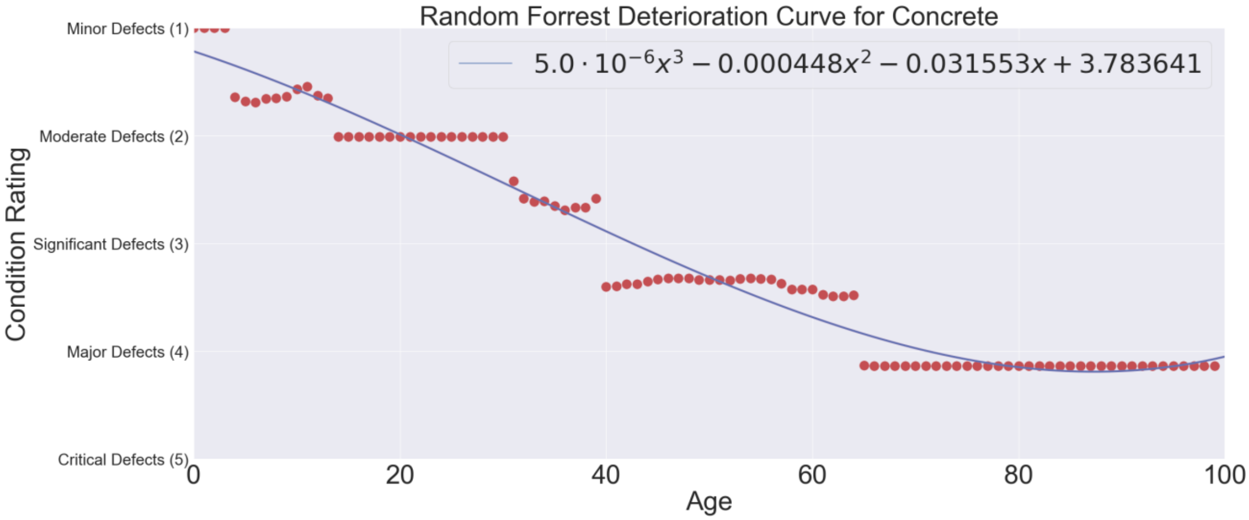


Figure 28-Deterioration curve for concrete culverts with Random Forest

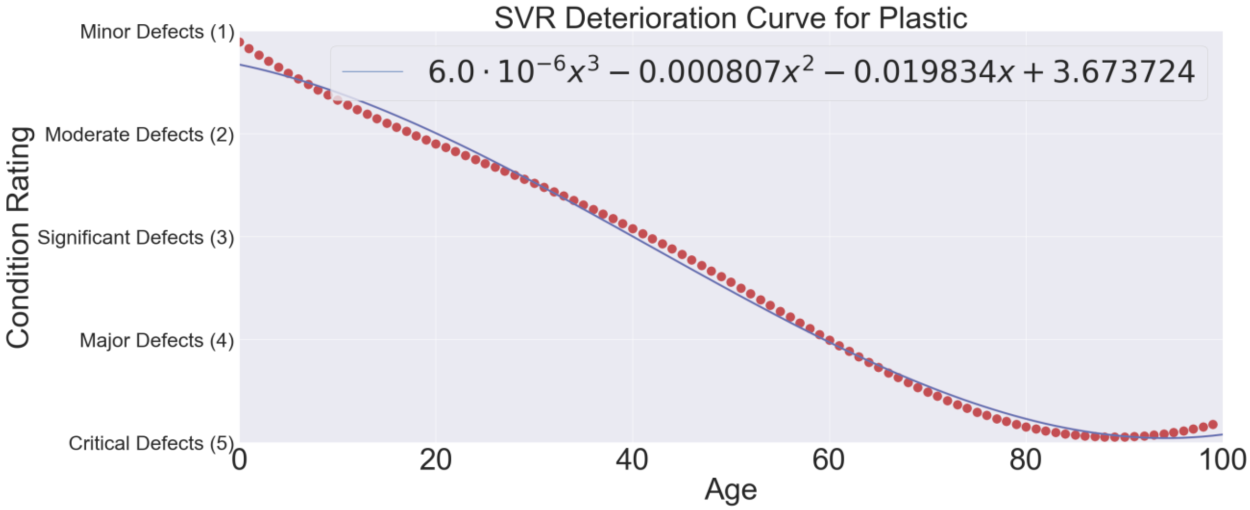


Figure 29-Deterioration curve for plastic culverts with SVR

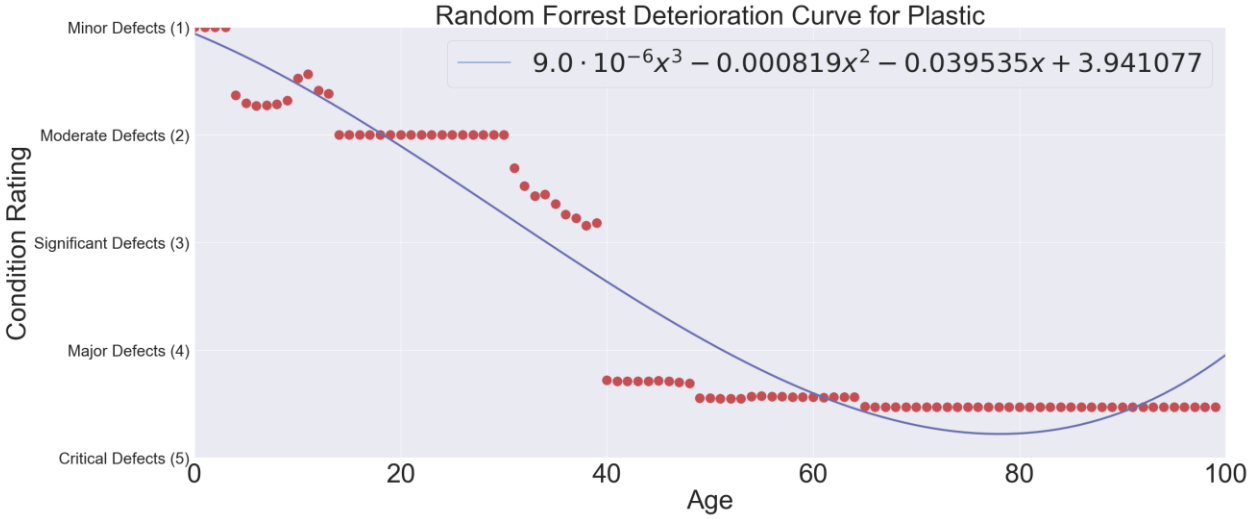


Figure 30-Deterioration curve for plastic culverts with Random Forest

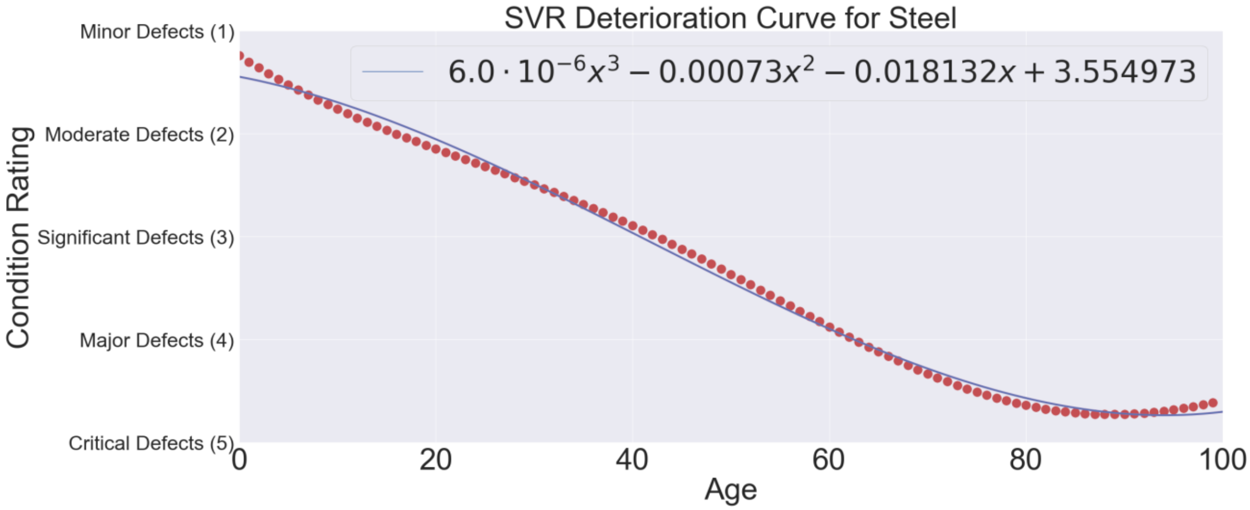


Figure 31-Deterioration curve for steel culverts with SVR

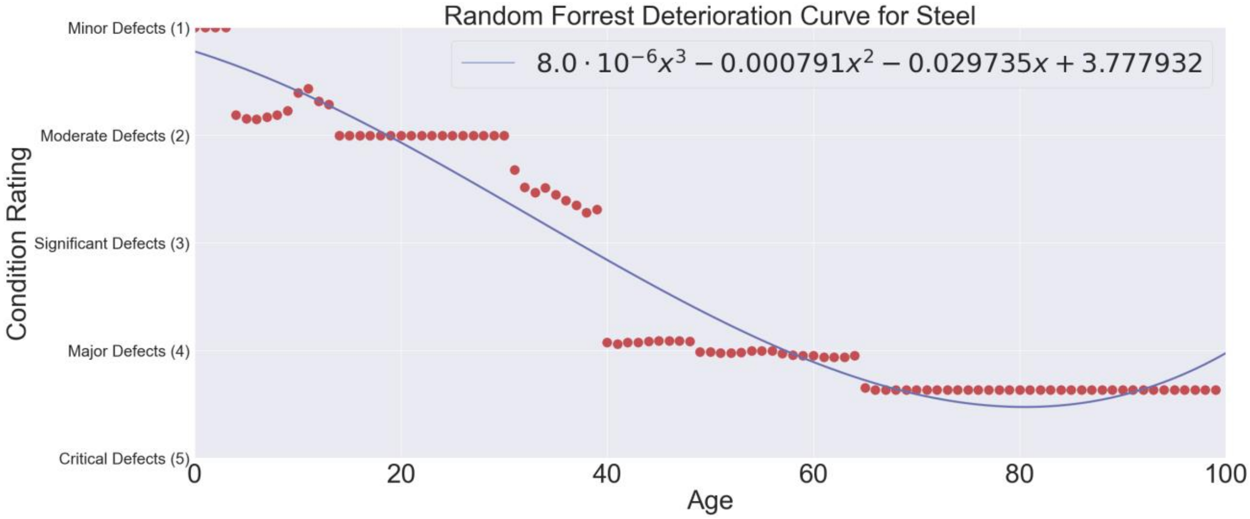


Figure 32-Deterioration curve for steel culverts with Random Forest

4.3 Inspection Frequency

The Utah 272-culverts dataset was collected between 2002 and 2003. Figure 33 depicts the distribution of culvert conditions in this dataset.

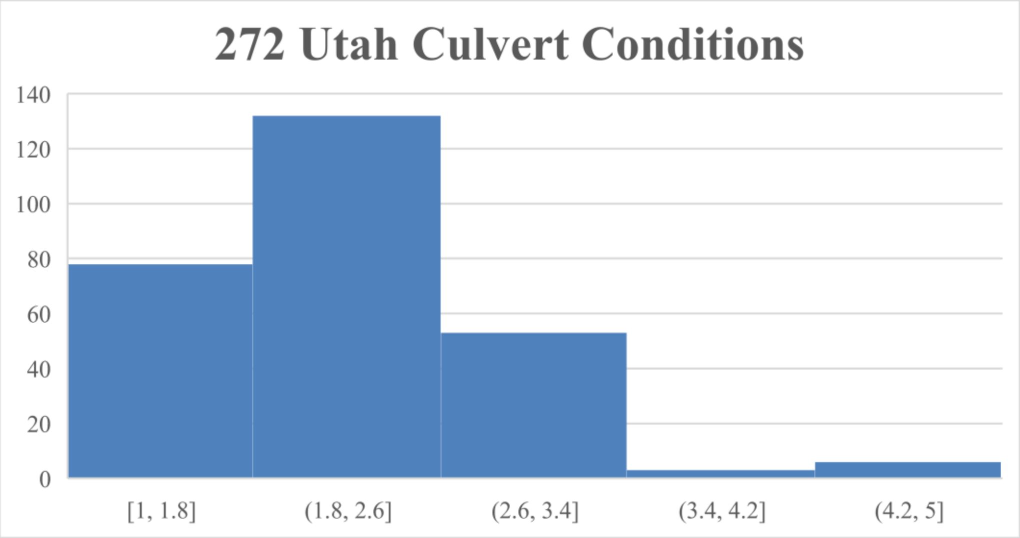
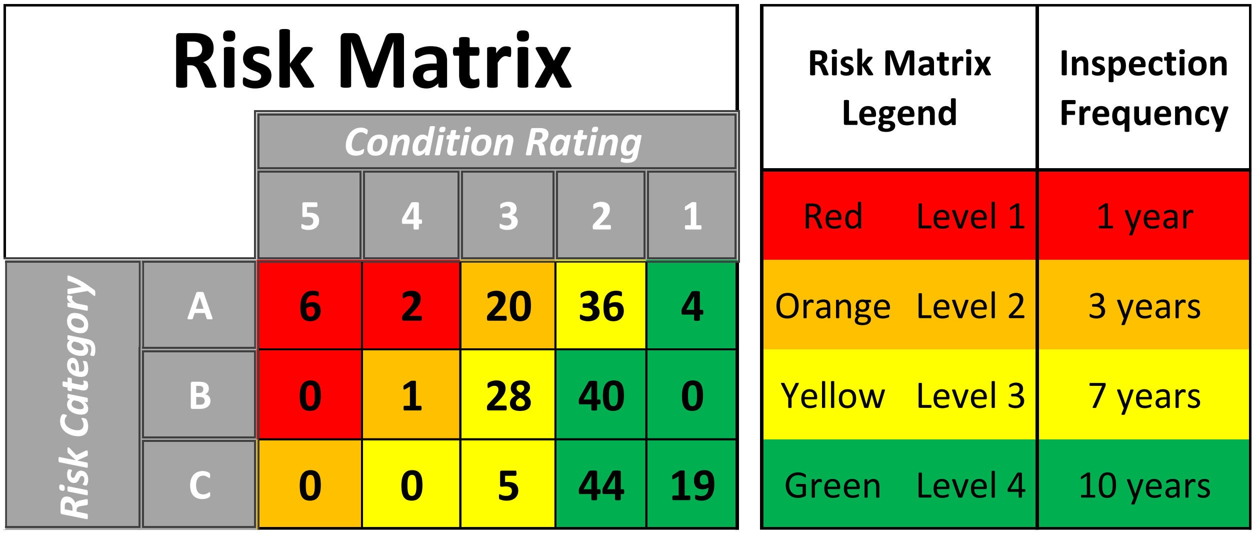


Figure 33-Utah culvert condition distribution

To calculate risk factors, we used two components: LOF and COF. As mentioned in section 2.4.1, LOF is calculated based on the condition of culverts and UDOT culvert risk assessment. For calculating COF, this study utilized numerous assumptions according to section 2.4.2. At last, the total cost of culvert failure was calculated based on the location of the culvert, as shown in Figure 6.

We determined each culvert's risk factor and category using section 2.4.3 and then generated the risk matrix for the entire Utah 272-culverts dataset. Figure 34 illustrates the results; the numbers within the matrix refer to the number of culverts with the associated rating and risk category. In this case, 67 culverts were in excellent condition (no need to be inspected), 107 culverts were in good condition (every 10 years inspection), 69 culverts were in fair condition (every 7 years inspection), 21 culverts were in poor condition (every 3 years inspection), and only 8 culverts were in critical condition (every year inspection). As a result of that, UDOT can save lots of money on Utah's culvert inspection while enhancing the culvert network's serviceability. UDOT can prioritize inspecting and maintaining critical culverts first and poor culverts second, depending on its culvert maintenance budget. UDOT must focus on 10% of inventory instead of the entire inventory, based on Figure 34. Compared to the traditional approach, this approach is more cost effective.



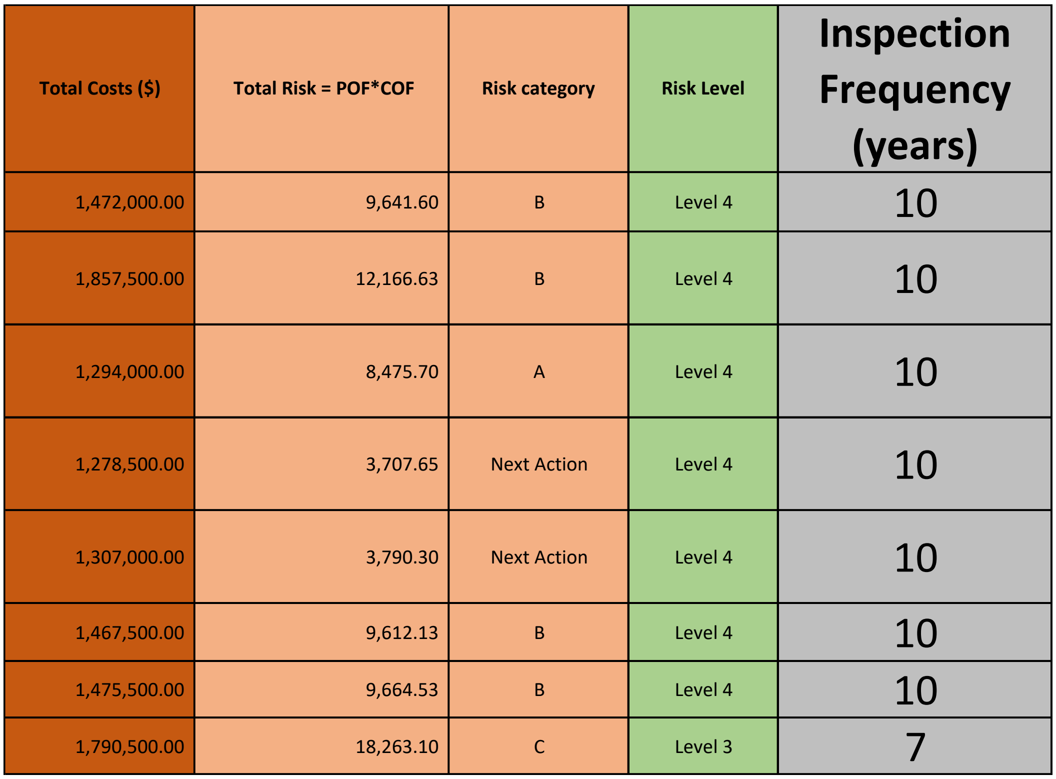
Risk Matrix

		Condition Rating				
		5	4	3	2	1
Risk Category	A	6	2	20	36	4
	B	0	1	28	40	0
	C	0	0	5	44	19

Risk Matrix Legend		Inspection Frequency
Red	Level 1	1 year
Orange	Level 2	3 years
Yellow	Level 3	7 years
Green	Level 4	10 years

Figure 34-Results of Utah dataset risk assessment

Using Table 8 in section 2.4.4 and the identified culvert risk levels, inspection frequencies were assigned to culverts. Figure 35 shows an example of this task.

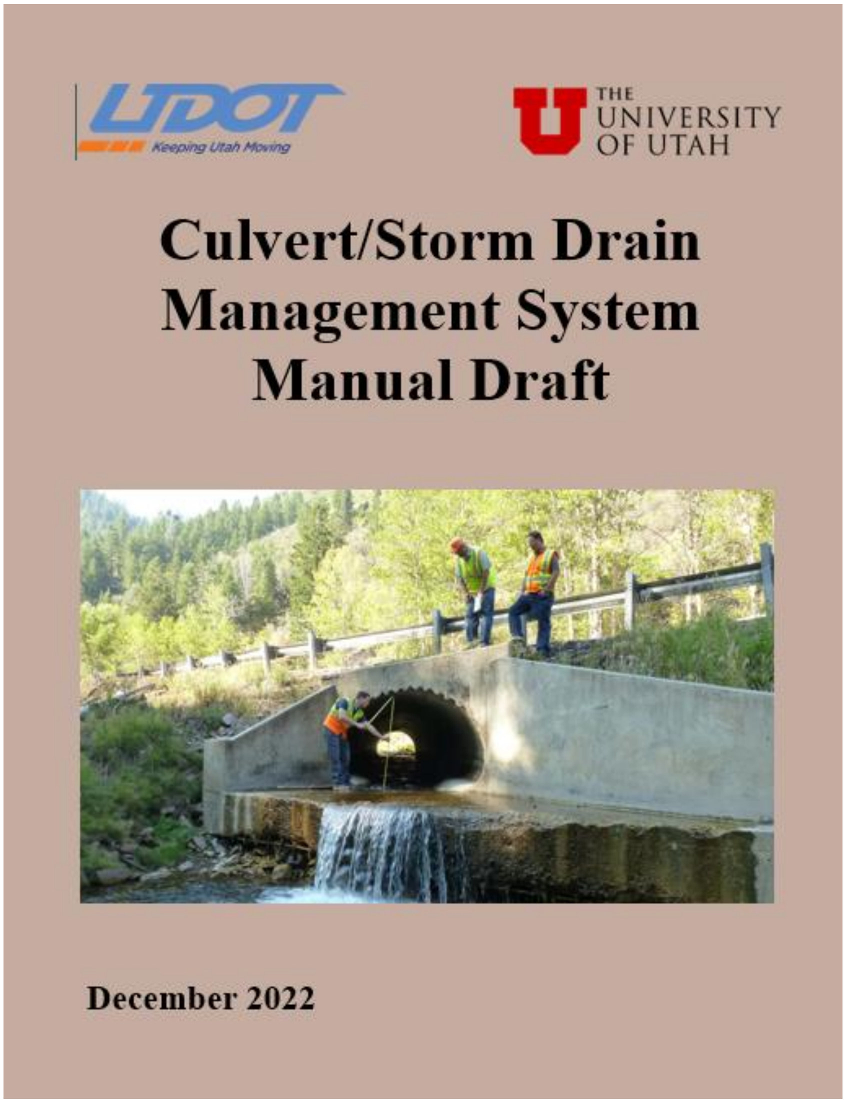


Total Costs ($)	Total Risk = POF*COF	Risk category	Risk Level	Inspection Frequency (years)
1,472,000.00	9,641.60	B	Level 4	10
1,857,500.00	12,166.63	B	Level 4	10
1,294,000.00	8,475.70	A	Level 4	10
1,278,500.00	3,707.65	Next Action	Level 4	10
1,307,000.00	3,790.30	Next Action	Level 4	10
1,467,500.00	9,612.13	B	Level 4	10
1,475,500.00	9,664.53	B	Level 4	10
1,790,500.00	18,263.10	C	Level 3	7

Figure 35-Example of assigning inspection frequency to culverts of Utah

4.4 Utah’s Culvert/Storm Drain Management System Manual Draft

Reviewing several manuals and guidelines for culvert inspection and maintenance resulted in a manual tailored to Utah's culverts. Among the topics addressed in this manual are Utah's pipe rating system, and proposed data-driven culvert inspection scheduling. It is the first draft of the manual, and the UDOT maintenance division could enhance it as needed in the future. It is anticipated by using this manual, UDOT can improve the performance of its culvert network and save money on maintenance. In addition, it can prevent serious damage to the transportation system's properties and the lives of its travelers.


UDOT Keeping Utah Moving

THE UNIVERSITY OF UTAH

Culvert/Storm Drain
Management System
Manual Draft

December 2022

Figure 36-The proposed culvert management manual

<u>5.0 CONCLUSIONS</u>

5.1 Summary and Findings

The Utah Department of Transportation (UDOT) has an incomplete data set of information and conditions on Utah culverts, posing a serious risk to the Utah transportation system and the traveling public's safety. Without a complete inventory and condition assessment, UDOT cannot properly manage this asset. Thus, UDOT plans to complete the inventory and condition assessment of culverts, establish an inspection cycle, and set up a mitigation strategy through a risk-based program to determine program funding needs. This research aims to assist UDOT in estimating the deterioration curve of culverts in Utah and recommending culvert inspection frequencies based on these curves as two essential steps in developing a comprehensive CMS for Utah. Another application of deterioration curves is for predicting the service life of culverts to rehabilitate or replace before they fail. The proposed method is based on machine learning algorithms and the risk-based prioritization approach. The developed system is intended to be integrated into the ATOM software, which combines asset and maintenance management.

Although Utah has over 47,000 culverts, UDOT's culvert inventory only contains complete information on 272 culverts. As a result, this study proposes to forecast Utah culvert deterioration curves using culvert inspection data collected from three states in the US. The final deterioration curves were derived using SVR and RFR algorithms and are based on culvert inventories from Colorado, Utah, and Vermont. The shape of the drawn curves was reasonable looking at the theory and limited data. Despite limited data availability, the developed models for Colorado, Vermont, and Utah datasets performed at between 60 and 80% accuracy, which is acceptable. Additionally, the model developed for the combination of Colorado, Vermont, and Utah datasets performed well as the accuracy for both SVR and RFR models was 71% and 79%, respectively.

Generating the deterioration curves of culverts in these three states can provide a better picture of the deterioration rate of culverts in Utah. Consequently, the final curves can be used to estimate the condition of culverts in Utah based on their age. Also, final culvert deterioration curve can be used to estimate the likelihood of failure, and following that, it can be used to determine the frequency of culvert inspection based on the risk-based prioritization approach. Another application of Utah's final culvert deterioration curve is proactive maintenance, which involves replacing or repairing culverts with poor condition ratings before they fail. As a result, the performance level of the culvert network system will considerably improve, while the potential for distribution in the network will reduce. In contrast to the traditional approach, UDOT may be able to save money and time by implementing this method.

In accordance with the proposed approach for inspecting culverts, we developed a draft of the Culvert/Storm Drain Management System Manual for Utah. As a result of reviewing culvert maintenance and inspection manuals published by the federal government and other state DOTs, we developed the manual for Utah. As the manual was developed for Utah's culverts, we used UDOT's rating system to inspect them. Contents of several manuals were combined and justified for Utah's culverts. Inspecting culverts, inventorying data, and maintaining culverts were the key sections of the manual.

5.2 Limitations and Challenges

- Due to limited data in Utah's culvert inventory, we used the culvert inventories of two other states. Their availability was the reason we used them. The performance of the models would be better validated with more data from Utah's culvert inventories.
- Considering that data were collected by humans, some errors could occur during the inspection of culverts, so we filtered data on the basis of their age and condition. Consequently, the data used for developing ML models was a part of the whole.

REFERENCES

AASHTO. (2020). AASHTO Culvert and Storm Drain System Inspection Guide. In *Culvert/Storm Drain Inspection Guide* (First, Issue August). AASHTO.

Agrawal, A. K., Kawaguchi, A., & Chen, Z. (2008). *Bridge element deterioration rates*. New York (State). Dept. of Transportation.

Anbari, M. J., Tabesh, M., & Roozbahani, A. (2017). Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. *Journal of Environmental Management*, *190*, 91–101.

Awad, M., & Khanna, R. (2015). Support vector regression. In *Efficient learning machines* (pp. 67–80). Springer.

Baik, H.-S., Jeong, H. S., & Abraham, D. M. (2006). Estimating transition probabilities in Markov chain-based deterioration models for management of wastewater systems. *Journal of Water Resources Planning and Management*, *132*(1), 15–24.

Bao, Y., Song, C., Wang, W., Ye, T., Wang, L., & Yu, L. (2013). Damage Detection of Bridge Structure Based on SVM. *Mathematical Problems in Engineering*, *2013*, 490372. https://doi.org/10.1155/2013/490372

Bealey, M. (1984). *PRECAST CONCRETE PIPE DURABILITY: STATE OF THE ART (DISCUSSION AND CLOSURE)* (Issue 1001).

Beaver, J. L., & McGrath, T. J. (2005). Management of Utah highway culverts. *Transportation Research Record*, *1904*, 113–123. https://doi.org/10.3141/1904-12

Bednar, L. (1989). Plain galvanized steel drainage pipe durability estimation with a modified California chart. *Transportation Research Record*, *1231*, 70–79.

Berwick, R. (2003). An Idiot's guide to Support vector machines (SVMs). *Retrieved on October*, *21*, 2011.

Betti, R. (2010). Aging Infrastructure: Issues. *Research, and Technology. Buildings and*

Infrastructure Protection Series. Infrastructure Protection and Disaster Management Division, Science & Technology Directorate, US Department of Homeland Security.

Bowers, J. D., Magers, S. R., Pyrz, J., & Bullock, D. M. (2014). *Processes of small culvert inspection and asset management.* Purdue University. Joint Transportation Research Program.

Burges, C. J. C. (1998). A tutorial on support vector machines for pattern recognition. *Data Mining and Knowledge Discovery*, *2*(2), 121–167.

Cahoon, J. E., Baker, D., & Carson, J. (2002). Factors for rating condition of culverts for repair or replacement needs. *Transportation Research Record*, *1814*(1), 197–202.

Chughtai, F., & Zayed, T. (2008). Infrastructure condition prediction models for sustainable sewer pipelines. *Journal of Performance of Constructed Facilities*, *22*(5), 333–341.

Colorado Urrea, G. J. (2014). *Service life of concrete and metal culverts located in Ohio Department of Transportation Districts 9 and 10*. Ohio University.

Degler, G. H., Cowherd, D. C., & Hurd, J. O. (1988). *An analysis of visual field inspection data of 900 pipe-arch structures* (Issue 1191).

Drucker, H., Burges, C. J., Kaufman, L., Smola, A., & Vapnik, V. (1996). Support vector regression machines. *Advances in Neural Information Processing Systems, 9*.

Eubanks, S. E. (2017). Asset Management and Criticality Assessment for Public Works Infrastructure. *2017 INAFSM Conference*.

FHWA. (2007). *Culvert Management Systems: Alabama, Maryland, Minnesota, and Shelby County*.

Gassman, S. L., Sasanakul, I., Pierce, C. E., Gheibi, E., Starcher, R., Ovalle, W., & Rahman, M. (2017). *Failures of Pipe Culverts from a 1000-Year Rainfall Event in South Carolina*. 114–124. https://doi.org/10.1061/9780784480441.013

Ghodoosi, F., Bagchi, A., Zayed, T., & Zaki, A. R. (2014). Reliability-based condition assessment of a deteriorated concrete bridge. *Structural Monitoring and Maintenance*, *1*(4), 357–369.

Heger, F. J., & Selig, E. T. (1994). Rigid Pipe Distress in High Embankments over Soft Soil Strata. *Transportation Research Record, 1431*.

Hickey, P. J., Erfani, A., & Cui, Q. (2022). Use of LinkedIn Data and Machine Learning to Analyze Gender Differences in Construction Career Paths. *Journal of Management in Engineering*, *38*(6), 4022060.

Kotze, R., Ngo, H., & Seskis, J. (2015). *Improved bridge deterioration models, predictive tools and costs*.

Kurt, C. E., & McNichol, G. W. (1991). Microcomputer-Based Culvert Ranking System. *Transportation Research Record, 1315*.

Laender, A. H. F., Ribeiro-Neto, B. A., da Silva, A. S., & Teixeira, J. S. (2002). A Brief Survey of Web Data Extraction Tools. *SIGMOD Rec.*, *31*(2), 84–93. https://doi.org/10.1145/565117.565137

Li, H., Parikh, D., He, Q., Qian, B., Li, Z., Fang, D., & Hampapur, A. (2014). Improving rail network velocity: A machine learning approach to predictive maintenance. *Transportation Research Part C: Emerging Technologies*, *45*, 17–26. https://doi.org/https://doi.org/10.1016/j.trc.2014.04.013

Mauch, M., & Madanat, S. (2001). Semiparametric hazard rate models of reinforced concrete bridge deck deterioration. *Journal of Infrastructure Systems*, *7*(2), 49–57.

McGrath, T. J., & Beaver, J. L. (2004). Condition Assessment of Utah Highway Culverts and Determination of Culvert Performance Measures. In *Utah Department of Transportation Report UT-81FR0132, Salt Lake City, UT*.

Meacham, D. G., Hurd, J. O., & Shisler, W. W. (1982). *Ohio culvert durability study*. Department of Transportation.

Meegoda, J. N., & Juliano, T. M. (2009). *Corrugated steel culvert pipe deterioration: final report,* *August 2009*. New Jersey. Dept. of Transportation.

Meegoda, J. N., Juliano, T. M., Potts, L., Tang, C., & Marhaba, T. (2017). Implementation of a drainage information, analysis and management system. *Journal of Traffic and Transportation Engineering (English Edition)*, *4*(2), 165–177. https://doi.org/10.1016/j.jtte.2017.03.002

Meegoda, J. N., & Zou, Z. (2015). Long-Term Maintenance of Culvert Networks. *Journal of Pipeline Systems Engineering and Practice*, *6*(4), 04015003. https://doi.org/10.1061/(asce)ps.1949-1204.0000194

Michigan Transportation Asset Management Council. (n.d.). *Michigan Non-NBI Culvert Structure Inspection* (Vol. 4, Issue 1).

Mitchell, G. F., Masada, T., Sargand, S. M., Tarawneh, B., Stewart, K., Mapel, S., & Roberts, J. (2005). Risk assessment and update of inspection procedures for culverts. *(No. FHWA/OH-2005/002).*, *February*. http://ntl.bts.gov/lib/56000/56000/56064/OH_14813FR.PDF

Mohammadi, P., Rashidi, A., Malekzadeh, M., & Tiwari, S. (2023). Evaluating various machine learning algorithms for automated inspection of culverts. *Engineering Analysis with Boundary Elements*, *148*, 366–375. https://doi.org/https://doi.org/10.1016/j.enganabound.2023.01.007

Morales, F. J., Reyes, A., Cáceres, N., Romero, L. M., Benitez, F. G., Morgado, J., Duarte, E., & Martins, T. (2017). Historical maintenance relevant information road-map for a self-learning maintenance prediction procedural approach. *IOP Conference Series: Materials Science and Engineering*, *236*(1), 12107.

Najafi, M., & Kulandaivel, G. (2005). Pipeline condition prediction using neural network models. In *Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy* (pp. 767–781).

NASSCO (National Association of Sewer Service Companies). (2001). *NASSCO's pipeline assessment and certification program Marriotsville. Marriotsville, MD: NASSCO.*

Noll, J., & Frascella, B. (2010). Practical factors and considerations related to culvert inspection. *CE News*, *22*(6), 1–5.

NYSDOT. (2006). *Culvert inventory and inspection manual - New York*. *May*. https://www.dot.ny.gov/divisions/operating/oom/transportation-maintenance/repository/CulvertInventoryInspectionManual.pdf

OhioDOT. (2021). CONDUIT MANAGEMENT MANUAL. *Design*, *2*(614).

Piratla, K. R., Jin, H., & Yazdekhasti, S. (2019a). A failure risk-based culvert renewal prioritization framework. *Infrastructures*, *4*(3), 1–14. https://doi.org/10.3390/infrastructures4030043

Piratla, K. R., Jin, H., & Yazdekhasti, S. (2019b). A Failure Risk-Based Culvert Renewal Prioritization Framework. In *Infrastructures* (Vol. 4, Issue 3). https://doi.org/10.3390/infrastructures4030043

Raucher, R. S. (2017). *Managing infrastructure risk: The consequence of failure for buried assets*. Water Research Foundation.

Renman, G. T., Kolota, C., Kasbekar, N., & Hammer, R. (2021). *Bridge Element Inspection Manual*. *2014*. https://deldot.gov/Publications/manuals/bridge_inspection/pdfs/bridge_element_inspection_manual.pdf

Richie, M. C., & Beaver, J. L. (2017). *Culvert and Storm Drain System Inspection Manual*.

Ring, G. W. (1984). *Culvert durability: where are we?* (Issue 1001).

Roads and Traffic Authority. (2010). *Culvert Risk Assessment Guideline V3.02*. *December*.

Salazar, D. A., Iván Vélez, J., & Salazar, J. C. (2012). *Comparison between SVM and Logistic Regression: Which One is Better to Discriminate? Comparación entre SVM y regresión logística: ¿cuál es más recomendable para discriminar?* *35*(2), 223–237.

Salem, O., Salman, B., & Najafi, M. (2012). Culvert asset management practices and deterioration modeling. *Transportation Research Record*, *2285*, 1–7. https://doi.org/10.3141/2285-01

Samuel, A. L. (2000). Some studies in machine learning using the game of checkers. *IBM Journal of Research and Development*, *44*(1.2), 206–226.

Schlotjes, M. R., Burrow, M. P. N., Evdorides, H. T., & Henning, T. F. P. (2015). Using support vector machines to predict the probability of pavement failure. *Proceedings of the Institution of Civil Engineers - Transport*, *168*(3), 212–222. https://doi.org/10.1680/tran.12.00084

Sezen, H. (2022). *Rehabilitation of Culverts and Buried Storm Drain Pipes*.

Sousa, F., Dias, S., Matos, J. C., & Camões, A. (2021). Development of Culvert Risk Condition Evaluation for Decision-Making Within Road Infrastructure Management. *Lecture Notes in Civil Engineering*, *153 LNCE*, 265–279. https://doi.org/10.1007/978-3-030-73616-3_19

Srikanth, I., & Arockiasamy, M. (2020). Deterioration models for prediction of remaining useful life of timber and concrete bridges: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *7*(2), 152–173. https://doi.org/10.1016/j.jtte.2019.09.005

Stoner, M., Pang, W., & Piratla, K. (2019). Predicting Culvert Deterioration Using Physical and Environmental Time-Independent Variables. *Journal of Pipeline Systems Engineering and Practice*, *10*(4), 04019035. https://doi.org/10.1061/(asce)ps.1949-1204.0000409

Thompson, P. D., Ford, K. M., Arman, M. H. R., Labi, S., Sinha, K., & Shirolé, A. (2012). NCHRP Report 713: Estimating life expectancies of highway assets. *Transportation Research Board of the National Academies, Washington, DC*.

U.S. Department of Transportation/Fedral Highway Administration (FHWA). (2017). 2015 Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Report to Congress. *Government Printing Office*.

Villwock-Witte, N., Clouser, K., & Fay, L. (2016). *Culvert Asset Management System: Best Practices/Pilot Project 13. Type of Report and Period Covered Final Report*. *September 2016*.

Vladeanu, G. J., & Koo, D. D. (2015). A comparison study of water pipe failure prediction models using Weibull distribution and binary logistic regression. In *Pipelines 2015* (pp. 1590–1601).

Vladeanu, G. J., & Matthews, J. C. (2019). Consequence-of-Failure Model for Risk-Based Asset Management of Wastewater Pipes Using AHP. *Journal of Pipeline Systems Engineering and Practice, 10*(2), 04019005. https://doi.org/10.1061/(asce)ps.1949-1204.0000370

Wang, W., Qin, Y., Li, X., Wang, D., & Chen, H. (2017). Comparisons of faulting-based pavement performance prediction models. *Advances in Materials Science and Engineering, 2017*.

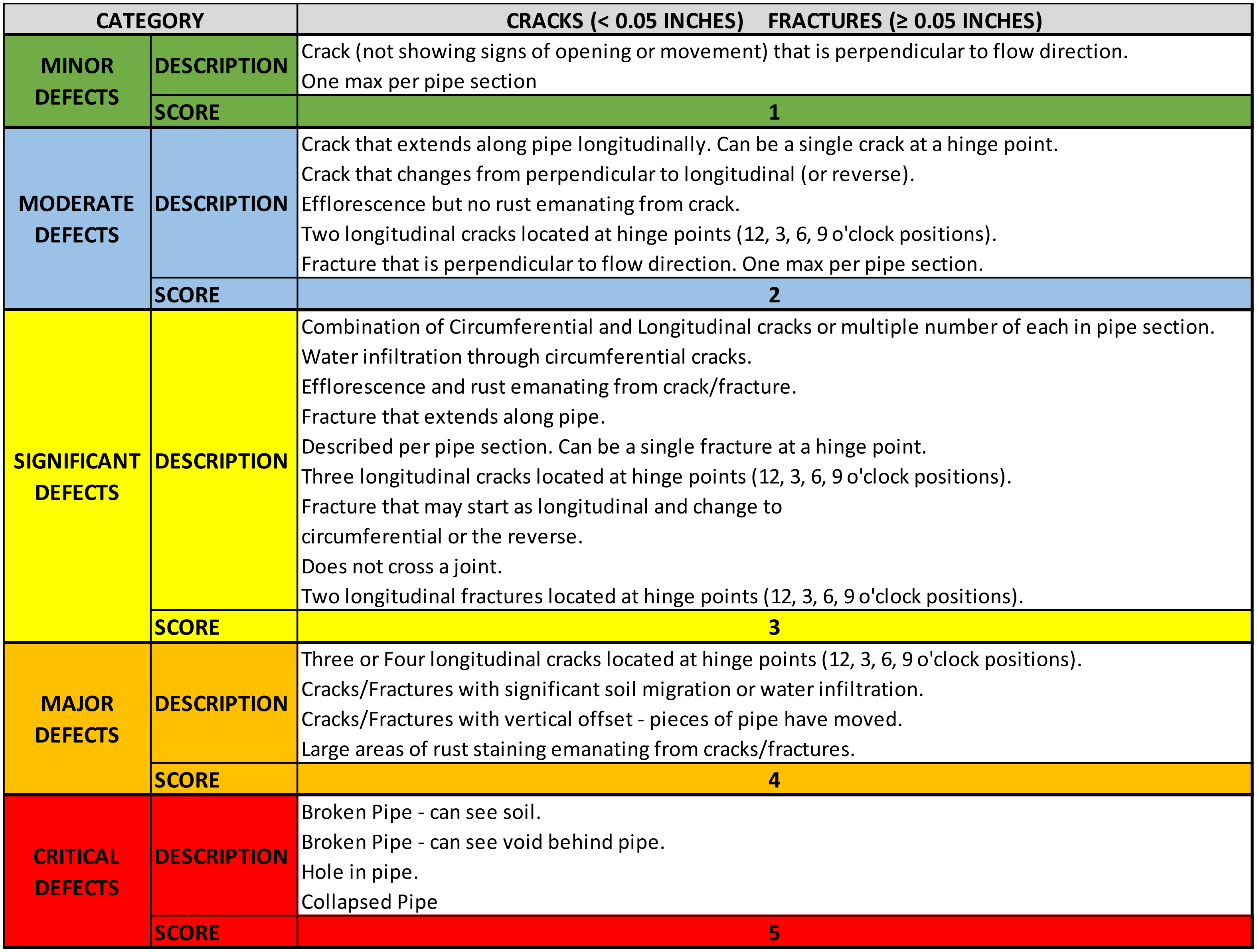
Web Soil Survey. (n.d.). Retrieved May 28, 2022, from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

Wirahadikusumah, R., Abraham, D., & Iseley, T. (2001). Challenging issues in modeling deterioration of combined sewers. *Journal of Infrastructure Systems, 7*(2), 77–84.

Yang, C. (2011). *Predicting deterioration rate of culvert structures utilizing a Markov model* (Issue August). Louisiana Tech University.

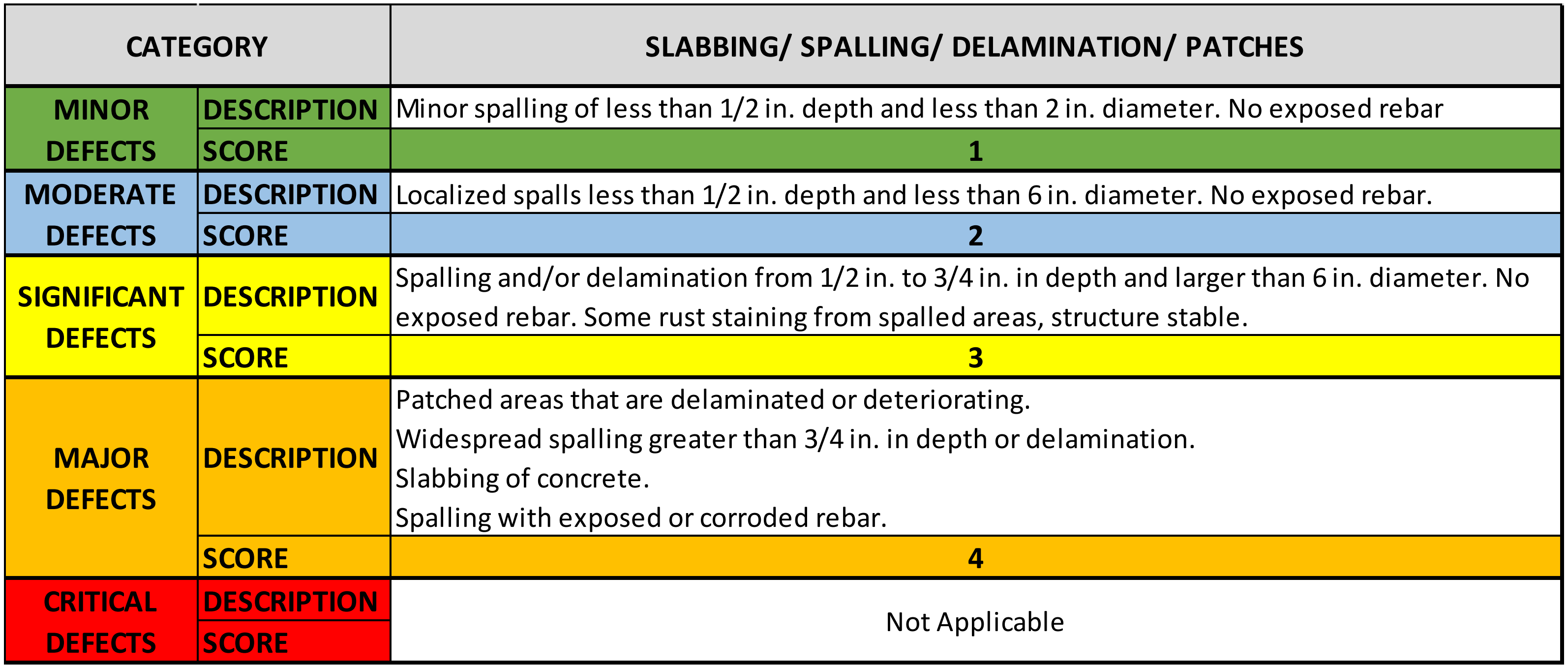
Zhang, C., & Ma, Y. (2012). *Ensemble machine learning: methods and applications*. Springer.

APPENDIX A: UDOT Pipe Defect Rating Sheets



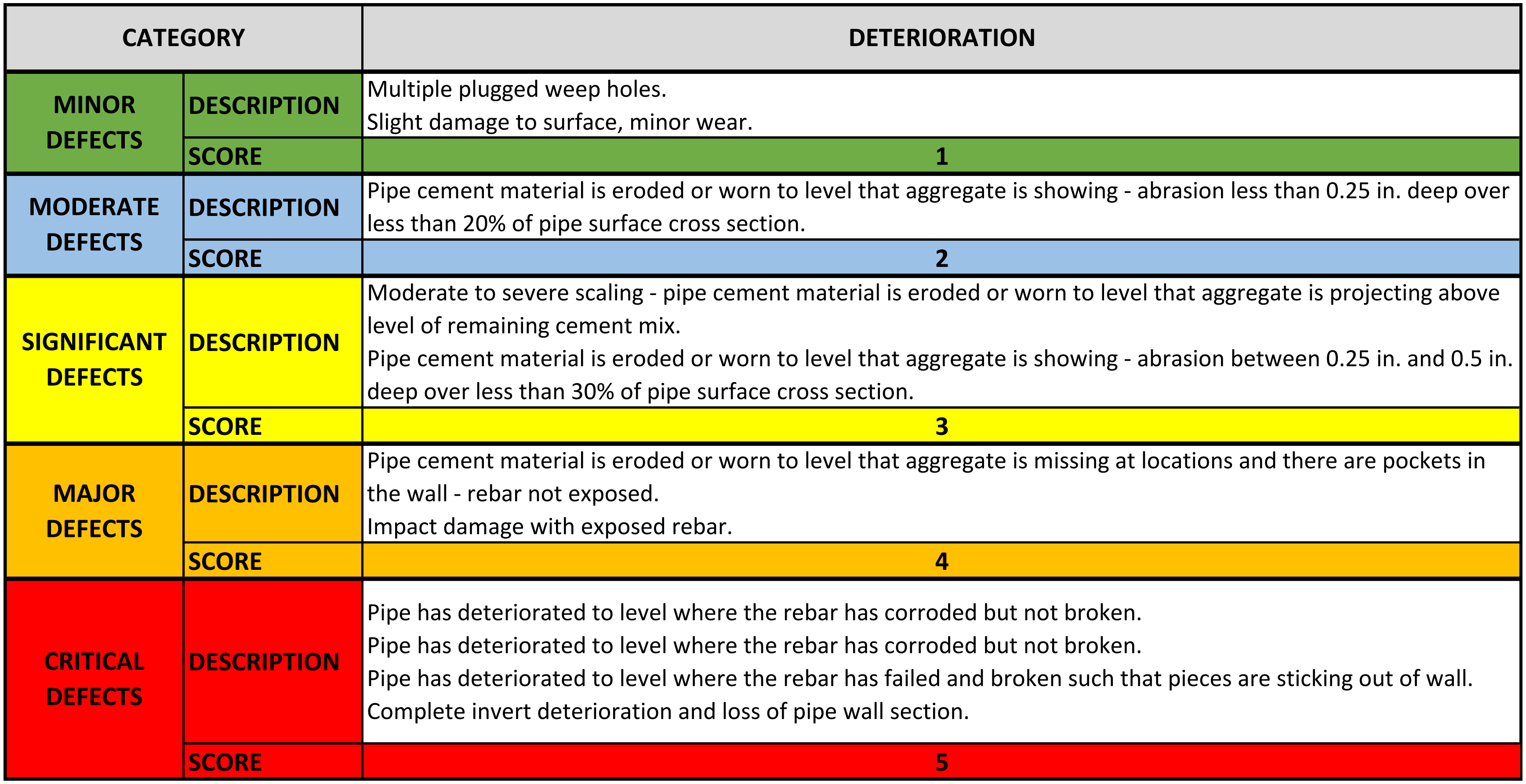
CATEGORY		CRACKS (< 0.05 INCHES) FRACTURES (≥ 0.05 INCHES)
MINOR DEFECTS	DESCRIPTION	Crack (not showing signs of opening or movement) that is perpendicular to flow direction. One max per pipe section
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Crack that extends along pipe longitudinally. Can be a single crack at a hinge point. Crack that changes from perpendicular to longitudinal (or reverse). Efflorescence but no rust emanating from crack. Two longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions). Fracture that is perpendicular to flow direction. One max per pipe section.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Combination of Circumferential and Longitudinal cracks or multiple number of each in pipe section. Water infiltration through circumferential cracks. Efflorescence and rust emanating from crack/fracture. Fracture that extends along pipe. Described per pipe section. Can be a single fracture at a hinge point. Three longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions). Fracture that may start as longitudinal and change to circumferential or the reverse. Does not cross a joint. Two longitudinal fractures located at hinge points (12, 3, 6, 9 o'clock positions).
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Three or Four longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions). Cracks/Fractures with significant soil migration or water infiltration. Cracks/Fractures with vertical offset - pieces of pipe have moved. Large areas of rust staining emanating from cracks/fractures.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Broken Pipe - can see soil. Broken Pipe - can see void behind pipe. Hole in pipe. Collapsed Pipe
	SCORE	5

Figure 37-Concrete culvert rating system-1



CATEGORY		SLABBING/ SPALLING/ DELAMINATION/ PATCHES
MINOR DEFECTS	DESCRIPTION	Minor spalling of less than 1/2 in. depth and less than 2 in. diameter. No exposed rebar
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Localized spalls less than 1/2 in. depth and less than 6 in. diameter. No exposed rebar.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Spalling and/or delamination from 1/2 in. to 3/4 in. in depth and larger than 6 in. diameter. No exposed rebar. Some rust staining from spalled areas, structure stable.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Patched areas that are delaminated or deteriorating. Widespread spalling greater than 3/4 in. in depth or delamination. Slabbing of concrete. Spalling with exposed or corroded rebar.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Not Applicable
	SCORE	

Figure 38-Concrete culvert rating system-2

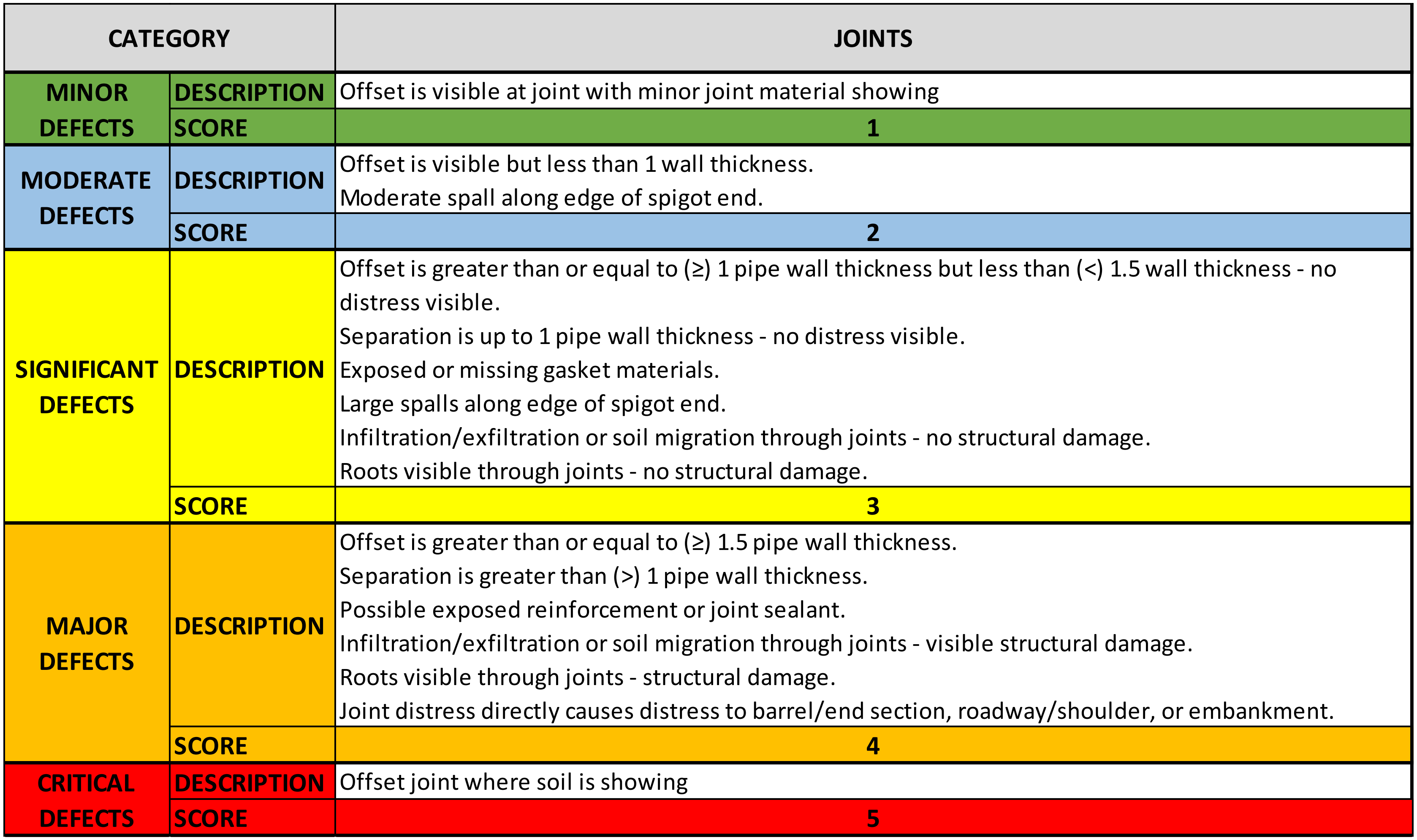


CATEGORY		DETERIORATION
MINOR DEFECTS	**DESCRIPTION**	Multiple plugged weep holes. Slight damage to surface, minor wear.
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Pipe cement material is eroded or worn to level that aggregate is showing - abrasion less than 0.25 in. deep over less than 20% of pipe surface cross section.
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Moderate to severe scaling - pipe cement material is eroded or worn to level that aggregate is projecting above level of remaining cement mix. Pipe cement material is eroded or worn to level that aggregate is showing - abrasion between 0.25 in. and 0.5 in. deep over less than 30% of pipe surface cross section.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Pipe cement material is eroded or worn to level that aggregate is missing at locations and there are pockets in the wall - rebar not exposed. Impact damage with exposed rebar.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Pipe has deteriorated to level where the rebar has corroded but not broken. Pipe has deteriorated to level where the rebar has corroded but not broken. Pipe has deteriorated to level where the rebar has failed and broken such that pieces are sticking out of wall. Complete invert deterioration and loss of pipe wall section.
	SCORE	**5**

Figure 39-Concrete culvert rating system-3

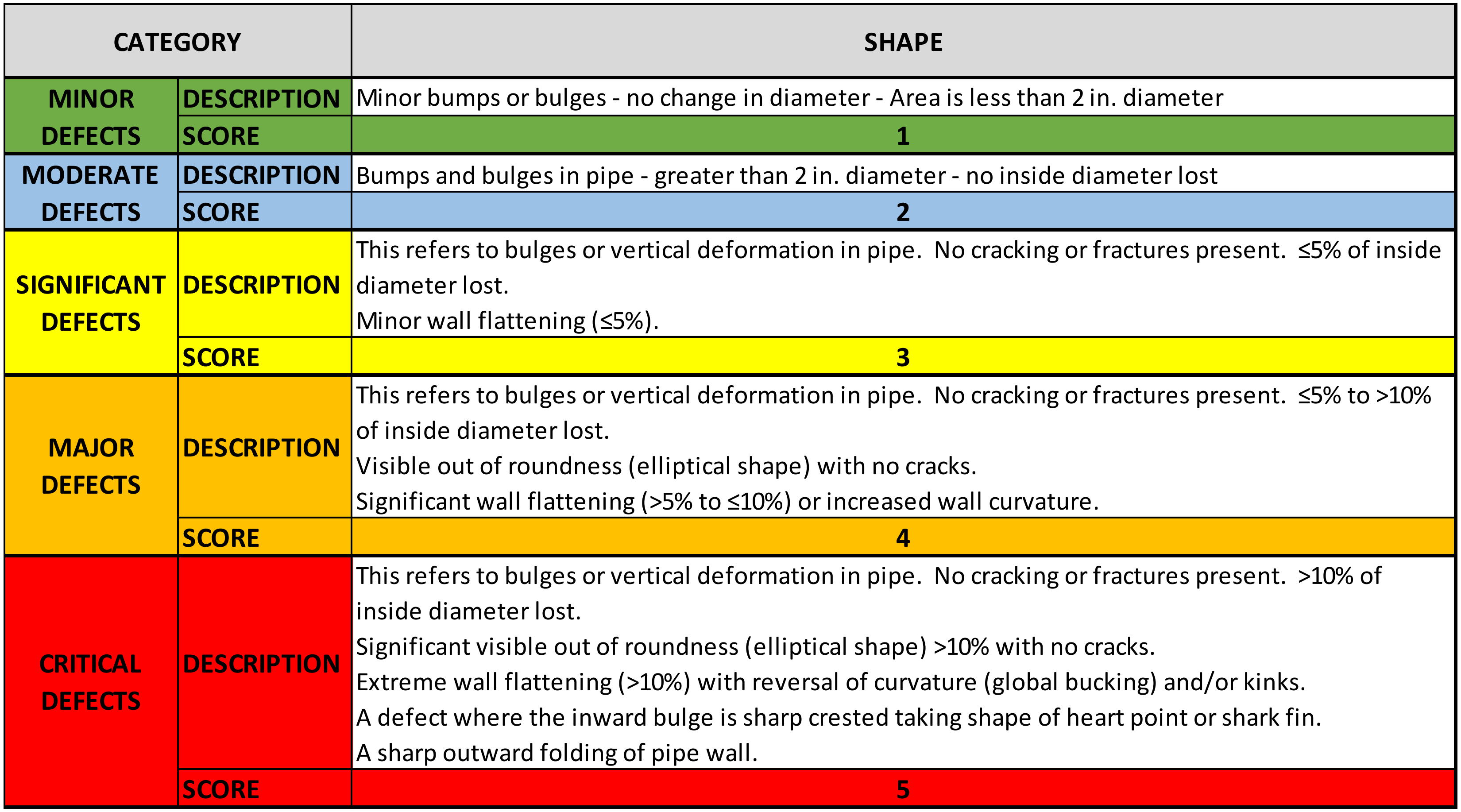
CATEGORY		BARREL ALIGNMENT
MINOR DEFECTS	**DESCRIPTION**	Horizontal alignment shows small visible deviations (<5%) from installed conditions and does not affect joints or barrel. Vertical alignment has minor sagging or heaving (<5%).
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Vertical misalignment with sags < 10% with sediment accumulation
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Change in alignment greater than (>) 5° and less than or equal to (≤) 10°. Alignment deviations that affect condition of joints or barrel. Vertical misalignment causing ponding or sediment accumulation at sags between 10% and 30% of diameter.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Change in alignment greater than (>) 10°. Alignment deviations that cause breakage at joints or barrel. Vertical misalignment causing ponding or sediment accumulation at sags > 30% of diameter.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Changes in alignment that cause hole in pipe. Changes in alignment causing blockage of pipe
	SCORE	**5**

Figure 40-Concrete culvert rating system-4



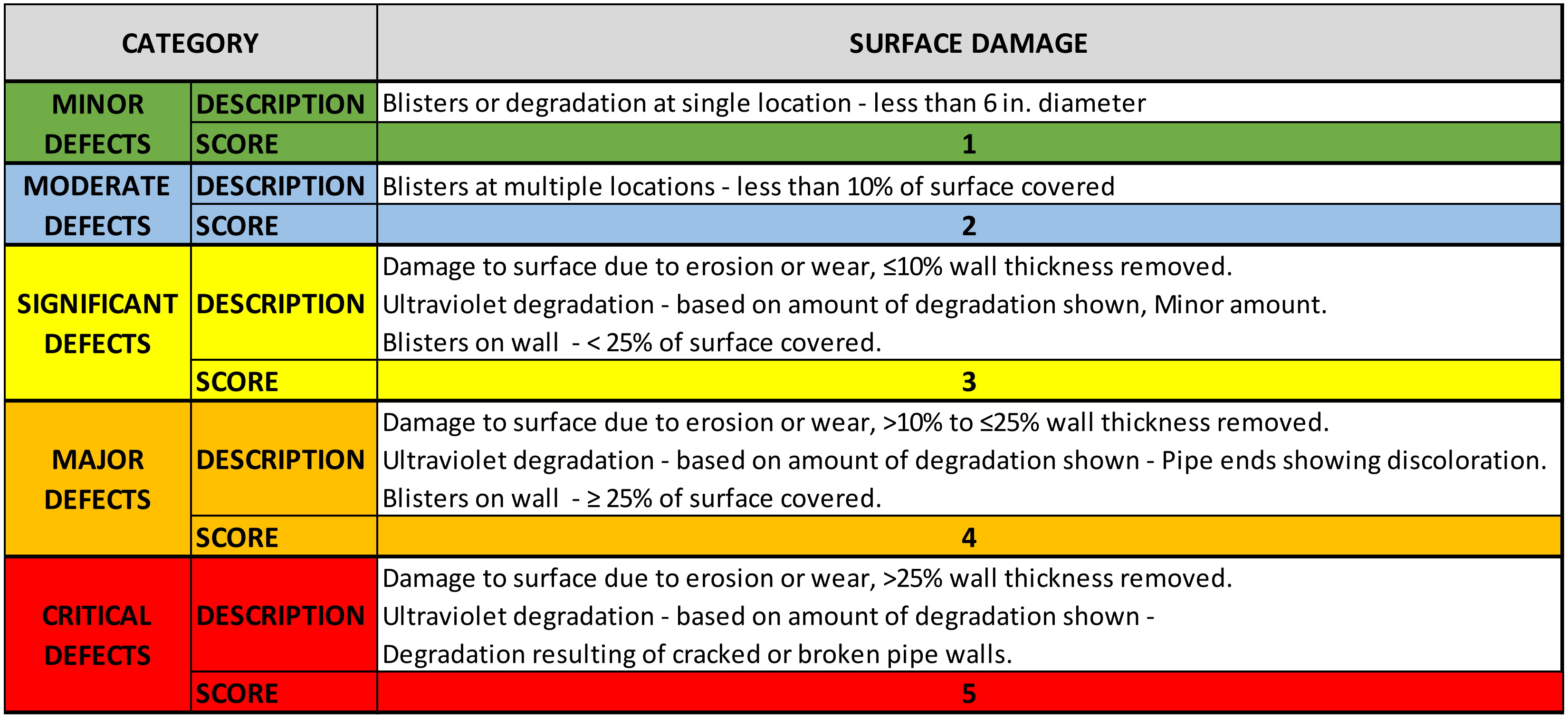
CATEGORY		JOINTS
MINOR DEFECTS	DESCRIPTION	Offset is visible at joint with minor joint material showing
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Offset is visible but less than 1 wall thickness. Moderate spall along edge of spigot end.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Offset is greater than or equal to (≥) 1 pipe wall thickness but less than (<) 1.5 wall thickness - no distress visible. Separation is up to 1 pipe wall thickness - no distress visible. Exposed or missing gasket materials. Large spalls along edge of spigot end. Infiltration/exfiltration or soil migration through joints - no structural damage. Roots visible through joints - no structural damage.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Offset is greater than or equal to (≥) 1.5 pipe wall thickness. Separation is greater than (>) 1 pipe wall thickness. Possible exposed reinforcement or joint sealant. Infiltration/exfiltration or soil migration through joints - visible structural damage. Roots visible through joints - structural damage. Joint distress directly causes distress to barrel/end section, roadway/shoulder, or embankment.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Offset joint where soil is showing
	SCORE	5

Figure 41-Concrete culvert rating system-5



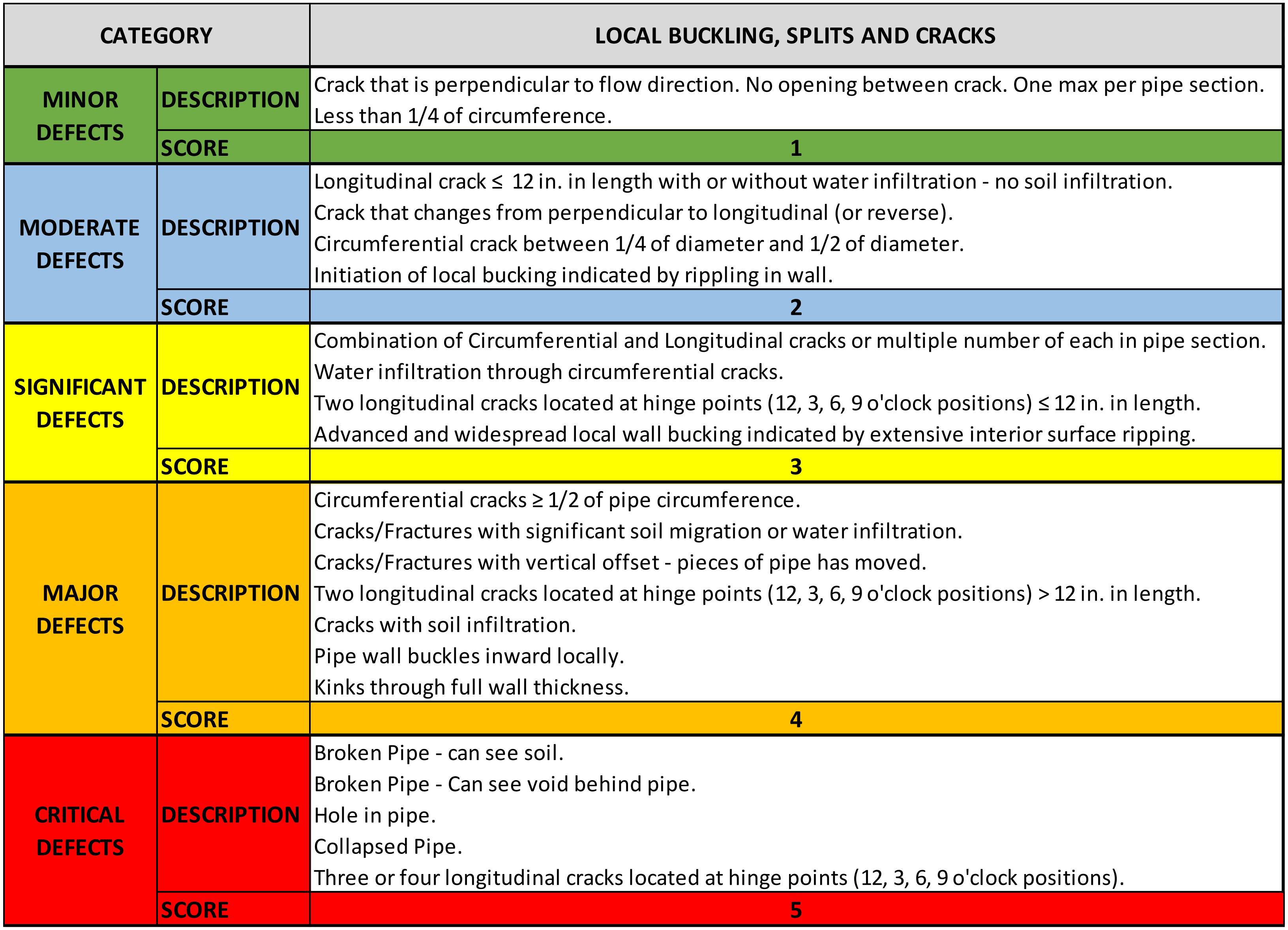
CATEGORY		SHAPE
MINOR DEFECTS	**DESCRIPTION**	Minor bumps or bulges - no change in diameter - Area is less than 2 in. diameter
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Bumps and bulges in pipe - greater than 2 in. diameter - no inside diameter lost
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	This refers to bulges or vertical deformation in pipe. No cracking or fractures present. ≤5% of inside diameter lost. Minor wall flattening (≤5%).
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	This refers to bulges or vertical deformation in pipe. No cracking or fractures present. ≤5% to >10% of inside diameter lost. Visible out of roundness (elliptical shape) with no cracks. Significant wall flattening (>5% to ≤10%) or increased wall curvature.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	This refers to bulges or vertical deformation in pipe. No cracking or fractures present. >10% of inside diameter lost. Significant visible out of roundness (elliptical shape) >10% with no cracks. Extreme wall flattening (>10%) with reversal of curvature (global bucking) and/or kinks. A defect where the inward bulge is sharp crested taking shape of heart point or shark fin. A sharp outward folding of pipe wall.
	SCORE	**5**

Figure 42-Plastic or HDPE pipe rating system-1



CATEGORY		SURFACE DAMAGE
MINOR DEFECTS	DESCRIPTION	Blisters or degradation at single location - less than 6 in. diameter
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Blisters at multiple locations - less than 10% of surface covered
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Damage to surface due to erosion or wear, ≤10% wall thickness removed. Ultraviolet degradation - based on amount of degradation shown, Minor amount. Blisters on wall - < 25% of surface covered.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Damage to surface due to erosion or wear, >10% to ≤25% wall thickness removed. Ultraviolet degradation - based on amount of degradation shown - Pipe ends showing discoloration. Blisters on wall - ≥ 25% of surface covered.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Damage to surface due to erosion or wear, >25% wall thickness removed. Ultraviolet degradation - based on amount of degradation shown - Degradation resulting of cracked or broken pipe walls.
	SCORE	5

Figure 43-Plastic or HDPE pipe rating system-2

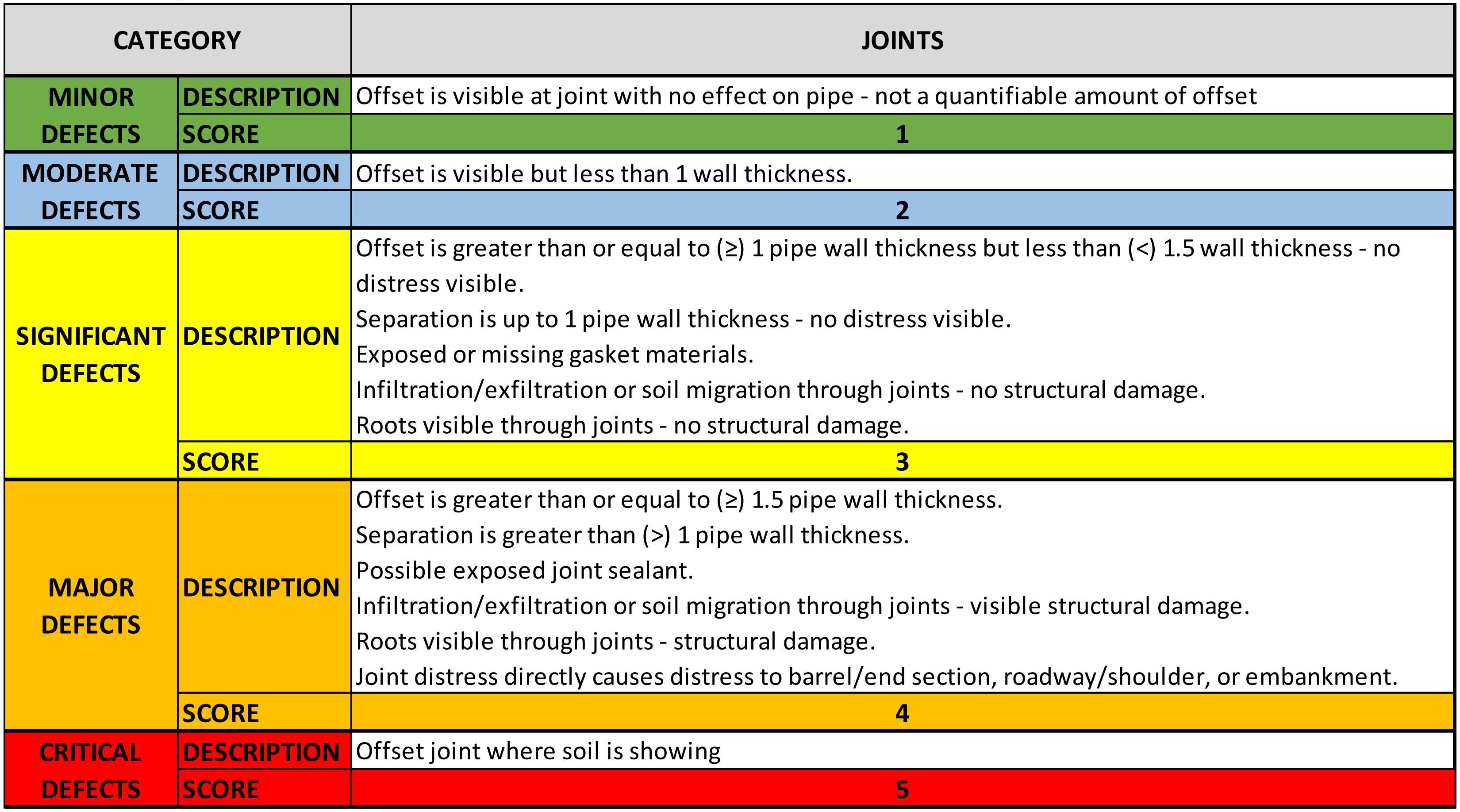


CATEGORY		LOCAL BUCKLING, SPLITS AND CRACKS
MINOR DEFECTS	DESCRIPTION	Crack that is perpendicular to flow direction. No opening between crack. One max per pipe section. Less than 1/4 of circumference.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Longitudinal crack ≤ 12 in. in length with or without water infiltration - no soil infiltration. Crack that changes from perpendicular to longitudinal (or reverse). Circumferential crack between 1/4 of diameter and 1/2 of diameter. Initiation of local bucking indicated by rippling in wall.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Combination of Circumferential and Longitudinal cracks or multiple number of each in pipe section. Water infiltration through circumferential cracks. Two longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions) ≤ 12 in. in length. Advanced and widespread local wall bucking indicated by extensive interior surface ripping.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Circumferential cracks ≥ 1/2 of pipe circumference. Cracks/Fractures with significant soil migration or water infiltration. Cracks/Fractures with vertical offset - pieces of pipe has moved. Two longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions) > 12 in. in length. Cracks with soil infiltration. Pipe wall buckles inward locally. Kinks through full wall thickness.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Broken Pipe - can see soil. Broken Pipe - Can see void behind pipe. Hole in pipe. Collapsed Pipe. Three or four longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions).
	SCORE	5

Figure 44-Plastic or HDPE pipe rating system-3

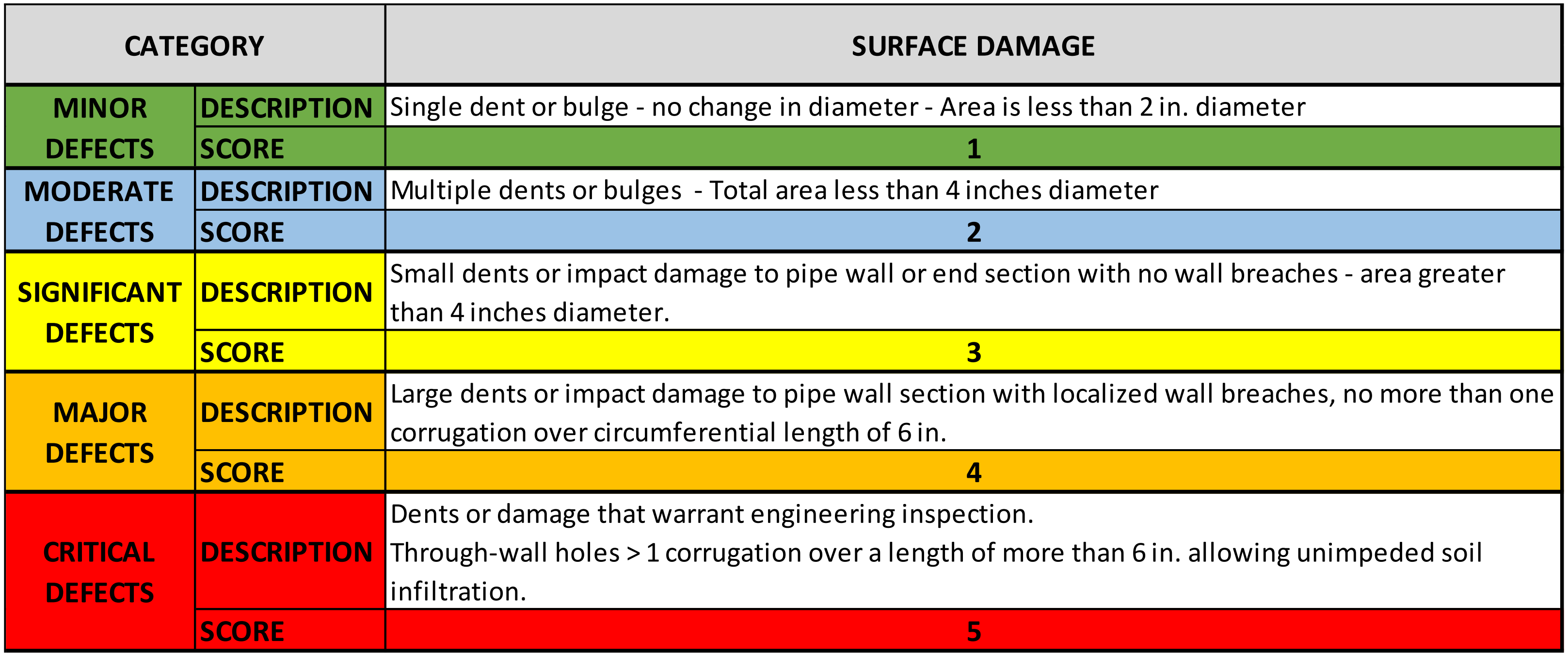
CATEGORY		BARREL ALIGNMENT
MINOR DEFECTS	**DESCRIPTION**	Horizontal alignment shows small visible deviations (<5%) from installed conditions and does not affect joints or barrel. Vertical alignment has minor sagging or heaving (<5%).
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Vertical misalignment with sags < 10% with sediment accumulation
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Change in alignment greater than (>) 5° and less than or equal to (≤) 10°. Alignment deviations that affect condition of joints or barrel. Vertical misalignment causing ponding or sediment accumulation at sags between 10% and 30% of diameter
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Change in alignment greater than (>) 10°. Alignment deviations that cause breakage at joints or barrel. Vertical misalignment causing ponding or sediment accumulation at sags > 30% of diameter.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Changes in alignment that cause hole in pipe. Changes in alignment causing blockage of pipe
	SCORE	**5**

Figure 45-Plastic or HDPE pipe rating system-4



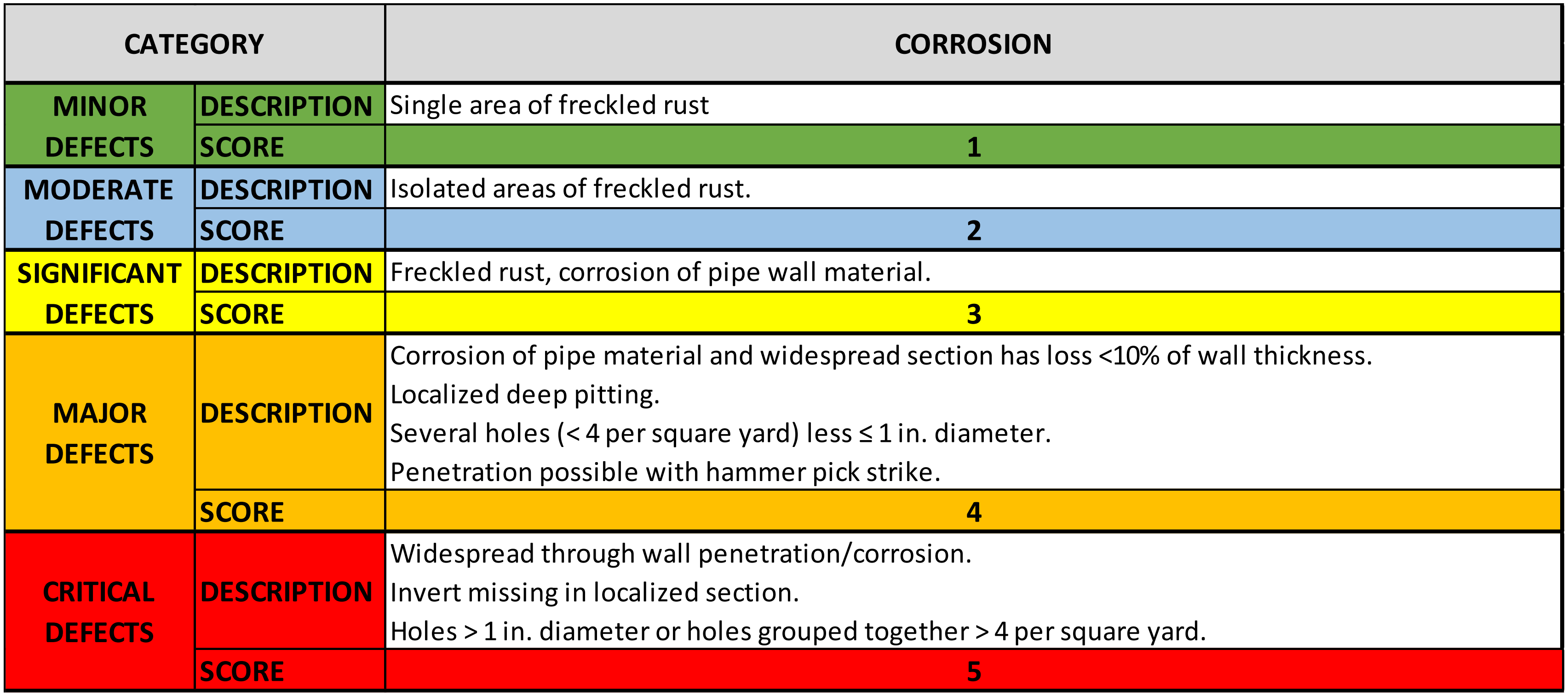
CATEGORY		JOINTS
MINOR DEFECTS	DESCRIPTION	Offset is visible at joint with no effect on pipe - not a quantifiable amount of offset
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Offset is visible but less than 1 wall thickness.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Offset is greater than or equal to (≥) 1 pipe wall thickness but less than (<) 1.5 wall thickness - no distress visible. Separation is up to 1 pipe wall thickness - no distress visible. Exposed or missing gasket materials. Infiltration/exfiltration or soil migration through joints - no structural damage. Roots visible through joints - no structural damage.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Offset is greater than or equal to (≥) 1.5 pipe wall thickness. Separation is greater than (>) 1 pipe wall thickness. Possible exposed joint sealant. Infiltration/exfiltration or soil migration through joints - visible structural damage. Roots visible through joints - structural damage. Joint distress directly causes distress to barrel/end section, roadway/shoulder, or embankment.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Offset joint where soil is showing
	SCORE	5

Figure 46-Plastic or HDPE pipe rating system-5



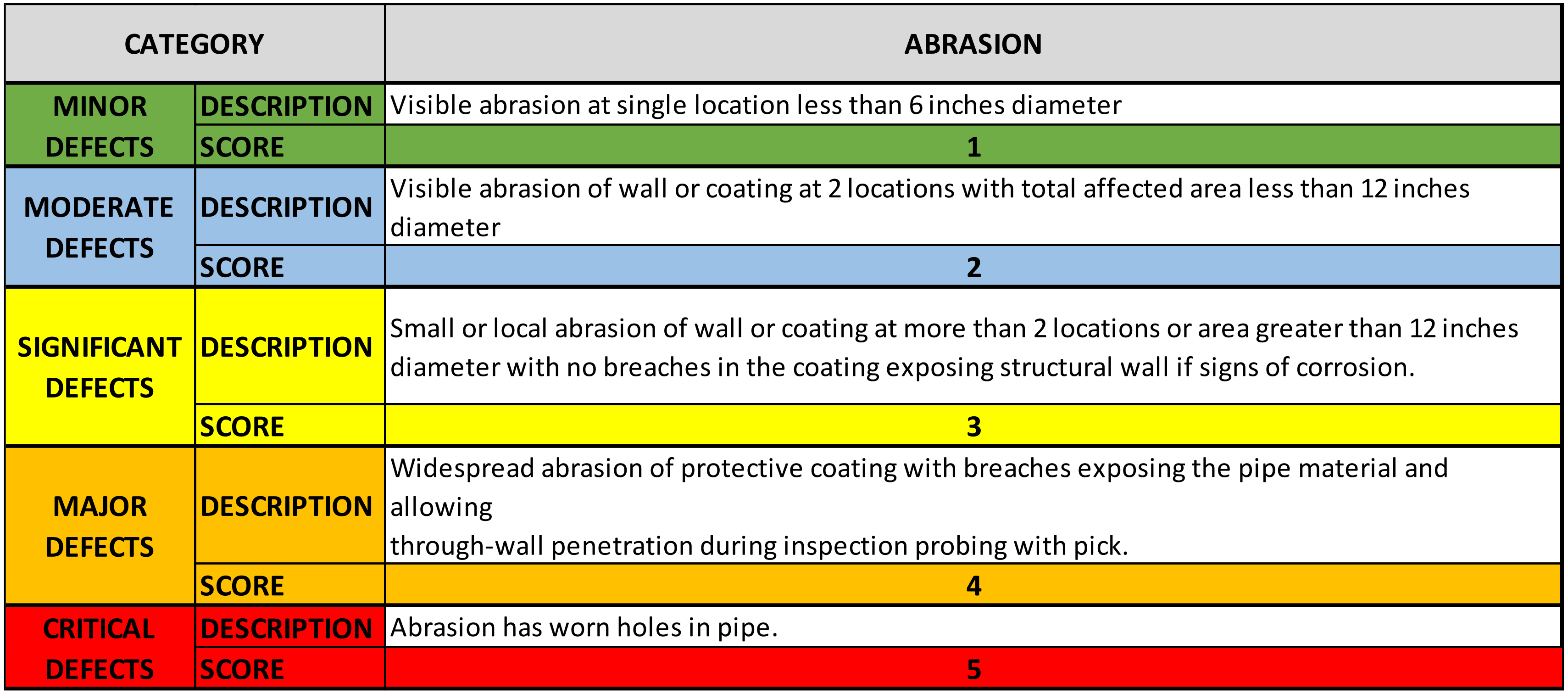
CATEGORY		SURFACE DAMAGE
MINOR DEFECTS	**DESCRIPTION**	Single dent or bulge - no change in diameter - Area is less than 2 in. diameter
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Multiple dents or bulges - Total area less than 4 inches diameter
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Small dents or impact damage to pipe wall or end section with no wall breaches - area greater than 4 inches diameter.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Large dents or impact damage to pipe wall section with localized wall breaches, no more than one corrugation over circumferential length of 6 in.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Dents or damage that warrant engineering inspection. Through-wall holes > 1 corrugation over a length of more than 6 in. allowing unimpeded soil infiltration.
	SCORE	**5**

Figure 47-Corrugated metal pipe rating system-1



CATEGORY		CORROSION
MINOR DEFECTS	DESCRIPTION	Single area of freckled rust
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Isolated areas of freckled rust.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Freckled rust, corrosion of pipe wall material.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Corrosion of pipe material and widespread section has loss <10% of wall thickness. Localized deep pitting. Several holes (< 4 per square yard) less ≤ 1 in. diameter. Penetration possible with hammer pick strike.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Widespread through wall penetration/corrosion. Invert missing in localized section. Holes > 1 in. diameter or holes grouped together > 4 per square yard.
	SCORE	5

Figure 48-Corrugated metal pipe rating system-2

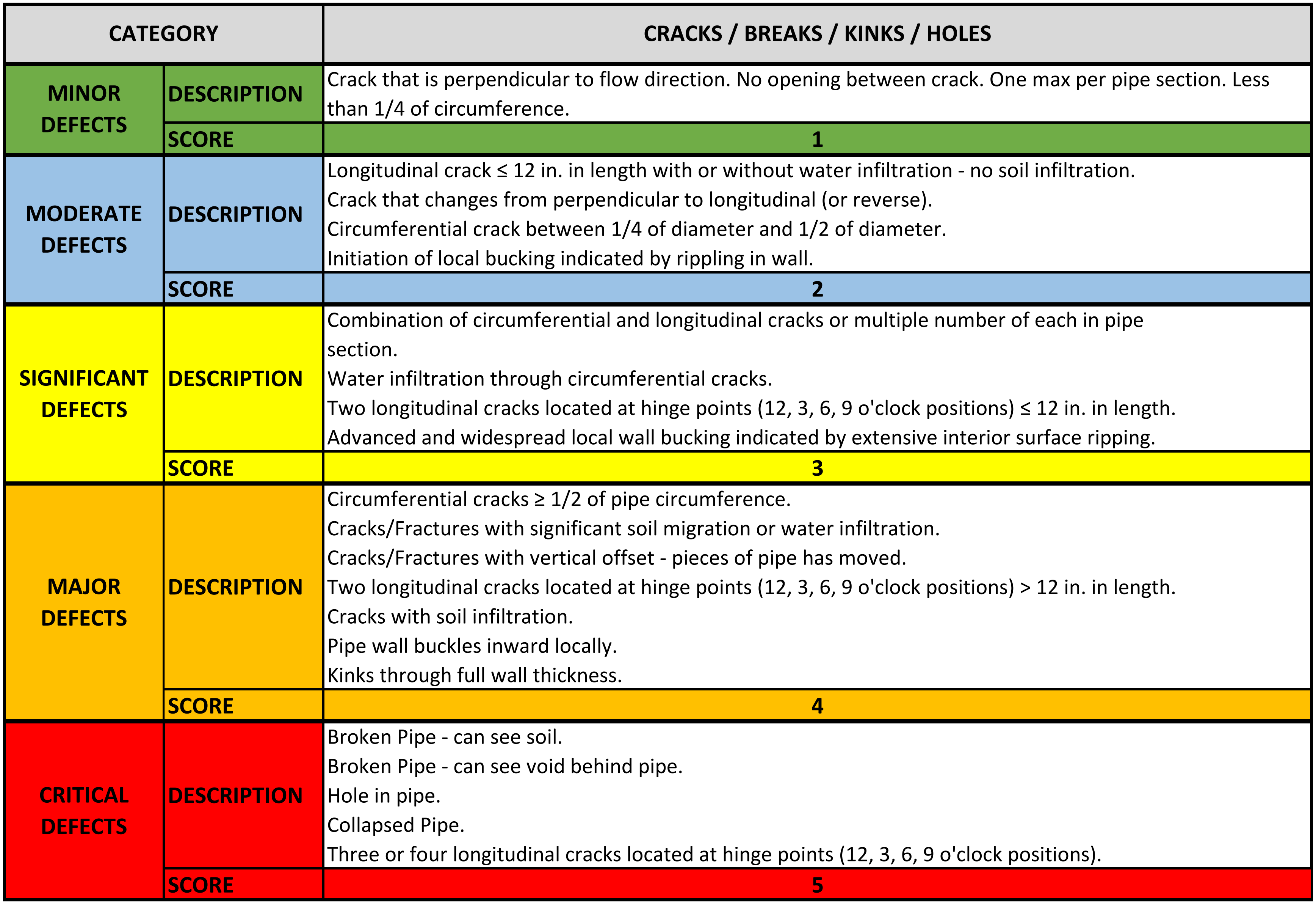


CATEGORY		ABRASION
MINOR DEFECTS	DESCRIPTION	Visible abrasion at single location less than 6 inches diameter
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Visible abrasion of wall or coating at 2 locations with total affected area less than 12 inches diameter
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Small or local abrasion of wall or coating at more than 2 locations or area greater than 12 inches diameter with no breaches in the coating exposing structural wall if signs of corrosion.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Widespread abrasion of protective coating with breaches exposing the pipe material and allowing through-wall penetration during inspection probing with pick.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Abrasion has worn holes in pipe.
	SCORE	5

Figure 49-Corrugated metal pipe rating system-3

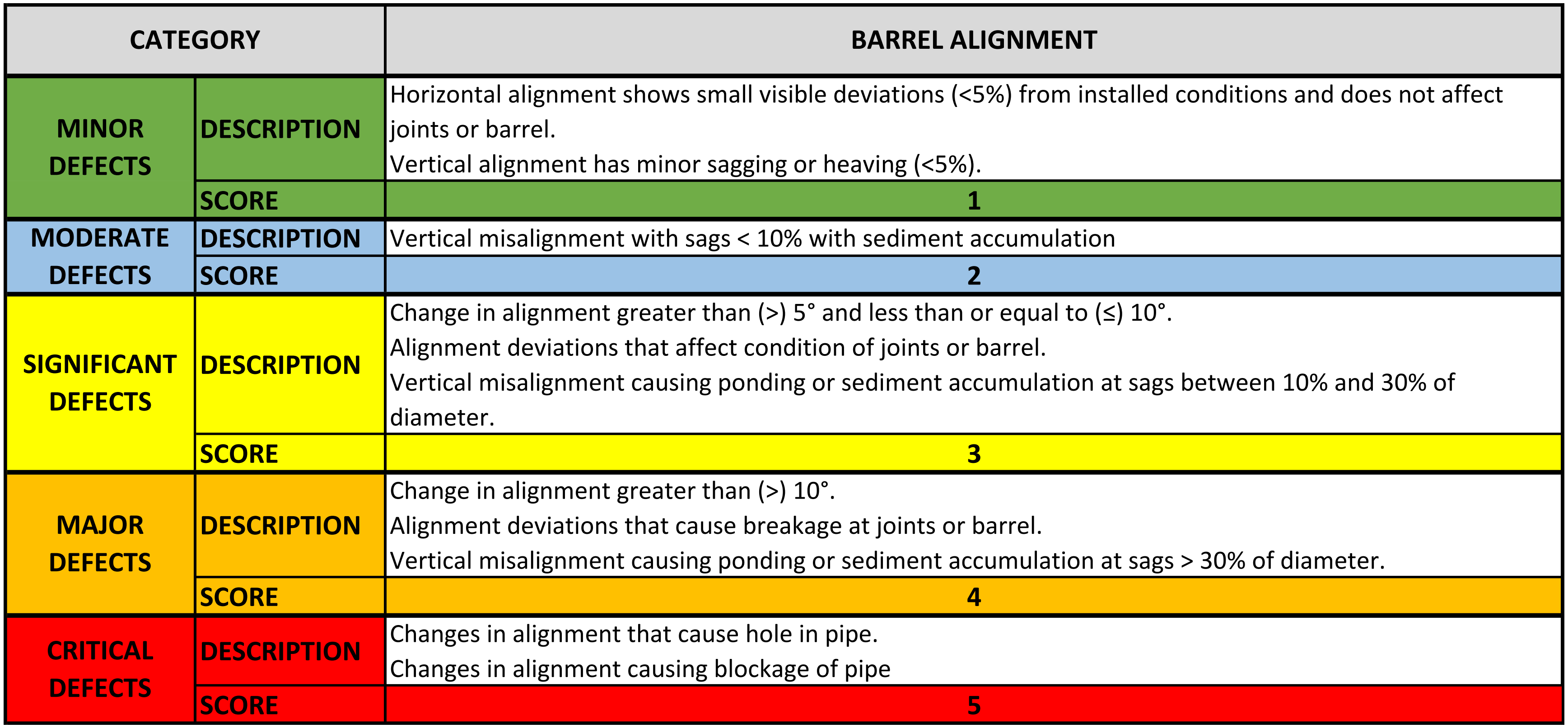
CATEGORY		SHAPE
MINOR DEFECTS	DESCRIPTION	Visible deformation. Isolated at single corrugation
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Smooth curvature of barrel, deformation <5% of inside diameter.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Deformation of barrel ≥5% to 10% of inside diameter. Minor wall flattening or bulges (≤5%).
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Deformation of barrel ≥10% to 15% of inside diameter. Visible out of roundness (elliptical shape) with no cracks. Significant wall flattening (>5% to ≤10%) or increased wall curvature.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Deformation of barrel ≥15% of inside diameter. Significant visible out of roundness (elliptical shape) >10% with no cracks. Extreme wall flattening (>10%) with reversal of curvature (global bucking) and/or kinks. A defect where the inward bulge is sharp crested taking shape of heart point or shark fin. A sharp outward folding of pipe wall.
	SCORE	5

Figure 50-Corrugated metal pipe rating system-4



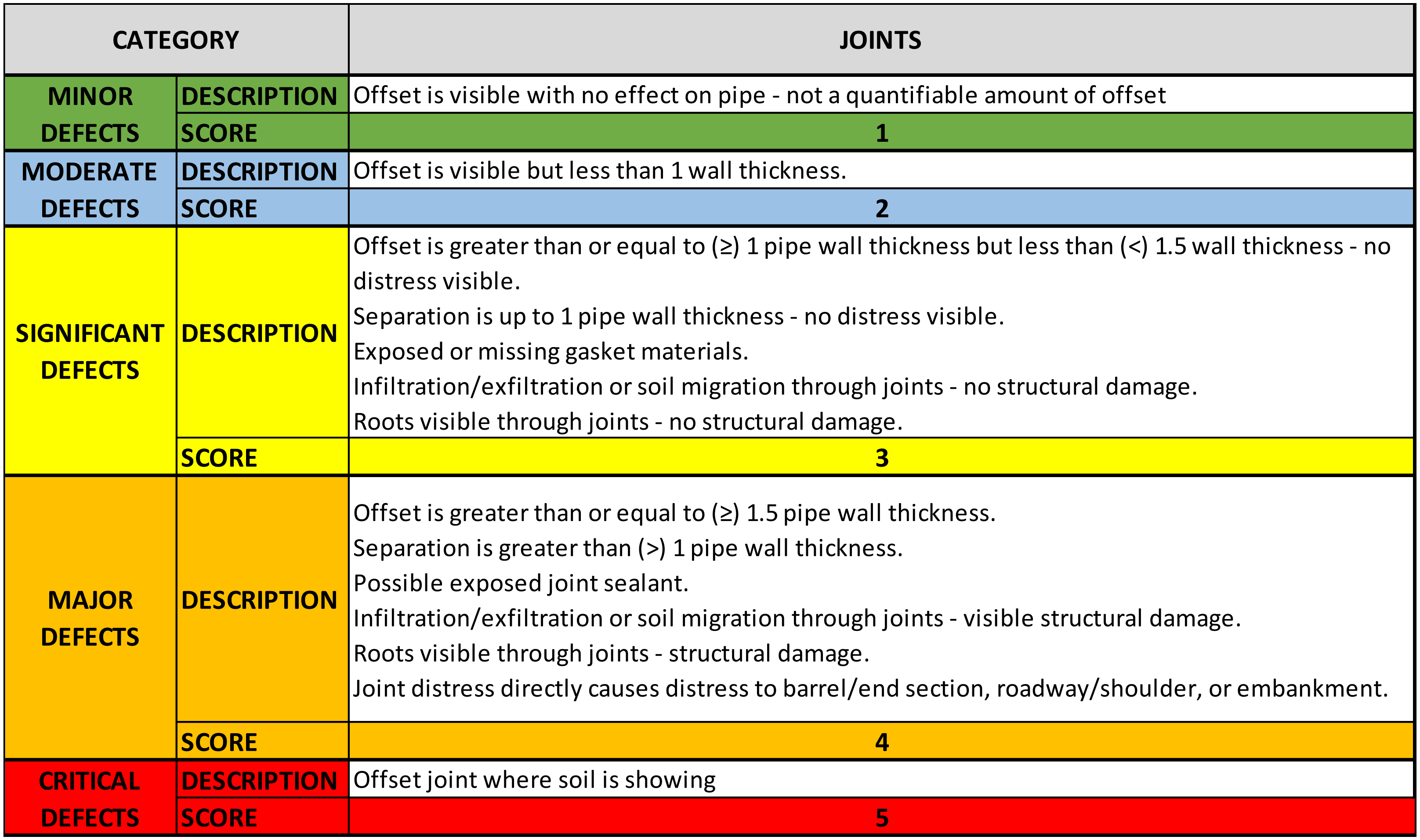
CATEGORY		CRACKS / BREAKS / KINKS / HOLES
MINOR DEFECTS	**DESCRIPTION**	Crack that is perpendicular to flow direction. No opening between crack. One max per pipe section. Less than 1/4 of circumference.
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Longitudinal crack ≤ 12 in. in length with or without water infiltration - no soil infiltration. Crack that changes from perpendicular to longitudinal (or reverse). Circumferential crack between 1/4 of diameter and 1/2 of diameter. Initiation of local bucking indicated by rippling in wall.
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Combination of circumferential and longitudinal cracks or multiple number of each in pipe section. Water infiltration through circumferential cracks. Two longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions) ≤ 12 in. in length. Advanced and widespread local wall bucking indicated by extensive interior surface ripping.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Circumferential cracks ≥ 1/2 of pipe circumference. Cracks/Fractures with significant soil migration or water infiltration. Cracks/Fractures with vertical offset - pieces of pipe has moved. Two longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions) > 12 in. in length. Cracks with soil infiltration. Pipe wall buckles inward locally. Kinks through full wall thickness.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Broken Pipe - can see soil. Broken Pipe - can see void behind pipe. Hole in pipe. Collapsed Pipe. Three or four longitudinal cracks located at hinge points (12, 3, 6, 9 o'clock positions).
	SCORE	**5**

Figure 51-Corrugated metal pipe rating system-5



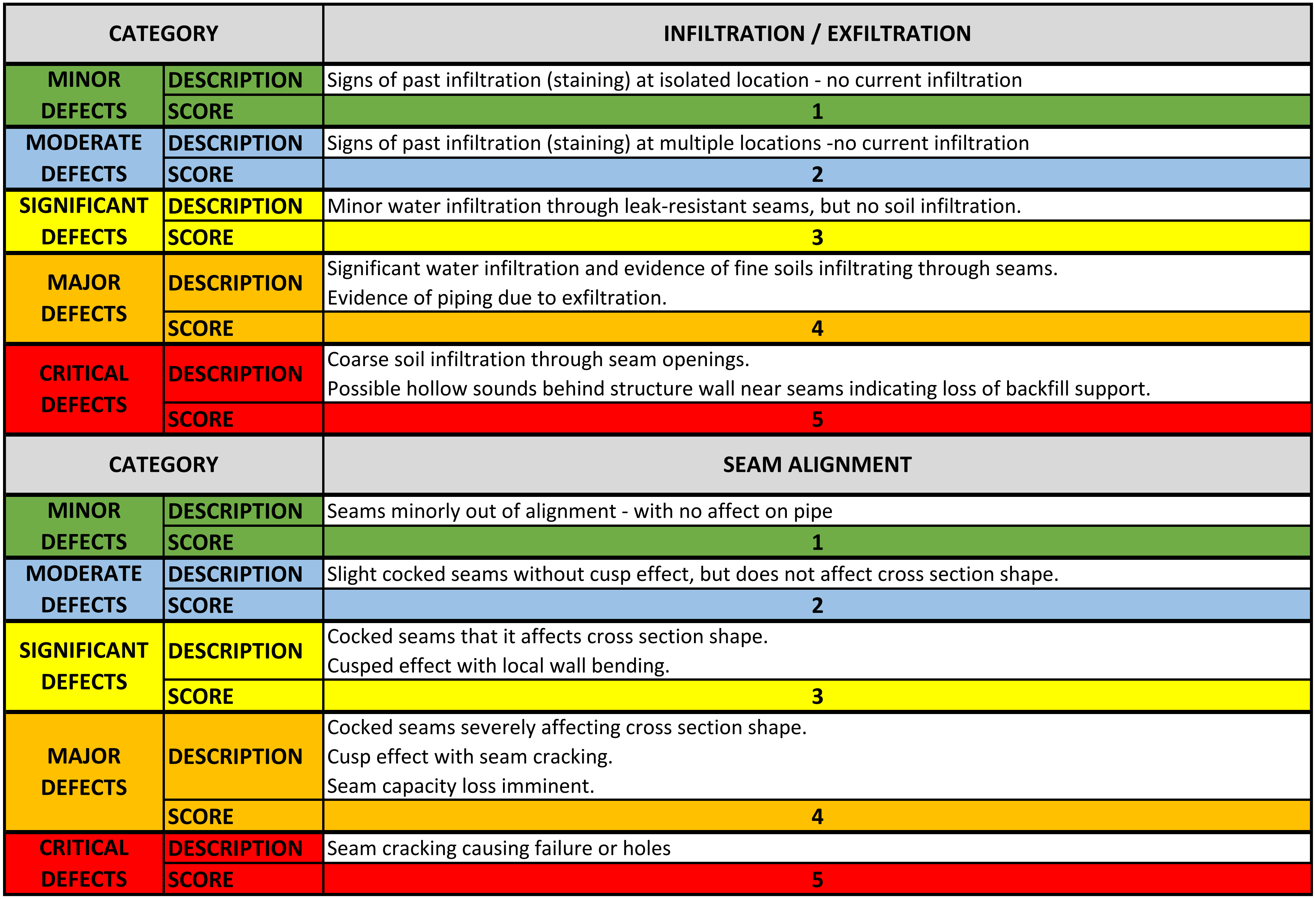
CATEGORY		BARREL ALIGNMENT
MINOR DEFECTS	**DESCRIPTION**	Horizontal alignment shows small visible deviations (<5%) from installed conditions and does not affect joints or barrel. Vertical alignment has minor sagging or heaving (<5%).
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Vertical misalignment with sags < 10% with sediment accumulation
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Change in alignment greater than (>) 5° and less than or equal to (≤) 10°. Alignment deviations that affect condition of joints or barrel. Vertical misalignment causing ponding or sediment accumulation at sags between 10% and 30% of diameter.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Change in alignment greater than (>) 10°. Alignment deviations that cause breakage at joints or barrel. Vertical misalignment causing ponding or sediment accumulation at sags > 30% of diameter.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Changes in alignment that cause hole in pipe. Changes in alignment causing blockage of pipe
	SCORE	**5**

Figure 52-Corrugated metal pipe rating system-6



CATEGORY		JOINTS
MINOR DEFECTS	**DESCRIPTION**	Offset is visible with no effect on pipe - not a quantifiable amount of offset
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Offset is visible but less than 1 wall thickness.
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Offset is greater than or equal to (≥) 1 pipe wall thickness but less than (<) 1.5 wall thickness - no distress visible. Separation is up to 1 pipe wall thickness - no distress visible. Exposed or missing gasket materials. Infiltration/exfiltration or soil migration through joints - no structural damage. Roots visible through joints - no structural damage.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Offset is greater than or equal to (≥) 1.5 pipe wall thickness. Separation is greater than (>) 1 pipe wall thickness. Possible exposed joint sealant. Infiltration/exfiltration or soil migration through joints - visible structural damage. Roots visible through joints - structural damage. Joint distress directly causes distress to barrel/end section, roadway/shoulder, or embankment.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Offset joint where soil is showing
	SCORE	**5**

Figure 53-Corrugated metal pipe rating system-7



CATEGORY		INFILTRATION / EXFILTRATION
MINOR DEFECTS	DESCRIPTION	Signs of past infiltration (staining) at isolated location - no current infiltration
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Signs of past infiltration (staining) at multiple locations -no current infiltration
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Minor water infiltration through leak-resistant seams, but no soil infiltration.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Significant water infiltration and evidence of fine soils infiltrating through seams. Evidence of piping due to exfiltration.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Coarse soil infiltration through seam openings. Possible hollow sounds behind structure wall near seams indicating loss of backfill support.
	SCORE	5

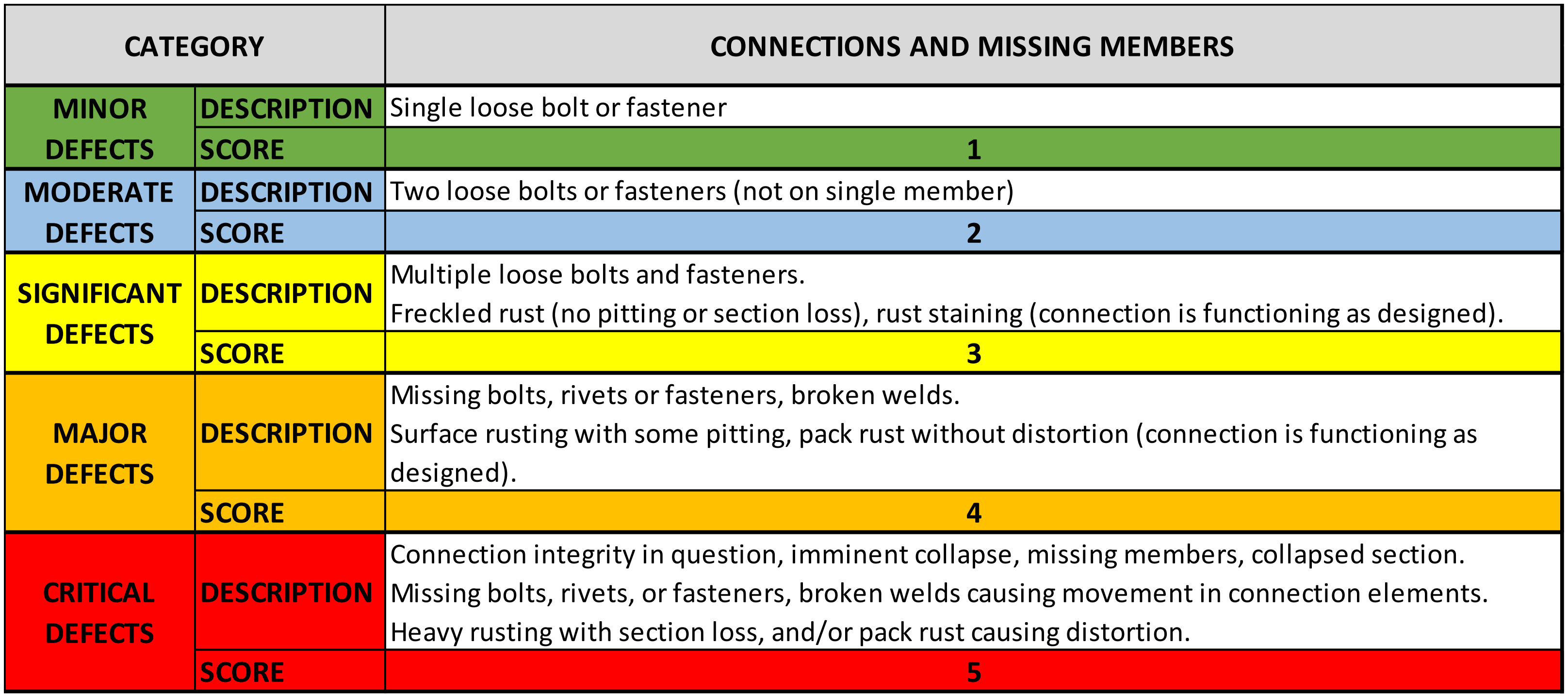
CATEGORY		SEAM ALIGNMENT
MINOR DEFECTS	DESCRIPTION	Seams minorly out of alignment - with no affect on pipe
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Slight cocked seams without cusp effect, but does not affect cross section shape.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Cocked seams that it affects cross section shape. Cusped effect with local wall bending.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Cocked seams severely affecting cross section shape. Cusp effect with seam cracking. Seam capacity loss imminent.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Seam cracking causing failure or holes
	SCORE	5

Figure 54-Corrugated metal pipe rating system-8

CATEGORY		SEAM BOLTS/ FASTENERS
MINOR DEFECTS	DESCRIPTION	Single missing bolt
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	<5% loose or missing bolts in any seam.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	5% to 15% loose or missing bolts in any seam.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	> 15% missing bolts in any seam.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	> 50% missing bolts in any seam
	SCORE	5

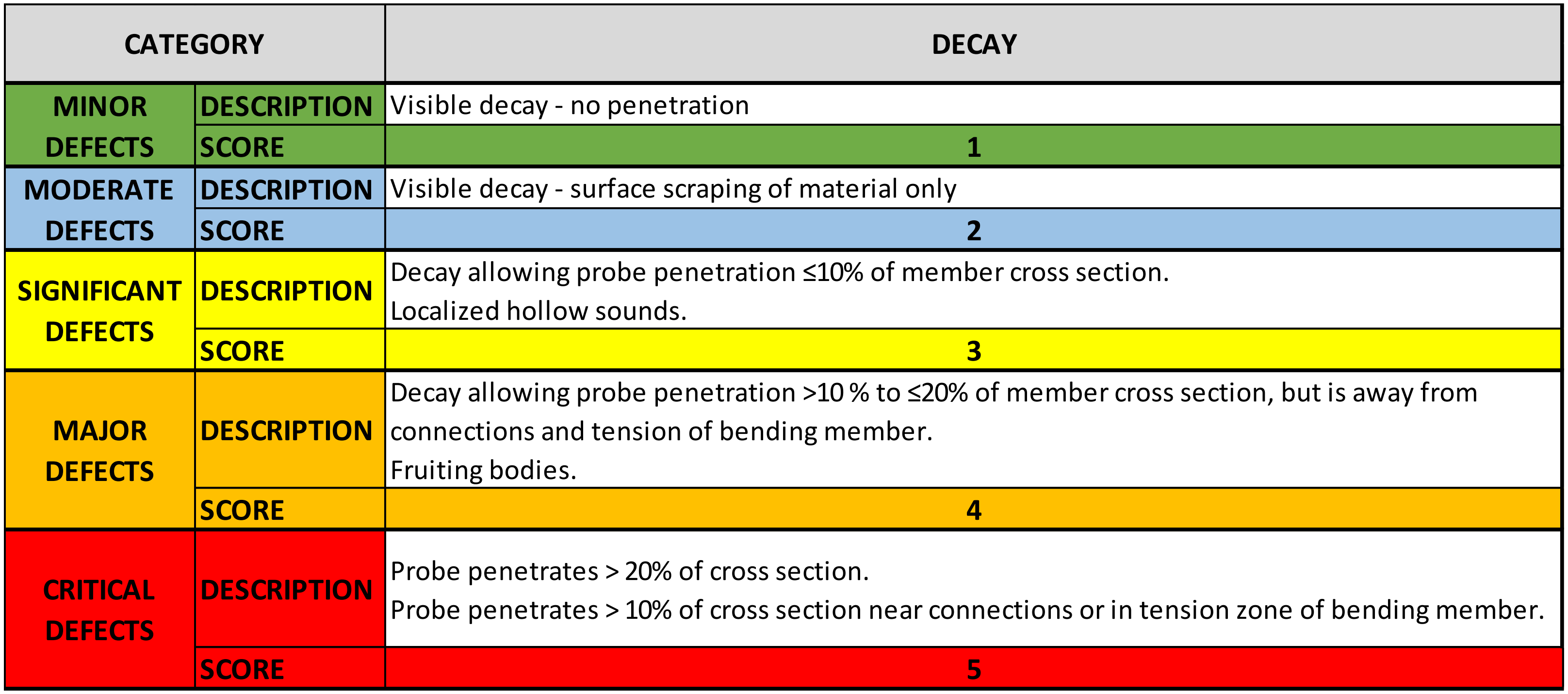
CATEGORY		SEAM BOLT HOLES
MINOR DEFECTS	DESCRIPTION	Cracking at single bolt hole
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Minor yielding of steel and/or cracking/splitting < 1 in. long local to bolt holes. Minor corrosion developing around bolt holes or on bolts.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Yielding of steel and/or cracking/splitting 1 in. up to 3 in. long local to bolt holes. Corrosion with section loss around bolt holes or on bolts.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Significant yielding of steel at bolt holes. Cracking/splitting >3 in. long local to bolt holes. Corrosion with major section loss around bolt holes or on bolts.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Bolt holes corroded to level that no bolts can be replaced - over 50% of bolt holes
	SCORE	5

Figure 55-Corrugated metal pipe rating system-9



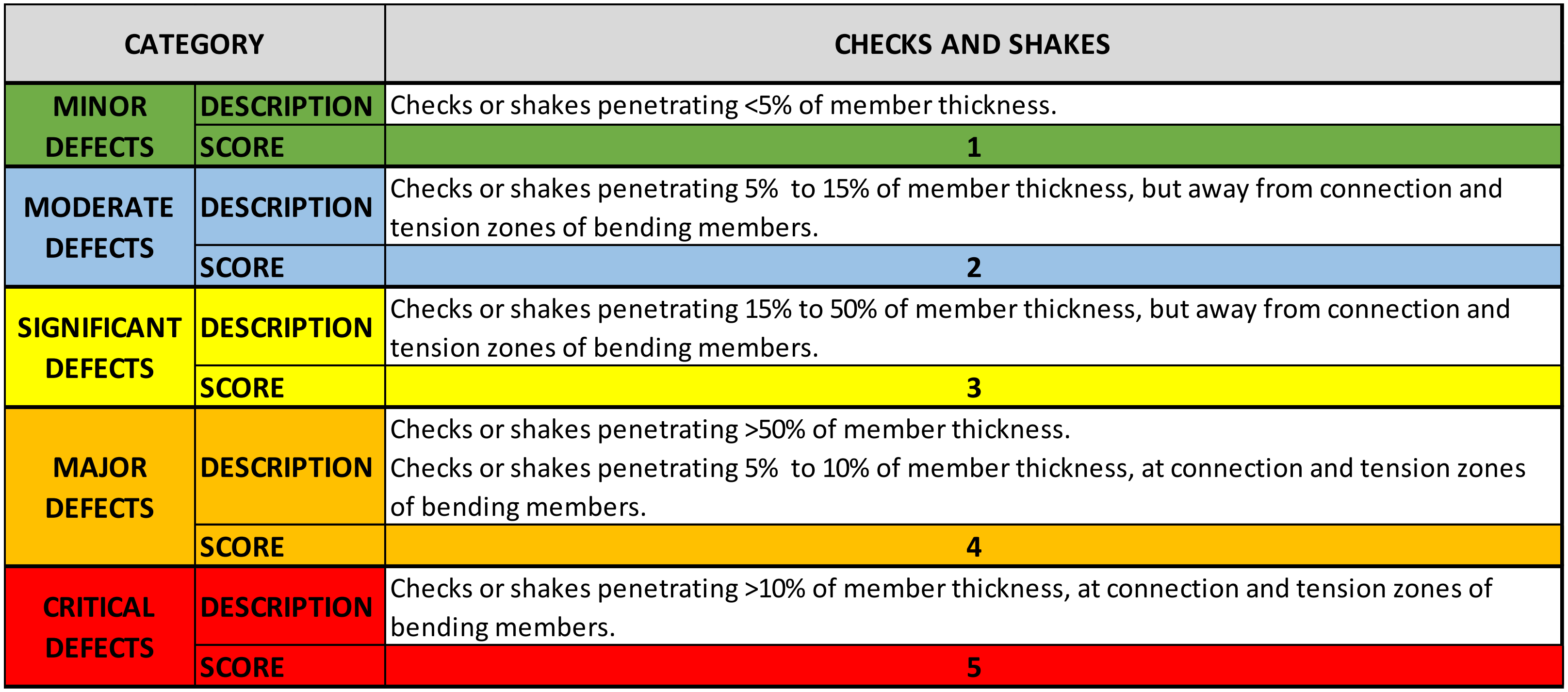
CATEGORY		CONNECTIONS AND MISSING MEMBERS
MINOR DEFECTS	**DESCRIPTION**	Single loose bolt or fastener
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Two loose bolts or fasteners (not on single member)
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Multiple loose bolts and fasteners. Freckled rust (no pitting or section loss), rust staining (connection is functioning as designed).
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Missing bolts, rivets or fasteners, broken welds. Surface rusting with some pitting, pack rust without distortion (connection is functioning as designed).
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Connection integrity in question, imminent collapse, missing members, collapsed section. Missing bolts, rivets, or fasteners, broken welds causing movement in connection elements. Heavy rusting with section loss, and/or pack rust causing distortion.
	SCORE	**5**

Figure 56-Timber pipe rating system-1



CATEGORY		DECAY
MINOR DEFECTS	**DESCRIPTION**	Visible decay - no penetration
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Visible decay - surface scraping of material only
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Decay allowing probe penetration ≤10% of member cross section. Localized hollow sounds.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Decay allowing probe penetration >10 % to ≤20% of member cross section, but is away from connections and tension of bending member. Fruiting bodies.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Probe penetrates > 20% of cross section. Probe penetrates > 10% of cross section near connections or in tension zone of bending member.
	SCORE	**5**

Figure 57-Timber pipe rating system-2

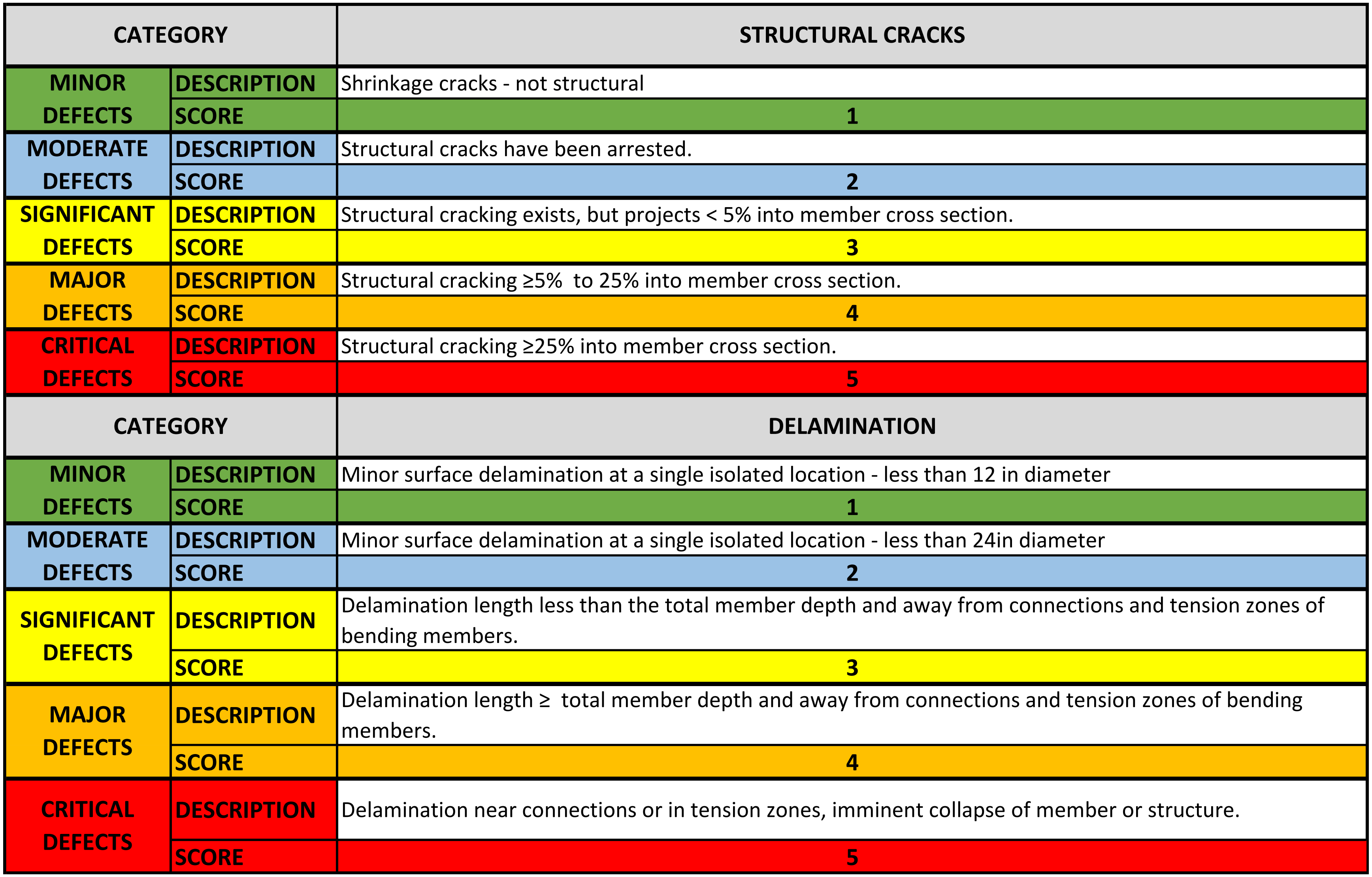


CATEGORY		CHECKS AND SHAKES
MINOR DEFECTS	DESCRIPTION	Checks or shakes penetrating <5% of member thickness.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Checks or shakes penetrating 5% to 15% of member thickness, but away from connection and tension zones of bending members.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Checks or shakes penetrating 15% to 50% of member thickness, but away from connection and tension zones of bending members.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Checks or shakes penetrating >50% of member thickness. Checks or shakes penetrating 5% to 10% of member thickness, at connection and tension zones of bending members.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Checks or shakes penetrating >10% of member thickness, at connection and tension zones of bending members.
	SCORE	5

Figure 58-Timber pipe rating system-3

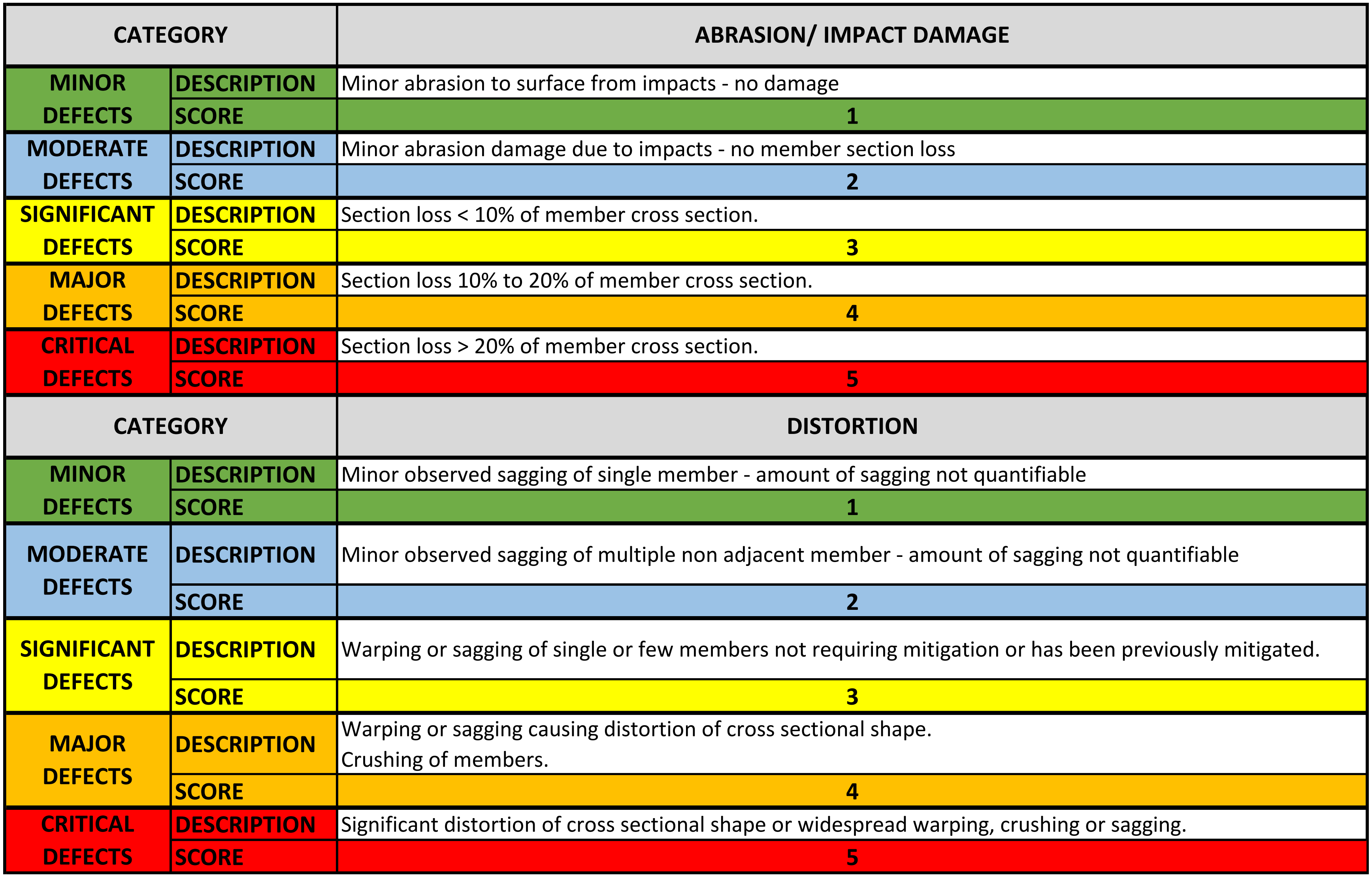
CATEGORY		SHAPE
MINOR DEFECTS	DESCRIPTION	Minor deflection visible, but not quantifiable
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Smooth curvature of barrel, deformation <5% of inside diameter.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Deformation of barrel ≥5% to 10% of inside diameter. Minor wall flattening or bulges (≤5%).
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Deformation of barrel ≥10% to 15% of inside diameter. Visible out of roundness (elliptical shape) with no cracks. Significant wall flattening (>5% to ≤10%) or increased wall curvature.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Deformation of barrel ≥15% of inside diameter. Significant visible out of roundness (elliptical shape) >10% with no cracks. Extreme wall flattening (>10%) with reversal of curvature (global bucking) and/or kinks. A defect where the inward bulge is sharp crested taking shape of heart point or shark fin. A sharp outward folding of pipe wall.
	SCORE	5

Figure 59-Timber pipe rating system-4



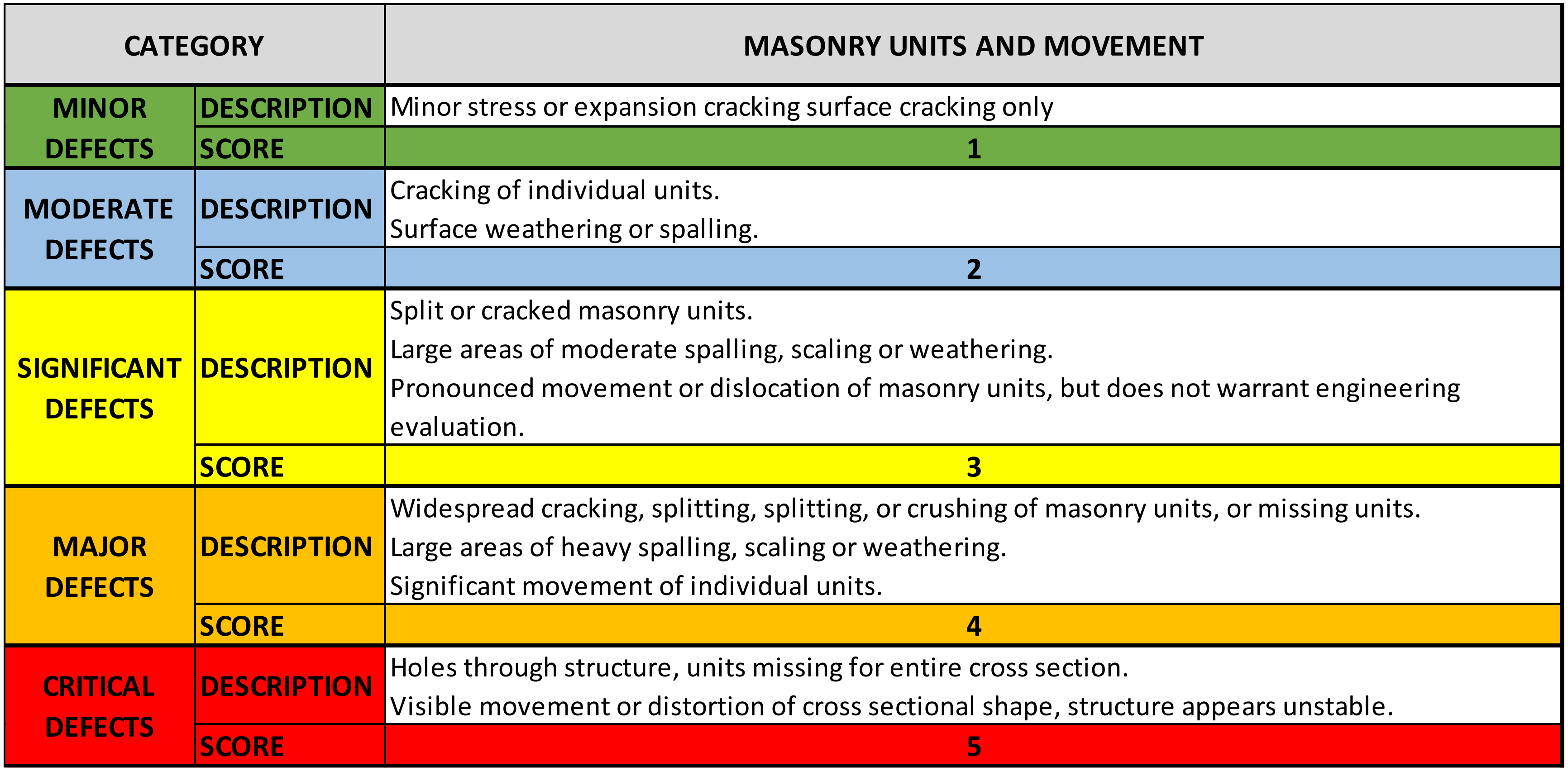
CATEGORY		STRUCTURAL CRACKS
MINOR DEFECTS	DESCRIPTION	Shrinkage cracks - not structural
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Structural cracks have been arrested.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Structural cracking exists, but projects < 5% into member cross section.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Structural cracking ≥5% to 25% into member cross section.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Structural cracking ≥25% into member cross section.
	SCORE	5
CATEGORY		DELAMINATION
MINOR DEFECTS	DESCRIPTION	Minor surface delamination at a single isolated location - less than 12 in diameter
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Minor surface delamination at a single isolated location - less than 24in diameter
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Delamination length less than the total member depth and away from connections and tension zones of bending members.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Delamination length ≥ total member depth and away from connections and tension zones of bending members.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Delamination near connections or in tension zones, imminent collapse of member or structure.
	SCORE	5

Figure 60-Timber pipe rating system-5



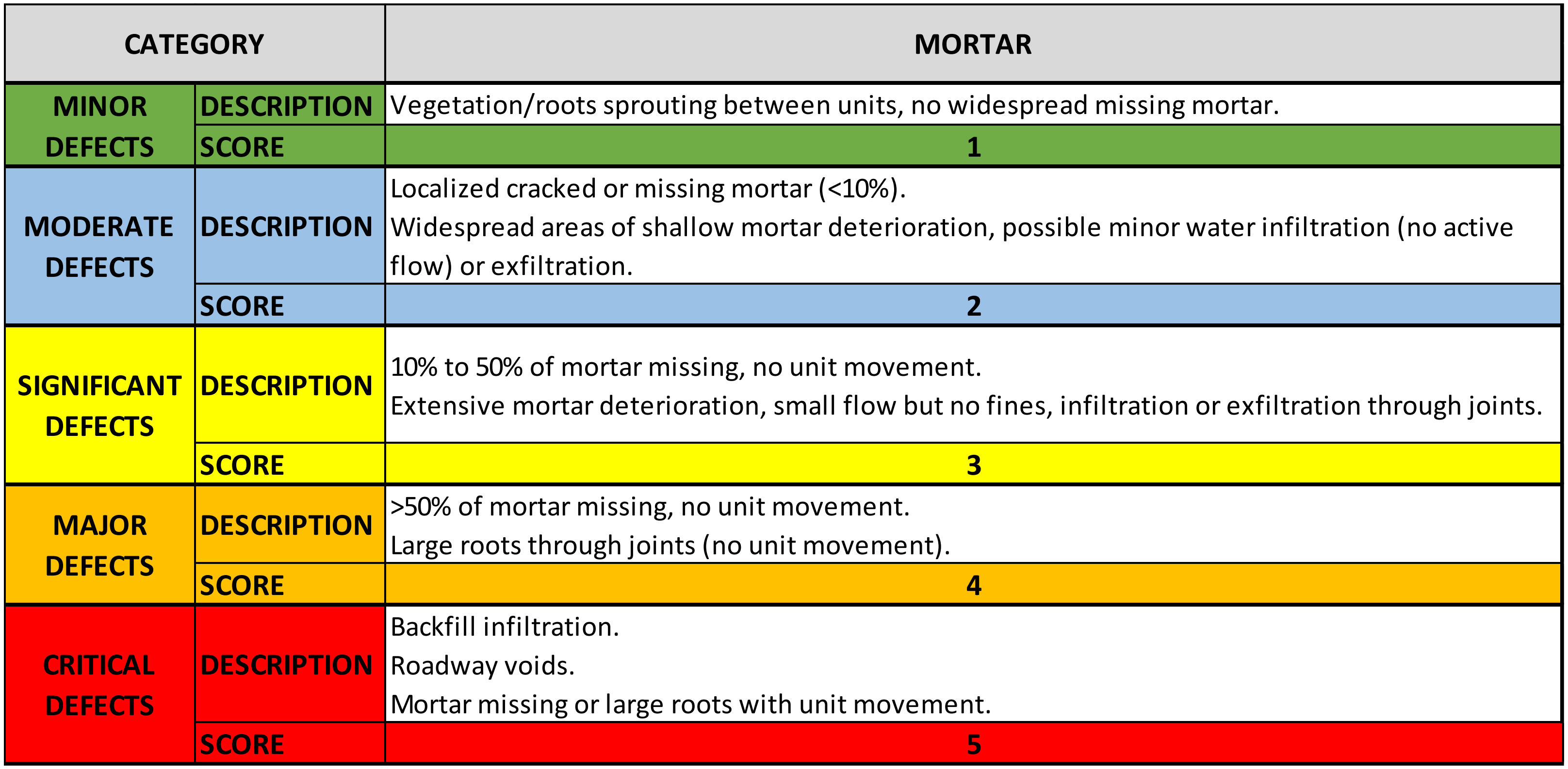
CATEGORY		ABRASION/ IMPACT DAMAGE
MINOR DEFECTS	DESCRIPTION	Minor abrasion to surface from impacts - no damage
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Minor abrasion damage due to impacts - no member section loss
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Section loss < 10% of member cross section.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Section loss 10% to 20% of member cross section.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Section loss > 20% of member cross section.
	SCORE	5
CATEGORY		**DISTORTION**
MINOR DEFECTS	DESCRIPTION	Minor observed sagging of single member - amount of sagging not quantifiable
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Minor observed sagging of multiple non adjacent member - amount of sagging not quantifiable
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Warping or sagging of single or few members not requiring mitigation or has been previously mitigated.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Warping or sagging causing distortion of cross sectional shape. Crushing of members.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Significant distortion of cross sectional shape or widespread warping, crushing or sagging.
	SCORE	5

Figure 61-Timber pipe rating system-6



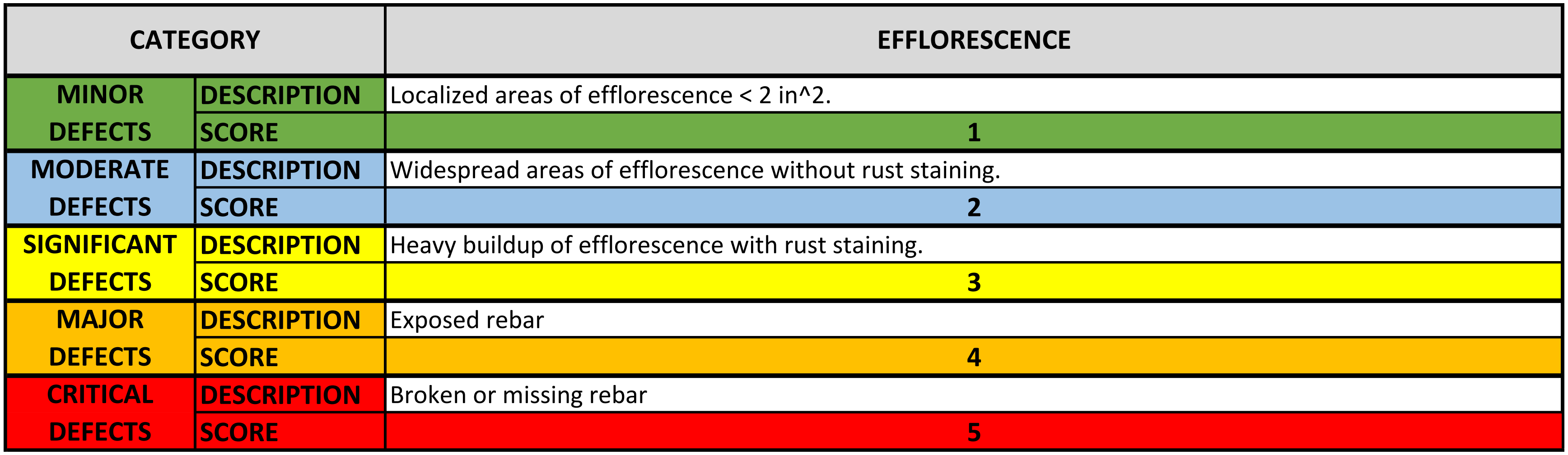
CATEGORY		MASONRY UNITS AND MOVEMENT
MINOR DEFECTS	**DESCRIPTION**	Minor stress or expansion cracking surface cracking only
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Cracking of individual units. Surface weathering or spalling.
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Split or cracked masonry units. Large areas of moderate spalling, scaling or weathering. Pronounced movement or dislocation of masonry units, but does not warrant engineering evaluation.
	SCORE	**3**
MAJOR DEFECTS	**DESCRIPTION**	Widespread cracking, splitting, splitting, or crushing of masonry units, or missing units. Large areas of heavy spalling, scaling or weathering. Significant movement of individual units.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Holes through structure, units missing for entire cross section. Visible movement or distortion of cross sectional shape, structure appears unstable.
	SCORE	**5**

Figure 62-Masonry pipe rating system-1



CATEGORY		MORTAR
MINOR DEFECTS	DESCRIPTION	Vegetation/roots sprouting between units, no widespread missing mortar.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Localized cracked or missing mortar (<10%). Widespread areas of shallow mortar deterioration, possible minor water infiltration (no active flow) or exfiltration.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	10% to 50% of mortar missing, no unit movement. Extensive mortar deterioration, small flow but no fines, infiltration or exfiltration through joints.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	>50% of mortar missing, no unit movement. Large roots through joints (no unit movement).
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Backfill infiltration. Roadway voids. Mortar missing or large roots with unit movement.
	SCORE	5

Figure 63-Masonry pipe rating system-2



CATEGORY		EFFLORESCENCE
MINOR DEFECTS	DESCRIPTION	Localized areas of efflorescence < 2 in^2.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Widespread areas of efflorescence without rust staining.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Heavy buildup of efflorescence with rust staining.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Exposed rebar
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Broken or missing rebar
	SCORE	5

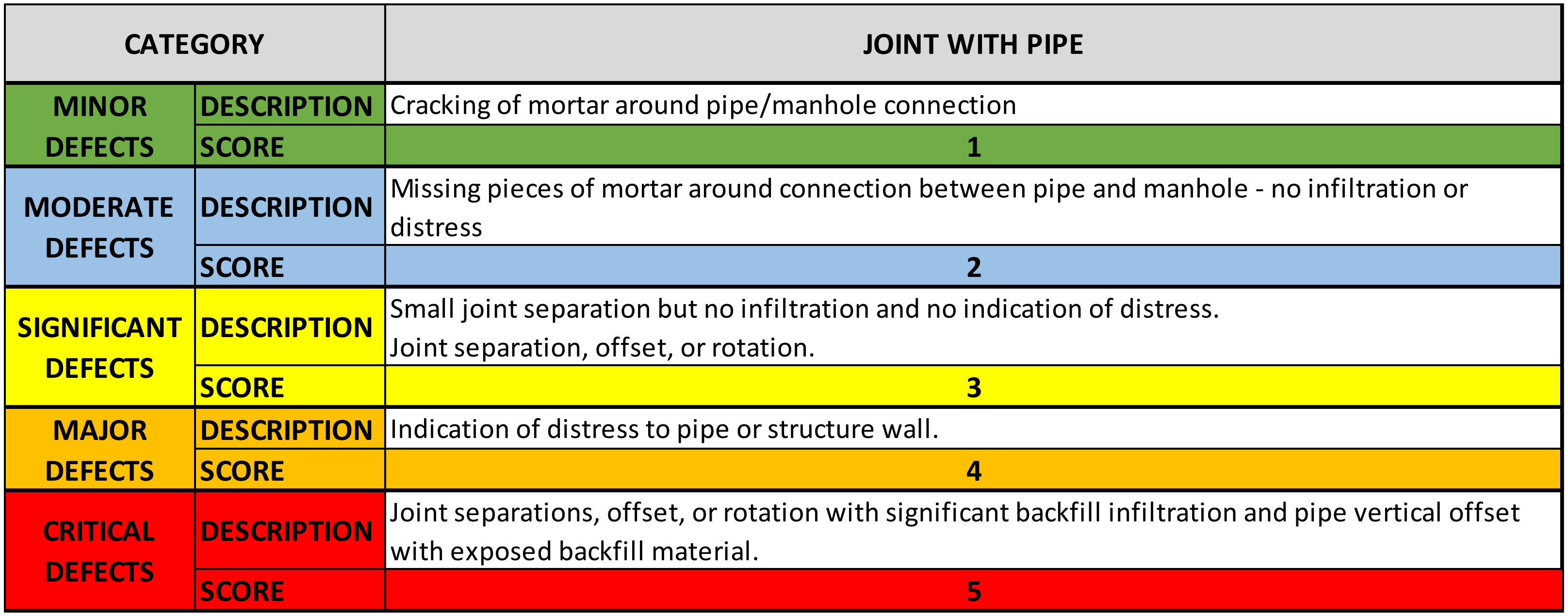
Figure 64-Masonry pipe rating system-3

CATEGORY		MATERIAL DEGRADATION OF INSIDE SURFACE
MINOR DEFECTS	DESCRIPTION	Crack (crack is a line in pipe that has not shown opening or deformation) that is vertical. No opening between crack. One max per manhole.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Multiple cracking between 0.01 in. and 0.05 in. width horizontal to grade. Single crack around interior or exterior (if visible) of manhole. Moisture on wall from seepage. Grate, MH Cover, slightly off proper grade. Localized spalls less than 1/2 in. depth and less than 6 in. diameter. No exposed rebar. Ladder and attachments have surface corrosion or light pitting. Efflorescence but no rust emanating from crack. Single open crack (fracture) - vertical. Missing brick in brick/masonry manhole in chimney, wall, or bench. No visible soil or void.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Split or cracked masonry units. Missing mortar in brick or masonry manhole. Slight discoloration of masonry units. Spalling and/or delamination from 1/2 in. to 3/4 in. in depth and larger than 6 in. diameter. No exposed rebar. Some rust staining from spalled areas, structure stable. Ladder and attachments have heavy corrosion, pitting on surface, minor loss of section. Displaced structural elements, minor visible movement of masonry units. Infiltration - no soils present. Efflorescence and rust emanating from crack/fracture. Exterior manhole cracking - are above grade. Single open crack (fracture) - horizontal.
	SCORE	3

Figure 65-Manholes, catch basins, Headwall & Wingwall, and buried junction structures rating system -1

CATEGORY		MATERIAL DEGRADATION OF INSIDE SURFACE
MAJOR DEFECTS	**DESCRIPTION**	Widespread cracking, splitting, splitting, or crushing of masonry units, or missing units. Significant movement of individual brick or masonry units. Spalling with exposed or minor corrosion of rebar - rebar still intact. Widespread spalling greater than 3/4 in. in depth or delamination. Slabbing of concrete. Ladder and attachments as heavy corrosion, pitting on surface, loss of section, not safe. Multiple open cracks (fractures) on inside or outside of manhole. Significant infiltration with soils. Minor change in shape of masonry cross section. Cracks/Fractures with significant soil migration or water infiltration. Cracks/Fractures with vertical offset - pieces of pipe have moved. Large areas of rust staining emanating from cracks/fractures. Manhole frame and cover offset from manhole.
	SCORE	**4**
CRITICAL DEFECTS	**DESCRIPTION**	Holes in concrete manhole. Visible movement or distortion of cross sectional shape, structure appears unstable. Visible corrosion of rebar. Major distortion in shape of masonry cross section. Masonry units missing through structure wall. Manhole frame or cover broken. Holes in brick manhole with soil visible or void visible. Hole in brick manhole in channel. Collapsed manhole. Offset joints in concrete manhole.
	SCORE	**5**

Figure 66-Manholes, catch basins, Headwall & Wingwall, and buried junction structures rating system-2



CATEGORY		JOINT WITH PIPE
MINOR DEFECTS	DESCRIPTION	Cracking of mortar around pipe/manhole connection
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Missing pieces of mortar around connection between pipe and manhole - no infiltration or distress
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Small joint separation but no infiltration and no indication of distress. Joint separation, offset, or rotation.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Indication of distress to pipe or structure wall.
	SCORE	4
CRITICAL DEFECTS	DESCRIPTION	Joint separations, offset, or rotation with significant backfill infiltration and pipe vertical offset with exposed backfill material.
	SCORE	5

Figure 67-Manholes, catch basins, Headwall & Wingwall, and buried junction structures rating system -3