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A RISK-BASED FRAMEWORK FOR OPTIMIZING INSPECTION PLANNING OF UTAH CULVERTS

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16. Abstract

Regular inspection and maintenance of culverts are critical to ensure the safe functioning of transportation infrastructure systems, preventing injuries, loss of life, and significant financial damage. Various state departments of transportation (DOTs) and the American Association of State Highway and Transportation Officials (AASHTO) have published culvert inspection and asset management manuals, which differ greatly between states. Therefore, this research aims to assist the Utah DOT (UDOT) in developing a comprehensive culvert management system by creating a robust model to estimate culvert conditions and providing a risk-based framework to enhance Utah's culvert inspection planning. The deterioration curves were calculated using the support vector regression (SVR) and random forest regression (RFR) algorithms based on culvert inventories from Colorado, Utah, and Vermont. Combining these inventories can estimate the final deterioration curve for Utah's culverts. Once the likelihood of failure has been determined based on Utah's final culvert deterioration curve, the frequency of culvert inspections can be established using a risk assessment approach. Therefore, culverts can be tracked based on their current condition and risk of failure. Most of the important life cycle risk factors are linked to the culvert and can be monitored to predict potential failures in the future. UDOT staff can repair/replace the culvert in advance and prevent high costs. Also, we created a draft of a Culvert/Storm Drain Management Manual for Utah at the end of this study. While creating it, the content from culvert inspection manuals of federal and other states was amalgamated and adapted for Utah's unique circumstances.

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A Risk-based Framework for Optimizing Inspection Planning of Utah Culverts

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ABSTRACT

Regular inspection and maintenance of culverts are critical to ensure the safe functioning of transportation infrastructure systems, preventing injuries, loss of life, and significant financial damage. Various state departments of transportation (DOTs) and the American Association of State Highway and Transportation Officials (AASHTO) have published culvert inspection and asset management manuals, which differ greatly between states. Therefore, this research aims to assist the Utah DOT (UDOT) in developing a comprehensive culvert management system by creating a robust model to estimate culvert conditions and providing a risk-based framework to enhance Utah's culvert inspection planning. The deterioration curves were calculated using the support vector regression (SVR) and random forest regression (RFR) algorithms based on culvert inventories from Colorado, Utah, and Vermont. Combining these inventories can estimate the final deterioration curve for Utah's culverts. Once the likelihood of failure has been determined based on Utah's final culvert deterioration curve, the frequency of culvert inspections can be established using a risk assessment approach. Therefore, culverts can be tracked based on their current condition and risk of failure. Most of the important life cycle risk factors are linked to the culvert and can be monitored to predict potential failures in the future. UDOT staff can repair/replace the culvert in advance and prevent high costs. Also, we created a draft of a Culvert/Storm Drain Management Manual for Utah at the end of this study. While creating it, the content from culvert inspection manuals of federal and other states was amalgamated and adapted for Utah's unique circumstances.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Historically, various theories, models, and management systems have been created to inspect, maintain, and repair visible infrastructure components, such as bridges and pavements. However, unseen critical infrastructures like culverts have often been neglected even though their failure can significantly impact the transportation network. To address this, many state departments of transportation, including the Utah Department of Transportation (UDOT), plan to create tailored comprehensive culvert management systems (CMS), including culvert management manuals for their respective states.

UDOT plans to categorize culverts as tier 1 assets due to their high quantity in Utah and the potential disruptions to roadways and property damage that could result from poorly maintained culverts. In light of this, the objective of this study is to assist UDOT in establishing a comprehensive CMS by creating a Utah culvert management manual. To achieve this, the researchers identified the culvert deterioration curves based on historical data from three U.S. states (Utah, Colorado, and Vermont). These curves are then employed by a risk-based framework for life cycle analysis to estimate the frequency of culvert inspections and service life. The proposed method for determining culvert deterioration curves and enhancing inspection planning involves using machine learning algorithms, including support vector regression (SVR) and random forest regression (RFR), as well as a risk assessment approach. The culvert life cycle was analyzed for risk assessment in order to consider associated risks during the culvert life cycle and estimate future risks. The developed solution is intended to be integrated into the ATOM software, which manages assets and maintenance for UDOT.

The developed models performed effectively in predicting culvert conditions with an accuracy of 71% for SVR and 79% for RFR. The proposed method was tested by scheduling the inspection of 272 culverts in Utah, revealing that UDOT could potentially focus on inspecting and maintaining 10% of the culverts instead of all 272. Following the development of this data-driven approach for monitoring culvert conditions, a draft manual for managing culverts in Utah was developed. The draft drew on the review of several culvert inspection and maintenance manuals from other states to shape Utah's culvert/storm drain management manual. A first draft of the manual was created by combining the content of these manuals with Utah's culvert rating system and the proposed data-driven approach. UDOT's maintenance division can refine and finalize this draft for use across the state. As a result, UDOT staff can repair/replace the culvert in advance and prevent high costs.

1. INTRODUCTION

1.1 Introduction

Culverts are engineered waterways constructed from various materials, which are designed to run either alongside or perpendicular to roads. Their purpose is to facilitate the flow of water from one side of an embankment to the other, all while withstanding the weight of the earth and any vehicular traffic above. Culverts across the country play a critical part in transportation and water control systems. The breakdown of these structures can lead to environmental harm and potential road blockages, causing travel disruptions [1]. In 2015, South Carolina was hit by a rainfall event of a magnitude seen once in a thousand years, leading to substantial infrastructural damage, including to culverts. Culvert failures in Richland and Lexington counties led to at least 15 prolonged road closures (Figure 1.1) [2]. Several culverts in the United States are in poor condition and nearing the end of their functional lifespan. A culvert losing its structural integrity can negatively impact the road above, causing surface depressions, significant cracking, or even total collapse in extreme cases. Therefore, it is imperative for transportation agencies to commit to regular inspection and maintenance of these infrastructures.

Figure 1.1 On October 4, 2015, flooding occurred on Caughman Road in Richland County [3]

Culverts often occupy locations that are challenging to access, making their routine inspections quite difficult for relevant agencies. Inspecting culverts in these areas requires not only specialized equipment but also well-trained personnel who are familiar with the intricacies of such infrastructures. Moreover, the process of inspecting culverts can be incredibly time-consuming. Each culvert must be individually assessed for physical damage, material degradation, blockages, and any other factors impacting its functional performance. Because of these complexities and constraints, agencies are often compelled to estimate the deterioration of culverts instead of conducting regular hands-on inspections. They leverage historical data, environmental conditions, and statistical models to predict the rate of culvert degradation. The deterioration estimation can be a crucial tool for these agencies to plan maintenance schedules, allocate resources efficiently, and most importantly, prevent catastrophic failures that could potentially impact road transportation and the environment.

Creating deterioration models is a crucial step in formulating any strategy for managing infrastructure assets. It aids in understanding the anticipated behavior of these assets and in unveiling factors that affect their condition states. By analyzing existing culvert datasets, such as inspection records, transportation agencies can develop deterioration models for culverts. This helps them determine how often inspections are needed and pinpoint crucial culverts that require immediate repair, restoration, or replacement to prevent failure [4]. Neglecting or omitting proper maintenance is predicted to adversely affect the asset's condition and performance, leading to a reduced service level, early deterioration, and eventually necessitating expensive restoration or replacement. Therefore, culverts, being vital parts of the transportation infrastructure, should be incorporated into a management plan by each transportation agency, with the initial step being the development of culvert deterioration models.

1.2 Problem Definition

The Utah Department of Transportation (UDOT) is responsible for a large inventory of over 47,000 culverts. As part of its current management practices, UDOT tends to react to issues as they arise and carries out maintenance on the surrounding embankments. Unfortunately, until now, there has been no systematic plan in place for regular inspection or maintenance of these crucial structures. Furthermore, no formal schedule has been devised for culvert replacement based on an estimation of their service life. While UDOT does maintain some records of problematic culverts, there is no comprehensive system to monitor the status of the entire culvert inventory [5].

The lack of historical performance data presents additional challenges. These data would be extremely valuable when specifying new culverts, particularly in terms of conducting a life cycle analysis. Life cycle analysis considers factors such as initial construction costs, ongoing maintenance expenses, and the expected lifespan of the infrastructure, thereby providing a comprehensive view of the total cost of ownership. Without such data, it becomes more difficult to make informed decisions about future culvert installations. Moreover, the absence of a proactive maintenance and inspection program indicates a looming issue, given a large part of the culvert inventory was put in place during the Interstate Highway System construction in the 1960s and 1970s. These culverts are now aging, increasing the risk of structural failures. If not properly addressed, these aging culverts could lead to serious environmental, safety, and traffic disruption issues.

Management of culvert assets holds significant importance for every state DOT. Considering the sheer number of culverts and the prospective risk of traffic disturbances and property destruction due to inadequately maintained culverts, it is essential to have a systematic approach for assessing their condition and conducting necessary maintenance. This should be the primary objective of any culvert management system. Several state DOTs, along with the American Association of State Highway and Transportation Officials (AASHTO), have issued guidelines on culvert inspection and asset management. However, the techniques used to evaluate culvert conditions can significantly vary from one state to another, as different states consider a range of quantitative and qualitative criteria such as pipe material/shape/coating, drain type, installation year, and highway importance. These guidelines are tailored to each state's unique circumstances and may not necessarily consider the specific environmental and soil conditions pertaining to culverts in Utah.

Due to the importance of these assets, UDOT intends to classify culverts as tier 1 assets. Consequently, UDOT needs to develop a comprehensive CMS to maintain culverts systematically. The previous guidelines are specific to each state and may not reflect Utah culvert conditions. As a result, we plan to develop a robust system that is capable of monitoring culverts in an efficient and automated approach. This system consists of the following modules (Figure 1.2): (1) estimating the deterioration curves for UDOT culverts, (2) developing a life cycle analysis, and (3) providing a risk-based framework for assessment prioritization and inspection frequency estimation. To achieve our goals, the upcoming section will delve into the key factors of culvert condition prediction models and review culvert inspection manuals available in academic literature. Subsequently, we will discuss the machine learning (ML) models and risk-based prioritization methods utilized in this study. The process of data gathering will then be outlined. In the end, we will elaborate on the outputs and discoveries made in this study.

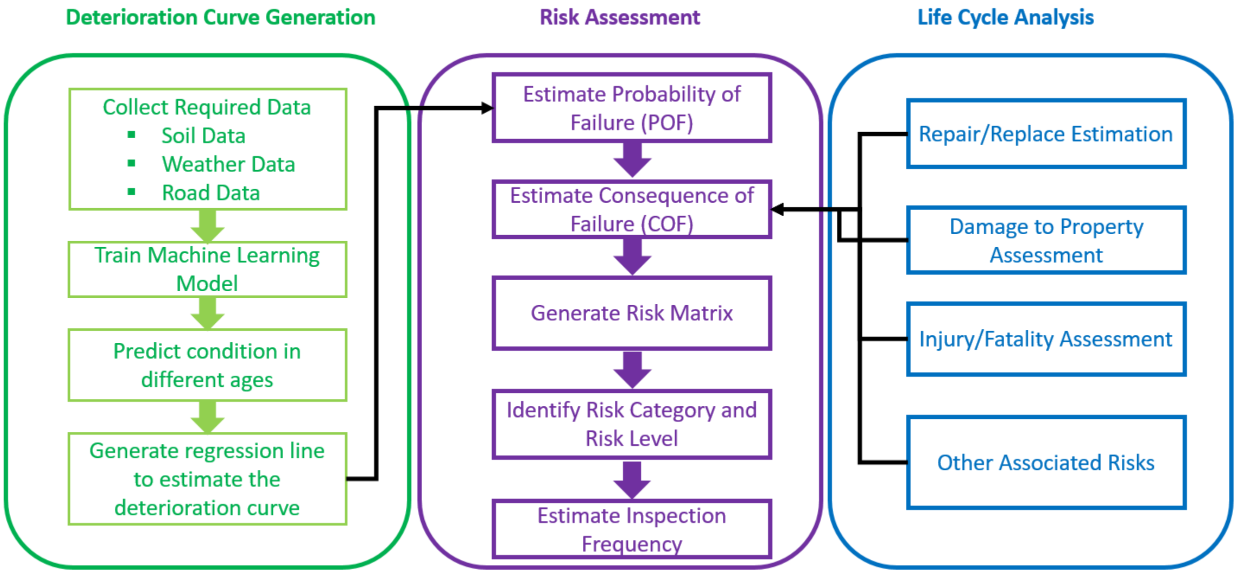


Figure 1.2 Framework of the life cycle analysis and risk assessment system

2. BACKGROUND

In this section, we review the literature regarding the applications of machine learning (ML) for predicting culvert conditions and key characteristics of culverts during prediction. Also, we discuss existing culvert management systems.

2.1 Culvert Condition Prediction Models

In the United States, the most common materials used in culvert construction are concrete and metal. While other materials like plastic and masonry are occasionally used in certain areas, they are less common. In the state of Utah, according to a study conducted by UDOT via UTRAC, 75% of culverts are made from corrugated steel, 25% from reinforced concrete, and 5% from plastic. There are also culverts constructed from other materials such as wood, brick, and rock, but these instances are limited (McGrath & Beaver, 2004). Given these statistics, the majority of research focuses on understanding the factors that influence the performance and longevity of concrete and metal culverts, and the findings from these studies will be discussed in the following sections.

A vast number of culverts are constructed from metal due to the material's versatility in terms of shape and size, and the flexibility it offers in design processes [6]. According to Bednar's study [7], key factors impacting the longevity of galvanized steel pipes include water pH, dissolved particles in the flow, hardness and alkalinity of the flow, water speed, temperature, and duration of water contact. Mitchell et al. [8] stated that metal culverts have a maximum lifespan of 60 to 65 years, with major factors impacting the culvert's rating being the type of culvert (corrugated metal pipe versus structural steel plate), pH and abrasiveness of the flow, flow speed, age, and pipe diameter. Degler et al. [9] conducted research on pipe-arch corrugated metal pipe structures, stating that the durability of these structures was dependent on their age and the presence of highly abrasive, low pH streams in southeastern Ohio. The most common failure modes were corrosion and pitting of the multiplate structure, and seepage and corrosion at bolted joints.

Concrete culverts, on the other hand, exhibit different properties from their metal counterparts. For instance, they are more resistant to corrosion and abrasion, and have greater rigidity than metal and steel culverts, allowing them to better bear backfill loads [6]. Bealey [10] stated that the durability of concrete culverts is most influenced by the presence of abrasion and erosion, sulfate soils, acids and chlorides, and freeze-thaw cycles. However, acid attack is the only factor with a potentially significant detrimental impact on precast concrete culverts. The service life of concrete culverts was estimated to be 70 to 80 years by Mitchell et al. [8]. The most significant factors influencing the culvert condition rating were found to be age, pH, and abrasiveness. The most common problems encountered during concrete culvert inspections were deterioration of the headwall, deterioration in the crown region of the top slab and inlet end, and transverse shear cracks on abutment walls. The soil conditions around concrete pipelines could also cause structural issues.

It is clear from the discussion above that prior studies have identified essential characteristics for each type of culvert. Alongside these, previous culvert condition prediction models have utilized various input variables based on the prediction model type, specific culvert type, and target output variables. For instance, Cahoon et al. [11] pinpointed the significant factors influencing overall condition ratings and the decision-making process for the repair or replacement of 460 culverts located in 11 Montana counties. This study used an ordered probit model for data analysis and a t-test to identify key characteristics. The results revealed that age, scour at the outlet, major failure signs, level of corrosion, invert wear, sedimentation, physical blockage, joint separation, and physical damage were key factors in determining the overall condition rating. In another study, Tatari et al. [12] created an artificial neural network (ANN) model to evaluate the condition of culverts using data from the Ohio DOT culvert inventory. The following variables were incorporated into the neural network model: wall thickness, flow velocity, average daily traffic (ADT), type of culvert, age, pH, abrasive condition, cover height, and rise. Despite choosing nine features, they only utilized 39 culverts in the development process of the ANN model, indicating a relatively small sample size.

Salem et al. [4] developed a preliminary deterioration model for metal culverts to assist decision makers in recognizing the primary elements impacting metal culvert deterioration and in prioritizing inspection operations. They used binary logistic regression and a forward stepwise variable selection method to develop the initial deterioration model. The Ohio DOT provided the dataset, consisting of a total of 99 records. Features like age, span, slope, and protection type were utilized in the development of the deterioration model. Most recently, a study by Mohammadi et al. [13] examined the application of ML models for culvert condition prediction. They evaluated five multiclass classification algorithms: decision tree, k-nearest neighbor, ANN, random forest, and support vector machine, utilizing a dataset of 2,555 culverts. According to their findings, the random forest model most accurately predicted culvert conditions. Moreover, their results highlighted that age, soil moisture, and soil pH were the three most significant factors in predicting culvert conditions.

Based on the review of existing literature, it's clear that the age of a culvert is consistently crucial in evaluating deterioration and estimating condition models [13]–[15]. The culvert's size, material, and slope were also commonly cited as key physical factors in these culvert condition prediction models. Alongside these physical traits, several environmental aspects relating to the culvert's location were deemed significant. Environmental elements such as the abrasiveness of stream beds, water pH, and characteristics of the water source flow were often accounted for [1]. However, due to the vast array of potential deterioration modes and possible quantitative defects or condition states, the relationship between these features and the culvert's condition can be complex. Therefore, the results of each study were intrinsically linked to the specific culvert attributes considered, which in turn depend entirely on their availability.

In contrast to most previous research, which predominantly used classification algorithms to predict the condition of culverts, our study will take a different approach. We intend to develop robust deterioration models based on regression algorithms and generate deterioration curves for each type of culvert. This method not only facilitates a more granular understanding of each culvert's deterioration pattern over time, but it also allows UDOT to seamlessly integrate these models into the culvert management system. This will provide a more detailed, predictive, and practical tool for UDOT's infrastructure maintenance planning, resulting in more efficient resource allocation and timely interventions for culvert maintenance and repair.

2.2 Culvert Management Systems

Different state transportation agencies formulate their culvert inspection strategies based on their unique criteria, drawn from the National Cooperative Highway Research Program (NCHRP) survey [16]. The Ohio DOT, for instance, utilized a three-tiered inspection system, determined by the culvert's condition and span [17]. The New York State DOT adopted a similar tiered approach, relying on culvert condition ratings [18]. The Minnesota DOT, on the other hand, inspected culverts with spans exceeding 10 feet every 12 to 24 months, with no inspection intervals exceeding two years [19]. The Indiana DOT followed a routine of inspecting culverts with spans less than 48 inches every four or five years, irrespective of their condition [20]. The Maryland DOT's Bridge Inspection and Remedial Engineering Division (BIRED) conducted culvert inspections every four years, but the frequency could be increased to biennially if the condition warranted [19]. Initially, UDOT proposed that new culverts be inspected every 10 years, good culverts every five years, fair culverts every three years, and poor culverts annually. However, these proposed culvert inspection schedules were not data-driven, implying they might not accurately reflect reality. They were mainly based on expert judgments and often only considered culvert condition, which was essential but insufficient.

Recently, DOTs have realized that planning culvert inspections solely based on culvert span and condition is ineffective, prompting the development of decision support systems for culvert inspection planning. Meegoda et al. [21] developed one such system for the New Jersey DOT to assess drainage infrastructure, estimate maintenance costs, and allocate budget funds accordingly. The integrated drainage information, analysis, and management system (DIAMS) comprised four main modules to manage and finance the inspection process effectively. More recent methods prioritize culvert maintenance based on the risk of failure, considering multiple factors affecting culvert conditions. Sousa et al. [22] developed a risk analysis framework for prioritizing culverts needing intervention. This approach, despite relying heavily on inspectors' judgments, enriched decision-making for culvert maintenance. For an efficient CMS, it is necessary to adopt a comprehensive risk-based approach that considers all risks associated with culvert failure.

A risk-based asset management system considers not only the condition of a culvert but also the potential costs of failure when deciding inspection frequencies. It quantifies the risk linked to each culvert, providing insight into the relative importance of different culverts. This approach allows culverts to be ranked according to their risk scores, identifying those most urgently needing future maintenance. Prioritizing the maintenance of assets with the highest risk of failure can help prevent potential failures that might lead to substantial economic, social, and ecological impacts. Additionally, the overall condition of the system can be enhanced by repairing or replacing the most critical assets before any severe failure occurs. Typically, the process of calculating an asset's risk of failure involves two steps: (1) ascertaining its likelihood of failure (LOF) and (2) determining its consequence of failure (COF). After these values have been established, several methods can be employed to determine the risk of failure, with the use of a risk matrix being the most common approach [23].

3. METHODOLOGY

Deterioration modeling refers to the process of modeling and predicting the future state or performance of an asset. Machine learning (ML) algorithms can be utilized to identify the relationships between influencing factors (independent variables) and the condition of assets (dependent variable). In this section, we will explain selected ML algorithms used for deterioration modeling, focusing on the condition of Utah's culverts. Subsequently, we will introduce the risk assessment approach used to prioritize inspection frequencies of culverts. After that, we will discuss the methods we used to collect data for this study. Lastly, we will delve into the draft of UDOT's culvert/storm drain management system manual proposed to the UDOT maintenance division.

3.1 Machine Learning Models

ML refers to the process by which a computer system learns without being explicitly programmed to do so [24]. Recently, researchers have expressed growing interest in utilizing ML for maintenance activities [25]–[27]. An ML method delves into complex interrelationships and patterns within a dataset with minimal human intervention. Predictive analytics are enhanced by ML as it learns from data rather than relying on subjective assumptions and simplifications. Several ML algorithms, such as support vector machine (SVM) and ANN, have been applied in transportation asset management [28].

This study uses two ML algorithms, SVM and random forest, to create culvert deterioration prediction models. These two algorithms are chosen over the ANN algorithm because they are less computationally expensive and do not require a large dataset.

3.1.1 Dynamic Modulus

SVM is a supervised learning algorithm used in machine learning for classification and regression analysis. Functioning as a discriminative classifier, SVMs categorize data points into separate classes based on an optimal hyperplane defined by the algorithm. SVM aims to identify the optimal hyperplane that best separates the data and maximizes the gap between different class data points [29]. The optimal separation hyperplane is equidistant from both classes (positive and negative), as illustrated in the example of the SVM model in Figure 3.1[30]. Support vectors are the data points closest to the hyperplane; in this example, they are the data points on the edges of the margin.

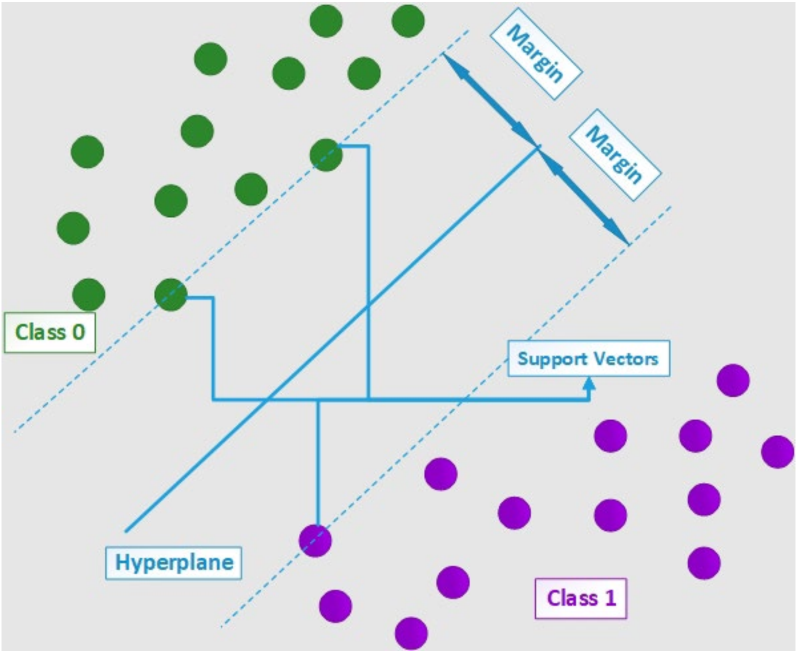


Figure 3.1 SVM model illustration

SVM has the following advantages: a) it is effective in high-dimensional spaces; b) it is still effective in situations when there are more dimensions than samples; c) it is memory-efficient due to relying on a subset of training points (called support vectors) for the decision function; and d) for the decision function, a variety of kernel functions are available [31], [32]. There are also disadvantages of SVM; for example, if the number of features is much more than the number of samples, avoiding overfitting in selecting kernel functions and regularizing terms is crucial. In addition, probability estimates are not directly provided by SVMs. They are calculated through five-fold cross-validation [31].

Many research studies have employed SVM classifiers to build predictive models for different types of infrastructure conditions or failures. Examples include predicting bearing failures in rail systems [33], foreseeing damage to bridge structures [34], and determining the probability of pavement failures [35]. These studies established that SVM is capable of accurately predicting asset conditions and failure.

While SVMs are widely recognized for their utility in classification problems, their application to regression problems, or support vector regression (SVR), is less frequently documented. SVR is a variant of SVM proposed by Drucker et al. [36] in 1996, and it is essentially a generalization of the classification problem to accommodate continuous variables. SVR introduces an epsilon-insensitive zone, known as the epsilon-tube, around the function to extend SVM. This tube reformulates the optimization problem, striking a balance between model complexity and prediction error, and identifying the best tube for predicting the continuous-valued function [37].

3.1.2 Random Forest Regression (RFR)

Random forest regression (RFR) is a supervised learning algorithm that addresses classification, regression, and other problems by generating a multitude of decision trees during the training phase. Ensemble learning improves prediction accuracy by amalgamating the predictions from various machine learning algorithms [38].

In classification tasks, the output of the random forest is the class selected by most trees. However, for regression tasks, the average prediction of each tree is returned, as depicted in Figure 3.2. A random forest consists of numerous random decision trees, with two forms of randomization ingrained. First, each tree is built on a sample randomly chosen from the original data. Second, a subset of features is randomly selected at each tree node to determine the optimal split. In doing so, random decision forests circumvent the problem of overfitting to their training set, which is a common issue with decision trees [39].

The random forest algorithm works as follows:

- Draw T bootstrap data samples.
- At each split, draw a subset of the available attributes.
- Train trees on each sample/attribute set to get T trees.
- Average the predictions of trees on out-of-bag samples.

A random forest algorithm offers several considerable benefits: a) it counteracts the overfitting common in decision trees and aids in increasing accuracy, b) it works efficiently with both categorical and continuous data, c) it can automatically manage missing data, d) it does not require data normalization, and e) it demonstrates resilience to outliers [31], [40]. However, in spite of these advantages, a random forest algorithm does come with its own set of drawbacks: a) it utilizes significant resources and computational power to build multiple trees and combine their outcomes, b) it necessitates a lengthier training phase, and c) its ensemble nature involving numerous decision trees makes it difficult to interpret [31].

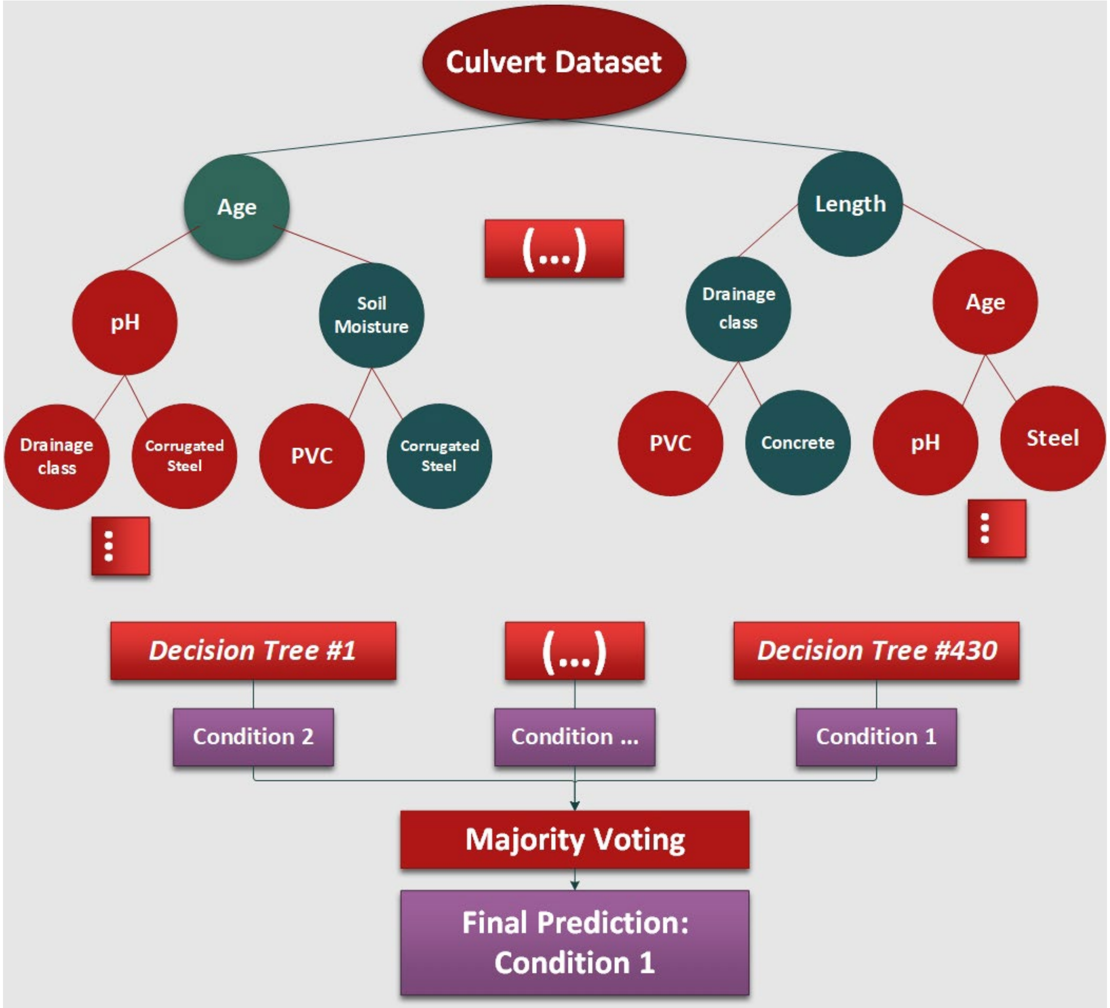


Figure 3.2 Random forest structure

3.2 Risk Assessment

Upon creating the deterioration curves for culverts, the next step was using these curves to calculate the inspection frequencies for culverts. It is standard practice to prioritize inspections of assets such as sewers, pipes, pavements, and bridges based on their risk factors. Similarly, this study performed a life cycle analysis and risk assessment to determine culvert inspection frequencies and help UDOT in decision-making. The risk factor is calculated as the product of the likelihood of failure (LOF) and the consequence of failure (COF) (as per Equation 1).

$$\boldsymbol{Culvert\ Risk\ Factor = LOF \times COF} \qquad \text{Eq. 1}$$

3.2.1 Likelihood of Failure (LOF)

The LOF is directly related to the current condition of the culvert. As culverts age, they become more susceptible to erosion and abrasion, thereby increasing the rate of failure. Several factors contribute to the LOF, such as the culvert's material, remaining useful life, repair history, soil type, and inspection rating. Given that the deterioration curves produced in the previous section consider most of these factors, they can be directly applied to estimate the LOF under varying circumstances. Figure 3.3 depicts the conditions of a culvert using a deterioration curve.

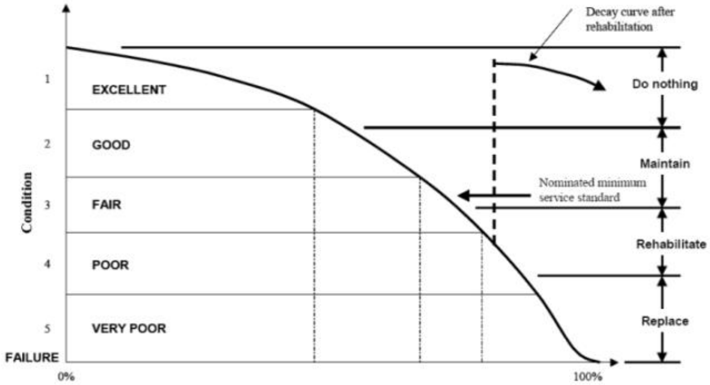


Figure 3.3 Sample deterioration curve for culvert [41]

In many studies, LOF is usually assigned a value between 0 and 1 for different condition ratings. However, using other ranges, such as 1 to 10 or 1 to 100, is also valid as long as the underlying principle holds true. Table 3.1 presents the LOF values as provided by UDOT for this study.

Table 3.1 LOFs based on UDOT culvert risk assessment

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

3.2.2 Consequence of Failure (COF)

Assessing risk factors means it may not be sufficient to solely identify culverts with a higher LOF, as inspecting all of them would still necessitate substantial investment. Therefore, the COF for each culvert should also be evaluated to include all critical factors in prioritizing inspections. For instance, a culvert under the I-15 highway with a lower LOF might present a higher risk than a culvert under a rural road with a higher LOF. COF is connected to asset types, and in this study, it is categorized into economic and social impacts.

Economic impacts include the costs of repair or replacement and damages to nearby properties. Some researchers have used indirect methods to quantify costs, as the actual economic impact comprises several cost items. For instance, a culvert's physical dimensions, such as diameter and length, were used to estimate repair or replacement costs. Although many variables can influence repair costs, the culvert type and its dimensions are among the most crucial. Historical repair data, published tables in guidelines, and approximation methods were all employed to calculate the repair cost per length or total repair costs.

In this study, repair costs are relatively calculated based on the culvert's material type and dimensions (Equation 2). Table 3.2 displays the relative weights for the cost per volume of each culvert material, approximated from historical repair data and other accessible reports. It is important to note that the base repair cost and coefficients can vary depending on the culvert's location, its condition, and etc. However, in order to make the calculation possible, we assumed that they are the same in this study. The relative weight values enable the comparison of a culvert's repair costs to others, highlighting the most critical ones. However, the final risk value does not provide the exact repair cost of the culvert.

$$\boldsymbol{Repair\ Costs = Cost\ per\ volume\ weight\ \times Volume\ of\ culvert} \qquad \text{Eq. 2}$$

Table 3.2 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

We used approximation methods to quantify the potential damage costs to nearby properties. Utilizing historical maintenance records, we estimated that the base damage cost to properties is set at $300,000, but UDOT can update this value later based on actual damage costs to properties in Utah. The costs of damages to adjacent properties can fluctuate based on various factors, such as location and condition. Hence, we used Equation 3 to calculate the direct damage costs to nearby properties. Assigning higher weights to culverts located in flood plains or sensitive watersheds is crucial, as their failure could pose more significant risks to nearby properties or facilities.

$$\boldsymbol{Direct\ Damage\ Costs = W1\ \times W2 \times Base\ Damage\ Costs} \qquad \text{Eq. 3}$$

To calculate W1 and W2, we considered the stream type and Federal Emergency Management Agency (FEMA) flood zones, using their assigned weights to estimate potential property damage in the event of a culvert failure. Table 3.3 and Table 3.4, respectively, display these weights.

Table 3.3 Weights related to each stream type

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

Table 3.4 Weights related to each flood zone

FEMA Flood Zones		**Definition**	**Weight (W2)**
A	A	**1% annual-chance** flood event generally determined using **approximate methodologies**	1
A	AE, A1-A30	**1% annual-chance** flood event determined by **detailed methods**	1
A	AH	**1% annual-chance** shallow flooding, typically areas of **ponding (average depths are between one and three feet)**	1
A	AO	**1% 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% annual-chance** flood event, but will ultimately be protected (**such as dikes, dams, and levees**)	1
A	V	**1% annual-chance** flood event (**Areas along coasts)**	1
A	VE, V1-V30	**1% 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% annual-chance** floodplain and the **0.2% annual-chance** floodplain	0.2
C	X (Unshaded), C	**Minimal flood hazards outside 0.2% annual-chance** floodplain	0.1
D	D	**Possible** but **undetermined flood risk**	0.1

A culvert failure can lead to both direct and indirect damages. Social impacts pertain to any repercussions on the local population in the event of a culvert failure. Among the significant social impacts is the cost of service loss, chiefly the cost of user delays. In this study, we deduced the cost of user delays via Equation 4, based on the following components:

- 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 (Cv= \$ per person-hour of delay)
- Average rate of freight delay in dollars per hour (Cf= \$ per freight-hour of delay)
- Percentage of passenger vehicles traffic (Vv= % vehicle passenger traffic)
- Vehicle occupancy factor (Vof = persons per vehicle)
- Percentage of truck traffic (Vf = % truck traffic)

$$\boldsymbol{Indirect\ Damage\ Costs} = \sum_{k=0}^{n} AADT_k \times t_k \times d_k \times (c_{vk} \times v_{vk} \times v_{ofk} + c_{fk} \times v_{fk}) \qquad \text{Eq. 4}$$

It is important to note that the “k” factor allows each user delay cost to be attributed to a specific period within the failure year, even though these factors may fluctuate in the future. Additionally, if the culvert is not situated under a roadway, the user delay cost should not be factored in. We estimated user delay costs in this study by assigning the values in Table 3.5 to the parameters of Equation 4. These values can vary depending on the road, AADT, availability of alternative roads adjacent to the main road, and the percentage of truck traffic, and they can be replaced by actual values as they are progressively acquired.

Table 3.5 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	-

Accordingly, the total consequence of culvert failure is calculated in relation to the culvert’s location, as indicated in Equation 5.

$$\boldsymbol{COF} = \boldsymbol{Repair\ Cost} + \boldsymbol{Direct\ Damage\ Cost} + \boldsymbol{Indirect\ Damage\ Cost}(\boldsymbol{if\ under\ roadway}) \qquad \text{Eq. 5}$$

3.2.3 Risk Level

After calculating the LOF and COF, we are able to create the risk matrix. Figure 3.4 displays a risk matrix that one axis represents the culvert’s LOF and the other axis represents the culvert’s COF. Culverts with higher LOF and COF are prioritized, whereas those with lower LOF and COF are given lower priority. As illustrated in Figure 3.4, assets with the highest priority are in the red zone, those with medium priority fall in the orange zone, and the ones with the lowest priority are in the green zone.

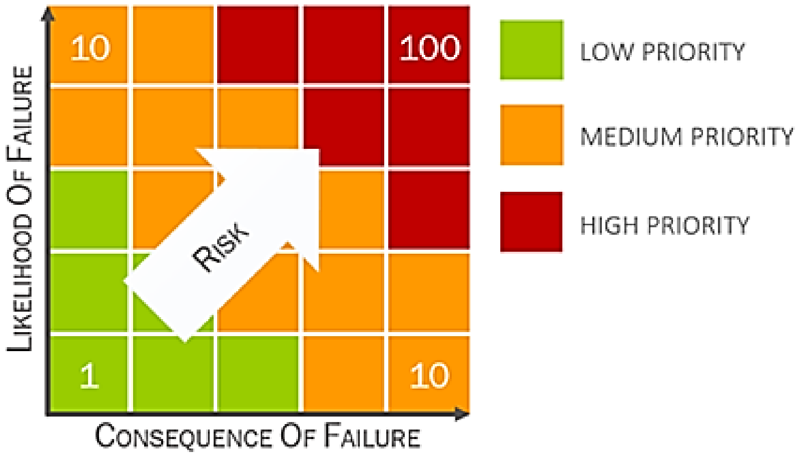
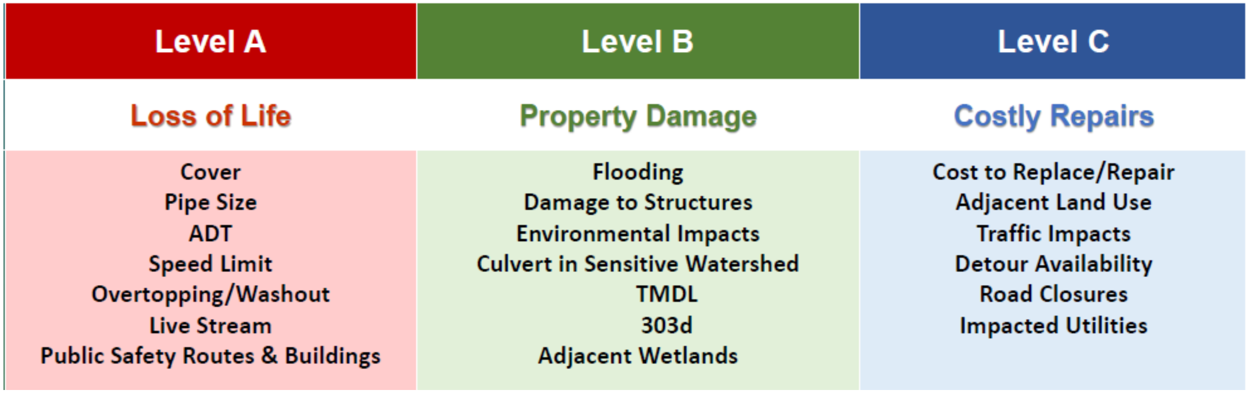


Figure 3.4 Risk matrix

According to UDOT, risk can be divided into three qualitative categories based on various factors, and we utilized these categories in creating the risk matrix. Table 3.6 showcases the categories provided by UDOT.

Table 3.6 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 risk factor of a culvert is calculated as the product of LOF and COF, as per Equation 1. Depending on the ranges of the risk factor, different risk categories will be allocated to each culvert. The following ranges were selected based on the risk distribution 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

Once each culvert is assigned its respective risk category and condition rating, one can determine the risk level of all culverts in accordance with the created risk matrix. Risk levels are categorized from level 1 to level 4, as shown in Figure 3.5. From level 1 to level 4, the criticality of culverts decreases, with level 1 being the most critical and level 4 being the least critical.

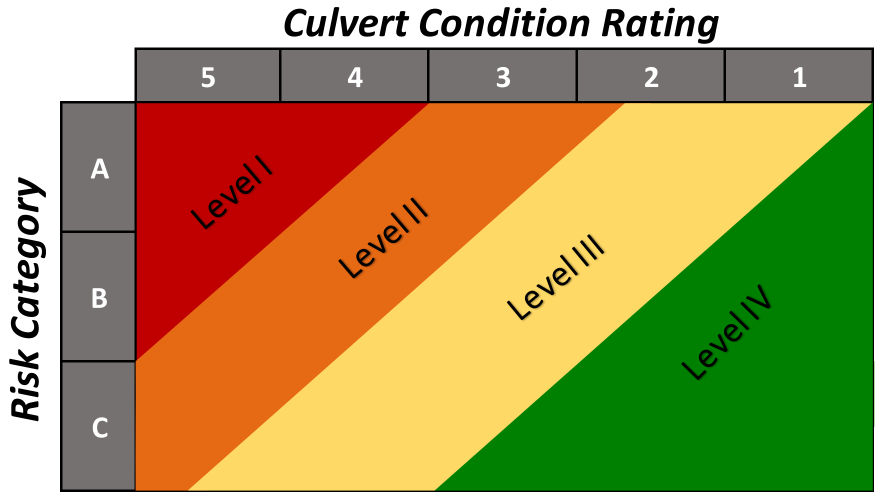


Figure 3.5 Risk matrix based on the risk factor and culvert condition rating

3.2.4 Inspection Frequency

The final step involves assigning inspection frequencies to culverts based on their identified risk level. According to the draft of the inspection cycle manual provided by UDOT, culverts in the level 4 zone should undergo an inspection every 10 years, those in level 3 every seven years, those in level 2 every three years, and those in level 1 annually. The frequencies in Table 3.7 may be subject to change as UDOT finalizes the overall budget required for culvert inspection. Level 1 culverts are considered critical, and inspecting them every year can lead to cost savings by preventing more expensive repairs.

Table 3.7 Inspection cycle table

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

3.3 Data Collection

Gathering input data is a crucial first step in building reliable ML models. For this study, we used three datasets to examine culvert deterioration. The culvert inventories for Colorado and Utah were provided by UDOT, while the Vermont culvert inventory was sourced from the Vermont Agency of Transportation. One downside of these datasets was the absence of soil data, so we had to download this from the Web Soil Survey (WSS) database. Moreover, these datasets needed to be pre-processed before being integrated into the Utah culvert management system. We utilized existing Python packages to deal with missing values in the dataset and eliminate outliers.

Based on existing literature, factors such as soil chemical properties, soil erosion characteristics, soil physical properties, and soil-related water features can all impact the deterioration curve of culverts. The WSS website, managed by the National Cooperative Soil Survey (NCSS), provides soil data and information. We used the latitude and longitude of each culvert to determine the associated soil properties and added them to the dataset, as depicted in Figure 3.6.

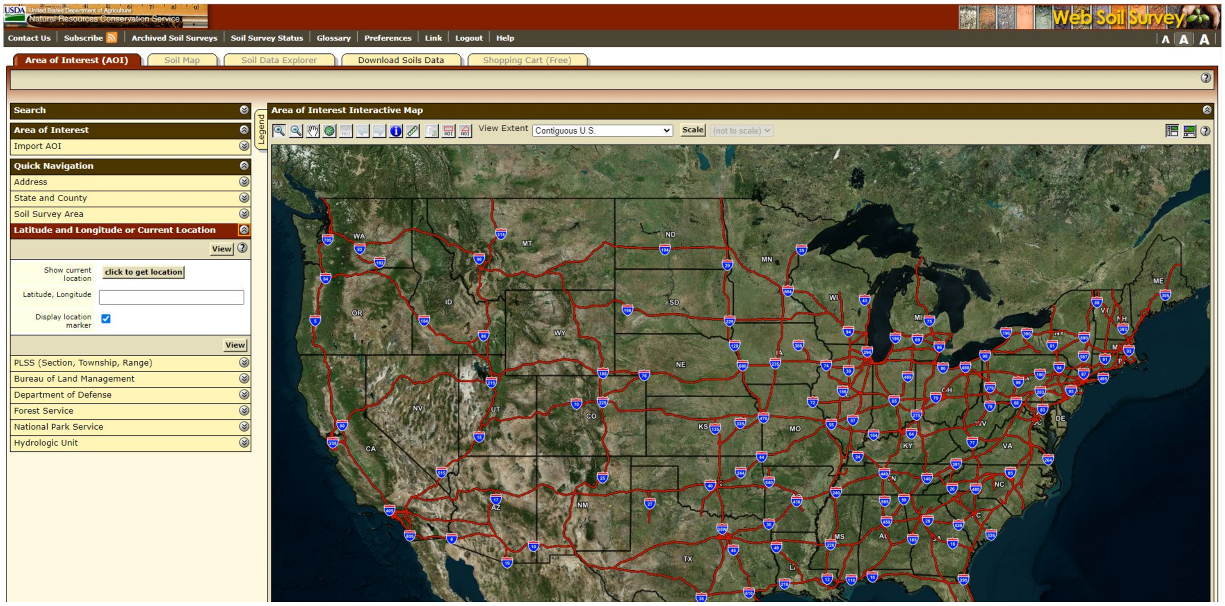
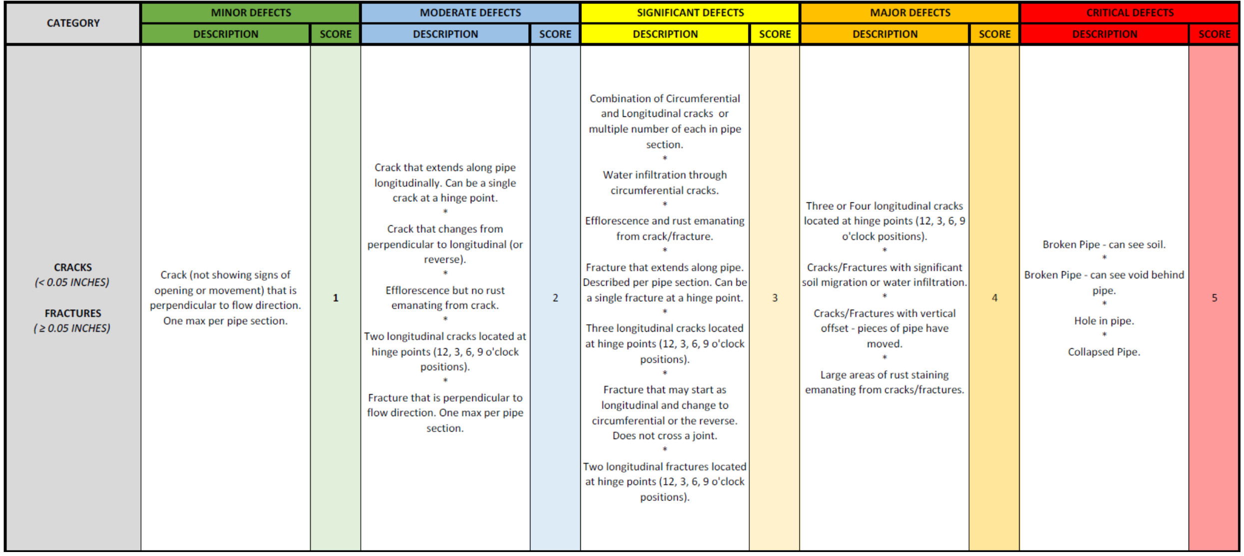


Figure 3.6 Web Soil Survey website

Figure 3.6 showcases the WSS website. Data extraction refers to the process of gathering data from unstructured or poorly structured data sources (like websites) for further processing (Laender et al., 2002). Unfortunately, data extraction was not feasible from the WSS website due to its complexity, outdated design, and requirement for authorization. As such, we manually gathered all soil attributes for approximately 2,000 culverts from this website. The final soil attributes and their definitions were sourced from the WSS website [42]. It is crucial to note that the impact of these features differs between steel and concrete culverts.

Additional modifications were necessary for these datasets to construct the deterioration curve for culverts in Utah. UDOT has proposed a unique 5-point rating system for culverts, which differs from the rating systems used in Colorado and Vermont. Table 3.8 provides an example of the Utah rating system for concrete culverts. Additionally, all pipe defect rating sheets developed by UDOT can be found in APPENDIX A: UDOT Pipe Defect Rating Sheets. Table 3.9 proposes a method for converting the rating systems based on each state’s manual definition for these rating scales. Similarly, deterioration curves are updated using the updated rating system.

Table 3.8 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 3.9 Rating conversion table

<table>
<tr><td>Colorado</td><td>9</td><td>8</td><td colspan="2">7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td></tr>
<tr><td>Utah</td><td colspan="2">Minor Defects</td><td colspan="2">Moderate Defects</td><td>Significant Defects</td><td>Major Defects</td><td colspan="4">Critical Defects</td></tr>
<tr><td>Vermont</td><td colspan="2">Excellent</td><td>Good</td><td>Fair</td><td>Poor</td><td>Critical</td><td colspan="2">Urgent</td><td colspan="2">Closed</td></tr>
</table>

3.4 Draft Manual for Utah's Culverts

The final step of this study involved formulating a manual for managing culverts and storm drains in Utah. To accomplish this, we reviewed various federal and state-specific culvert inspection manuals, such as the AASHTO Culvert & Storm Drain System Inspection Guide [43] and FHWA Culvert Inspection Manual [19]. Despite their different layouts or chapters, these manuals essentially cover the same principles and offer the necessary content for drafting Utah's Culvert/Storm Drain Management Manual.

The most frequently observed chapters in the inspection manuals were the Inventory Guideline, Inspector Characteristics, Inspection Procedures, and Rating System. Aside from inspecting culverts, their maintenance also plays a vital role in culvert management. Thus, the proposed management system manual for UDOT also includes a chapter on maintaining culverts and storm drains. Based on the reviewed manuals, we proposed the following outline for Utah's Culvert/Storm Drain Management System Manual:

- 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 is Utah-specific and is drafted by integrating aspects from the reviewed manuals. It covers everything from introducing the subject of culvert and storm drain system inspections in Chapter 1 to listing the documents used in creating the manual in Chapter 8. Other sections include information such as the inspector's duties, qualifications, and required equipment; inspection planning and sequence; the calculation of inspection frequency; and the rating of culvert and storm drain system conditions.

4. RESULTS AND DISCUSSION

As outlined in the previous sections, machine learning models were created to develop various deterioration curves using culvert inventory data from Colorado, Vermont, and Utah. Initially, we created separate deterioration curves for Utah, Colorado, and Vermont culverts. Subsequently, we merged the three datasets and developed deterioration curves based on the consolidated data. The inspection frequencies for Utah culverts were then determined using the results from the final model.

4.1 Deterioration Curves

4.1.1 Dataset of Utah

UDOT provided a dataset containing information on Utah culverts. Following pre-processing, the finalized dataset included 272 rows and 49 columns (features). The following figures represent the deterioration curves the SVR and RFR models generated. Our performance evaluation method involved a 90% to 10% data split, meaning the dataset was divided into a training set (90% of the data) and a testing set (10% of the data). The developed RFR and SVR models from the Utah culvert dataset achieved 80% and 62% accuracy, respectively, in predicting culvert conditions based on specific features like soil data and age. For accuracy determination, we employed R-squared (R2), a statistical measure representing the proportion of the dependent variable’s variance that can be predicted from the independent variable.

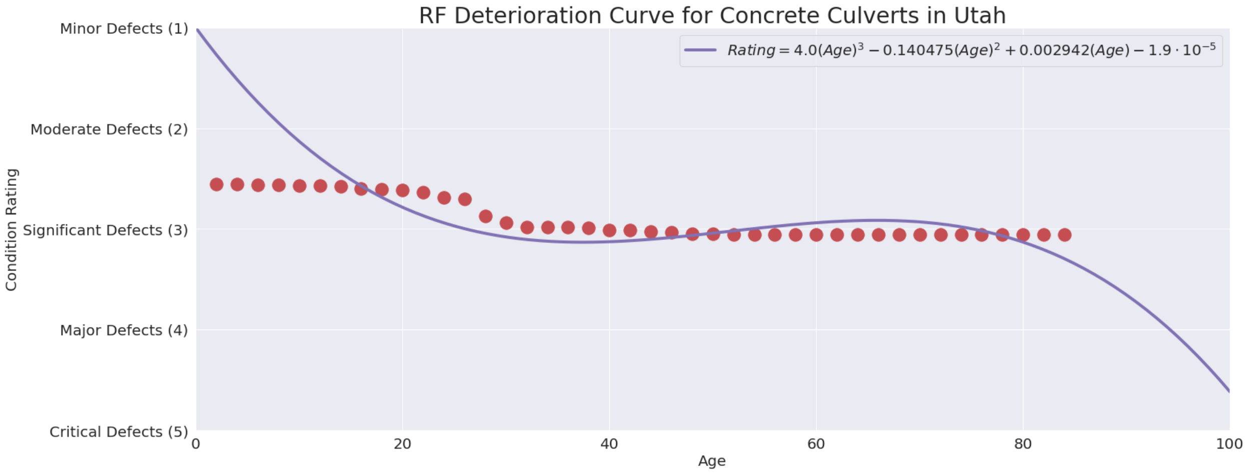


Figure 4.1 Deterioration curve with random forest for concrete culverts in Utah

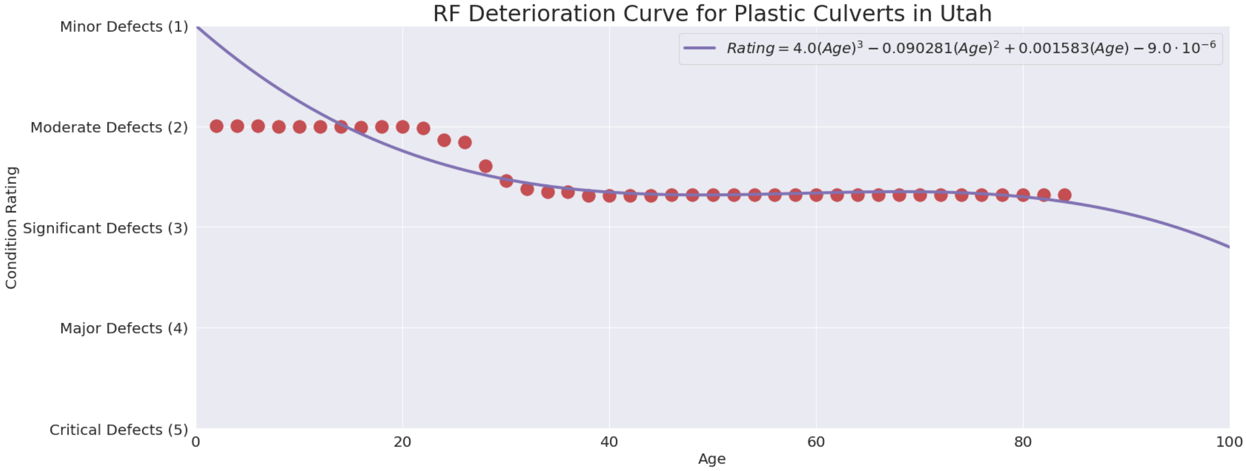


Figure 4.2 Deterioration curve with random forest for plastic culverts in Utah

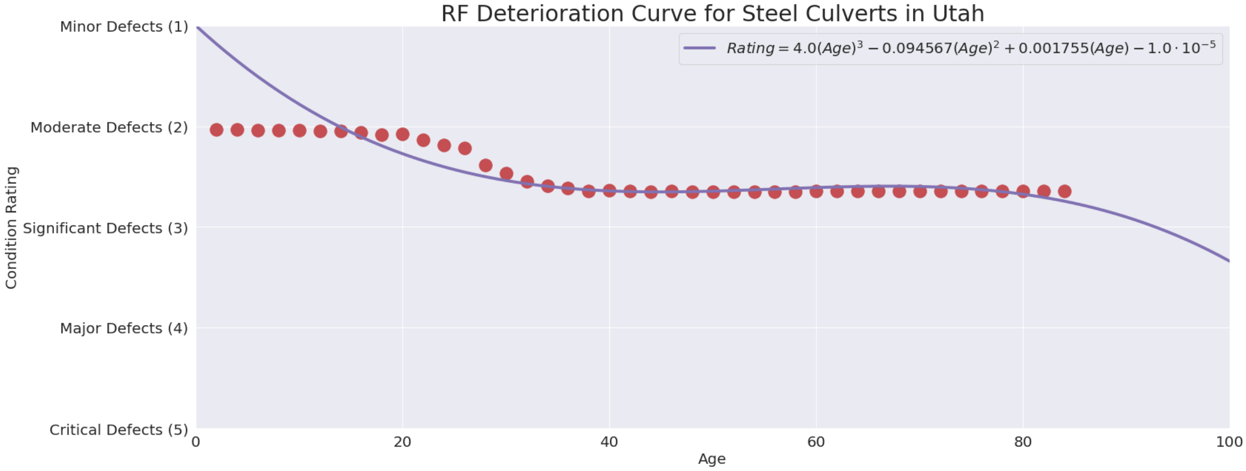


Figure 4.3 Deterioration curve with random forest for steel culverts in Utah

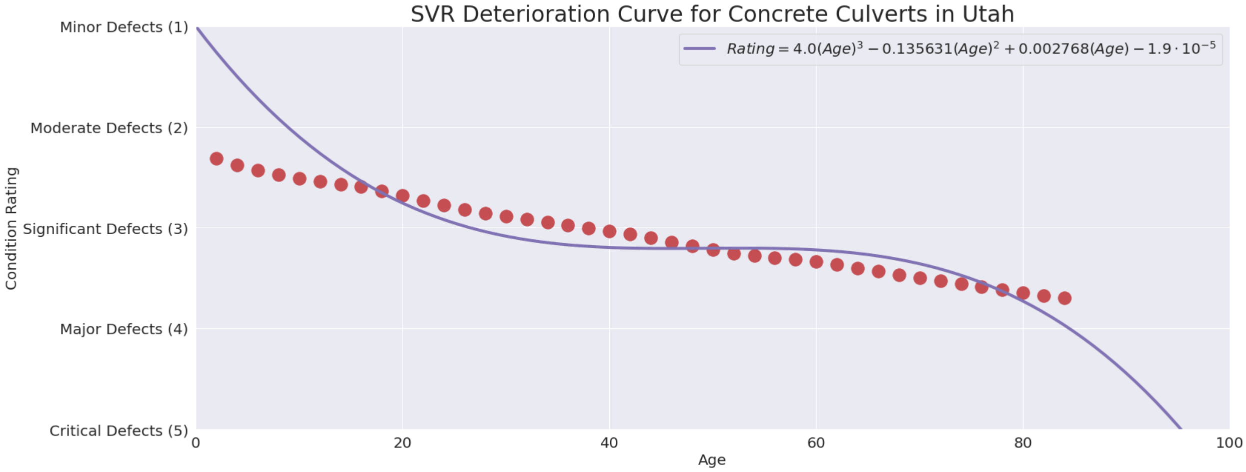


Figure 4.4 Deterioration curve with SVR for concrete culverts in Utah

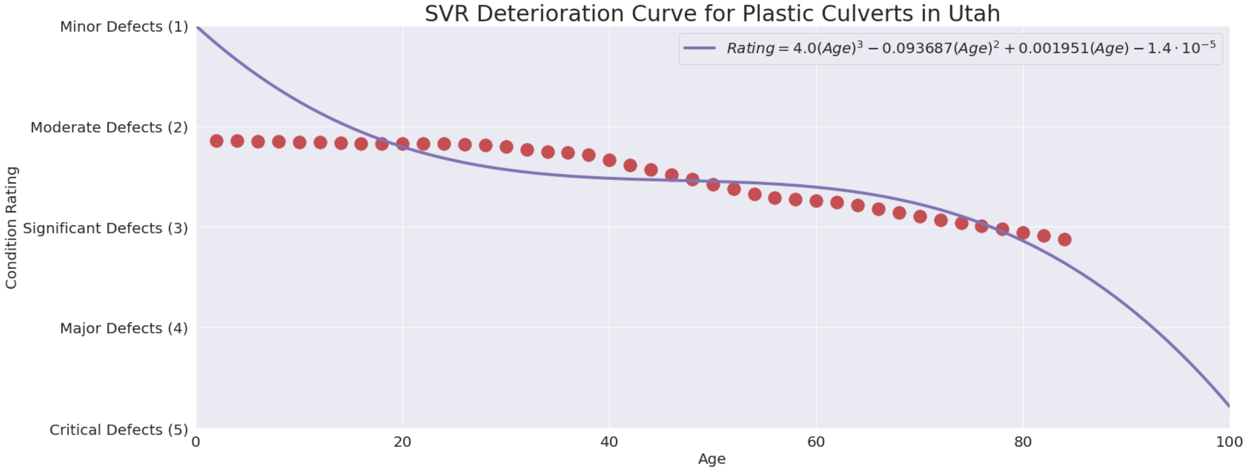


Figure 4.5 Deterioration curve with SVR for plastic culverts in Utah

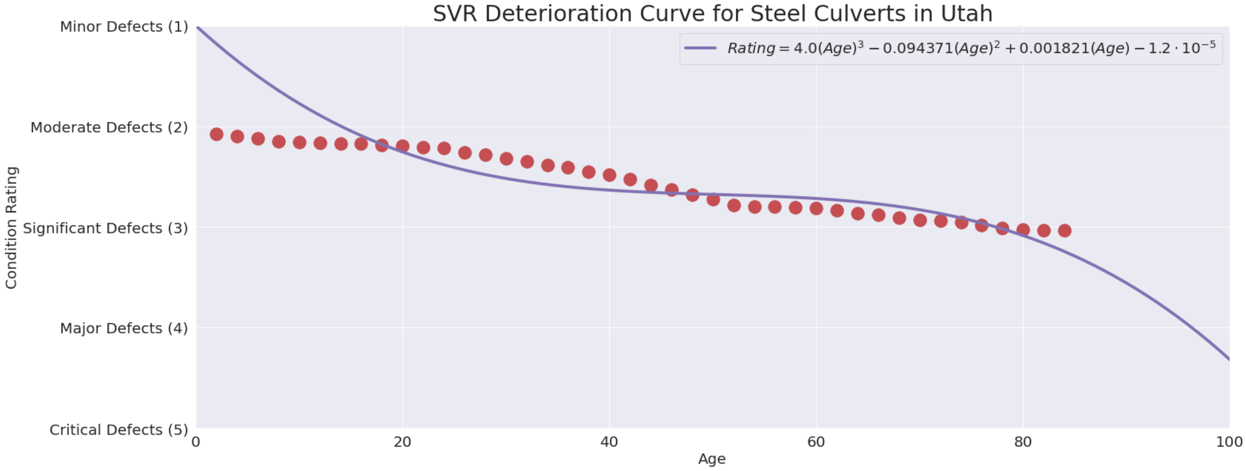


Figure 4.6 Deterioration curve with SVR for steel culverts in Utah

4.1.2 Dataset of Colorado

The Colorado culvert inventory data were provided by UDOT in two separate datasets. We merged these two datasets to create a comprehensive dataset for Colorado culverts. After pre-processing, the final dataset included 813 rows and 25 columns (features). The figures below individually depict the deterioration curves for steel and concrete culverts generated by the SVR and RFR models. Based on specified features like soil data and age, the RFR and SVR models developed for the Colorado culverts' dataset achieved accuracy levels of 81% and 61%, respectively, in predicting the condition of the culverts.

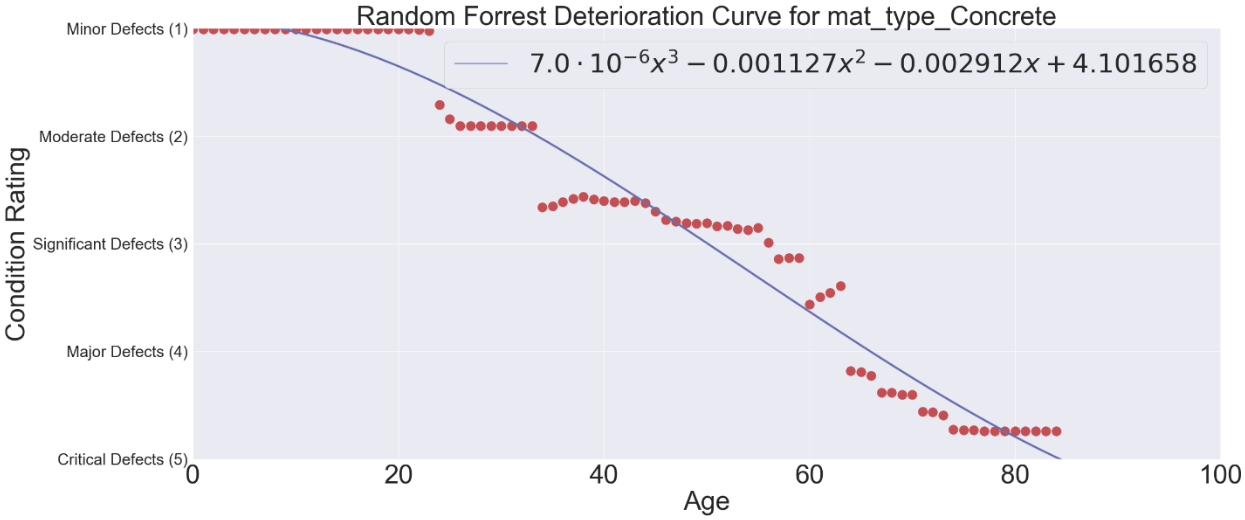


Figure 4.7 Deterioration curve with random forest for concrete culverts in Colorado

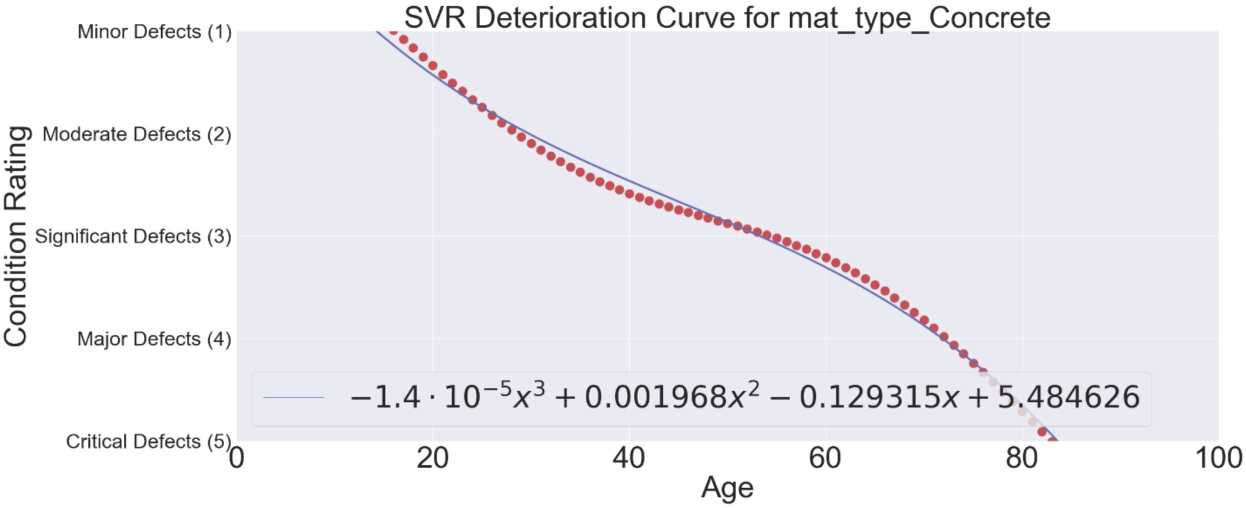


Figure 4.8 Deterioration curve with SVR for concrete culverts in Colorado

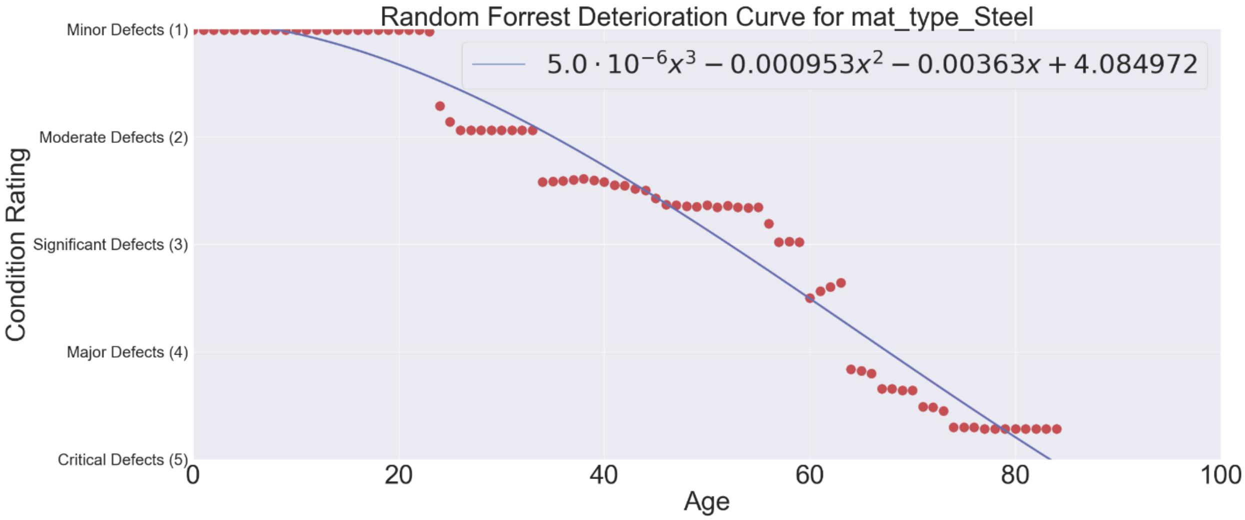


Figure 4.9 Deterioration curve with random forest for steel culverts in Colorado

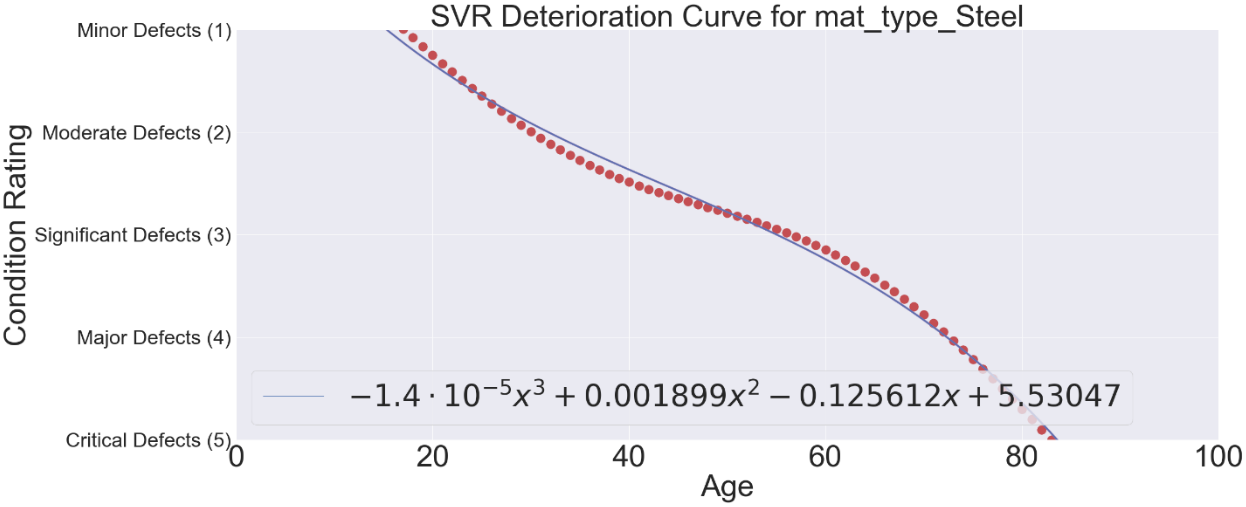


Figure 4.10 Deterioration curve with SVR for steel culverts in Colorado

4.1.3 Dataset of Vermont

The Vermont culvert dataset was gathered from the Vermont Agency of Transportation database. Initially, it consisted of 107,524 rows and 39 columns (features). After the data filtering and pre-processing steps, it was reduced to 1,130 rows and 24 columns (features). The SVR and RFR models generated the subsequent deterioration curves. The RFR and SVR models developed on the Vermont culverts achieved 71% and 60% accuracy, respectively, in forecasting the condition of the culverts. In contrast to Colorado and Utah, Vermont's dataset contains plastic culverts as well as concrete and steel culverts (road importance is abbreviated as RI).

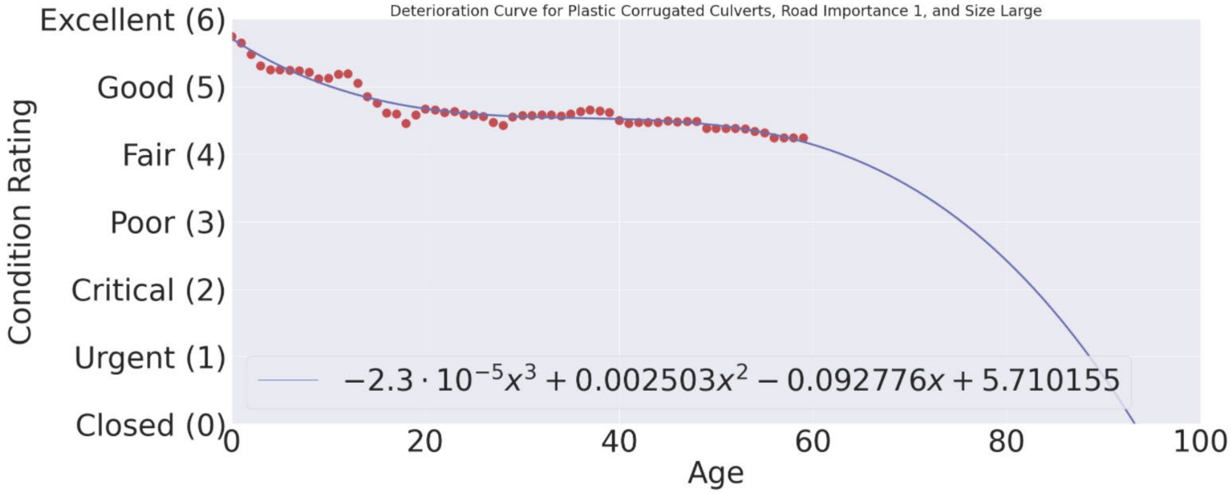


Figure 4.11 Deterioration curve for plastic corrugated culverts with random forest RI = 1

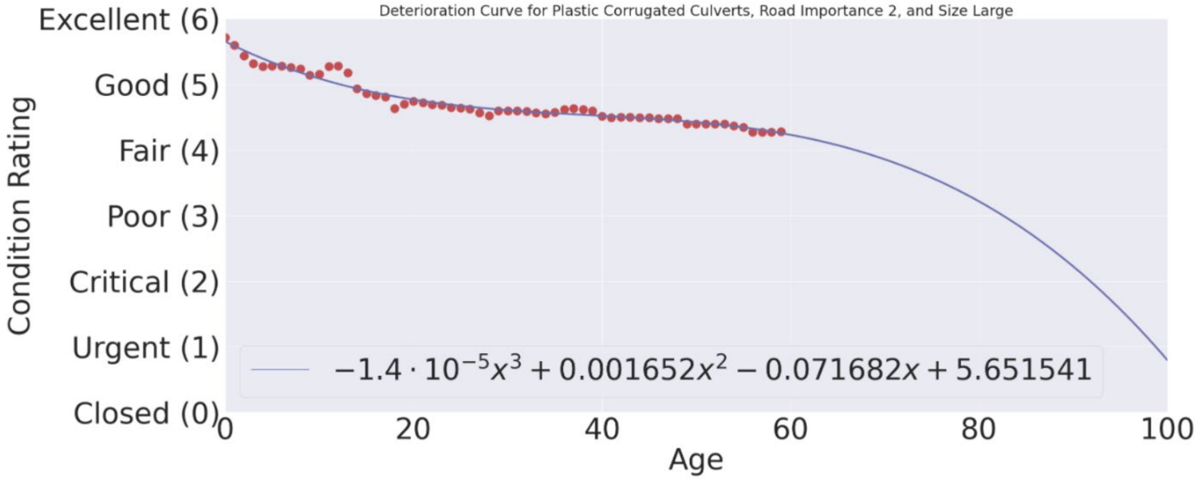


Figure 4.12 Deterioration curve for plastic corrugated culverts with random forest, RI = 2

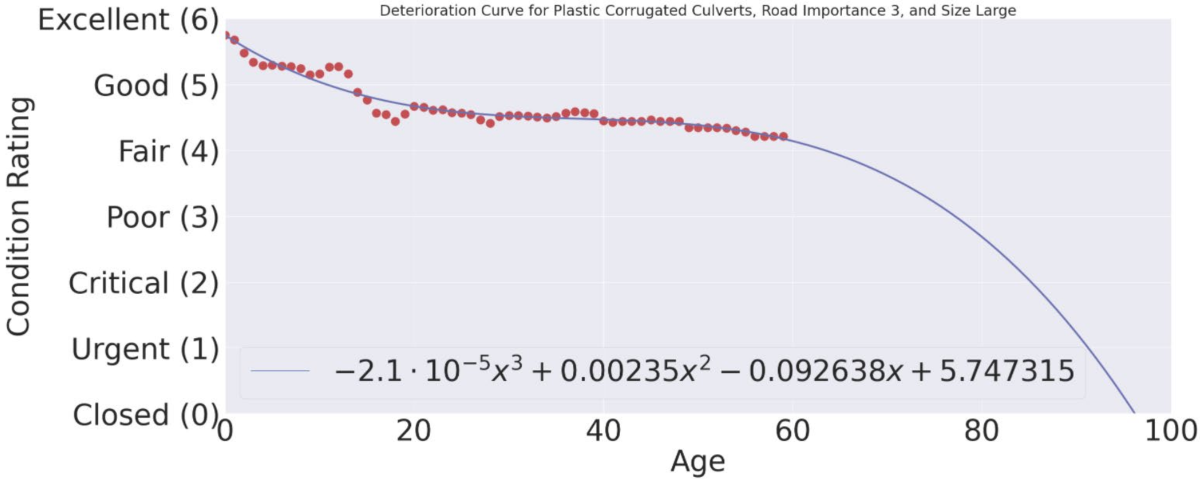


Figure 4.13 Deterioration curve for plastic corrugated culverts with random forest, RI = 3

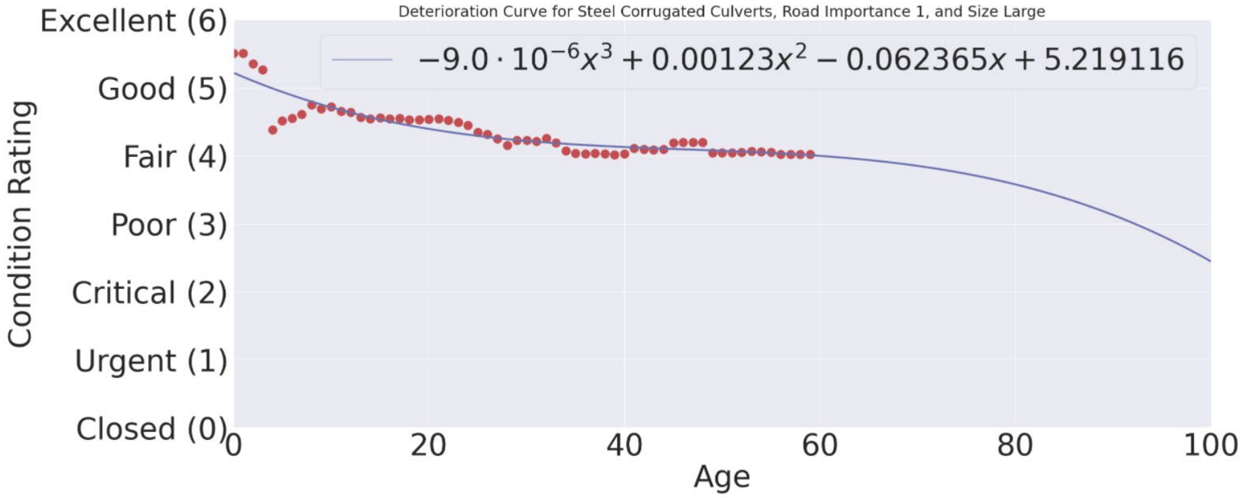


Figure 4.14 Deterioration curve for steel corrugated culverts with random forest, RI = 1

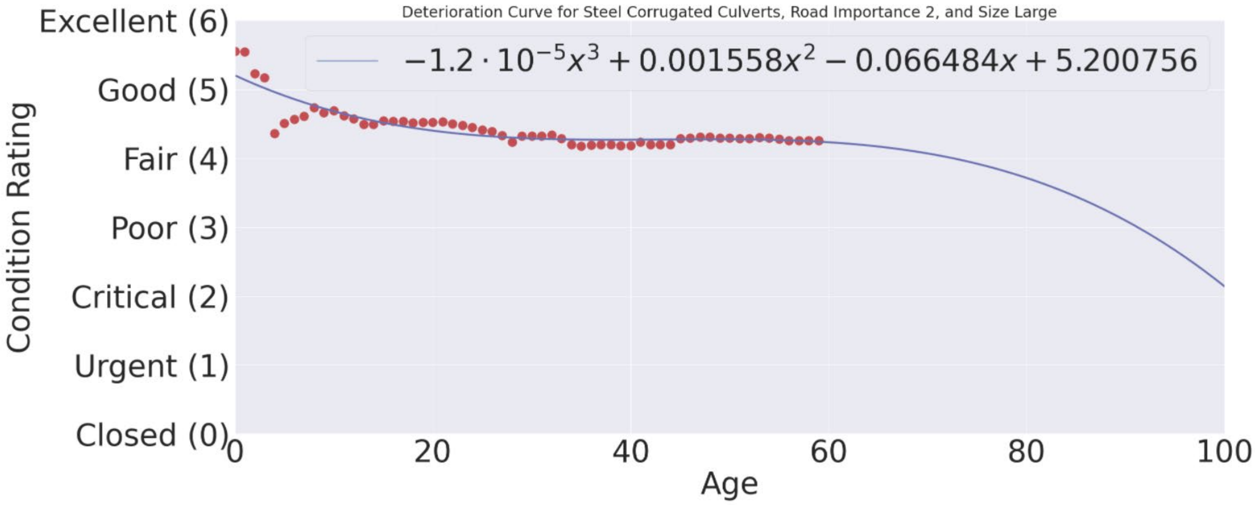


Figure 4.15 Deterioration curve for steel corrugated culverts with random forest, RI = 2

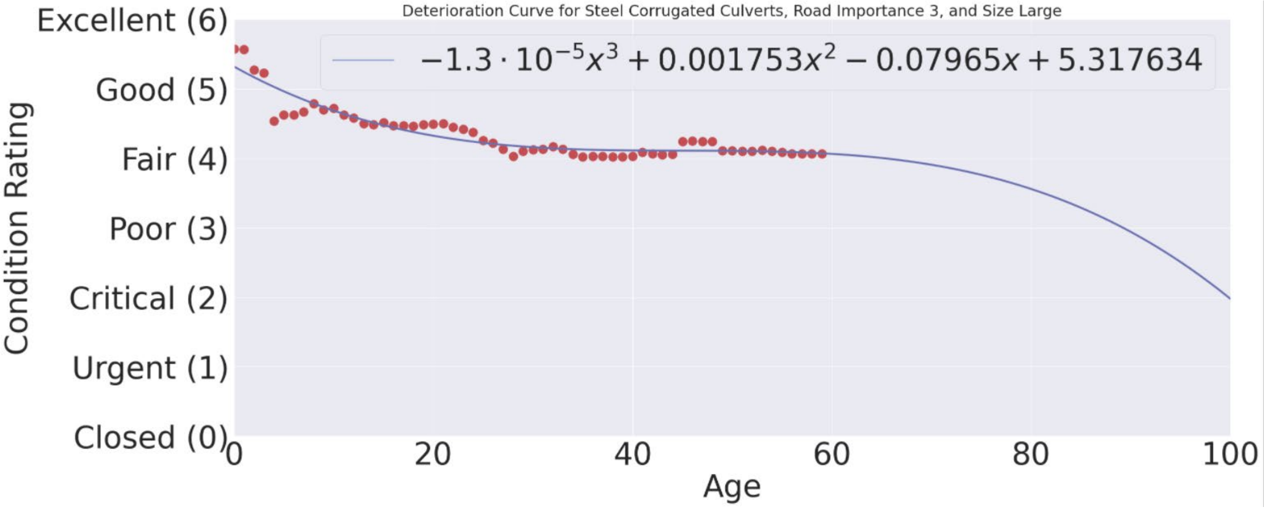


Figure 4.16 Deterioration curve for steel corrugated culverts with random forest, RI = 3

4.1.4 Consolidated Data

The culvert inventory from Utah was combined with the culvert inventories from Colorado and Vermont. We had to perform pre-processing to align the data from the other two inventories with the format of Utah's culvert inventory. This resulted in a dataset similar to Utah's in terms of culvert features but with more data rows. After pre-processing, the final dataset included 2,070 rows. The SVR and RFR models produced the ensuing deterioration curves for various culvert materials, such as concrete, plastic, and steel. The RFR and SVR models crafted for this combined dataset achieved 79% and 71% accuracy, respectively.

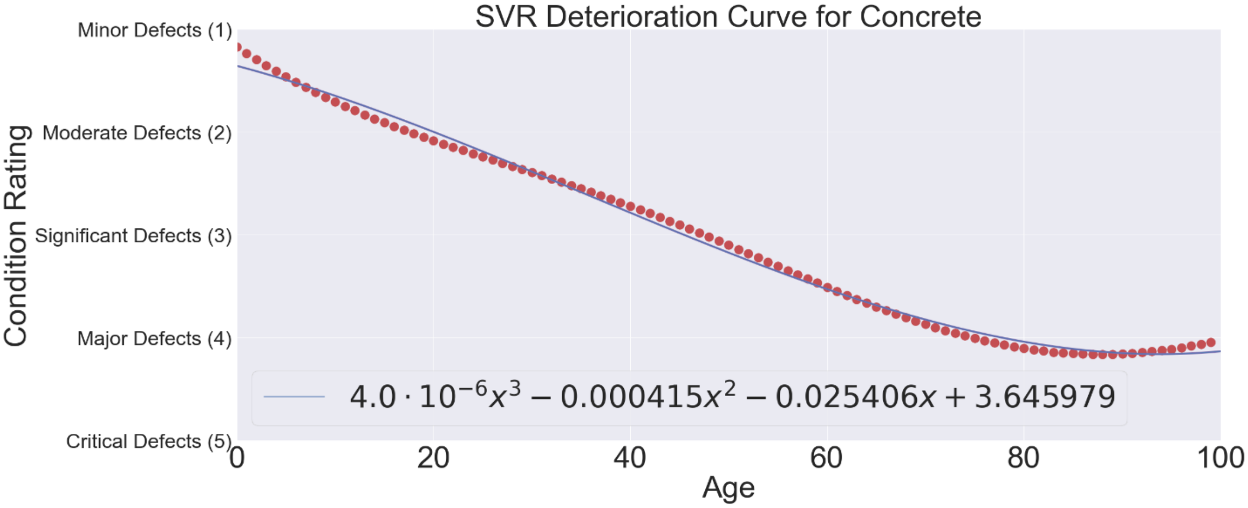


Figure 4.17 Deterioration curve for concrete culverts with SVR

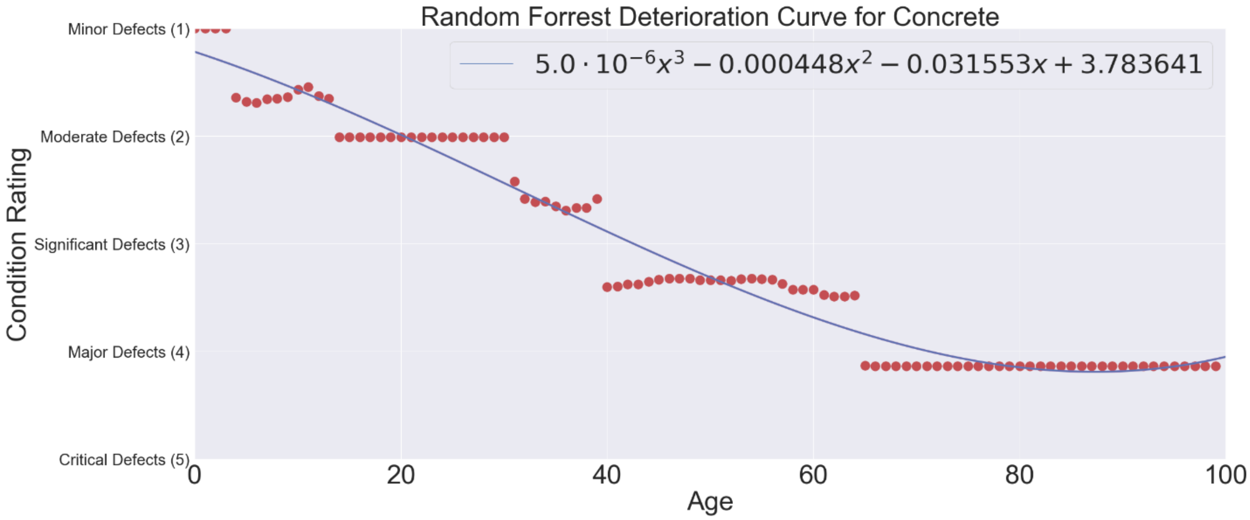


Figure 4.18 Deterioration curve for concrete culverts with random forest

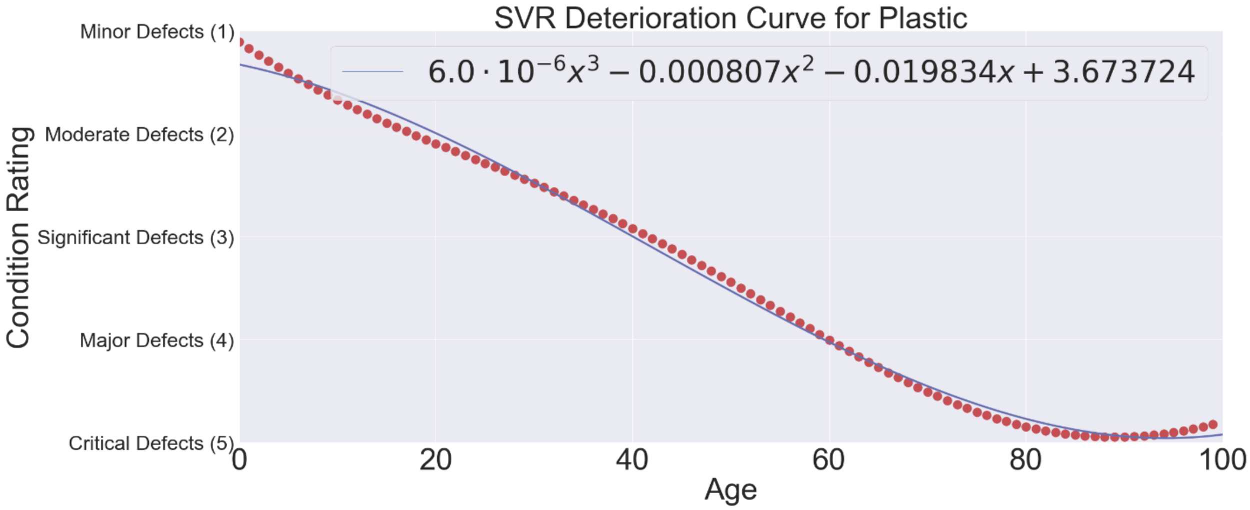


Figure 4.19 Deterioration curve for plastic culverts with SVR

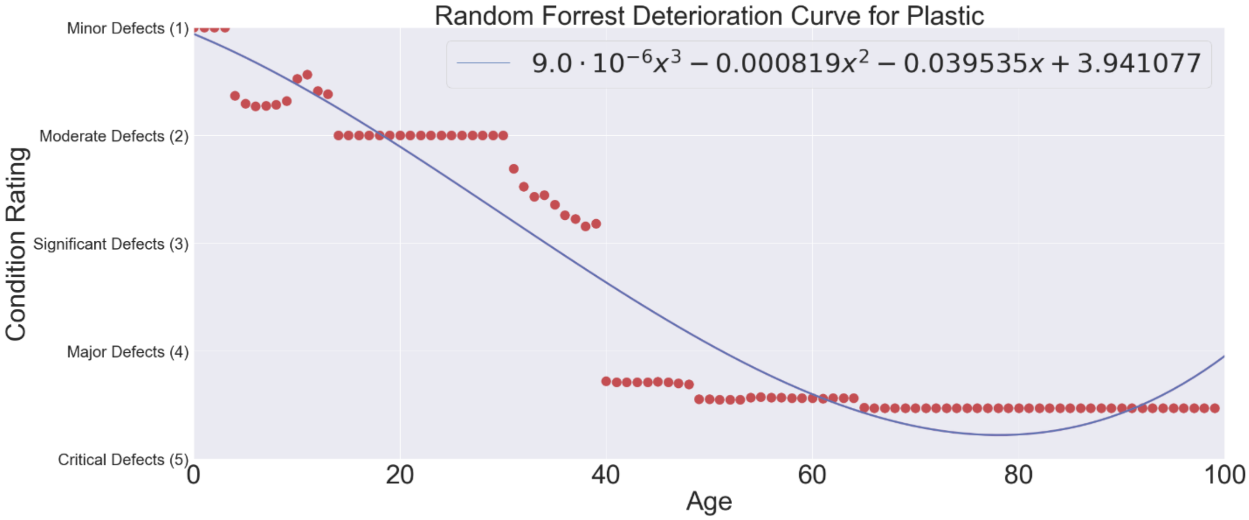


Figure 4.20 Deterioration curve for plastic culverts with random forest

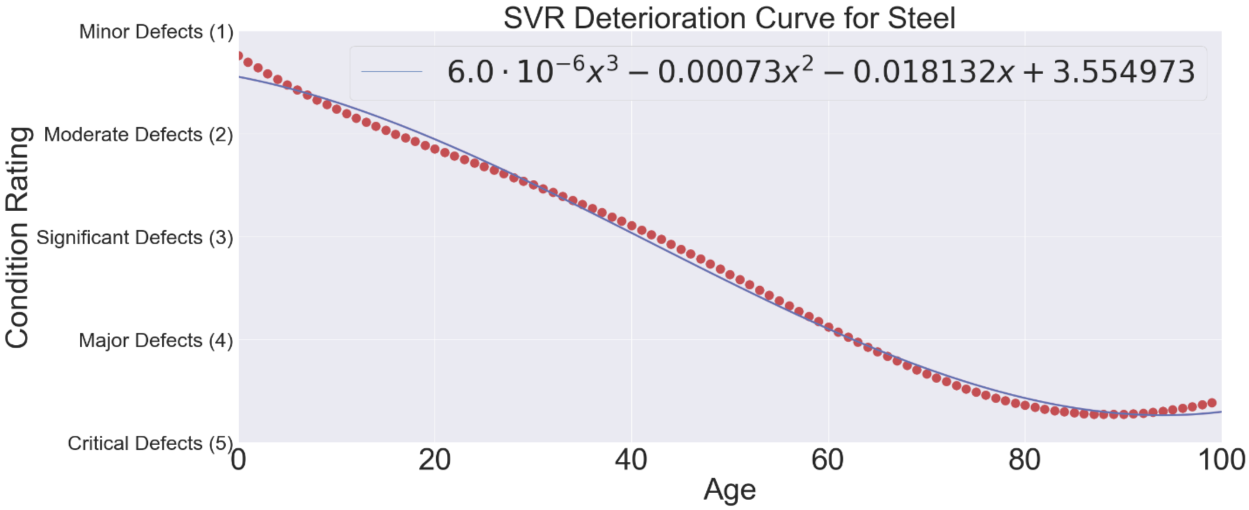


Figure 4.21 Deterioration curve for steel culverts with SVR

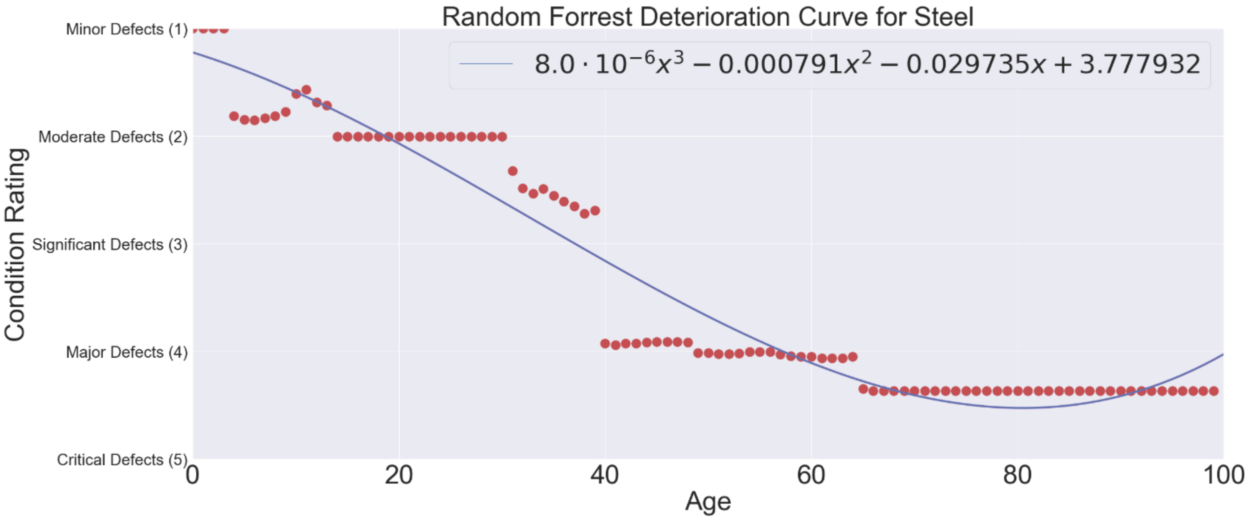


Figure 4.22 Deterioration curve for steel culverts with random forest

4.2 Risk Assessment

The dataset consisting of 272 culverts in Utah was gathered between 2002 and 2003. The distribution of culvert conditions within this dataset is shown in Figure 4.23.

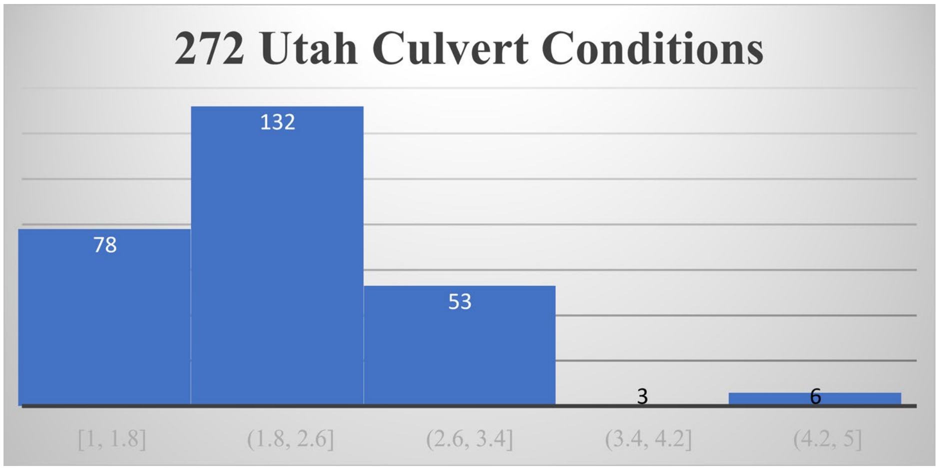
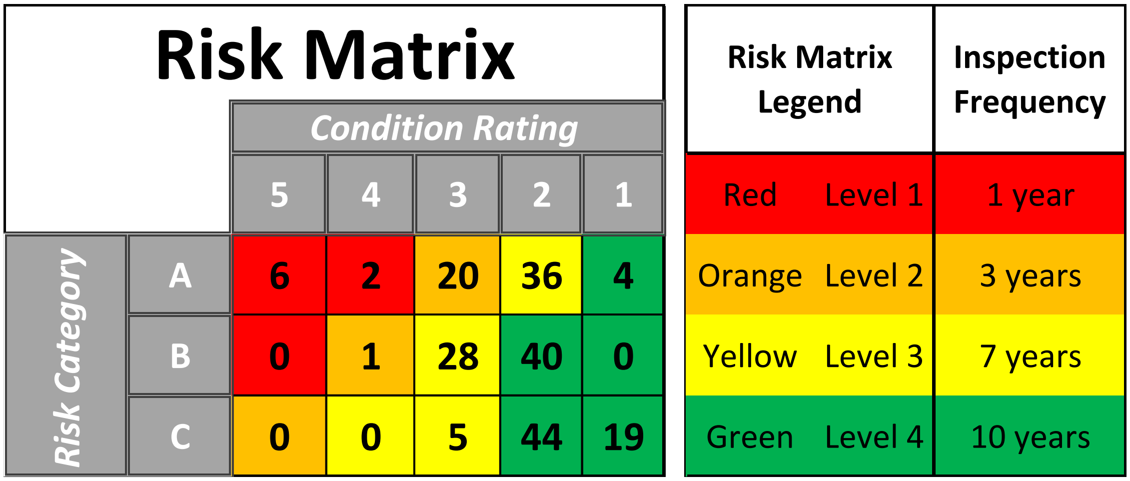


Figure 4.23 Utah culvert condition distribution

To compute risk factors, we employed two elements: LOF and COF. As outlined in the Methodology section, the LOF is derived from the condition of the culverts and UDOT's culvert risk assessment. We made several assumptions for the computation of COF according to section 3.2.2 Consequence of Failure (COF). Ultimately, the total cost of culvert failure was determined based on the culvert's location.

We assigned each culvert a risk factor and category using the method from section 3.2.3 Risk, and then developed the risk matrix for the Utah 272-culvert dataset. Figure 4.24 displays the results, with the numbers within the matrix representing the number of culverts with the corresponding rating and risk category. Specifically, 67 culverts were rated as excellent (no inspection required), 107 as good (requiring inspection every 10 years), 69 as fair (requiring inspection every seven years), 21 as poor (requiring inspection every three years), and eight as critical (requiring annual inspection). As a result, UDOT can make significant savings on culvert inspection in Utah while improving the serviceability of the culvert network. Depending on its budget for culvert maintenance, UDOT can prioritize the inspection and maintenance of critical and poor culverts. Based on Figure 4.24, UDOT only needs to concentrate on 10% of the inventory instead of the entire network, making this method far more cost-efficient than traditional approaches.



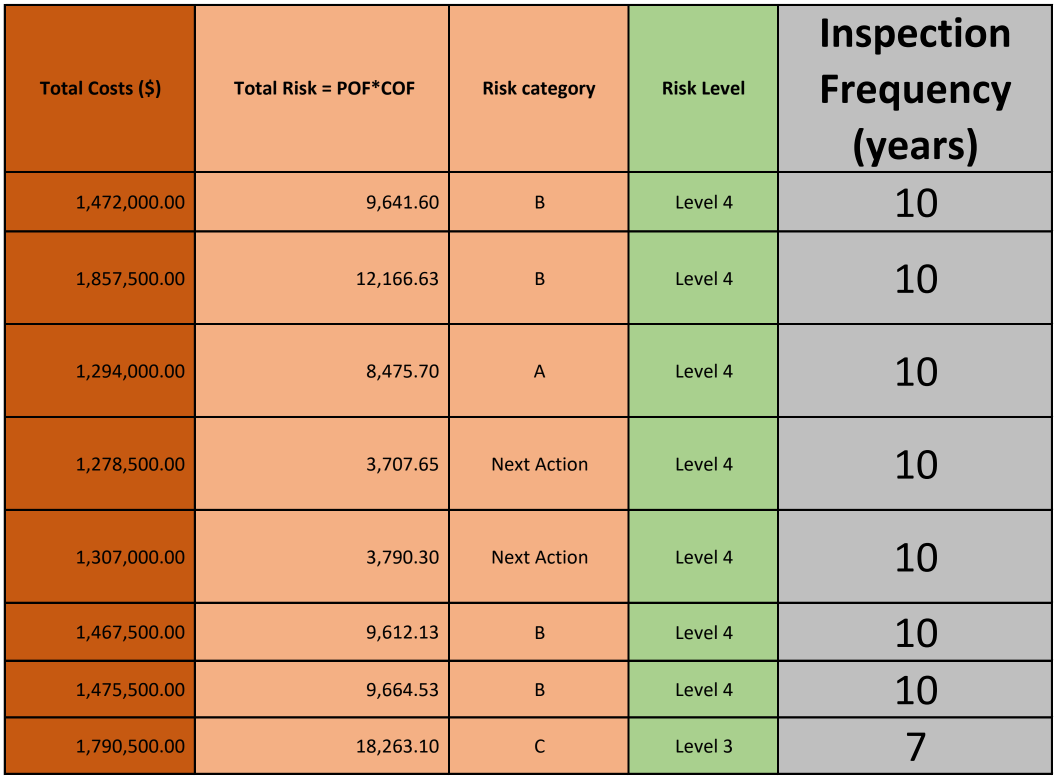
Risk Matrix

Risk Category		*Condition Rating* 5	4	3	2	1
	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 4.24 Results of Utah dataset risk assessment

Using Table 3.7 in section 3.2.4 Inspection Frequency and the identified culvert risk levels, inspection frequencies were assigned to culverts. Figure 4.25 shows an example of this task.

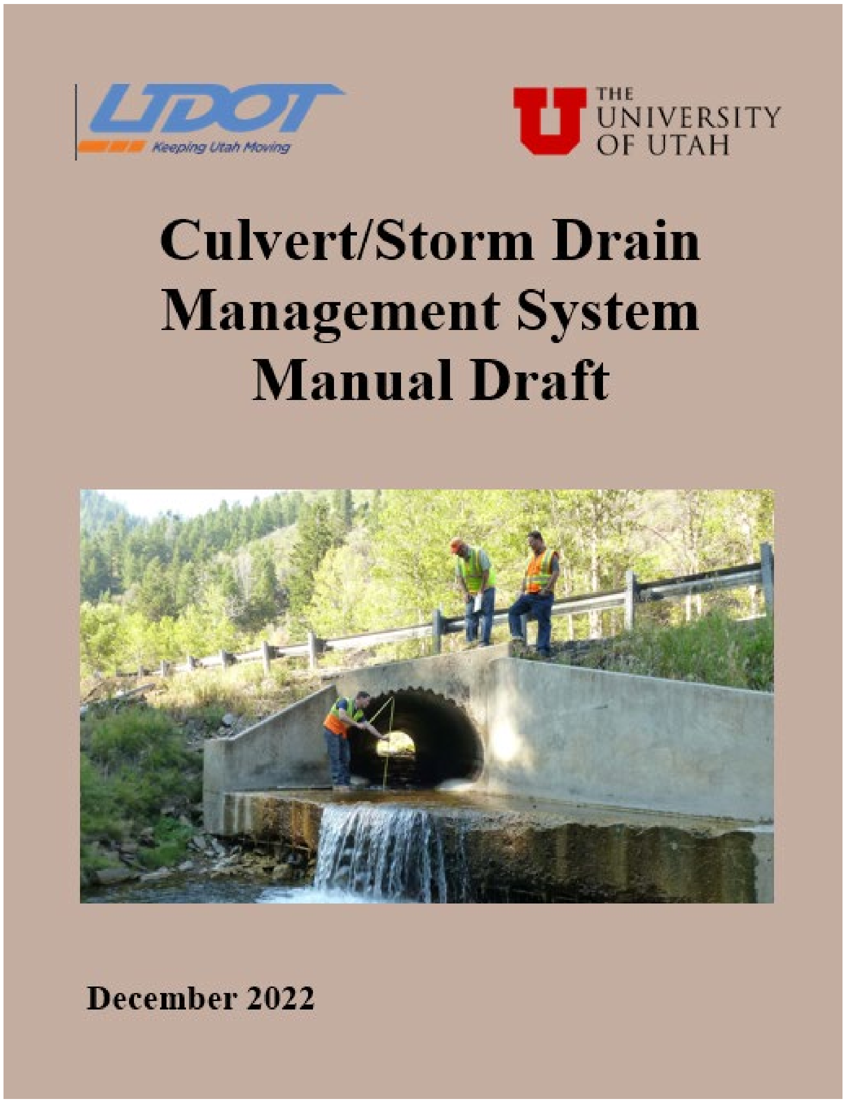


Total Costs ($)	Total Risk = POF*COF	Risk category	Risk Level	Inspection Frequency (years)
1,472,000.00	9,641.60	B	Level 4	10
1,857,500.00	12,166.63	B	Level 4	10
1,294,000.00	8,475.70	A	Level 4	10
1,278,500.00	3,707.65	Next Action	Level 4	10
1,307,000.00	3,790.30	Next Action	Level 4	10
1,467,500.00	9,612.13	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 4.25 Example of assigning inspection frequency to culverts of Utah

4.3 Draft Manual for Utah's Culverts

The evaluation of various manuals and guidelines for culvert inspection and maintenance led to the creation of a manual specifically designed for Utah's culverts. This manual covers topics such as Utah's pipe rating system and a suggested data-driven approach to scheduling culvert inspections. While this is the initial draft of the manual, the UDOT maintenance division can augment it as necessary in the future. The expectation is that using this manual will enable UDOT to enhance its culvert network's functioning while reducing maintenance costs. Moreover, it could aid in preventing significant harm to the transportation system's infrastructure and safeguarding its users' lives.



UDOT
Keeping Utah Moving

THE UNIVERSITY OF UTAH

Culvert/Storm Drain
Management System
Manual Draft

December 2022

Figure 4.26 The proposed culvert management manual

5. CONCLUSIONS

UDOT has an incomplete dataset on the condition of Utah's culverts, which poses a significant risk to the transportation system and public safety. Without a comprehensive inventory and condition assessment system, UDOT cannot manage these assets efficiently. Therefore, UDOT plans to finalize the inventory and condition assessment of culverts, establish an inspection schedule, and assess culvert risks using life cycle analysis to ascertain necessary program funding. This study aims to support UDOT in optimizing Utah's culvert inspection planning based on the estimated deterioration curve of Utah's culverts and life cycle analysis. These steps are crucial in creating a comprehensive CMS for Utah. Deterioration curves are also valuable for predicting culvert service life, facilitating proactive replacement or repairs before failure. The suggested method relies on machine learning algorithms and a risk assessment approach. The framework developed is intended to be incorporated into the ATOM software, which combines asset and maintenance management.

Despite having over 47,000 culverts, UDOT's culvert inventory only includes complete information for 272 culverts. Hence, this study proposes to generate Utah culvert deterioration curves using culvert inspection data from three U.S. states. The final deterioration curves were formulated using SVR and RFR algorithms, utilizing culvert inventories from Colorado, Utah, and Vermont. Given the theoretical understanding and the data limitations, the curve forms appeared reasonable. Despite the limited data, the models developed for the Colorado, Vermont, and Utah datasets achieved between 60% and 80% accuracy, which is deemed acceptable. The model developed using the consolidated dataset also performed well, with 71% accuracy for the SVR model and 79% for the RFR model.

Creating these culvert deterioration curves can provide a more accurate depiction of culvert degradation rates in Utah. Therefore, the final curves can be employed to estimate Utah culvert conditions based on age. Additionally, the final culvert deterioration curve can estimate the likelihood of failure and subsequently help decide the inspection frequency through the risk assessment approach. During the life cycle analysis of culverts, all associated risks were considered and estimated to better prepare for future risks. By adopting this method, UDOT may be able to save both money and time, compared with traditional approaches. According to the case study results, UDOT should focus on only 10% of its inventory rather than spending a substantial amount of money inspecting all culverts regularly. Another potential use for Utah's final culvert deterioration curve is proactive maintenance, which can significantly improve the culvert network system's performance and reduce potential disruptions.

As part of the suggested culvert inspection approach, we drafted a Culvert/Storm Drain Management System Manual for Utah. This was developed after reviewing multiple culvert maintenance and inspection manuals issued by the federal government and other state DOTs. The manual was designed specifically for Utah's culverts and utilized UDOT's inspection rating system. It amalgamates contents from several manuals tailored for Utah's culverts and focuses on key aspects such as culvert inspections, data inventory, and maintenance.

5.1 Challenges and Limitations

The limited data in Utah's culvert inventory necessitated using culvert inventories from two other states. The decision to use these was based solely on their availability, and the model's performance could have been better validated with more data from Utah's culvert inventories.

Given that the data were collected manually, potential errors could occur during culvert inspections. Therefore, we filtered data based on age and condition. As a result, only a portion of the total data was used for developing the ML models.

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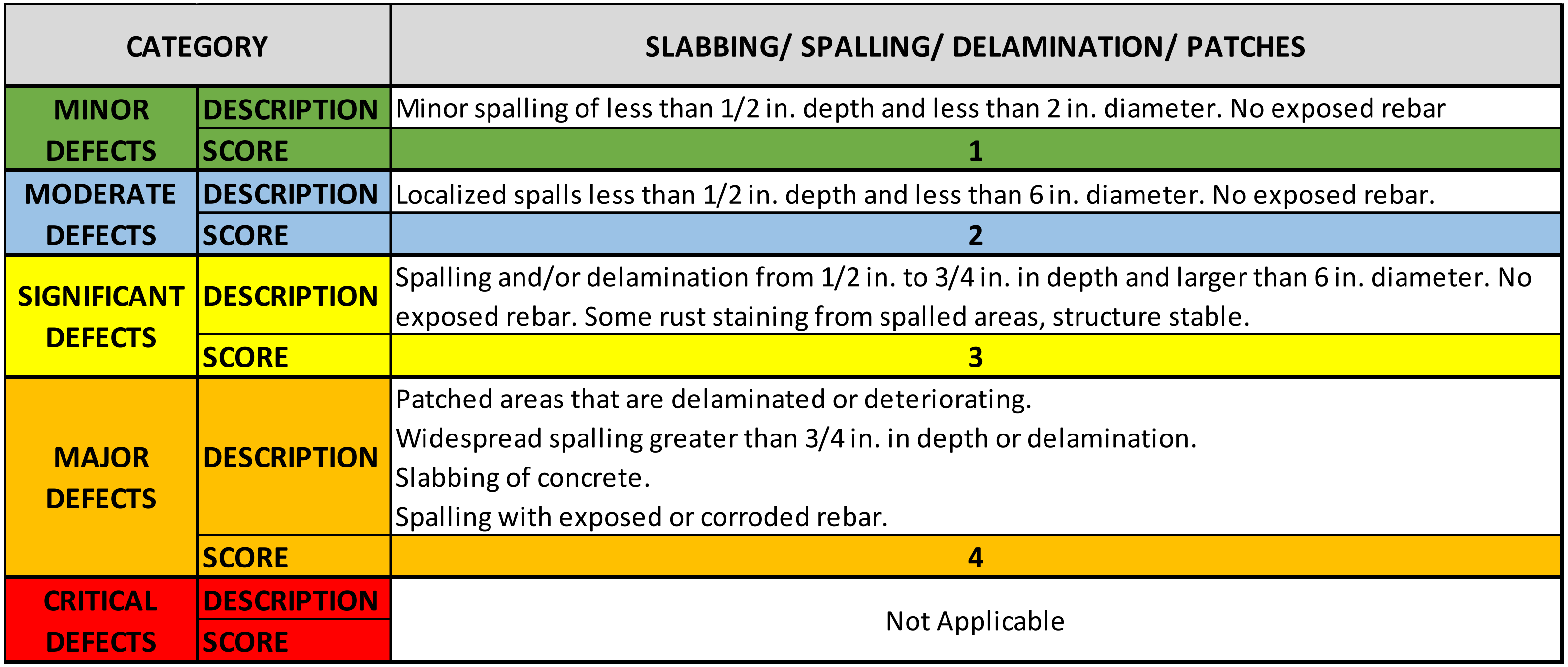
APPENDIX A: UDOT Pipe Defect Rating Sheets

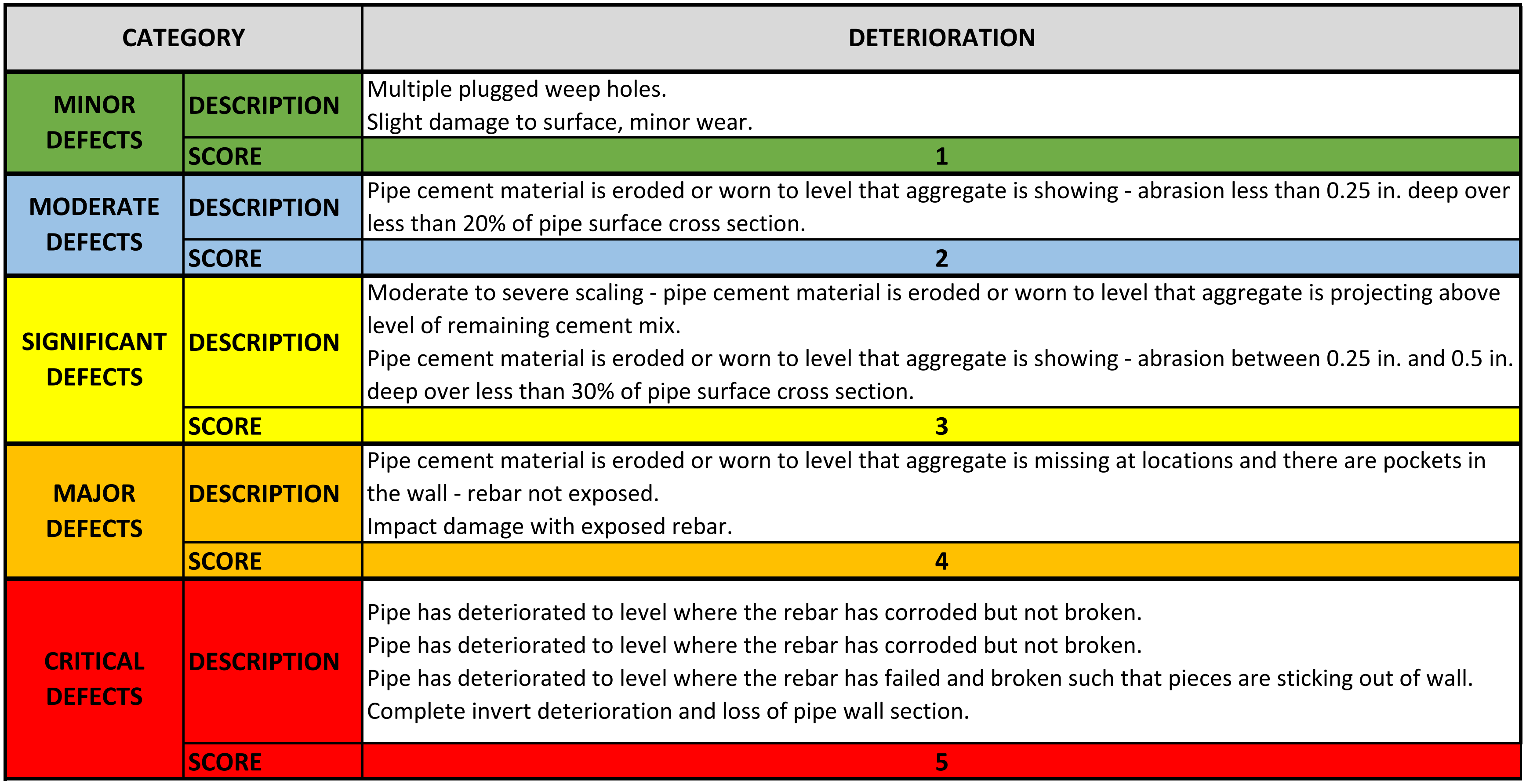
CATEGORY		CRACKS (< 0.05 INCHES) FRACTURES (≥ 0.05 INCHES)
MINOR DEFECTS	**DESCRIPTION**	Crack (not showing signs of opening or movement) that is perpendicular to flow direction. One max per pipe section
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Crack that extends along pipe longitudinally. Can be 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 A.1 Concrete culvert rating system-1



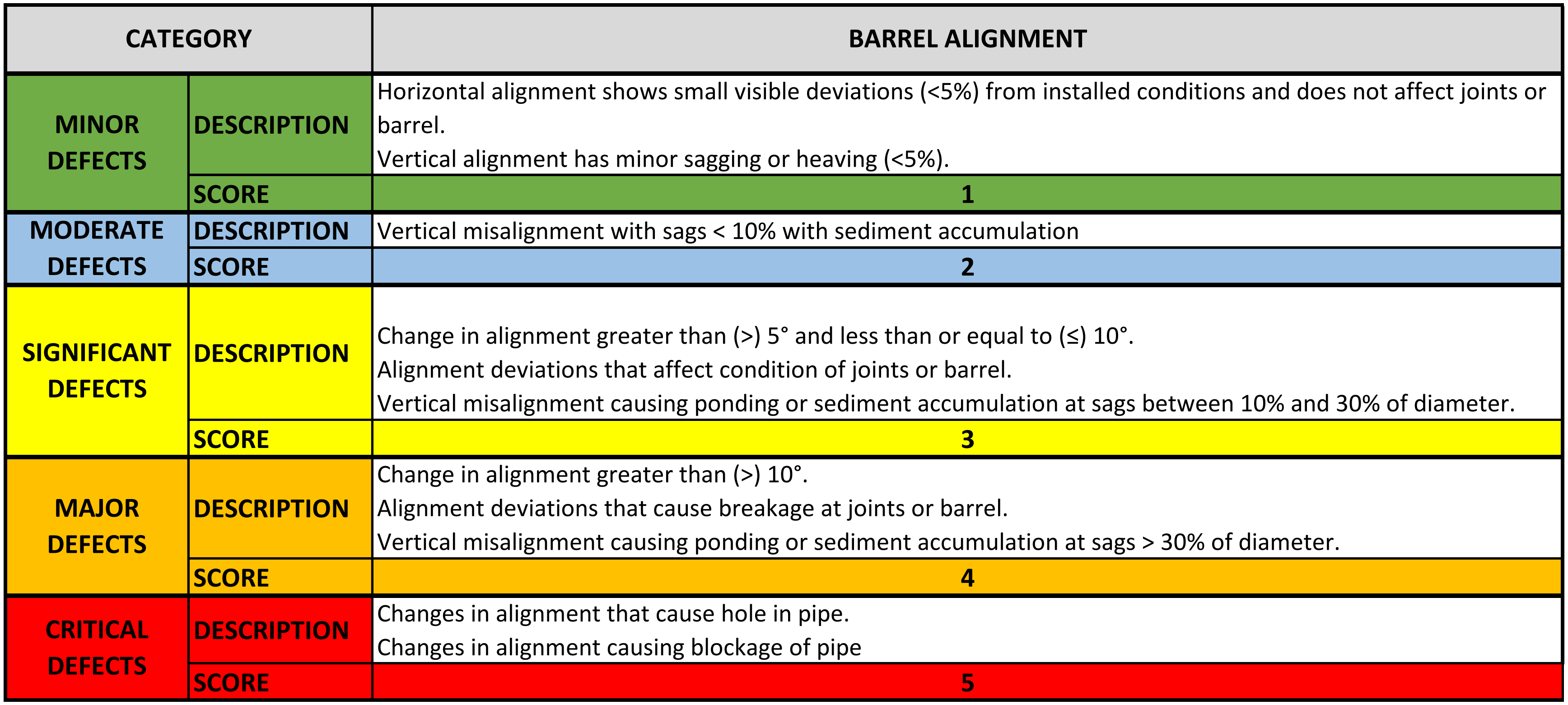
CATEGORY		SLABBING/ SPALLING/ DELAMINATION/ PATCHES
MINOR DEFECTS	DESCRIPTION	Minor spalling of less than 1/2 in. depth and less than 2 in. diameter. No exposed rebar
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Localized spalls less than 1/2 in. depth and less than 6 in. diameter. No exposed rebar.
	SCORE	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 A.2 Concrete culvert rating system-2



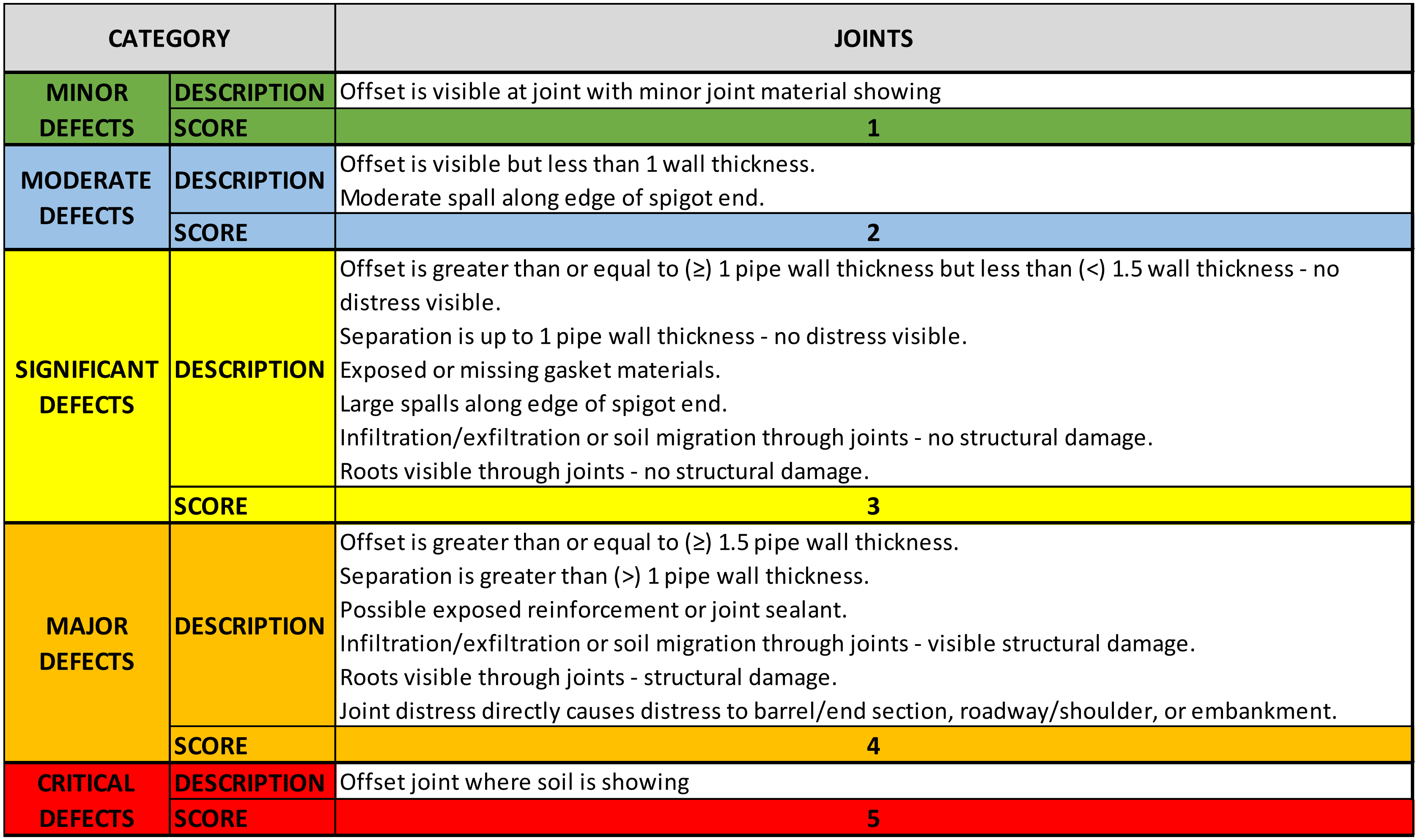
CATEGORY		DETERIORATION
MINOR DEFECTS	DESCRIPTION	Multiple plugged weep holes. Slight damage to surface, minor wear.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Pipe cement material is eroded or worn to level that aggregate is showing - abrasion less than 0.25 in. deep over less than 20% of pipe surface cross 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 A.3 Concrete culvert rating system-3



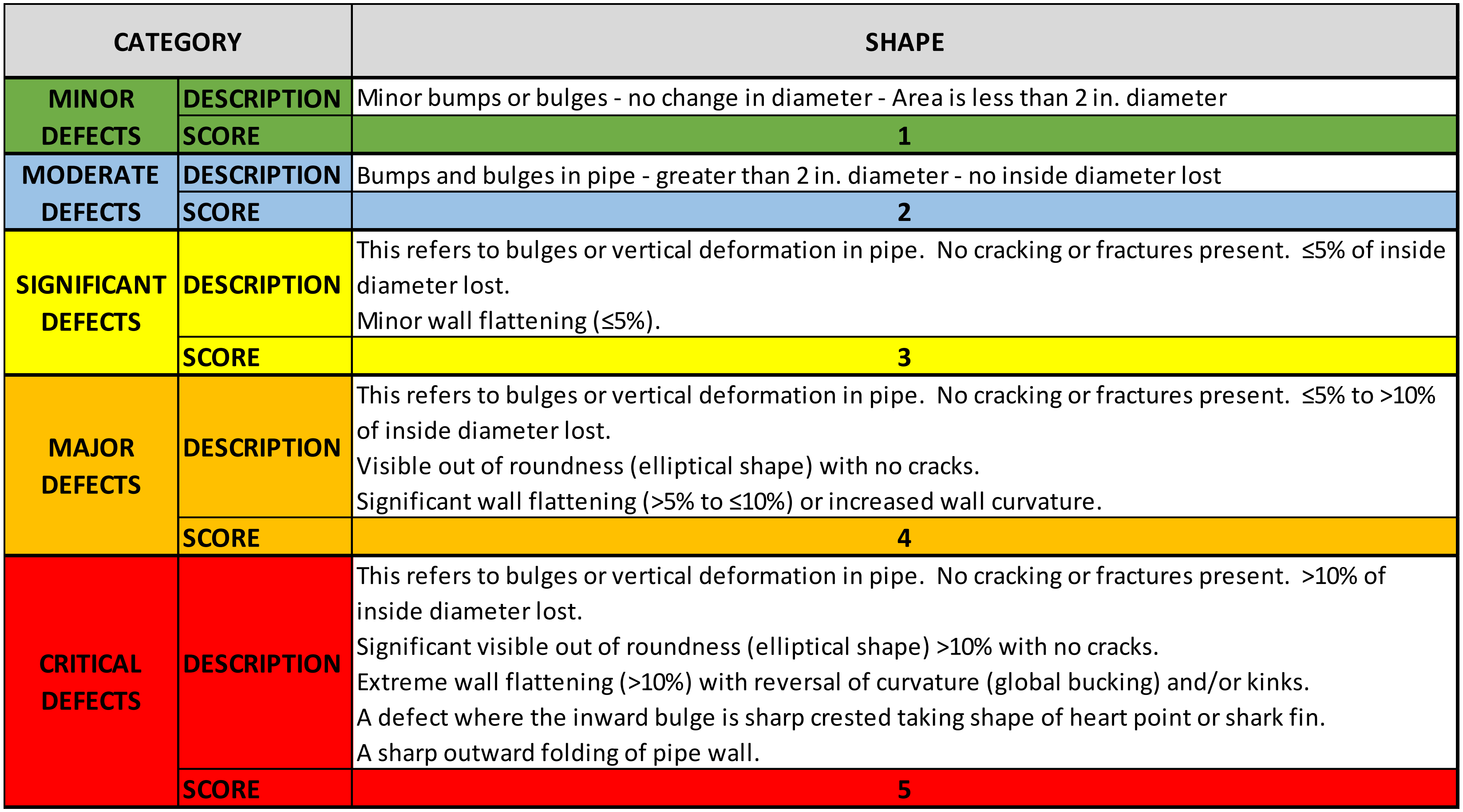
CATEGORY		BARREL ALIGNMENT
MINOR DEFECTS	**DESCRIPTION**	Horizontal alignment shows small visible deviations (<5%) from installed conditions and does not affect joints or barrel. Vertical alignment has minor sagging or heaving (<5%).
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Vertical misalignment 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 A.4 Concrete culvert rating system-4



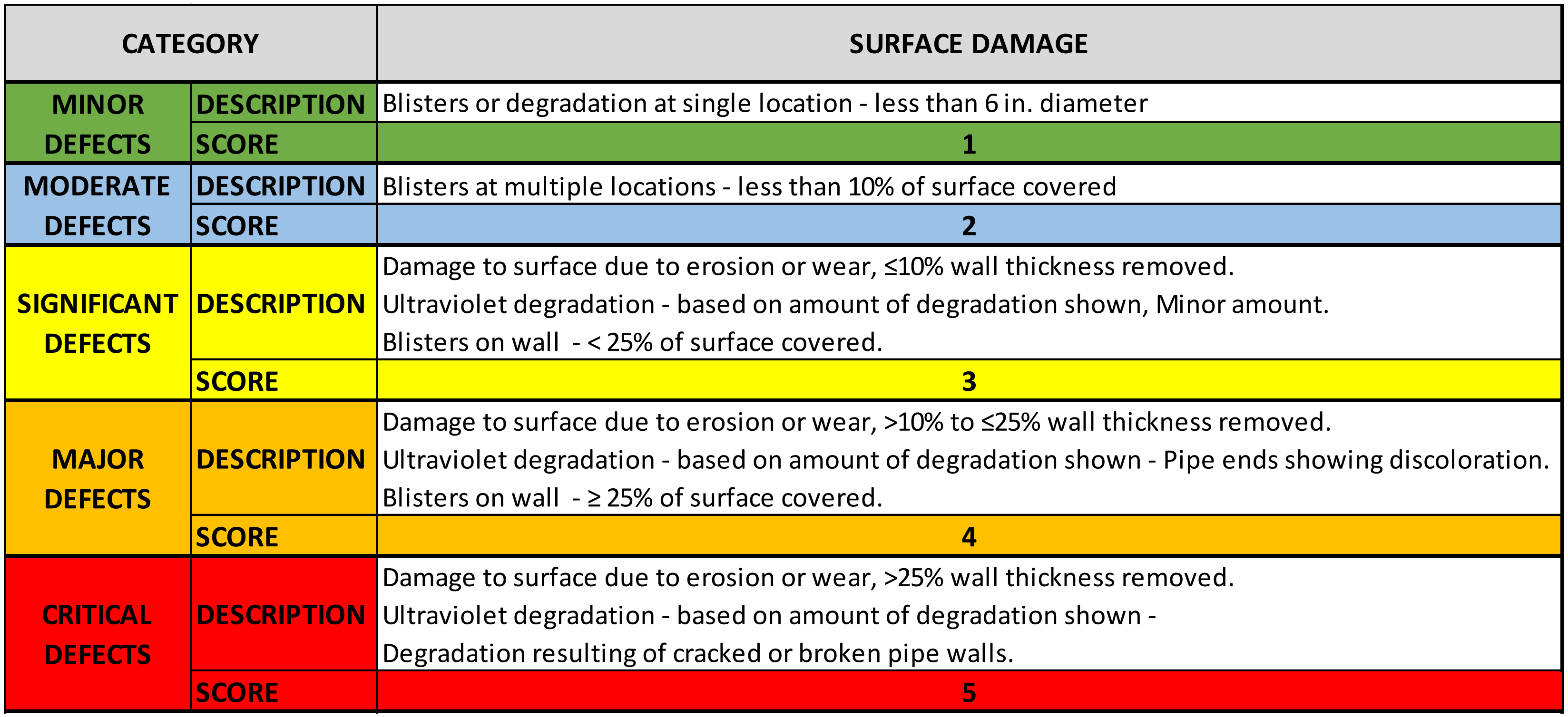
CATEGORY		JOINTS
MINOR DEFECTS	**DESCRIPTION**	Offset is visible at joint with minor joint material showing
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Offset is visible but less than 1 wall thickness. Moderate spall along edge of spigot end.
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Offset 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 A.5 Concrete culvert rating system-5



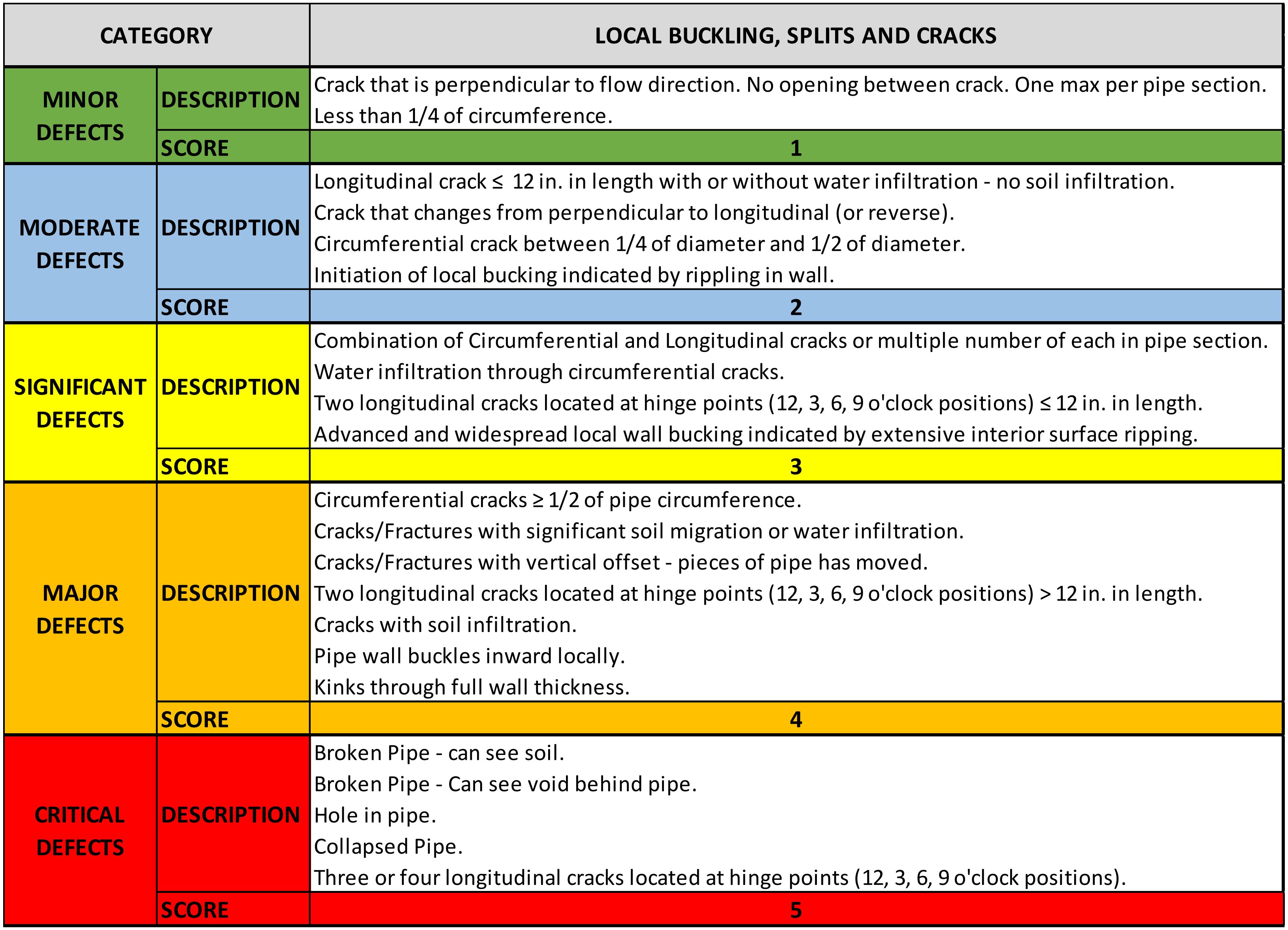
CATEGORY		SHAPE
MINOR DEFECTS	DESCRIPTION	Minor bumps or bulges - no change in diameter - Area is less than 2 in. diameter
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Bumps and bulges in pipe - greater than 2 in. diameter - no inside diameter lost
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	This refers to bulges 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 A.6 Plastic or HDPE pipe rating system-1



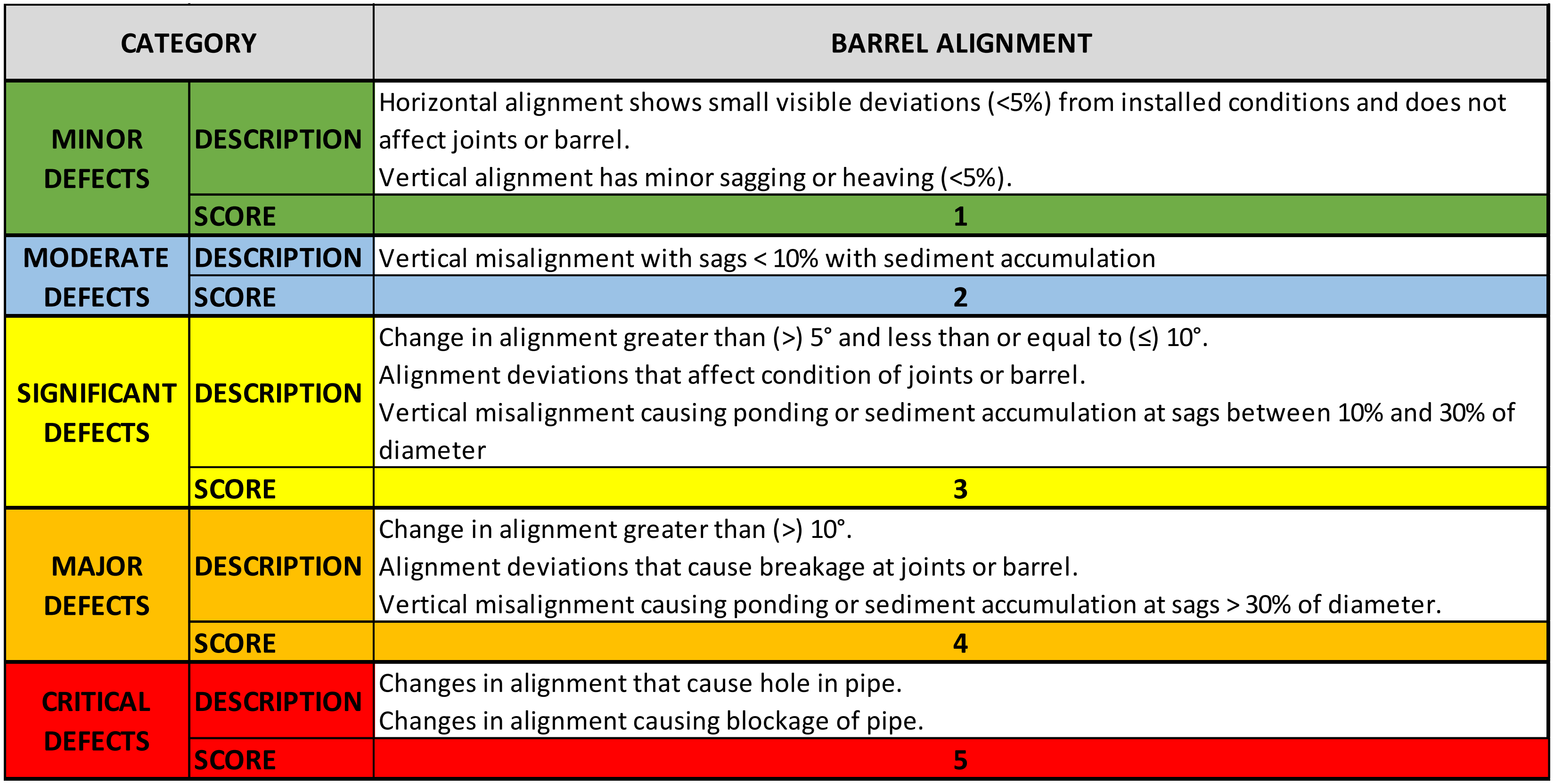
CATEGORY		SURFACE DAMAGE
MINOR DEFECTS	DESCRIPTION	Blisters or degradation at single location - less than 6 in. diameter
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Blisters at multiple locations - less than 10% of surface covered
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Damage to surface due to erosion or 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 A.7 Plastic or HDPE pipe rating system-2



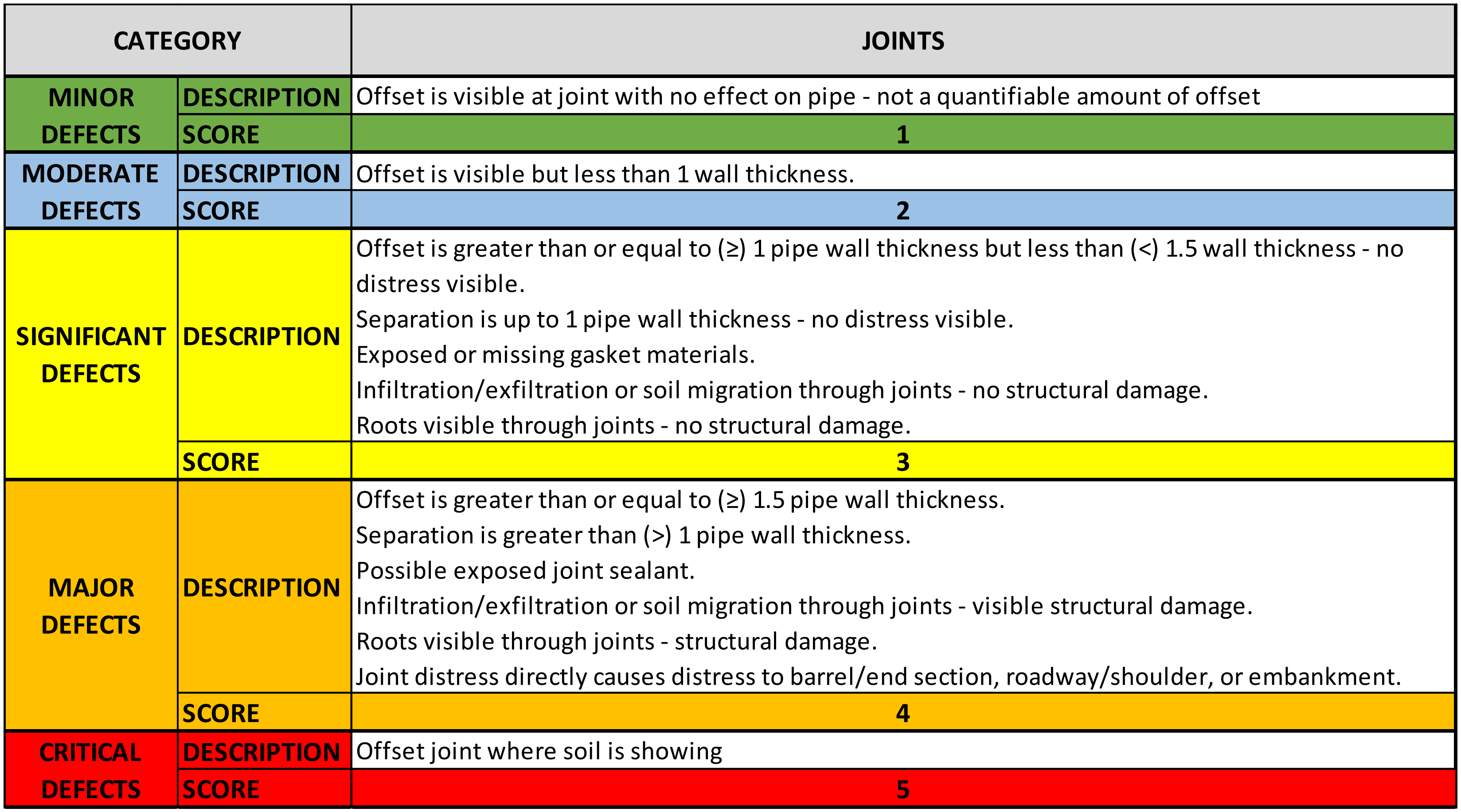
CATEGORY		LOCAL BUCKLING, SPLITS AND CRACKS
MINOR DEFECTS	**DESCRIPTION**	Crack that is perpendicular to flow direction. No opening between crack. One max per pipe section. Less than 1/4 of circumference.
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Longitudinal crack ≤ 12 in. in length with or without 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 A.8 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 A.9 Plastic or HDPE pipe rating system-4

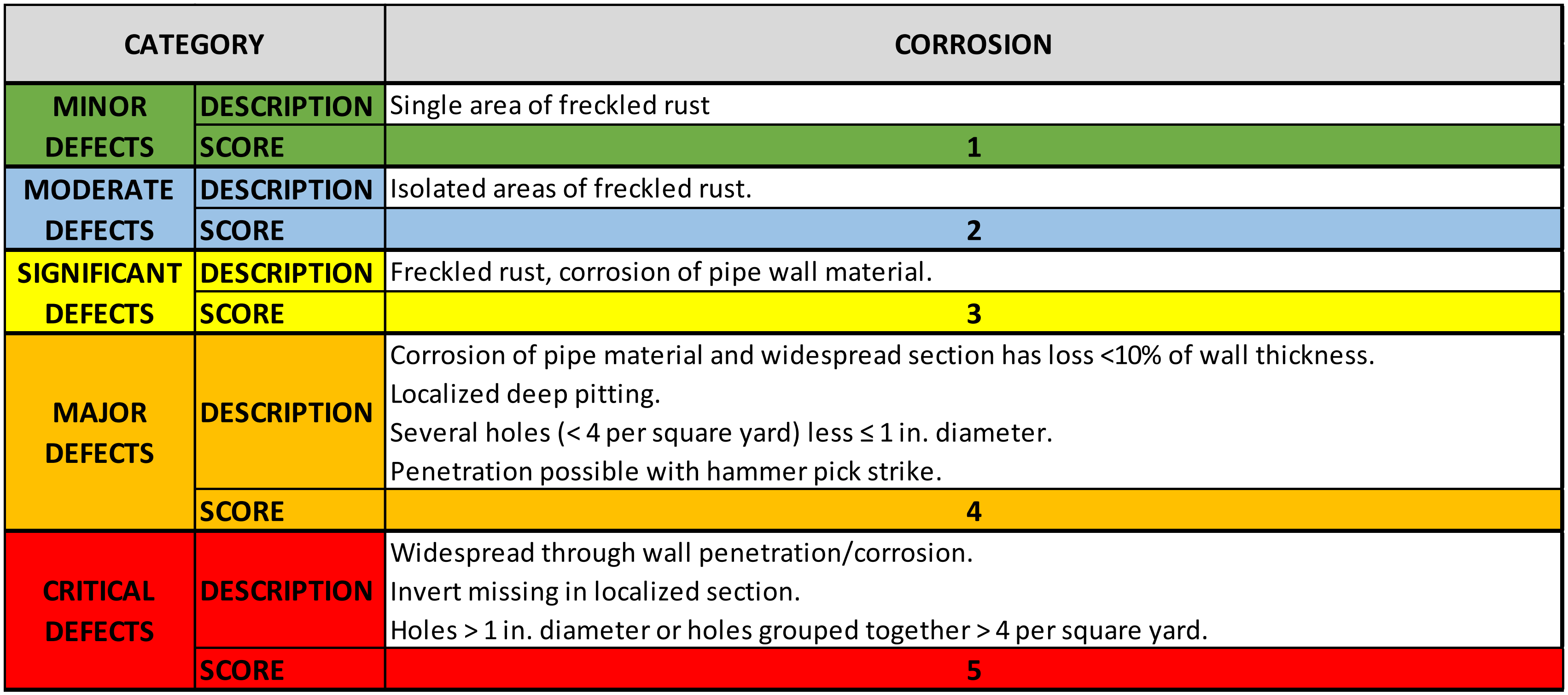


CATEGORY		JOINTS
MINOR DEFECTS	**DESCRIPTION**	Offset is visible at joint with no effect on pipe - not a quantifiable amount of offset
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Offset is visible but less than 1 wall thickness.
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Offset is greater than 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 A.10 Plastic or HDPE pipe rating system-5

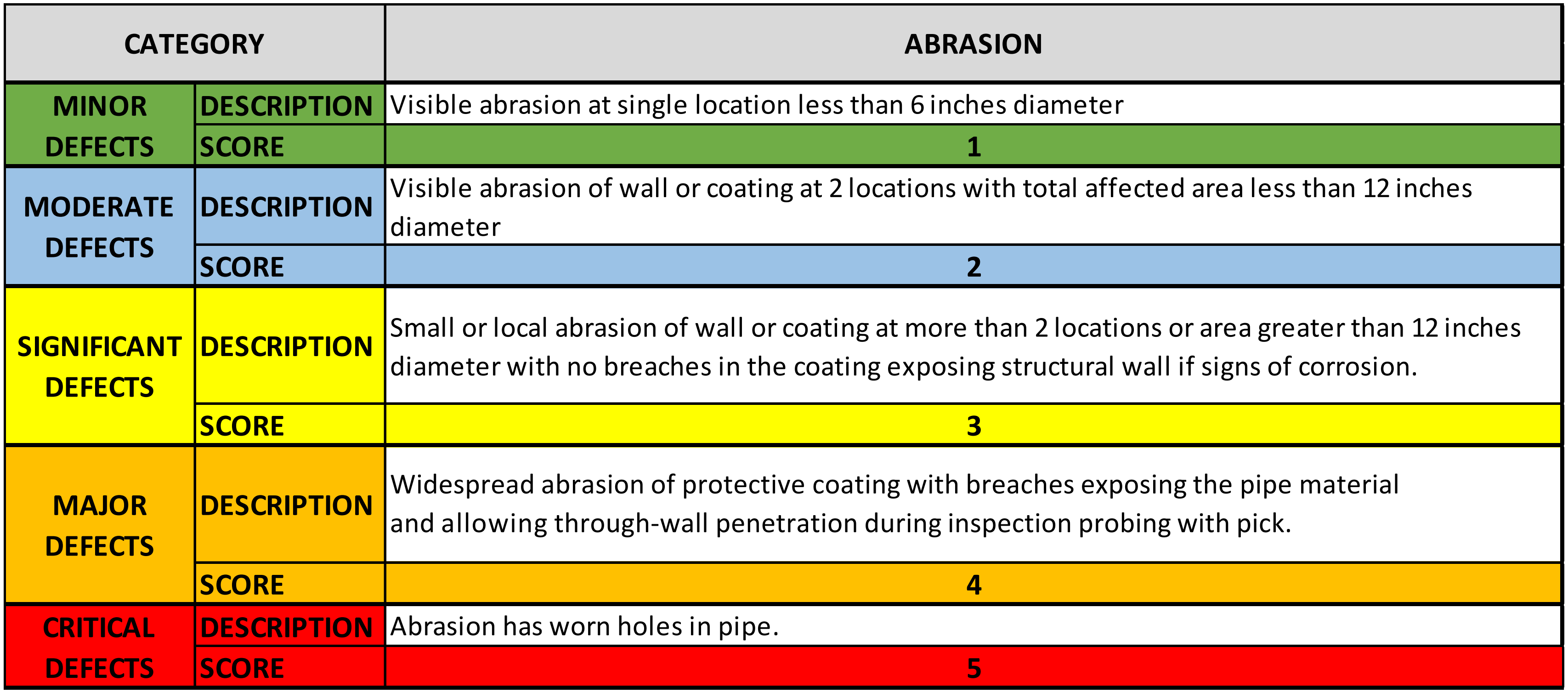
CATEGORY		SURFACE DAMAGE
MINOR DEFECTS	DESCRIPTION	Single dent or bulge - no change in diameter - Area is less than 2 in. diameter
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Multiple dents or bulges - Total area less than 4 inches diameter
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Small dents or impact damage 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 A.11 Corrugated metal pipe rating system-1



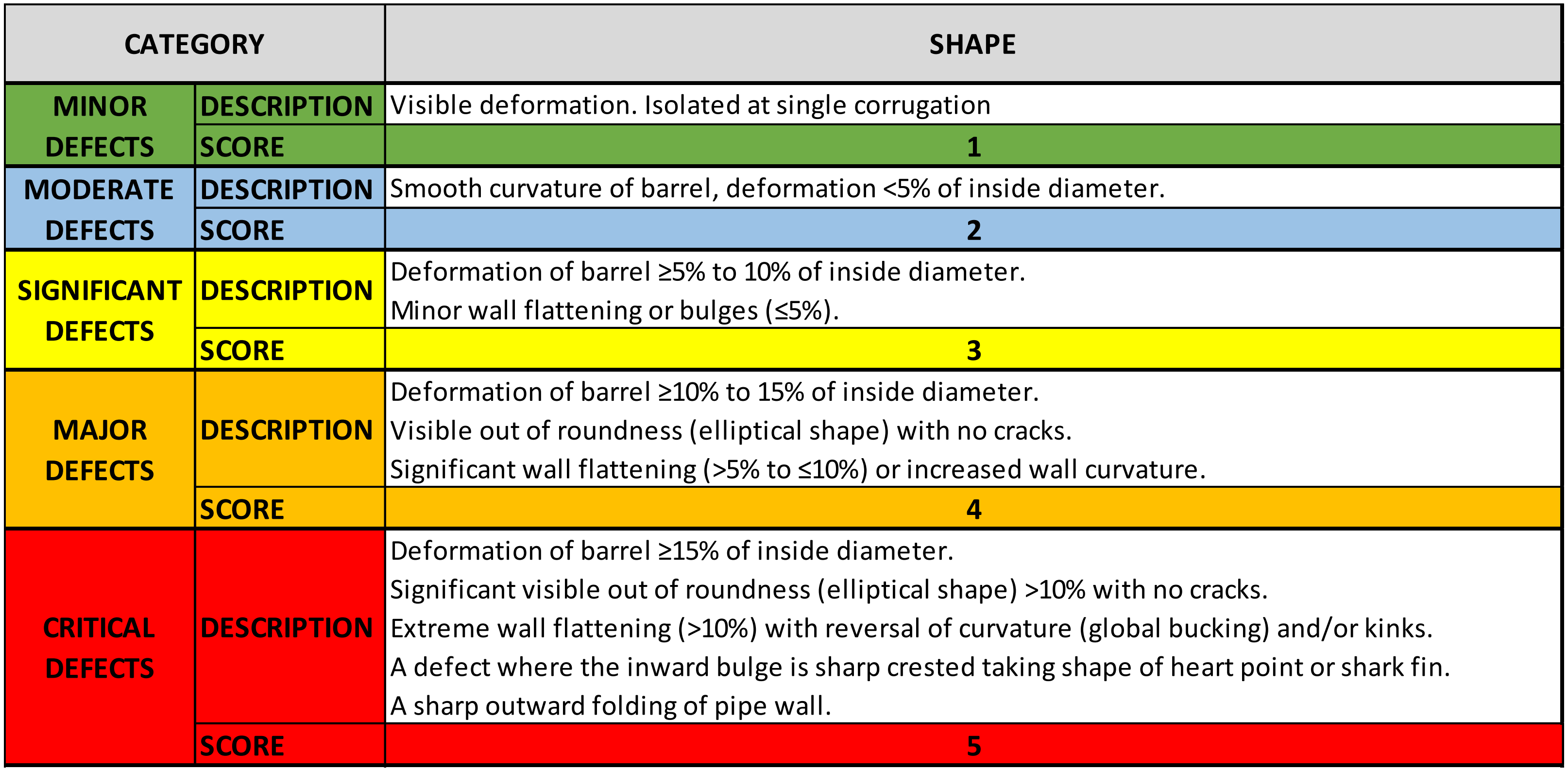
CATEGORY		CORROSION
MINOR DEFECTS	DESCRIPTION	Single area of freckled rust
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Isolated areas of freckled rust.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Freckled rust, corrosion of pipe wall material.
	SCORE	3
MAJOR DEFECTS	DESCRIPTION	Corrosion of pipe material and 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 A.12 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 A.13 Corrugated metal pipe rating system-3

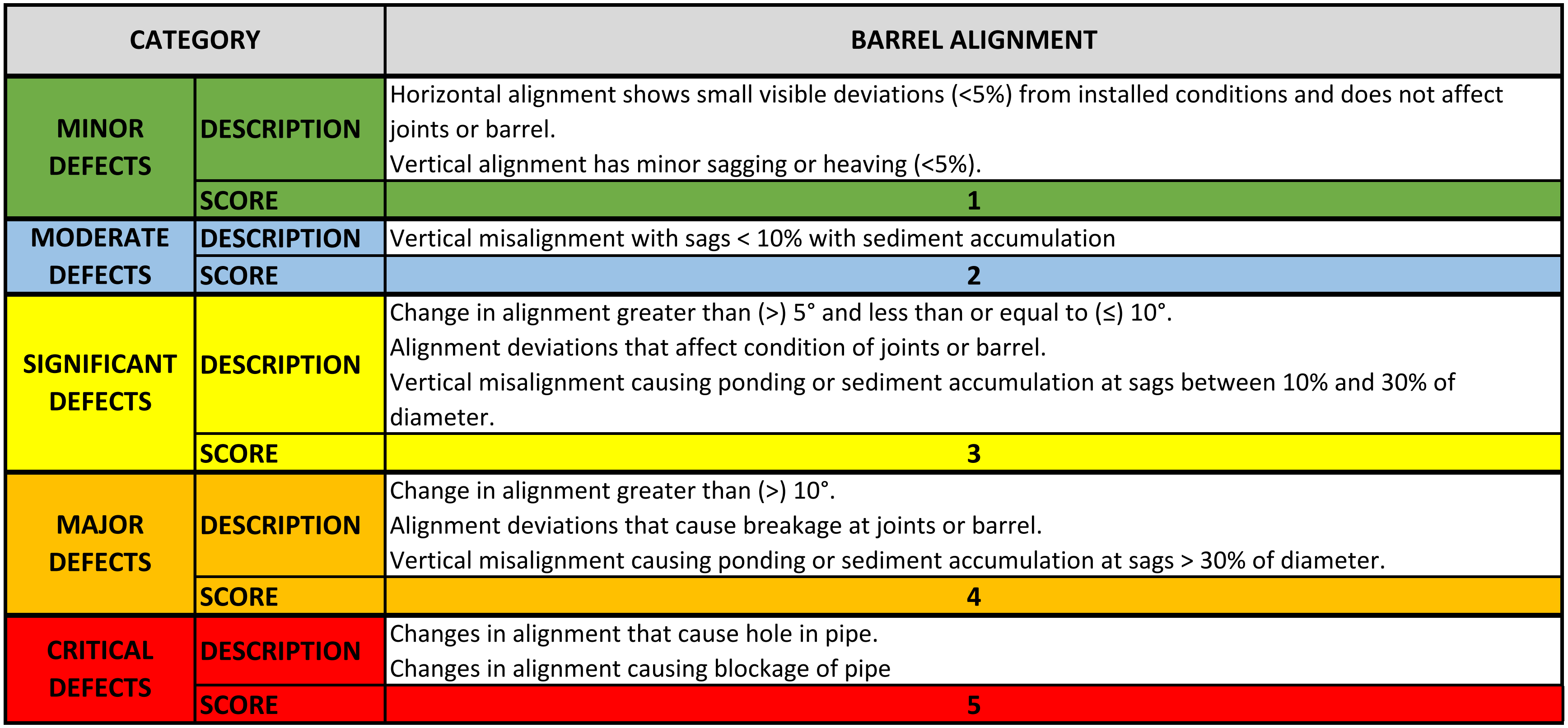


CATEGORY		SHAPE
MINOR DEFECTS	DESCRIPTION	Visible deformation. Isolated at single corrugation
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Smooth curvature of barrel, deformation <5% of inside diameter.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Deformation of barrel ≥5% to 10% of inside diameter. Minor wall 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 A.14 Corrugated metal pipe rating system-4

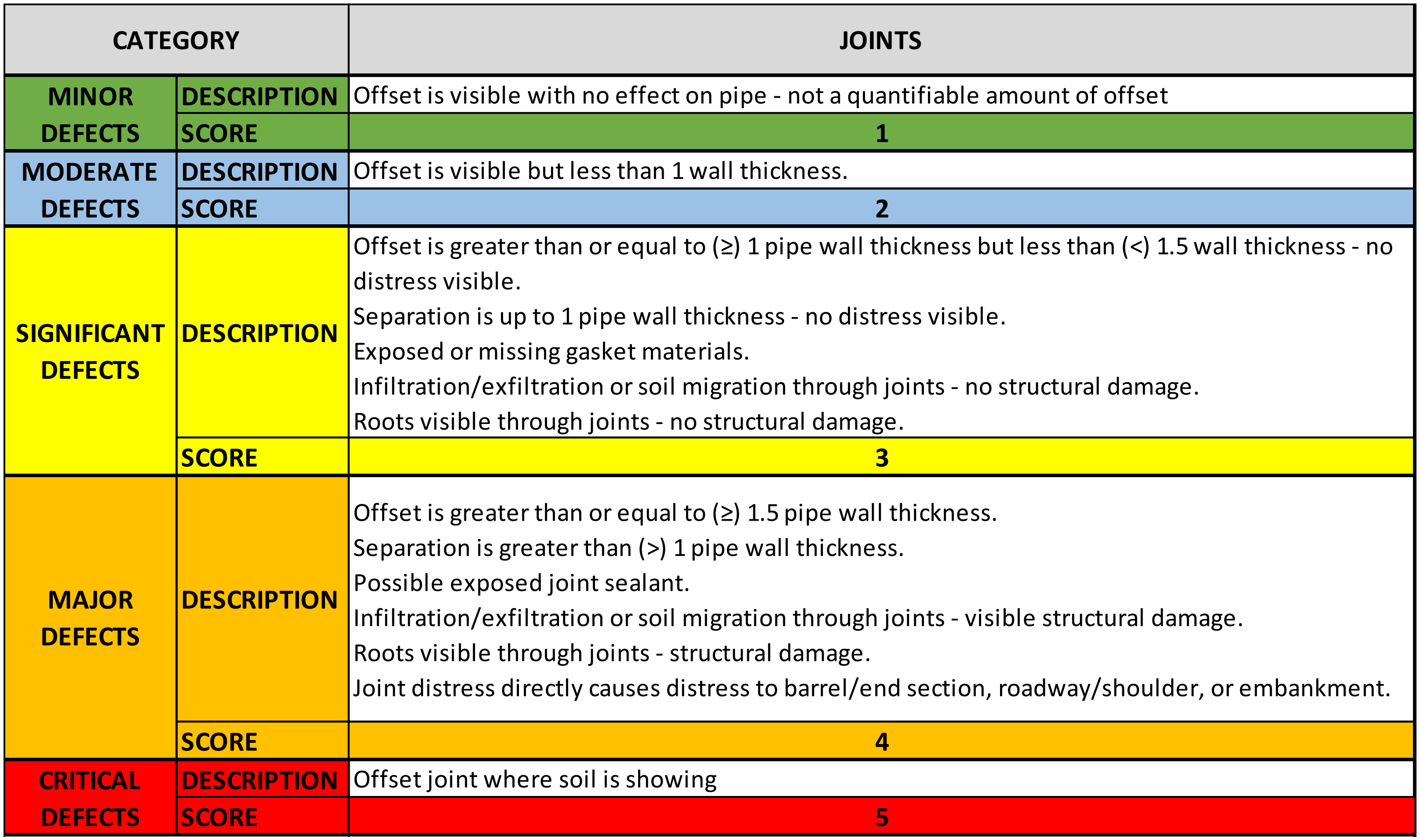
CATEGORY		CRACKS / BREAKS / KINKS / HOLES
MINOR DEFECTS	**DESCRIPTION**	Crack that is perpendicular to flow direction. No opening between crack. One max per pipe section. Less than 1/4 of circumference.
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Longitudinal crack ≤ 12 in. in length with or without 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 A.15 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 A.16 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 A.17 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

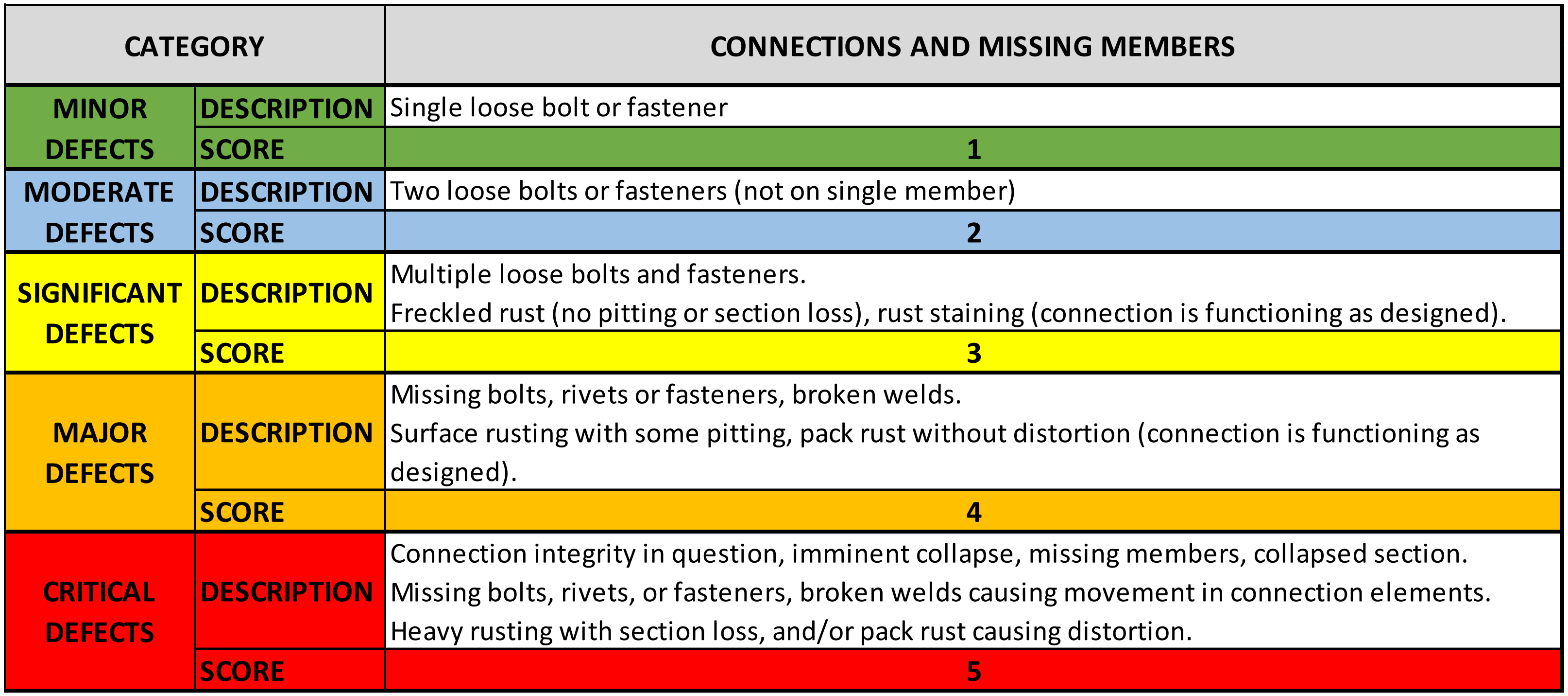
CATEGORY		SEAM ALIGNMENT
MINOR DEFECTS	DESCRIPTION	Seams minorly out of alignment - with no affect on pipe
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Slight cocked seams without cusp effect, but does not affect cross section shape.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Cocked seams that it affects cross 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 A.18 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

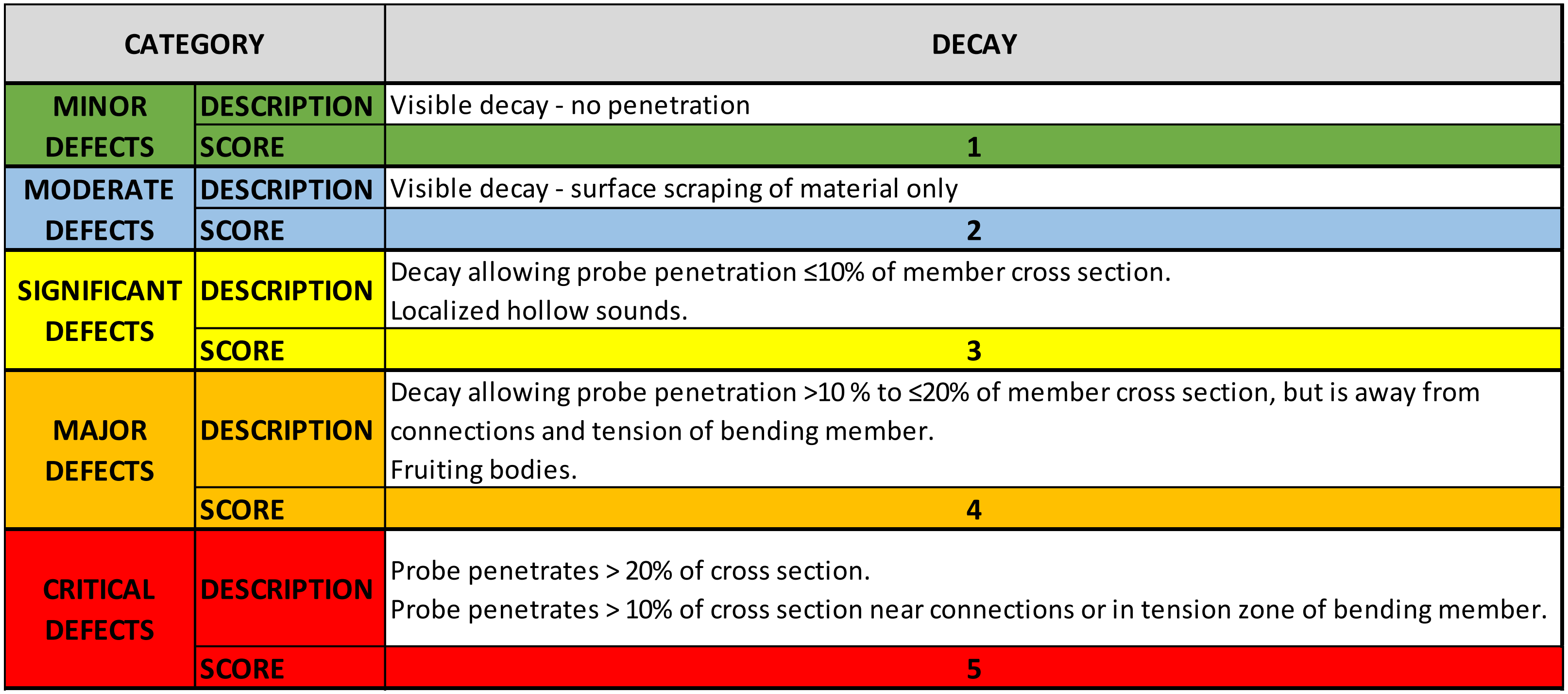
CATEGORY		SEAM BOLT HOLES
MINOR DEFECTS	DESCRIPTION	Cracking at single bolt hole
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Minor yielding of steel and/or cracking/splitting < 1 in. long local to bolt holes. Minor corrosion developing around bolt holes or on bolts.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	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 A.19 Corrugated metal pipe rating system-9



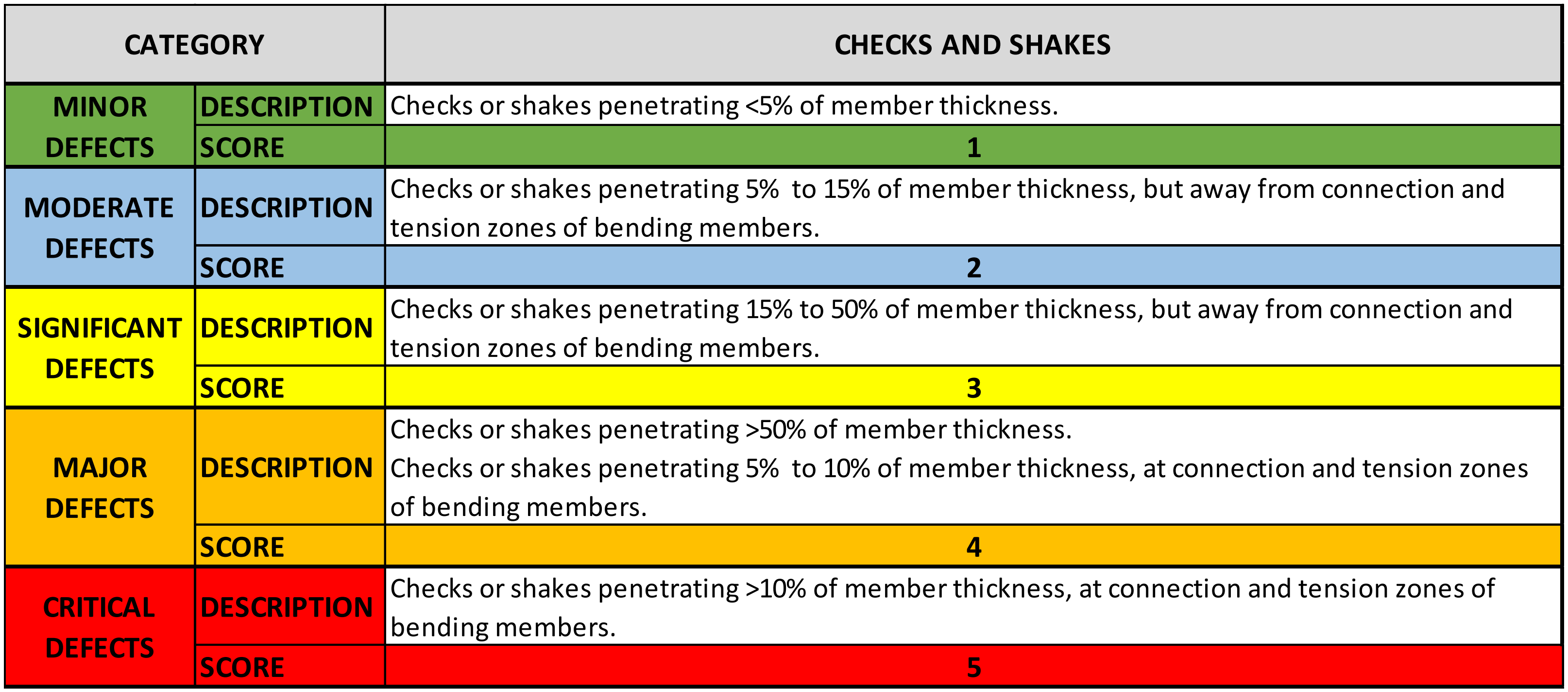
CATEGORY		CONNECTIONS AND MISSING MEMBERS
MINOR DEFECTS	**DESCRIPTION**	Single loose bolt or fastener
	SCORE	**1**
MODERATE DEFECTS	**DESCRIPTION**	Two loose bolts or fasteners (not on single member)
	SCORE	**2**
SIGNIFICANT DEFECTS	**DESCRIPTION**	Multiple loose bolts and fasteners. Freckled rust (no 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 A.20 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 A.21 Timber pipe rating system-2

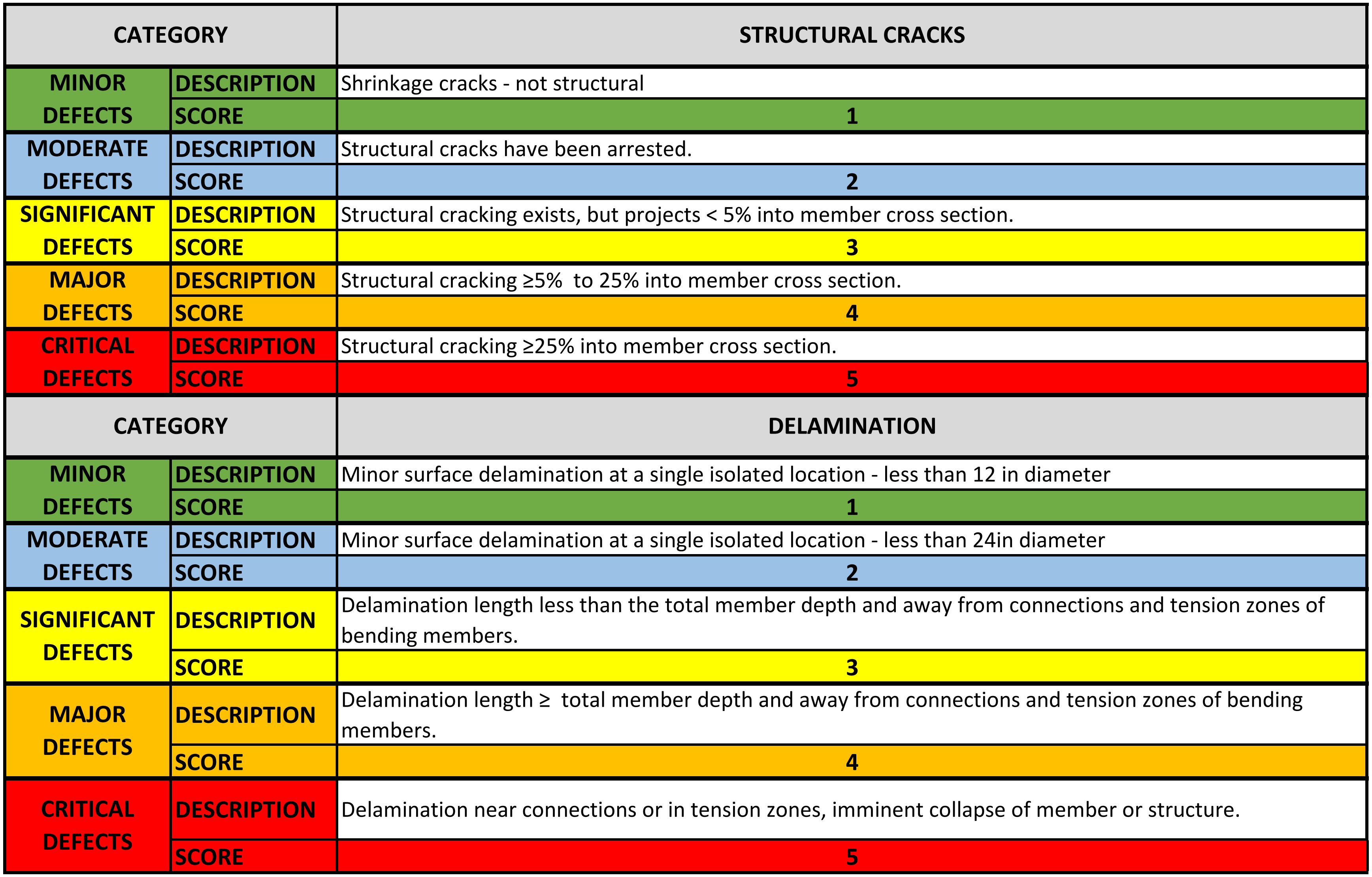


CATEGORY		CHECKS AND SHAKES
MINOR DEFECTS	DESCRIPTION	Checks or shakes penetrating <5% of member thickness.
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Checks or shakes penetrating 5% to 15% of member thickness, but away from connection and tension zones of bending members.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	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 A.22 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**

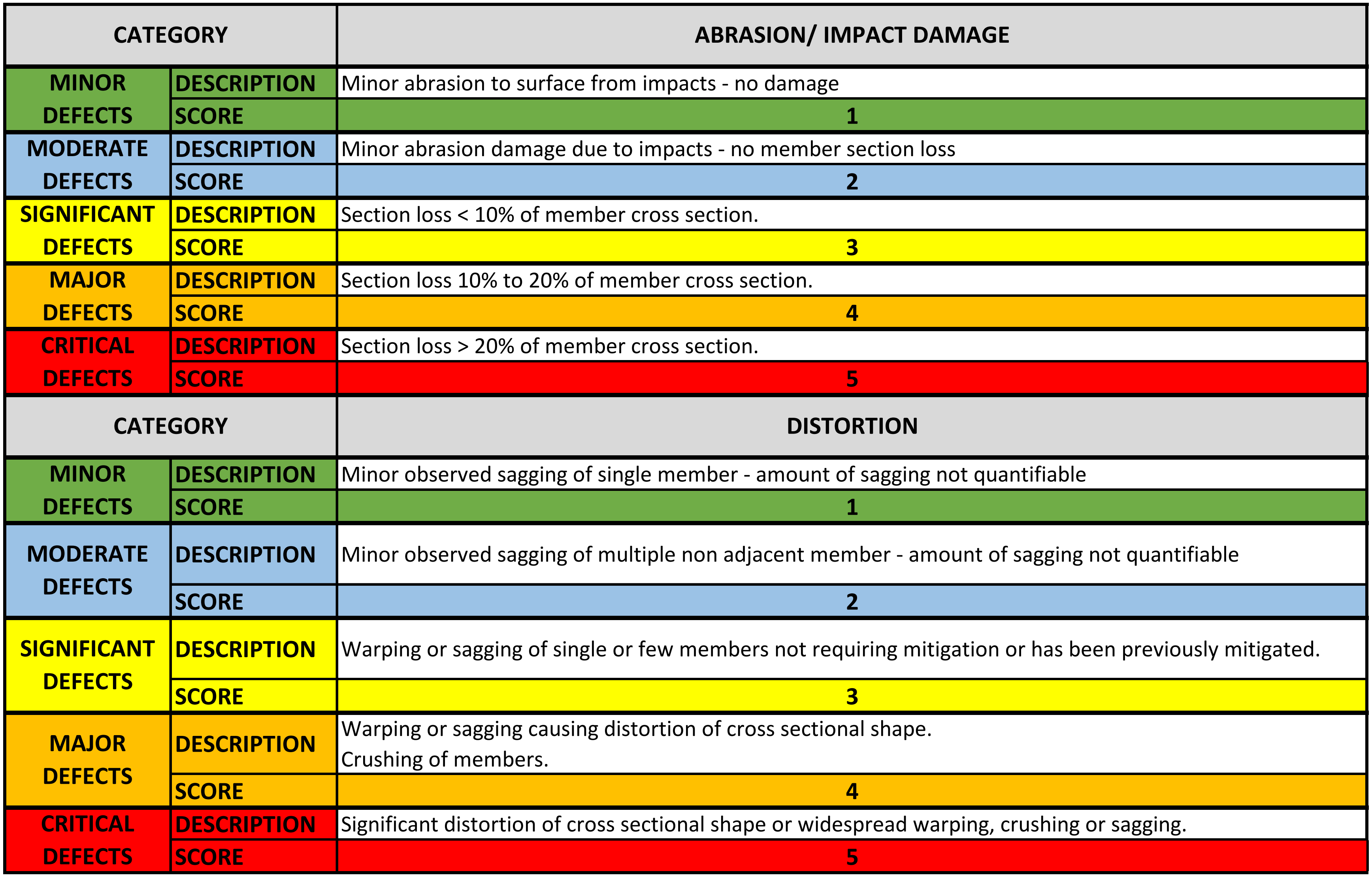
Figure A.23 Timber pipe rating system-4



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

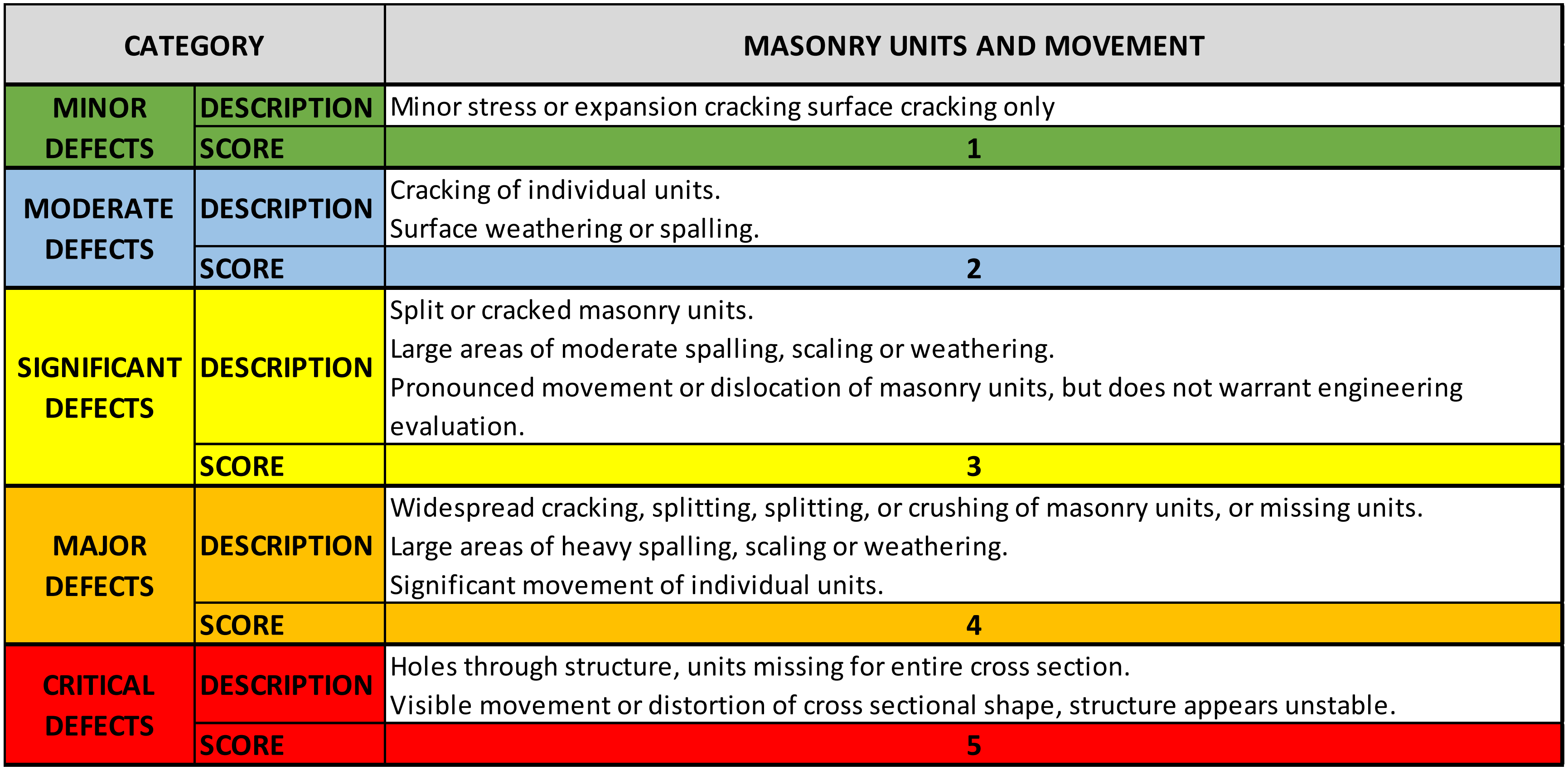
Figure A.24 Timber pipe rating system-5



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

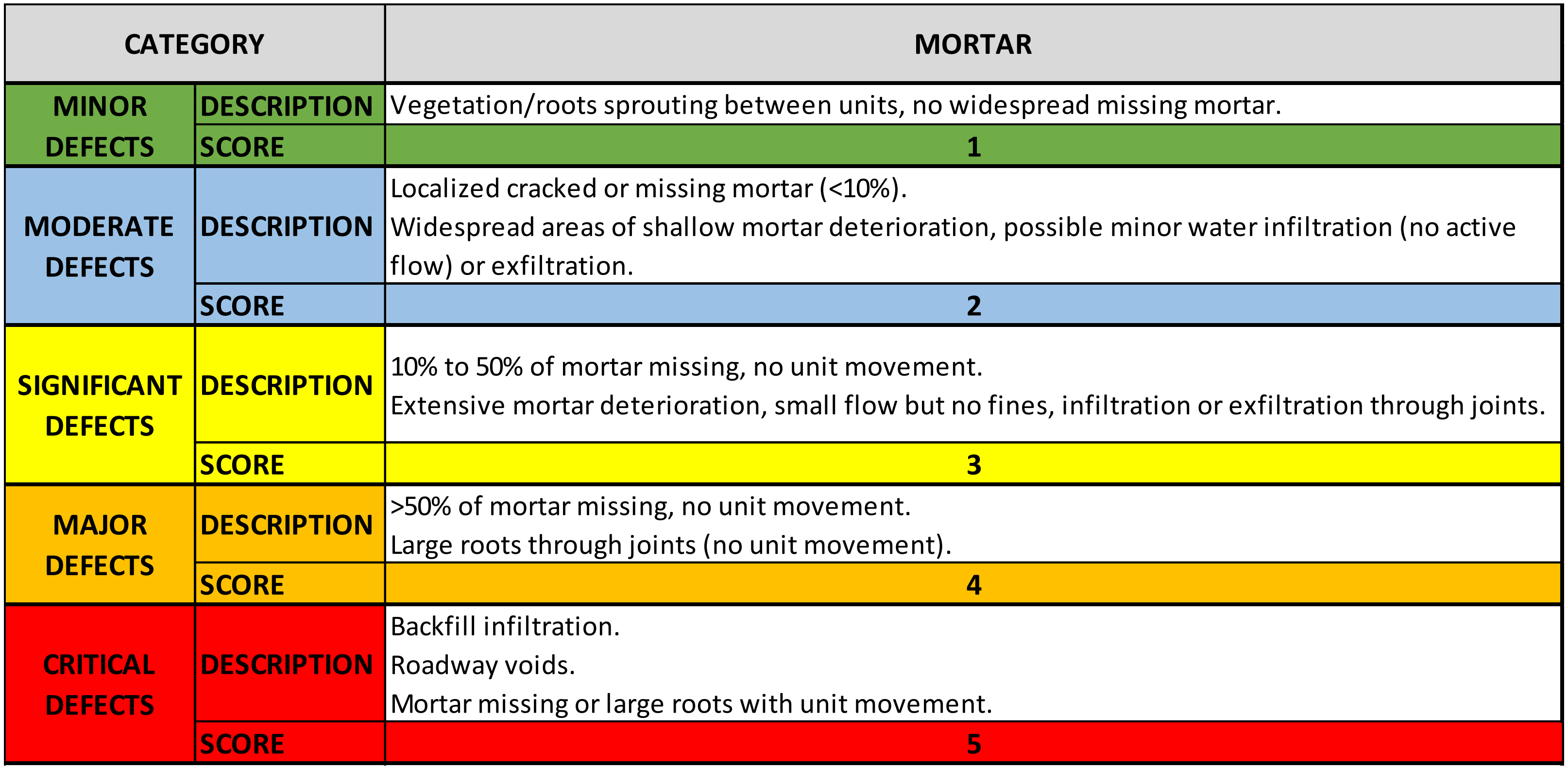
CATEGORY		DISTORTION
MINOR DEFECTS	DESCRIPTION	Minor observed sagging of single member - amount of sagging not quantifiable
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Minor observed sagging of multiple non adjacent member - amount of sagging not quantifiable
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Warping 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 A.25 Timber pipe rating system-6



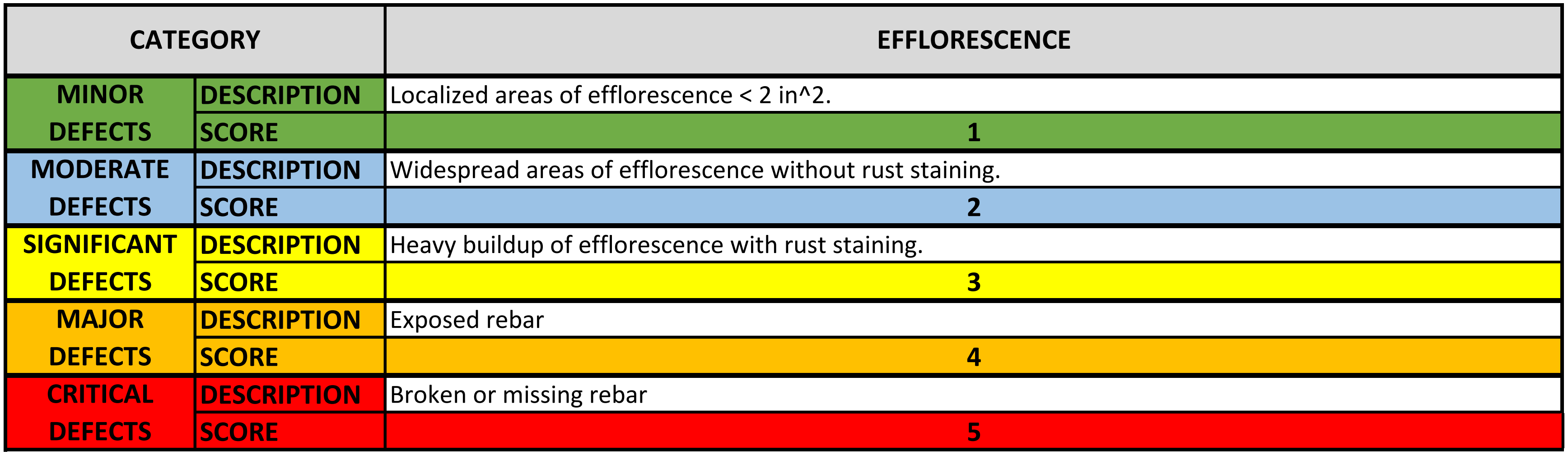
CATEGORY		MASONRY UNITS AND MOVEMENT
MINOR DEFECTS	DESCRIPTION	Minor stress or expansion cracking surface cracking only
	SCORE	1
MODERATE DEFECTS	DESCRIPTION	Cracking of individual units. Surface weathering or spalling.
	SCORE	2
SIGNIFICANT DEFECTS	DESCRIPTION	Split or cracked masonry units. Large areas 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 A.26 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 A.27 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

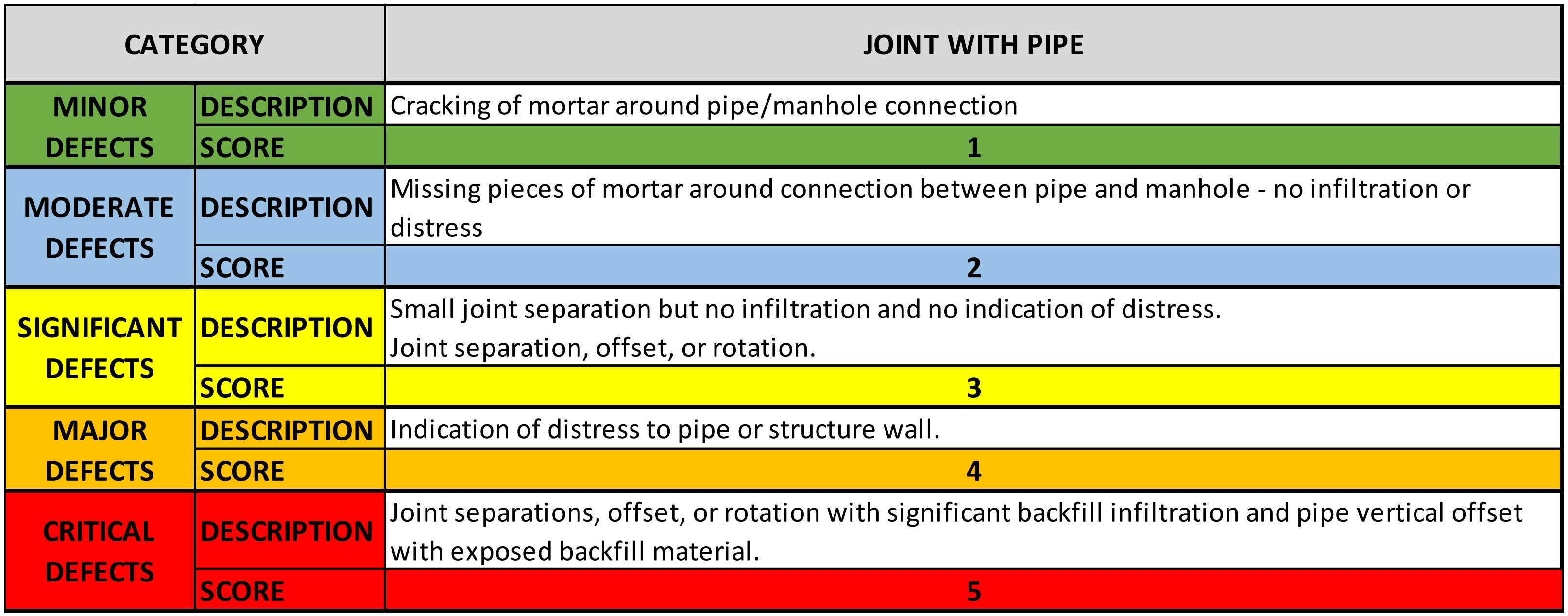
Figure A.28 Masonry pipe rating system-3

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 A.29 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 A.30 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 A.31 Manholes, catch basins, Headwall & Wingwall, and buried junction structures rating system-3