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Understanding Causes of Concrete Culvert Pipe Joint Separation

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16. Abstract (Limit: 250 words)

Joint separations affect approximately 20% of the Minnesota concrete pipe inventory (Taylor and Marr 2012). The goals of this research are to determine the factors that contribute to joint separation and recommend practices to mitigate this problem. Research efforts follow a three-pronged approach: (1) Examination of TAMS HydInfra database; (2) field survey of concrete culverts; and (3) computational modeling of soil-culvert systems. Database investigations were conducted using a Random Forest model along with individual feature analysis to determine factors that correlate with joint separations. Geographic features such as the county and route number of the culvert are more important for predicting joint separation than geometric features such as culvert size or cover depth. Field surveys reveal that separations typically occurred at the ends of pipes, or in the first untied joint from the end of the pipe if only some joints were tied. Joint separation was often observed alongside other distress such as infiltration or inslope voids. Computational modeling results show that embankment self-weight and traffic loading concentrate their highest demands under the center of the road, which did not match with field inspections. Soil freezing or changes of water-table level impose greater demands than traffic, and these maximum demands are located at the pipe ends, and thus these mechanisms are more likely to result in joint separation. Recommendations include tying all joints on installation, properly compacting the backfill, and limiting freezing expansion of the embankment materials, particularly if a cohesive soil cap is used.

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Understanding Causes of Concrete Culvert Pipe Joint Separation

Final Report

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Executive Summary

The purpose of this research is to determine the factors that contribute to joint separation in concrete culverts. Culverts, an essential component in urban and rural infrastructure, guide water under roads and embankments (Ramadan et al. 2022). This study focuses on round precast concrete culverts, which remain a popular choice due to effective quality control, cost efficiency, durability, and short road closure times during installation. Roughly 75% of the highway culverts owned by the state of Minnesota are concrete, nearly 87% of which are round pipes (Taylor and Marr 2012).

A common form of damage culverts experience is joint separation between culvert segments, affecting approximately 20% of the Minnesota concrete pipe inventory (Taylor and Marr 2012). Consistent with the Minnesota Department of Transportation (MnDOT) Transportation Asset Management System (TAMS) *HydInfra Inventory and Inspection Manual* (Minnesota Department of Transportation 2025), joint separation is defined in this study as opening of the joint by more than 1 in. (2.5 cm), as a gap of 1 in. is considered acceptable for new installations. The purpose of this research is to determine the factors that contribute to joint separation in concrete culverts.

Research efforts followed a three-pronged approach: (1) examination of the TAMS HydInfra database; (2) field survey of concrete culverts; and (3) computational modeling of soil-culvert systems.

Building on the previous study by Taylor and Marr (2012), the research team reviewed data from the TAMS HydInfra database to determine the scope of the problem of joint separation in concrete pipes. A Random Forest algorithm, a machine learning model consisting of a set of decision trees, was trained on the database. This model used the recorded culvert geographical, geometric, and condition data as inputs to predict the likelihood that a given pipe would experience joint separation. The primary purpose of this model was to observe which inputs had the greatest importance in predicting joint separation. Condition features, and particularly the presence of infiltration, were the most important predictor for joint separation. Geographic features were the second most important set of features, with county and route number being the most significant contributors. Pipe geometry was the least important set of features. These results mean that joint separation was regularly accompanied by further distress such as infiltration, roadway voids, and formation of cavities in the embankment. The Random Forest model provided no insight into causation, but the most likely interpretation was that culvert joint separation leads to further damage in and around the culvert. The results related to the relative importance of geography over pipe geometry were not conclusive as to whether different district practices were better at controlling joint separation. Rather, the importance of route number may have some correlation with date of installation and annual daily traffic, while the importance of county may relate primarily to site conditions common throughout that region; both concepts point toward an interpretation that the installation site is more important than the culvert when examining joint separation.

Further investigation of the TAMS HydInfra database focused on the correlation between joint separation and individual features from the database. This investigation confirmed some of the results of the Random Forest model but also illustrated some correlations that were not observed by the machine learning model. For example, joint separation was most often observed throughout southern Minnesota in counties that have a high density of intermittent streams, confirming the importance of pipe location. Furthermore, nearly all pipes with infiltration also have joint separation and most have inslope cavities or roadway voids, confirming the correlation that joint failures regularly lead to further distress. However, some features that the model identified as unimportant still showed strong correlations. Increased soil cover and lack of pipe ties both correlate with an increased rate of joint separation. Part of the discrepancy between the Random Forest model and individual feature analysis may be explained by overlapping or correlated features. For example, county and maintenance district features were nearly perfectly correlated to each other, with county the more precise indicator of location.

Field inspection sites were selected from among those in the database to observe how joint separation may, or may not, manifest over a variety of site conditions, soil types, pipe connections, pipe ages, and districts. During the summer of 2024, 86 culverts were investigated in the field. Representative sites were selected from multiple districts, sampling a variety of joint details, pipe sizes, and joint separation severity. Joint separation in the inspected culverts often manifested as a roughly uniform opening of the joint around the pipe circumference, occasionally with a variation of 1 or 2 in. between opposite sides of the pipe. In some cases, separation was paired with other damage, such as breakage of the concrete joint. Most joint separations occurred at joints without pipe ties, but rare instances of pipe separation or minor infiltration were observed across tied joints. 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.

To augment the field inspections, a survey was distributed to MnDOT personnel to gather input on likely causes and possible solutions for concrete culvert pipe joint separation. The most common suggestion from the survey results was to provide pipe ties on all joints to prevent separation. The other common response was that improper compaction of the backfill material around the pipe could lead to separation. Some respondents highlighted the likelihood of freeze-thaw damage, particularly at the ends of pipes with cohesive soil caps, which could expand far more than the granular backfill material compacted around the pipe.

Three-dimensional soil-structure models were developed using the finite difference method via FLAC3D (Itasca Consulting Group, Inc. 2023) and the finite element method via ANSYS (ANSYS Inc. 2022). Effects of traffic loading, embankment weight, soil freezing and thawing, and elevation changes of the phreatic surface were investigated. Finite difference models were primarily used as an exploratory tool for the different loading scenarios, while finite element modeling was the primary tool for parametric studies in which soil properties, culvert diameter, and fill height were varied. Two different joint models were considered in the finite element modeling: (i) continuous joints capable of transferring force, and (ii) discrete joints unable to transfer any load. These joint models were intended to provide bounds for possible joint behaviors, with realistic culvert joints exhibiting behavior with some combination of partial force transfer with restricted joint movement.

Model results indicated separation potential under traffic loading was not strongly correlated to the soil cover depth. Instead, increasing cover increased demands due to self-weight of the embankment. These maximum demands due to self-weight, however, were not at the ends of the pipes, but rather under the middle of the embankment, which contradicts with field observations that joint separation typically occurs at pipe ends. Investigations of the TAMS HydInfra database revealed that greater depths of soil cover were correlated to greater rates of joint separation. These seemingly contradictory findings indicate that traffic loading and embankment self-weight likely do not lead to significant joint separation by themselves. Instead, stresses that build up during pipe installation may lead to greater incidence of joint separation due to demands that have greater impacts at the ends of the pipes where separations most often occur, such as rise of the phreatic surface and soil freezing.

Both the rise of the phreatic surface and soil freezing cause larger joint demands than traffic loading in the models, particularly on end culvert segments nearest the outside face of the embankment. This aligns with field observations and inspector experience. The most significant parameters predicting the magnitude of joint separation for soil freezing were the length of the culvert segments (longer segments induce more separation in the first untied joint) and the amount of volumetric expansion exhibited by the soil upon freezing. Well-drained soil, such as the typical fine aggregate bedding (i.e., sand) compacted around culvert installations, likely has negligible expansion upon freezing. However, saturated cohesive soil, such as that used for a cohesive soil cap, could have significant expansion upon freezing. Even if the cap were only 3-ft deep, this could result in separation of the apron or first pipe joint on the order of 1 in. per winter, much of which may not be recoverable. Furthermore, model results confirmed that the practice of partially tying pipes, where only the apron is tied to the first pipe segment or only the first few joints from the pipe ends are tied, can amplify the amount of separation induced at the first untied joint. This corroborates with field inspections where the first untied joint was often seen to have separated.

The overall recommendations of this study, both from the research team and from the survey of MnDOT personnel, are to provide pipe ties on all concrete pipe joints during installation and to focus on proper compaction of the bedding and placement of the pipes. Further work on classifying the frost-heave susceptibility of typical bedding and cohesive cap materials is recommended. Swelling of a cohesive cap could easily lead to large separations at the ends of pipes, so specifications on material expansion limits may be justified.

Chapter 1: Introduction

1.1 Research Motivation

The purpose of this research was to determine the factors that contribute to joint separation in concrete culverts. Culverts are an essential component in urban and rural infrastructure, guiding water under roads and embankments (Ramadan et al. 2022). Culverts are classified by their material, construction, shape, and geometry. This study focused on round precast concrete culverts, which remain a popular choice due to effective quality control, cost efficiency, durability, and short road closure times during installation. Roughly 75% of the highway culverts owned by Minnesota are concrete, nearly 87% of which are round pipes (Taylor and Marr 2012).

A common form of damage experienced by culverts is joint separation between culvert segments, affecting approximately 20% of the Minnesota concrete pipe inventory (Taylor and Marr 2012). Consistent with the Minnesota Department of Transportation (MnDOT) Transportation Asset Management System (TAMS) *HydInfra Inventory and Inspection Manual* (Minnesota Department of Transportation 2025), joint separation was defined in this study as opening of the joint by more than 1 in. (2.5 cm), as a gap of 1 in. is considered acceptable for new installations.

NCHRP Synthesis Report 474 (Maher et al. 2015) identified two knowledge gaps in need of additional research: (i) the structural and hydraulic performance of different types of pipe joints and (ii) the impacts that joint failure may have on culvert service life. Joint performance issues can lead to culvert pipe failures. For example, joint separation may cause backfill material to enter the pipe (i.e., infiltration), which in extreme cases may result in plugged pipes or a sinkhole forming in the road above. Repairs may be conducted on larger pipes by joint sealing or injection, or by using internal flexible rubber seals and retaining bands (Wagener and Leagjeld 2014).

The factors that lead to joint separation in culverts have not been thoroughly researched. Studies by Moore et al. (2012) and Sheldon et al. (2015) have examined joint separation under vehicular live load. Under this loading scenario, joint separation in the vertical direction is much greater than in the longitudinal direction. However, these studies focused primarily on how longitudinal bending affected joints, neglecting the mechanisms that lead to axial separation across joints. They also did not address the broader forces that can act on culverts, such as superimposed dead load from the embankment, freezing of the embankment, or rise of the phreatic surface.

1.2 Background

There are two primary categories of pipe joints that are defined based on their mechanical behavior and response to external loads: (i) moment-release or (ii) moment-transfer joints (Moore et al. 2012). Moment-release joints are engineered to allow rotational movement between the connected pipes. This design approach effectively reduces longitudinal bending stresses that may stem from surface loads or variations in the support conditions (i.e., the subgrade stiffness). Examples of moment-release joints include bell-and-spigot or tongue-in-groove joints, both with and without gaskets. Joints in concrete culverts are often moment-release joints. Moment-transfer joints, in contrast, are designed to limit rotational movement and facilitate the transfer of bending stresses from one pipe segment to another. Examples of moment-transfer joints include band joints and welded connections. The addition of pipe ties, which are metal bars or rods that cross the joint and connect two pipe segments together, allow for concrete pipe joints to resist axial forces and possibly bending moments, depending on their quantity and position around the circumference and the direction of the moment.

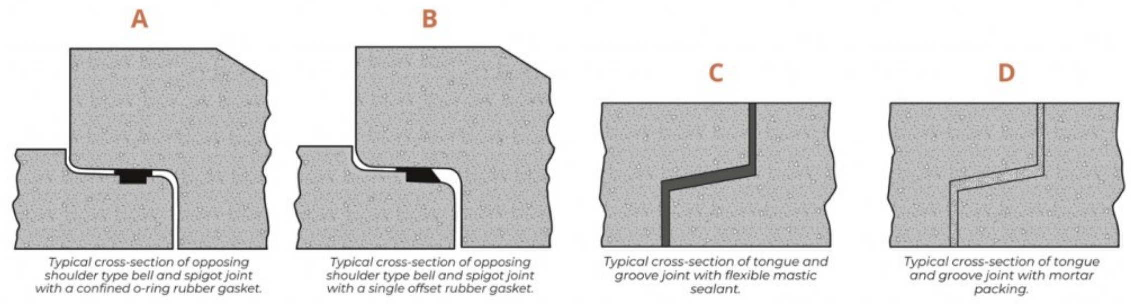
Design considerations for culvert joints involve assessing their capacity to withstand vertical shear forces, bending moments (if applicable), axial forces, and rotational behavior under various loading and burial conditions. While Moore et al. (2012) emphasized the impact of longitudinal bending on joint performance, they acknowledged that their research did not investigate the transfer of other forces, such as axial forces across joints.

Proper joint design in concrete culverts is critical to ensuring the mechanical performance and longevity of these structures. Perminov et al. (2017) noted that a well-designed joint is crucial for the even distribution of loads across the structure, ensuring proper load transfer between individual pipe sections. This prevents localized stress concentrations, thereby reducing the risk of damage or failure, whereas poorly designed joints can lead to structural vulnerabilities. Vetter et al. (2016) discussed how joint design must accommodate certain degrees of movement, such as thermal expansion and contraction or minor ground shifts, without compromising structural performance. Some allowance for movement may prevent stress accumulation, ensuring the culvert is resilient to environmental changes.

Achieving tight connections is another important goal of joint design for durable culverts, but the need for watertight connections depends on the culvert system and application. Haktanir et al. (2006) stressed the importance of watertight joint connections in concrete sewage pipes to decrease soil erosion and prevent contamination of groundwaters. Sezen et al. (2021) summarized different state departments of transportation practices for waterproofing of concrete culvert joints. They stated that protection was especially vital in low-cover situations where the top and sides of the concrete were susceptible to premature degradation due to water ingress through the joints. Walker (2022) also addressed joint design to avoid corrosion and deterioration of concrete culverts.

Pei et al. (2020) addressed the economic implications of joint design, noting that it can significantly impact the overall cost of the culvert system, affecting both material and labor expenses. Efficiently designed joints that ensure water- or soil-tightness as appropriate, structural integrity, and durability can decrease the need for frequent maintenance, thereby reducing the lifecycle costs associated with the culvert system. This economic efficiency highlights the value of investing in quality joint design from the outset.

For the drainage systems examined in this study, soil-tight connections are desired to prevent infiltration of fine materials into the pipe. In practice, Minnesota largely uses two types of culvert joints for round concrete pipes: gasketed bell-and-spigot joints and tongue-in-groove joints without gaskets (see Figure 1.1). The pipes are often wrapped with a geotextile to limit soil infiltration.



Typical cross-section of opposing shoulder type bell and spigot joint with a confined o-ring rubber gasket.

Typical cross-section of opposing shoulder type bell and spigot joint with a single offset rubber gasket.

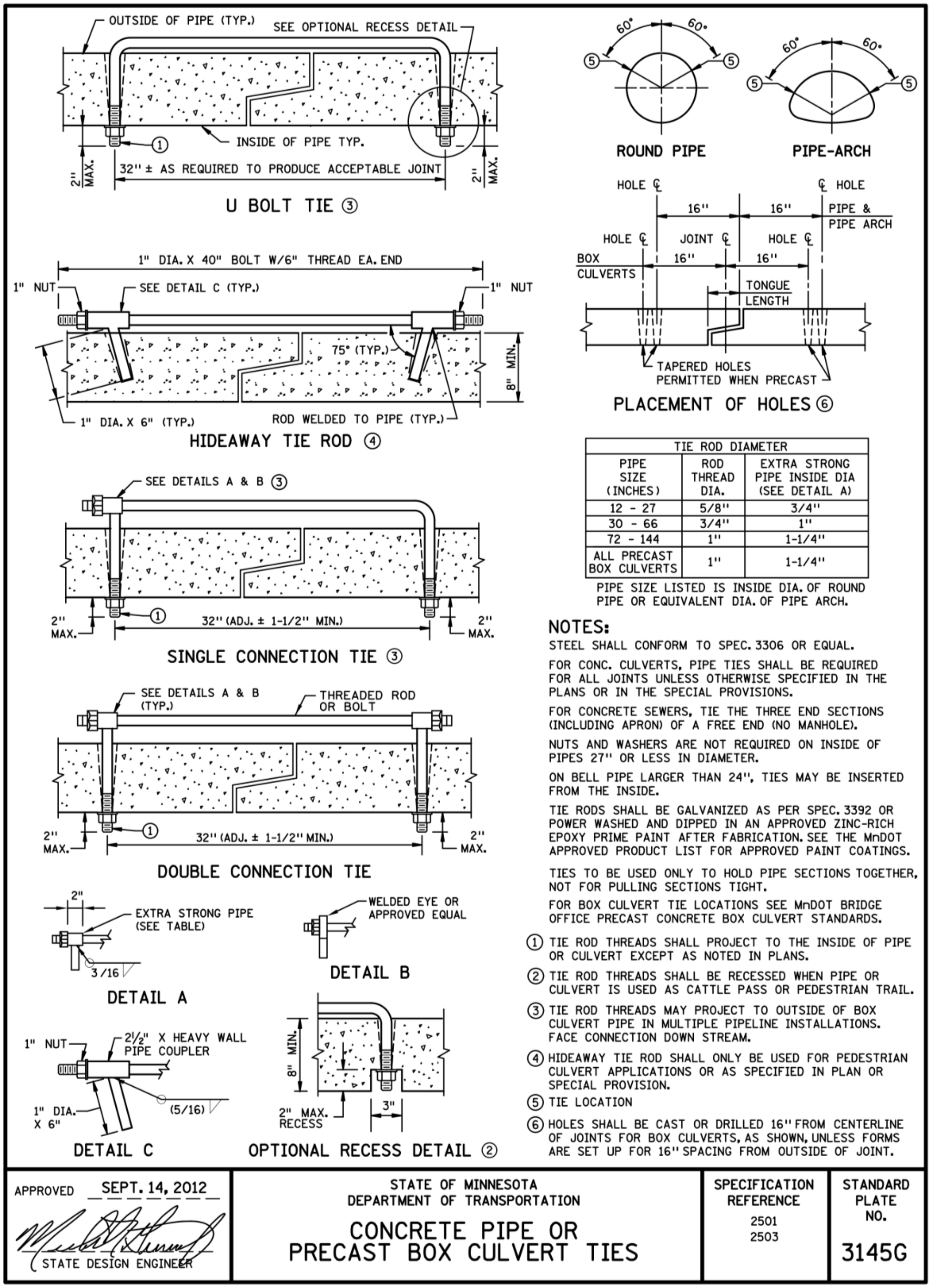
Typical cross-section of tongue and groove joint with flexible mastic sealant.

Typical cross-section of tongue and groove joint with mortar packing.

Figure 1.1: Reinforced concrete pipe joints: bell-and-spigot joints with (a) confined o-ring gasket (b) single offset gasket, or tongue-in-groove joints with (c) mastic sealant or (d) mortar packing (American Concrete Pipe Institute, https://blog.concretepipe.org/debunking-misconceptions-about-concrete-pipe-performance).

Pipe ties are intended to hold pipe segments together but not pull them together during installation. Figure 1.2 shows a concrete pipe installation with exterior pipe ties and geotextile wrap at each joint. Plate 3145G, which presents standard details for pipe ties, is shown in Figure 1.3. Pipe ties may be included on all joints, no joints, only between the apron and first pipe segment on each end, or only across the first three joints at each end. When included, pipe ties generally consist of two metal bars per joint located at the 10-o-clock and at 2-o-clock positions; this practice limits the transfer of bending moments across the joint. Larger diameter pipes may have more than two ties per joint, which may allow for moment transfer across the joint.

Figure 1.2: In-progress reinforced concrete pipe installation showing pipe ties and geotextile wrap



U BOLT TIE ③

HIDEAWAY TIE ROD ④

SINGLE CONNECTION TIE ③

DOUBLE CONNECTION TIE

DETAIL A

DETAIL B

DETAIL C

OPTIONAL RECESS DETAIL ②

ROUND PIPE

PIPE-ARCH

PLACEMENT OF HOLES ⑥

TIE ROD DIAMETER		
PIPE SIZE (INCHES)	ROD THREAD DIA.	EXTRA STRONG PIPE INSIDE DIA (SEE DETAIL A)
12 - 27	5/8"	3/4"
30 - 66	3/4"	1"
72 - 144	1"	1-1/4"
ALL PRECAST BOX CULVERTS	1"	1-1/4"

PIPE SIZE LISTED IS INSIDE DIA. OF ROUND PIPE OR EQUIVALENT DIA. OF PIPE ARCH.

NOTES:

STEEL SHALL CONFORM TO SPEC. 3306 OR EQUAL.

FOR CONC. CULVERTS, PIPE TIES SHALL BE REQUIRED FOR ALL JOINTS UNLESS OTHERWISE SPECIFIED IN THE PLANS OR IN THE SPECIAL PROVISIONS.

FOR CONCRETE SEWERS, TIE THE THREE END SECTIONS (INCLUDING APRON) OF A FREE END (NO MANHOLE).

NUTS AND WASHERS ARE NOT REQUIRED ON INSIDE OF PIPES 27" OR LESS IN DIAMETER.

ON BELL PIPE LARGER THAN 24", TIES MAY BE INSERTED FROM THE INSIDE.

TIE RODS SHALL BE GALVANIZED AS PER SPEC. 3392 OR POWER WASHED AND DIPPED IN AN APPROVED ZINC-RICH EPOXY PRIME PAINT AFTER FABRICATION. SEE THE MnDOT APPROVED PRODUCT LIST FOR APPROVED PAINT COATINGS.

TIES TO BE USED ONLY TO HOLD PIPE SECTIONS TOGETHER, NOT FOR PULLING SECTIONS TIGHT.

FOR BOX CULVERT TIE LOCATIONS SEE MnDOT BRIDGE OFFICE PRECAST CONCRETE BOX CULVERT STANDARDS.

① TIE ROD THREADS SHALL PROJECT TO THE INSIDE OF PIPE OR CULVERT EXCEPT AS NOTED IN PLANS.

② TIE ROD THREADS SHALL BE RECESSED WHEN PIPE OR CULVERT IS USED AS CATTLE PASS OR PEDESTRIAN TRAIL.

③ TIE ROD THREADS MAY PROJECT TO OUTSIDE OF BOX CULVERT PIPE IN MULTIPLE PIPELINE INSTALLATIONS. FACE CONNECTION DOWN STREAM.

④ HIDEAWAY TIE ROD SHALL ONLY BE USED FOR PEDESTRIAN CULVERT APPLICATIONS OR AS SPECIFIED IN PLAN OR SPECIAL PROVISION.

⑤ TIE LOCATION

⑥ HOLES SHALL BE CAST OR DRILLED 16" FROM CENTERLINE OF JOINTS FOR BOX CULVERTS, AS SHOWN, UNLESS FORMS ARE SET UP FOR 16" SPACING FROM OUTSIDE OF JOINT.

APPROVED SEPT. 14, 2012 STATE DESIGN ENGINEER	STATE OF MINNESOTA DEPARTMENT OF TRANSPORTATION CONCRETE PIPE OR PRECAST BOX CULVERT TIES	SPECIFICATION REFERENCE 2501 2503	STANDARD PLATE NO. 3145G

Figure 1.3: Plate 3145G for pipe ties details

1.3 Research Overview

Research efforts followed a three-pronged approach: (1) examination of TAMS HydInfra database; (2) field survey of concrete culverts; and (3) computational modeling of soil-culvert systems.

Building upon the previous study by Taylor and Marr (2012), the research team reviewed data from the TAMS HydInfra database to determine the scope of the problem of joint separation in concrete pipes. The TAMS HydInfra database, hosted by the Minnesota Department of Transportation, contains inventory and inspection tables for the state's hydraulic infrastructure. Field survey sites were selected from among those in the database to observe how joint separation may, or may not, manifest over a variety of site conditions, soil types, pipe connections (i.e., gasketed versus tongue-in-groove), pipe ages, and districts. During the summer of 2024, 86 culverts were investigated in the field. Representative sites were selected from multiple districts, sampling a variety of joint details, pipe sizes, and joint separation severity.

Three-dimensional soil-structure models were developed using the finite difference method via FLAC3D (Itasca Consulting Group, Inc. 2023) and the finite element method via ANSYS (ANSYS Inc. 2022). Effects of traffic loading, embankment weight, soil freezing and thawing, and elevation changes of the phreatic surface were investigated. Finite difference models were primarily used as an exploratory tool for the different loading scenarios, while finite element modeling was the primary tool for parametric studies in which soil properties, culvert diameter, and fill height were varied. Two different joint models were considered in the finite element modeling: (i) continuous joints capable of transferring force, and (ii) discrete joints unable to transfer any load. These joint models were intended to provide bounds for possible joint behaviors, with realistic culvert joints exhibiting behavior with some combination of partial force transfer with restricted joint movement.

1.4 Report Organization

Chapter 2 presents the investigation of the TAMS HydInfra database, highlighting the extent of joint separation throughout the MnDOT highway culvert inventory and showing trends for different culvert variables. Chapter 3 contains the observations and findings from the field inspections, plus a summary of survey responses from MnDOT construction and inspection personnel. Chapter 4 presents the results from finite difference and finite element modeling, further investigating trends that were observed in the database. This report concludes in Chapter 5 with conclusions on the causes of concrete culvert joint separation and recommendations for future action.

Chapter 2: Database Investigations

2.1 Database Properties

The likelihood of concrete pipe joint separation has been analyzed using data from the Transportation Asset Management Systems (TAMS) HydInfra Database provided by MnDOT. This database contains information on over 31,000 concrete highway culverts. Database features capture the geometric, geographical, and other details of the culvert alongside a series of culvert condition metrics obtained from inspections. Table 2.1 outlines the features of interest to this research study, which were incorporated in the following analysis.

Table 2.1: TAMS HydInfra features included in analysis

Feature Tag	Description	Data Type
Depth of Soil Cover	Fill depth above 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 Ties	Presence of long bolts, bars, or plates that cross and secure the pipe joints	Binary, yes/no
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
Inslope Cavity	Indicates cave-ins or holes in inslope 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 below

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 above which joint separation is considered deleterious according to MnDOT inspectors, as a gap of 1 in. is considered acceptable for new installations). Prior to 2018, joint separation was entered into the database using two fields: (1) a yes/no binary field indicating the presence or absence of joint separation, and (2) a field wherein the maximum observed joint separation in inches was recorded. In

2018, these two fields were merged into a single numeric value. During this transition, all entries containing a yes in the binary field but no entry in the maximum joint separation field were given a value of 99. In inspections occurring these two fields were merged, joint separation observed to be less than 1 in. were logged using the entry "<1".

In the version of the database used for this research, no entries explicitly containing zero in the joint separation field, though nearly 70% of the entries are blank. The field was blank if joint separation could not be observed during inspections. This could mean either no separation was present or that no separation was observed due to an inability to access the pipe. Furthermore, joint separation may develop after the latest inspection. This led 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 have introduced a bias towards underestimating the scope of joint separation.

In the following analysis, joint separation was examined as a binary yes/no, where any separation greater than 1 in. (including entries of 99) was classified as a yes. For all other entries, database fields for inspection comments, suggested repairs, and number of joints to fix were consulted. Among these, the entries with suggested joint repairs, other comments that indicated a joint issue, or an entry that at least one joint needed to be fixed were classified as a yes, while entries with no comments regarding joint performance and an entry that no joints needed to be fixed were classified as a no.

The database was filtered such that only round concrete culverts were examined. Nearly 87% of the MnDOT concrete pipe inventory is composed of round culverts (27,219 round culverts among 31,228 total); other shapes such as boxes, ellipses, arches, and cattle pass structures are less common. Round culverts are the second most likely shape in the database to have joint separation; cattle pass structures have the highest recorded rate of joint separation among all shapes but only constitute 256 entries. Other practically implausible culvert entries, such as entries with a recorded total length of zero feet, were filtered from the database (509 entries removed total), resulting in 26,710 examined culvert records.

Other features that may be of interest for predicting joint separation but that were not consistently recorded in the HydInfra database include date of installation, installation method, backfill method, roadway slope, and joint slope. A small subset of the database entries does have information on gasketed versus non-gasketed joints, but because this was unknown for more than 95% of the entries, this feature was ignored for model training and thus excluded from Table 2.1.

2.2 Methodology

In addition to manual database exploration, the research team employed a Random Forest algorithm (Breiman 2001) as a predictive model for examining joint separation. Using this machine-learning approach, a set of decision trees was trained from 80% of the database entries (i.e., the training set), randomly selected from the 26,710 remaining after database filtering. The results of all the decision trees were combined and weighted to arrive at a predicted likelihood of joint separation. The model was validated against the remaining 20% of the database (i.e., the test set) to ensure the predictions were reliable.

Random Forests have been shown to excel in capturing complex relationships between features of multiple variable types and scales without necessitating transformations (Cutler et al. 2007; Tien Bui et al. 2016). The method is also robust against overfitting (Liaw and Wiener 2002), and resilient against missing data (Stekhoven and Bühlmann 2012). Because the model presents a likelihood of joint separation, and not merely a yes or no answer, the model results can provide information on feature importance (Genuer et al. 2010) and may be used as a predictive tool to indicate which culverts under which conditions are most likely to have joint separation (Nicodemus 2011).

2.3 Feature Importance Results

Figure 2.1 provides a pie chart illustrating the relative importance of the input features used in the Random Forest model. The presence of infiltration was the most prominent predictor for joint separation, as would be expected as significant joint separation will often lead to infiltration problems. The Route ID (i.e., the route number) is the second most influential feature, accounting for 14.5% of the model's predictive capacity, followed closely by the county in which the culvert is located, at 13.1% of the model's predictive capacity.

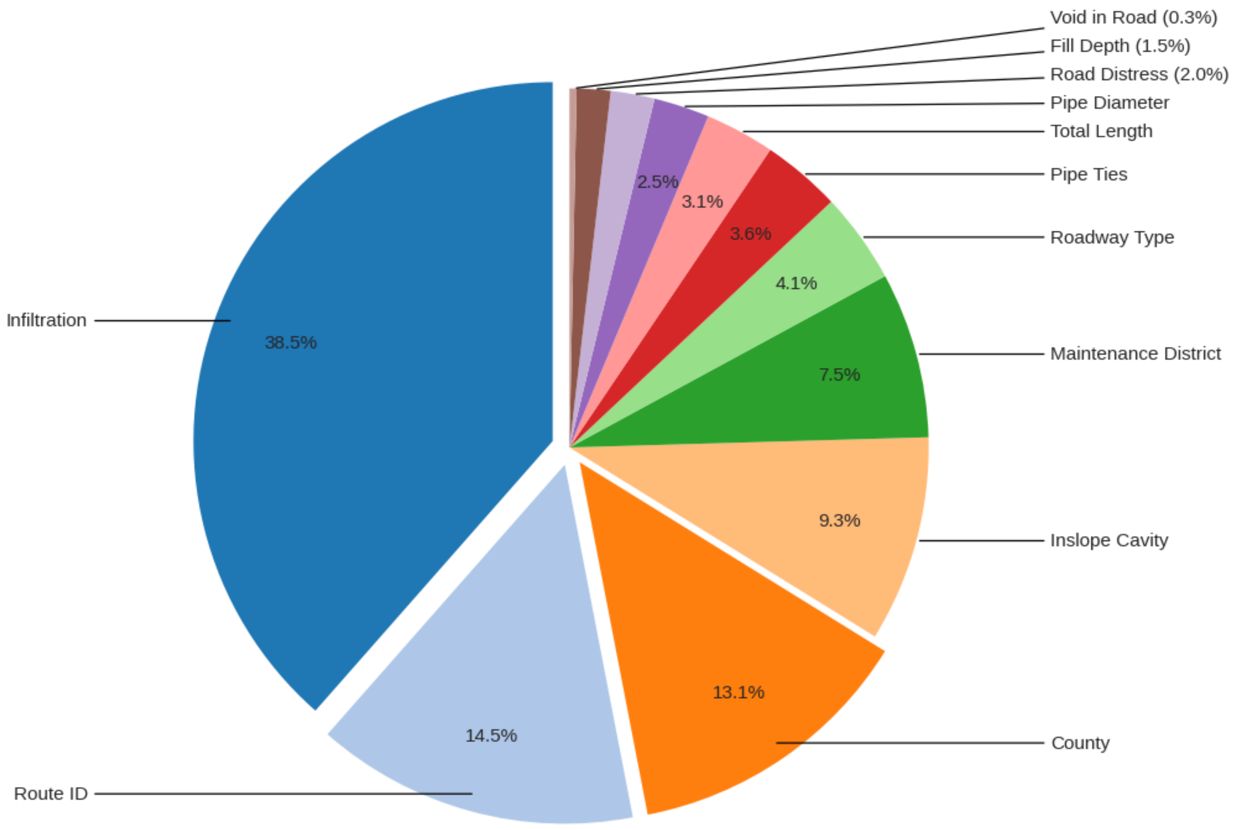


Figure 2.1: Feature importance for predicting joint separation in MnDOT round concrete culverts

The three geographic identifiers of route number, county, and maintenance district were all significant predictors of joint separation, together making up just over 35% of the total feature importance. While maintenance district was nominally the least significant of these three, there was considerable overlap between the features that may obscure any specific conclusions. County is, overall, a more precise indicator of location than maintenance district, and therefore likely subsumed the significance of the maintenance district as a critical feature. Maintenance subareas, which are recorded in the database as "Administrative Unit," were excluded from this analysis because they appear to have a very high overlap with county, though likely a similar model could be trained substituting the administrative unit for county. Route number, on the other hand, may have some correlation with date of installation and annual daily traffic (ADT), which might explain its increased significance compared to other geographic features. However, ADT was not recorded in the TAMS HydInfra database and was not explicitly used in this analysis. These results are not conclusive as to whether different district practices are better at controlling joint separation, though overall geography appears to be a significant predictor.

Other than the presence of inslope cavities (9.3% of feature importance), which might be caused by large joint separation and infiltration, all other features were each less than 5% of the total feature importance. Surprisingly, features such as cover and the presence of pipe ties were not strong predictors of joint separation. The database does not provide any details on what types of pipe ties are used for each culvert, or whether these were installed at construction or sometime later for remediation. Furthermore, the geographic indicators for county and maintenance district may have acted as a proxy for this metric, as the type of pipe ties and manner of installation would likely depend on local maintenance practices.

Overall, 72% of the culverts that were known to have joint separation from the database were correctly classified by the Random Forest (i.e., the model recall was 72%), and 71% of the culverts predicted by the model to have joint separation did indeed have joint separation in the database (i.e., the model precision was 71%). Model predictions of joint separation rate were typically within 3% of the actual rates found in the database, though the Random Forest had a subtle tendency to underestimate the incidence of joint separation.

Database exploration by feature, shown in Section 2.4, appeared to reveal some contradictory trends compared to the feature analysis shown here. For example, presence of pipe ties seems to have negligible effect according to the Random Forest feature analysis, but intuition and the database entries support that pipe ties are effective at preventing joint separation. This contradiction likely occurred because no single variable explains joint separation fully, and many of the variables may have overlap or correlations (i.e., the variables examined herein were not independent from each other). This is especially true for geographic variables such as county and maintenance district. Rates of joint separation are different in each maintenance district, but that does not necessarily mean maintenance district must be a critical predictor using feature analysis because county is effectively a subset of maintenance district and thus "steals" its importance.

The features discussed herein can be roughly grouped into three categories:

1. Pipe geometry containing total length, current inside width, cover, and pipe ties
2. Pipe geography containing maintenance district, county, roadway type, and route number
3. Pipe condition containing infiltration, void in road, road distress, and inslope cavity

Summing the contributions for each category, pipe geometry accounts for 11% of the predictive capacity, pipe geography for 39%, and pipe condition for the remaining 50%. These results indicate that pipe condition and the presence of joint separation are strongly correlated. The most likely explanation is that joint separation consistently leads to distress such as infiltration and inslope cavities. The relative predictive strength of pipe geography over pipe geometry implies that location, usage, and installation of pipes is more important than the type of pipe.

2.4 Results for Joint Separation by Feature

The features of interest in Table 2.1 were investigated in the database to observe their correlations with joint separation. Figures were created to show the number of entries in the database with that feature (blue bar = Bin Count), the number of those entries that have joint separation (green bar = Joint Separation), and the percentage of those entries with joint separation (red line = Joint Separation Rate). The number labels in the figures indicate the Bin Count for each feature to help highlight bins that have very few entries.

Figure 2.2 shows the rate of joint separation by culvert length (L). No clear trend is evident except that very short culverts (length less than 12 ft) rarely have joint separation. Otherwise, most bins have between 19% and 22% of culverts with joint separation, regardless of length.

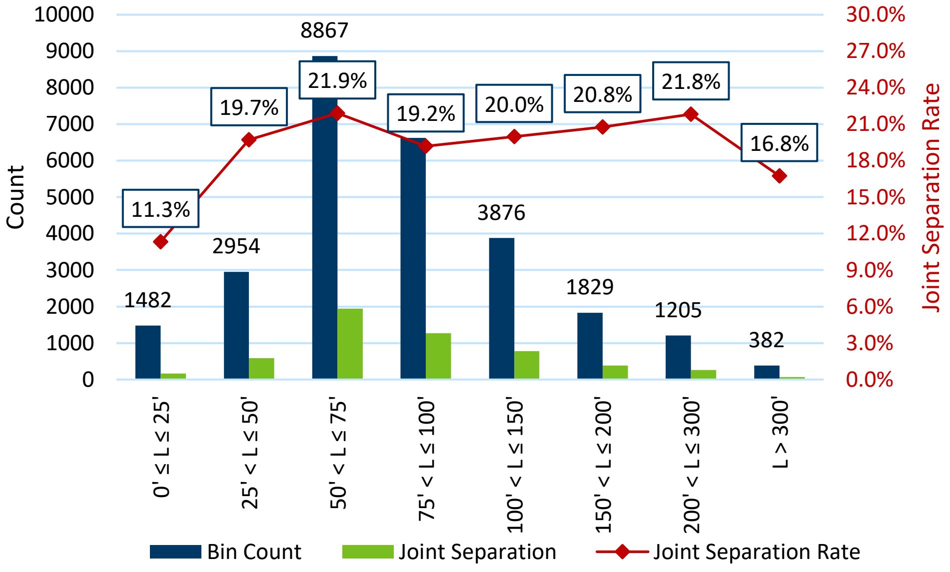


Figure 2.2: Rate of joint separation by culvert length (L)

Figure 2.3 examines the impact of culvert width (w), equivalent to the inside diameter for round culverts. The Random Forest model gave this feature insignificant importance, and the only observed trend was that very small culverts (less than 18-in. diameter) seldom have joint separation. It was not clear from the data whether this is because these culverts are more resilient, or because joint separation may be difficult to detect in small culverts with limited access. Joint separation appears to be notably more prevalent for culverts with diameter equal to 24 in. or greater than 48 in., with joint separation rates nearing or exceeding 25%.

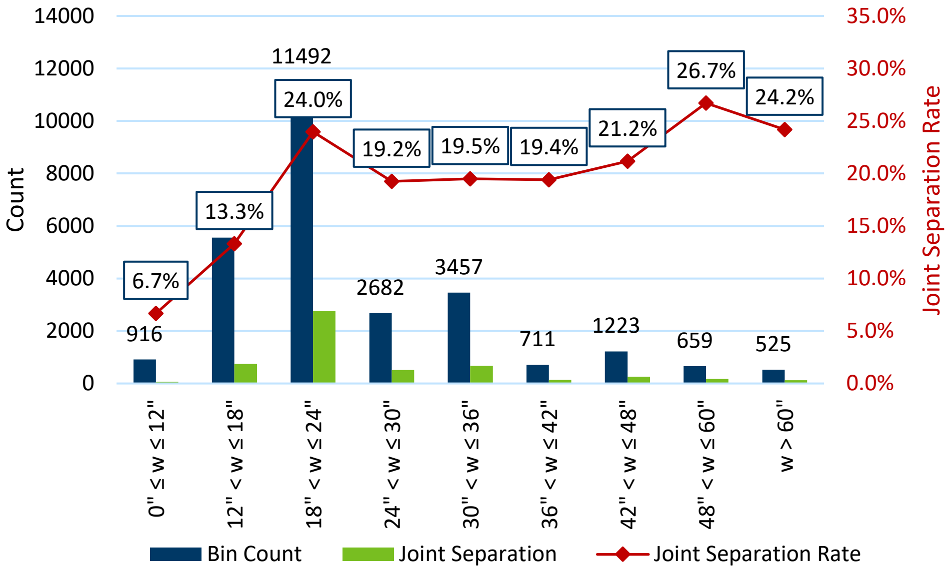


Figure 2.3: Rate of joint separation by culvert width (w)

Data in Figure 2.4 show the impact of depth of soil cover (d) on joint separation. This feature was unimportant in the Random Forest model, but a clear trend was evident in the database. The topmost bin (cover greater than 16 ft) had significant rates of separation exceeding 30%.

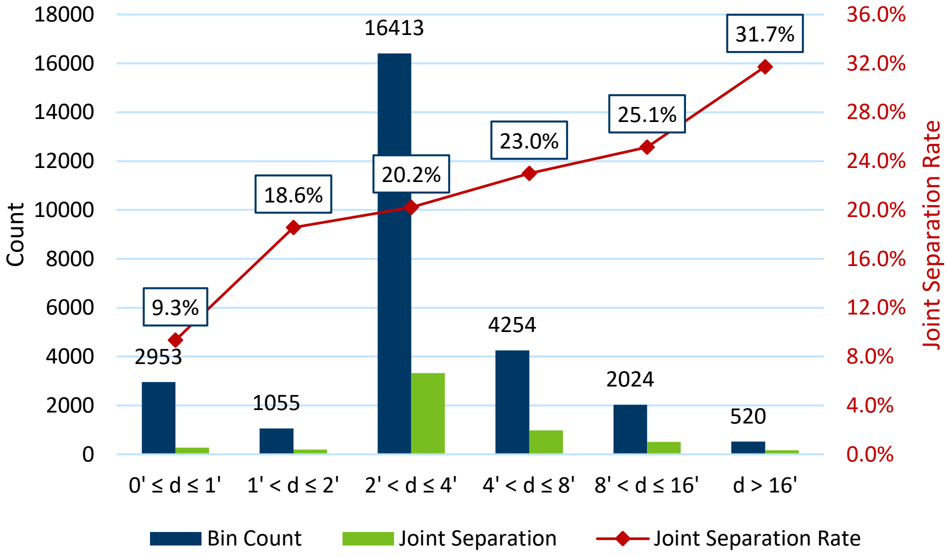


Figure 2.4: Rate of joint separation by depth of soil cover (d)

Figure 2.5 shows the rates of joint separation observed in the eight MnDOT maintenance districts (shown in Figure 2.6). Districts 6 and 8 appear to have considerably higher rates of joint separation issues than the other districts. To observe if this observation was correlated with different pipe tie practices in different districts, the percentage of round pipes in each district with pipe ties is provided in Table 2.2. While the prevalence of joint ties is lower in District 6 as compared to other districts (except Metro), it seems unlikely that this fully explains the dramatic increase in joint separation incidents in that district. Metro district appears to have far more blank pipe tie entries compared to other districts, and none of the more recently constructed entries from Metro district (post 2015) have information on pipe ties; the low number of pipe ties in the Metro district was deemed anomalous and likely not reflective of reality. Figure 2.7 shows the rate of joint separation for all culverts with or without pipe ties. The presence of pipe ties decreases the incidence of joint separation significantly.

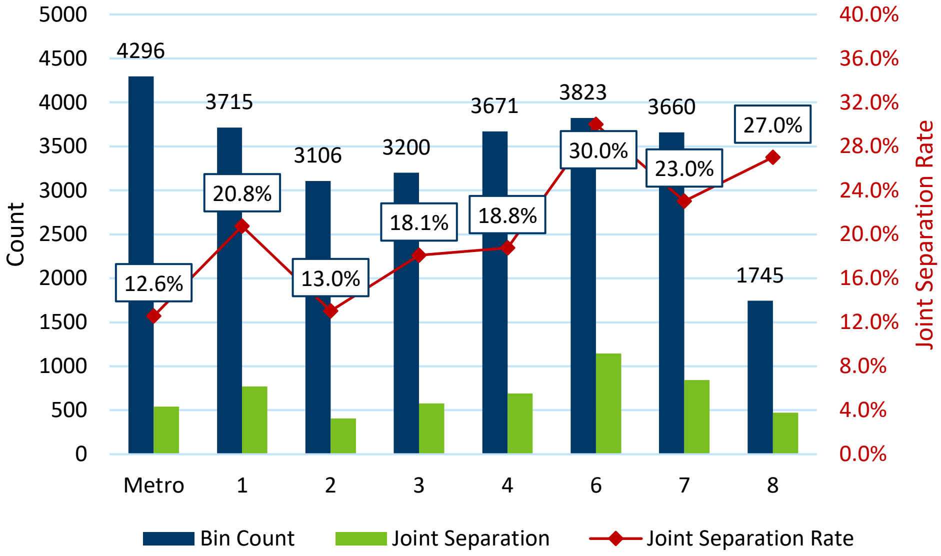


Figure 2.5: Rate of joint separation by maintenance district

Table 2.2: Pipes in each maintenance district with pipe ties recorded in database

District	Total Pipe Count	Pipes with Joint Separation	Joint Separation Rate	Pipes with Ties	Pipe Tie Rate
Metro	4296	540	12.6%	703	16.4%
1	3715	771	20.8%	2563	69.0%
2	3106	405	13.0%	2021	65.1%
3	3200	579	18.1%	2098	65.6%
4	3671	689	18.8%	2106	57.4%
6	3823	1147	30.0%	2034	53.2%
7	3660	842	23.0%	1976	54.0%
8	1745	471	27.0%	984	56.4%

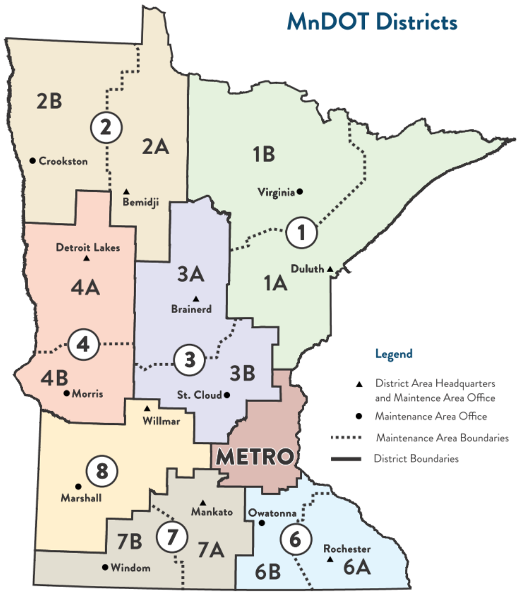


Figure 2.6: Map of MnDOT maintenance districts

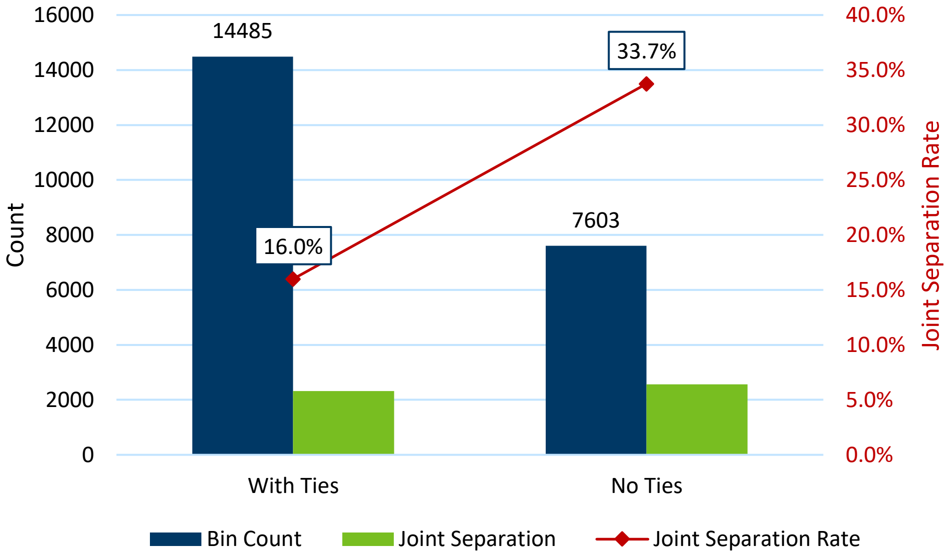


Figure 2.7: Rate of joint separation with (With Ties) or without (No Ties) pipe ties

Most entries within the database do not contain information on the types or number of pipe ties installed on the culvert. However, 579 database entries contained comments indicating that pipe ties were not included along the entire length of the culvert, a practice known as partial pipe ties. Partial pipe ties are placed at the ends of culverts across only the first few culvert joints; a typical historical practice was to tie the apron joint plus the first three pipe joints from each end, though some partially tied pipes may have fewer tied joints. Among the 579 entries with partial pipe ties, 220 had joint separation, indicating a joint separation rate of 38%. While this sample size is small and underestimates the number of culverts with partial pipe ties, the results imply that the practice of partial pipe ties does not control joint separation and may in fact exacerbate the problem.

Though most entries in the database have no information regarding whether the pipe uses a gasketed or non-gasketed joint, nearly 1200 entries do contain this information. Of these entries, non-gasketed pipes appear to have a higher likelihood of joint separation, as shown in Figure 2.8. However, the rates of joint separation for these pipes, peaking at 14.6% for the non-gasketed pipes, were notably lower than the overall rate of joint separation throughout the database, which was roughly 20%. Ditch block culverts are short culverts, not under pavement and typically found in medians or ditches, that drain into a centerline culvert.

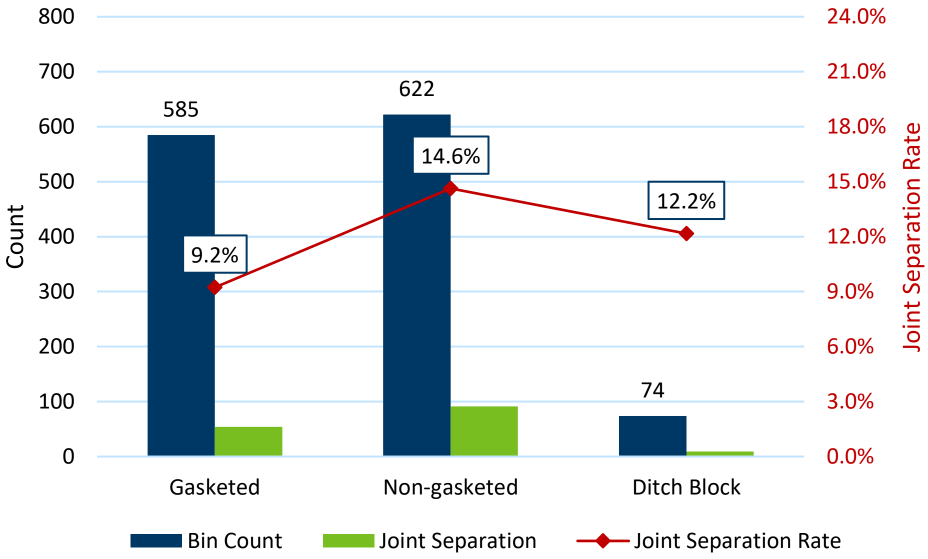


Figure 2.8: Rate of joint separation by pipe type

Figures 2.9 through 2.12 show the rates of joint separation when four types of damage are recorded, namely infiltration, road distress, roadway voids, and inslope cavities. Unsurprisingly, infiltration has an extremely high correlation with joint separation, such that nearly 90% of pipes with infiltration also have recorded joint separation. Plots for roadway voids and inslope cavities are similar, though with slightly lower rates around 80%. Joint separation is also prevalent where road distress is present, though this type of damage has the lowest rate of joint separation at approximately 50%. Logically, these plots illustrate that joint separation leads to further distress at relatively high rates, not that these types of damage lead to joint separation.

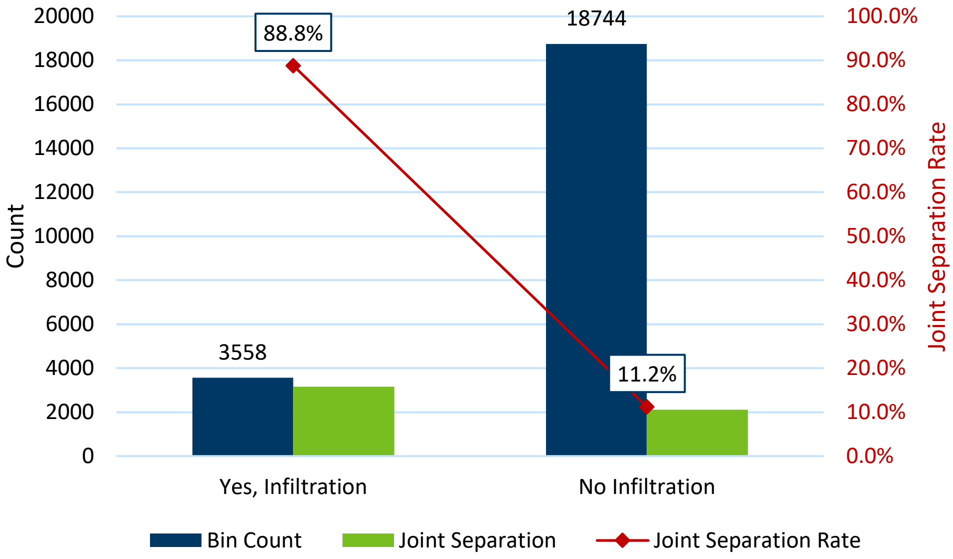


Figure 2.9: Rate of joint separation with (Yes) or without (No) infiltration

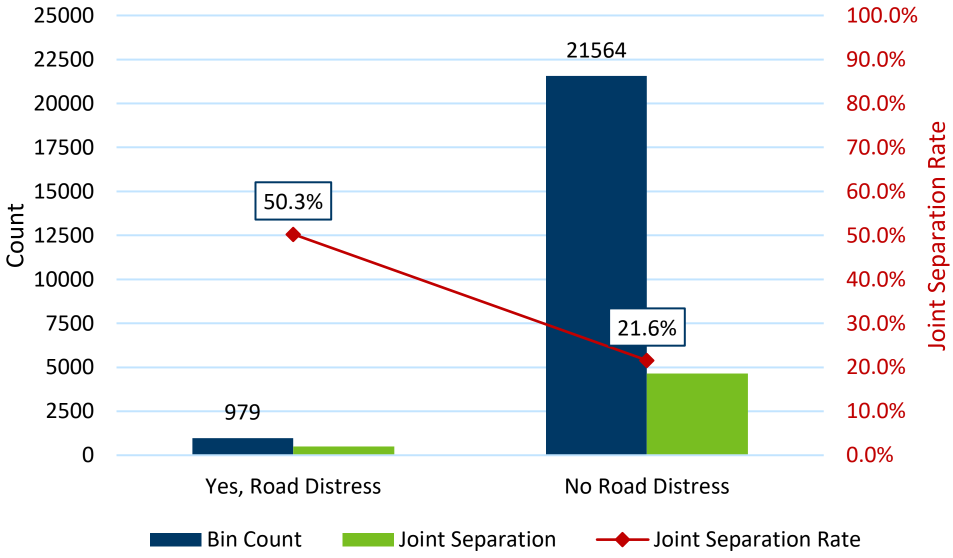


Figure 2.10: Rate of joint separation with (Yes) or without (No) road distress

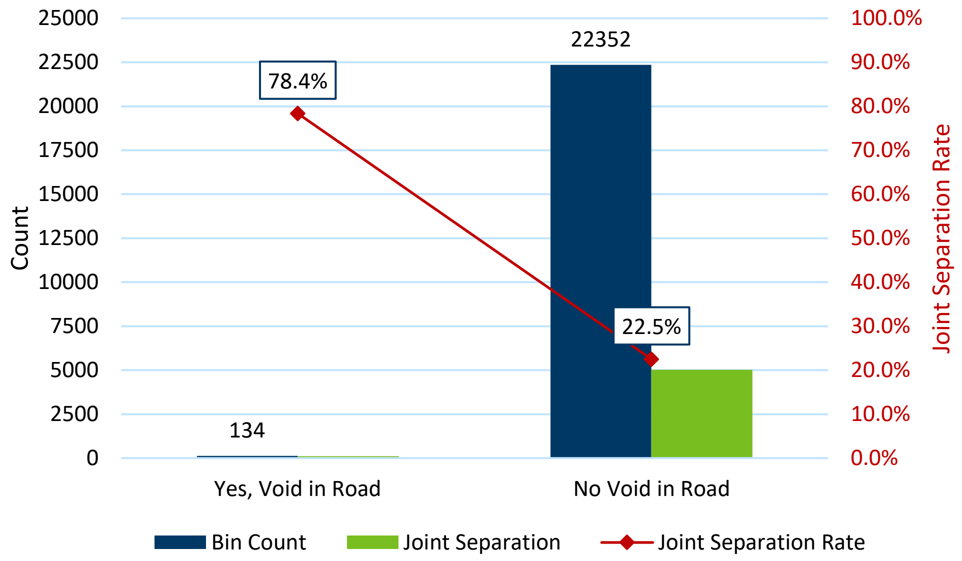


Figure 2.11: Rate of joint separation with (Yes) or without (No) roadway voids

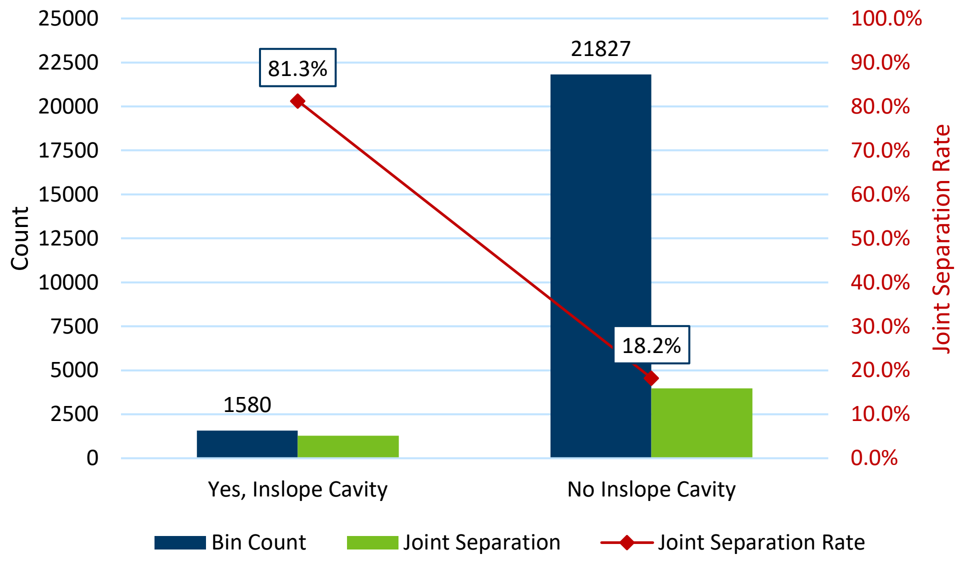


Figure 2.12: Rate of joint separation with (Yes) or without (No) inslope cavities

The filtered database contained culverts from 172 different routes. Figure 2.13 shows the incidence of joint separation for culverts located on Interstate, US Highway, State Highway, and Other routes. State highways tended to have a slightly higher joint separation rate than interstate and federal highways, but the difference was not significant. The Other category contained any entry not located within the preceding three categories and was too small to be statistically significant.

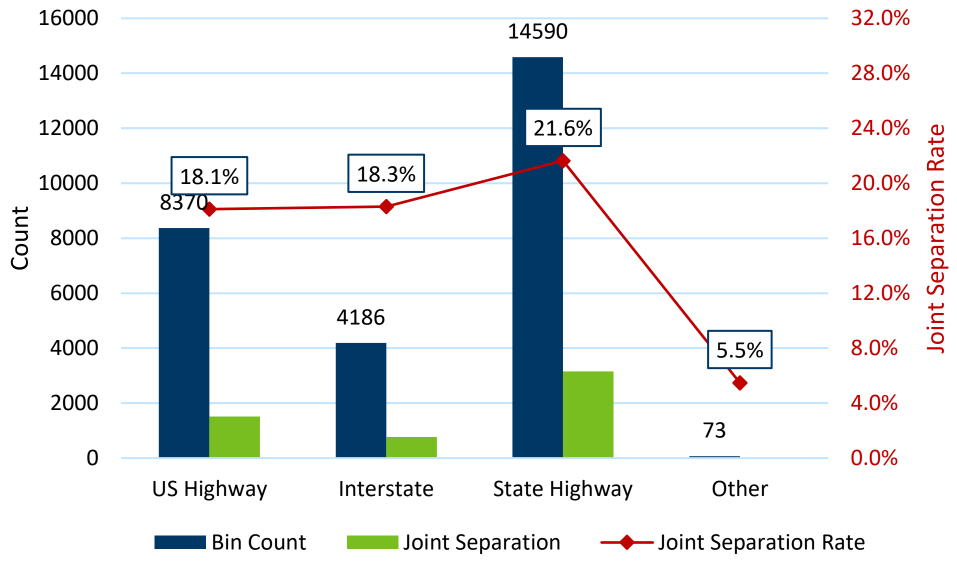


Figure 2.13: Rate of joint separation for different Route ID types

Joint separation rates were analyzed for the 87 different counties throughout Minnesota. Table 2.3 presents data for counties with the highest rates of joint separation, in excess of 30%. Figure 2.14 shows a map of Minnesota with joint separation rates for all counties.

Table 2.3: Counties with highest rates of joint separation, in excess of 30%

County	Pipe Count	Pipes with Joint Separation	Joint Separation Rate
Lincoln	76	50	65.8%
Lac Qui Parle	155	84	54.2%
Pipestone	61	27	44.3%
Houston	159	70	44.0%
Chippewa	115	49	42.6%
Brown	163	68	41.7%
Rice	390	154	39.5%
Le Sueur	244	86	35.2%
Freeborn	388	134	34.5%
Morrison	263	90	34.2%
Redwood	132	45	34.1%
Fillmore	267	87	32.6%
Todd	235	76	32.3%
Winona	459	144	31.4%
Goodhue	460	143	31.1%
Wadena	42	13	31.0%
Rock	228	70	30.7%
Nobles	372	114	30.6%

The highest rates of joint separation were consistently observed in southern Minnesota, aligning with District 6 (Lincoln, Pipestone, and Lac qui Parle counties), District 7 (Brown and Le Sueur counties), and District 8 (Houston and Rice counties) from Figure 2.5. A secondary critical region was noted in central Minnesota in District 3 (Morrison, Todd, and Wadena counties). Many of these regions, particularly in southeast Minnesota, have topography with a high density of intermittent streams and rapidly changing geomorphology, as shown in Figures 2.15 through 2.18. The topographical map of Minnesota in Figure 2.19 further highlights the complex and rapidly changing elevation in southeast Minnesota.

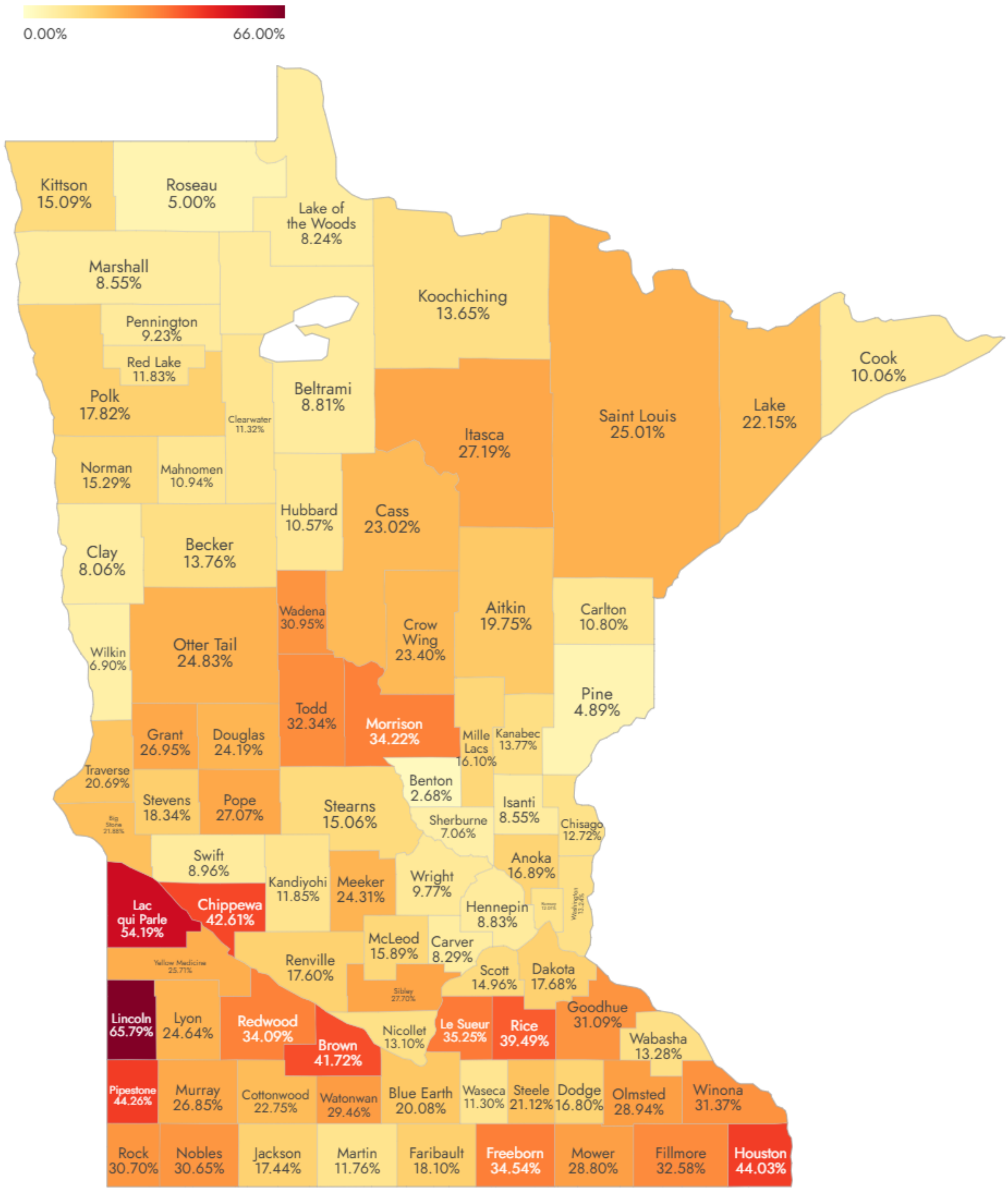


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Figure 2.14: Rate of joint separation for Minnesota counties

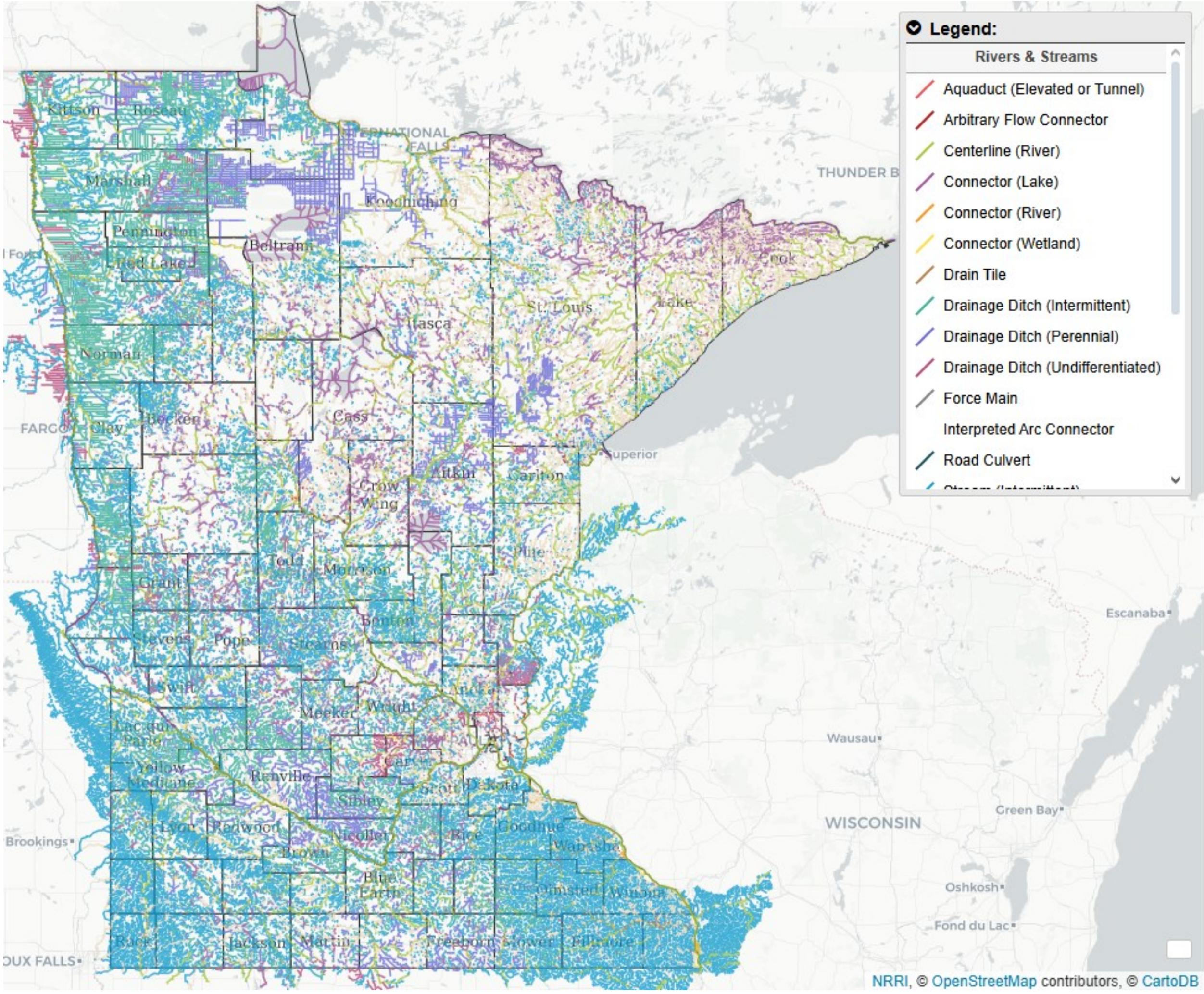
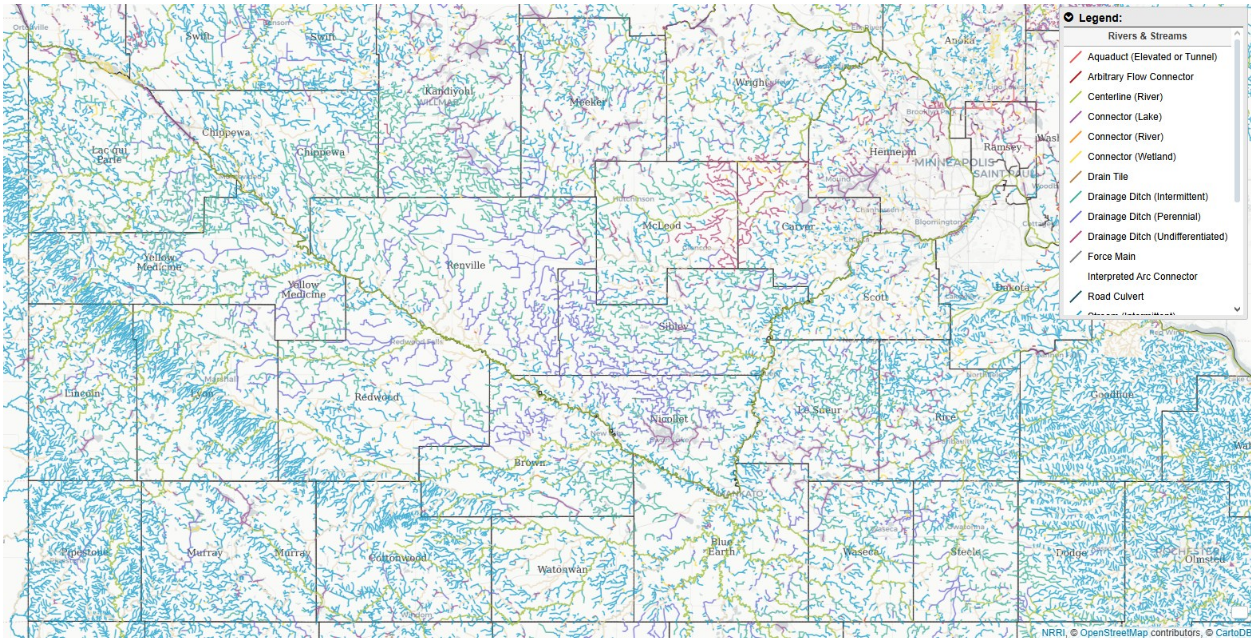
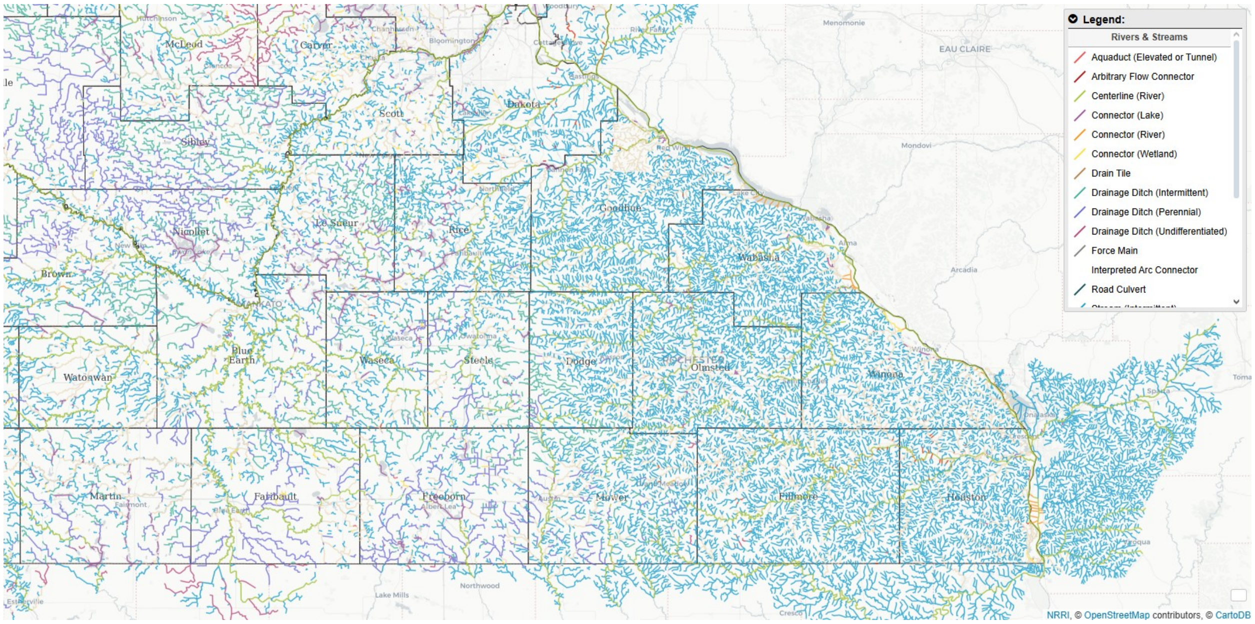


Figure 2.15: Rivers and streams throughout Minnesota (Natural Resources Research Institute)



(a) Southwest Minnesota



(b) Southeast Minnesota

Figure 2.16: Rivers and streams throughout (a) southwest and (b) southeast Minnesota show high concentrations of intermittent streams (cyan) feeding into rivers (green-yellow) (Natural Resources Research Institute)

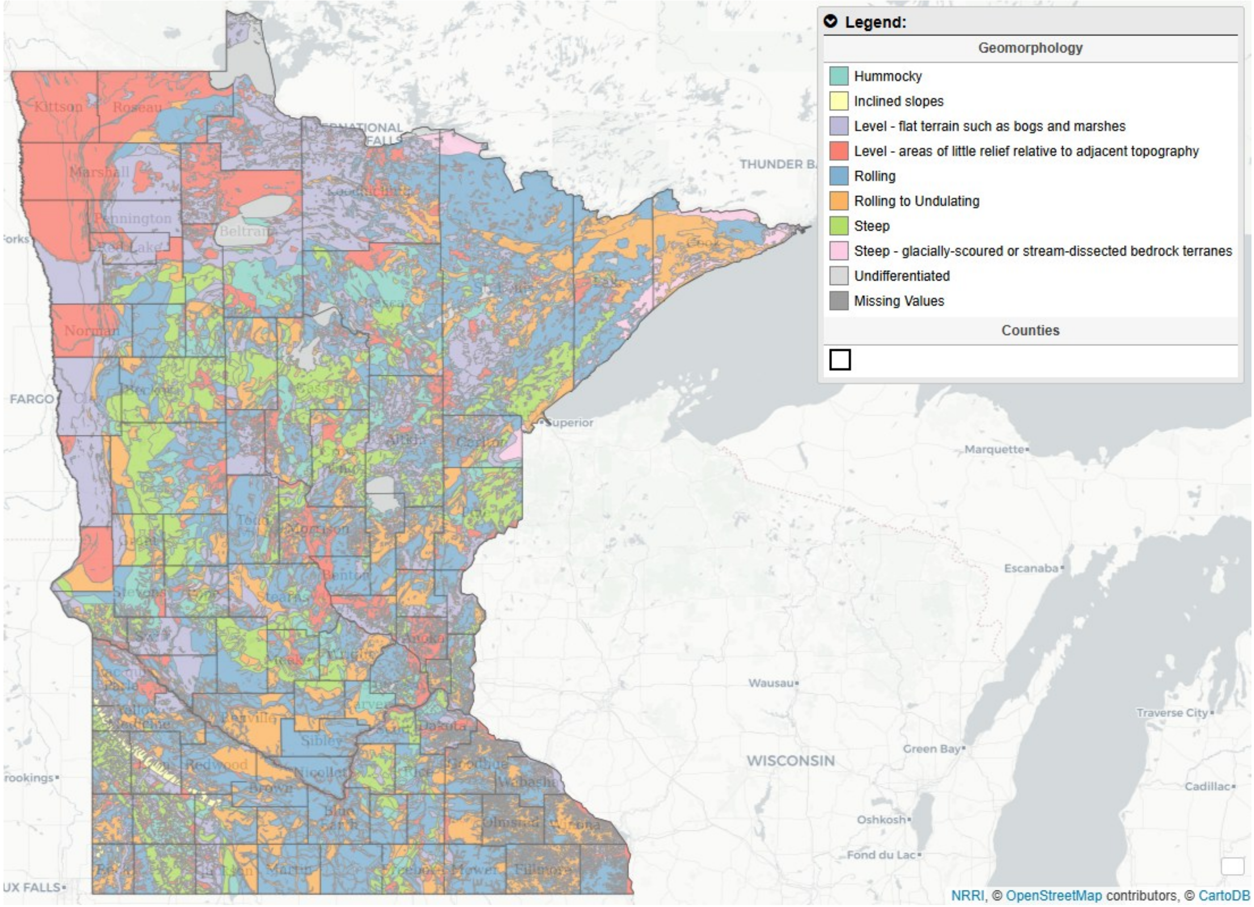
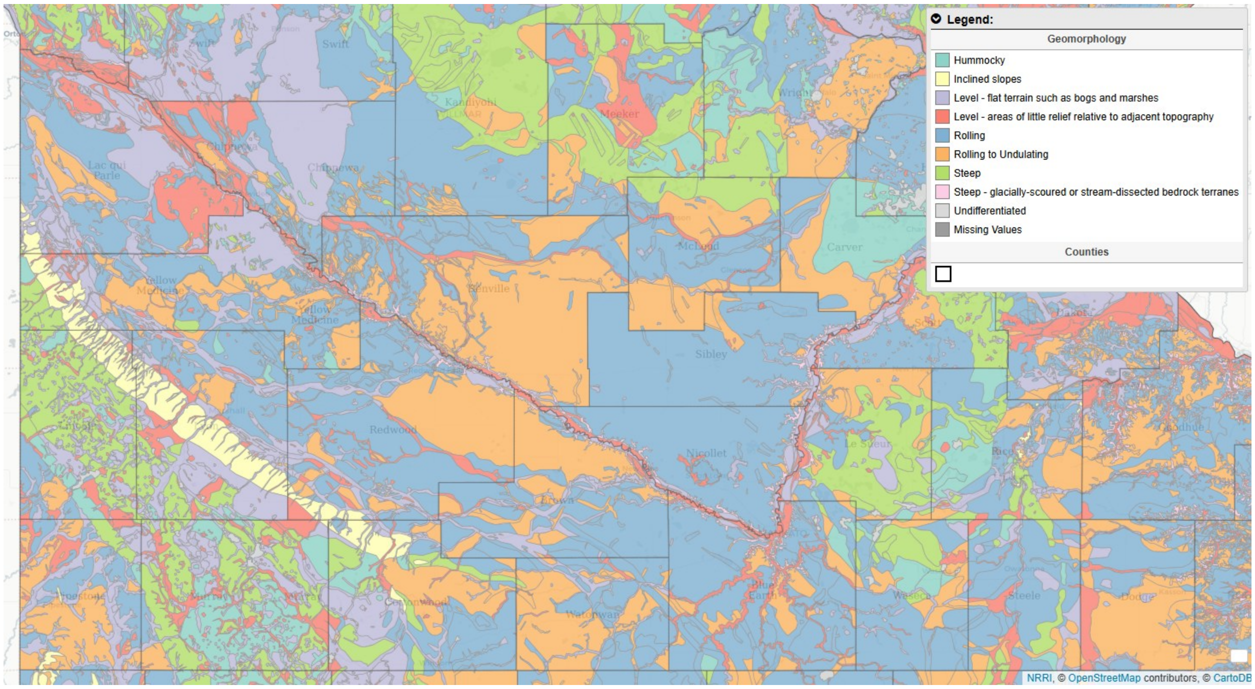
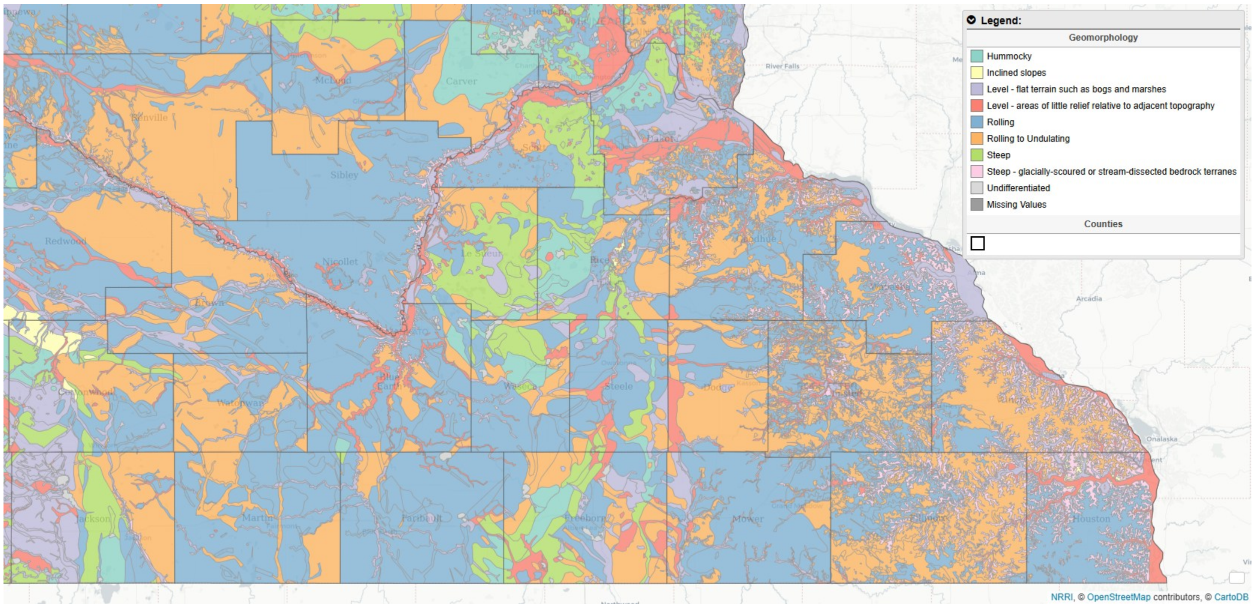


Figure 2.17: Geomorphology throughout Minnesota (Natural Resources Research Institute)



(a) Southwest Minnesota



(b) Southeast Minnesota

Figure 2.18: Geomorphology throughout (a) southwest Minnesota shows high concentration of steep slopes, particularly in Lincoln County, while (b) southeast Minnesota has rapidly changing geomorphology from rolling to undulating (orange) to glacially-scoured steep (pink) features (Natural Resources Research Institute)

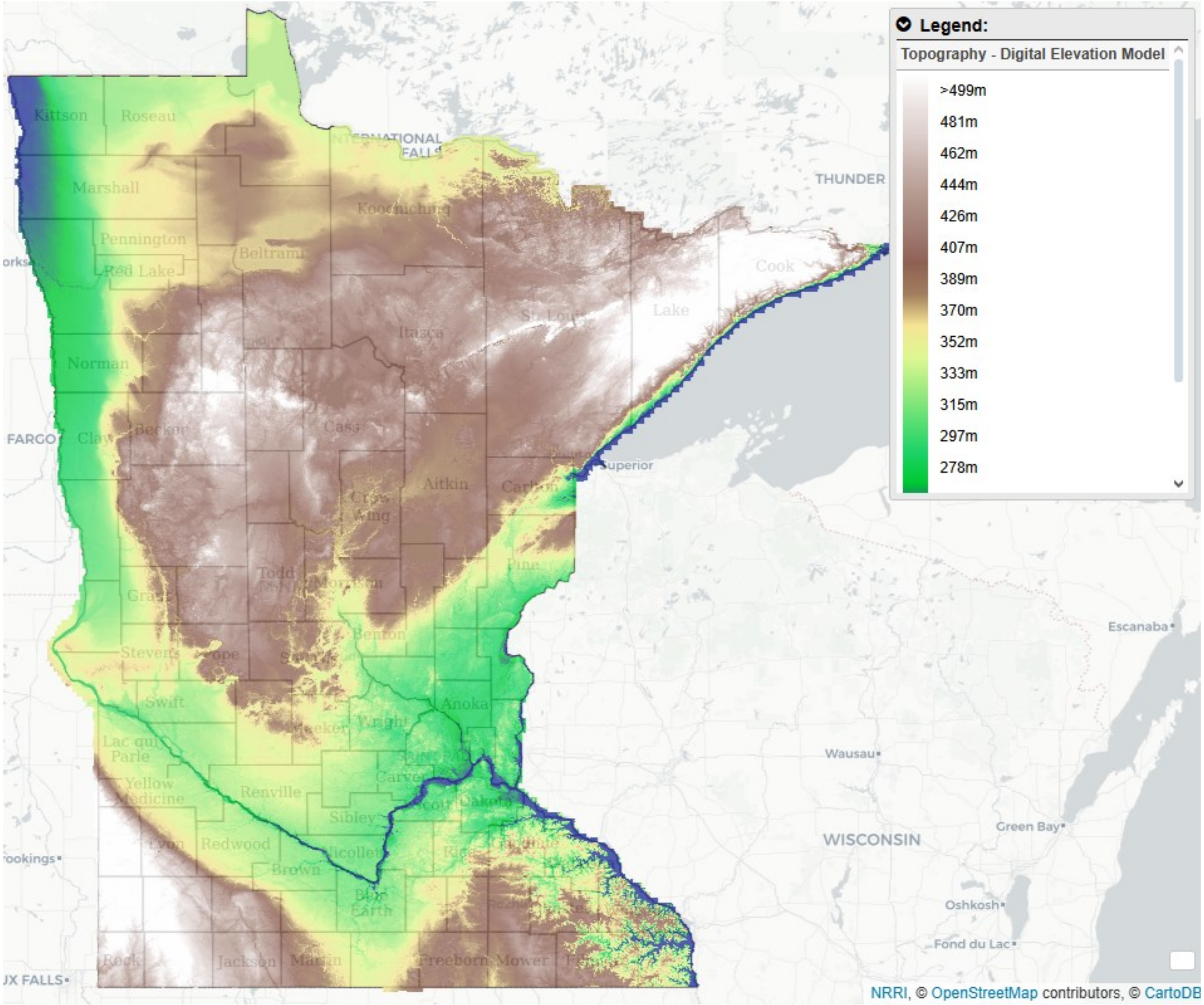


Figure 2.19: Topographical map of Minnesota (Natural Resources Research Institute)

2.5 Summary

Database results showed that joint separation is a multifaceted problem and that no single variable stands out as the primary cause. Feature importance results from the Random Forest model indicated that pipe condition was the most important predictor for joint separation, followed by geographic factors, and finally pipe geometry. The strong correlation between pipe condition and joint separation indicated that joint separation leads to further distress, particularly infiltration and the formation of inslope cavities. This model showed that the most important features for predicting joint separation were the presence of infiltration, route number, and county in which the pipe was located.

Investigation of individual features within the database confirmed some of the results of the Random Forest model. For example, joint separation was most often observed throughout southern Minnesota in counties with a high density of intermittent streams, and nearly all pipes with infiltration also have joint separation. However, some features that the Random Forest model identified as unimportant still showed strong correlations when investigated further, considering individual features. Increased soil cover and lack of pipe ties both correlated with an increased rate of joint separation. Part of the discrepancy between the Random Forest model and individual feature analysis may be explained by overlapping or correlated features; for example, county contains effectively all the information of maintenance district but with more specificity.

Chapter 3: Field Inspections and MnDOT Survey

3.1 Field Inspections

Eighty-six (86) concrete culverts were inspected throughout Minnesota during the summer of 2024. Figure 3.1 shows the culvert locations. The sampling plan clustered culverts along travel loops beginning and ending in Duluth to maximize the number of culverts that could be investigated. This represents a change from the original research plan, which called for the inspection of 40 culverts more evenly distributed throughout the state. The executed plan allowed for the inspection of multiple similar culverts, constructed at around the same time and all under the same road surface, which allowed for some local trends to be observed in the regions where inspections were conducted. However, the adopted strategy provided less overall geographic variety than proposed in the original sampling plan. This left some potentially key locations without any inspections, such as Lac qui Parle and Houston counties, which have significant joint separation issues according to TAMS HydInfra database records.

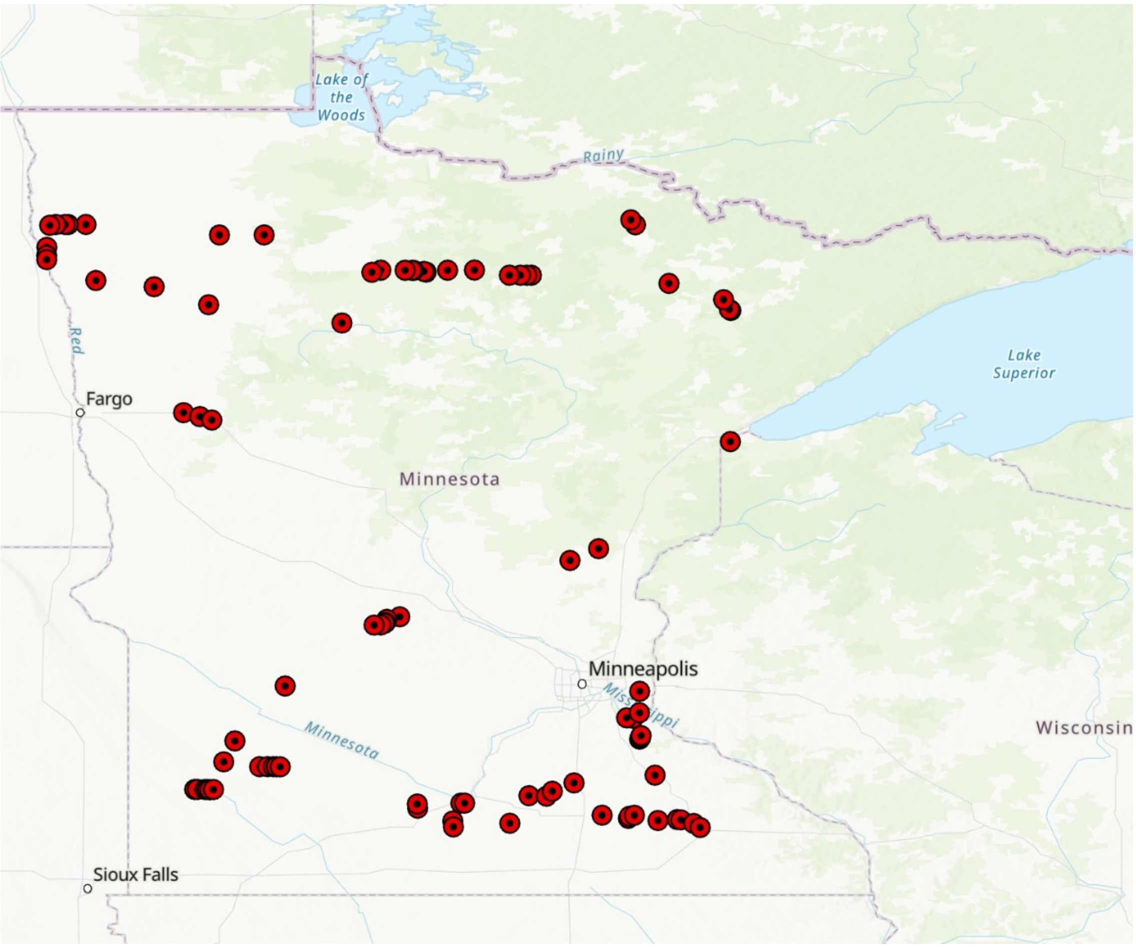


Figure 3.1: Locations of inspected culverts

Table 3.1 summarizes the culverts inspected from each district. The first inspections were performed in District 4, and only a few culverts were inspected here as a trial run.

For inspection purposes, joint separation was classified as an opening in the joint greater than or equal to 1 in. The cause or time of origin of these separations could not be directly observed; it is likely that some of these so-called “separations” have been present since culvert installation, while others developed over time. Furthermore, the numbers in Table 3.1 indicating the number of culverts with joint separation or joint repair do not correlate with the severity of the problem in that district. Instead, culverts were sampled to ensure inspection of a mixture of sites with and without joint separation in each district. A spreadsheet of inspection notes is provided in Appendix A.

Table 3.1: Summary of inspected culverts

District	Total Culverts Inspected	Inspected Culverts with Joint Separation	Inspected Culverts with Joint Repairs
Metro	7	5	2
1	11	6	3
2	22	12	4
3	8	5	0
4	4	1	0
6	12	8	3
7	9	3	1
8	13	9	2
Total	86	49	14

The joints in 81 of the 86 pipes listed in Table 3.1 could be directly inspected; five of the pipes had full-length repairs, liners, or bands on every joint that prevented inspection of the joints. The research team’s classification of joint separation matched the TAMS HydInfra records for 61 out of these 81 culverts. For the remaining 20 culverts where the research team’s classification did not match the TAMS HydInfra database, most were for culverts for which the research team observed small amounts of joint separation (roughly 1 in.) but the database record had either zero or less than 1 in. of separation. Thus, these differences were associated with the subjective nature of visual inspections; the research team tended to err on the side of logging minor joint separations even if they would not compromise the culvert function.

3.1.1 Observations of Joint Separation

Joint separation often manifested as a uniform opening of the joint around the pipe circumference, occasionally with a variation of 1 or 2 in. between opposite sides of the pipe. Figure 3.2 shows some examples of observed joint separation.

Joint separation was often coupled with other types of distress, though this was not always consistent. For example, Culvert 2251008 in District 8, shown in Figure 3.2(a), and many other similar culverts along Highway 68 had significant infiltration at all joints even with only minor separations. However, Culvert 2251023 in District 8, shown in Figure 3.2(b), had larger separation in the first joint but no infiltration, despite being able to fit a hand through the separated joint and touch soil. Any evidence of infiltration could be washed away by high flow events, so lack of deposited material at a joint does not necessarily mean that no material had previously infiltrated through that joint.

Most joint separations occurred at joints without pipe ties, but rare instances of pipe separation or minor infiltration were observed across tied joints. For example, Culvert 2187828 in District 6 had roughly 2 in. of joint separation across a joint with external ties, as indicated by the bolts on either side of the joint in Figure 3.2(c). Observations could not be made to the condition of external ties, which may or may not be broken, but no interior pipe ties were found to be broken. Joints with pipe ties rarely, if ever, had separation greater than 2 in.; only three inspected culverts with pipe ties on every joint had between 2-3 in. of separation at any joint, and none had separation greater than 3 in. 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. In such cases, the magnitude of separation at this first untied joint was typically 2-4 in.

Many culverts with large (greater than a few inches) joint separation also had other damage around the joint. Typically, the inside “tongue” of the joint would be broken away in places, as shown in Figure 3.2(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.

3.1.2 Pipe Tie Types

Several practices for pipe ties were observed in inspections, as shown in Figure 3.3. One primary distinction is between interior and exterior ties. The presence of exterior ties is indicated by the bolts or threaded rods on the inside of the pipe, as shown in Figure 3.3(a). From discussion with inspectors, the primary 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 3.3(b), can be directly inspected. Figure 3.3(c) shows a combination of interior pipe ties with flat tie bars. The flat tie bars in this case were likely installed as a remediation method.

All the inspected culverts with pipe ties had two ties crossing each joint at roughly the 2-o’clock and 10-o’clock positions. Plate 3145G and discussion with MnDOT staff and inspectors indicated that this was the most common arrangement, but other arrangements might be used for larger pipes.

(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 3.2: Typical examples of observed joint separation

(a) Culvert 2207834 in District 8, Exterior Ties

(b) Culvert 2183548 in District 2, Interior Ties

(c) Culvert 2181739 in District 3, combination of flat bar ties and interior ties

Figure 3.3: Example pipe tie installations

Pipe ties were not always placed at all joints. Some partially tied pipes would have one, two, or three sets of pipe ties installed from each end of the culvert, starting with the joint between the apron and the first pipe segment. For example, Culvert 2207834 shown in Figure 3.4(a) had 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. This culvert had misalignment and nearly 3-4 in. separation in the segment immediately after the end of the pipe ties; such observations were common in partially tied pipes. Unfortunately, the presence of partial ties was not clearly defined in the TAMS HydInfra database, as the “Pipe Ties” entry is a “Yes” or “No” value. However, as noted in Section 2.4, 38% of the 579 database entries with comments indicating partial ties had recorded joint separation, compared to 20% of all pipes having recorded joint separation. Thus, field inspections corroborated the database investigation indicating that the practice of partial pipe ties may exacerbate the potential for joint separation.

3.1.3 Observed Repairs

Joint repairs were observed in several inspected culverts; some examples are shown in Figure 3.4. Figure 3.4(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 Figures 3.4(b) and 3.4(c). Finally, some pipes had cured-in-place pipe (CIPP) liners, shown in Figure 3.4(d). Yet others, not shown, simply had grouted or oakum-packed joints.

3.1.4 Observed Installation

On September 24, 2025, the installation of two concrete arch pipes on Highway 25 near Pierz was observed. The pipes had already been aligned and pulled together before the research team arrived on site, so observations were primarily related to the filling and compaction of the fine-grained backfill material around the pipes. Figure 3.5 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 in., as shown in Figure 3.5(b). Compaction near the pipe was completed with a vibratory compactor attached to an excavator, shown in Figure 3.5(c), until 1 to 2 ft 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, constructions vehicles like the roller and excavator directly loaded the pipes once a nominal 1 to 2 ft 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 actual ADT 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 the placement of fill and compaction around the ends of the pipes and about the apron was not observed because it occurred after the research team 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) 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 3.4: Example joint repairs on inspected culverts

(a) Pipe prior to backfill (b) Typical joint with mastic seal

(c) Compaction of backfill (d) Fine-granular bedding around pipe

Figure 3.5: Installation of concrete arch pipe on Highway 25 near Pierz

3.2 Survey of MnDOT Personnel

A Qualtrics survey was distributed to MnDOT construction and inspection personnel to gather their input on likely causes and possible solutions for concrete culvert pipe joint separation. The survey was distributed on February 18, 2025, and 22 completed responses were received. In addition to demographic data, the primary data collected via the survey were answers to the following four questions:

1. Describe what training you have been given (or you have given to others) regarding concrete pipe installation.
2. How often do you see joint issues (separation, breakage, etc.) during pipe installation? Please describe the most common types of issues encountered.
3. What practices have you adopted to prevent joint separation, joint breakage, or soil infiltration in new installations?
4. Please suggest any new practices for culvert installation you would like to have implemented.

The full survey results are presented in Appendix B; relevant results and conclusions from this survey are presented below.

3.2.1 Responses on Probable Causes for Joint Separation

Many survey respondents (35%) had concerns specifically regarding bedding (particularly at the haunches or bells), soil compaction, and general placement of the pipes. Several also commented on breakage of the bells and flanges during installation. During field inspections performed during Summer 2024, the research team noted that many culverts with joint separation greater than a few inches rarely had pipe ties but often had other damage around the joint; see, for example Figure 3.2(d). Measurements of joint separation represent a static measurement at the time of inspection, and do not indicate how much that joint has continued to open with time. Thus, the correlation between breakage and opening could be explained by one or multiple causes:

1. Improper installation could result in broken joints and large separations during installation.
2. Joint breakage during installation may result in decreased resistance of the joint to separation forces and may further increase separation forces if soil or other backfill can infiltrate the joint. This pushes the pipe sections apart over time through material expansion.
3. Large amounts of joint separation negatively impacts the ability to transfer forces across the joints, resulting in joint breakage after separation.

The first two of these explanations appear likely, judging from the survey results indicating bell and flange damage during installation.

3.2.2 Recommended Measures for Installation

The most common suggestion from the survey was to tie all concrete pipe joints, with one respondent stating to use some materials that do not degrade with time. Any steel component should be either stainless steel or at least galvanized. While no details currently exist for nonmetallic pipe ties (for example, glass-fiber reinforced polymers), further exploration of these as a possible solution is recommended. Central to the adoption of using pipe ties across all joints is ensuring that installation and alignment are simple. Further comparison of joint details among the districts is encouraged to determine which details are most feasible. In addition, the practice of placing ties on the outside of the pipe, while desirable from an installation and initial inspection standpoint, makes future inspection of the ties impossible once the trench is filled; therefore, durability of the ties is paramount.

Tie strength is also important to maintain longevity of the tied joints. Typical details use tie diameters ranging from 5/8-in. for pipes of 27-in. diameter or less all the way up to 1-in. for pipes of 72-in. diameter or more. Assuming Grade 36 steel (per Standard Specification 3306), a 5/8-in. diameter tie will yield at 11 kips, while a 1-in. diameter tie will yield at 28 kips. Model results, discussed in Chapter 4, for a 24-in. diameter culvert under 8 ft of cover show that joints under these conditions may have 40 to 80 kips of tension, depending on the soil stiffness, with high stiffness soils transferring lower forces into the pipe. Two 5/8-in. diameter ties, the typical practice for such a culvert, would yield at 22 kips. This implies yielding and possible fracture of the ties, though several practical features of tied joints are cause for relief. First, it is unlikely that 100% of the joint forces are transferred through the pipe ties. Second, any slip in the ties, joint, or soil-concrete interface will reduce these stresses. Third, because ties are not intended to pull segments together, they likely begin installation with some small amount of freedom of movement and thus would not pick up load until the tie itself is taut (though, as a corollary, the improper practice of using ties to pull joints tight would exacerbate this concern as any freedom of movement in the tie would be removed by such tightening). Fourth, alternative tie details, such as flat bars, may substantially increase the strength of the ties. Each flat bar, shown in Figure 3.6, with dimensions of 3/8-in. by 3-in. and made of Grade 36 steel would have a yield capacity of 40.5 kips, far exceeding the capacity of even a 1-in. diameter tie. Because of this high yield strength, flat bars are likely to be controlled by their anchorage strength to the concrete, though this is still twice that of the anchorage strength of typical round ties.

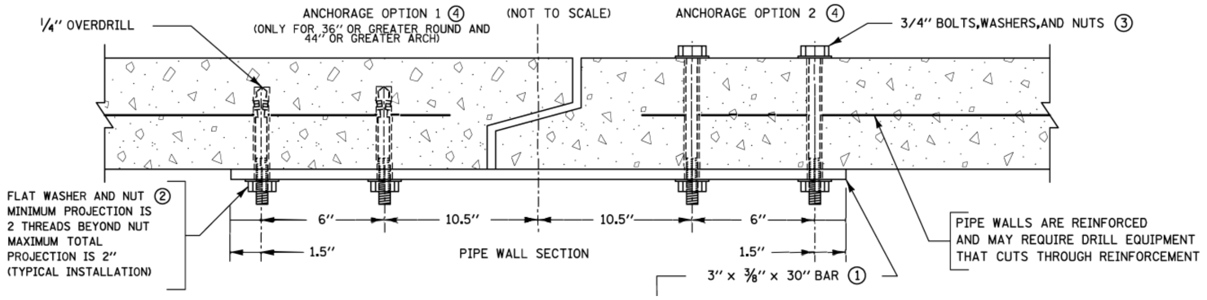
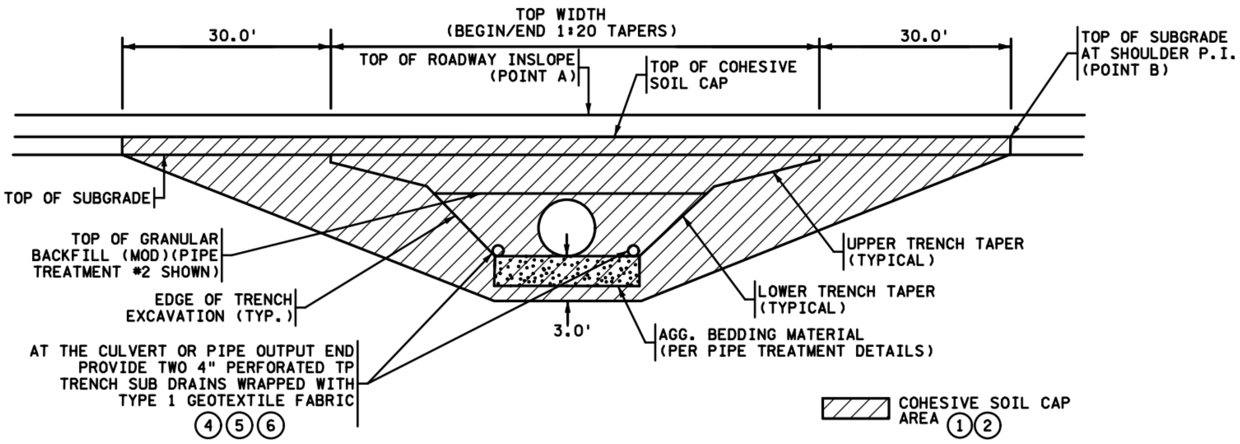


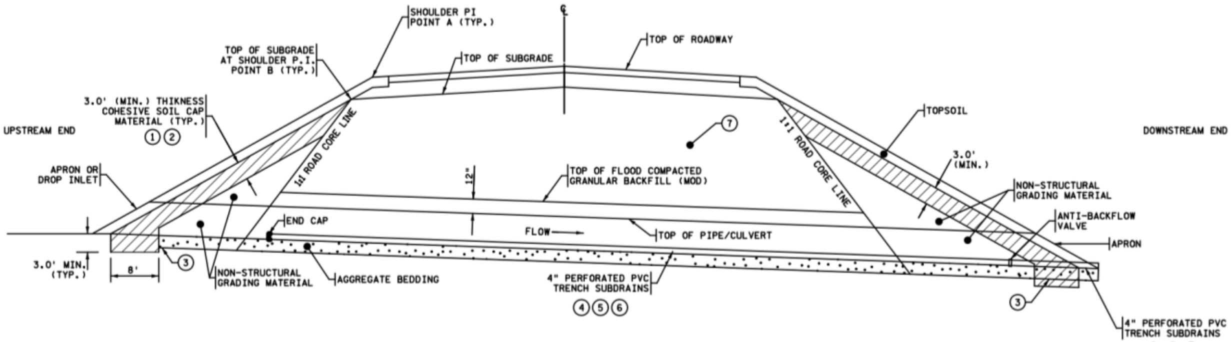
Figure 3.6: Tie bar details provided by District 1

Other installation suggestions received from the survey were related to conditions at the ends of the culvert. One comment highlighted the practice of using clay plugs: "In wet areas, where course filter aggregates are used for pipe bedding, clay plugs are typically used for aprons to prevent water from flowing through the aggregate bedding. I've seen/replaced/reset many aprons where the frost heaves them from the pipe. The clay caps swell more than bedding and cause aprons to move more." Figure 3.7 shows a schematic of a clay plug, also known as a cohesive soil cap, with further figures given in Appendix B. In such a scenario, the coarse filter aggregate is likely to have essentially no expansion upon freezing, but the clay plug may have significant expansion, pushing the apron up and away from the road centerline. Further geotechnical investigations of the frost-heave susceptibility of embankment soils and clay plug material (if present) should be conducted on sites with large joint separations.

Alternative designs for aprons with a toe key or some other form of anchorage may also resist motion, possibly preventing joint separation of the apron or in the last segments of the pipe. Figure 3.8 shows a schematic of one possible design; Appendix B shows another possible design. If the apron is unable to move laterally away from the other segments because of lateral soil pressure on the front of the toe-wall, separation is effectively prevented. However, this design does not prevent motion entirely if, for example, the entire body of soil on both sides of the toe wall move together. More research must be conducted on the viability of this method.



COHESIVE SOIL CAP -- END VIEW



COHESIVE SOIL CAP -- SECTION VIEW

Figure 3.7: Schematic of cohesive soil cap

Most other suggestions obtained from the survey focus on proper compaction of the subgrade and selection of subgrade materials: “I would like to also see at least one person on the pipe crew who must be certified in Grading and Base, so they understand the needs for water and compaction correlation. Good subgrade material is what holds the pipe in place and the road from being excessively impacted by freeze thaw cycles. Joints are less likely to separate when the subgrade has good compaction and is able to drain water out of the surrounding area.” Several respondents noted that adequate water must be used when compacting the fine aggregate bedding: “It’s almost impossible to get contractors to add water during compaction of fine aggregate bedding, it’s also hard to get passing DCP's. Including a requirement to add water during compaction as needed called out in the drainage plans may help.”

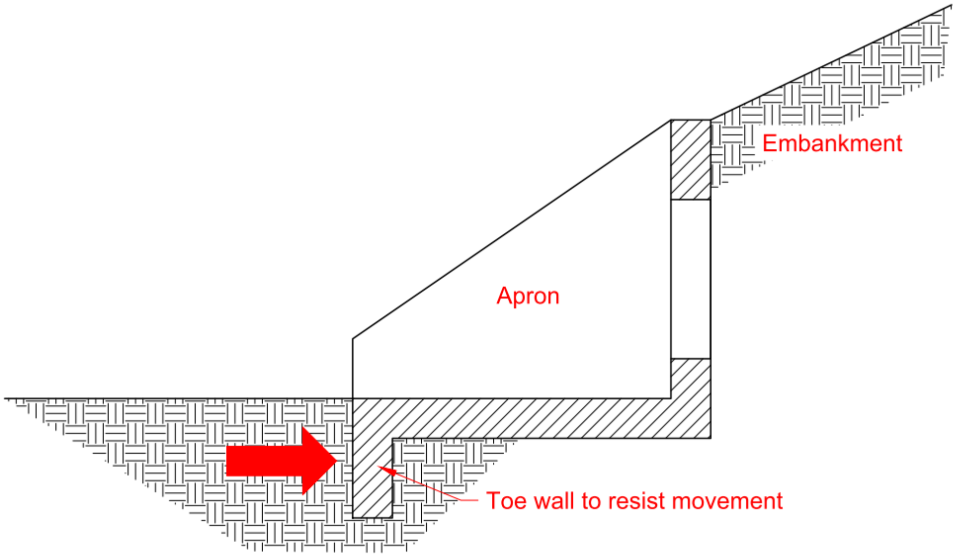


Figure 3.8: Schematic of an apron with a toe wall for anchorage

3.2.3 Recommended Repairs for In-Service Culverts

The survey results did not focus on repairs or retrofits. If the goal of the repair is to prevent infiltration, cured-in-place pipe (CIPP) liners, shown in Figure 3.4(d), have been installed on multiple pipes throughout the state. However, further research is needed to determine the long-term reliability of these repairs.

3.3 Summary

Field investigations highlighted the importance of pipe ties in controlling joint separation. Entries in the TAMS HydInfra database listed with pipe ties do not necessarily have ties on all joints, and a common historical practice has been to tie only a few joints at the ends of the pipes. This practice, called “partial pipe ties” in this report, tends to push joint separation to the first joint just past the ties. In the absence of pipe ties, joint separation was most often observed near the ends of pipes but was occasionally observed deeper within the embankment or under the road surface. Some untied pipes, such as those along Highway 68 east of Marshall in District 8, had joint separation at every joint. Joints with very large separations greater than 5 or 6 in. often had some other damage in the pipe, such as breakage of the concrete tongue. Demands during pipe installation, including the compaction of granular backfill above and around the pipe plus live loading from construction vehicles, may induce significant separation demands, especially for pipes with large depth of cover.

Results from surveys of MnDOT personnel included recommendations for controlling joint separation. The most common suggestion was to provide pipe ties on all joints. Others highlighted the likelihood of freeze-thaw damage, particularly at the ends of pipes. The demands placed on pipe ends may be exacerbated by the presence of cohesive soil caps, which could expand far more than the granular backfill material compacted around the pipe.

Chapter 4: Computational Modeling

Finite difference (FLAC3D) and finite element (ANSYS) numerical models of an embankment and culvert were used to quantify forces transmitted from soil to culvert segments. These forces act along the longitudinal axis of the culvert pipe are postulated to lead to culvert joint separation. The models depicted round concrete pipes buried within an embankment, as these are the most common highway culvert in the MnDOT inventory. FLAC3D was to construct the base model of a continuous culvert (i.e., a culvert with joints capable of transferring load) with typical dimensions and mechanical properties for soil and concrete. This model was used to investigate traffic loading, rise of phreatic level, and soil freezing. Vertical loading was also simulated in a companion ANSYS model to validate the results of FLAC3D and to explore the effects of different fill heights and culvert diameters. Finite element models were constructed for both the continuous culvert case and for discrete pipe segments unable to transfer load across joints.

This chapter presents details of the modeling process and results obtained from the models, focusing on the distribution of induced shear and axial forces on the culvert. Traffic loading, embankment self-weight, rise of phreatic surface, and soil freezing produced different degrees of lateral movement of the soil around the culvert. This lateral movement induced axial (tensile) loading on the culvert, which is expected to produce separation of culvert segments at the joints.

4.1 Finite Difference (FLAC3D) Numerical Model

4.1.1 Methodology

The software FLAC3D (Fast Lagrangian Analysis of Continua in Three Dimensions) is a commercial finite difference code developed by Itasca Consulting Company (2023) that is widely used in geo-mechanical analyses; it was adopted for this study to create the base model. The geometry of the base model consisted of an embankment and culvert as represented in Figure 4.1. Because of symmetry, only one quarter of the embankment and culvert was modeled. A stretch of embankment 18-ft (5.5-m) wide and 49-ft (15-m) long was modeled (these dimensions are effectively doubled per symmetry). A round culvert with 24-in. (0.61-m) inside diameter and 30-in. (0.76-m) outside diameter with a cover of 4 ft (1.2 m) below the road surface was emplaced within. To simplify modeling, the culvert and roadway surface were both level, though the road surface would normally have a crown and the culvert would have a nominal downstream slope.

Figure 4.2 shows a mesh for the base model depicted in Figure 4.1. The soil and culvert were meshed using 8-node hexahedral elements. An interface of shell elements between soil and culvert elements was included in the model, fully bonding the two components together. The culvert was modeled as a continuous pipe that extends to the embankment slope, approximating the behavior of tied joints.

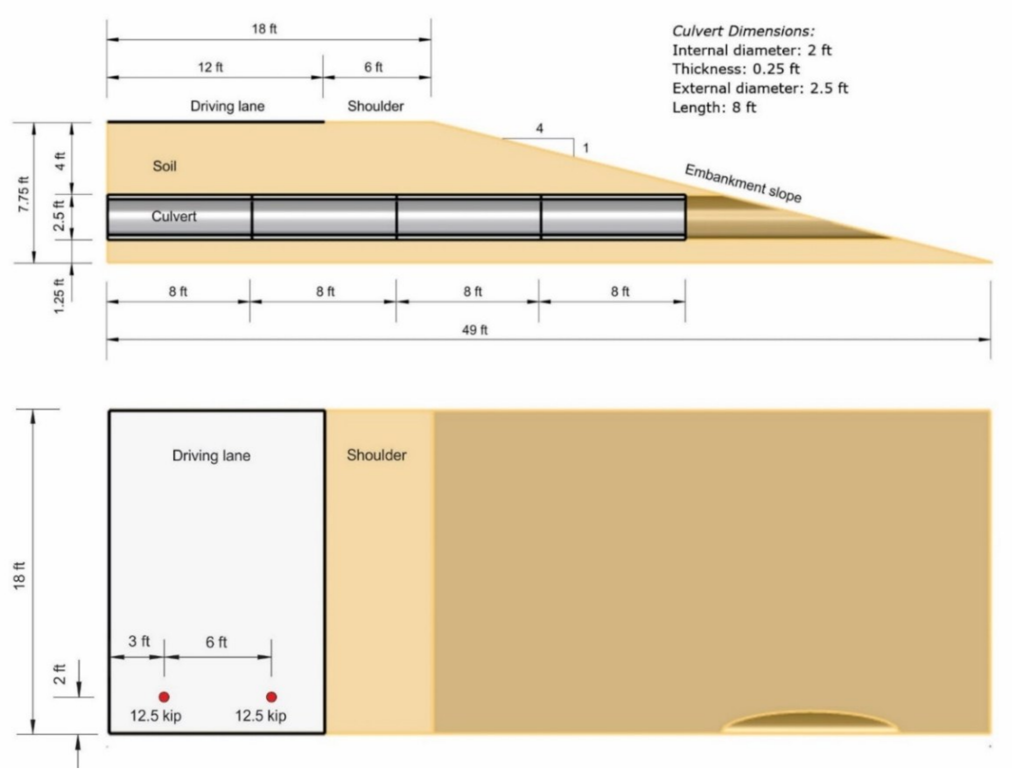


Figure 4.1: Geometry of the embankment-culvert model used in FLAC3D

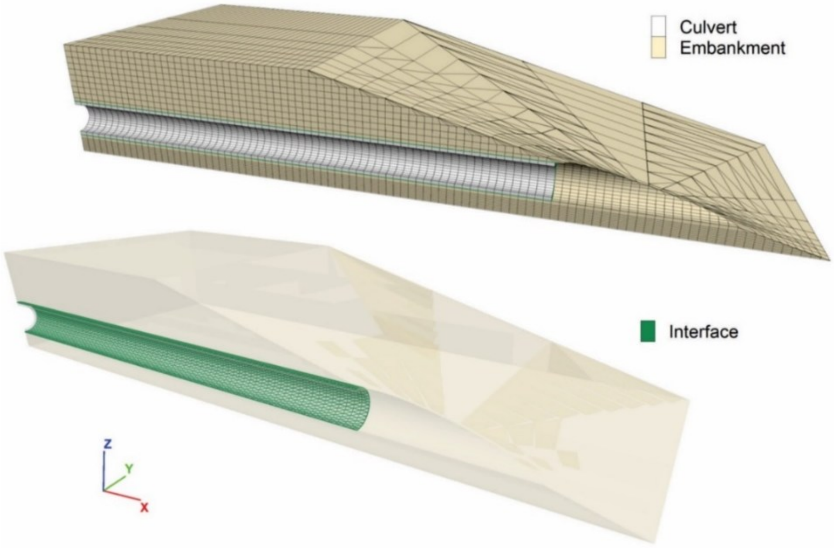


Figure 4.2: FLAC3D meshes showing embankment, culvert, and soil-concrete interface

Boundary conditions were assigned such that the vertical plane representing the road centerline and the vertical plane cutting the culvert along its length would have no displacement in their normal directions, thus enforcing model symmetry. The remaining vertical plane also had no displacement along its normal, reflecting a semi-infinite embankment continuing in the direction of traffic. The bottom horizontal plane was given zero displacement in the vertical direction, meaning the subgrade was modeled as infinitely stiff.

The mechanical properties utilized in the model are listed in Table 4.1. Material properties were chosen to mimic typical values for concrete and silty sand but were otherwise not chosen to match any specific installed system. To simplify the analysis, the soil and concrete materials were assumed to be elastic and isotropic. Inclusion of water in the model for the rise of phreatic level scenario was done by means of a coupled mechanical-hydraulic analysis in FLAC3D. Simulation of soil freezing was done by imposing the frozen soil volumetric expansion to all elements in the model (i.e., the freezing soil scenario assumes that all soil in the embankment freezes and expands).

Table 4.1: Mechanical properties utilized in the FLAC3D model

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
Lateral Earth Pressure Coefficient	0.5
Phreatic Level Model	
Soil Porosity	25%
Soil Saturation	100%
Water Density, lb/ft^3 [kg/m^3]	62.4 [1,000]
Saturated Soil Density, lb/ft^3 [kg/m^3]	141 [2,250]
Water Bulk Modulus, ksi [MPa]	290 [2,000]
Soil Hydraulic Conductivity, ft/s [m/s]	3.28e-5 [1.0e-5]
Soil Freezing Model	
Soil Porosity	25%
Soil Saturation	91.8%
Ice Density, lb/ft^3 [kg/m^3]	56.8 [910]
Frozen Soil Density, lb/ft^3 [kg/m^3]	138 [2,209]
Ice Bulk Modulus, ksi [MPa]	1,280 [8,824]
Water-to-Ice Volumetric Expansion	9%
Frozen Soil Volumetric Expansion	0.0125%

4.1.2 Finite Difference Model Results

To simulate traffic loading, a 50-kip (220-kN) design tandem load was applied to the model per AASHTO LRFD (2020) section 3.6.1.2.3. The two 12.5-kip (55-kN) forces represented on the lower diagram in Figure 4.1 correspond to this traffic load, and the other two 12.5-kip (55-kN) forces are implicitly considered because of the symmetry of the model. Furthermore, because of symmetry of the model across the road and embankment centerline, the application of a second design tandem simultaneously in the other lane is also implicitly considered.

The plot at the top of Figure 4.3 represents the contours of displacement in the soil and culvert resulting from application of the traffic loads. Vectors of displacement magnitude have been superimposed to (parts of) the contour representation. Although the largest "settlement" displacements take place below the point loads, there was also lateral soil movement towards the free surface of the embankment slope. This lateral soil movement induced shear stresses on the soil-concrete interface, which in turn induced axial (tensile) forces on the culvert. The lower plot of Figure 4.3 represents the distribution of the applied force $\Delta T_x(x)$ obtained from the model. Because of model symmetry, the applied shear force computed from FLAC3D and shown in this figure is only half the total applied load; this applied load was subsequently doubled when evaluating the axial demands on the culvert.

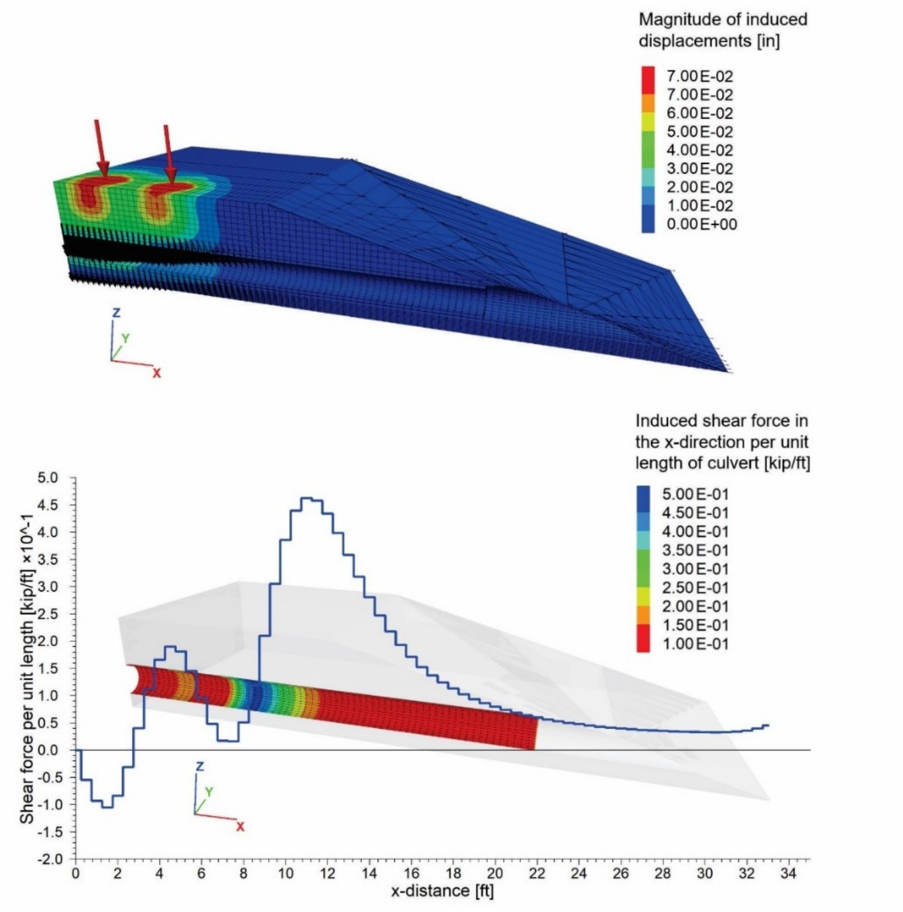


Figure 4.3: Contours of displacements (top), and contours of shear force and diagram of applied shear force ΔT_x on soil-concrete interface (bottom) for the traffic load model

Net separation force was defined as the axial force applied to a single segment of the culvert. Thus, the net separation force for each culvert segment was equal to the integral of the soil-concrete interface force $\Delta T_x(x)$ over the length of that culvert segment. The axial force represents the accumulated demands along the length of the culvert that must be carried across the culvert joints. According to statics, the axial force must be zero at the ends of the pipe, and so axial force was calculated as the integral of the soil-concrete interface force $\Delta T_x(x)$ from the end of the culvert back to position x.

The resulting axial forces on the culvert from the tandem load are shown in Figure 4.4. A view of the culvert split into four 8-ft (2.4-m) segments has been included in these diagrams. The labeled points in the diagram correspond to the values of the axial force at the culvert joints, indicating the axial force demand across that culvert joint assuming that these demands can be readily transmitted from one culvert segment to the next. For the traffic loading scenario, the largest axial forces occurred at the road centerline. For a single design tandem, normally the maximum axial force would be expected to be directly beneath the load. However, because of model symmetry and the implied design tandem simultaneously in the other lane, the demands at road centerline were marginally higher.

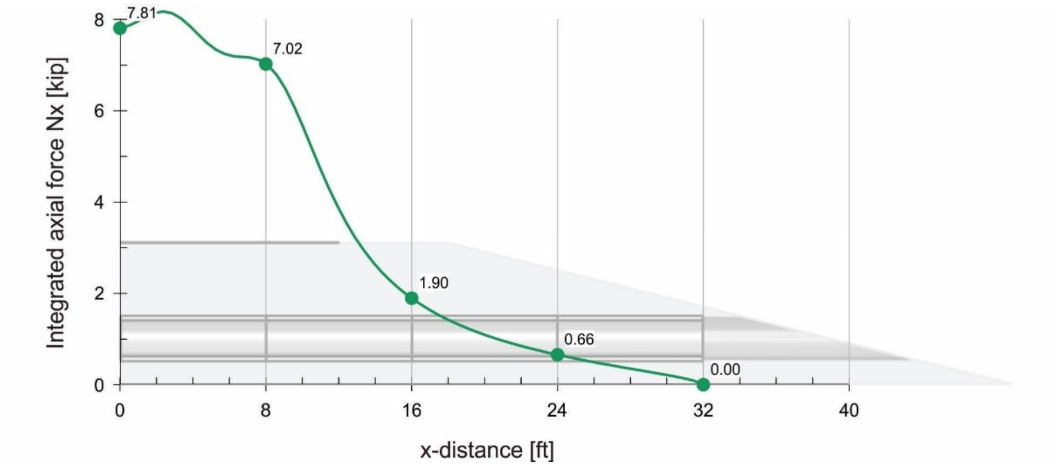


Figure 4.4: Diagram of axial force along the culvert length for the traffic load model

Rise of the water phreatic surface within a soil produced a decrease of the effective stresses with a consequent expansion of soil. For the embankment-culvert problem considered here, this soil expansion induced displacements of the soil towards the free surfaces of the embankment, which in turn generated separation axial forces along the culvert. The scenario considered in this study began with the soil in the embankment as initially dry; then, as water pore-pressure builds (e.g., due to rain), the soil became fully saturated and the phreatic surface was raised to the surface of the embankment and slope.

The resulting internal axial forces on the culvert from the rise of the phreatic surface are shown in Figure 4.5. In contrast with the traffic load scenario, the raise of phreatic level scenario applied the largest net separation forces to the culvert segments closest to the embankment slope, though the accumulation of load along the length of the pipe still resulted in the maximum axial forces at the road centerline. Had an apron been included in this model, it is likely that the apron would have even higher net separation forces, pulling it away from the pipe segment closest to the embankment slope.

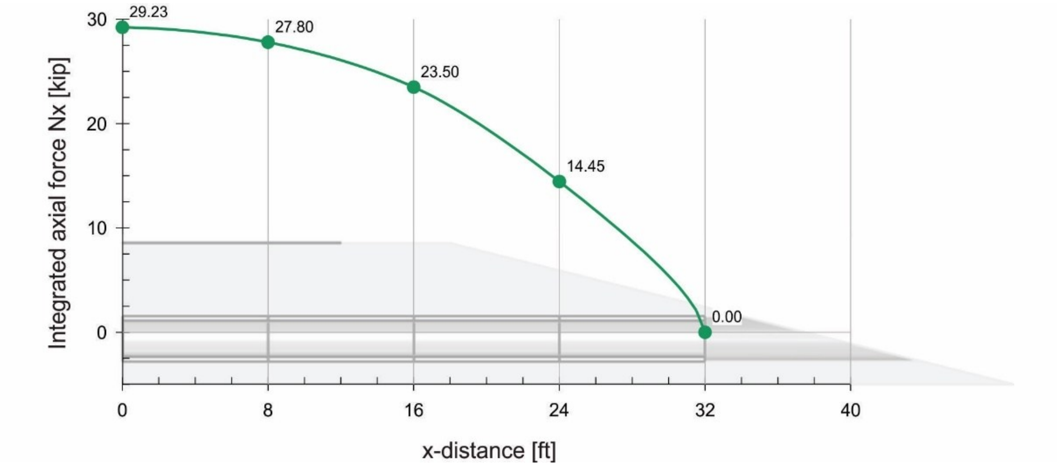


Figure 4.5: Diagram of axial force along the culvert length for the rise of phreatic level model

Soil freezing produces soil expansion. For the embankment-culvert problem, this soil expansion induced displacements of the soil towards the free surfaces of the embankment, which in turn generated axial forces along the culvert. To simplify the analysis and to show the soil expansion mechanism, the limiting (and extreme) case of the full soil of the embankment freezing simultaneously was considered. The resulting internal axial forces along the length of the culvert from soil freezing are shown in Figure 4.6. Like the rise in phreatic surface, the largest net separation forces were applied to the culvert segments closest to the embankment slope. The very abrupt increase in axial force (that is, accumulated force along the pipe length) from the end of the pipe to the first joint indicated that soil freezing concentrated nearly all the net separation force into the single segment nearest the embankment.

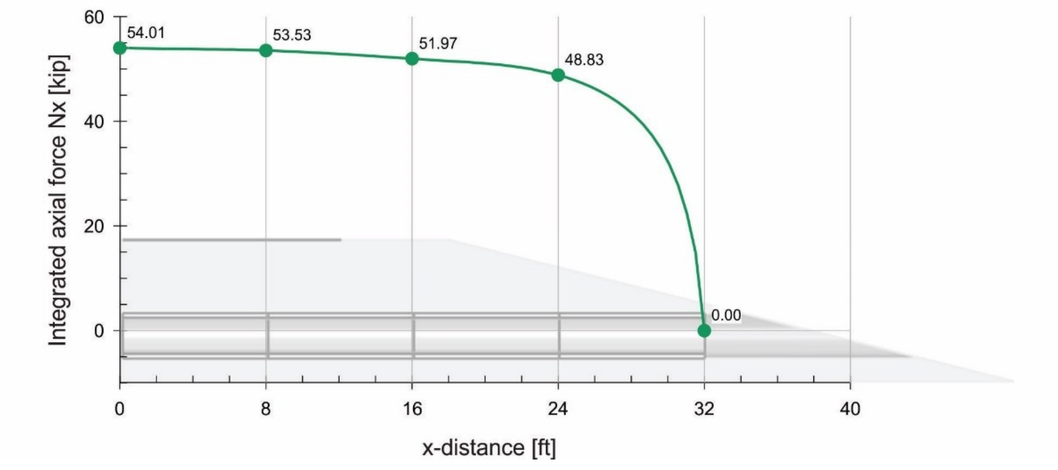


Figure 4.6: Diagram of axial force along the culvert length for the soil freezing model

Table 4.2 includes a summary of the axial force values at the end points of the 8-ft (2.4-m) culvert segments, as determined from the diagrams in Figures 4.4, 4.5, and 4.6. Location *x* is measured from the centerline line of the road (i.e., *x* = 0 represents the road centerline). Table 4.3 summarizes the net separation forces acting on each culvert segment, numbered such that segment 1 is adjacent to the road centerline and segment 4 is nearest the embankment.

Table 4.2: Summary of culvert axial forces at each joint

Location *x*, ft [m]	Traffic Load, kips [kN]	Phreatic Surface, kips [kN]	Soil Freezing, kips [kN]
0 [0]	7.81 [34.7]	29.2 [130]	54.0 [240]
8 [2.4]	7.02 [31.2]	27.8 [124]	53.5 [238]
16 [4.9]	1.90 [8.4]	23.5 [105]	52.0 [231]
24 [7.3]	0.66 [2.9]	14.5 [64.3]	48.8 [217]
32 [9.8]	0.00 [0]	0.00 [0]	0.00 [0]

Table 4.3: Summary of net separation forces applied to each culvert segment

Segment	Traffic Load, kips (kN)	Phreatic Surface, kips (kN)	Soil Freezing, kips (kN)
1	0.78 [3.5]	1.43 [6.3]	0.48 [2.1]
2	5.13 [22.8]	4.30 [19.1]	1.56 [6.9]
3	1.24 [5.5]	9.05 [40.3]	3.14 [14.0]
4	0.66 [2.9]	14.45 [64.3]	48.8 [217]

Comparing the values of net separation force to different culvert segments under the three investigated scenarios, the maximum separation force for the raise of phreatic level scenario was more than twice that for the case of traffic load (i.e., 5.13 kip [22.8 kN] in segment 2 for traffic load compared to 14.5 kip [64.3 kN] for segment 4 for raise of phreatic level). Ground freezing produced a significantly larger magnitude of separation force, with a maximum of 48.8 kip [217 kN].

The series of assumptions made with this model, such as elastic soil conditions, perfectly bonded soil-culvert interfaces, and a continuous concrete pipe rather than a jointed system, all served to overestimate the axial force demands placed on the pipe. Among these assumptions, the bonded soil-culvert interface likely had the greatest impact, as the soil-concrete friction angle is generally less than or equal to the internal friction angle for a soil if a Mohr-Coulomb failure criteria is used. Thus, the assumption for interface friction was evaluated to determine a maximum net separation force that could be transferred through the soil-culvert interface; computed forces exceeding this limit will likely cause slip between the soil and concrete. The properties from Table 4.1 and the following equation were used to compute the axial force that each culvert segment may resist before overcoming static friction according to ASCE (1984) guidelines for pipeline systems:

$$F_A = 0.5\gamma' H\left(\pi D L\right)\left(1+K_0\right)\tan\delta \tag{4.1}$$

where γ′ is the soil effective unit weight, *H* is the depth to pipe centerline, *D* is the pipe outer diameter, *L* is the pipe length, K_0 is the coefficient of lateral earth pressure at-rest, and *δ* is the interface friction angle between the soil and the pipe. Multiple studies (e.g., Meidani et al. 2018, Daiyan et al. 2011, Weerasekara and Wijewickreme 2008) show that this simple expression may underestimate the axial resistance by a significant margin. Assuming an interface friction angle of 25° and geometry matching that of the FLAC3D base model, Equation (4.1) returns F_A = 14.4 kips (64 kN) per segment under dry conditions and F_A = 9.0 kips (40 kN) per segment under saturated and submerged conditions.

Comparing the net separation forces in Table 4.3 to the estimated frictional axial resistance of 9.0 kips (40 kN) per segment under saturated and submerged conditions indicated that static friction would be overcome in the end segments for both rise of phreatic surface and soil freezing. The frictional axial resistance under dry conditions does not apply to the results for rise of phreatic surface or soil freezing due to the nature of these applied loads. While this estimate neglects the apron, which almost certainly can transfer higher frictional loads, these results imply that the soil may slide relative to the culvert end segments under these two load scenarios. On the other hand, net separation forces caused by traffic loading did not exceed the frictional axial resistance under either dry or saturated conditions.

4.2 Finite Element Numerical Model for Continuous Pipes

4.2.1 Methodology

Finite element models were constructed using ANSYS (2022) to perform parametric modeling while varying soil cover depth, pipe diameter, soil stiffness, and subgrade stiffness. This modeling was performed for continuous pipes (i.e., all pipe joints bonded, representing a fully tied system) and discrete pipes (i.e., all pipe joints unbonded, representing a system with no ties). In either case, material properties reflect those given in Table 4.1, but only the concrete and soil mechanical properties were required, as phreatic level and soil freezing scenarios were not explored.

For the continuous pipe case, three different model geometries were created in ANSYS: (i) 4-ft (1.2-m) cover model with 5 culvert segments, (ii) 6-ft (1.8-m) cover model with 6 culvert segments, and (iii) 8-ft (2.4-m) cover model with 7 culvert segments. Dimensions for these models are shown in Figure 4.7, which is to-scale for the 6-ft cover model. The pipe inside diameter was always 2 ft (0.6 m), and pipe segments were 8-ft (2.4-m) long. The out-of-plane dimensions, loading positions and magnitudes, etc., were identical to those shown in Figure 4.1 for the FLAC3D model.

The impact of embankment stiffness was investigated using two different values for the Young's Modulus of the soil: (i) poor embankment stiffness of 2.9 ksi (20 MPa) and (ii) high embankment stiffness of 29 ksi (200 MPa).

Three different subgrade stiffness values were examined: (i) poor subgrade with stiffness of 100 lb/in^3 (27.1 MPa/m), (ii) good subgrade with stiffness of 500 lb/in^3 (136 MPa/m), and (iii) excellent subgrade with stiffness of 1000 lb/in^3 (271 MPa/m).

In total, 18 finite element models were examined for the continuous pipe case, corresponding to 3 values of cover, 2 values of embankment soil stiffness, and 3 values of subgrade stiffness.

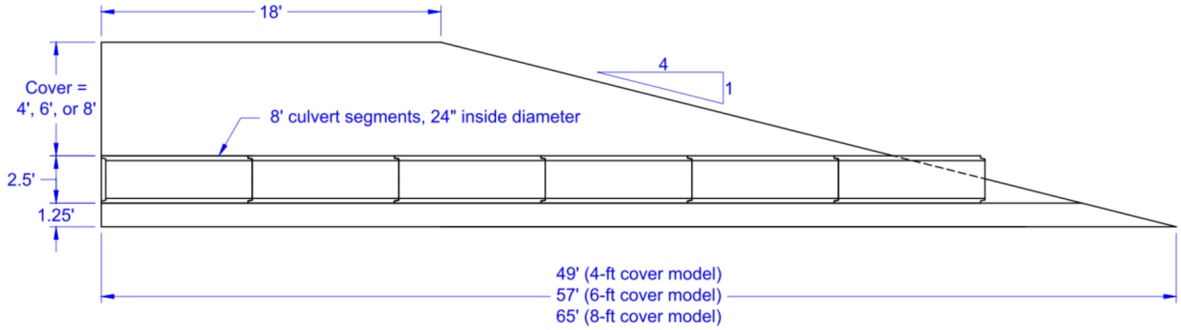


Figure 4.7: Dimensions for finite element models constructed in ANSYS

A half cross-section of the 6-ft (1.8-m) cover model is shown in Figure 4.8. The models with 4 ft (1.2 m) or 8 ft (2.4 m) of cover were similar but are not shown here. The soil and culvert segments were all meshed using second-order 10-node tetrahedral elements. Even though individual culvert segments were modeled, the segments were bonded together along the length and to the surrounding embankment soil around their circumference; thus, no separation between segments was possible. Like the FLAC3D model, these ANSYS models reflected a concrete pipe with joints capable of moment and force transfer and a fully bonded soil-culvert interface.

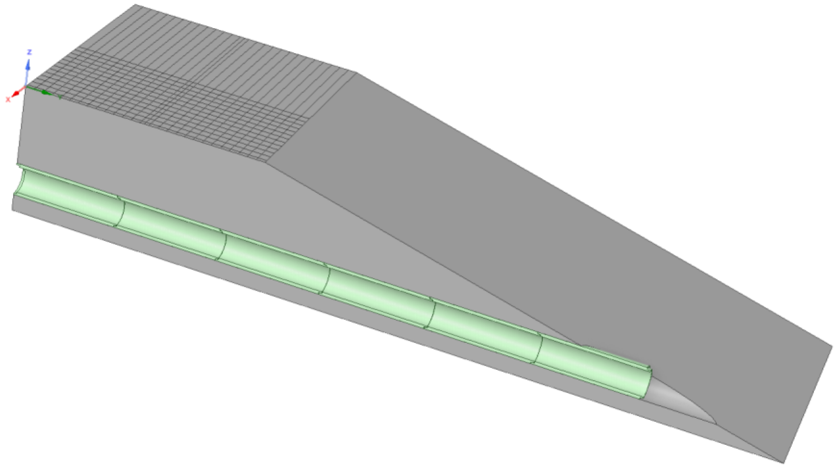


Figure 4.8: Cross section of 6-ft cover model in ANSYS

Model boundary conditions were implemented so that only half of the total embankment needed to be modeled. The vertical plane of the embankment corresponding to the road centerline was assigned zero displacement in its normal direction. The other two vertical sides of the model were restrained to have no displacement in their normal directions, mimicking a semi-infinite embankment in the direction of the roadway. Unlike with the FLAC3D model, the horizontal plane below the embankment was assigned an elastic support boundary condition using the subgrade stiffness values noted above.

4.2.2 Results for Continuous Pipe Finite Element Model

Finite element model results were computed separately under embankment and culvert self-weight, or under the 50-kip (220-kN) design tandem load. The combination of self-weight and design tandem was equivalent to the summation of these two loadings because the model was linear elastic. Sample results in Figure 4.9 showing the displacement throughout the embankment for the self-weight plus design tandem loading for the 6-ft cover model with soil modulus equal to 2.9 ksi (20 MPa) and soil subgrade stiffness equal to 100 lb/in^3 (27.1 MPa/m); contour colors correspond to the horizontal displacement, and the wireframe shows the original embankment position with displacements magnified for visualization purposes. As expected, the embankment moved horizontally outward, thrusting out and inducing tensile axial force into the culvert.

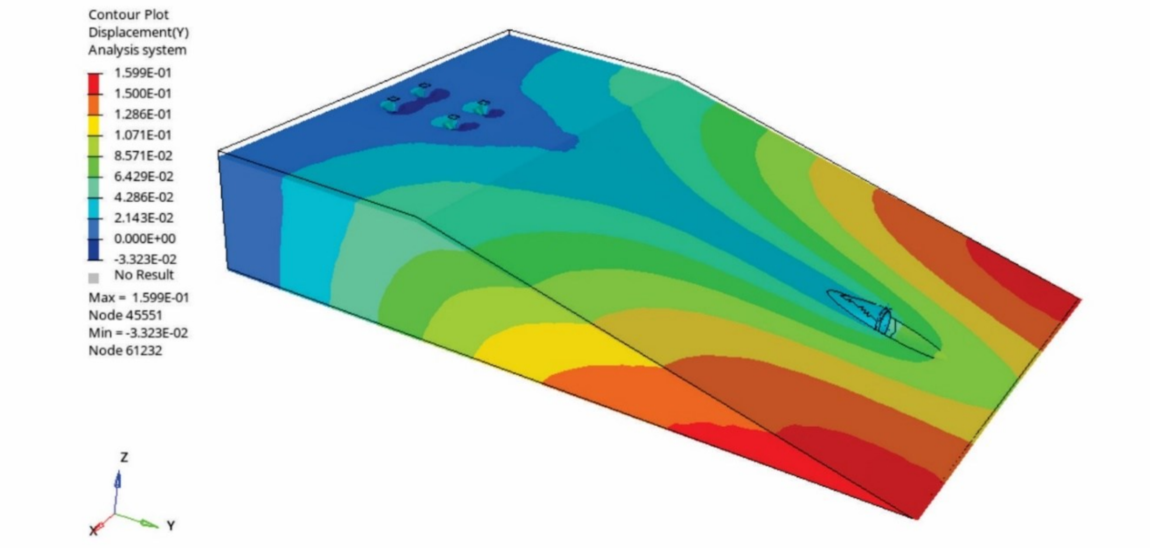
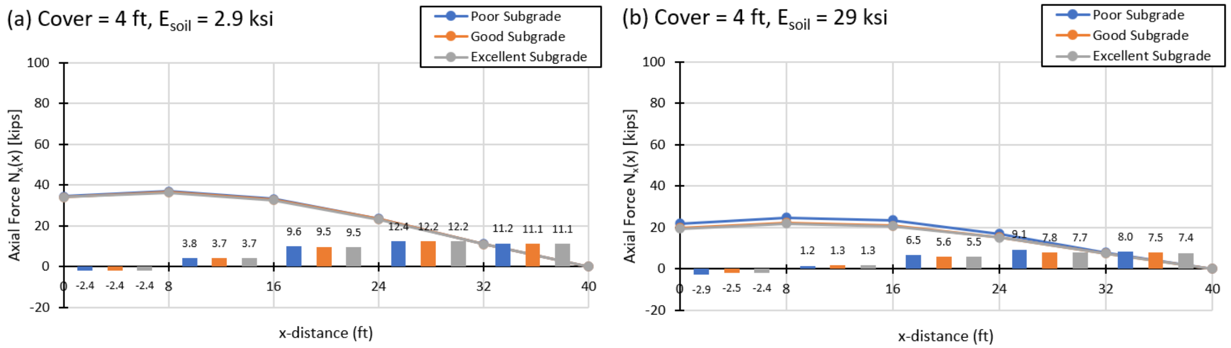


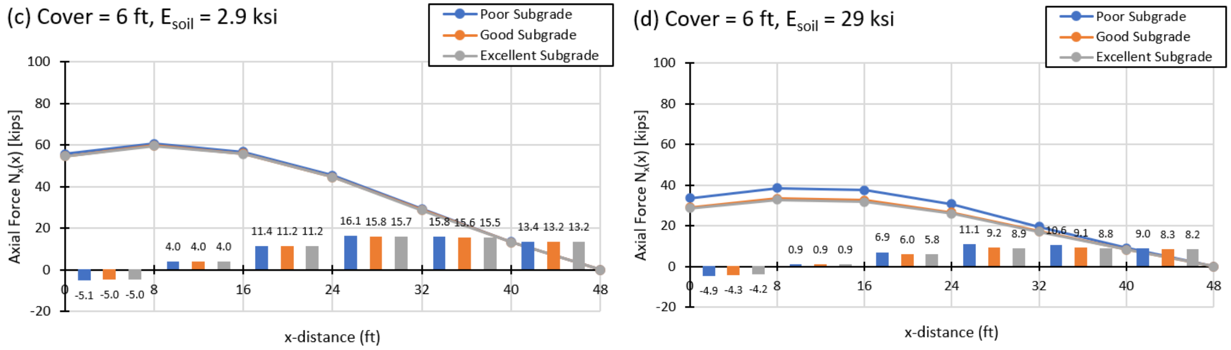
Figure 4.9: Displaced shape of 6-ft cover embankment under self-weight plus design tandem load; color contours correspond to horizontal displacement in inches

For each of the modeled load scenarios, the resultant forces across the concrete-to-soil interfaces for each culvert segment were calculated by ANSYS. The magnitude of these forces in the axial direction of the culvert equals the net separation force applied to that culvert segment. The integration of these forces along the length of the culvert results in axial forces across each joint, calculated in the same manner as for the FLAC3D model.

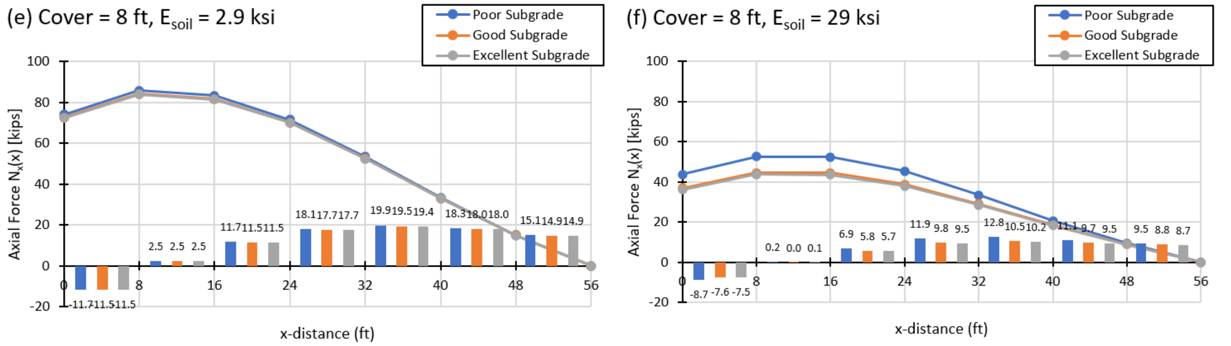
Figure 4.10 shows the calculated axial force at each joint (shown by the lines) and the net separation forces applied to each segment (shown by the bars with values) under self-weight alone. These are not exactly the loading demands at the end of construction, because the construction sequence was not modeled but rather these loads were placed on the final geometry as shown, but they do provide an indication of direction and an approximation of separation potential in lieu of any other separation mechanism. The three lines or bars on each subfigure correspond to different subgrade stiffness values, with blue being a poor subgrade with 100 lb/in^3 (27.1 MPa/m), orange being a good subgrade with 500 lb/in^3 (136 MPa/m), and grey being an excellent subgrade with 1000 lb/in^3 (271 MPa/m). Furthermore, Figures 4.10(a) through (f) present different amounts of cover or soil stiffness, as noted in the subfigure captions.


(a) Cover = 4 ft, E_{soil} = 2.9 ksi

(b) Cover = 4 ft, E_{soil} = 29 ksi


(c) Cover = 6 ft, E_{soil} = 2.9 ksi

(d) Cover = 6 ft, E_{soil} = 29 ksi


(e) Cover = 8 ft, E_{soil} = 2.9 ksi

(f) Cover = 8 ft, E_{soil} = 29 ksi

Figure 4.10: Diagram of axial force (lines) along the culvert length for the finite element models under self-weight only. Bars with values indicate the net separation forces on each culvert segment in kips.

Results from Figure 4.10 (a, c, and e) indicate that the subgrade stiffness made essentially no difference if the embankment had low stiffness. The culvert under the low stiffness embankment experienced nearly twice the axial force compared to that from the stiff embankment with a good or excellent subgrade. Even for equivalent subgrade stiffness, the net separation forces with the low stiffness embankment were 30-50% greater compared to the higher stiffness embankment. When the embankment soil stiffness was greater, the subgrade stiffness appeared to have an effect; poor subgrade stiffness amplified net separation forces by roughly 10-20% compared to good or excellent subgrade stiffnesses. The peak axial forces increased roughly proportionately to the amount of soil cover. Maximum net separation forces also increased as soil cover increases but not proportionately; the 8-ft cover models had roughly 25-50% greater net separation forces compared to the 4-ft cover models. Overall, self-weight alone caused the largest axial forces in the pipe joint near, but not directly under, the road centerline and the largest net separation forces in the second or third segments from the end of the culvert. The magnitudes of these net separation forces for the high stiffness embankment were similar to those caused by the rise in phreatic surface as calculated using the FLAC3D model.

Figure 4.11 shows the calculated axial force at each joint (shown by the lines) and the net separation forces applied to each segment (shown by the bars with values) under the 50-kip (220-kN) design tandem alone. Organization of this figure is similar to that of Figure 4.10. As a check, the axial force and net separation force results in Figure 4.11(a) representing the 4-ft cover model with a 2.9 ksi (20 MPa) embankment soil and an excellent subgrade were very similar to the FLAC3D model results under the tandem load. The primary difference between these two models, other than their underpinning numerical formulations, was that the FLAC3D model had an effectively infinite stiffness subgrade (zero displacement boundary condition) while the ANSYS model had a finite subgrade stiffness. The similarity in these results lends credence to the validity of the modeling strategies pursued herein.

Unlike for the demands under self-weight in Figure 4.10, the embankment soil stiffness did not have a significant effect on the separation forces caused by traffic load in Figure 4.11, such that the low stiffness embankment had lower peak net separation forces compared to the corresponding high stiffness embankment. The lower embankment stiffness did, however, contribute to increased total axial forces in the joints, primarily because the demands “spread” out to the segments closer to the outside of the embankment, whereas for the high stiffness embankment the separation forces were more concentrated into the single segment beneath the applied load. Again, the subgrade stiffness made little difference for the low stiffness embankment. This was not the case for the high stiffness embankment, where the culvert over the poor subgrade experienced roughly 20% more net separation forces under the design tandem load compared to those with good or excellent subgrades. Increasing cover did not monotonically increase the joint axial forces or the net separation forces.

The three cover depths resulted in different frictional axial resistance computed using Equation (4.1) per ASCE (1984) guidelines. For dry conditions, the maximum frictional resistance was equal to 14.4 kips (64 kN), 19.9 kips (89 kN), and 25.4 kips (113 kN) for the 4-ft, 6-ft, and 8-ft cover models, respectively. For saturated and submerged conditions, these were reduced to 9.0 kips (40 kN), 12.4 kips (55 kN), and 15.9 kips (71 kN) for the 4-ft, 6-ft, and 8-ft cover models, respectively. These values considered only the weight of the embankment and neglected the additional normal force that would be induced by live loading. The dry condition axial resistance was never exceeded in any culvert segment under combined self-weight plus live loading. Model results with a low embankment stiffness exceeded the submerged condition values, however, by approximately 25% for all three cover depths in the three or four pipe segments near the edge of the embankment. This indicated that sliding between the pipe and surrounding soil was likely when the embankment stiffness is low and the phreatic surface is high.

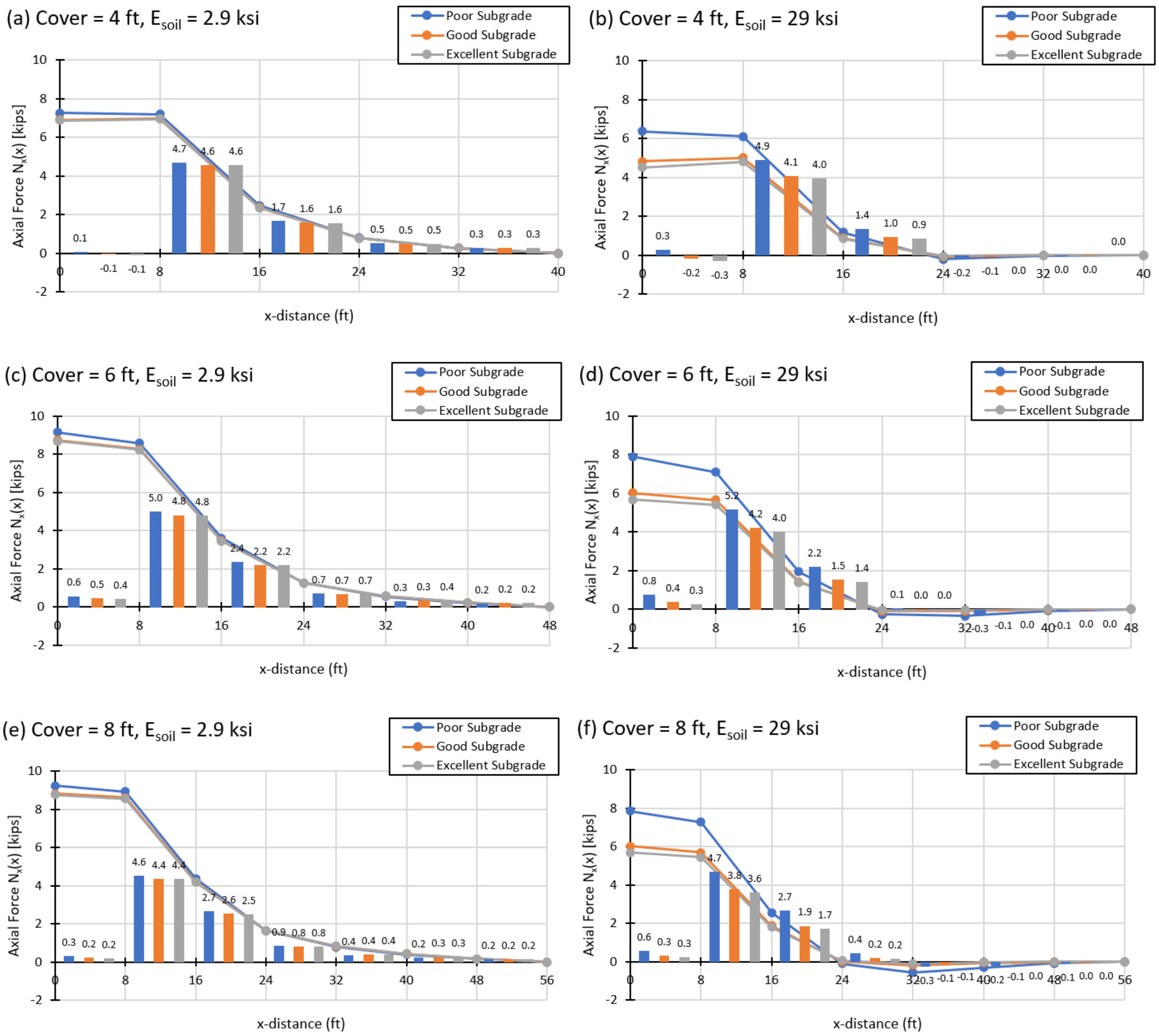


Figure 4.11: Diagram of axial force (lines) along the culvert length for the finite element models under design tandem load only. Bars with values indicate the net separation forces on each culvert segment in kips.

4.3 Finite Element Numerical Model for Discrete Pipes

4.3.1 Methodology

Finite element models were further developed for discrete pipes unable to transfer loading from one pipe segment to another. To achieve this, pipe segments were no longer bonded to each other and a frictional interface (static coefficient of friction equal to 0.5) between the concrete pipes and the surrounding soil was introduced. These models were again used to examine the demands under self-weight of the embankment and traffic loading. However, unlike for the continuous pipe models, axial force demands could not build up along the length of the pipe. Instead, the primary output of interest was the horizontal opening of each joint in inches (millimeters). For the joint at the road centerline, this was equal to twice the average displacement of the left end (from the perspective of Figures 4.7 and

4.8) of the middle culvert segment. For all other joints, joint opening was the average horizontal displacement of the left end of the segment located to the right of the joint minus the average horizontal displacement of the right end of the segment located to the left of the joint (again, from the perspective of Figures 4.7 and 4.8). The use of average horizontal displacements eliminated any rotational opening of the joints, for example where the top of the joint opens more than the bottom, and was thus consistent with the use of axial force demands in the continuous pipe models. This methodology treated joint separation as a change in displacements under loading, which was not equivalent to what was measured during inspections wherein joint separation was recorded as the absolute distance between the two culvert segments.

The introduction of the frictional interface made the model nonlinear, so traffic loading could no longer be placed on the model alone without considering the weight of the soil and the resulting friction this induced. Therefore, the presented results for traffic load represent the results applying self-weight plus the traffic load minus the results applying only self-weight. Furthermore, when the analysis first began, no load or friction was present within the system; consequently, the pipes were free to slide along effectively frictionless interfaces until the first load increment was applied. This initial sliding was occasionally large, exceeding 1 in. in some cases, and was largest in the segments on the outside edge of the embankment, likely because these were the least “confined” pipe segments. However, it was believed that this motion did not represent true load-induced demands on the pipes, and even applying only 1% of the self-weight greatly stabilized the behavior of all segments in the simulation. Therefore, this initial sliding was neglected by taking the initial state as that under 1% of self-weight loading. Separation results under self-weight only may slightly underestimate joint opening, as these represent, effectively, motion caused by 99% of the weight rather than 100%.

Variables investigated for the discrete pipe model include:

- Two pipe diameters: 24 in. (0.6 m) and 72 in. (1.8 m)
- Two cover depths: 4 ft (1.2 m) and 8 ft (2.4 m)
- Two soil stiffnesses: poor = 2.9 ksi (20 MPa) and high = 29 ksi (200 MPa)
- Three subgrade stiffnesses: poor = 100 lb/in^3 (27.1 MPa/m), good = 500 lb/in^3 (136 MPa/m), and excellent = 1000 lb/in^3 (271 MPa/m).

In total, 24 models were analyzed for the discrete pipe case. In addition, 32 more models were analyzed to verify the consistency of the results, using cover depths varying from 2 ft (0.6 m) to 16 ft (4.9 m) and diameters from 12 in. (0.3 m) to 72 in. (1.8 m), all with high soil stiffness and excellent subgrade stiffness. The results from these 32 additional models are provided in Appendix C for reference.

4.3.2 Results for Discrete Pipe Finite Element Model

Figures 4.12 and 4.13 present the joint separation for the 24-in. (0.6-m) and 72-in. (1.8-m) diameter culverts, respectively, under self-weight alone, and five key results were observed. First, the magnitude of the modeled joint separation was fractions of inches, which clearly does not align with field observations of separations on the order of inches. Large joint openings in the field may, therefore, be due to cyclic accumulation of displacements, though self-weight alone obviously is not cyclic. Second, while the plots for joint separation did not precisely match the axial force diagrams of the continuous pipes (see, for example, Figure 4.10), the shapes were similar. This means that the axial force diagrams for continuous pipes can be reasonably used to locate the joints most likely to have joint separation issues, even for untied culvert joints. Third, embankment stiffness had the most significant effect on the magnitude of joint opening. Comparing the low stiffness embankments in parts (a) and (c) of Figures 4.12 and 4.13 with the high stiffness embankments in parts (b) and (d) of the same figures reveals that the joint opening was inversely proportional to the soil stiffness. Furthermore, as observed with the continuous model, the subgrade stiffness only had a measurable effect if the embankment stiffness is high. Fourth, doubling the cover depth increased joint separation by around 50%. Fifth, increasing the culvert diameter increased the amount of joint separation, which was attributed to the increased depth to the culvert centerline (i.e., the cover plus the culvert radius). Comparing models with equivalent depth to the culvert centerline in Figure 4.14 reveals that, while not a perfect predictor, the maximum joint opening under self-weight was proportional to the depth to the culvert centerline.

Figures 4.15 and 4.16 present the joint separation for the 24-in. (0.6-m) and 72-in. (1.8-m) diameter culverts, respectively, induced by the 50-kip (220-kN) design tandem, and three key results were observed. First, the magnitude of the modeled joint separation was fractions of inches. This is consistent with field testing performed by Sheldon et al. (2015), where longitudinal deflections across a reinforced concrete pipe joint under a 45.6-kip (203-kN) truck load were on the order of 0.002 in. (0.05 mm) or less, which is similar to the results from the high soil-stiffness models. Embankment stiffness was the most important variable for joint separation, such that joint separation was inversely proportional to the embankment stiffness. Second, while the shapes of the joint opening curves for the discrete pipes were similar to the axial force demands for the continuous pipes (see, for example, Figure 4.11), the discrete pipes had more notable joint closing (that is, negative joint opening). In fact, for all discrete pipe models, traffic loading caused joint opening directly below the load but caused joint closing away from the loading and out towards the edge of the embankment. Third, higher cover depths correlated with higher joint opening. However, results from models with 16 ft (4.9 m) of cover contradict this observation, decreasing the joint separation as compared to models with 8 ft (2.4 m) of cover. The observed increase in joint separation from the 4-ft cover models to the 8-ft cover models was due to interaction of the two tandem loads applied on either side of the road centerline because of model symmetry.

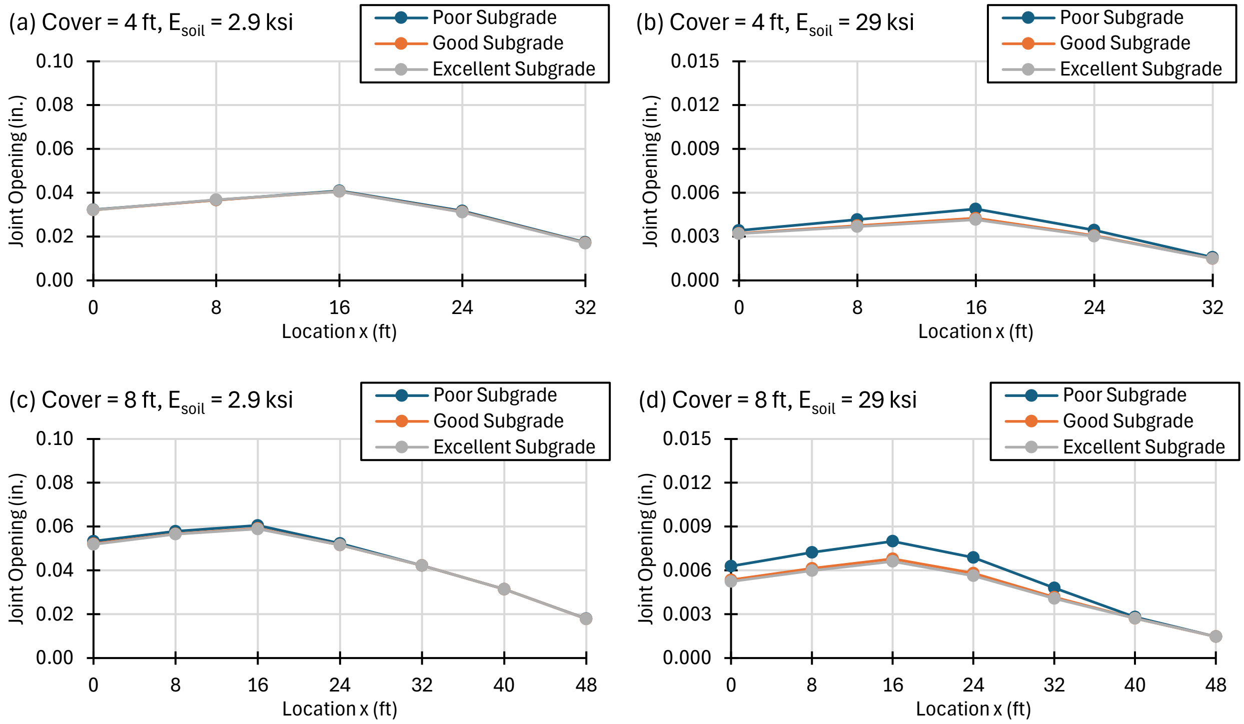


Figure 4.12: Diagram of joint separation along the culvert length for the 24-in. (0.6-m) diameter discrete pipe models under self-weight only.

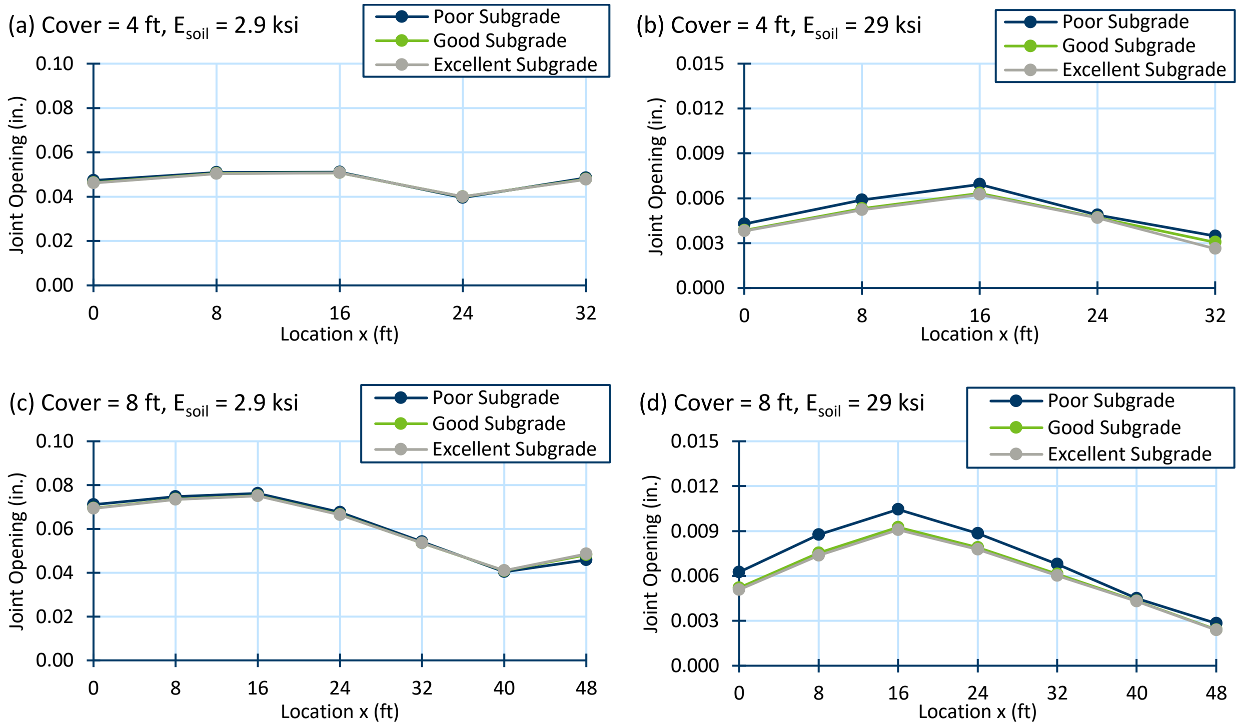


Figure 4.13: Diagram of joint separation along the culvert length for the 72-in. (1.8-m) diameter discrete pipe models under self-weight only.

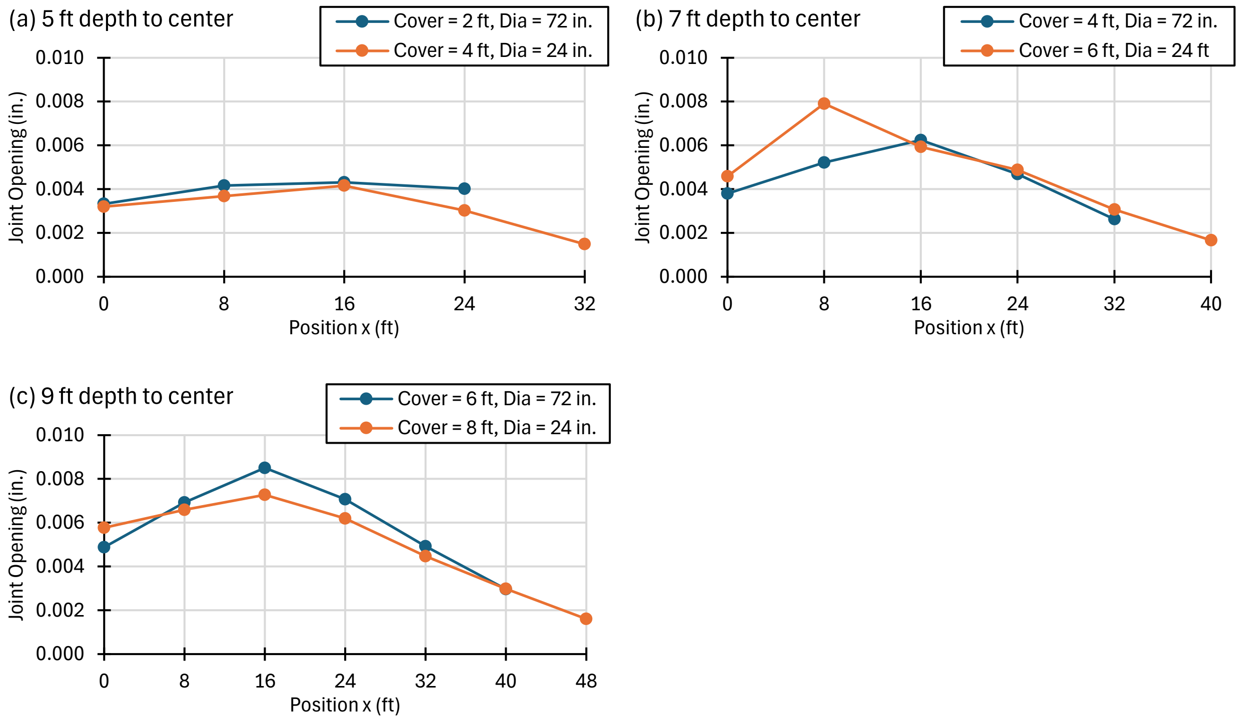


Figure 4.14: Diagram of joint separation along the culvert length for the discrete pipe models with equal depth to culvert centerline under self-weight only.

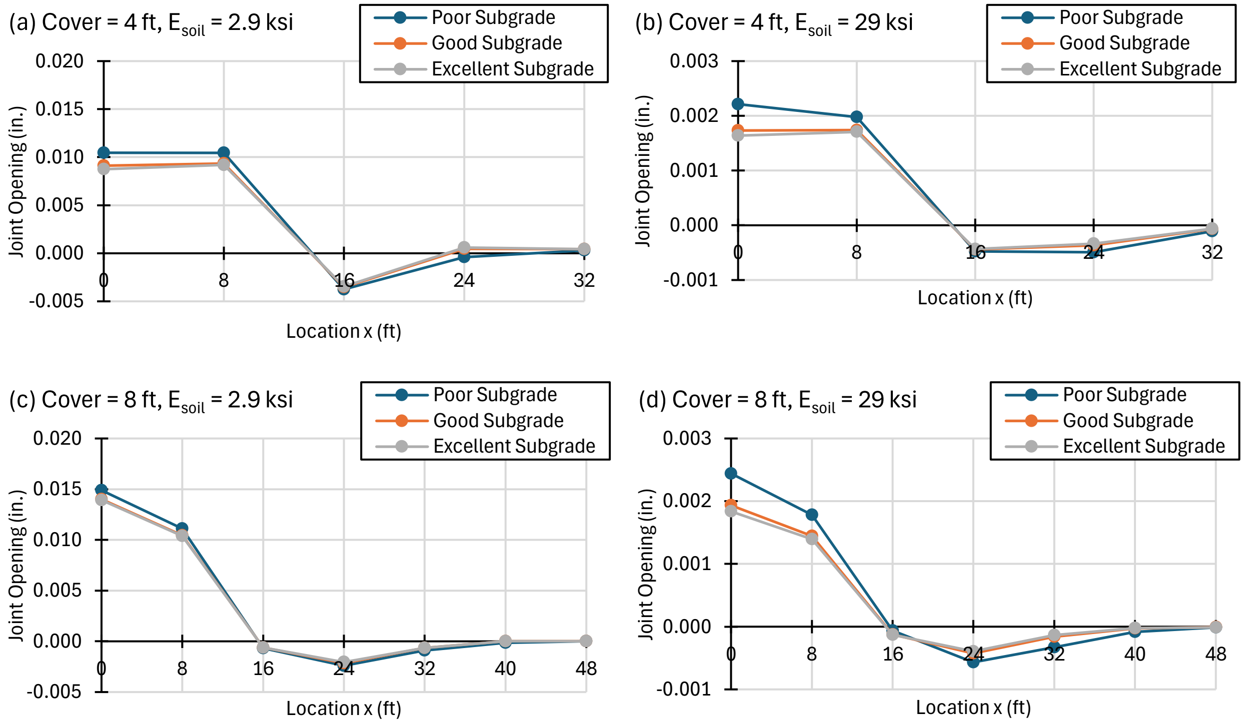


Figure 4.15: Diagram of joint separation along the culvert length for the 24-in. (0.6-m) diameter discrete pipe models under design tandem.

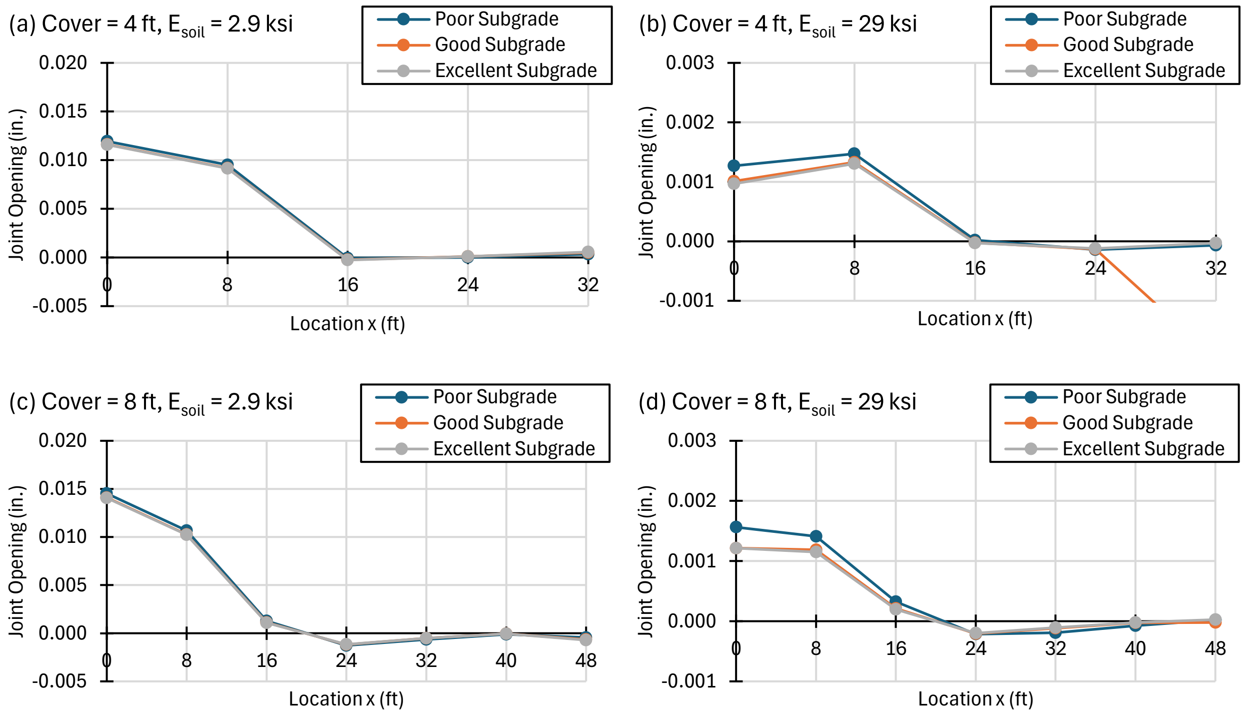


Figure 4.16: Diagram of joint separation along the culvert length for the 72-in. (1.8-m) diameter discrete pipe models under design tandem.

Lastly, the discrete pipe model was used to investigate typical magnitudes of joint opening under the soil freezing case. An expansion of 0.000125 (see Table 4.1) was imposed on the soil within the top 6 ft (1.8 m) of the embankment, as shown in Figure 4.17 for a 12-in. (0.3-m) diameter culvert under 8 ft (2.4 m) of cover. For this example, only the last several segments are fully within the frost depth. Frost depths throughout the state of Minnesota range from 3-6 ft (0.9-1.8 m). The selected frost depth reflects the maximum observed during the 2024-2025 winter in Orr, Minnesota, as obtained from Minnesota DOT public frost depth sensors (Minnesota Department of Transportation 2025).

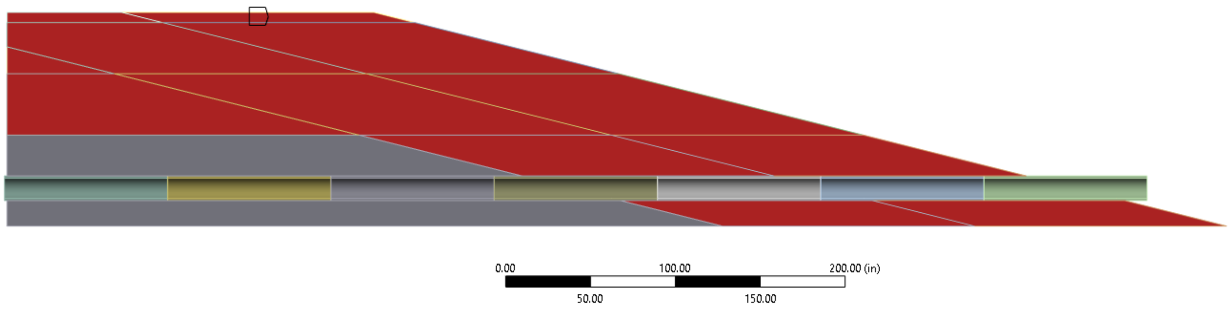


Figure 4.17: Cross section of modeled embankment showing location, highlighted in red, of the frost depth imposed on discrete pipe finite element model of a 12-in. (0.3-m) diameter culvert with 8 ft (2.4 m) of cover

Joint separation results for the 12-in. (0.3-m) diameter culvert under 8 ft (2.4 m) of cover are shown in Figure 4.18. The low and high embankment stiffness corresponded to E_{soil} = 2.9 ksi (20 MPa) or 29 ksi

(200 MPa), respectively, and both plots used the excellent subgrade reaction of 1000 lb/in^3 (271 MPa/m). To simplify comparisons, the amount of soil expansion when frozen was not adjusted to account for this change in soil stiffness. Models with other culvert diameters returned similar results, and lower cover depth pushed the joint separation back towards the center of the road; thus, for a culvert that is fully within the frost depth along its entire length, the separation in all joints was roughly equal to the peaks observed in Figure 18. Increasing the embankment stiffness pushed the joint separation further into the embankment, but only slightly reduced the maximum separation values, which are consistently observed in the second joint from the end of the culvert. This independence from soil modulus was expected for the soil freezing mechanism since joint opening is primarily displacement- or strain-driven rather than load-driven, as was the case for self-weight and traffic loading.

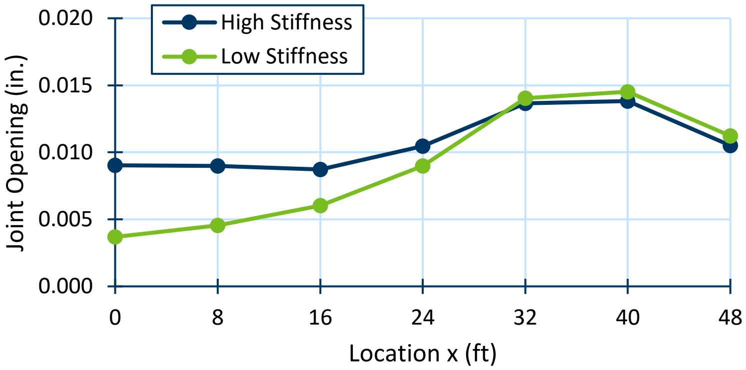


Figure 4.18: Diagram of joint separation along the culvert length for the 12-in. (0.3-m) diameter culvert under 8 ft (2.4 m) of cover under soil freezing

From field observations and discussions with MnDOT personnel (Chapter 3), many concrete pipes throughout the state are tied only across a few segments at the end of the pipe, nominally to control separations witnessed at the ends of pipes. For example, a common historical practice was to tie only the three joints nearest the pipe end, or to tie only the apron to the first pipe segment. However, in such partially tied pipes, joint separations were most often observed in the first untied joint from the end. The same soil freezing scenario illustrated above was repeated for the low-stiffness embankment, but with the last three pipe joints bonded together in the model (locations x = 32, 40, and 48 ft from the road centerline), thus enforcing no opening at these locations. The results are shown in Figure 4.19. Even though the first untied joint is past the frost depth (see Figure 4.17), model predictions indicated that this first untied joint had greater separation compared to when all joints were left untied. The tied culvert segments move outwards together, thus increasing the effective length of the end segment and concentrating a greater separation into this first untied joint.

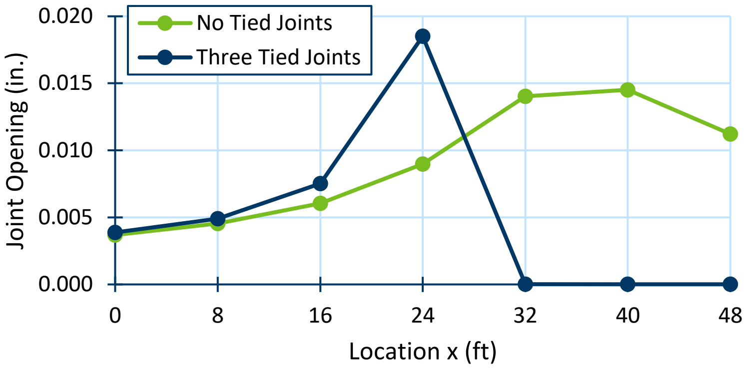


Figure 4.19: Diagram of joint separation along the culvert length under soil freezing, comparing pipe with no tied joints to a pipe with only the three end joints tied.

For the applied traffic loading and soil freezing scenarios on the discrete pipe model, removing the load effectively brought the joint opening back to its initial state, meaning no residual joint opening was observed in the model upon unloading. Further model refinements are necessary to examine the possibility of cyclic accumulation of joint separation, investigating different values of soil-concrete friction coefficients, including soil plasticity, and modeling the apron which would make joint opening during loading (pushing primarily on the flared apron) asymmetric with joint closing during unloading (pulling primarily on the culvert walls).

Models with other culvert diameters returned similar results. Lower cover depth meant that the entire pipe, even directly under the road surface, was subjected directly to freezing soil. This pushed joint separation back towards the center of the road; model results show that a culvert that is fully within the frost depth along its entire length has equal amounts of separation in all joints, with peak separations similar to the values in Figure 4.18. Increasing the embankment stiffness also pushes the joint separation further into the embankment, but only slightly reduces the maximum separation values, which are consistently observed in the second joint from the end of the culvert. This independence from soil modulus is expected for the soil freezing mechanism, because joint opening is primarily displacement or strain driven rather than load driven as was the case for self-weight and traffic loading.

The modeled magnitudes of separation under soil freezing correspond closely with the total expansion of the soil along the length of one segment multiplied by $1+\nu$ to account for plane strain conditions, where ν is Poisson's ratio of the soil. For example, using the assumed expansion of 0.0125% along an 8-ft (2.4-m) segment with a Poisson's ratio of 0.3, joint separation is predicted to be 0.000125 × 96 in. (2440 mm) × 1.3 = 0.0156 in. (0.396 mm), which only slightly overestimates the maximum modeled separation. From these results, the most significant parameters predicting the magnitude of joint separation for soil freezing are the length of the culvert segments and the amount of volumetric expansion exhibited by the soil.

The assumed soil expansion of 0.0125% is relatively small considering that water expands roughly 9% upon freezing. This mimics a soil that is well-drained, permitting the water to expand within the soil pores. Such soils are not strongly susceptible to frost-heave. Other literature (see Figure 4.20 for an example from Arabchobdar et al. 2025) indicate that saturated soils susceptible to frost-heave may swell by 1-5%. If the soil expansion is even 1%, then the expected joint opening during freezing would be 1.3 in., much of which would not recover upon thaw. Such expansion would rapidly separate aprons or end pipe segments within a few winters after installation.

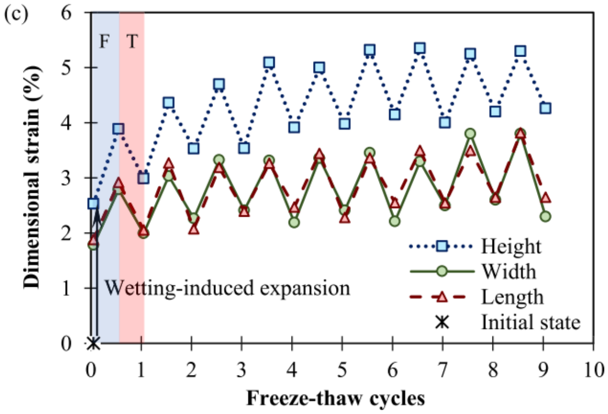


Figure 4.20: Freeze-thaw strain of saturated elastic silt from Figure 6c of Arabchobdar et al. (2025)

4.4 Modeling Conclusions

Overall model results indicated that traffic loading, rise of phreatic surface, soil freezing, and embankment self-weight can all lead to the development of tension across joints, which means they could all theoretically lead to joint separation. Among these, traffic loading appeared to cause the smallest forces, though they may still be significant; axial forces across a joint may be between 10-20% of the vertical traffic load magnitude. Furthermore, on high volume roads the traffic load may be more often cycled than other sources of tension. However, the models constructed in this study were unable to account for cyclic behavior or progressive opening of joints, and discrete pipe models indicated that traffic load induced closing of the joints near the edges of the embankment. Thus, cycled traffic loading, if it has an effect at all, could only result in progressive opening of joints under the road surface. Embankment stiffness did not have a significant effect on the magnitude of the separation forces for continuous pipes but had a profound effect on joint opening for discrete (untied) pipe segments. Along with the depth to the culvert centerline, being equal to the cover depth plus the culvert radius, embankment stiffness was the most important variable for predicting the amount of joint separation.

Although investigations of the TAMS HydInfra database (Chapter 2) revealed that greater amounts of cover were correlated to greater rates of joint separation, model results indicated separation potential under the traffic load alone was not strongly correlated to the cover depth. However, increasing cover did increase demands due to self-weight of the embankment. Under self-weight only, the total axial force in the pipe for continuous pipes and joint separation for discrete pipes was roughly proportional to the depth to the culvert centerline. Peak self-weight demands occurred under the top of the embankment, not at the culvert ends. This is seemingly at odds with discussions with culvert inspectors that outside segments tend to have the highest rates of joint separation. While this could be explained by sample bias, as there are far more culverts in the Minnesota inventory with less than or equal to 4 ft

(1.2 m) of cover compared to those with greater than 4 ft (1.2 m) of cover, more investigation is warranted. A more likely explanation, however, is that traffic loading and embankment self-weight do not by themselves lead to significant joint separation, which is more likely to be driven by improper pipe installation or by demands that are greater at the ends of the pipes, such as rise of the phreatic surface and soil freezing.

Rise of the phreatic surface and soil freezing caused larger joint demands than traffic loading, particularly on end culvert segments nearest the outside face of the embankment. The scenarios explored herein, particularly the soil freezing scenario wherein the entire embankment freezes and expands, likely overestimated the force magnitudes on these outside segments. However, as noted above, separation in these end locations aligns with inspector experience. Furthermore, this study did not model apron geometry; the flared geometry of an apron, compared to the straight pipe segment, may increase separation demands on the first joint in from the edge of the embankment as the embankment expands or is otherwise displaced outward. This could be exacerbated by other issues not explored in this study, such as loss of support under the apron.

These results imply that the practice of providing pipe ties only on a few joints at the ends of pipes, nominally to control joint opening at the ends of pipes, could amplify the net joint demands in the first untied joint from the end. For example, many culverts in Minnesota have ties connecting only the apron to the first pipe segment. The net joint demands between the first and second pipe segments would therefore become the net separation force on the apron plus that on the first segment minus that on the second segment. In resisting concentrated horizontal loads applied directly to the apron, the logic of tying only the end joints is that these forces can be resisted through soil-concrete friction that develops over multiple end segments that have higher confining normal force than the apron alone. However, it does not follow that this practice is necessarily advantageous when the soil embankment displaces outward, as occurred for the scenarios explored herein and explicitly shown in Figure 4.19, as the tied segments move together. It follows that the best practice is to tie all joints rather than only a few.

Continued research is needed to consider other possible actions (e.g., freezing water or soil directly infiltrating into the joint, 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. Further research and modeling are recommended for evaluating the joints in culverts composed of different materials (i.e., steel and HDPE).

Chapter 5: Conclusions and Recommendations

Joint separation affects nearly 20% of the MnDOT round concrete culvert inventory. This is a multifaceted problem, and the research conducted herein did not determine a singular variable that causes joint separation. However, through an exploration of the TAMS HydInfra database, field inspections, a MnDOT personnel survey, and computational modeling, joint separation trends were observed and recommendations for concrete pipe installation practices to avoid significant joint separation were developed.

Investigation of the TAMS HydInfra database highlighted that joint damage regularly led to further issues such as infiltration and formation of inslope cavities. Field inspections showed that large levels of joint separation were commonly accompanied by some other type of joint damage, often breakage of the spigot or "tongue" side of the joint. This clearly highlights the importance of good joint performance on the integrity of both the pipe and the roadway.

Through the development of a Random Forest model (Chapter 2), it was determined that the most important features for predicting joint separation were largely geographic. The most important features for predicting joint separation (other than infiltration which, while almost perfectly correlated with joint separation, obviously does not cause it) were the county and the route number. Joint separation was most common in southeastern and southwestern Minnesota. The importance of route number implied some dependency on geography or possibly on the date and type of installation, as different culverts along a stretch of road were more likely to be installed during the same job and thus were likely to have similar installation practices. The counties with the highest rates of joint separation often had many intermittent streams and rapidly changing geomorphology (i.e., changes in slopes); however, without more thorough geological investigations, these can only be interpreted as correlations and not directly linked to any kind of causal mechanism.

Culvert modeling (Chapter 4) revealed that culvert systems were effectively always in tension and thus being pulled apart, even under only the self-weight of the roadway embankment. For continuous (i.e., tied) pipes, the self-weight of the embankment placed significant tensile forces along the entire length of the pipe. As the cover increases, these demands due to self-weight of the embankment increased proportionately to the distance to the centerline of the culvert. Traffic loading induced zones of tension under the load and compression at the outside of the embankment, but these forces did not overcome the pre-existing tension from self-weight unless cover was less than 1-2 ft. For pipes with untied joints, self-weight resulted in a small amount of joint opening, less than 0.1 in. even for low stiffness soil. Similarly, small amounts of joint opening were induced by traffic loading, primarily below the road surface, or the raise of phreatic surface or soil freezing, primarily near the ends of the pipes. While these modeled joint openings were small, they were directionally consistent in driving further joint separation if the loads were cycled. However, the locations of commonly observed joint separations, typically near culvert ends (Chapter 3), and the correlation observed in the database (Chapter 2) between cover depth and likelihood of separation implied that improper installation, rise of phreatic surface, and soil freezing were more likely to induce separations than traffic.

Among these investigated loading scenarios, soil freezing merits additional discussion. While joint separation has been observed anywhere along the length of concrete culverts, separations were most often observed at the ends, particularly at the aprons, or (if partially tied) just after termination of joint ties after the third joint. This position was aligned with the locations of peak separations from soil freezing models. The most significant parameters predicting the magnitude of joint separation for soil freezing were the length of the culvert segments (longer segments induced more separation in the first untied joint) and the amount of volumetric expansion exhibited by the soil. Well-drained soil, such as the typical fine aggregate bedding (i.e., sand) compacted around culvert installations, likely has negligible expansion upon freezing. However, saturated cohesive soil, such as that used for a cohesive soil cap, could have significant expansion upon freezing. Even if the cap were only 3-ft deep, this could result in significant separation of the apron or first pipe joint of an inch or so per winter, much of which may not be recoverable.

The primary recommendation resulting from this project was that ties should be installed across all joints in newly installed concrete pipes. The research did not narrow this practice to one optimal detail, though flat-bar ties proposed by MnDOT District 1 (Figure 3.6) have theoretically higher strength than other details using tie rods (Figure 1.3). For high-cover (e.g., greater than 8 ft) applications where large magnitudes of built-in tie forces may be developed during construction, engineers are encouraged to adopt higher strength tie details, whether using flat-bar ties or additional tie rods. Field inspections did not reveal any clear deficiencies of using tie rods, so long as they were placed at every joint, but the condition of these rods on in situ structures was difficult to observe as most were placed on the outside of the pipe. The research team encourages districts to adopt practices that prioritize cost and ease of installation, promoting widespread adoption of fully tied pipes. The research team also recommends further research into the efficacy of different pipe tie details and materials (e.g., glass-fiber reinforced polymer bars).

The practice of partially tying pipes, where only the apron is tied to the first pipe segment or only the first three joints are tied, is discouraged. Model results confirm that this practice can amplify the amount of separation induced at the first untied joint, which is further corroborated by the database investigations and field inspections where the first untied joint is often seen to have separated.

The other primary recommendation is to focus on proper compaction of the bedding and placement of the pipes. Model results show that opening of untied joints under embankment self-weight and traffic loading is proportional to soil stiffness. However, opening due to soil freezing is independent of soil stiffness, so no amount of compaction will help when frost-heave susceptible soils are used. Further work on classifying the frost-heave susceptibility of typical bedding and cohesive cap materials is recommended.

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Appendix A: Field Inspection Records

Pipe ID	Main. District	Repaired	Misalignment	Infiltration	Sediment	Inspected Joint Separation	Database Joint Separation	Inspection Match Database?	Pipe Ties	Comments
2196332	Metro	N	N	Y	N	Y	Y	TRUE	N	6"-7" separation in the joint just under the edge of the asphalt roadway
2186528	Metro	N	N	N	Y	N	N	TRUE	Partial	First three segments tied, some sediment, but otherwise good
2186496	Metro	N	Y	N	Y	Y	Y	TRUE	N	Apron broken, 4" joint separation
2186499	Metro	N	N	Y	Y	Y	Y	TRUE	Partial	Ties only on first segment and apron, joint separation is small but infiltration is present
2277053	Metro	Grouted	Y	N	N	Y	N	FALSE	Partial	Ties only on apron and first segment, one joint repaired by grout
2197945	Metro	N	Y	N	N	Y	Y	TRUE	N	Significant joint separation, more than 3 in on several joints
2202373	Metro	CIPP Lined	N/A	N/A	N/A	N/A	Y	N/A	N	CIPP lined, could not observe joints
4314481	1	N	N	N	N	N	N	TRUE	Y	Looks good
2225234	1	N	N	N	N	Y	Y	TRUE	Y	Joint separation between apron and first segment on curve road mud in culvert with water
2225236	1	Single Band	Y	N	N	Y	Y	TRUE	Y	an interesting repair, much joint separation, pipe ties on every segment
2318619	1	Y	Y	Y	Y	Y	Y	TRUE	N	Big JS, lots of infiltration, Big crack on pavement
2318361	1	N	N	N	N	Y	N	FALSE	Y	
2318471	1	N	N	Y	Y	Y	Y	TRUE	Y	Lots of infiltration, pipe ties
2318468	1	Single Band	N	N	N	N	Y	FALSE	Y	Interesting repair, no JS, no infiltration, there is a minor gap
2264023	1	N	N	N	N	N	N	TRUE	Y	Long interior ties, no joint separation
2217863	1	N	N	Y	Y	Y	N	FALSE	Y	Pipe Ties on every segment
2217860	1	N	N	N	N	N	N	TRUE	Y	Pipe Ties on each segment, no JS, no infiltration, some tree branches in the culvert
2217854	1	N	N	N	N	N	N	TRUE	Y	pipe Ties on every segment, the culvert is at an intersection
3802303	2	N	Y	N	N	N	N	TRUE	Y	

Pipe ID	Main. District	Repaired	Misalignment	Infiltration	Sediment	Inspected Joint Separation	Database Joint Separation	Inspection Match Database?	Pipe Ties	Comments
2183548	2	N	Y	N	N	N	N	TRUE	Y	Pipe ties on every segment, rotation and misalignment, some separation on apron
2245361	2	N	N	N	N	Y	N	FALSE	Y	Pipe ties on every segment, some minor joint separation
2245359	2	N	N	Y	Y	Y	Y	TRUE	Partial	Extreme infiltration, Pipe Ties just in first segment
2245353	2	N	N	N	N	N	N	TRUE	Partial	No infiltration, pipe ties only on second segment
2181459	2	N	N	N	N	Y	N	FALSE	Partial	Joint separation, but no infiltration, pipe ties only first segment/apron
2245351	2	N	N	N	N	N	N	TRUE	Y	Pipe ties at each segment
2245548	2	N	Y	N	N	N	N	TRUE	Y	Pipe ties at each segment, no infiltration
2245540	2	N	N	N	N	N	N	TRUE	Y	Pipe ties at each segment
2187015	2	N	N	Y	Y	Y	Y	TRUE	Y	Pipe ties at each segment, a little infiltration and a little joint separation
2191437	2	N	N	N	N	Y	N	FALSE	Y	no infiltration, very little joint separation at two joints, pipe ties at every segment
2188063	2	Joint Seal	N	N	N	Y	N	FALSE	Y	Cretex pipe joint seal, a little gap at some other end, Pipe Ties in every segment
2188061	2	Joint Seal	N	N	N	Y	N	FALSE	Partial	Cretex pipe joint seal, Pipe ties to third segment
2275174	2	N	N	N	N	Y	Y	TRUE	Y	One end blocked with some lid
2193015	2	Y	N	N	N	Y	Y	TRUE	Partial	Some infiltration, one end ties between first segment and the second one, no ties on other end
2269135	2	N	N	N	Y	N	N	TRUE	Y	no joint separation, no Infiltration, it crosses intersection so we have skewness, pipe ties at every segment
2194517	2	CIPP Lined	N/A	N/A	N	N/A	Y	N/A	N	culvert repair with liner CIPP
2194519	2	N	N	N	Y	Y	Y	TRUE	N	it turnes, it is diagonal, big gap, no infiltration
2295257	2	N	N	Y	N	Y	Y	TRUE	Y	under rural road, pipe ties at every segment

Pipe ID	Main. District	Repaired	Misalignment	Infiltration	Sediment	Inspected Joint Separation	Database Joint Separation	Inspection Match Database?	Pipe Ties	Comments
2191463	2	N	N	N	Y	Y	N	FALSE	Y	pipe ties at each segment, no infiltration, just joint separation between apron & the first segment
5445050	2	N	N	Y	N	N	N	TRUE	Y	it seems okay, pipe ties at every segment
2194944	2	N	N	N	N	N	N	TRUE	Partial	Pipe ties more than 10 segments on one end, other end has only one joint tied. No infiltration, No JS
2246498	3	N	N	N	N	N	Y	FALSE	Partial	Pipe ties to fourth segment, but no observed separation
2246525	3	N	N	N	N	Y	N	FALSE	Y	Difficult to see, maybe some minor joint separation
2181735	3	N	N	N	N	Y	Y	TRUE	Partial	Pipe ties only on first two segments, some separation
2181741	3	N	N	N	N	Y	Y	TRUE	Y	Very new pipe, 2" joint separation, some damage during installation?
2181739	3	N	N	N	N	Y	Y	TRUE	Y	Some minor separation in top of first joint
2181553	3	N	N	N	N	Y	N	FALSE	Partial	Pipe ties only on first two segments, joint separation
2300495	3	N	N	N	N	N	N	TRUE	N	30% of water, seems good
2300453	3	N	N	N	Y	N	N	TRUE	Y	Sediment, but otherwise good
2195099	4	N	Y	N	Y	Y	N	FALSE	N	Half full of water, could see joints partially
2195034	4	N	N	N	N	N	N	TRUE	N	Looks good
2206852	4	N	N	N	N	N	N	TRUE	N	Looks good
2279563	4	N	N	N	N	N	N	TRUE	Y	75% full of water, but didn't see any issues
2227404	6	N	N	N	N	Y	Y	TRUE	Partial	Pipe ties only on first two segments, separation occurs after ties end
2274553	6	N	N	N	Y	N	N	TRUE	N	Lots of sediment and some apron separation
4447989	6	N	N	N	N	Y	Y	TRUE	Y	Small separations on first joint
4449135	6	N	N	N	N	N	N	TRUE	Y	Database says minor separations, but didn't really see anything of note
2252102	6	N	Y	N	N	Y	N	FALSE	Y	

Pipe ID	Main. District	Repaired	Misalignment	Infiltration	Sediment	Inspected Joint Separation	Database Joint Separation	Inspection Match Database?	Pipe Ties	Comments
2180600	6	N	Y	N	N	Y	N	FALSE	Y	Joint separation in third joint
2271961	6	N	N	N	N	Y	N	FALSE	Y	Minor separation on top of a joint, but otherwise looks great
2187828	6	Y	N	N	N	Y	Y	TRUE	Partial	Pipe ties only on first two segments
2187925	6	N	N	Y	Y	Y	Y	TRUE	N	Lots of infiltration on first joint
2288274	6	Grouted	N	N	N	N	N	TRUE	Y	Some seperation at apron, but grouted as repair
2253376	6	N	N	N	Y	N	N	TRUE	Y	Sediment, but otherwise good
2184508	6	CIPP Lined	N/A	N/A	N/A	N/A	N	N/A	N	CIPP lined, could not observe joints
2198126	7	N	N/A	N/A	N/A	N	Y	FALSE	N	Half full of water, could not see joints clearly
2240657	7	N	Y	Y	Y	Y	Y	TRUE	N	13"-16" separation, crack in road, lots of infiltration and vegetation
2242130	7	N	N	Y	N	Y	Y	TRUE	N	Apron separation and joint separation at first joint (2" perhaps)
2308749	7	N	N	N	N	N	N	TRUE	Y	Erosion on apron but no separation
2276728	7	N	N	N	N	N	N	TRUE	Y	1/4 full of water, but otherwise seems fine
2276721	7	N	N	Y	N	Y	N	FALSE	Y	
2209146	7	N	N	N	N	N	N	TRUE	Y	1/4 full of water, but otherwise seems fine
4308531	7	N	N	N	N	N	N	TRUE	Y	Looks good
2214249	7	Metal Bands	N/A	N/A	N/A	N/A	N	N/A	N	Internal bands, could not see joints
2231492	8	HDPE Lined	N/A	N/A	N	N/A	N	N/A	N	Lined, could not observe joints
2207649	8	N	N	N	N	Y	Y	TRUE	Y	1"-2" sep. between apron and first segment
2207873	8	N	Y	N	Y	N	N	TRUE	Y	Minor misalignment, but otherwise good
2207822	8	N	Y	Y	Y	Y	N	FALSE	Y	
2207825	8	N	N	N	N	N	N	TRUE	Y	Looks good
2207832	8	N	Y	Y	N	Y	Y	TRUE	Partial	Pipe ties only on first two segments, 4"-5" separation in third joint, just after ties end

Pipe ID	Main. District	Repaired	Misalignment	Infiltration	Sediment	Inspected Joint Separation	Database Joint Separation	Inspection Match Database?	Pipe Ties	Comments
2207834	8	Y	Y	N	N	Y	Y	TRUE	Partial	Pipe ties only on first two segments, 3"-4" separation in third joint, just after ties end
2207836	8	N	N	N	N	N	N	TRUE	Y	Looks good
2251008	8	N	Y	Y	Y	Y	Y	TRUE	N	Lots of separation, infiltration on all joints
2251014	8	N	N	Y	Y	Y	Y	TRUE	N	2"-3" separation in all joints
2251020	8	N	N	Y	Y	Y	Y	TRUE	N	Lots of infiltration, but not at the first joint
2251023	8	N	N	Y	Y	Y	Y	TRUE	N	Apron separation (3"-4") and joint separation (2"-3") at first joint. Can reach through joint and touch soil.
2251028	8	N	N	Y	Y	Y	Y	TRUE	N	Lots of infiltration, joint separation is small (1"-2") but can touch soil through joint

Appendix B: MnDOT Employee Survey Results

Survey Responses

Question 1: Describe what training you have been given (or you have given to others) regarding concrete pipe installation.

On site training, in field inspection
Previously worked in Hydraulics, doing more pipe inspection and design work. Construction oversight is current role.
Grading and Base I & II 4 decades of experience
Grading and Base Classes. And reading the Spec
Pipe manufacturers got together about 6 years ago and out on a class. It was very informative because they talked about all different types of pipe that can go into the ground. Concrete, metal, plastic, and possibly some rubber.
Pipe installation class in Kato in 2018
Field training as an installer in private sector, 14 years as grading inspector with MnDOT. No formal training
Primarily on the job and technical college.
Grading and Base plus onsite experience including asking questions and watching installations. The Schedule of Material Controls testing requirements not found in the specifications book.
On the job training from other inspectors, some culvert topics covered in Certification training.
no training
on the job training
On the job
did heavy equipment maintenance and building roads for 7years.
AASHTO online training and in the field training
Training from senior inspectors in the field, Grading & Base training, following MnDOT specifications and standard plates.
Fundamentals of construction inspection, Co Worker Training.
oJT, contract admin manual and spec book
On the job training.
On-site and code
Culvert Hydraulics & Design, OTJ, AA Degree in Civil Engineering

Question 2: How often do you see joint issues (separation, breakage, etc.) during pipe installation? Please describe the most common types of issues encountered.

involved in mostly new installation, issues seen come from poor soil conditions or inaccurate information on new installation ground conditions.
I'm not an inspector, but visiting project sites I have not seen many installation issues.
Common, joints separate as pipe sections drift (culvert gets longer)
I see issues getting contractor to get the joints tight. Or not getting the bed under the pipe. To much slope and get breaks
During installation I haven't seen many issues. If there are with the pipe we reject them or use them where they have to cut for certain length.
Rarely, I make sure we have a good bottom and proper bedding. A good foundation is essential
I generally do not see these issues now. In the past there were issues and I changed what I have the contractors do when installing pipe.
Not often
During Installation - any pipe after the 3rd joint does not require pipe ties, the mastic joint sealer calls for 2 layers and sometimes limits pulling the pipe together at the joint. This can limit the pipe from connecting properly. Also the pipe tolerances at the male and female ends varies enough that it doesn't completely seal without a lot of extra effort by the contractor. Other things to note: most inspectors try to get the contractor to follow compaction per the Schedule of Material Control, however, watering and compaction efforts by the contractor vary from little to exceptional and that can lead to frost and moisture moving the pipe.
rarely
don't see a lot during installation.
in the last few years we've since an increase of box culverts arriving with flanges out of tolerance that are not able to be seated properly. This mostly occurred in 2022.
Alot of fitment issues. Poor/ uneven joint finishing during production
concrete piping is the worst. crushing is most common and just out of date.
Sometimes. I see damage from pipe transportation and/or pipes being shipped too green.
Not often when installing. Common concerns that are corrected while installing are gaskets being dirty or shifting off when installing pipe.
very minimal
Occaisonally see some spalling if the contractor is forcing the alignment.
The most common issue I see is contractors trying to use pipes with broken bells.
Occasionally. Saturated bedding causes movement. Poor handling by equipment operator during installation cases chips & spalss.

Question 3: What practices have you adopted to prevent joint separation, joint breakage, or soil infiltration in new installations?

Flood compaction, insuring tie bars are installed correctly, substituting backfill materials that are appropriate for the ground conditions.
Using joint ties seems to help significantly, but it must be the entire pipe length. Inspecting pipes that had the end sections reset and tied just pushed the separations further under the roadway.
Installing the flatbar ties are effective, but need to tie all joints.
wrap has been used on concrete pipe and have seen it on CSP also. Gaskets on RCP
Use mastic all around the pipe. Contractors like to just put it at the bottom or where possible water might be. Make sure they use a shovel to work material in the haunch of the pipe.
Proper pipe installation techniques and following the Spec.
I have the contractor subcut 2' under all pipes (not just culvert pipe like the Standard plans show. We have them compact the bottom 18" and leave the top 6" loose so they can set the pipe. Definitely need to make them knife-in or preferably shovel handle pack under the haunch the whole length of the pipe. I pay for 18" of the pipe bedding, since 6" is incidental to storm sewer. I have to calculate the quantities of this extra materials used under storm sewer since the designers only calculate/include pipe bedding quantities for pipe culvert applications. I also have already talked to our Resident Engineer about having the contractor use pipe bedding about 18" to 2' wide around drainage structures, all the way up so we don't have any more issues of trying to get excavated materials to pass density tests, of course we will pay for this quantity as an extra also.
I personally use the gradation number of the granular material to find optimum moisture and share that with the contractor (the biggest problem I have encountered is getting them to use water and enough water for proper compaction). I also follow the Schedule of Material controls per transverse pipe (structure) compaction of every 2 ft. I also watch and check random joints for mastic rolling, and excessive gaps in between the pieces.
soil compaction, fabric wrap on joints
tighten them up and wrap them with fabric
D3 has a special standard to wrap the outside of the boxes at the joints. This helps with concerns over soil migration into the pipes should not be a fix for the fabrication issues
Setting and pulling sections multiple times to try and correct. Double mastic on joints, grout in flowline
by installing it correctly and putting the correct material around the pipe.
geofabric around the seams and pipe ties for culverts.
Tie bars are required on culvert pipes, but not on storm sewer. Seeing specs require fabric over joints before backfilling recently.
Our office has all joints gasketed, tied, and wrapped in fabric.
Tied joints, pipe bedding, and fabric wrap to prevent material from infiltrating.
Tie all joints together
Ensure pipes are "sent home" and have a good connection. Putting lubricant on the casket helps. Making sure ties are used when required.
Correct compaction and testing

Proper bedding, proper mastic installation around complete circumference between pipe sections.

Question 4: Please suggest any new practices for culvert installation you would like to have implemented.

More training, difficult to train new staff when projects are already understaffed.
Tying all joints on RCP. Perhaps consider alternate pipe materials that can reduce joints, recently the HOBAS pipes have been required by RR, or some stronger plastic pipe types
Need to install lateral arrest anchorage on inplace pipe as a retro-repair.
not at this time
With some of our construction areas I think we should tie all pipe together with a material that won't deteriorate.
Flood Compaction with SGE 5% to the top of the pipe. No Plastic Soils
You cannot DCP under the haunch due to the DCP does not really work at an angle, we have a compaction tester that I sometimes use to check compaction. With concurrence from the Grading & Base Office, I use this tool to check. You get a base number on the compacted bedding next to the pipe with the tester straight up & down, than you use said tester at an angle into the haunch area under the pipe, G & B office figured it is probably pretty close if you read at least 50% of your base number.
Tie all pipes
It is not in the special provisions or specification books, stating the transverse pipe is NOT quality compaction, it does have compaction requirements, (It is only found in the SMC under structures). I think it should be in both the specifications and the SMC. I would like to also see at least one person on the pipe crew who must be certified in Grading and Base, so they understand the needs for water and compaction correlation. Good subgrade material is what holds the pipe in place and the road from being excessively impacted by freeze thaw cycles. Joints are less likely to separate when the subgrade has good compaction and is able to drain water out of the surrounding area.
Its almost impossible to get contractors to add water during compaction of fine aggregate bedding, its also hard to get passing DCP's. including a requirement to add water during compaction as needed called out in the drainage plans may help.
would like easier access to coarse aggregate when undesirable soils are encountered.
just making field staff aware of what to watch for, but fabrication issues need to be addressed with the fabricators if still occurring, We are put in difficult positions if they arrived marked approved and have defect. The road is often under detour and rejecting the material is not a great solution at that point with long lead times.
Go back to an inspector at the production facility 100% of the time
making sure to put the correct rip rap around the inlet or outlet to stop erosion
In wet areas, where course filter aggregates are used for pipe bedding, clay plugs are typically used for aprons to prevent water from flowing through the aggregate bedding. I've seen/replaced/reset

many aprons where the frost heaves them from the pipe. The clay caps swell more than bedding and cause aprons to move more. On the same note, where clay caps aren't used, I've seen water flow through course bedding while installing pipe and after the treatment has been completed. Causing water to remain in the bedding after the pipe becomes live - possibly resulting in the whole pipe to swell more & creating pipe separation & potholes (defeating the purpose of a pipe treatment) Keeping water out of the trench is key. Hard to do a lot of the times. Need sheeting, pumping/bypass & $$$$$$!
I feel like even storm sewer should have tied joints.
Consider installing culvert liners with the new installation.
None

Additional Feedback from MnDOT Employees

Dwayne Stenlund

[Email, February 18, 2025, 9:22 AM] I was not able to locate photos quickly, but

1. This year a whole batch of pipe had to be rejected due to poor quality manufacturing. They would not fit together. I think this was TH59 Pelican Rapids.
2. I have seen chunks of the bell get busted off during swinging the pipe into place. Concrete seems very brittle (accelerated cure).
3. The contactor did not set the laser level properly (D3 TH27). The infall was too high due to this error. Rather than reset completely, did a partial reset and 'bent' the pipe (now has a belly).
4. Gold Line BRT (Ames), uneven pipe placement. I have a photo where I can fit my fingers in the joints at the top (no wrap). I complained to no avail. But if the pipe settles, the joint could tighten, or it could (most likely due to a soil fill) push apart.
5. Work in water saturated base. Seems to me this leads to uneven bearing.
6. Poor design implementation of culvert end section bearing soil and anti-pumping loss of soil from underneath. Perched ends put a lot of strain on tie-bars, and at least one more pipe section in.
7. Speed. Low bid is not helping for quality.

Other states do not allow precast pipe (at least of a certain size). All centerline is cast in place. I know SDDOT was surprised that MnDOT uses precast for all (as far as I can tell based on observations).

Ken Slama

[Email from Nick Olson, February 19, 2025]

I took some notes during a call I received from Ken Slama (D3, copied), who is a principal engineer for MnDOT in Construction out of Baxter, MN:

In recent years, there have been several pipes/box sections received that were stamped approved, but were out of spec (e.g., bad flanges)

- These out of spec pipes were challenging to create deducts for, or to send back to plant, especially since there were long lead times in recent years (pandemic issues fixed now?)
- They were able to fill the separation in one box with an oakum rope and used an exterior wrap to seal joints.

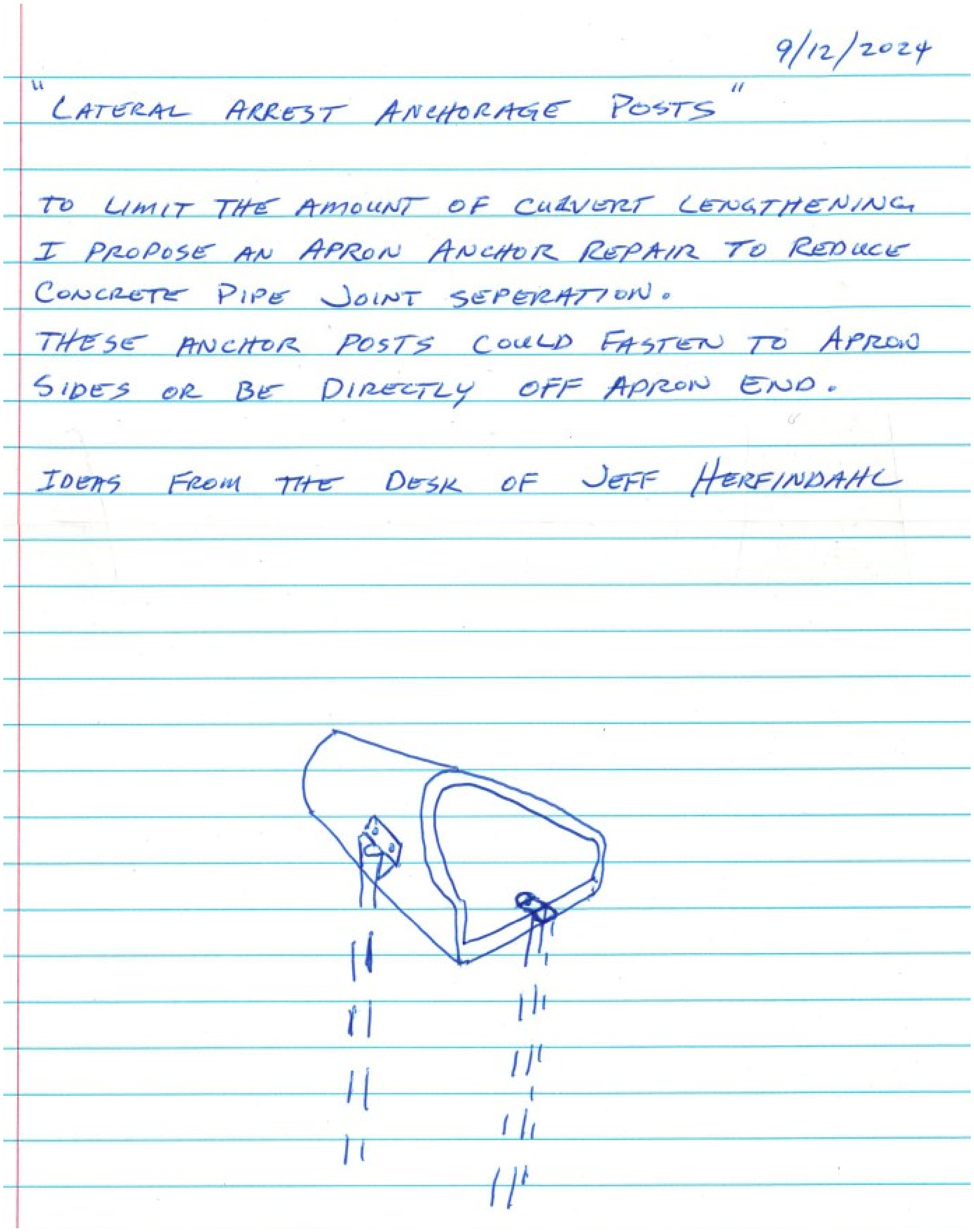
This got us thinking about what quality assurance guidance could be developed for construction staff to help approve/reject pipe. Ken and I discussed that deducts can be challenging, bc we are not entirely sure how to formulate a service life loss or risk to public.

Ken—please feel free to edit or elaborate on anything we discussed. I very much appreciated the call and interest in helping us reduce separation issues.

Jeffrey Herfindahl

[Email 1, February 18, 2025, 9:18 AM] Nick this is an idea I had this fall after working on a district 1 culvert contract. There was one pipe that had flatbar ties added to the apron because of joint separation 4 years ago and now the lateral forces were separating the next two joints and those joints had flatbar ties added. Need to keep culverts from getting longer. Hope this helps.

[Email 2, February 18, 2025, 10:13 AM] In reading my message it might not be clear, but we added flat bar ties to the next two joints during this falls repair. Also I have questioned the need to not compact the last 6" of pipe bedding. I know at some point there was an issue with cracked bells. This bedding practice is not needed for non bell joints and may cause settlement and separation issues later.



9/12/2024

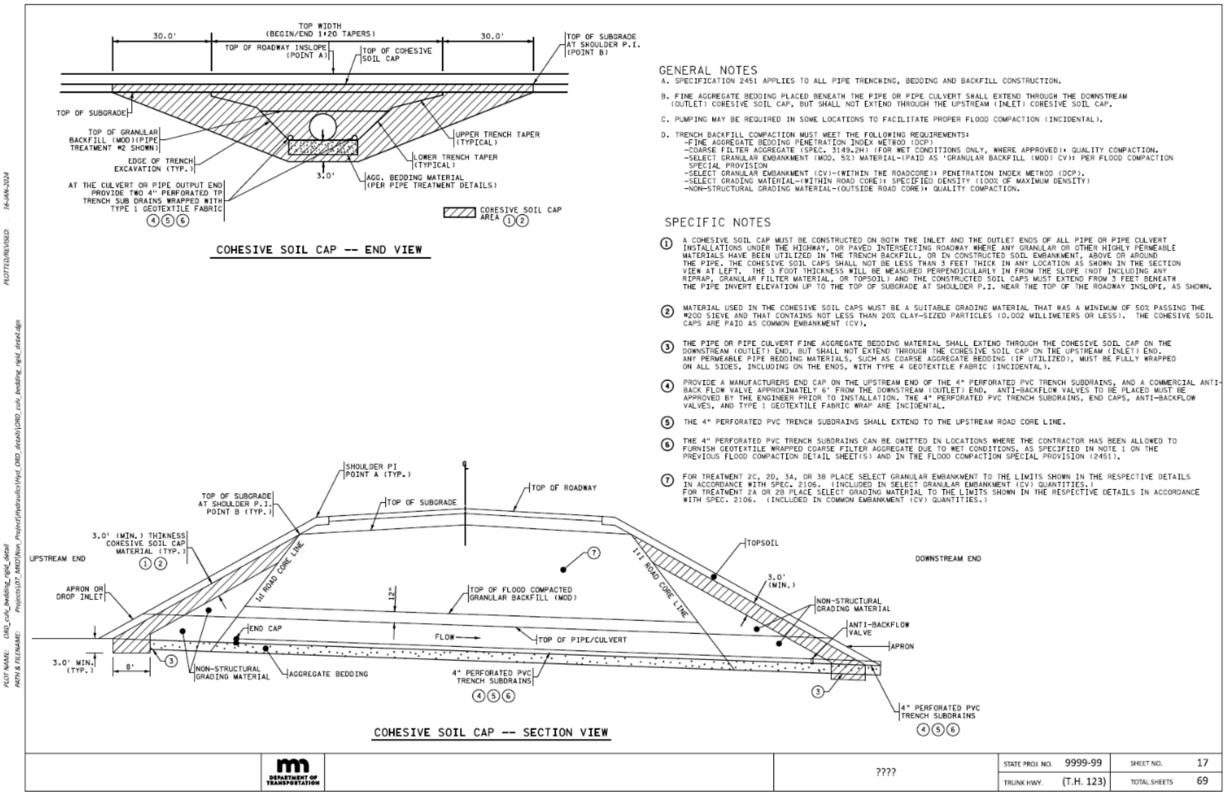
"LATERAL ARREST ANCHORAGE POSTS"

TO LIMIT THE AMOUNT OF CULVERT LENGTHENING I PROPOSE AN APRON ANCHOR REPAIR TO REDUCE CONCRETE PIPE JOINT SEPERATION.

THESE ANCHOR POSTS COULD FASTEN TO APRON SIDES OR BE DIRECTLY OFF APRON END.

IDEAS FROM THE DESK OF JEFF HERFINDAHL

Figure B.1: Schematic for anchoring culvert aprons, provided by Jeff Herfindahl



GENERAL NOTES

A. SPECIFICATION 2451 APPLIES TO ALL PIPE TRENCHING, BEDDING AND BACKFILL CONSTRUCTION.

B. FINE AGGREGATE BEDDING PLACED BENEATH THE PIPE OR PIPE CULVERT SHALL EXTEND THROUGH THE DOWNSTREAM (OUTLET) COHESIVE SOIL CAP, BUT SHALL NOT EXTEND THROUGH THE UPSTREAM (INLET) COHESIVE SOIL CAP.

C. PUMPING MAY BE REQUIRED IN SOME LOCATIONS TO FACILITATE PROPER FLOOD COMPACTION (INCIDENTAL).

D. TRENCH BACKFILL COMPACTION MUST MEET THE FOLLOWING REQUIREMENTS:
-FINE AGGREGATE BEDDING PENETRATION INDEX METHOD (DCP)
-COARSE FILTER AGGREGATE (SPEC. 3149.2H) (FOR WET CONDITIONS ONLY, WHERE APPROVED): QUALITY COMPACTION.
-SELECT GRANULAR EMBANKMENT (MOD. 5%) MATERIAL-(PAID AS 'GRANULAR BACKFILL (MOD) CV): PER FLOOD COMPACTION SPECIAL PROVISION
-SELECT GRANULAR EMBANKMENT (CV)-(WITHIN THE ROADCORE): PENETRATION INDEX METHOD (DCP).
-SELECT GRADING MATERIAL-(WITHIN ROAD CORE): SPECIFIED DENSITY (100% OF MAXIMUM DENSITY)
-NON-STRUCTURAL GRADING MATERIAL-(OUTSIDE ROAD CORE): QUALITY COMPACTION.

SPECIFIC NOTES

① A COHESIVE SOIL CAP MUST BE CONSTRUCTED ON BOTH THE INLET AND THE OUTLET ENDS OF ALL PIPE OR PIPE CULVERT INSTALLATIONS UNDER THE HIGHWAY, OR PAVED INTERSECTING ROADWAY WHERE ANY GRANULAR OR OTHER HIGHLY PERMEABLE MATERIALS HAVE BEEN UTILIZED IN THE TRENCH BACKFILL, OR IN CONSTRUCTED SOIL EMBANKMENT, ABOVE OR AROUND THE PIPE. THE COHESIVE SOIL CAPS SHALL NOT BE LESS THAN 3 FEET THICK IN ANY LOCATION AS SHOWN IN THE SECTION VIEW AT LEFT. THE 3 FOOT THICKNESS WILL BE MEASURED PERPENDICULARLY IN FROM THE SLOPE (NOT INCLUDING ANY RIPRAP, GRANULAR FILTER MATERIAL, OR TOPSOIL) AND THE CONSTRUCTED SOIL CAPS MUST EXTEND FROM 3 FEET BENEATH THE PIPE INVERT ELEVATION UP TO THE TOP OF SUBGRADE AT SHOULDER P.I. NEAR THE TOP OF THE ROADWAY INSLOPE, AS SHOWN.

② MATERIAL USED IN THE COHESIVE SOIL CAPS MUST BE A SUITABLE GRADING MATERIAL THAT HAS A MINIMUM OF 50% PASSING THE #200 SIEVE AND THAT CONTAINS NOT LESS THAN 20% CLAY-SIZED PARTICLES (0.002 MILLIMETERS OR LESS). THE COHESIVE SOIL CAPS ARE PAID AS COMMON EMBANKMENT (CV).

③ THE PIPE OR PIPE CULVERT FINE AGGREGATE BEDDING MATERIAL SHALL EXTEND THROUGH THE COHESIVE SOIL CAP ON THE DOWNSTREAM (OUTLET) END, BUT SHALL NOT EXTEND THROUGH THE COHESIVE SOIL CAP ON THE UPSTREAM (INLET) END. ANY PERMEABLE PIPE BEDDING MATERIALS, SUCH AS COARSE AGGREGATE BEDDING (IF UTILIZED), MUST BE FULLY WRAPPED ON ALL SIDES, INCLUDING ON THE ENDS, WITH TYPE 4 GEOTEXTILE FABRIC (INCIDENTAL).

④ PROVIDE A MANUFACTURERS END CAP ON THE UPSTREAM END OF THE 4" PERFORATED PVC TRENCH SUBDRAINS, AND A COMMERCIAL ANTI-BACK FLOW VALVE APPROXIMATELY 6' FROM THE DOWNSTREAM (OUTLET) END. ANTI-BACKFLOW VALVES TO BE PLACED MUST BE APPROVED BY THE ENGINEER PRIOR TO INSTALLATION. THE 4" PERFORATED PVC TRENCH SUBDRAINS, END CAPS, ANTI-BACKFLOW VALVES, AND TYPE 1 GEOTEXTILE FABRIC WRAP ARE INCIDENTAL.

⑤ THE 4" PERFORATED PVC TRENCH SUBDRAINS SHALL EXTEND TO THE UPSTREAM ROAD CORE LINE.

⑥ THE 4" PERFORATED PVC TRENCH SUBDRAINS CAN BE OMITTED IN LOCATIONS WHERE THE CONTRACTOR HAS BEEN ALLOWED TO FURNISH GEOTEXTILE WRAPPED COARSE FILTER AGGREGATE DUE TO WET CONDITIONS, AS SPECIFIED IN NOTE 1 ON THE PREVIOUS FLOOD COMPACTION DETAIL SHEET(S) AND IN THE FLOOD COMPACTION SPECIAL PROVISION (2451).

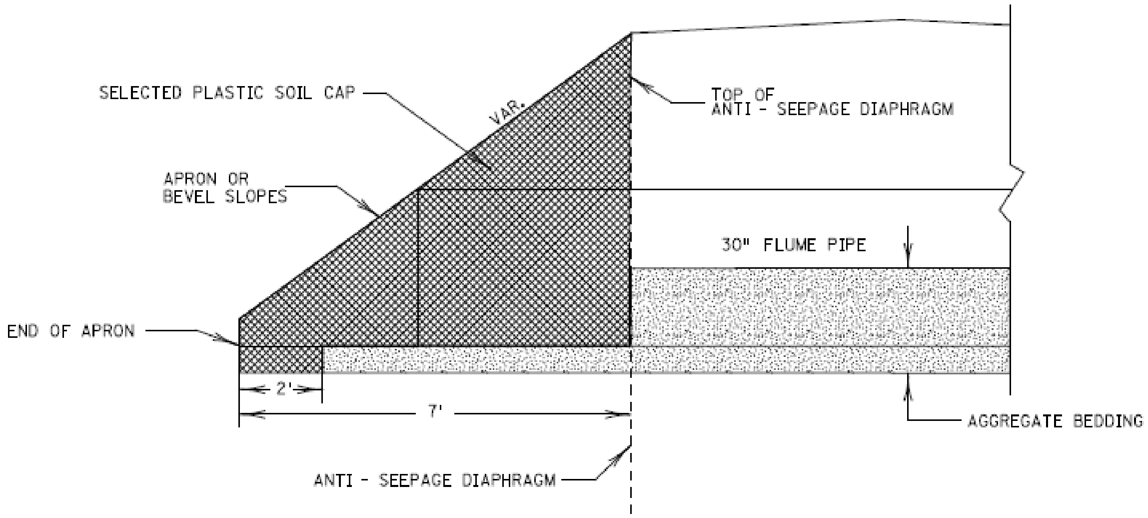
⑦ FOR TREATMENT 2C, 2D, 3A, OR 3B PLACE SELECT GRANULAR EMBANKMENT TO THE LIMITS SHOWN IN THE RESPECTIVE DETAILS IN ACCORDANCE WITH SPEC. 2106. (INCLUDED IN SELECT GRANULAR EMBANKMENT (CV) QUANTITIES.)
FOR TREATMENT 2A OR 2B PLACE SELECT GRADING MATERIAL TO THE LIMITS SHOWN IN THE RESPECTIVE DETAILS IN ACCORDANCE WITH SPEC. 2106. (INCLUDED IN COMMON EMBANKMENT (CV) QUANTITIES.)

????

STATE PROJ. NO. 9999-99
SHEET NO. 17
TRUNK HWY. (T.H. 123)
TOTAL SHEETS 69

Figure B.2: MnDOT standard cohesive soil cap installation

APRON-5
PLASTIC SOIL CAP TREATMENT AT FLUME INLET & ANTI SEEPAGE DIAPHRAGM LOCATION

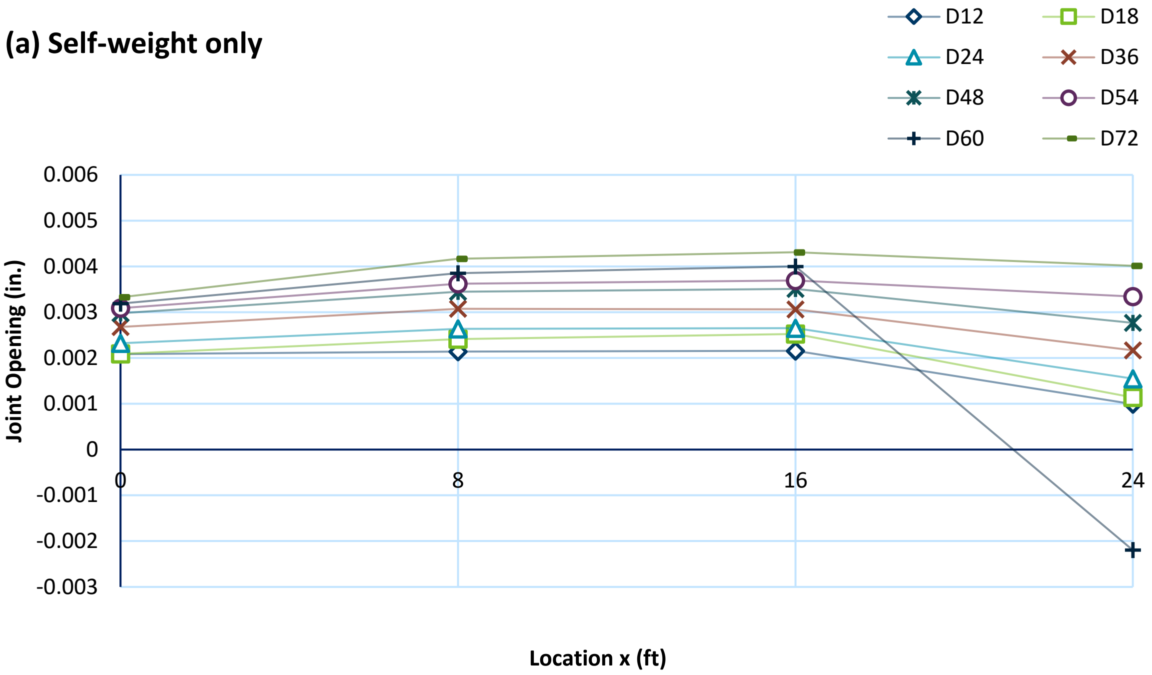


1. WIDTH OF PLASTIC SOIL CAP IS FULL WIDTH OF GRANULAR TREATMENT PLUS 3 FEET ON EACH END.
2. REMOVAL OF EXISTING SOIL FOR PLASTIC SOIL CAP SHALL BE CONSIDERED INCIDENTAL.
3. PAID FOR AS PLASTIC SOILS CAP (CV). (SPEC. 2451).

Figure B.3: Alternative cohesive soil cap installation

Appendix C: Additional Results for Discrete Pipe Finite Element Models

(a) Self-weight only



(b) Traffic load plus self-weight

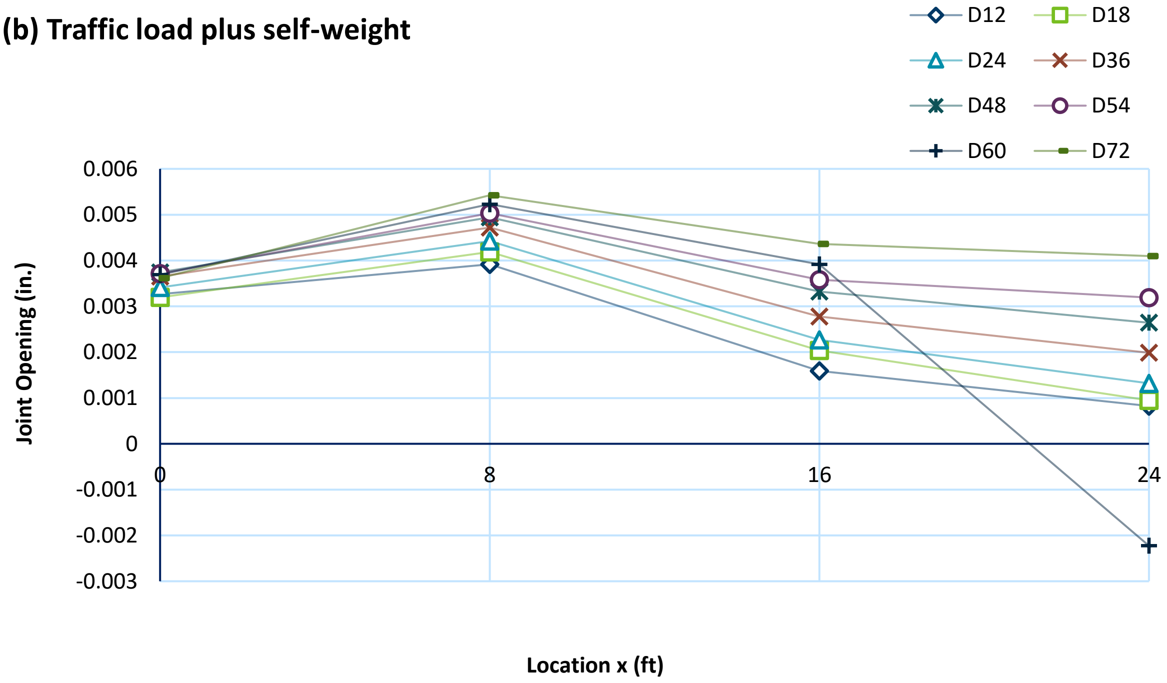
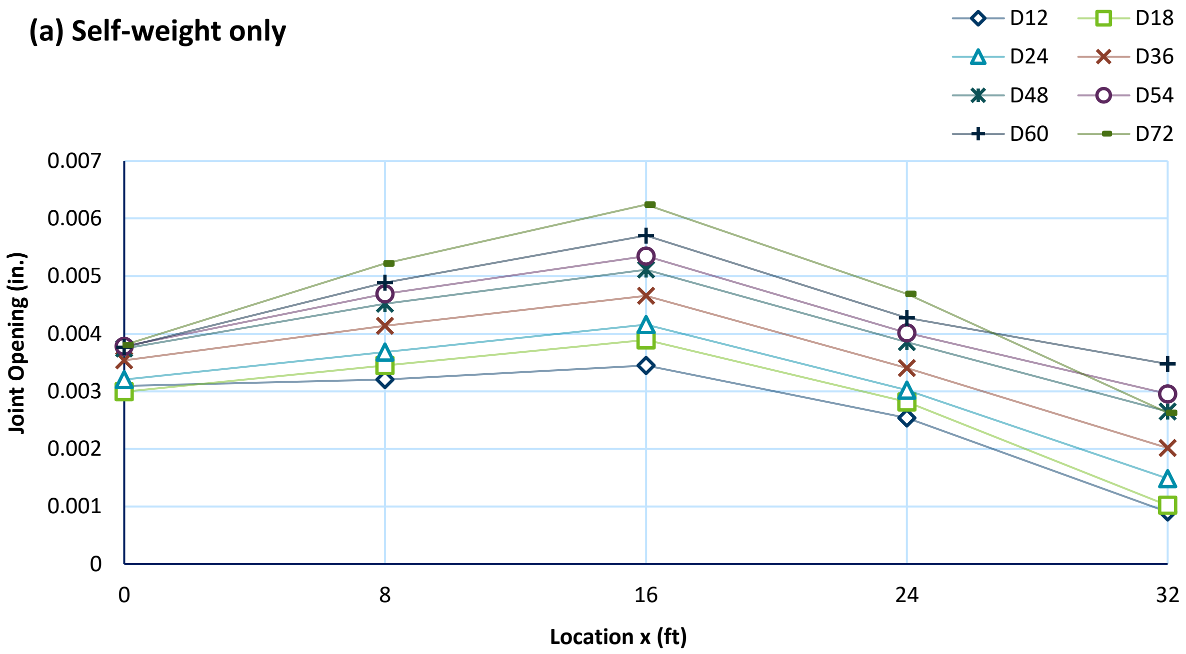


Figure C.1: Modeled Joint opening for different diameters for soil cover depth of 2 ft under (a) self-weight and (b) combined traffic load with self-weight



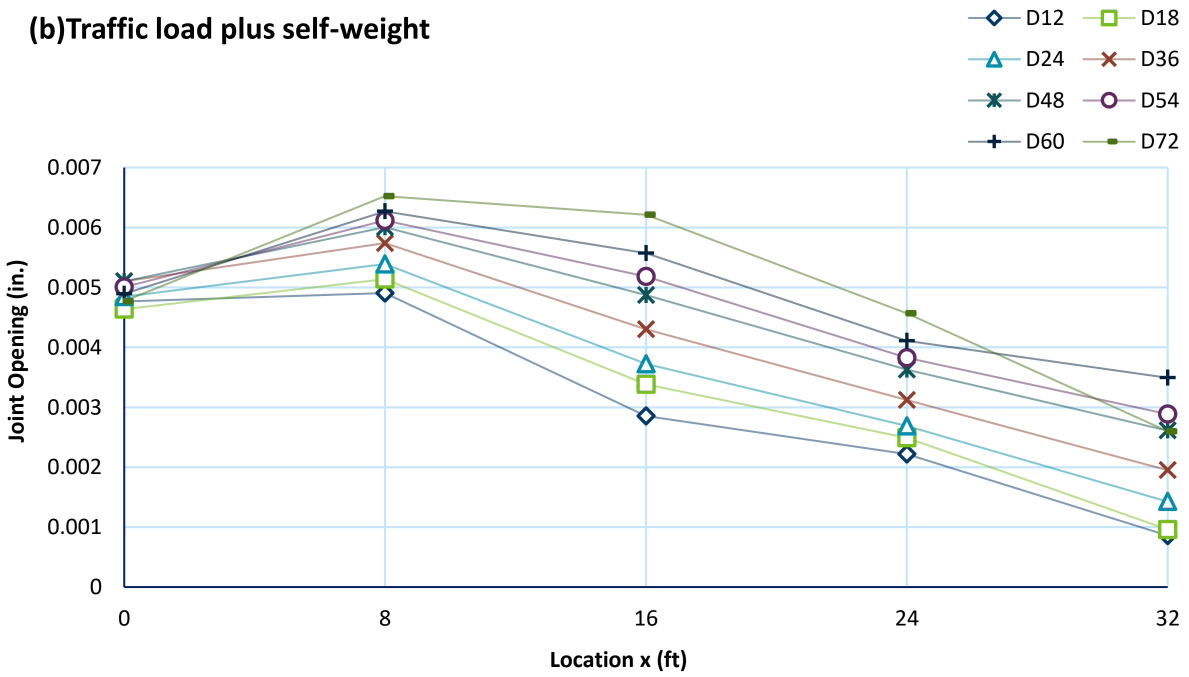
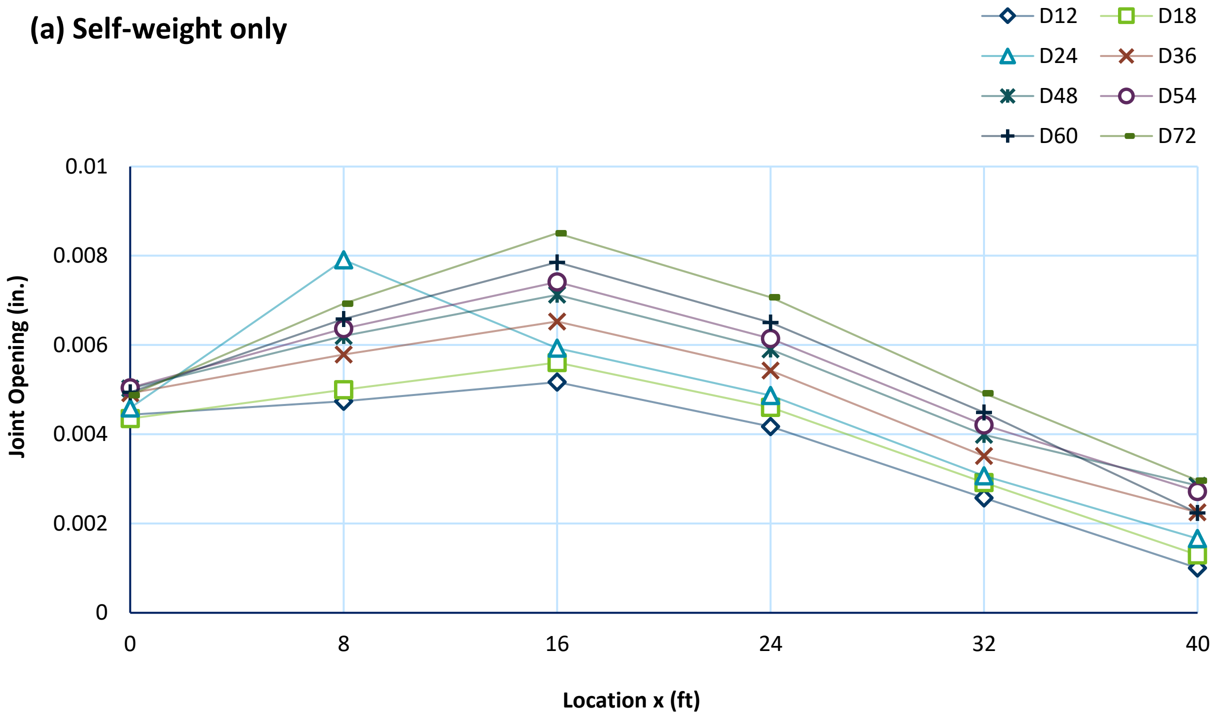


Figure C.2: Modeled Joint opening for different diameters for soil cover depth of 4 ft under (a) self-weight and (b) combined traffic load with self-weight

(a) Self-weight only



(b) Traffic load plus self-weight

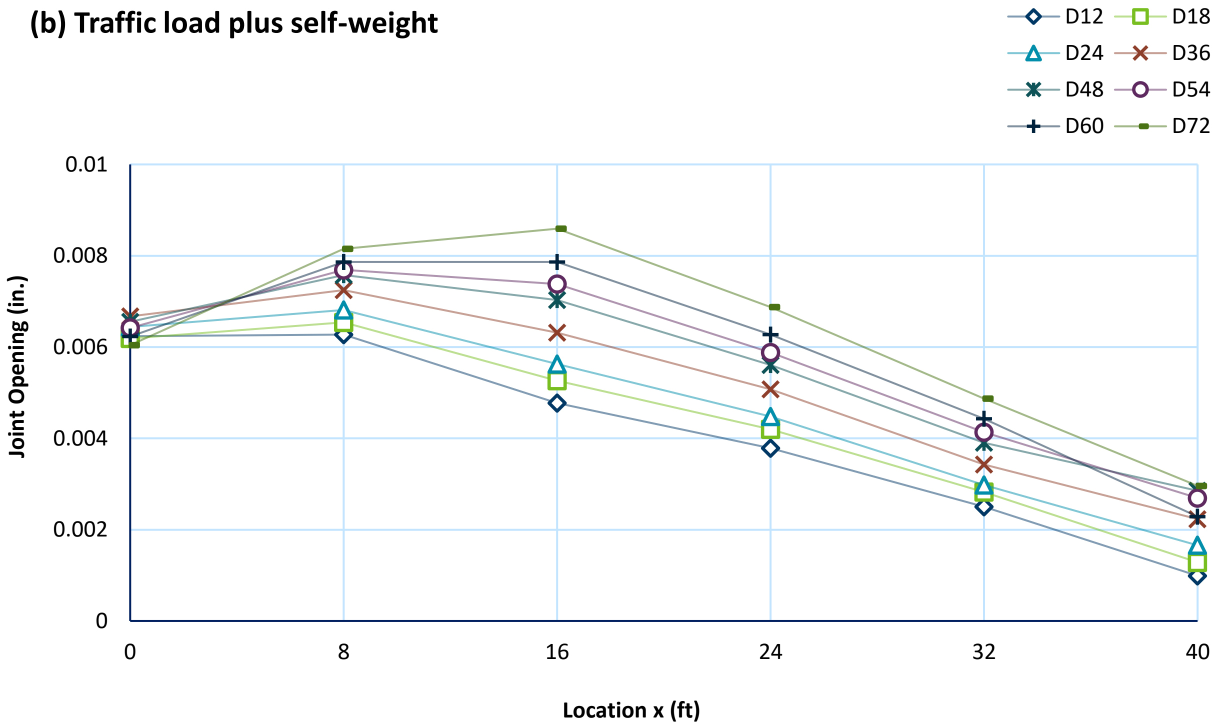
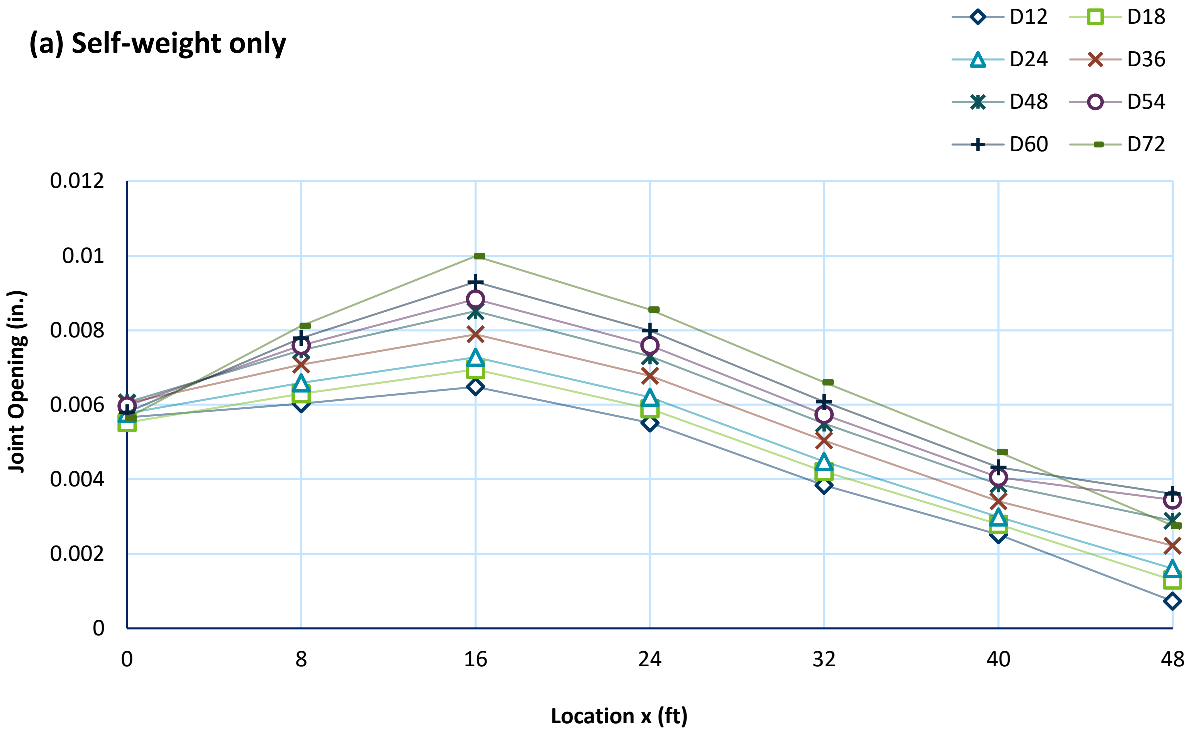
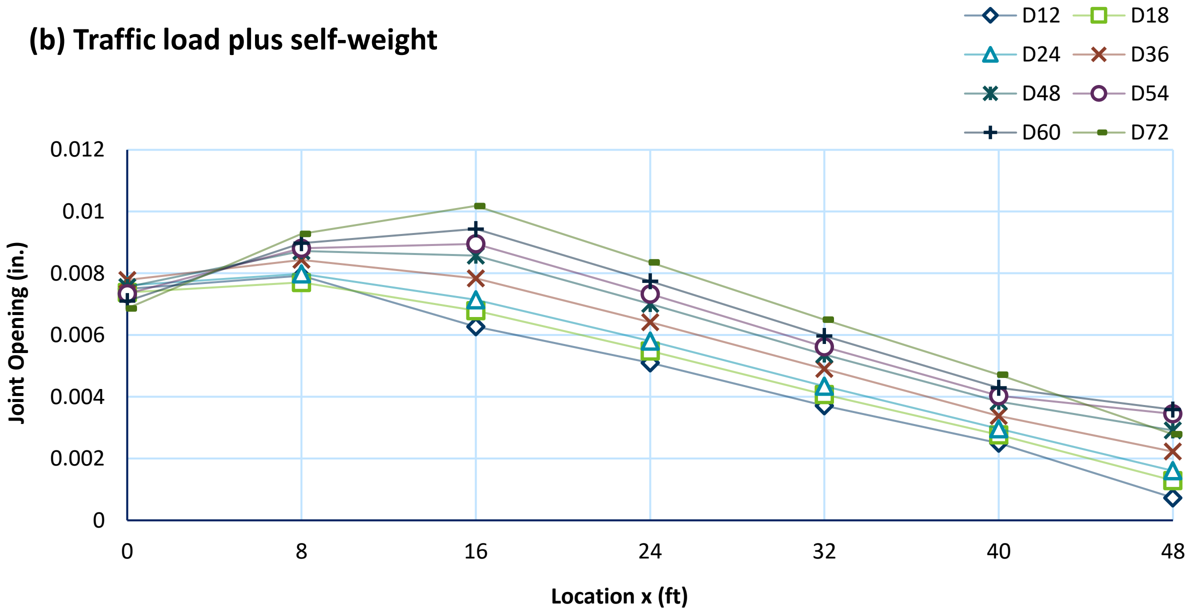


Figure C.3: Modeled Joint opening for different diameters for soil cover depth of 6 ft under (a) self-weight and (b) combined traffic load with self-weight

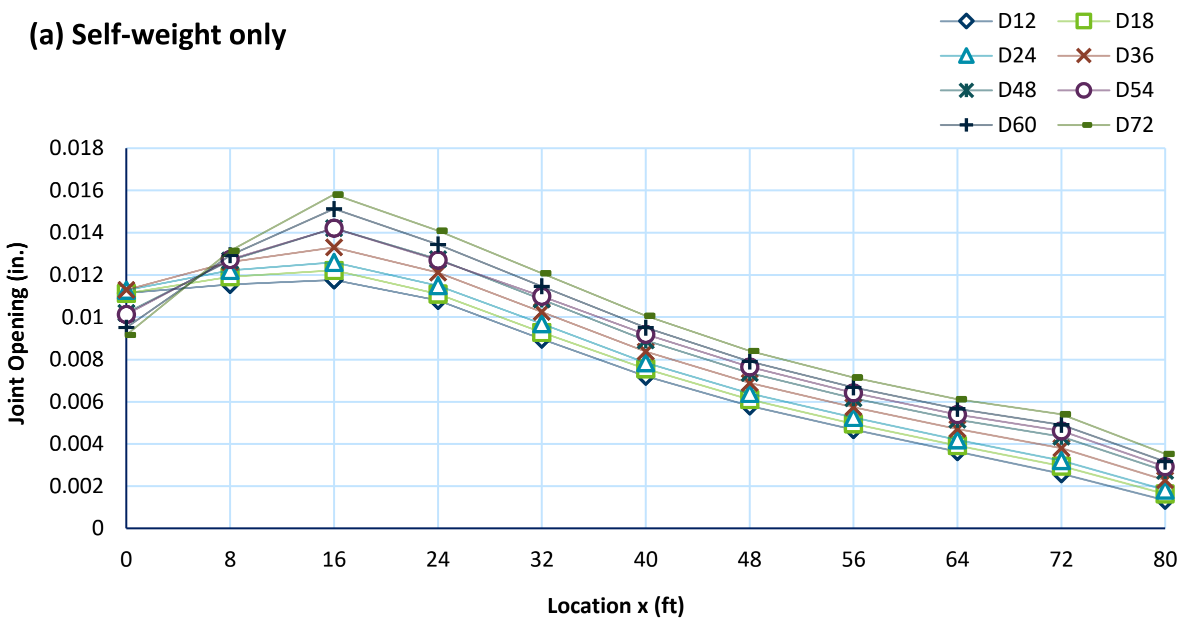


(a) Self-weight only



(b) Traffic load plus self-weight

Figure C.4: Modeled Joint opening for different diameters for soil cover depth of 8 ft under (a) self-weight and (b) combined traffic load with self-weight


(a) Self-weight only

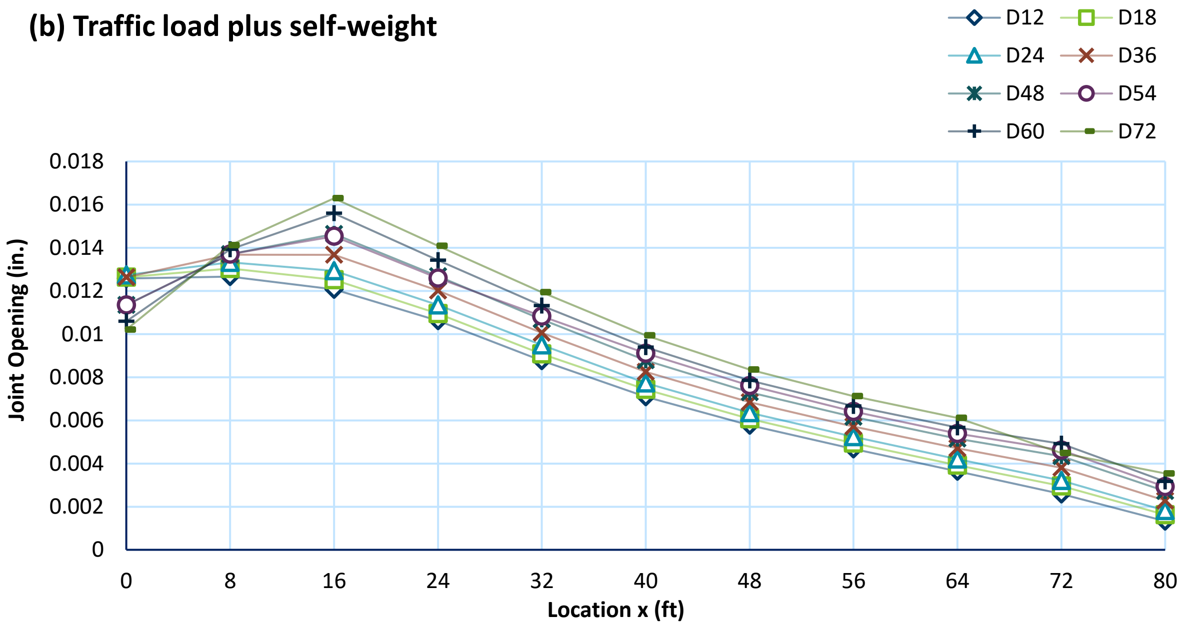

(b) Traffic load plus self-weight

Figure C.5: Modeled Joint opening for different diameters for soil cover depth of 16 ft under (a) self-weight and (b) combined traffic load with self-weight