Understanding Causes of Concrete Culvert Pipe Joint Separation

A THESIS

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BY

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Disclaimer

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Abstract

One of the damages experienced by culverts is joint separation between segment of culverts. Joint failure can lead to water and soil seepage through the culvert, culminating in soil support and finally result in the settlement of roadway. The reason and how joint separation happens and which parameters play critical role for this occurrence are unclear.

Although past researches have done some analyses about flexural demands across joints, the analysis of which parameters play role in the occurrence and the analysis of the axial tension demands across culvert joints has not been done by any current research.

For this purpose, first database related to all round concrete culverts database of Minnesota Department of Transportation (MnDOT) was investigated and a machine learning model (Random Forest) had been developed and then finite element model of round concrete culverts were created to investigate the potential of separation because of axial demands on culvert segments, and after these, field inspection had been done to assure that the database and finite element model align with the reality. Accuracy of about seventy percent achieved by the machine learning model, random forest mode, after using MnDOT's culvert database and total length, maintenance district, pipe diameter, in slope cavity and roadway type were identified as the main features in predicting of joint separation in concrete culverts.

Traffic loading and soil embankment load were investigated through finite element method. The finite element method was used to assess traffic loading, and also was used to investigate dead load related to self-weight of embankment for different conditions. During these numerical analyses, field inspections were conducted to give us the better understanding of how joint separation has been occurred in different situations. Finite element model showed that traffic loading and soil embankment load generate tensile forces to separate the culvert's segment, however traffic load affects 10 to 20 percent. Also, soil embankment stiffness and its depth were detected the most critical factors in joint separation. In future researches, cyclic traffic load and freeze thaw effect should be considered.

Table of Contents

Contents

List of Tables

List of Figures

Chapter 1. Introduction

Culverts are pipelike structures that are essential for allowing water to pass under roads. Culverts have different shapes and materials, and concrete culverts are popular due to their strength and longevity. Concrete culverts are more popular than other types of culverts because they offer better quality at lower cost and are fast to build (Ramadan et al. 2022).

Joint separation is a common problem in concrete culverts, which means that the segments of concrete culverts can separate from each other either along the length of the culverts or perpendicular to them. This occurrence can worsen the stability of a culvert and allow water to seep into it, increasing the probability of road settlement (Sheldon et al. 2015). The separation occurs when the culverts move or change shape either along their length or around their circumference. Taylor and Marr (2012) summarized relevant literature, design and construction practices, and databases to assess culvert life spans in Minnesota. Although concrete culverts are generally considered durable and strong with low risk, joint separation was found to affect approximately 20% of Minnesota concrete culverts and was the most commonly observed failure mode. Based on an investigation of the database, joint separation was most common in medium culvert sizes (24 to 36 in), and increased cover depth was correlated with higher rates of joint separation.

Three different approaches were considered for this thesis. First, the MnDOT database was analyzed to develop a predictive model; second, a finite element model was developed using ANSYS software; and third, selected concrete culverts in Minnesota were inspected. Chapter 2 provides a review of relevant literature, Chapter 3 presents investigations of the database and applications of machine learning in concrete culvert prediction, Chapter 4 presents field inspection and data collection, and Chapter 5 presents numerical analysis using the finite element method.

Chapter 2. Literature Review

Because there are different methodologies and steps toward finding the correlations and causation of joint separation occurs between the segments of concrete culverts, this chapter is divided into three different sections; machine learning applications for infrastructure prediction, maintenance and computational modeling of buried culvert systems and inspection field approach.

2.1 Machine learning Applications for Predictive Modeling

Effective maintenance needs to have accurate models of prediction of concrete culvert. These models are essential not only to understand how culverts behave over time but also to make judicious decisions about maintaining and repairing them.

Nowadays, reactive maintenance strategies are widely used, meaning that problems occurred and after that maintenance started. Mohammadi et al. (2023) proposed to use proactive maintenance, using real-time data and predictive models, which is more secure and more cost-effective. They found and expressed how costly and inefficient reactive maintenance can be, by showing Utah Department of Transportation (Udot) spends significant amount of money each year fixing culverts. Using traditional, manual methods addressing individual culverts, the past methods are less efficient compared to newer ones, because of the large number of culverts should inspect, as an example Udot manages over 47000 culverts. Mohammadi et al. suggests that using Machine Learning (ML) algorithms can better predict when culverts need attention, saving time and money.

Gao (2019) investigated the maintenance of over 90,000 culverts in Ohio and developed a new system using ML and data analysis, which was more effective than the previous way of scheduling inspections. Allowing inspectors to focus on high-risked culverts, the ML approach uses resource especially human and money effectively. To develop better infrastructure management systems, Gao's work also looked at how culverts are related to nearby structures by using data from Ohio Department of Transportation TIMS (Transportation Information Mapping System).

Continuing this work, Gao and Elzarka (2021) developed a decision tree model that provided accurate predictions of culvert condition for over 80% of the training set and 75% of the testing set. The models showed that using a machine-learned based inspection system could cut down the need for inspections by 44%. While Gao and Elzarka focused on Ohio, the methods could be used anywhere else with similar data. The study also summarizes how to improve data management and reporting for culverts to aid in future development of machine learning management tools.

Ahmed et al. (2021) developed a machine learning-based tool for predicting the collapsing of tunnels in the US, they gathered and processed data of Federal Highway Administration. They implemented several machine learning algorithms, such as k-nearest neighbors (KNN), random forest (RF), artificial neural networks (ANNs), and support vector machine (SVM) to create predictive models. Implementing these algorithms, they found out that 18 important variables deteriorate tunnel structures, when tunnel width having the greatest impact. Reaching the accuracy of more than 85%, the random forest algorithm was found to be the most reliable algorithm.

The goal of this section is to create a model that can predict accurately joint separation in concrete culverts in Minnesota, by using a database that they are available in the Minnesota Department of Transportation (MnDOT) database. This model helps to find out which culverts are more exposed to joint separation based on their features such as geometry features and geographical features. Random forest algorithm stands out in the field of predictive modeling because of its ability to handle complex data and variables (Breiman, 2001). Considering non-linear relationships between features and the target variable, random forest outperforms other algorithm because it does not need to transform variables (Cutler et al., 2007). Another important benefit of random forest, especially when dealing with large datasets, is its strength to overfitting. This benefit comes from forming multiple decision tress and averaging their predictions, improving generalizability (Liaw & Wiener, 2002). Moreover, although careful data preprocessing is still advisable, random forest is relatively good at handling missing values, (Stekhoven & Bühlmann, 2012).

Random forest's ability to handle raw data without the need for standardization or normalization is valuable in managing diverse datasets. For instance, health monitoring or environmental impact assessments of infrastructure, engineers deal with from small-scale material properties to large-scale environmental factors. Furthermore, random forest algorithm doesn't require all the features to be one the same scale, which means that no need to have continuous or discrete variables or even nonnumeric Tien Bui et al. (2016). Tien Bui et al demonstrated the effectiveness of random forest to process various kinds of unstandardized data, which is good for keeping the health of the original data and developing a model with high accuracy.

Regarding model interpretation and application, random forest gives understanding of feature importance, meaning how the model influences the target feature (Genuer, Poggi, & Tuleau-Malot, 2010). It is also able to predict the probability of different results, which is helpful for evaluating risks and making decision (Nicodemus, 2011).

The model uses the Random Forest machine learning algorithm to predict the probability of joint separation in concrete culverts in Minnesota. The novelty of this study is its use of machine learning algorithm on a large dataset of 27220 records of concrete culvert from the Minnesota Department of Transportation and using 12 different features, including total length, maintenance district and so on.

2.2 Culvert Joint Design and Performance

As it was mentioned, one of the popular form of damages in concrete culvert is joint separation between culvert segment, which has an effect on nearly 20% of the concrete pipe in Minnesota (Taylor, 2012). Aligned with the Minnesota department of Transportation (MnDOT) Hydraulic inspection manual, 1 inch and more opening of the joint between the culvert segments is defined as joint separation in the structurally analysis of joint separation. NCHRP Synthesis Report 474 indicates the impact of joint failure on service life of culvert as a missing knowledge in the investigation of culverts (Maher, 2015). Issues in joint performance can cause culvert pipe failures. For example, joint separation may allow backfill soil material to seep into the pipe as infiltration, causing the pipe plugged. For maintenance of such pipes, injection or joint sealing are used through internal flexible rubber seals and retaining bands (Wagener 2014).

The reasons of joint separation in concrete culverts are not completely researched. Moore et al. (2012) and Sheldon et al. (2015) have investigated joint performance under live load of vehicle. They found that joint separation under vehicle loading is much greater in the vertical direction than in the longitudinal direction. But they focused on longitudinal moment on joint, ignoring the mechanisms that cause axial separation across joints. Numerical analyses have been used to quantify forces transferred from soil embankment to culvert segment, finite element models (ANSYS). These forces act along the longitudinal axis of the culvert pipe are hypothesized to cause the culvert joint separation. The popular concrete culverts are round ones modeled within an embankment. For assessing the effect of traffic loading. ANSYS model has also been used to establish the results of and for exploring different pipe diameters and different fill heights.

There are two primary categories based on the mechanical behavior and response to external loads in the pipe joint design: moment-release or moment-transfer joints (Moore, 2012). Moment-release joints are engineered to allow rotational movement between the connected pipes. This design approach successfully decreases longitudinal bending stresses that may stem from surface loads or differences in the conditions of support (i.e., the subgrade stiffness). Bell-and-spigot or tongue-in-groove joints, both with or without gaskets are the examples of moment-release joints. Joints in concrete culvert are not always moment-release joints. For limiting rotational movement and ease the transfer of bending stresses from one pipe segment to another, moment-transfer joints are designed. Band joints and welded connections are fine examples of moment-transfer joints. Pipe ties, which are metal bars or rods, crossing the joint, causing the concrete pipe joint to resist axial forces and possibly bending moments, being based on the number of ties and position of them around the circumference and the direction of the moment.

Assessing the capacity to withstand vertical shear forces, bending moment (if applicable), axial forces, and rotational behavior under different loading and burial conditions should be considered for design criteria. Moore et al. (2012) underscore the effect of longitudinal bending on joint performance, but they did not investigate the mechanisms of axial forces across joints in their research.

To ensure about the mechanical performance and longevity of joint structure, appropriate joint design in concrete culverts must be done. Well-designed joint is crucial for the uniform distribution of loads across the structures, ensuring appropriate load transfer between individual pipe sections, preventing concentrated stress, thereby decreasing the damage damage-risk or failure-risk, whereas poorly designed joints can cause structural failures (Perminov et al. 2017). Vetter et al. (2016) examine how joint design must provide certain degrees of movement, such as contraction or ground shifts and thermal expansion, without compromising structural performance.

Another important purpose of joint design for reliable culverts is reaching tight connections, but the necessity of watertight connections relies on the whole culvert system and application. The watertight joint connections in concrete sewage pipes for reducing the soil erosion and inhibiting contamination of groundwaters (Haktanir et al. 2006). Different state DOT practices for waterproofing of concrete culvert joints have been summarized by Sezen et al. (2021). They confirm that protection in low cover situations where the top and sides of the concrete are subject to early degradation due to water seeping through the joints is essential. Walker (2022) also investigated joint design to prevent corrosion and degradation of concrete culverts.

The economic implications of joint design noting that it can significantly impact the overall cost of the culvert system, which affects both material and labor expenses was addressed by Pei et al. (2020).

2.2.3 Types of defects identified in concrete culverts

In concrete culverts, there are different types of defects, including cracking, spalling, misalignment, defective joints, end section drop-off, slabbing, soil erosion, corrosion and abrasion, that can all reduce structural integrity and functionality of concrete culverts.

Cracking can be detected as longitudinal or circumferential fractures. Spalling is another type of defects that can be detected by visible breaking off of concrete pieces, typically stem from internal pressure, bond failure, impact loads, or rebar corrosion. Misalignment and defective joints happen, where pipe sections are not suitably aligned or have separated, often result in infiltration or exfiltration of water. Erosion of supporting material leads to end section drop-off. (Huston et al., 2021)

2.3 Inspection Approach

2.3.1 Methods of Inspection

One of the fundamental processes in infrastructure management is culvert inspection, aiming at condition assessment to find deterioration and defects in culvert. There are two main inspection methods:

1- Man-Entry method

This method is possible when the diameter of culvert 30 inches or more in diameter. However, factors like water depth, flow velocity, debris, or hazardous conditions can limit this type of inspection.

Visual inspection; Cracks, spalls, and other surface defects and defective joint can be observed directly by inspectors.

Direct measurements; Diameter and alignment measurements (e.g., using a laser) help to detect shape distortion and pipe misalignment or non-uniform curvature.

- A sounding hammer can aid inspection. A hollow sound in concrete culverts indicates delaminated areas, but good concrete area can be detected by a solid sound.

2- Nondestructive Inspection (NDI) or nondestructive Testing (NDT) methods

If there is no way for man to enter concrete culverts, non-man entry culvert method should be used. Many NDI and NDT methods exist; however, for small culverts the most practical option is not optical inspection.

- Optical methods

CCTV (Closed-Circuit Television)

One common way for small culverts to be inspected is a camera on a wheeled platform. Using CCTV, various surface defects, deformation, defective joints and shape distortion can be videotaped. The name of it is Hydraulic Inspection Vehicle Explorer (HIVE).

There are two models of were studied. One is HIVE 1.0 was developed by Minnesota Department of Transportation, another, HIVE 2.0 was developed by VTrans (Vermont Department of Transportation). There are some issues in HIVE 1.0:

A camera, 2.4 GHz Sony Action Camera, mounted to the HIVE 1.0 has difficulty to transmit video beyond 40 feet (12.2 m) in an 18-inch (0.46) culvert, meaning it does not meet the requirement for footage available through small culverts or through drop inlets.

Another problem is maneuverability. The HIVE 1.0 often encounters issues during inspections in Minnesota, such as:

- Unable to pass through mud or heavily sedimented culverts.
- Having difficulty to navigate around debris like sticks and leaf litter.
- Unable to pass separation gaps in pipes (6 inches), resulting in it getting stuck
- Unable to brake efficiently, leading to roll downhill on slopes (e.g., 20-degree slopes)

Also, imprecise location tracking is a minor problem in HIVE 1.0.

Therefore, to solve these problems, VTrans introduced HIVE 2.0.

Table 1 shows some characteristics that HIVE 1.0 did not meet while HIVE 2.0 improved (Huston, 2021).

Table 1 - Features of HIVE 2.0 versus HIVE 1.0 (Huston et al., 2021)

VTrans Requirements	Engineering Features	HIVE 1.0	HIVE 2.0
Footage deep into small culverts	Viewable live footage from at least 80’ (24.4 m) into 18-inch (0.457 m) culvert	Does not satisfy criteria	Satisfies criteria
Footage through drop inlets	Viewable live footage at least 80’ (24.4 m) into culvert with drop inlet	Does not satisfy criteria	Satisfies criteria
Capable of crossing separation gap in pipes	Passing a gap of at least 6 inch (16.240 cm)	Does not satisfy criteria	Satisfies criteria
Ability to stop from rolling down hills	Vehicle should remain still on 20-degree slope	Does not satisfy criteria	Satisfies criteria
Vehicle’s location detectable by user	User should know how much distance the vehicle traveled through the culvert (305 mm)	Moderately satisfies criteria	Satisfies criteria

Chapter 3. Investigation of Database

3.1 Methodology

Data Collection and Preprocessing

In this research, using data from the Transportation Asset Management Systems (TAMS) HydInfra Database provided by the Minnesota Department of Transportation (MnDOT), the percentage of concrete pipe joint separation rate has been predicted.

This database contained information on over 31,000 concrete culverts. Database features of interest capture the geometric, geographical, and other details of the culvert alongside a series of culvert condition metrics obtained from inspections. Table 2 outlines the features of interest incorporated in the present analysis.

Table 2. TAMS-HydInfra Features Included in Analysis

Feature Tag	Description	Data Type
Cover at Upstream Road Edge	Depth of fill above from top of pipe to surface of road at upstream end of pipe	Numeric, units of feet
Total Length	Length of pipe	Numeric, units of feet
Inside Width	Width of inside of pipe, equal to inside diameter for round pipes	Numeric, units of inches
Pipe Classification	Presence of long bolts, bars, or plates that cross and secure the pipe joints	Discrete Categories; No Yes (Full Ties) Yes (Partial Ties)
Maintenance District	MnDOT district in charge of inspection and maintenance of culvert	Discrete values, districts include 1, 2, 3, 4, 6, 7, 8, and Metro
Roadway Type	Type of road or crossing over culvert	Text, roadway description
Route ID	Route/road number	Text, route number
County	Minnesota county, location	Text, county name
Road Distress	Indicates pavement distress such as road bumps, dips, patches, etc.	Binary, yes/no
Void in Road	Indicates sagging pavement, patches, holes, or other evidence of fill loss from around pipe	Binary, yes/no
In slope Cavity	Indicates cave-ins or holes in in slope above apron or pipe	Binary, yes/no
Infiltration	Indicates seepage of water or soil through pipe	Binary, yes/no
Joint Separation	Indicates presence, and sometimes maximum observed magnitude, of joint separation	Variable, see text
Overall Condition	Five categories determined by inspectors	Discrete Categories; 0 – Unable to inspect 1 – Like New 2 – Fair 3 – Poor 4 – Severe Unknown

After inspection of around 80 culverts in different regions of Minnesota (see Chapter 4), some discrepancies have been found about the database. For example, if the database states that a culvert has pipe ties, it does not often clarify if pipe ties are just in the first segment of the culvert or located across all joints. In one example, the database stated no pipe ties, but field inspection confirmed pipe ties exist in the first three segments, as shown in Figure 1. After running the ML model multiple times, tie classification was used in place of pipe tie input, because of having pipe ties features in it and also it includes three kinds of data, no, full Ties, partial Ties; No means there is no pipe ties in culvert, Full ties, meaning every segment has pipe tie and partial ties meaning there are pipe ties in some segments.

Figure 1 - a culvert in district 8 with pipe ties just to third segment

Joint separation in the database was listed as a numeric value representing the greatest magnitude of joint separation, in inches, if the joint separation was greater than or equal to 1 in. (the cutoff at which joint separation is considered deleterious according to MnDOT inspectors). Prior to 2018, a value of 99 was entered into the database if joint separation was observed, but no measurement was provided. If joint separation was not observed during inspection, whether because there was no joint separation or because access limitations prevented the confirmation of the joint separation, then the entry was left blank. Beginning in 2018, for culverts confirmed to have no joint separation or joint separation less than one inch, the entry "<1" was provided. There are no entries explicitly containing zero, though nearly 70% of the entries are blank. This all leads to some ambiguity with the blank entries. Except for more recent entries with "<1", the database does not explicitly distinguish between cases whereby the joint separation was observed as equal to zero or whether joint separation could not be observed. This may introduce a bias towards underestimating the scope of joint separation. In the following analysis, this uncertainty in the individual joint separation entries was not considered, meaning the database records were treated as ground truth for each culvert. Clearly, this may lead to inaccuracies in the predictive model that could be explored in future studies.

AI-based natural language processing tools were used to process and classify inspectors' comments into five categories: apron separation, joint separation, none, other, and blank. These categorized comments were then transformed into structured features and incorporated into the machine learning model. The model outputs a predicted probability of joint separation ranging from 0 to 100%, where higher percentages indicate greater likelihood and confidence of joint separation. The database was filtered such that only round concrete culverts were examined. Nearly 87% of the Minnesota state concrete pipe inventory is composed of round culverts; other shapes such as boxes, arches, and cattle pass structures are less common. From a preliminary examination of the database, round culverts were also the most likely shape to have joint separation other than cattle pass structures, of which over 60% of the 256 structures in the inventory had joint separation. Other practically implausible culvert entries were filtered from the database, for example, entries with a Total Length value less than 2 ft. Filtering resulted in 26,710 remaining culvert records examined in the model.

Several steps were done to handle missing and zero values in MnDOT dataset, making sure that the machine learning model based on reliable data. No values in columns representing inside width (in), total length (ft), were replaced with their respective mode values. The statistics for these three features (inside width (in), total length (ft), soil cover depth (ft)) are given in Table 3. A zero value in these contexts was likely indicative of missing or incorrectly recorded data rather than a genuine measurement. This decision was based on the lesser susceptibility of the mode to extreme values and outliers. While the median also serves as a robust measure of central tendency and is less influenced by skewed data (notably in the case of total length (ft)), the mode is also a viable option and best captures the “typical” concrete culvert used throughout the state. The mode was the clear choice for inside width (in) and soil cover depth (ft), as these entries tended to be selected from a discrete set of values rather than a continuous spectrum. For instance, inside widths are nearly always found in 0.5-ft or 1-ft increments, as those are the commonly available precast pipe sizes, and cover is recorded only to the nearest foot. Mean imputation and K-Nearest Neighbors (KNN) imputation were also considered, but the mode provided the most satisfactory results in terms of model recall.

Table 3. Statistics of inside width (in), total length (ft), and soil cover depth (ft) features

Feature	Mean	Median	Mode	Min	Max	Standard Deviation
inside width (in)	27.74	24.0	24.0	1.0	260.0	12.11
total length (ft)	94.80	78.0	60.0	2	5436.0	72.35
soil cover depth (ft)	5.77	4.0	4.0	0	115.0	3.94

For pipe ties as a variable, showing the presence or absence of pipe ties, pipe classification feature was used as mentioned in Table 2. Blank entries for road distress, void in road, in slope cavity and infiltration were assumed to mean that these distresses were not present.

Model Architecture

From scikit-learn (Pedregosa et al., 2011), random forest classifier was used as a predictive model because of its robustness to overfitting and its ability for keeping accuracy even when dealing with noisy data. Aggregating the decisions from multiple decision tress, the ensemble approach of random forest has been used, which is more reliable by reducing variance and increasing the generalizing of the model.

A segment of a single decision tree depicted in Figure 2 and Figure 3 are graphical representations of one of the trees from our random forest ensemble. This visualization showcases the first four levels of the tree. Each decision node (Markovic et. al 2024) in the visualized depth represents a decision boundary that divides the data into distinct classes based on the feature criteria leading to that node; samples that meet the criteria are sorted to the left, while others are sorted to the right.

Node colors indicate the relative distribution of samples without (red) or with (blue) joint separation, with darker colors indicating higher uniformity within that node.

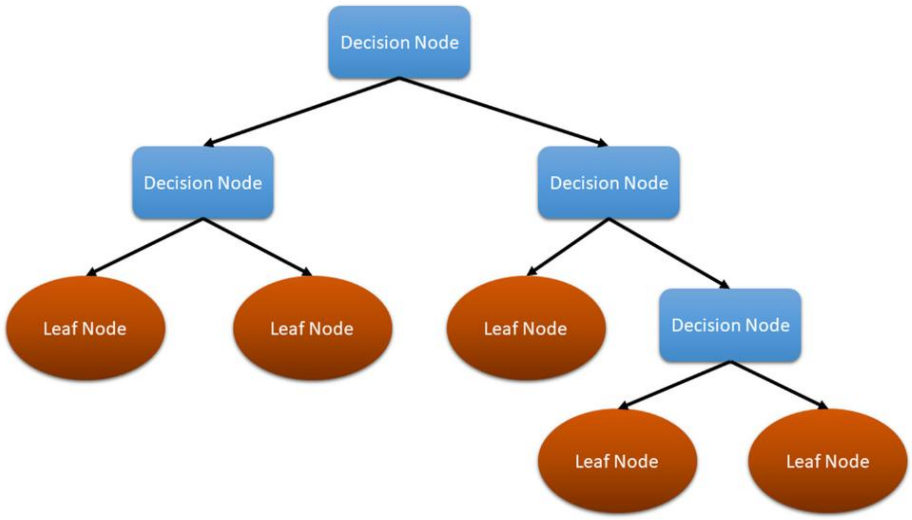


Figure 2 - Decision tree overview - the decision nodes choose based on data attribute. The leaf nodes are the final node that have been concluded. (Markovic et. al 2024)

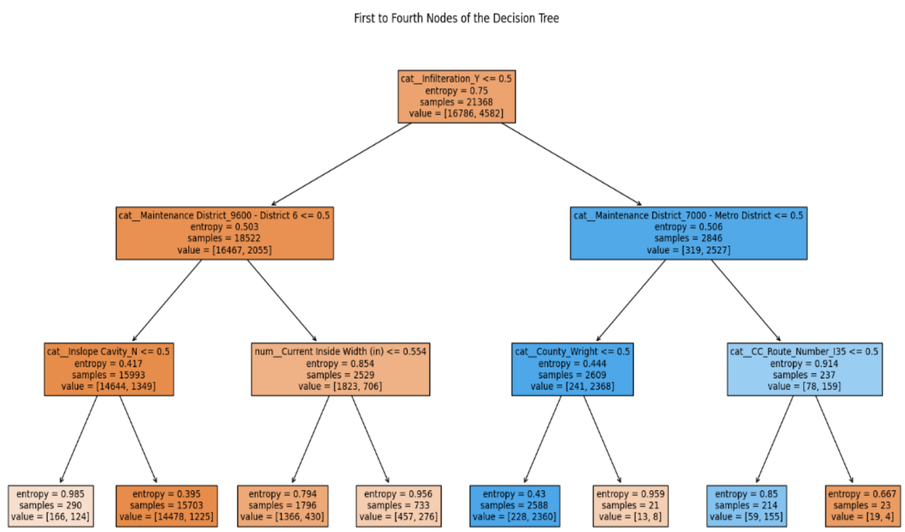


Figure 3 - one snippet of the Random Forest model

This tree begins with a split according the infiltration feature, which is a binary no (split to the left) or yes (split to the right) feature. The size of the sample is 21,368 culverts, with entropy of 0.75. Entropy E is the measurement of impurity or disorder in a node, defined as:

$$E = -\sum_{i=1}^{n} p_i \log_2(p_i) \tag{1}$$

where p_i is the probability of the target variable being in state i, which can take up to n different values. For this classification, the target variable is the presence of joint separation, so $n = 2$ (binary no or yes) and the probability p_i is the number of culverts without (for $i = 1$) or with (for $i = 2$) joint separation divided by the total samples in the node. The "value" vector displayed in each node is the count of the number of culverts without or with joint separation, respectively, present in that node, and "samples" is the total number of samples in the node. Entropy ranges from 0 to 1, where 0 presents perfect purity and 1 means maximum impurity (achieved by a 50-50 split of without or with joint separation in this case). Model training aims to maximize information gain measured as a decrease in entropy in the downstream nodes, such that entropy is minimized in the bottommost leaf nodes.

The architecture of the Random Forest aggregates the decision-making process across many decision trees, increasing the strength and predictive accuracy of the model by decreasing the variance and bias intrinsic to individual trees. For this study, the number of trees in the ensemble was set to 200. The distribution of "yes" and "no" predictions among each of the individual trees results in a predicted likelihood of joint separation. Using the information gain achieved at each node among all decision trees, this can also provide information on feature importance (Genuer, Poggi, and Tuleau-Malot, 2010), which may then be used as a predictive tool as to which culverts under which conditions are most likely to lead to joint separation (Nicodemus, 2011). The machine learning model predicts the joint separation; this prediction is a percentage between zero to 100, which represents the average result of the 200 decision trees.

In analysis where a simple binary prediction is desired, a "yes" or "no" prediction may be returned based on a simple majority vote of the individual trees.

To prevent overfitting, max depth has been set to 80, meaning each decision tree may expand until it reaches 80 levels of nodes deep. Another parameter defined in the model is the minimum samples to split, set equal to two, indicating that a node must have at least two samples before it can be split into further nodes. Finally, the minimum samples per leaf is set to 1, indicating that all defined leaf nodes must include at least one sample from the training set. The maximum number of leaf nodes is not limited so it has been set to none, for flexibility of trees to create as many leaf nodes as needed. Minimum impurity decrease has been set to 0 (default value), which means that a node keeps splitting while there is any reduction in impurity, however it is small.

To increase the predictability of our model, we added some uncertainties based on Reis et al (2019) research, to our model to find out it can help our model predict well, but the result shows that there is no change in accuracy of our model in spite of adding more complexity and time that this feature added to the model when we used Probabilistic Random Forest (PRF).

At the end of preprocessing, the database entries were split into the training set (80%) and the test set (20%). The training set contained 21,368 entries, and the remaining 5,543 entries were assigned to the test set.

Model Validation

The evaluation of the model used the confusion matrix with the four primary classes: True Positives (TP), False Negatives (FN), True Negatives (TN), and False Positives (FP). In this study, a positive result is the detection of joint separation, whereas a negative represents no detected joint separation. As noted above, negative results in the database may have some ambiguity, as they do not necessarily indicate the absence of joint separation but rather that no joint separation was observed. Similarly, positive classifications may also involve subjectivity, as pipes with marginal joint separation (e.g., up to approximately 1 inch) may be recorded as having joint separation by some inspectors and as not having joint separation by others. These classes were used to compute the performance metrics of precision = TP/(TP+FP), recall = TP/(TP+FN), and accuracy = (TP+TN)/(TP+TN+FP+FN). Precision tells you how often the items labeled as positive were actually positive. Recall tells you how many of the real positives you successfully found, and accuracy tells you how often the method was correct overall.

The F1-score is the harmonic mean of precision and recall.

$$F1 = 2 \times (\text{Precision} \times \text{Recall}) / (\text{Precision} + \text{Recall})$$

The F1-score provides a metric that balances both precision and recall, which is useful when the class distribution is imbalanced or when you want to consider false positives and false negatives equally. Precision, accuracy and recall were selected because they can address the uncertainty of dataset, which means positives are confirmed but there is uncertainty for negatives. Other confusion-matrix metrics needs actual true negatives, which the database does not provide.

There are five different folds in the random forest model and the result below were obtained from the first fold. Following model training, evaluation of the test set yielded the precision of 87%, the recall of 83%, F1 score of 85%and the accuracy of 94%. In this evaluation, the recall metric was considered to be the most important because of the biased knowledge of positive vs negative states in the database, as described above.

Table 4 indicates the confusion matrix for the entire dataset, the numbers show the number of culverts in specific values.

Table 4. Confusion matrix for the entire dataset

	Predicted Positive	Predicted Negative
Actual Positive	TP: 4856	FN: 512
Actual Negative	FP: 283	TN: 21059

K-fold cross-validation has been used to assess the random forest model performance as well as ensuring an unbiased assessment. Specifically, the dataset was randomly divided into five equal-sized subsets; for each iteration, one subset was the test set, and the remaining four were the training set. This process was repeated five times, with each subset serving as the test set exactly once.

Accuracies obtained from Iteration 39; Fold accuracies: 0.9495, 0.9403, 0.9343, 0.9387, 0.9427 with the mean value of 0.94. The numbers show consistency across different folds, indicating valid performance by the model, with minimum variance indicating that the model is discovering fine to undetected data. The absence of significant discrepancies among these scores provides evidence against the model substantially overfitting to specific segments of the data.

3.2 Results and Discussion

3.2.1 Feature Importance Results

Figure 4 shows a detailed pie chart, the relative importance of various features used in a random forest model, which predicts joint separation in round concrete culverts. The figure shows how the random forest model concluded about the probability of joint separation

The first feature that can show joint separation is overall condition which has the significant of 35.9%. The second feature is infiltration of the culvert, which has a significant 22.6% of the model's consideration. Joint separation is highly correlated with the overall condition of the pipe and with infiltration.

Route ID is the third most important feature, responsible for 7.9% of the model's predictive capacity, meaning codes from MnDOT's Linear Reference System (LRS) where first two digits differentiate the road level. Because this feature is mostly accurate in database, it can help the random forest model use it well to predict joint separation rate. County, similar to route ID, is an informative feature for the model, contributing 6.5%. Inslope cavity, indicating that the condition of the slope adjacent to the culvert, and roadway type with contributions of 5.3% and 3.9% respectively are also prominent features.

Other minor features include water observed (3.5% importance), total length (3.2 % importance), tie classification (2.9% importance) and culvert width (2.9% importance).

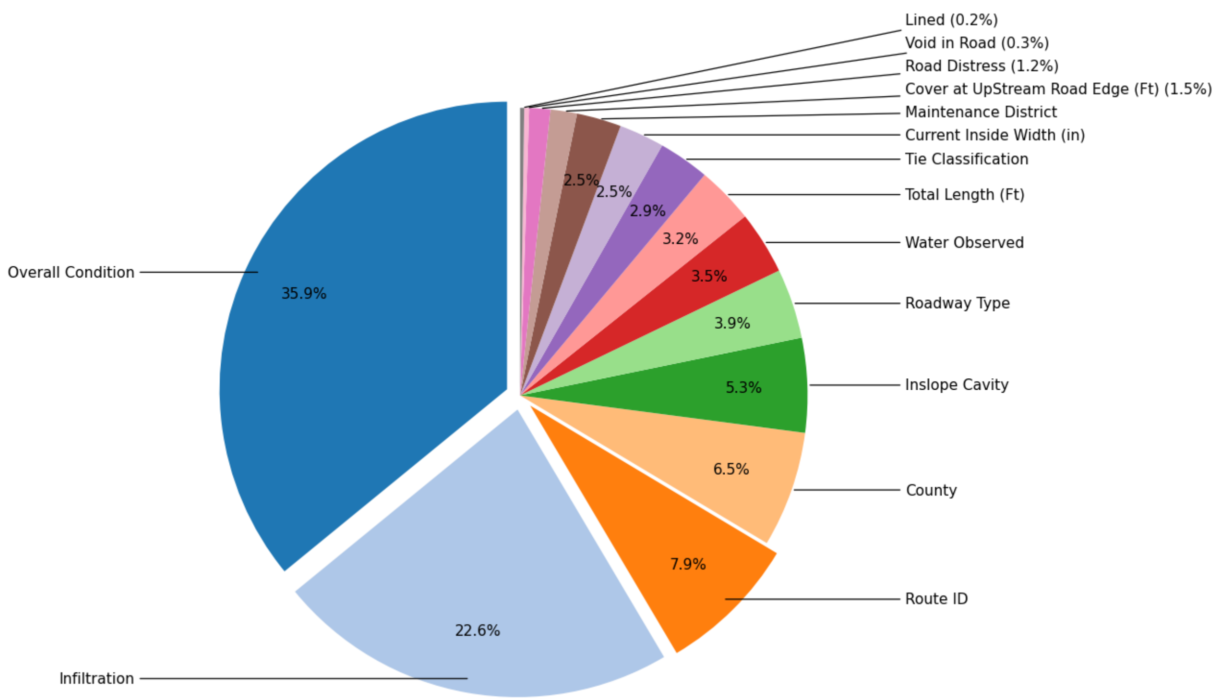


Figure 4 - Feature Importance for Predicting Joint Separation in Minnesota's Concrete Culverts

Results for Joint Separation by Features

In the following plots, those are the average of separation percentage not average of numbers of Y or N. It can be seen in Figure 5 that the rate of joint separation in round concrete culverts in Minnesota, in terms of total length predicted by our random forest model, is compared with the actual joint separation percentage. The accuracy of the model is evident in this figure, which shows that the model reasonably follows the trend of joint separation based on pipe length, but slightly overestimates the overall occurrence of joint separation. There is no continuous trend in the figure, but higher rates of joint separation occur in culverts between 200 and 300 feet in length and in culverts between 50 and 75 feet. Culverts with short lengths (0 to 12 feet) have the lowest probability of joint separation, likely due to having fewer segments and possibly a smaller soil cover.

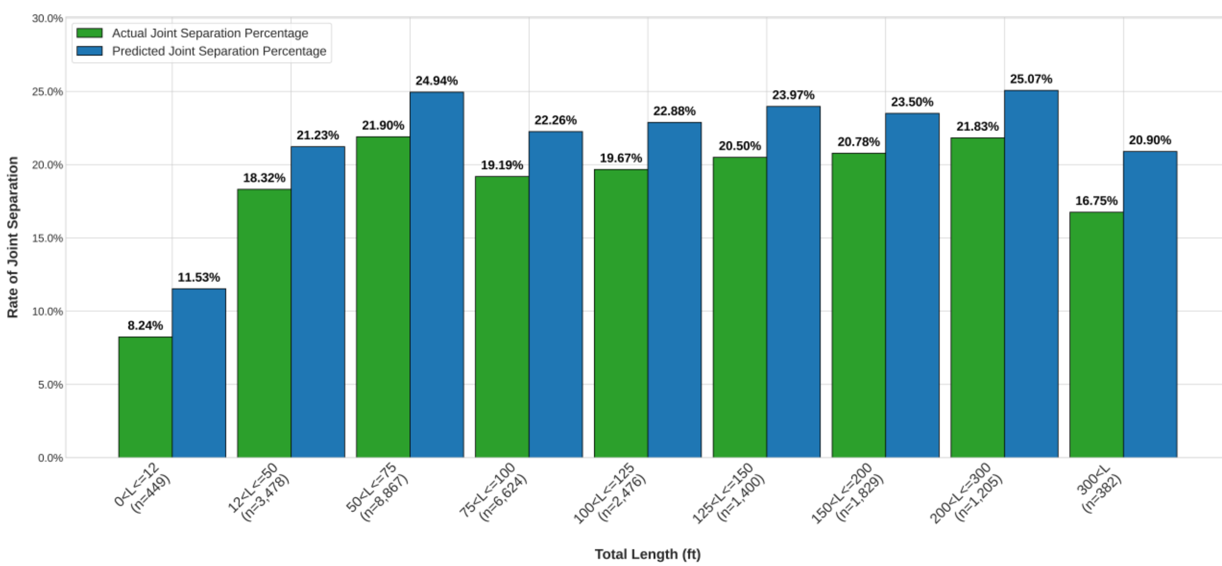


Figure 5 - Impact and count of Total Length category on Joint separation

Although soil cover as feature in the model has not contributed much in the decision made by the model, it is important to show whether the high soil depth cover has more probability of joint separation in concrete culverts or not. Figure 6 indicates that by increasing soil depth above culverts, the probability of joint separation increases, excluding the culverts with soil cover less than 1 feet.

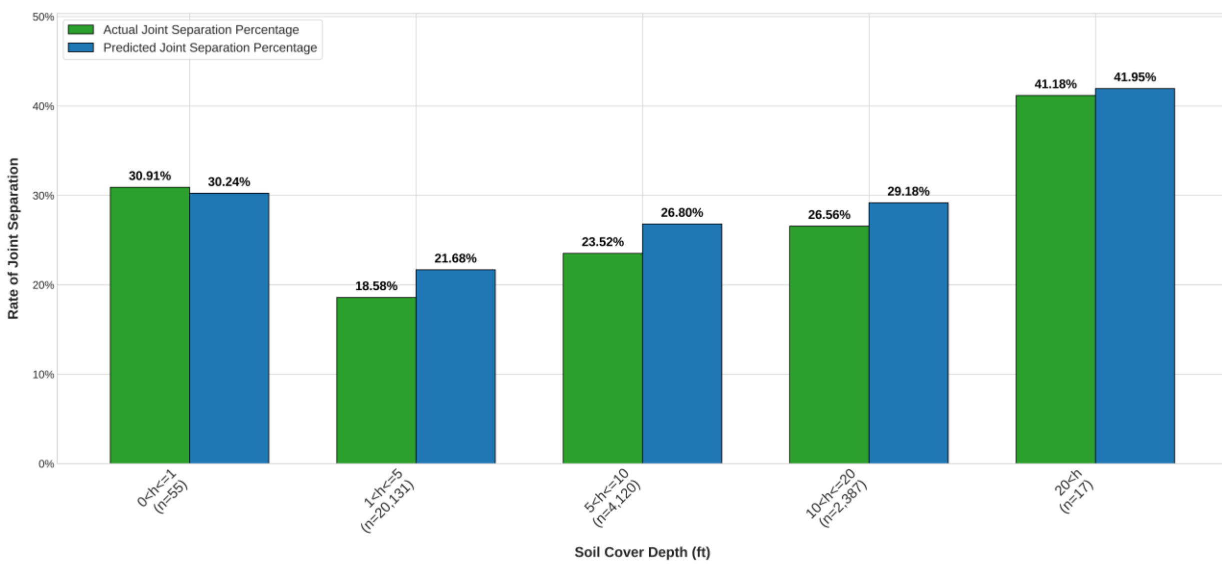


Figure 6 - Impact and count of Cover category on Joint separation

In Figure 7, the frequency of round concrete culverts within various inside width intervals is contrasted against the probabilities of joint separation, both observed and predicted. Figure 7 shows that in Minnesota, culverts with an inside width from 18 to 24 inches are found the most.

Although there is no specific trend that we can conclude on this figure, the two smallest culverts in terms of diameter have the least probability of joint separation and the width from 54 to 60 inches has the most rate of joint separation in round concrete culverts in Minnesota.

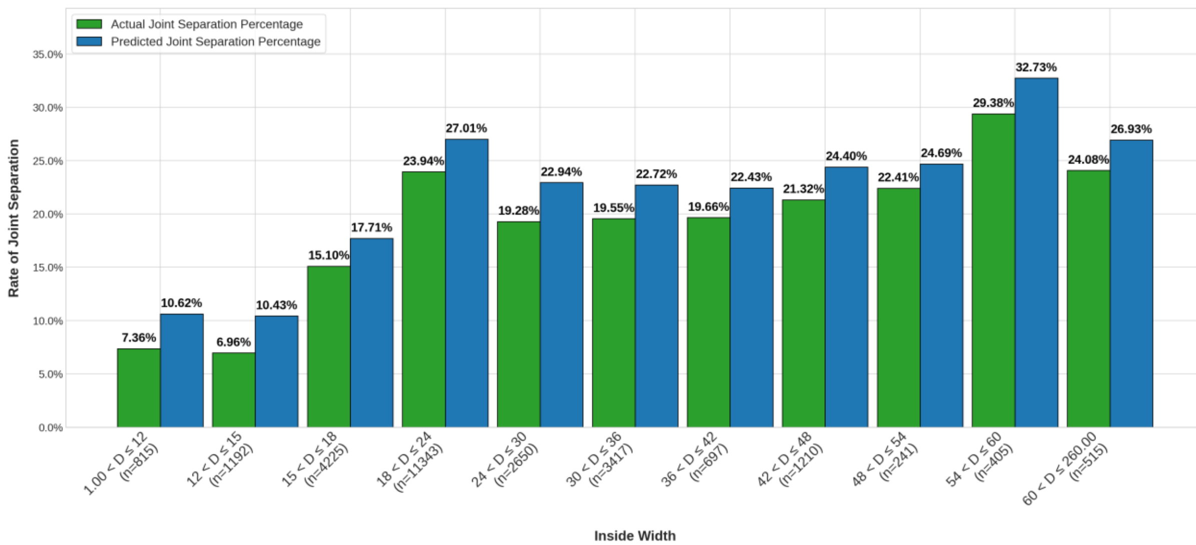
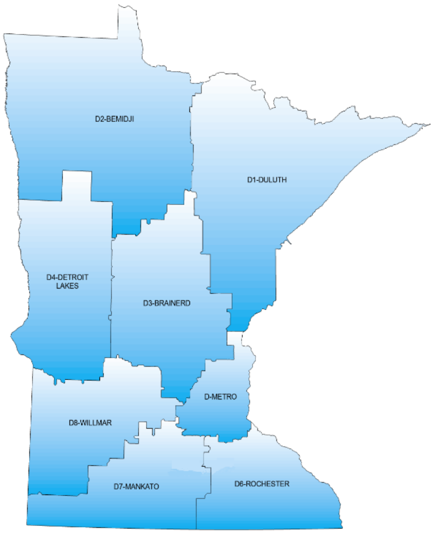
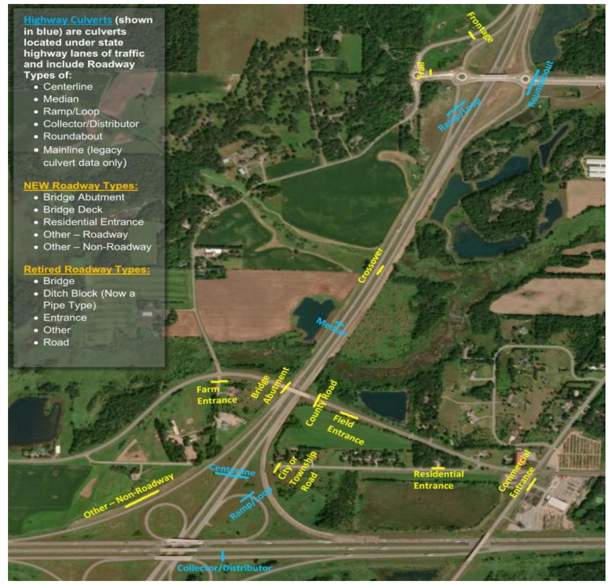


Figure 7 - Impact and count of Inside Width category on Joint separation

In Figure 8, there are locations of construction districts in Minnesota (a), different types of road that the random forest used (b). In Figure 8 (c), distribution of streams and rivers in Minnesota that can have an impact on joint separation and (d) the top counties with the highest rate of joint separation in concrete culverts have been shown.

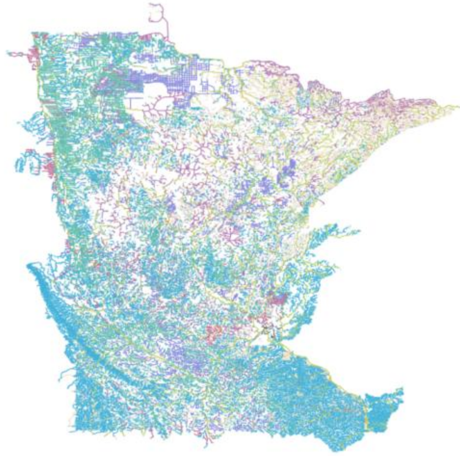


8 (a) - Locations of Districts of Minnesota



8 (b) - Description of roadway types from

HydInfra Inspection Manual (MnDOT, 2022)



8 (c) – Distribution of streams and river throughout Minnesota (Minnesota Department of Natural Resources, 2024)

8(d) - Minnesota counties and the ten highlighted counties that have the greatest joint separation

Figure 8 – Seeing Joint Separation from different perspectives

District 6 and 8 have higher rates of joint separation, showing something specific about these regions or the way of maintaining the culverts there, as shown in Figure 9. And, metro district has the least rates of joint separation maybe because of urban area, which can be good for future studies. By considering Figure 8 (c), it can be cautiously said that the higher rate of joint separation in district 6 and 8 are due to more streams and rivers in those areas. The predicted values represent the average predicted probability of joint separation produced by the model, not binary (yes/no) predictions. The higher predicted value in District 6 reflects a greater concentration of culverts with characteristics associated with elevated joint separation risk, such as older age and higher loading conditions, rather than false positives.

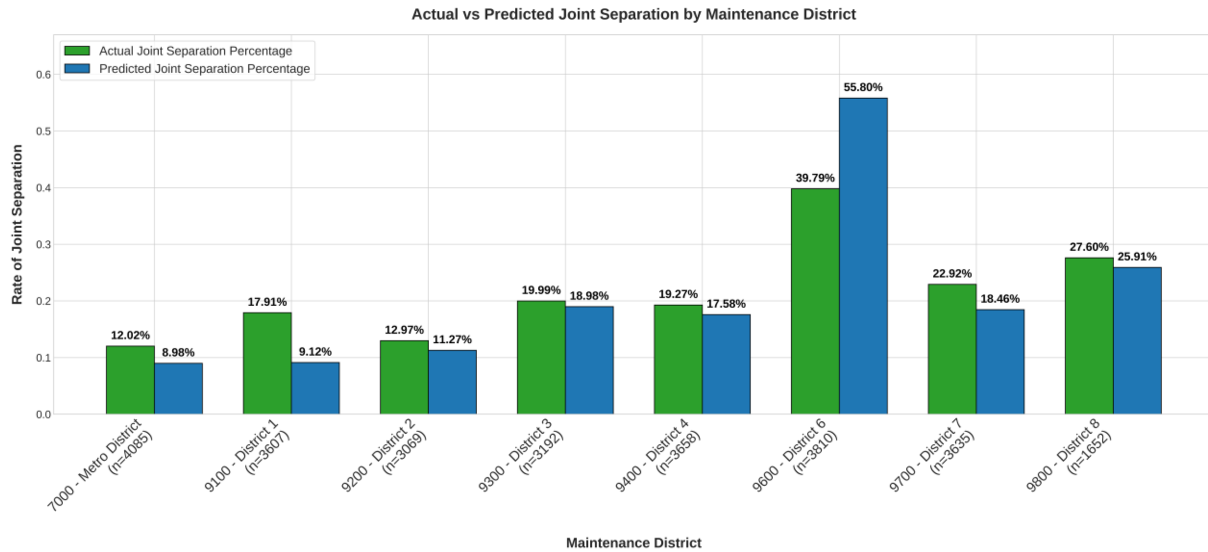


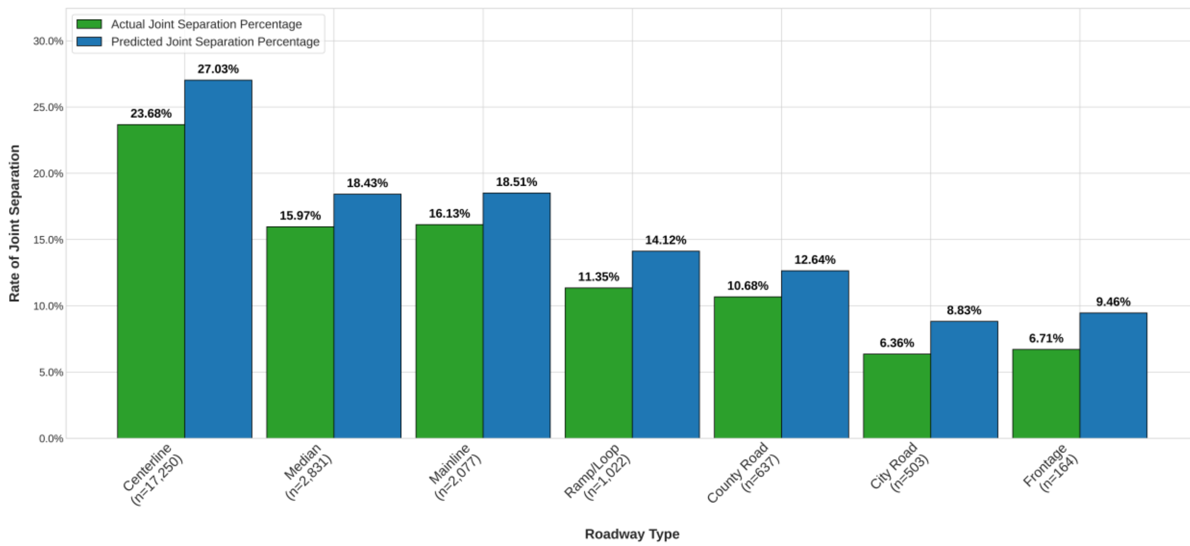
Figure 9 - Analysis of Joint Separation Probability and Culvert Distribution Across Maintenance Districts

Table 5 and Figure 8 (d) shows ten counties that have the greatest rates of joint separation. The interesting part is that, with the exception of Brown County in district 7, they are all within districts 6 and 8 which have the greatest chance of joint separation among the eight MnDOT districts.

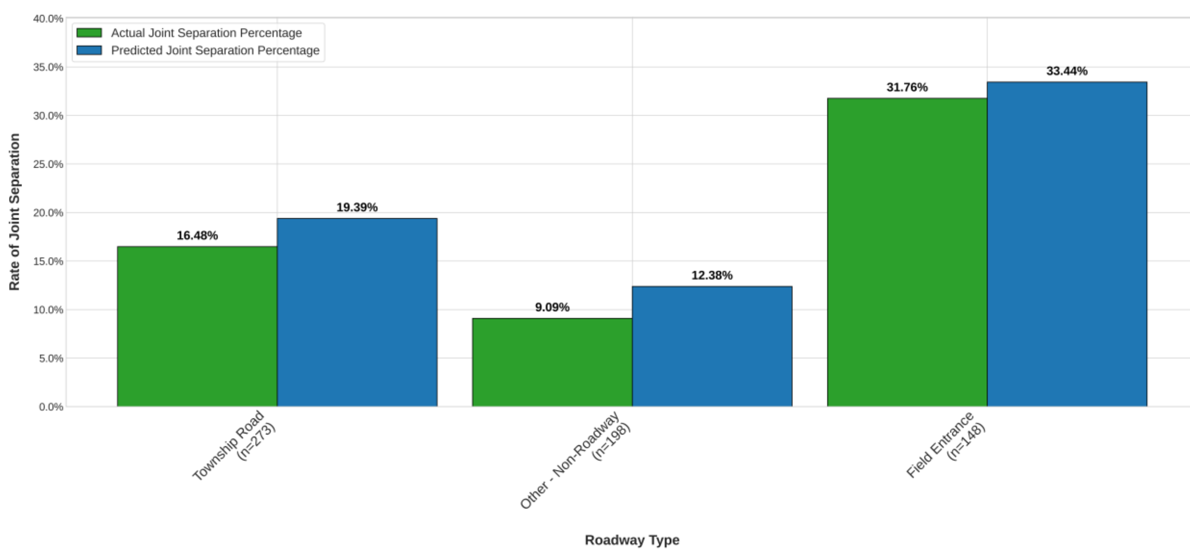
Table 5. The first ten counties with highest rates of joint separation

County	Total Count	Actual Rate of Joint Separation	Predicted Rate of Joint Separation
Lincoln	74	66.21%	68.91%
Lac Qui Parle	150	55.33%	52.67%
Freeborn	385	50.90%	53.50%
Rice	389	49.35%	48.07%
Houston	157	45.22%	42.03%
Fillmore	266	44.73%	43.98%
Chippewa	104	43.26%	44.23%
Pipestone	60	41.67%	40.00%
Brown	161	41.61%	41.61%
Goodhue	459	39.65%	37.69%

In Figure 10(a) and (b), there is joint separation rate in concrete culverts in terms of roadway type-culverts. It can be seen the first four categories of roadway types with the greatest number of culverts belong to highway types, including centerline, median, mainline and ramp/loop as shown in Figure 8(b). The four different categories are highly exposed to traffic loads. In these seven, centerline category has the most probability of joint separation, around 27%. But the most probability of joint separation in all categories belongs to field entrance, more than 33%, which is one of the main category Entrance Pipes (Residential Entrance, Field Entrance, Farm Entrance, Commercial Entrance). These classifications indicate how joint separation rate can be varies across roadway types, showing which culverts experience greater rate of joint separation and should be prioritized for inspection.



(a)



(b)

Figure 10 - Correlation Between Roadway Types, Joint Separation Probability, and Culvert Counts – (a) Group 1 (b) Group 2

3.2.3 Future Inspection

Our random forest model predicted some culverts with more than 70% of probability of joint separation, however they are not listed as the culverts with joint separation in database. So, for future inspection we suggest to inspect these culverts to prevent the culverts from more maintenance and as a result avoid additional expenses, Figure 11. These predictions do not confirm that these culverts are critical, but they detect the locations where joint separation may have been missed due to the incomplete negative labels in the database.

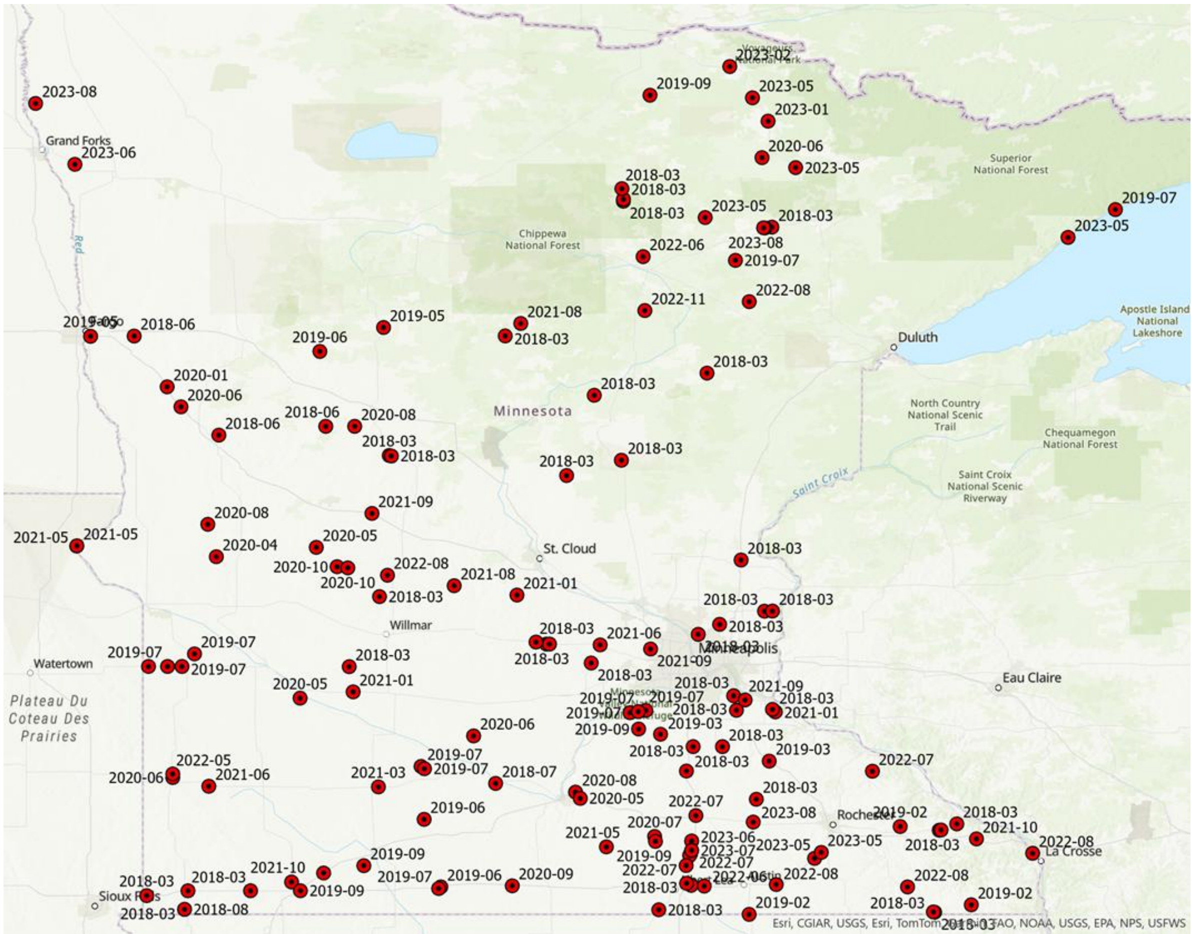


Figure 11 - Predicted High-Risk Round Concrete Culverts for Joint Separation in Minnesota with last inspection date

3.3 Summary and Conclusion

Feature importance results from the Random Forest model indicated conditions features have the most importance, followed by pipe geographic features, while geometric features have the least importance. The most important features are overall pipe conditions, infiltration, route ID, and county. These features did not always line up with those predicted to be important from simple examination of the database, where soil cover, maintenance district, and pipe ties were all found to have a correlation with joint separation. This discrepancy can be explained by overlapping or correlated features; for example, county contains effectively all the information of maintenance district but with more specificity. Database results show that joint separation is a multifaceted problem, and that no single variable stands out as the primary cause. Field investigations in chapter 4 will support this database work by gaining more specificity and detail on a select number of culverts that are predicted to have high or low likelihoods of joint separation.

Chapter 4: Field Inspection and Data Collection

Figure 12 shows eighty-seven concrete culverts were inspected throughout Minnesota during summer 2024. For inspection, concrete culverts were chosen based on routes from Duluth.

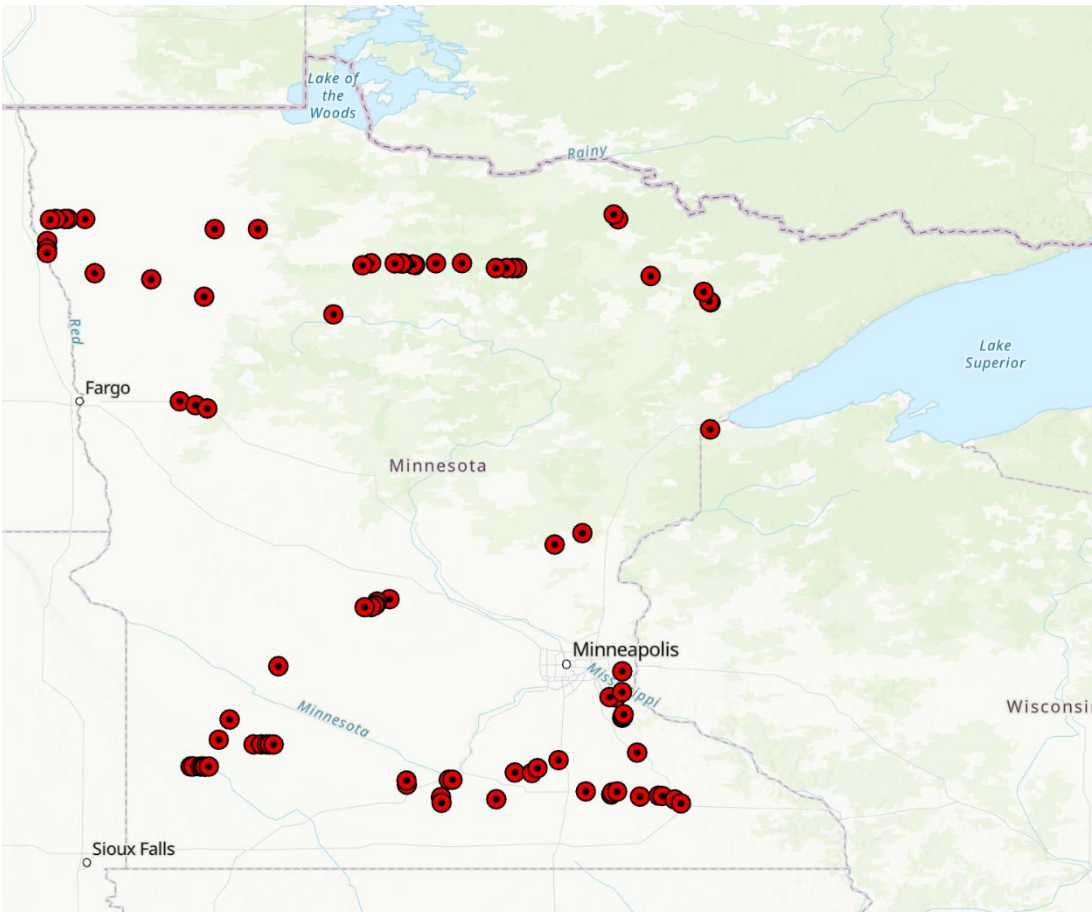


Figure 12 - Locations of inspected culverts

Table 6**Error! Reference source not found.** summarizes the culverts inspected from each district. During inspection, greater than or equal to one inch was considered as joint separation. If there was time, it would be interesting to check database to estimate the time and origin of joint separations; it is likely that some of these so-called "separations" were always present since culvert installation, while others developed over time. Furthermore, the rate of joint separation or repairs in Table 6 should not be understood as the severity of the problem in that district.

Table 6. Summary of inspected culverts

District	Culverts Inspected	Joint Separation	Joint Repairs
Metro	7	5	2
1	12	6	3
2	22	12	4
3	8	5	0
4	4	1	0
6	12	8	3
7	9	3	0
8	13	9	2
Total	87	49	14

4.1 Joint Separation Observations

1- or 2-inches distance between two adjacent segments of the pipe sometimes considered as joint separation that Figure 13 shows some examples of observed joint separation.

Often some types of distress accompanied with joint separation, though this was not always consistent. For instance, culvert 2251008 in District 8, shown in Figure 13(a), and many other similar culverts along Highway 68 had major infiltration at all joints even with only minor separations. In contrary to the culvert 2251008 Figure 13(a), culvert 2251023 in District 8 Figure 13(b) has larger separation in the first joint but no infiltration, despite being able to fit a hand through the separated joint and touch soil. High flow events can wash away any sign of infiltration, so lack of deposited material at a joint does not necessarily mean that no material had previously infiltrated through that joint.

Through inspection, however there are rare instances of pipe separation, most joint separations occur at joints without pipe ties. For instance, Culvert 2187828 in district 6 had approximately 2 in. of joint separation across a joint with external ties, as shown by the bolts on both sides of the joint in Figure 13(c). Joints with pipe ties rarely, if ever, had separation greater than 2 inches. If pipe ties were not present across all joints, but instead only the apron or the first several joints were tied, then joint separation was most likely to be observed in the first joint just after the end of the ties.

The greater than a few inches of joint separation, large joint separation, also have other damage around the joint. Usually, the inside "tongue" of the joint would be broken away in places, as shown in Figure 13(d) for Culvert 2196332 in the Metro District, often leading to infiltration or at least exposing the soil surrounding the culvert. It is not clear if this distress was due to an installation error, had developed because of large magnitudes of joint separation, or was the cause of large joint separation.

(a) Culvert 2251008, District 8: Some separation and infiltration at all joints

(b) Culvert 2251023, District 8: 3 in. separation at first joint

(c) Culvert 2187828, District 6: 2-in. separation on joint with exterior pipe ties

(d) Culvert 2196332, Metro District: 6-7 in. of separation, breakage of joint

Figure 13 - Typical examples of observed joint separation

4.2 Pipe Tie Types

For holding concrete culvert segment together, pipe ties are used. Pipe ties are installed after the installation of pipes to pull them together. During inspection, several works were observed. One of the main differences were observed is there are interior and exterior pipe ties. The exterior ties can be seen by the bolts and interior ties by the threaded roads on the inside of the pipe, as shown in Figure 14(a). From discussion with inspectors, the main advantage of exterior ties is in connecting the ties during installation of the pipe, as the worker does not need to install the ties within a confined space. The downside of such ties is that the condition of the tie, for example if it has rusted through, cannot be inspected. Interior ties, as shown in Figure 14(b), can be directly inspected. The position of pipe ties is roughly at the 2-o'clock and 10-o'clock positions. There are not always pipe ties on every segment of concrete culverts.

For instance, the first two or three segments of a pipe from each end are pulled together by pipe ties, "partially ties". For example, culvert 2207834 shown in Figure 14(a) have three sets of ties at each end, with the first between the apron and the first pipe segment and the last between the second and third pipe segments. As it can be seen, there is misalignment and separation right after the end of pipe ties.

(a) Culvert 2207834 in District 8, Exterior Ties

(b) Culvert 2183548 in District 2, Interior Ties

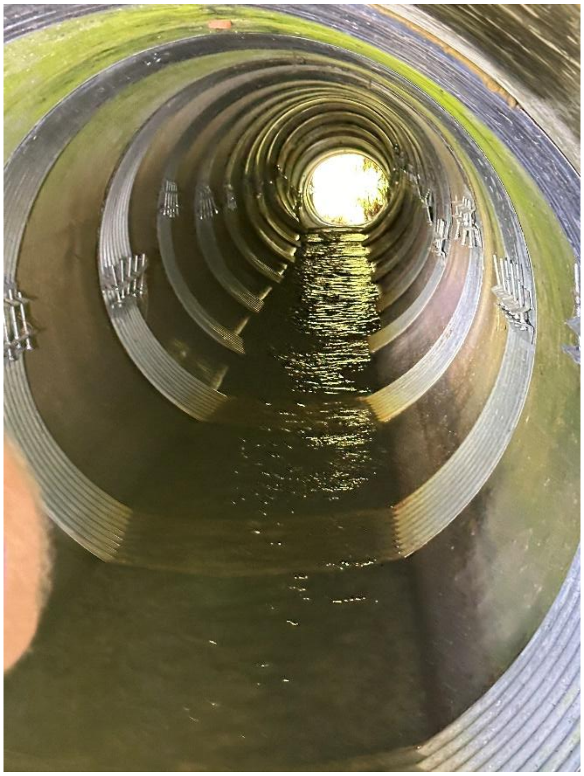
Figure 14 - Exterior versus interior pipe ties

4.3 Observed Repairs

Through inspection some joint repairs were observed in some concrete culverts, some examples are shown in Figure 15 (a) shows a pipe with an HDPE liner sealed with grout between the liner and the original concrete pipe. Similar repairs were observed using PVC liners. Several culverts had repairs to individual joints using internal bands, as shown in Figure 15(b) and Figure 15(c). Finally, some pipes had cured-in-place pipe (CIPP) liners. Yet others, not shown, simply had grouted or oakum-packed joints.

(a) Culvert 2231492, District 8: HDPE Liner

(b) Culvert 2225236, District 1: Elastomer Bands



(c) Culvert 2214249, District 7: Metal bands

(d) Culvert 2184508, District 6: CIPP Liner

Figure 15 - Example joint repairs on inspected culverts

4.4 Observed Installation

On September 24, 2025, the installation of two concrete arch pipes was observed on Highway 25 near Pierz. The pipes had already been aligned and pulled together before we arrived on site, so our observations were primarily on the filling and compaction of the fine-grained backfill material around the pipes. Figure 16 shows photos of one of the pipes at various stages of backfilling and installation. All joints on both pipes were filled with a mastic sealer, tied using two exterior pipe ties at the 10-o-clock and 2-o-clock positions, and wrapped with landscaping fabric. Joint gaps were typically 0.5 inches, as shown in Figure 16(b). Compaction near the pipe used a vibratory compactor attached to an excavator, shown in Figure 16(c), until one to two feet of material were placed upon the pipe, at which point compaction was done using a roller.

Compaction tests were taken by MnDOT personnel during the installation, and the embankment satisfied the requirements. However, there was no feasible way to ensure compaction in the haunch region directly below the pipes. Furthermore, construction vehicles like the roller and excavator directly loaded the pipes once a nominal one or two feet of fill was placed upon the pipe; it may be possible that these "traffic" live loads have more direct impacts on the pipe joints than traffic loading after installation was complete, particularly for pipes with high cover depths. Furthermore, compaction did not proceed along the entire length of the pipe simultaneously. The roadway area was placed and compacted first, but we were unable to observe the placement of fill and compaction around the ends of the pipes and about the apron, which occurred after we left the site. Compaction of soil first in the middle of the pipe followed by compaction at the ends could result in an overall outward motion of the embankment, pulling particularly at the pipe ends.

(a) Pipe prior to backfill

(b) Typical joint with mastic seal

(c) Compaction of backfill

(d) Fine-granular bedding around pipe

Figure 16 - Installation of concrete arch pipe on Highway 25 near Pierz

Chapter 5: Numerical Analysis Using Finite Element Method

5.1 Methodology

By using ANSYS (2022) to perform parametric modeling, finite element models were developed. The parameters include soil cover depth, pipe diameter, soil stiffness, subgrade stiffness; for soil cover depth, 4 ft, 6 ft and 8 ft were used. For Pipe diameters, 12 , 18, 24, 36, 48, 54, 60 and 72 inches were used and the soil stiffnesses and subgrade stiffnesses were mentioned in Table 7 and Table 8. Two types of models were performed one is continuous pipes, meaning a fully tied culvert system, another is discrete pipes, meaning pipe joints are unbonded. In both cases, material properties given in Table 5 were used. The models were performed separately under embankment and culvert self-weight or under 50-kip (220-kN) design tandem load. Figure 17; according to AASHTO LRFD Bridge Design Specifications, the design tandem is defined as:

Two axles, each with load = 25 kip (≈ 111 kN)

Axle spacing (longitudinal) = 4 ft (1.22 m)

Wheels on each axle are spaced 6 ft (1.83 m) apart transversely

So the total tandem load is:

$$2 \times 25 \text{ kip} = 50 \text{ kip} \approx 220 \text{ kN}$$

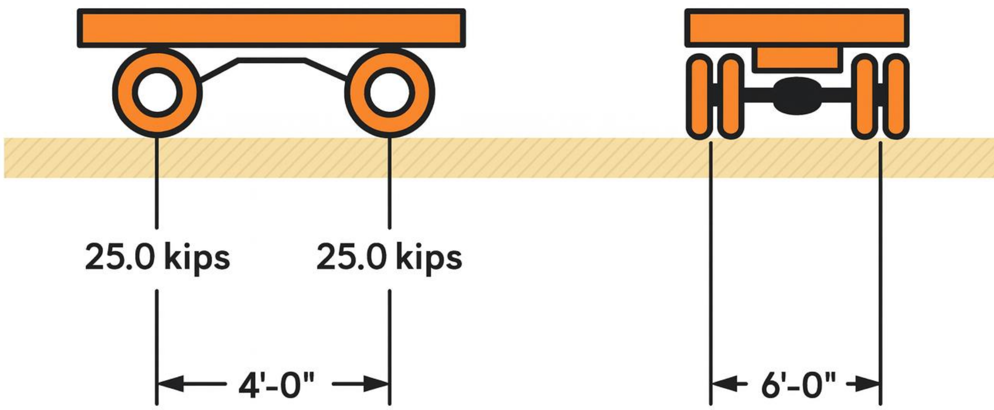


Figure 17 – Design Tandem load (AASHTO)

Figure 18 presents a half cross-section of the 6-ft cover model, with the locations of the boundary conditions highlighted by red arrows. These faces are fully constrained, with zero displacement prescribed in all translational degrees of freedom.

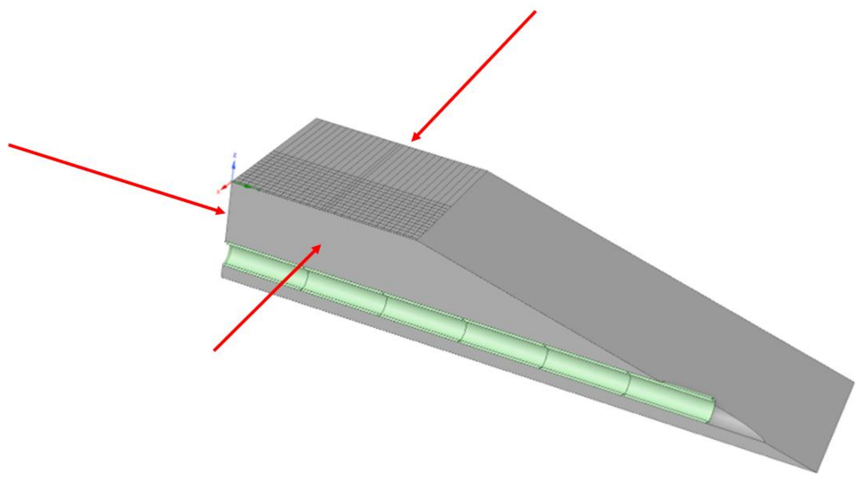


Figure 18 - Cross section of 6-ft cover model in ANSYS

Table 7. Mechanical properties for Ansys model (Poor embankment stiffness)

Concrete Culvert Material	
Density, lb/ft^3 [kg/m^3]	144.83 [2,320]
Young's Modulus, ksi [MPa]	3,916 [27,000]
Poisson's Ratio	0.2
Soil Material	
Dry Density, lb/ft^3 [kg/m^3]	125 [2,000]
Young's Modulus, ksi [MPa]	2.9 [20]
Poisson's Ratio	0.3

Table 8. Mechanical properties for Ansys model (High embankment stiffness)

Concrete Culvert Material	
Density, lb/ft^3 [kg/m^3]	144.83 [2,320]
Young's Modulus, ksi [MPa]	3,916 [27,000]
Poisson's Ratio	0.2
Soil Material	
Dry Density, lb/ft^3 [kg/m^3]	125 [2,000]
Young's Modulus, ksi [MPa]	29 [200]
Poisson's Ratio	0.3

Table 9. Number of culvert segment for each soil cover depth

Soil cover depth	Number of culvert Segments	Length of concrete culvert
2-ft	3	24
4-ft	4	32
6-ft	5	40
8-ft	6	48
16-ft	10	80

In this study, it has been considered 2.9 ksi (20 MPa) as poor embankment stiffness and 29 ksi (200 MPa) as high embankment stiffness. Also, it has been considered 100 lb/in^3 (27.1 MPa/m) as poor subgrade stiffness, 500 lb/in^3 (136 MPa/m) as good subgrade and 1000 lb/in^3 (271 MPa/m) as excellent subgrade.

5.1.1 Contacts

Bonded contacts in ANSYS between soil and concrete culverts and between each segment of concrete culverts have been used for continuous model. For discrete model, frictional contact with friction coefficient of 0.5 and normal stiffness factor of 0.2 for contacts between soil and concrete culverts has been used. In discrete model, no contact determined between each segment of concrete culvert. No contacts means pipe joints unbonded, representing a system with no ties.

5.1.2 Boundary Conditions

The two lateral faces of the soil model have been supported in X direction. Also, the base support of the soil was considered elastic with different stiffnesses.

5.1.3 Mesh

WThe mesh of full-model in Figure 19 has been showed. Using 10-node tetrahedral elements, the soil and culvert segments were all meshed. The soil and culvert segments were all meshed using second-order 10-node tetrahedral elements, using 4 inches mesh size.

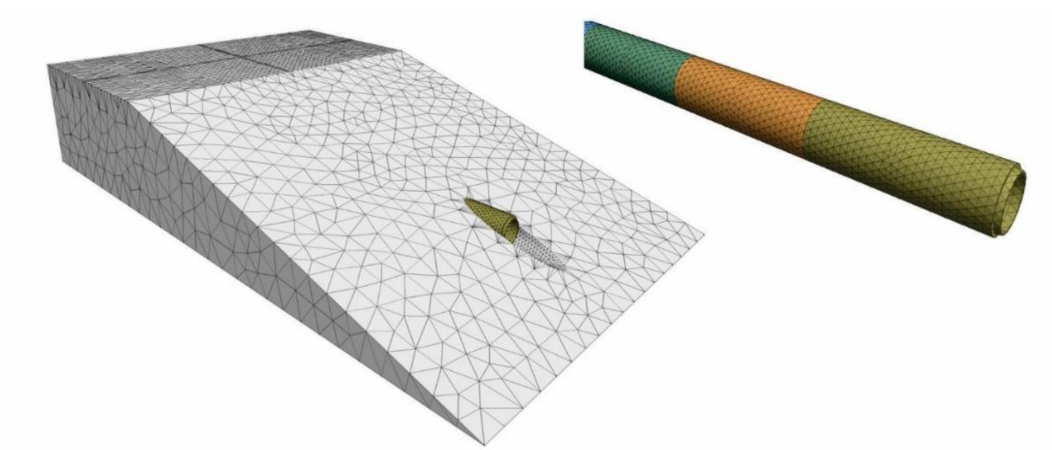


Figure 19 - Mesh for finite element model of (a) embankment and (b) culvert segments

Six different soil cover depths (2, 4, 6, 8, and 16 ft) and eight different pipe diameters (12, 18, 24, 36, 48, 54, 60, and 72 in) were modeled using ANSYS finite element software. All combinations of cover depth and pipe diameter were analyzed to investigate the structural response of concrete culverts under the specified loading conditions.

5.2 Results and Discussion

5.2.1 Continuous Pipe Finite Element Model Results

Applying the combination of the self-weight and design tandem, the computation of continuous pipe model has been done in. Figure 20 shows the sample results for 4-ft cover model with soil modulus equal to 29 ksi (200 MPa) and soil subgrade stiffness equal to 1000 lb/in^3 (271 MPa/m), indicating the horizontal displacement throughout the embankment for combined self-weight and design tandem loads; contour colors show the horizontal displacement, and the wireframe shows the initial embankment position. Displacements are magnified for visualization purposes.

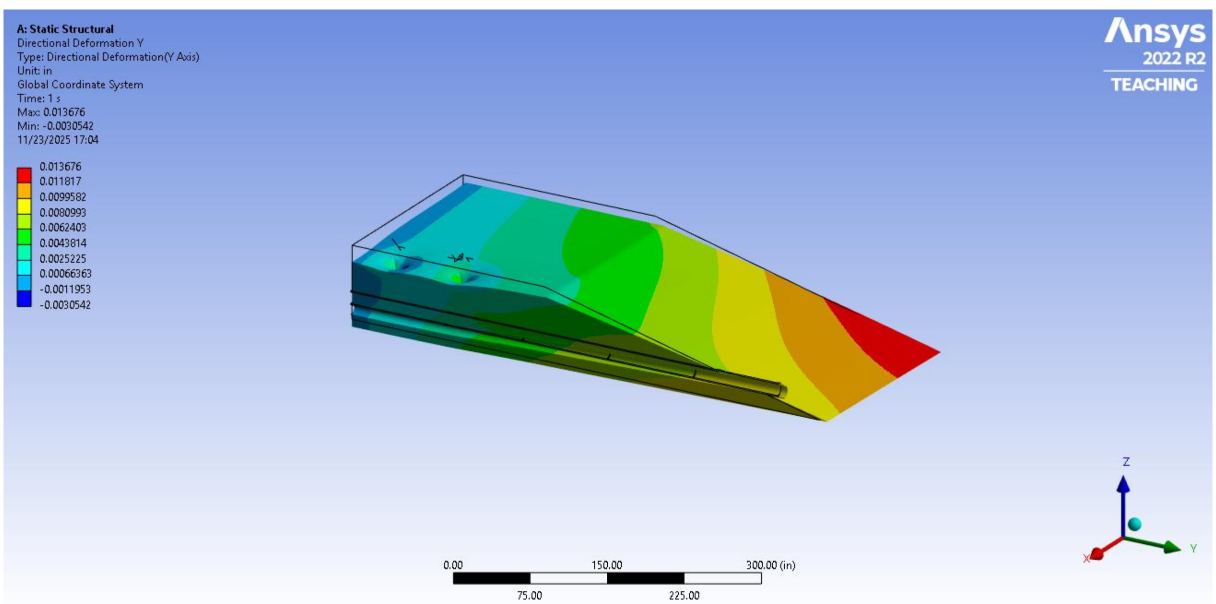
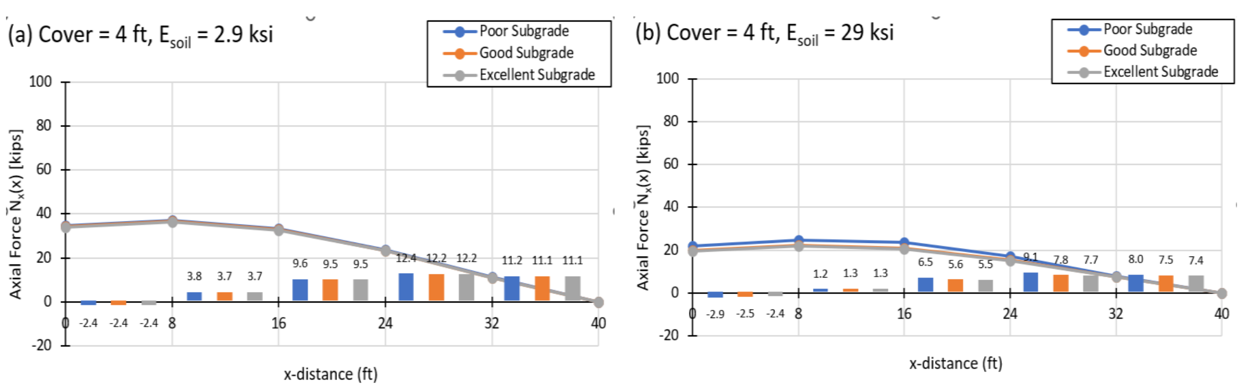


Figure 20 - Displaced shape of 4-ft cover embankment under self-weight plus design tandem load; color contours correspond to horizontal displacement in inches

Axial force refers to the internal force acting along the axis of the culvert segment (usually in tension or compression). The net separation force represents the difference in axial forces between the two ends of a single culvert segment.

Figure 20 presents axial forces (lines) and net separation forces (bars) under soil embankment load for 4-ft, 6-ft, and 8-ft soil cover depths, with blue, orange, and grey representing subgrade stiffness values of 100 lb/in³ (27.1 MPa/m), 500 lb/in³ (136 MPa/m), and 1000 lb/in³ (271 MPa/m), respectively; the results show that increasing soil embankment stiffness has a major effect on axial forces, reducing them by about half when stiffness increases tenfold from 2.9 ksi to 29 ksi, while also reducing net separation. Figure 21 shows the same parameters under traffic loads and the same soil cover depths and subgrade stiffness values, demonstrating that increasing the soil embankment stiffness still reduces axial forces, though only slightly, while slightly increasing net separation values.



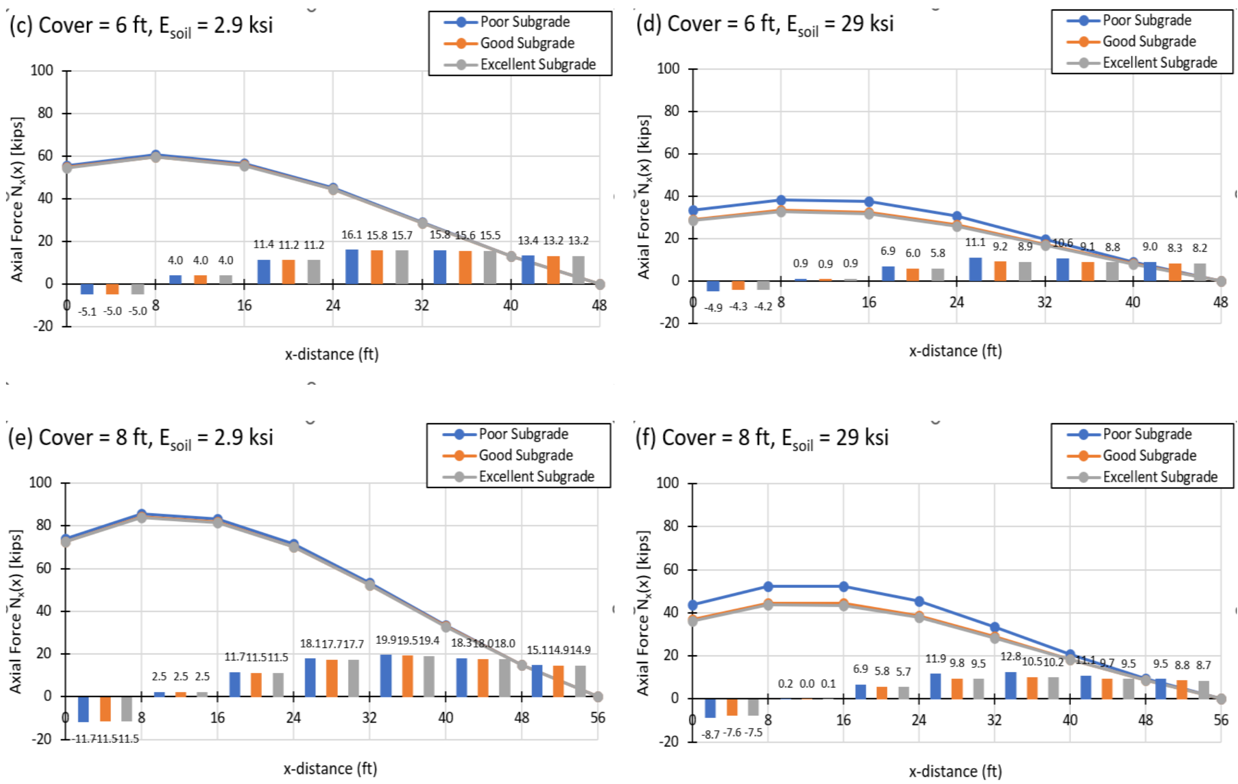
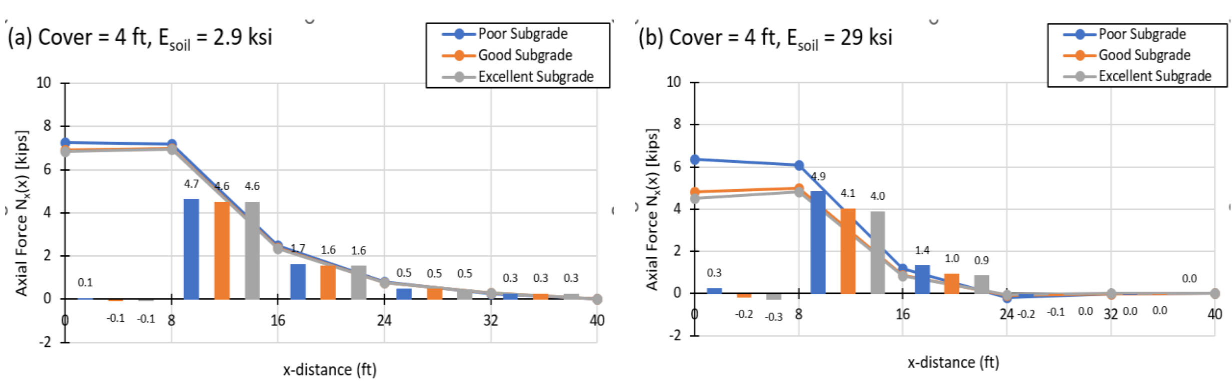


Figure 21 - Diagram of axial force (lines) along the culvert length for the finite element models under just soil embankment load. Bars also show the net separation forces values on each culvert segment in kips



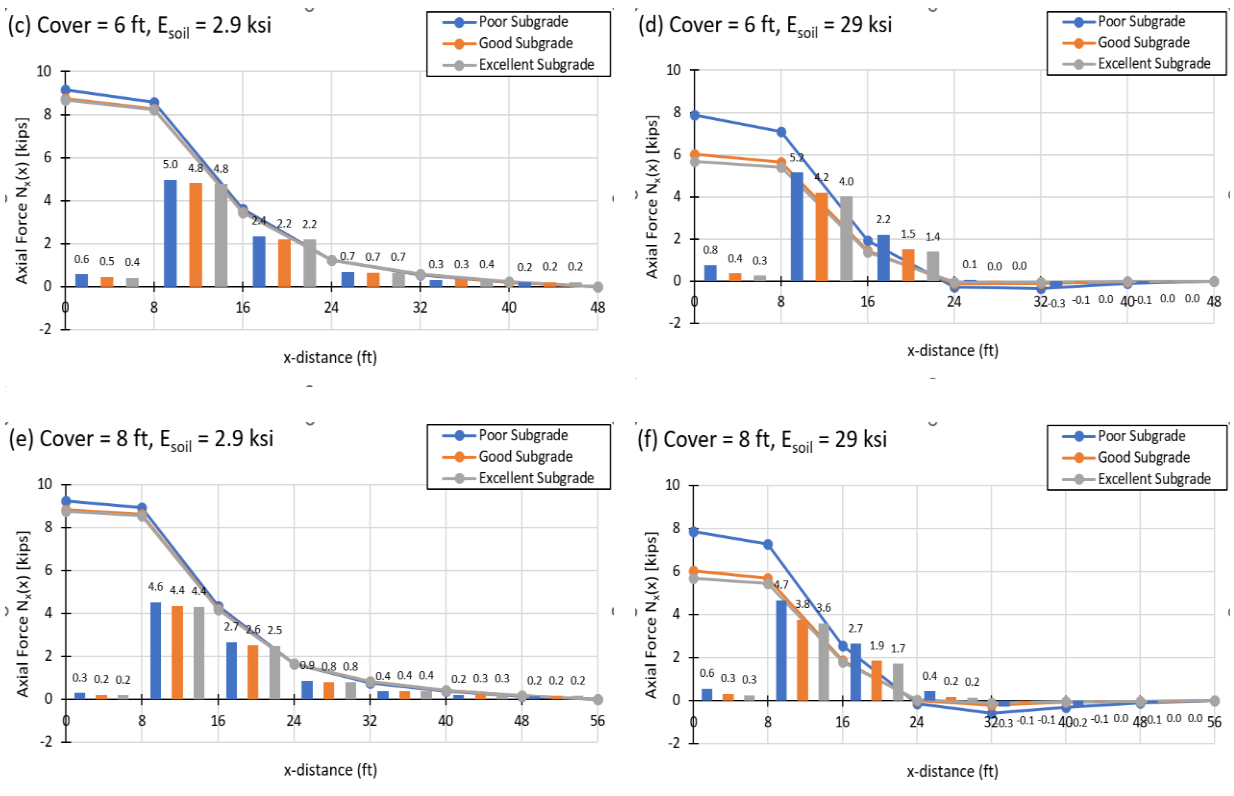


Figure 22 - Diagram of axial force (lines) along the culvert length for the finite element models under just traffic load. Bars also show the net separation forces values on each culvert segment in kips

5.2.2 Discrete Segment Model Results

In this section, all culverts were modeled using unbonded contact conditions between the culvert segments. For the 2-ft soil cover depth, the culvert consisted of three concrete segments, each with a length of 8 ft, resulting in a total culvert length of 24 ft. Accordingly, four joint locations were considered for joint separation analysis. For a soil cover depth of 4 ft, five joint locations were analyzed. For 6 ft soil cover depth, six joint locations were considered, while for 8 ft and 16 ft soil cover depths, seven and eleven joint locations were analyzed, respectively. The following figures illustrate the total culvert length and the locations of the joints for each soil cover depth.

For joint opening for discrete segments, it has been used of Table 8 mechanical properties for below results (High embankment stiffness). Figure 23 (b) to Figure 25 (b) shows joint opening along the length of culverts for different pipe diameters under combined loads; soil embankment load and traffic load. This happens just in model of 2-ft soil cover depth but for other soil cover depth, 4-ft, 6-ft, 8-ft, 16-ft, the maximum joint opening happens at the joint between second segment and third segment as you can see from the Figure 24(b) to Figure 26(b). There is a slight change in joint opening when traffic load applies, for example joint opening between the first segment and second segment shifts from 0.0039 inches to 0.0050 inches in culverts with diameter of 50 inches when there is 2 ft soil cover above the culverts; Figure 23 (b)

At 2-ft cover, joint separation happened mainly as pipe diameter increases; Larger diameters indicate greater joint separation under both load cases. Adding traffic load to embankment self-weight increases the joint separation slightly, which peaks under the traffic load specifically and decreases towards the length of the culvert. Therefore, for shallow cover although traffic load acting as not significant amplifier of joint separation.

In general, the larger culvert, the greater joint separation under soil embankment load. It can be seen that this trend is consistent across all studied cover depths and soil stiffnesses, noting the geometric importance of culvert in joint separation. So, the maintenance of larger culverts with greater soil cover depth should be prioritized over culverts with different diameters and cover depths.

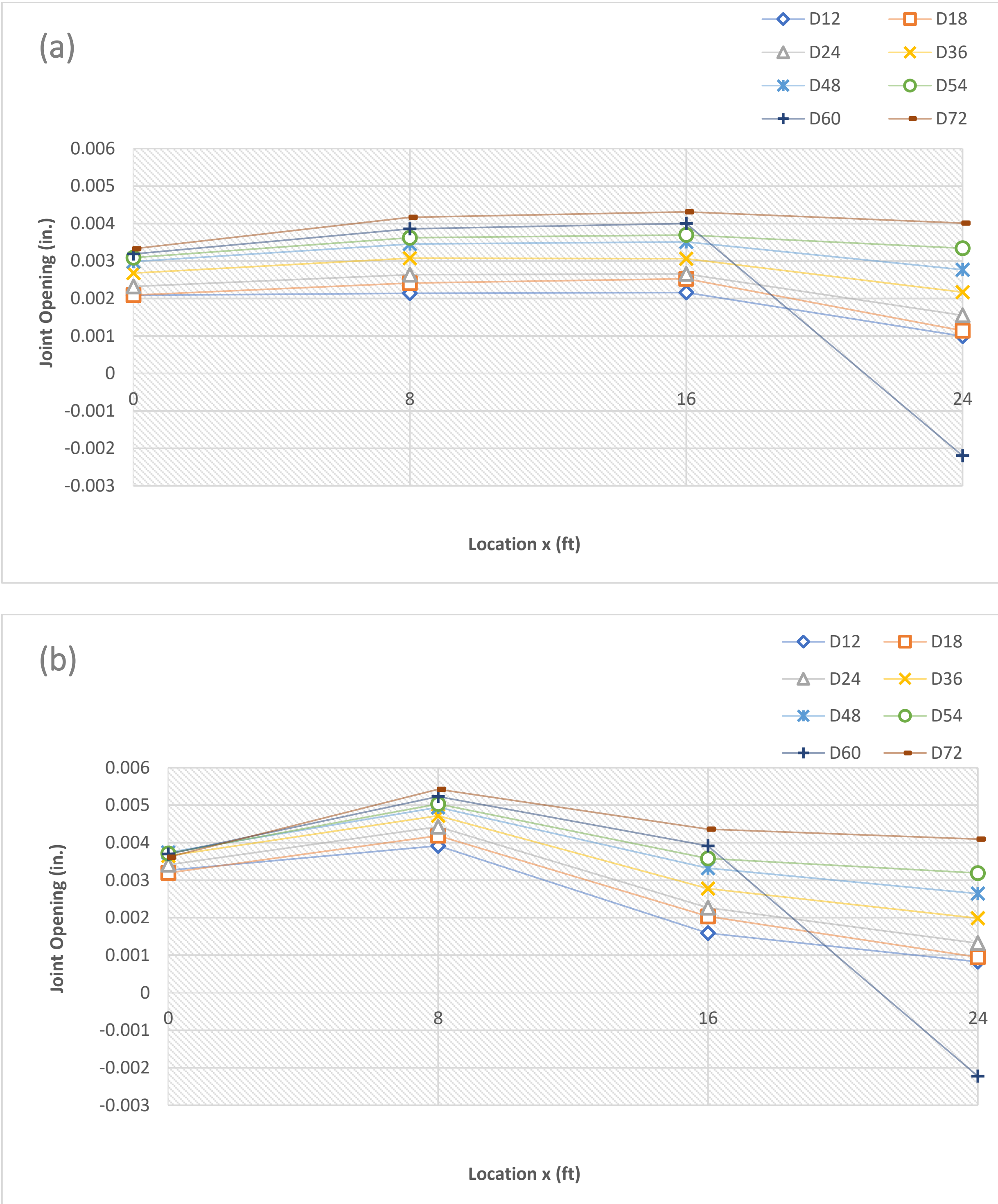
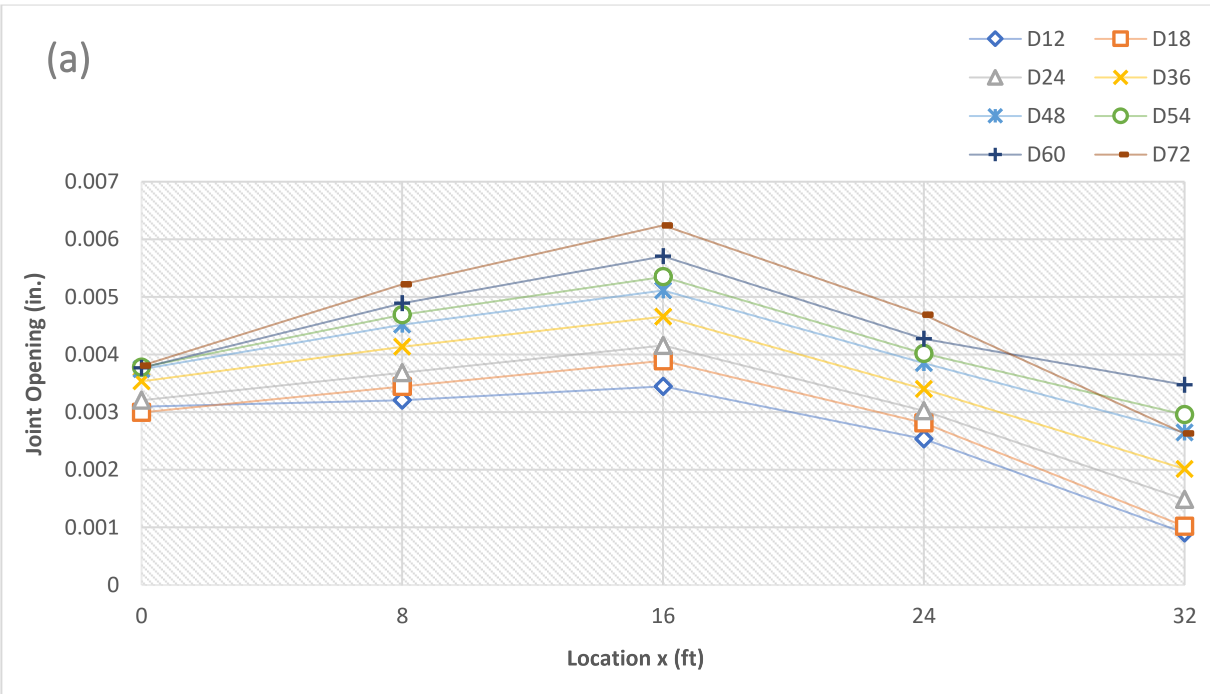


Figure 23 - joint opening for different diameters for soil cover depth of 2 ft (a) embankment load (b) combined traffic load and embankment load

In Figure 24, 4-ft soil cover depth, there is specific trend in joint openings in each joint between the first segment and second segment and so on. Therefore, by increasing the diameter of concrete culvert, the amount of joint opening increases. And the maximum joint opening happens at the joint 2 from left when just embankment load applies, but by applying traffic load, the maximum joint opening shift from the second joint from the left to first joint.



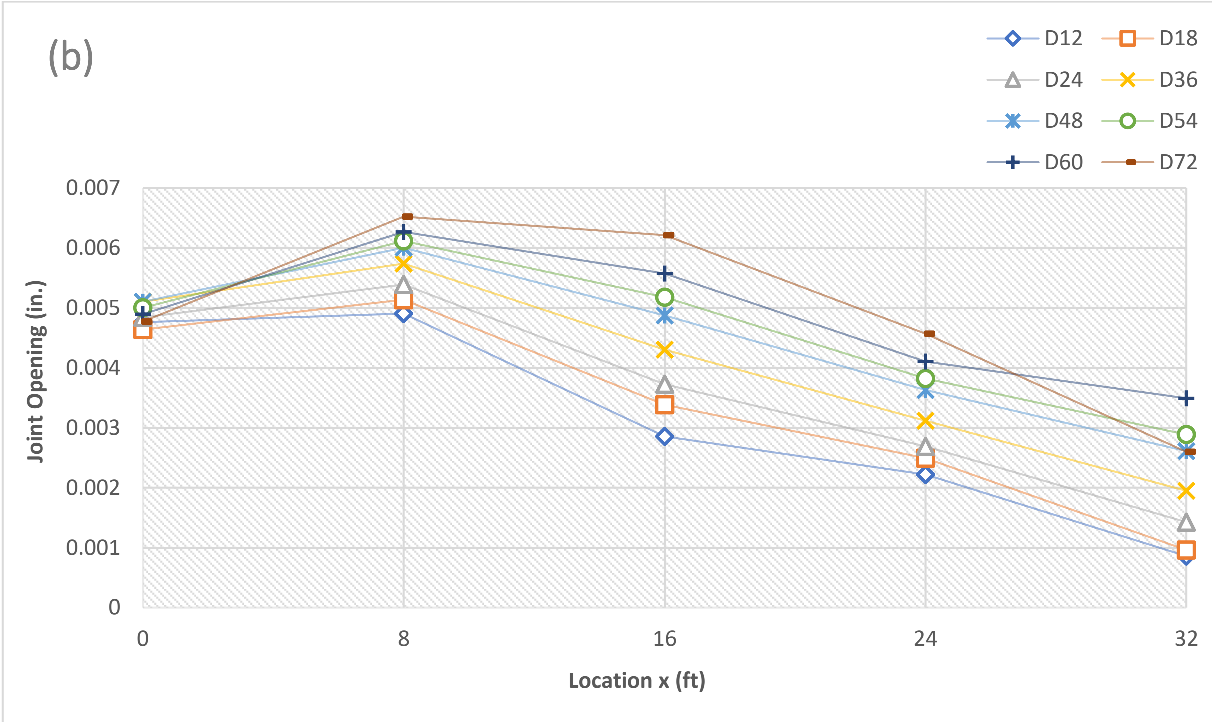
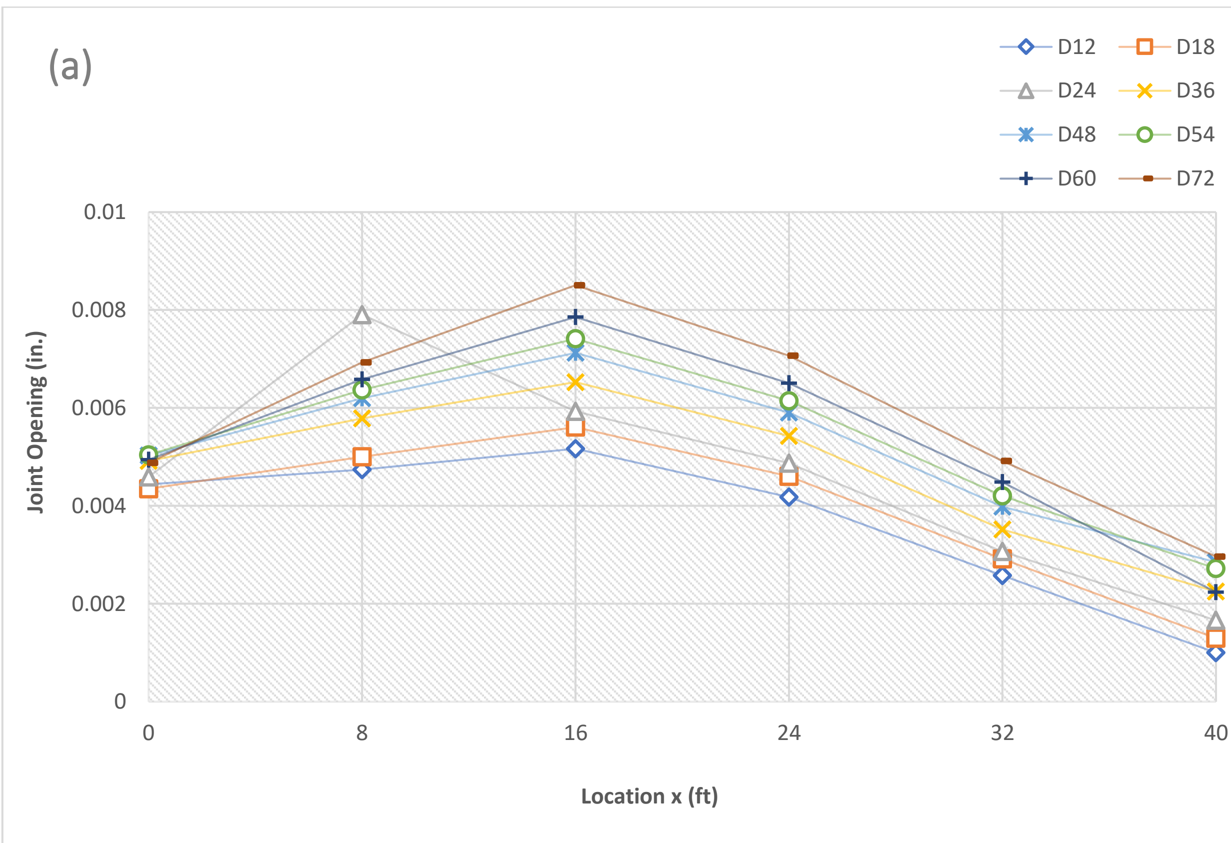


Figure 24 - joint opening for different diameters for soil cover depth of 4 ft (a) embankment load (b) combined traffic load and embankment load

For 6-ft, 8-ft, and 16-ft soil cover depths, the results indicate a strong pattern in joint separation as culvert diameter increases. In Figures 25 and 26 (6-ft and 8-ft covers), increasing the pipe diameter generate larger joint openings across all joints. However, for both soil covers, the position of the maximum joint opening does not change under traffic loading, which means joint 2 from the left always shows the greatest opening. Traffic load has an impact on the magnitude of joint opening but has not impact on the position of the maximum joint opening.

Figure 27 (16-ft cover) shows the same trend; larger culvert diameters can lead to greater joint openings under both only embankment load and combined loads, embankment load plus traffic loads. Excluding joint 1, joint from 2 the left experiences the maximum amount of joint opening. Traffic load introduces a small increase in opening magnitude but does not alter the joint at which the maximum occurs.

In general, for all soil cover depths, increasing culvert diameter increases amount of joint opening, while joint 2 from the left consistently indicates the maximum opening regardless of traffic load.



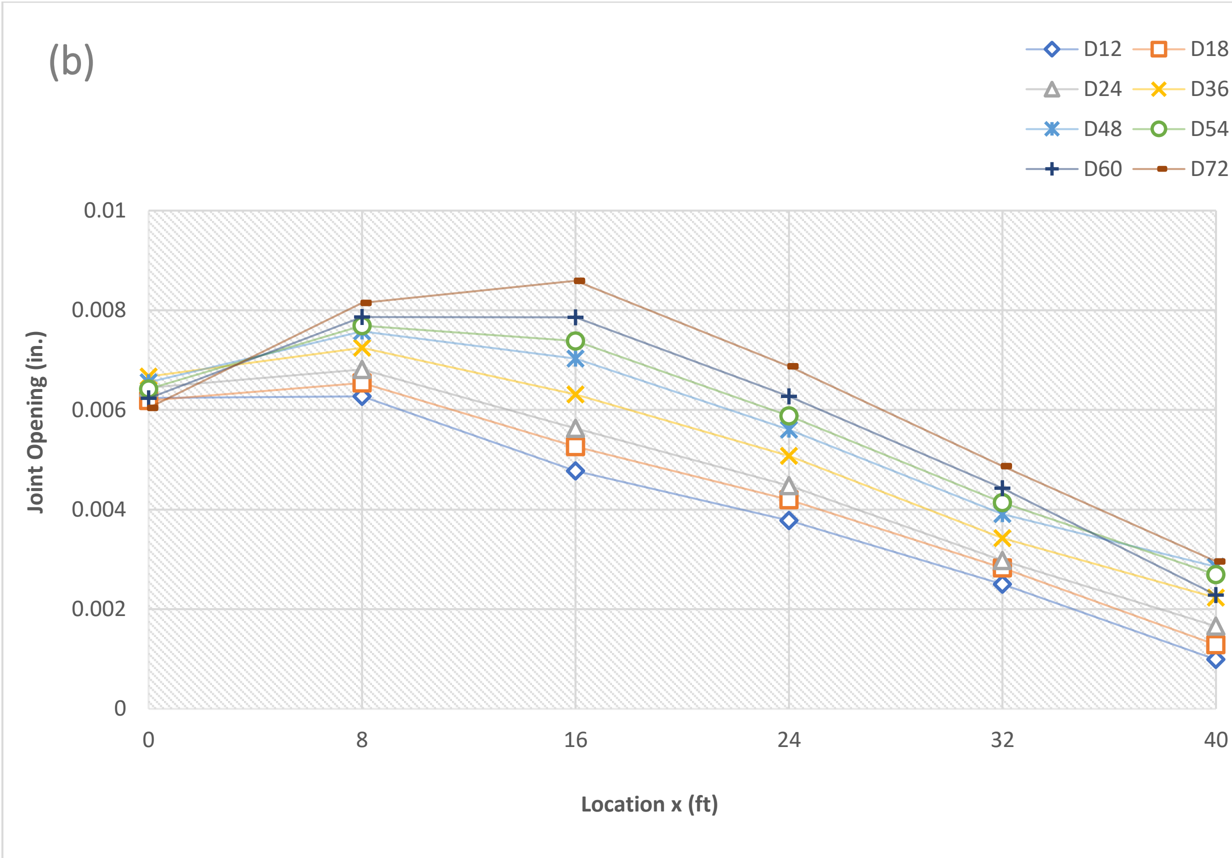
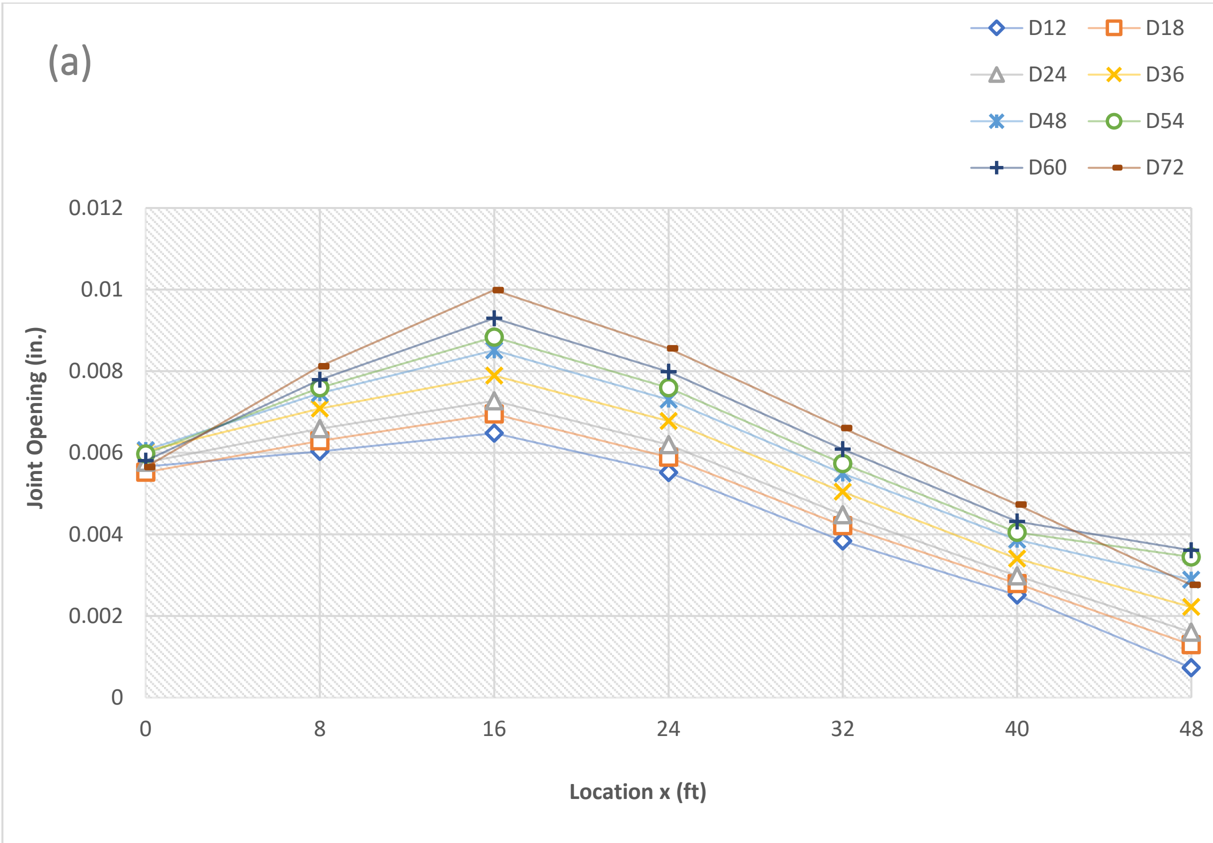


Figure 25 - joint opening for different diameters for soil cover depth of 6 ft (a) embankment load (b) combined traffic load and embankment load


(a)
D12
D18
D24
D36
D48
D54
D60
D72
Joint Opening (in.)
0.012
0.01
0.008
0.006
0.004
0.002
0
0
8
16
24
32
40
48
Location x (ft)

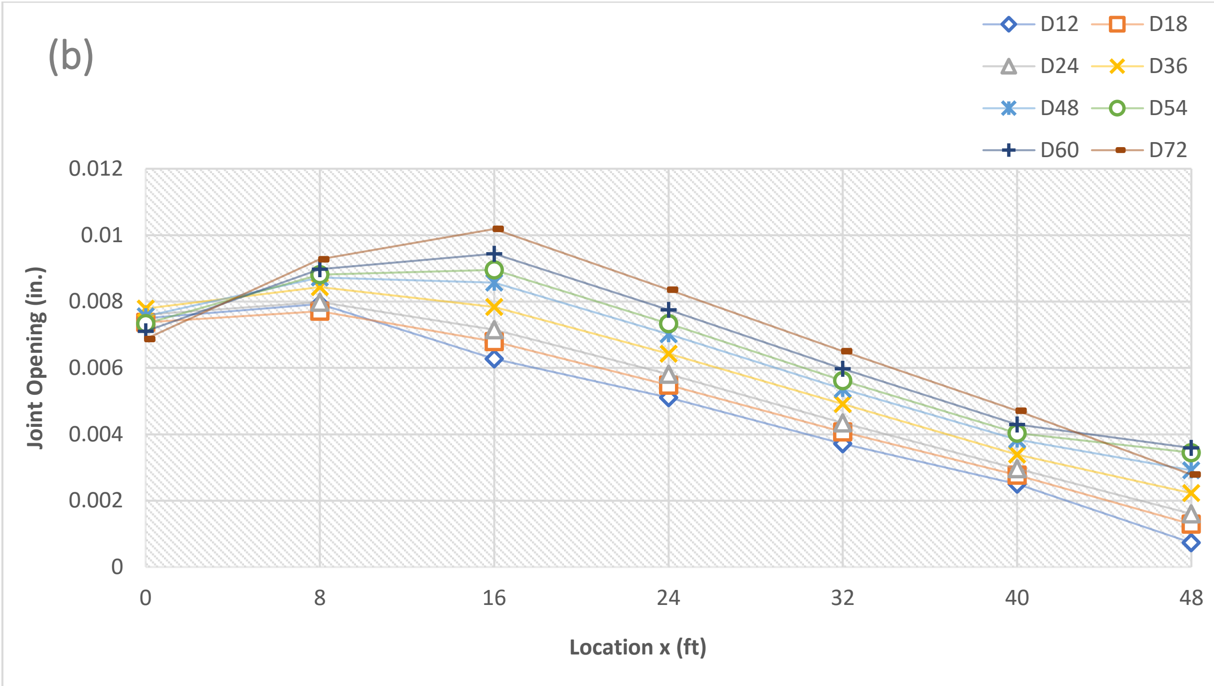


Figure 26 - joint opening for different diameters for soil cover depth of 8 ft (a) embankment load (b) combined traffic load and embankment load

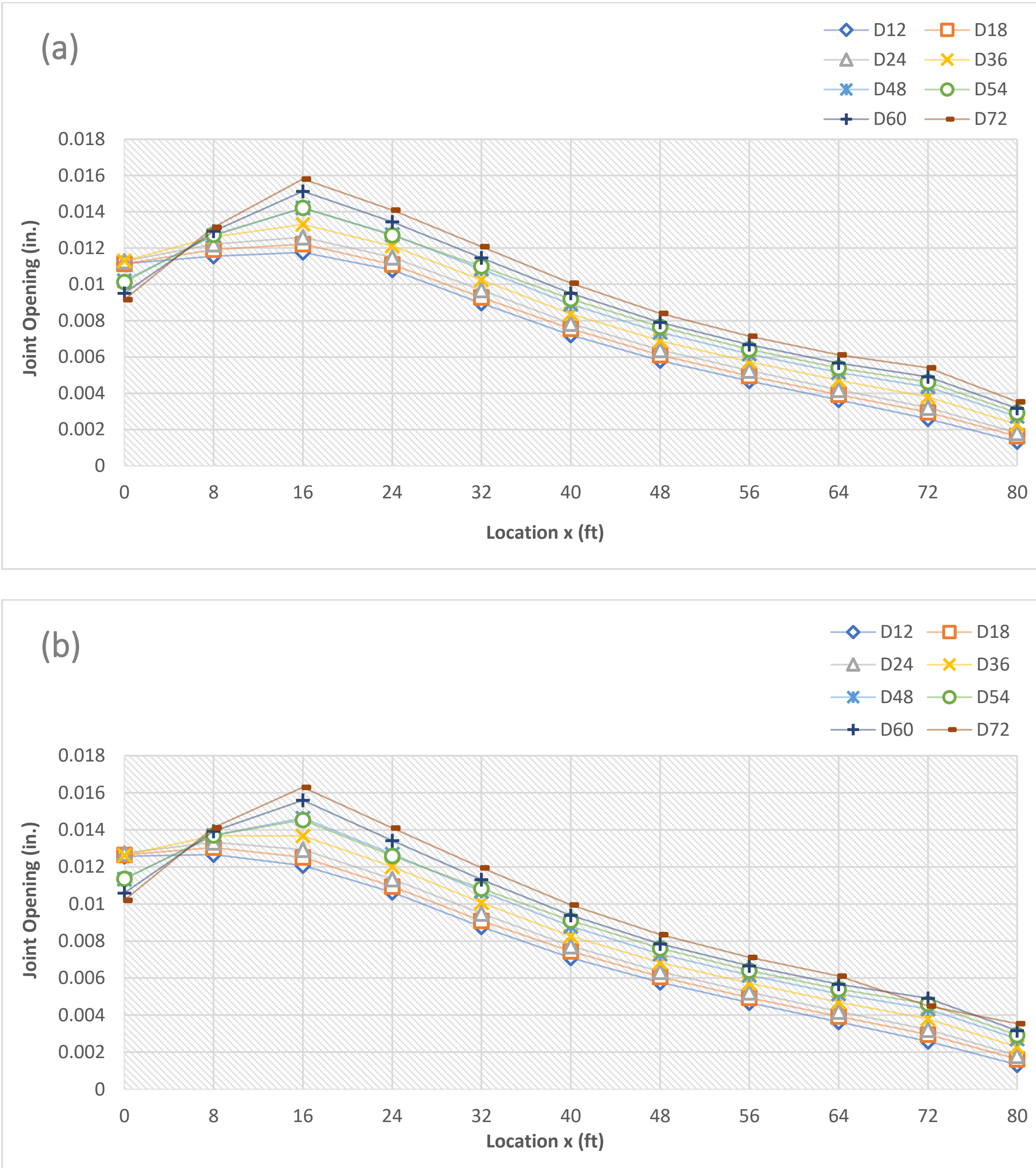


Figure 27 - joint opening for different diameters for soil cover depth of 16 ft (a) embankment load (b) combined traffic load and embankment load

Figure 28shows the joint opening behavior in one specific diameter 36-in pipe as an example for different soil cover depth, and the trend of this figure happens in all other pipe diameters too.

This is for diameter of 36 inches, one of the common concrete culverts in Minnesota. For this diameter, these values are obtained; the same conclusion applies to other diameters as well. As it can be seen, the most of the joint opening is because of embankment load not traffic load and the maximum joint opening happens when we have the more soil above the culverts.

This indicates that the addition of traffic loading, even if small in comparison with the embankment load, can still increase joint separation about 0.001 inch

In general, the figure shows that both soil cover depth and traffic loading contribute to higher joint separation potential, which is critical for assessing the durability and serviceability of concrete culverts.

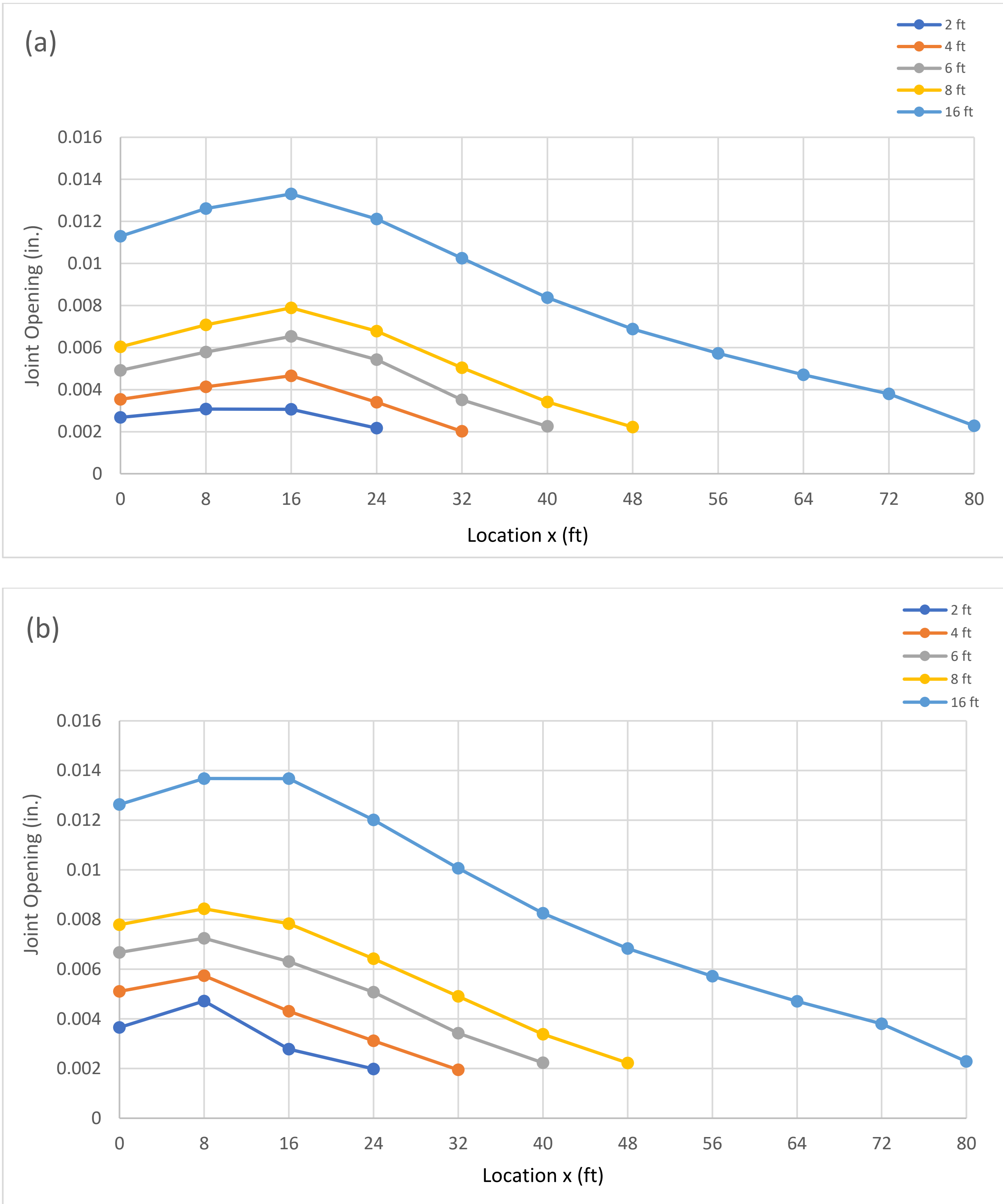


Figure 28 - joint opening for 36 inches diameter for different soil cover depth (a) embankment load (b) combined traffic load and embankment load

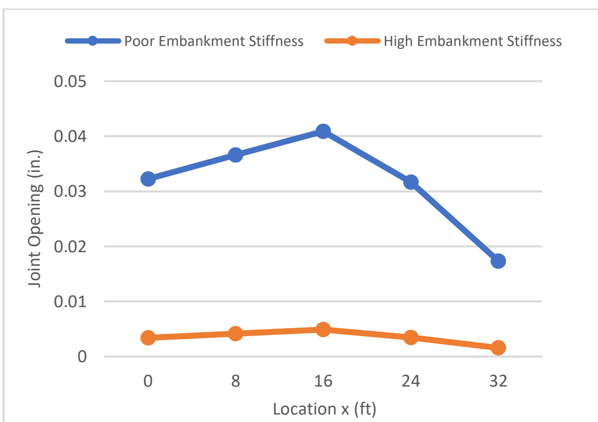
5.2.2.1 Joint Openings for constant subgrade stiffnesses and different soil stiffnesses for under Combined Traffic and Embankment Loads and just embankment load

In Figure 29 to Figure 31, difference between joint opening under embankment load and joint opening under traffic load and embankment load in 24-inch culverts for three different subgrade stiffnesses, poor subgrade with 100 lb/in^3 (27.1 MPa/m), good subgrade with 500 lb/in^3 (136 MPa/m) and excellent subgrade with 1000 lb/in^3 (271 MPa/m) have been shown. As it can be seen, there is not much difference when traffic load has been added to soil embankment load, because of significant effect of soil embankment load, it was placed in advance, and the impact of traffic load is minor. Also, Figure 29 (c) to Figure 31 (c) show only the joint opening under traffic load. In some cases, and locations, negative values indicate that the traffic load can close the joint opening that was caused by the soil embankment load.

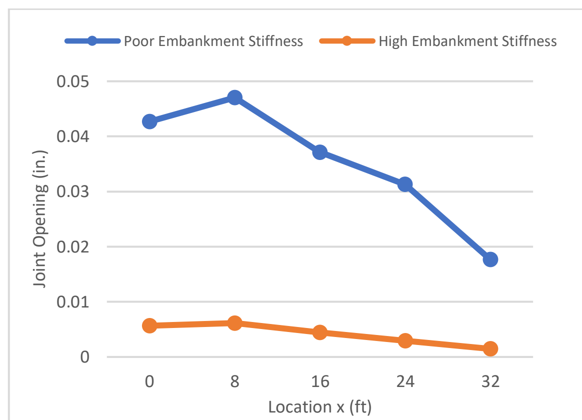
The results show that changing subgrade stiffness from poor to subgrade does not have an impact on the magnitude of joint separation in 24-inch culverts with 4 ft soil cover. In all cases, joint openings are largest near under the center of the road and decreases along the length of culverts. Also, it can be seen the changing embankment stiffnesses from poor to high can significantly decreases the joint openings in all subgrade stiffness- poor stiffness, good stiffness and excellent stiffness.

In considering the two loading conditions, the combined traffic and embankment loads makes greater joint openings than the mere embankment load, about more than 1%. The major joint opening is because of soil embankment load, not traffic load, but the cyclic traffic load should be investigated in future research. When the traffic load added to the soil embankment load the maximum joint opening shifts from joint 2 to joint 1 from the left side of culverts.

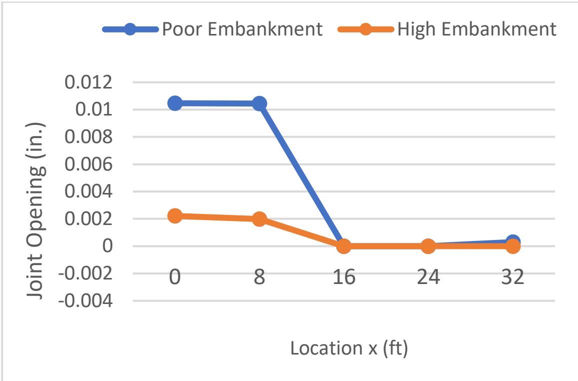
Overall, the results indicate that high soil embankment load and poor soil embankment stiffness together lead to highest risk of joint separation. So, enhancing the backfill stiffness can be a significant mitigation in concrete culvert joint separation.



a) embankment load.

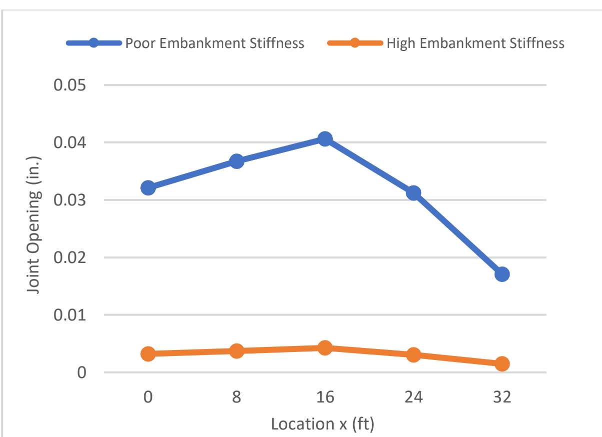


b) combined traffic and embankment loads.

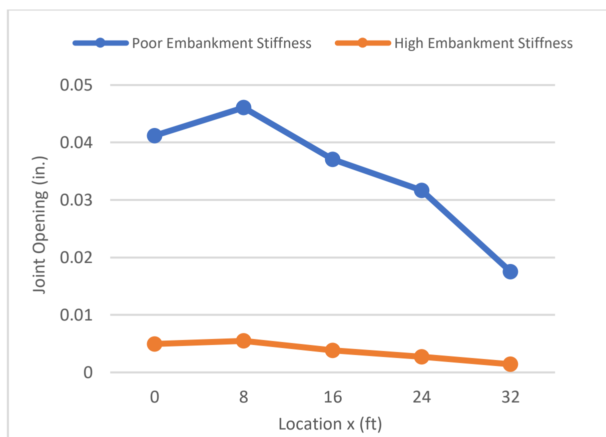


c) just traffic loads

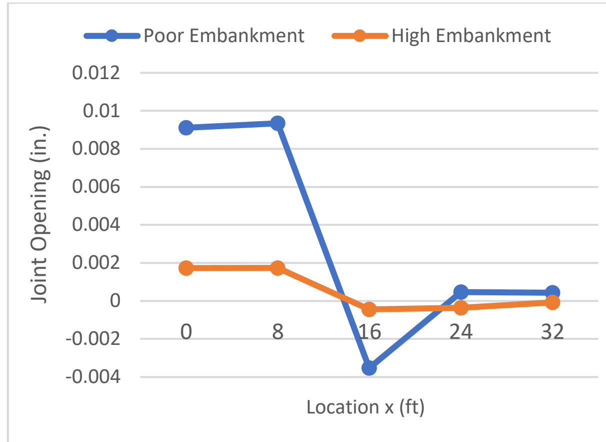
Figure 29 - Comparison of joint openings in a 24-inch culvert with 4 ft soil cover under poor subgrade stiffness, for poor and high embankment stiffness, subjected to (a) embankment load or (b) combined traffic and embankment loads (c) just traffic load



a) embankment load.

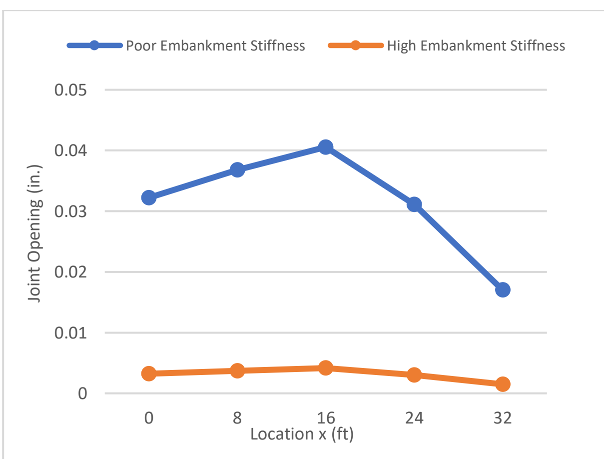


b) combined traffic and embankment loads.



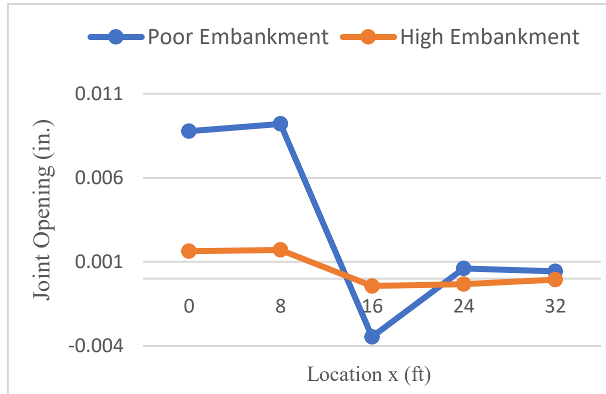
a) just traffic loads

Figure 30 - Comparison of joint openings in a 24-inch culvert with 4 ft soil cover under good subgrade stiffness, for poor and high embankment stiffness, subjected to (a) embankment load or (b) combined traffic and embankment loads (c) just traffic load



a) embankment load.

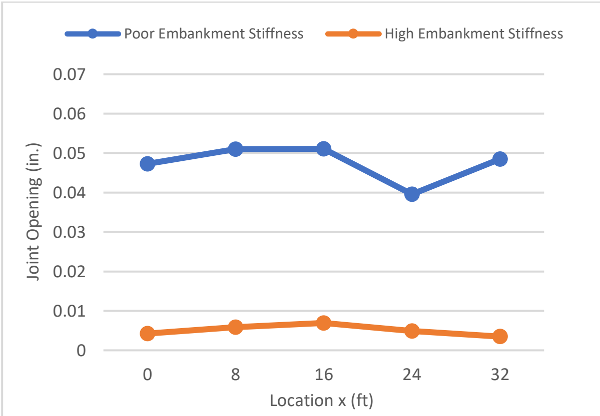
b) combined traffic and embankment loads.

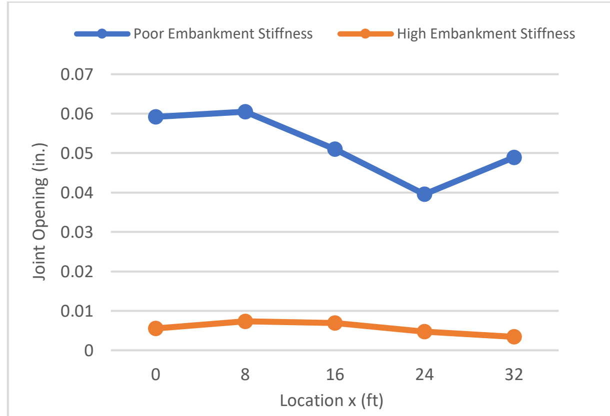


c) just traffic load

Figure 31 - Comparison of joint openings in a 24-inch culvert with 4 ft soil cover under excellent subgrade stiffness, for poor and high embankment stiffness, subjected to (a) embankment load or (b) combined traffic and embankment loads (c) just traffic load

The Figure 32 to Figure 33 show joint openings in 72-inch culverts under two conditions—embankment load alone and combined embankment plus traffic load—for subgrade stiffnesses of 100, 500, and 1000 lb/in³. In all stiffness values, adding traffic load generate just a small change in joint opening. Because the embankment load is applied first and includes the most structural response, the additional effect of traffic loading is minimal.

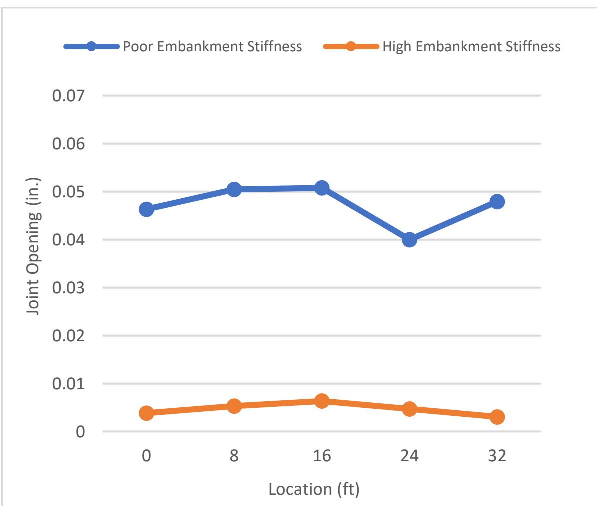


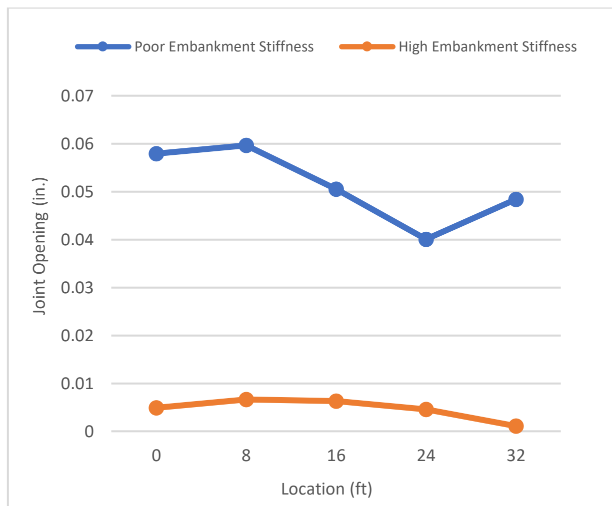


a) embankment load.

b) combined traffic and embankment loads.

Figure 32 - Comparison of joint openings in a 72-inch culvert with 4 ft soil cover under poor subgrade stiffness, for poor and high embankment stiffness, subjected to (a) embankment load or (b) combined traffic and embankment loads

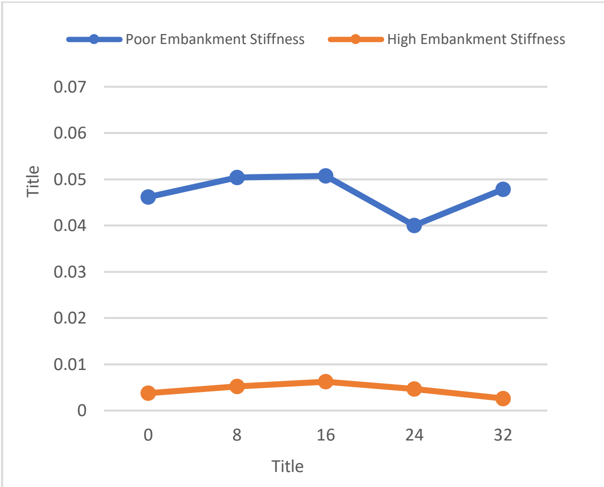




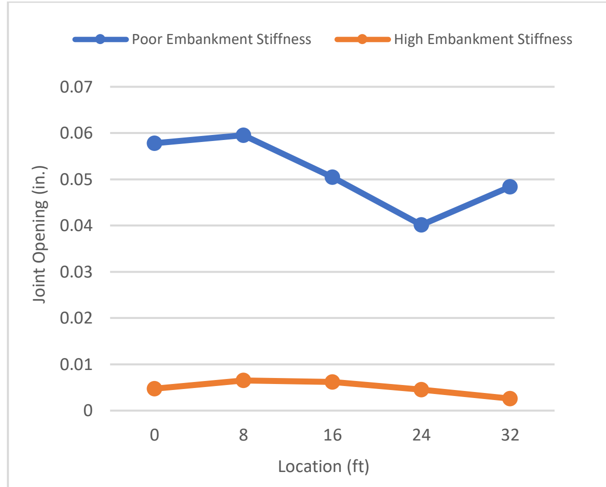
a) embankment load.

b) combined traffic and embankment loads.

Figure 33 - Comparison of joint openings in a 72-inch culvert with 4 ft soil cover under good subgrade stiffness, for poor and high embankment stiffness, subjected to (a) embankment load or (b) combined traffic and embankment loads



a) embankment load.



b) Combined traffic and embankment loads.

Figure 34 - Comparison of joint openings in a 72-inch culvert with 4 ft soil cover under excellent subgrade stiffness, for poor and high embankment stiffness, subjected to (a) embankment load or (b) combined traffic and embankment loads

Chapter 6: Summary and Conclusion

6.1 Summary of Study

This thesis studied the causes and rates of joint separation in round concrete culvert by combining three approaches.

The machine learning model, random forest, was trained to predict the rate of joint separation; culverts with predicted rate higher than fifty percent were considered as likely to exhibit joint separation, and higher values indicating greater confidence. field investigations, were used to interpret and compare the ground observations with the predictions and simulations. At the end, the FEM method quantified the influence of soil stiffness, subgrade stiffness, joint contact conditions, and load combinations (embankment and traffic) on joint separation.

6.2 Key Findings

The findings from this study reveal that joint separation in concrete culverts is impacted by a complex interaction of material, geotechnical, and loading factors, which can be understood through both data-driven prediction and mechanical modeling.

By training the machine learning model on the culvert database of Minnesota Department of Transportation, overall condition, infiltration, route id and county were identified as the most important factors in predicting joint separation. The model is reliable having nearly seventy percent accuracy and the culverts with higher rate of joint separation, above eighty percent, showing the most likelihood of joint separation.

By using Ansys, finite element model developed and indicated that traffic loading and embankment self-weight can be effective for generating tensile forces across culverts, thereby contributing to separation. Traffic loading produced relatively small axial forces, nearly ten to twenty percent of vertical load caused by soil embankment load. The simulation showed that embankment stiffness and embankment depth play decisive roles in joint separation in concrete culverts.

6.3 Recommendations for Future Works

Future research is needed to consider other possible actions (e.g., freezing water or soil directly infiltrating into the joint, poor installation, scour or loss of apron support) and other model refinements. For example, while the direct separation demands of traffic loading appeared to be smaller compared to those caused by a rise of phreatic surface or soil freezing, traffic loads are cycled far more times per year. To investigate progressive joint opening over time under repeated load cycles, the model may need to incorporate soil plasticity, incremental settlement, different frictional models, and the apron geometry. Future research should also focus on detailed field observations to confirm the most likely locations of and conditions that lead to joint separation in concrete culverts.

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