IMPROVING RATING AIDS FOR THE EVALUATION OF EXISTING CONCRETE CULVERTS IN TENNESSEE

FINAL REPORT

David Lee, Ph.D. 1/10/20

Project No. 28012 – ED 1236527

Submitted to

Tennessee Department of Transportation
Suite 900, James K. Polk Building
Nashville, Tennessee 37243-0334

By

X. Sharon Huo, Ph.D., P.E.
Professor of Civil Engineering

Brandon Bartrom, E.I.
Graduate Research Assistant

Heath Kaufman, E.I.
Graduate Research Assistant

July 2015

Tennessee Technological University
P.O. Box 5032
Cookeville, Tennessee 38505

This privileged Document is prepared solely for the appropriate personnel of the Tennessee Department of Transportation and the Federal Highway Administration in review and comment. The opinions, findings, and conclusions expressed here are those of authors and not necessarily those of the Tennessee Department of Transportation and/or the Federal Highway Administration. The document is not to be released without permission of the Tennessee Department of Transportation.

Technical Report Documentation Page

1. Report No. 28012 – ED 1236527	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Improving Rating Aids for the Evaluation of Existing Concrete Culverts in Tennessee		**5. Report Date** July 2015 **6. Performing Organization Code**
7. Author(s) X. Sharon Huo, Brandon Bartrom, and Heath Kaufman		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Center for Energy Systems Research Box 5032, Tennessee Technological University Cookeville, TN 38505-0001		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address Structures Division Tennessee Department of Transportation James K. Polk Building, Suite 1100 505 Deaderick Street, Nashville, TN 37243-0339		**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

Within the Tennessee transportation system, TDOT is responsible for nearly 20,000 highway bridges/transportation structures. Approximately 44% of these structures are classified as culverts. Existing culverts in Tennessee date back as far as 1905 and some of these culverts need to be evaluated for their structural capacity due to aging and wear. Additionally, all culverts that have been designed, built, and maintained by TDOT have to be in compliance with the load rating requirements of the NBIS. The main objective of this research project was to improve upon a set of rating aids that were developed to assist in the assessment of reinforced concrete culverts in Tennessee. Literature reviews were conducted on relevant material for the analyses presented in this paper. After the literature reviews were completed, culverts were modeled in multiple programs to begin the analyses. The analyses include: a verification analysis, a horizontal soil pressure analysis, a rating factor analysis for TDOT dump truck loads, a shear capacity and shear rating factor analysis, and a moment continuity analysis. One of the objectives of this research project was to improve the Culvert Rating Aids to better assist in the assessment of culverts in Tennessee. The improvements included additions of unique features that created a user-friendly interface for the navigation of both the box and slab culvert Rating Aids. Use of the improved Rating Aids only requires a few basic culvert details such as the year they were made, number of cells, cell size, and skew angle, and the Rating Aids best meet the needs of rating engineers for culvert assessment.

17. Key Words BRASS Culvert, Rating Aids, rating factors, and reinforced concrete culverts		**18. Distribution Statement**	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 130	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of Completed page authorized**

EXECUTIVE SUMMARY

Within the Tennessee transportation system, TDOT is responsible for nearly 20,000 highway bridges/ transportation structures. Approximately 44% of these structures are classified as culverts. Existing culverts in Tennessee date back as far as 1905 and some of these culverts need to be evaluated for their structural capacity due to aging and wear. Additionally, all culverts that have been designed, built, and maintained by TDOT have to be in compliance with the load rating requirements of the National Bridge Inspection Standards (NBIS). Since there are hundreds of standard TDOT drawings for concrete box and slab culverts with various site conditions, a rating of over 8,500 culverts requires tremendous efforts both at the onset and in the long run. Therefore, it is essential that efficient tools be developed for culvert rating.

The main objective of this research project was to improve the Culvert Rating Aids to assist in the assessment of culverts in Tennessee. The improvements were accomplished in various ways, including the refinement of existing values and the addition of features in the Rating Aids to assist in their use. Well over 1000 standard concrete box and slab culverts had to be investigated over the course of this project. The sheer size of the Box and Slab TDOT Culvert Rating Aids necessitated simplistic searching and updating methods. The refinement of rating factors included a moment continuity and shear analysis. The functional improvements and numerical refinements will be summarized in the following paragraphs.

The functional improvements of the Rating Aids include: a single user-friendly search page, only needing a mouse or touchpad to function (excluding the updating process), able to return from any page to the search page with a button, a built-in user manual, and a built in method to update values with BRASS Culvert output files. Having a single page to search from makes the program simpler to use, and allows refined searches for desired culverts. The fact that all

navigation of the Rating Aids can be performed with a mouse also means easier use with touch-screen devices. The user manual will be accessible from the Search Page of the Rating Aids (the opening page), so any confusion with the program can be sorted out with little complication. Finally, a method to revise rating factors based on revised BRASS Culvert output is available in the Rating Aids. Manual transfer of rating factor values from the BRASS Culvert output to the Rating Aids is still required, but the Rating Aids have built in functions to intelligently sort the data into a useable format, as well as create an updated set of rating factors based on user specifications.

The refinement of the rating factors included: a moment continuity analysis, a shear rating factor analysis, and several other analyses. The moment continuity analysis resulted in a general increase in flexural rating factors for the culverts analyzed. The shear analysis resulted in the shear rating factors of the Rating Aids being ignored and removed. Both moment continuity and shear analyses, along with their conclusions, are presented in Chapters 8 and 7, respectively.

ACKNOWLEDGEMENTS

The authors wish to express grateful acknowledgement for the financial and technical support of the Tennessee Department of Transportation on this research project. Particularly, the authors would like to thank Wayne Seger, Terry Leatherwood, Tom Quinn, and the engineers at the TDOT Structures Division for their guidance and assistance. The authors would also like to thank the former Director of the TDOT Structures Division, Mr. Edward Wasserman, for his support and guidance over the years.

The authors gratefully acknowledge the additional financial support and project management of the Center for Energy Systems Research at Tennessee Technological University. In particular, Dr. Periasamy Rajan, Etter Staggs, Linda Lee, and Tony Greenway were all very helpful.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
ACKNOWLEDGEMENTS 3
TABLE OF CONTENTS 4
LIST OF TABLES 5
LIST OF FIGURES 6
CHAPTER 1 INTRODUCTION 8
CHAPTER 2 LITERATURE REVIEW 14
CHAPTER 3 RATING FACTORS AND CAPACITY 25
CHAPTER 4 CULVERT MODELING 43
CHAPTER 5 HORIZONTAL SOIL PRESSURE ANALYSIS 54
CHAPTER 6 RATING FACTOR ANALYSIS FOR TDOT DUMP TRUCK 65
CHAPTER 7 SHEAR ANALYSIS 73
CHAPTER 8 MOMENT CONTINUITY ANALYSIS 109
CHAPTER 9 RATING AIDS 119
CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS 125
REFERENCES 129
APPENDIX A EXAMPLE CALCULATION OF SHEAR RATING FACTORS 131
APPENDIX B MATHCAD CODE FOR LOAD DETEMINATION 138
APPENDIX C CULVERT MODELING IN STAAD PRO 149
APPENDIX D STAAD PRO VERIFICATION 153
APPENDIX E CULVERT MODELING IN BRASS CULVERT 163
APPENDIX F CULVERT MODELING IN RESPONSE-2000 170
APPENDIX G TDOT DUMP TRUCK RATING FACTOR ANALYSIS RESULTS 175
APPENDIX H SEARCH CODE FOR TDOT RATING AIDS 191

LIST OF TABLES

Table 2.1: Comparison of Results of 430 Tests with MCFT Analysis.....16
Table 2.2: Test Results of Six R/C Box Culverts.....18
Table 3.1: AASHTO LRFD Table (3.11.6.4-1).....42
Table 4.1: Box Culverts for TDOT Dump Truck Rating Factor Analysis.....44
Table 4.2: Slab Culverts for TDOT Dump Truck Rating Factor Analysis.....44
Table 4.3: Culverts for Horizontal Soil Pressure Flexure Analysis.....45
Table 4.4: Culverts for Horizontal Soil Pressure Rating Factor Comparison.....46
Table 4.5: Verification Database Culverts by Burns.....47
Table 4.6: Verification Database Culverts by Abolmaali and Garg.....47
Table 4.7: TDOT Database of Box Culverts for Shear Analysis.....48
Table 4.8: TDOT Database of Slab Culverts for Shear Analysis.....49
Table 5.1: LFR/LFD EH Difference Comparison.....61
Table 5.2: Comparison of Operating Rating Factors vs Horizontal Soil Pressure.....63
Table 7.1: Culvert Properties and Dimensions for Shear Analyses.....75
Table 7.2: Forces in the Top Slab at the Critical Shear Location.....77
Table 7.3: AASHTO LRFD Bridge Design Specifications Table (3.4.1-2).....77
Table 7.4: AASHTO Standard Specifications Table (3.22.1A).....78
Table 7.5: Various Equations for Shear Strength.....82
Table 7.6: Verification Database- Nominal Shear Capacities.....83
Table 7.7: TDOT Database of Box Culverts- Nominal Shear Capacities.....85
Table 7.8: TDOT Database of Slab Culverts- Nominal Shear Capacities.....88
Table 7.9: Box Culvert Shear Rating Factors.....106
Table 7.10: Slab Culvert Shear Rating Factors.....107

LIST OF FIGURES

Figure 1.1: Reinforced Concrete Culvert 9
Figure 1.2: Box and Slab Culvert Diagram 10
Figure 2.1: Derivation of Design Equation (5-11) 15
Figure 2.3: Effect of Transverse Reinforcement Ratio on Shear Capacity 21
Figure 2.4: Effect of Axial Force on Ultimate Shear Capacity 21
Figure 2.5: Load-Deflection Curves for Beams with Three No. 4 Bars 23
Figure 2.6: Effect of a/d on Cracking and Ultimate Shear Capacity 23
Figure 3.1: Typical Dead Load Case from STAAD Pro 39
Figure 3.2: Typical Centipede Load 41
Figure 3.3: AASHTO LRFD HS20-44 Load Example 42
Figure 3.4: Typical Live Load Case from STAAD Pro 42
Figure 4.1: STAAD Pro Modeling and Rating Process 53
Figure 5.1: Culvert Section Labels 55
Figure 5.2: Top Exterior Wall LFR/LFD EH Moment Comparison 56
Figure 5.3: Right Bottom Slab LFR/LFD EH Moment Comparison 57
Figure 6.1: Truck Load Configurations 67
Figure 6.2: Flexural Rating Factor Comparison for Box Culverts- Exterior Span 69
Figure 6.3: Flexural Rating Factor Comparison for Box Culverts- Interior Span 70
Figure 6.4: Flexural Rating Factor Comparison for Slab Culverts- Exterior Span 71
Figure 6.5: Flexural Rating Factor Comparison for Slab Culverts- Interior Span 72
Figure 7.1: Brass Culvert Partial Output 79
Figure 7.2: Response-2000 Sectional Response Output 80
Figure 7.3: Verification Database- Nominal Shear Capacity Comparison 83
Figure 7.4: TDOT Database of Box Culverts- Nominal Shear Capacity Comparison 86
Figure 7.5: TDOT Database of Slab Culverts- Nominal Shear Capacity Comparison 89
Figure 7.6: Box Culvert Shear Rating Factor Comparison 105
Figure 7.7: Slab Culvert Shear Rating Factor Comparison 106
Figure 8.1: Top Exterior Wall Rating Factors – Zero & Five Feet Fill 112

Figure 8.2: Right Top Slab Rating Factors – Zero & Five Feet Fill 113
Figure 8.3: Top Slab Moments from Modeling with Full Continuity 115
Figure 8.4: Top Slab Moments from Modeling with Zero Continuity.....115
Figure 8.5: Distinguished Rating Factor Patterns – Right Top & Bottom Slabs 116
Figure 8.6: Extra Negative Reinforcement Added at Interior Wall Connections 117
Figure 8.7: No Extra Negative Reinforcement at Interior Wall Connections.....117
Figure 9.1: Partial One Cell Box Culvert Selection Page.....120
Figure 9.2: Typical Box Culvert Rating Factor Page 120
Figure 9.3: Box Culvert Search Page 122
Figure 9.4: Search Page in Use - Year Parameter Removed 123

CHAPTER 1

INTRODUCTION

TDOT is responsible for nearly 20,000 highway bridges and transportation structures within the Tennessee transportation system. Approximately 44% of these structures are classified as culverts. It is very important to regularly load rate and evaluate these culverts for their structural capacity due to aging, wear and possible deterioration in members. Since there are hundreds of standard TDOT drawings for reinforced concrete culverts and various site conditions, the rating of over 8,500 culverts requires tremendous efforts both at the onset and in the long run. Therefore, it is essential that efficient tools be developed for culvert rating. This is the second report concerning the TDOT Culvert Rating Aids, and covers the improvements made to the Rating Aids by Heath Kaufman and Brandon Bartrom under Dr. Sharon Huo.

This report consists of 10 chapters. Chapter 2 overviews relevant literature on various topics regarding reinforced concrete structures. Chapter 3 covers capacity and rating factor equations. Chapter 4 has a database selection section and looks at culvert modeling in various programs. Chapter 5 contains an analysis on horizontal soil pressures' effect on rating factors. Chapter 6 goes through an analysis of rating factors for a TDOT dump truck load compared to that of an HS20. Chapter 7 is an analysis of several shear capacity equations from various codes and programs, and has a comparison of the equations and programs to test results of reinforced concrete culverts. Chapter 8 consists of a moment continuity analysis for the rating factors of reinforced concrete box and slab culverts. Chapter 9 contains an explanation of a pair of Rating Aids for box and slab culverts that were developed for TDOT, and covers their overall applicability to the rating

process. Lastly, Chapter 10 consists of the conclusions and recommendations derived from these studies.

1.1 Reinforced Concrete Culverts

Culverts are structures typically used to allow water to flow under road ways. Sometimes, culverts are used as short-span bridges. There are many kinds of culverts, such as corrugated steel pipe and reinforced concrete types. This thesis focuses on box and slab type reinforced concrete culverts. A box culvert is differentiated from a slab culvert by the presence of a slab on the bottom. A picture of a reinforced concrete culvert can be seen in Figure 1.1. Some common terminology used when referencing dimensions or members of a culvert can be seen in Figure 1.2. When referring to skew angle of a culvert, it is defined as the angle between a line normal to the centerline of the road way and the centerline of the culvert's walls by AASHTO LRFD Specifications [1]. The load rating process of reinforced concrete culverts is used to evaluate existing structural members' capacities. Chapter 3 details the process by which culverts are rated.

Figure 1.1: Reinforced Concrete Culvert [15]

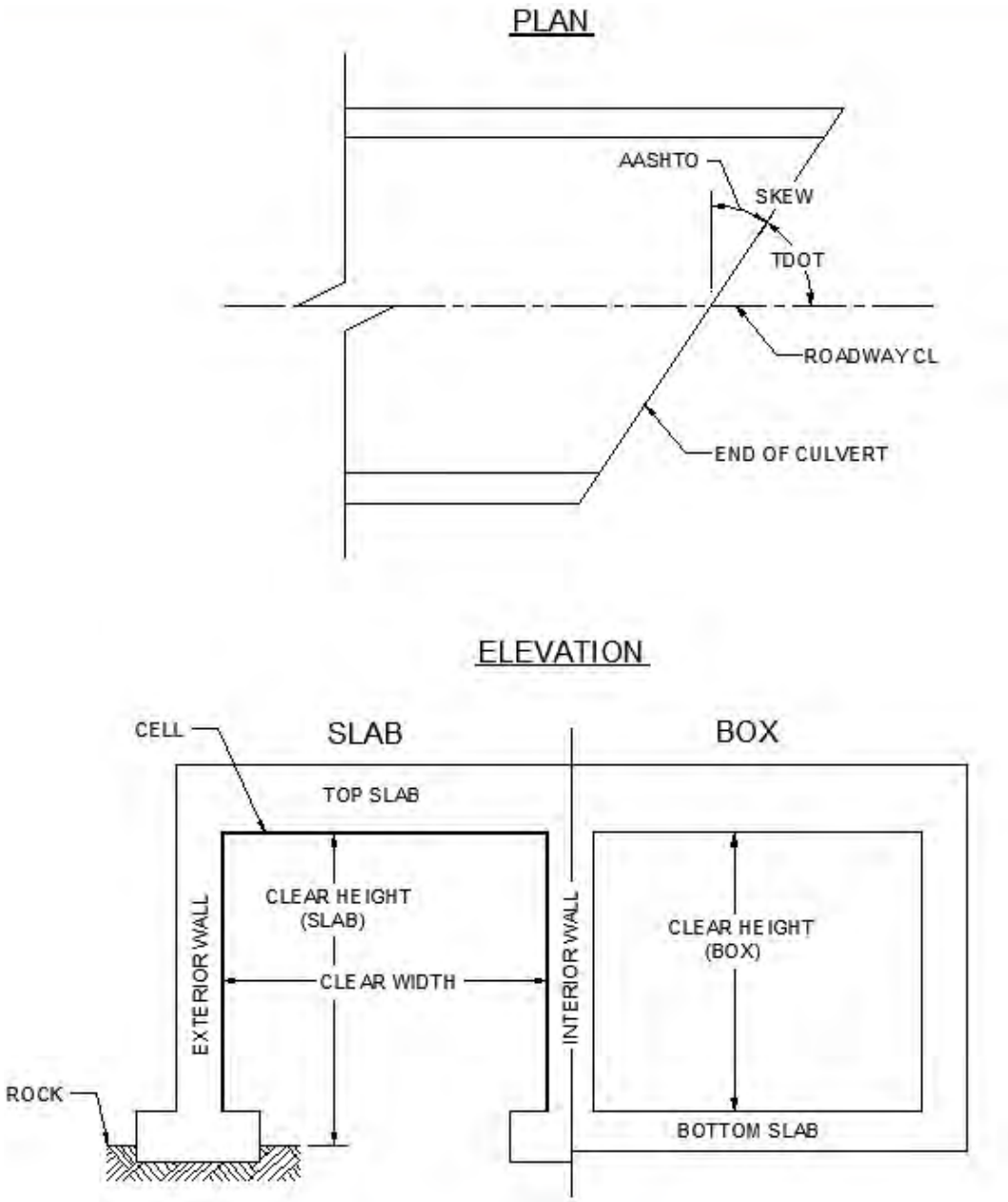


Figure 1.2: Box and Slab Culvert Diagram

1.2 Federal Mandates

The Federal Highway Administration currently requires all states to load rate highway bridges [12]. According to AASHTO's Manual for Bridge Evaluation (MBE), culverts beyond a

certain length are classified as bridges and thus fall into the aforementioned load rating requirement [2]. To initiate the process of load rating applicable culverts, TDOT gave the Civil and Environmental Engineering (CEE) department of Tennessee Technological University (TTU) the task of creating a culvert rating factor database. Past graduates of TTU's CEE department completed the initial database of rating factors. The work by the authors of this report was performed in order to further refine the rating factor database for TDOT's box and slab culverts.

1.3 Goal and Objectives

This thesis focuses on refining flexural rating factors and overlooking conservative shear rating factors. The goal of this research project was the refinement and enhancement of the TDOT Culvert Rating Aids. To accomplish this goal, five main objectives were established:

- Determine the impact of varying horizontal soil pressure
- Analyze rating factors for the TDOT Dump Truck and standard trucks
- Analyze shear capacity of reinforced concrete culverts with various codes and programs
- Analyze flexural rating factors when using full or no moment continuity
- Improve the usability and accuracy of the TDOT Culvert Rating Aids

The magnitude of lateral earth pressure, also known as horizontal earth pressure (EH), which is generated upon culvert's exterior walls, is calculated based on soil densities and depth below the surface. The horizontal soil pressure analysis involved changing the unit weight of the soil used to calculate the horizontal soil pressure acting on the exterior walls of a culvert for the LFR method. This study was formed because according to the AASHTO Standard Specifications for Highway Bridges (SSHB) in Article 6.2.1 a unit weight of horizontal soil of either 30 or 60

pounds per cubic foot can be used to calculate the horizontal soil pressure acting on the exterior walls of a culvert, and it is unknown how this difference in soil pressure affects the moments acting on the members of a culvert and the rating factors for the culvert members [4]. The goal of this study was to determine the effects on the rating factors of reinforced concrete culverts created by using different values of lateral earth pressure.

To assess how much of a change in rating factors could be achieved for reinforced concrete culverts by using a TDOT dump truck instead of a standard HS20 or H15, a database of 10 box and 10 slab culverts were modeled and analyzed from TDOT's standard drawing database. Flexural and shear, operating rating factor values were recorded from the culvert analysis program known as BRASS Culvert (Version 2.3.6) for each of the 20 models. The comparison was done for a range of various skews, number of cells, clear heights, clear spans, fills, and design years. Once the analysis was completed, the lesser rating factor value between the HS20 and H15 trucks was compared to the TDOT dump truck's rating factor for each member location and fill depth.

To better understand shear capacity with regards to reinforced concrete culverts, equations from multiple codes and three programs were used to analyze many standard TDOT culvert drawings. The Specifications used were AASHTO LFD, AASHTO LRFD, and ACI. The programs used to analyze the culverts were STAAD Pro, BRASS Culvert, and Response-2000. Also, axial load was considered in some equations to see its effect on the rating process overall. The final step was to take the code based calculations of shear capacity, as well as the programs' output of shear capacity, and compare them to test results.

The moment continuity analysis involved changing the moment continuity of the connections of the top and bottom of the exterior walls with the slabs for culverts that did not have

negative moment reinforcement for these regions. Since these connections have zero negative moment reinforcement to resist the negative moment being applied, the connection should not have full continuity but should have zero continuity. The continuity of both the top and bottom of the exterior walls were changed. All culverts from TDOT's database that did not have negative moment reinforcement at the top and bottom of the exterior walls were analyzed in this study. This included 124 box culvert drawings and 34 slab culvert drawings. STAAD Pro was used to analyze the culverts for this study. Once the analysis was complete, the rating factors for the culverts were transferred to the Rating Aids.

To conveniently utilize all rating factors determined for TDOT standard culvert drawings, the Rating Aids were developed in Microsoft Excel. The Rating Aids were partially completed for TDOT by past TTU graduate students, Caleb Jones, Michael Bednarcyk, and Kyle Zhang. One of the objectives of this research project was to improve the Culvert Rating Aids to better assist in the assessment of culverts in Tennessee. The improvements included additions of unique features that created a user-friendly interface for the navigation of both the box and slab culvert Rating Aids. These Rating Aids best meet the needs of rating engineers.

CHAPTER 2

LITERATURE REVIEW

The research and studies presented will be grouped into four main topics, including: reviews of currently available methods for shear strength calculations, tests and evaluations of shear capacity equations, effects of axial load on shear capacity, and horizontal soil pressure's effect on flexural rating factors.

2.1 Reviews of Currently Available Methods for Shear Strength Calculations

2.1.1 ACI-ASCE Committee 326 [7]

The ACI-ASCE Committee 326 Report on shear and diagonal tension was conducted in or order to, "Present a review of scientific knowledge, engineering practice, and construction experiences regarding shear and diagonal tension in reinforced concrete beams, frames, slabs, and footings." The introduction in this paper covers the early development of shear equations. The first and earliest equation mentioned is based on horizontal forces being the main cause of shear failures. The more currently accepted diagonal tension equation based on 45 degree tensile stresses from a case of pure shear stress is also presented in its original form. The later part of the report covers shear in reinforced concrete beams with and without web reinforcement [7].

The fifth chapter of Committee 326's report covers the derivation of shear in beams without web reinforcement. In the fifth chapter, it is emphasized that the design procedures proposed by the ACI committee are empirical in nature. Derivation of ACI Equation (5-11) in this report came from the test results of 194 beams, and the test results and Equation (5-11) can be seen in Figure

2.1. Also, Table 2.1 presents the results of 430 beams without web reinforcement versus the calculated values as per Equation (5-11) from the ACI-ASCE committee report to further validate their findings. In conjunction with the fifth chapter of the ACI-ASCE report, the seventh chapter further refines the moment term in Equation (5-11) to account for axial loading in addition to bending and shear forces with Equation (7-8). Equation (7-8) can be seen on Page 34 of this thesis as ACI Equation (11-6). These equations are currently used in ACI codes for the determination of shear strength [7].

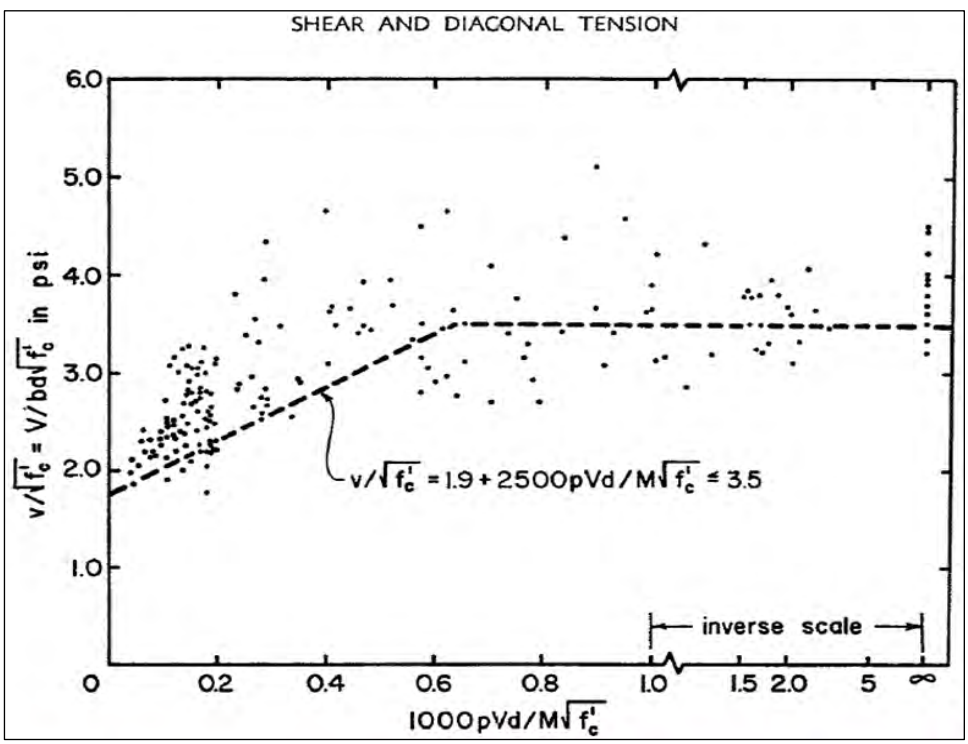


Figure 2.1: Derivation of Design Equation (5-11) [7]

2.1.2 Bentz, Vecchio, and Collins [10]

This paper covers the history of the Modified Compression Field Theory (MCFT); illustrates the simplification of the MCFT for use with shear capacity calculations in reinforced concrete members; and compares the predictions of the MCFT, simplified MCFT, and ACI

Table 2.1: Comparison of Results of 430 Tests with MCFT Analysis [7]

Type of test beam	Cross section	Loading	No. of test beams	Test / Calc	Coefficient of variation, percent
Beams used in derivation of Eq. (5-11)					
Simple	Rectangular	Concentrated	45	1.076	15.8
Simple with stub	Rectangular	Concentrated	48	1.239	13.5
Restrained	Rectangular	Concentrated	86	1.041	8.4
Continuous	Rectangular	Concentrated	15	1.031	13.0
Other beams					
Simple	Rectangular	Uniform	64	1.192	10.9
Simple	Rectangular	Concentrated	124	1.300	14.9
Restrained and continuous	Rectangular	Concentrated	14	1.091	13.8
Simple and restrained	T-beams	Concentrated and uniform	34	1.221	19.6
All beams			430	1.180	16.2

methods against test results. The goal of this paper is to numerically show that the simplified MCFT equations for shear capacity can give good predictions when compared to test results for load cases including shear, moment, and axial forces. In addition to accuracy, this paper also shows that the simplified MCFT predicts shear capacity with a reasonably simple method when compared to full MCFT solutions [10].

From the comparison between test results and different methods for determining shear capacity, it was shown that the MCFT best predicted shear capacity. While the simplified MCFT was more conservative than the MCFT on average, it was less conservative than ACI equations. The ACI approach to estimating shear strength produced the most conservative results, especially for upper limits on shear capacity. With a similar ease of use when compared to ACI equations and a better prediction of shear capacity when compared to test results, the simplified MCFT was concluded to be the preferable method. The simplified MCFT equation can be seen in current AASHTO codes [10].

2.2 Tests and Evaluations of Shear Capacity Equations

2.2.1 Abolmaali and Garg [5]

Abolmaali and Garg further addressed the research done by McGrath et al. (2004). McGrath and company performed a study of live load distribution widths by means of a 2D finite element method (FEM) analysis. From this study, McGrath concluded that live load distribution widths for shear were narrower than bending moment distribution widths, and thus controlled the design process. In 2005, AASHTO implemented these findings in their code by equating live load distribution widths based on shear forces. AASHTO code also suggested that shear transfer devises be implemented in the design process if the distribution width is greater than the distance between joints [5].

While the 2D FEM analyses of McGrath were modeled as linear elastic, Abolmaali and Garg's 3D FEM analyses were nonlinear inelastic. Not only was Abolmaali and Garg's FEM analysis method more complex, it was shown to be accurate when compared to test data. The

tested models in this paper include six reinforced concrete box culverts with varying load locations as well as having or not having distribution steel. The culverts were loaded at the critical shear sections, as well as at a distance equal to 1.5 and 2 times that distance from the tip of the haunch. The test results of the six culverts can be seen in Table 2.2 [5].

Table 2.2: Test Results of Six R/C Box Culverts [5]

		Test/load [kN (kip)]					
Event number	Event	SP_2438-1219-1219_N_d	SP_2438-1219-1219_Y_d	BL_2438-1219-1219_N_d	BL_2438-1219-1219_Y_d	SP_2438-1219-1219_Y_1.5d	SP_2438-1219-1219_Y_2d
1.	First nonmeasurable flexural crack on inside fact of top slab under the load plate	187 (42)	160 (36)	125 (28)	116 (26)	133 (30)	107 (24)
2.	First negative flexural crack on outside fact of top slab	231 (52)	245 (55)	205 (46)	214 (48)	200 (45)	187 (42)
3.	First flexural crack initiated on outside face of wall	222 (50)	334 (75)	311 (70)	214 (48)	200 (45)	187 (42)
4.	Flexural crack at left haunch on inside face of bottom slab	231 (52)	289 (65)	311 (70)	267 (60)	245 (55)	222 (50)
5.	First serviceability flexural crack (0.01 in.)	334 (75)	356 (80)		311 (70)	311 (70)	267 (60)
6.	First shear crack initiated at the Loading end	334 (75)	378 (85)	334 (75)	312 (70)	356 (80)	356 (80)
7.	First serviceability shear crack	334 (75)	423 (95)	400 (90)	334 (75)	356 (80)	311 (70)
8.	Ultimate failure	543 (122)	480 (108)	400 (90)	391 (88)	480 (108)	445 (100)

From Table 2.2 the first serviceability shear cracks always occurred at or after the first serviceability flexural cracks. This is significant because the culverts were loaded in a manner that should produce the worst loading case for the top slab in shear by loading the critical shear location. Even so, the culverts tended to fail first in flexure. The shear failures tended to occur at almost twice the factored wheel live load as presented in the Interim AASHTO LRFD Bridge Design Specifications (2005). Because of these results, it was concluded that the Interim AASHTO (2005) based on McGrath et al. findings should be reevaluated [5].

2.2.2 Burns [11]

Burns conducted an experimental study on shear capacity in reinforced concrete culverts by loading four box culverts to failure. Each culvert was 4 feet by 4 feet by 4 fet where the thickness of the top slab was 7.5 inches, the walls were 5 inches thick, and the thickness of the bottom slab was 6 inches. The loading of the top slabs was done through a steel plate that was 10 inches by 20 inches to replicate a wheel load placed on the spigot end of the culverts. The load was placed 1.5 inches before the critical shear location for two models where one had bedding and the other did not. Of the other two tested culverts, one was loaded at the critical shear location and the other was loaded 5 inches beyond the critical shear location away from the wall. The test models are named with the following acronyms [11]:

- S – Spigot end
- B – Bell end
- SB – Single box culvert
- DB – Double box culvert
- SRL – Dimensions of the culvert [Span (ft), rise (ft), and joint length (ft)]
- NB – No bedding
- WB – With bedding
- P – Distance from inside edge of adjacent haunch to center of loading plate (in)

Test one of S-SB-444-WB-5 experienced the first serviceability shear crack width limit at a load of 95 kilo-pounds (kip). Test two, S-SB-444-NB-5, resulted in a load of 100 kip before serviceability shear cracks developed. Test three of S-SB-444-NB-6.5 did not develop serviceability shear cracks until a load of 115 kip. The final test, S-SB-444-NB-11.5, experienced a load of 95 kip before serviceability cracks developed. Between the four tests, it was noted that the test loads were, on average, almost twice as high as the predicted load capacities of the culverts as per AASHTO codes [11].

Burns concluded that the four box culverts were adequate in shear as they failed in flexure first at a load above that which AASHTO codes would give. A physical phenomenon was also noted that supported the claim of culverts being governed by flexural forces. It was seen that the top slabs underwent an additional bending moment when the corner joints rotated. Like Abolmaali and Garg, Burns used his test data to further refute AASHTO LRFD 2005 Section (12.11.2) concerning edge beam criterion and the research of McGrath et al. from 2004 that the code was based on [11].

2.3 Axial Load's Effect on Shear Capacity

2.3.1 Wu [18]

Wu compared both Membrane2000 and Response-2000, programs that analyze the response of loaded reinforced concrete sections, to test results from various sources. Membrane2000 and Response-2000 are able to use load cases that include shear, bending, and axial forces as the logic of both programs is based off of the Modified Compression Field Theory (MCFT). There were two overarching themes noted from the test results. The first trend noted was the increase in shear capacity with increased axial compression. The opposite was also true, increases in axial tension decreased shear capacity. This trend can be seen in Figure 2.3. The other trend involved the comparison of the predicted MCFT based shear strength values, as per Membrane-2000 and Response-2000, to test data. In all cases, the experimental data was greater than that predicted by the programs as seen in Figure 2.4. In the restrained support case, there was one experimental value that corresponded with the predicted value of Response-2000; however, that value was considered to be an outlier [18].

2.3.2 Baron and Siess [9]

Baron and Siess conducted load tests on 20 reinforced concrete beams to analyze the effects that axial load had on shear strength. To allow the results to be applicable to reinforced

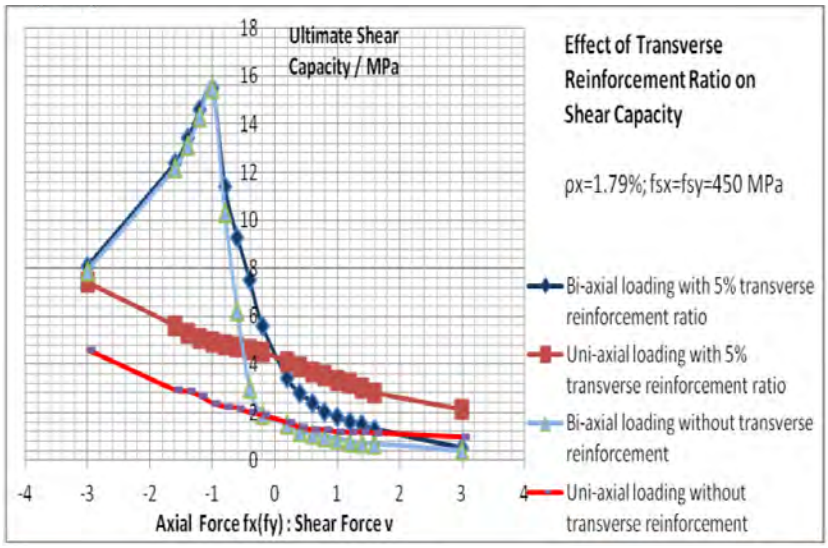
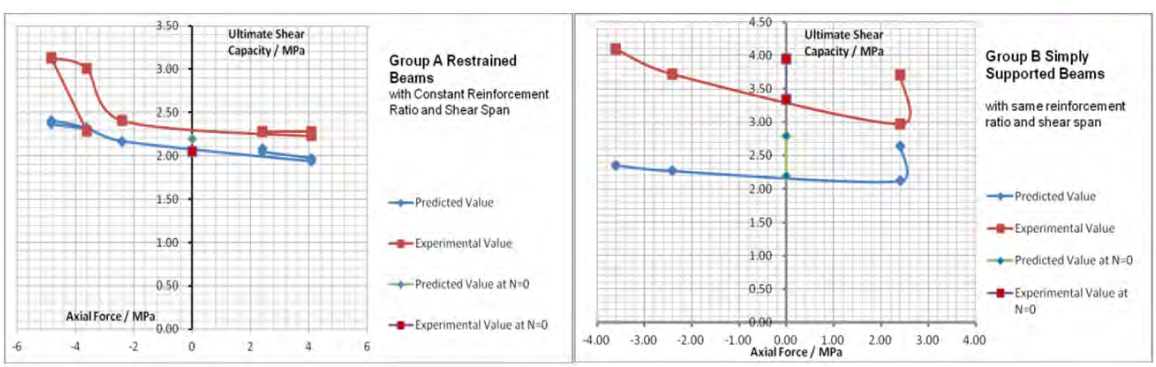


Figure 2.3: Effect of Transverse Reinforcement Ratio on Shear Capacity [17]



a.) **b.)**

Figure 2.4: Effect of Axial Force on Ultimate Shear Capacity under (a.) Restrained Support and (b.) Simply Supported Conditions [17]

concrete box culverts, none of the test specimens were cast with web reinforcement. The test variables included axial load, span length, and steel percentage. There were three types of ultimate failure noted. With ten beams out of twenty, the most common method of failure was diagonal tension. These failures occurred at the cracking load. Eight beams failed in shear-compression. Shear-compression failure was classified as beams that developed diagonal tension cracks prior to failure. Flexural failure was the least common and only occurred in two beams. Flexural failures were denoted by their large deflections even though they also developed inclined cracks at failure in a similar manner to diagonal tension failures [9].

There were ten different kinds of beams tested, and each beam had a duplicate. Of the like pairs, one beam was tested with an axial load and the other without. The midspan load vs. deflection curves for the 20 specimen can be seen in Figure 2.5. The general trend was that axial compression increased the load carrying capacity of the members. Figure 2.6 shows the trend of shear capacity as a function of shear span per effective depth (a/d). For both the cracking and the ultimate shear, it can be seen that the effect axial load has on shear strength diminishes as a/d increases. So, axially compressive loads were shown to have a diminishing effect of increasing shear strength as the length of the members increased. It was also noted that beams with a higher steel percentage received less of an increase in shear strength [9].

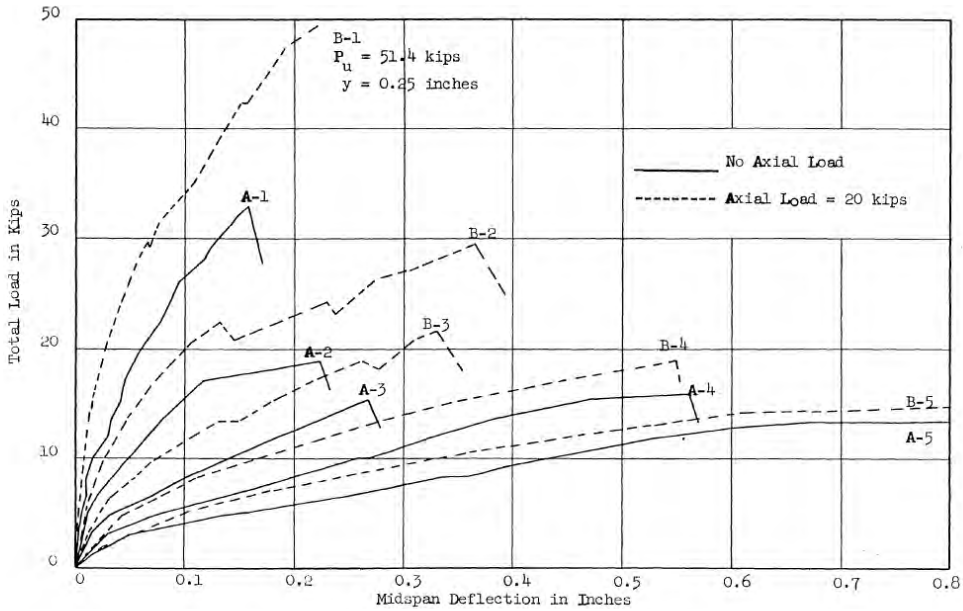


Figure 2.5: Load-Deflection Curves for Beams with Three No. 4 Bars [9]

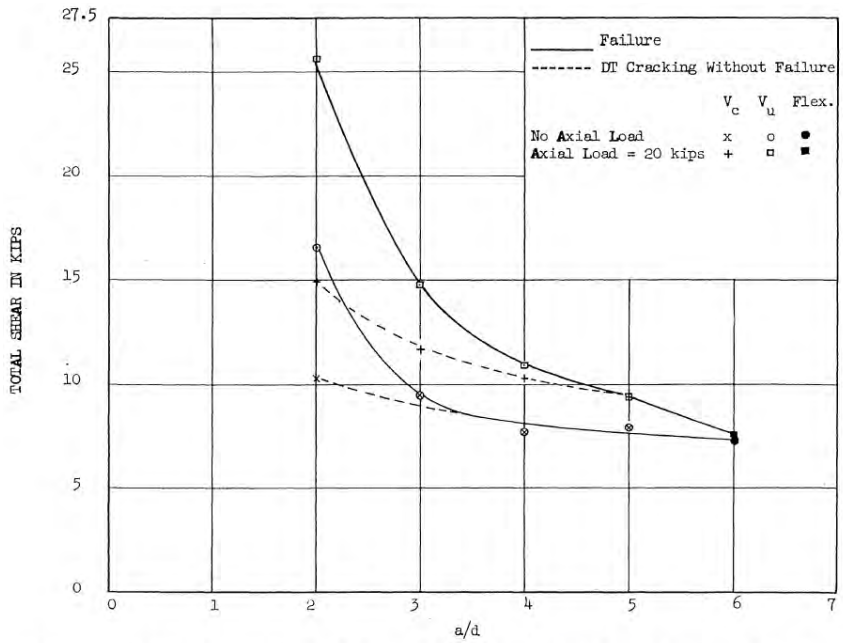


Figure 2.6: Effect of a/d on Cracking and Ultimate Shear Capacity for Beams with Three No. 4 Bars [9]

2.4 Horizontal Soil Pressure's Effect on Flexural Rating Factors by W. Lawson et. Al. [14]

A group, W. Lawson, T. Wood, C. Newhouse, and P. Jayawickrama, from Texas Technological University did several experiments on culverts which include determining how changing the lateral earth pressure acting the walls of a culvert affects the rating factors.

Lawson et al. calculated the inventory rating factors for culvert having lateral earth pressure values range from 40 pcf to 100 pcf at 20 pcf increments [14]. No changes were made to the other loading cases of the culvert while the lateral earth pressure was changed.

In their results, Lawson et al. showed that the changing of the lateral earth pressure only affects culverts that have higher clear heights, taller exterior walls, when there is little to no fill on the culvert [14]. The change did not affect culverts which had smaller clear heights when there is little to no fill on the culvert. However, the culverts that have small walls were affected when the fill depth was increased. This led Lawson et al. to perform a fill depth experiment on the culverts. When the fill depth was increased, no matter the culvert size, the effect of the lateral earth pressure also increased [14]. This indicates that the distance from the top of the fill to the bottom the culvert is a crucial distance to know, since this distance is responsible for the overall affect the lateral earth pressure.

CHAPTER 3

RATING FACTORS AND CAPACITY

Once capacity and the factored dead and live loads are determined, rating factors can be calculated to quickly assess a structural member's capability to withstand dead and live loads at different locations of each member. First, this chapter details the process of determining and applying rating factors. The second section goes over flexural capacity equations. The third section covers shear capacity as per the ACI, LFD, and LRFD Specifications. The final section of this chapter goes through the process of determining the factored forces used in shear capacity calculations. Appendix A contains an example calculation of rating factors from dead and live loads to final rating factors by AASHTO LFRD equations with shear capacities from Response-2000 for TDOT box culvert M-1-91.

3.1 Rating Factors

The AASHTO Manual for Bridge Evaluation (MBE) equation for calculating rating factors is,

$$RF = \frac{C - \gamma_{DL} DL}{\gamma_{LL} LL(1 + IM)} \qquad Equation\ 3.1$$

where C is the structural member's capacity, IM is the impact factor, DL and LL are dead and live loads, respectively, and γ_{DL} and γ_{LL} are dead and live load factors, respectively. Rating factors greater than 1 denote that a structural member's capacity is large enough to handle all expected dead and live loads. If a rating factor is less than 1, but greater than 0, that structure has a live load that exceeds its capacity. If a rating factor is equal to or less than 0, it is taken to be 0, and implies that the capacity is less than even the dead loads. There are multiple levels of rating factors.

Although the equation does not change for various levels of rating factors, the dead and live load factors can. The two levels of rating factors described below are inventory and operating [2].

3.1.1 Inventory Rating Factors

The inventory rating level is a more strenuous test of a structural member's capacity when compared to the operating level. The inventory rating level considers a structural member's current condition (possible deterioration and/or loss of sections) and is used with standard design loads. This rating level allows the loads to be applied for an indefinite period without compromising a structural member's lifespan. The dead load factor (γ_{DL}) for the inventory rating level equals 1.3, and the live load rating factor (γ_{LL}) equals 2.17 [2].

3.1.2 Operating Rating Factors

The operating rating level pertains to the use of maximum permissible live loads. Loads at the operating rating level may reduce the lifespan of the subjected structure if used without limit. Unlike the inventory rating level, the operating rating level does not consider deterioration of the structure. For the inventory rating level, both the dead load factor (γ_{DL}) and the live load factor (γ_{LL}) equal 1.3. Since the live load factor is the only part of the rating factor equation (Equation 3.1) that changes between inventory and operating rating factors, the operating rating factor equation produces rating factors 1.67 times greater than the inventory level [2].

3.2 Flexural Capacity

The flexural capacity of a culvert member is determined by six capacity calculation steps derived from the SSHB. Due to culvert members having both axial and bending forces acting on them, they must be designed and analyzed as beam-columns. The six capacity calculation steps derived from the SSHB assume that the axial force on the culvert member is less than the SSHB's axial check, which allows flexure to be the controlling force over axial for the member [4,17]. The six capacity calculation steps take into account that the axial check force is the maximum axial force the member in question will experience. This axial check is in accordance with Article (8.16.4.3) of the SSHB [4]. Normally for culverts the axial force is less than the axial check and if this is true, then the six capacity calculation steps may be used to calculate the flexural capacity of the culvert member. If the axial force is larger than the axial check, which is rarely the case for culverts, then the equations of the SSHB in Article (8.16.4) must be used [4,17]. The SSHB's axial check is calculated using the following the equation [4,17]:

$$P = 0.1\, f_c'\, A_g \qquad \textit{Equation 3.2}$$

In this equation, Equation 3.2, P is the axial check force in kips, f_c' is the 28 compressive strength of the concrete in ksi, and A_g is the cross-sectional of the culvert member in square inches.

If the axial check proves that flexure controls the culvert member, the following six capacity calculation step equations are valid. The first capacity step calculation determines the centroid of the culvert member at ultimate capacity. The centroid of the culvert member is calculated by using the following equations [4,17]:

$$c_1 = \frac{(87000 - 0.85 f'_c) A'_s - (F_y\, A_s)}{0.85\, f'_c\, \beta_1 b} \qquad \textit{Equation 3.3}$$

$$c_2 = \sqrt{\left[\frac{(87000 - 0.85 f'_c) A'_s - (F_y\, A_s)}{0.85\, f'_c\, \beta_1 b}\right]^2 + \left[\frac{4 * (87000 A'_s\, d')}{0.85\, f'_c\, \beta_1 b}\right]} \qquad \textit{Equation 3.4}$$

$$c = c_2 - c_1 \qquad \textit{Equation 3.5}$$

In these equations, Equations 3.3, 3.4, and 3.5, c is the centroid of the culvert member in inches, F_y is the yield strength of the steel reinforcement in psi, f'_c is the 28 compressive strength of the concrete in psi, A_s is the area of the tensile reinforcement in square inches, A'_s is the area of the compression reinforcement in square inches, d' is the distance from the extreme compression fiber to the centroid of the compression reinforcement in inches, b is the width of the culvert member (the one foot design width) in inches, and β_1 is the factor relating the depth of the equivalent rectangular compressive stress block to the neutral axis depth. According to the SSHB in Article (8.16.2.7), β_1 is determined as follows [4]:

$$\beta_1 = 0.85 \qquad f'_c \leq 4000 \text{ psi} \qquad \textit{Equation 3.6}$$

$$\beta_1 = 1.05 - f'_c * 0.0005 \qquad 4000 \text{ psi} < f'_c < 8000 \text{ psi} \qquad \textit{Equation 3.7}$$

$$\beta_1 = 0.65 \qquad f'_c \geq 8000 \text{ psi} \qquad \textit{Equation 3.8}$$

The second capacity step calculation determines the stress in the compression steel in the culvert member. The stress in the compression steel in the culvert member is calculated by using the following equation [4,17]:

$$0 \leq F'_s = 87000 \left(\frac{c - d'}{c}\right) \leq F_y \qquad \textit{Equation 3.9}$$

In this equation, Equation 3.9, F'_s is the stress in the compression steel in psi, c is the centroid of the culvert member calculated from Equation 3.5 in inches, d' is the distance from the

extreme compression fiber to the centroid of the compression reinforcement in inches, and F_y the yield strength of the steel reinforcement in psi. If there is no compression steel in the culvert member, F_s' is zero. If there is compression steel in the culvert member, F_s' must not be greater than the yield strength of the steel reinforcement, F_y.

The third capacity step calculation determines the stress in the compression steel at balanced conditions in the culvert member. The stress in the compression steel at balanced conditions in the culvert member is calculated by using the following equation [4,17]:

$$F_b' = 87000 - \left(\frac{87000 * d'}{d}\right)\left(\frac{87000 + F_y}{87000}\right) \leq F_y \qquad \textit{Equation 3.10}$$

In this equation, Equation 3.10, F_b' is the stress in the compression steel at balanced conditions in psi, d' is the distance from the extreme compression fiber to the centroid of the compression reinforcement in inches, d is the distance from the extreme compression fiber to the centroid of the tension reinforcement in inches, and F_y the yield strength of the steel reinforcement in psi. If the stress in the compression steel, F_s' calculated from Equation 3.9, is zero, then the stress in the compression steel at balanced conditions, F_b', is also zero.

The fourth capacity step calculation determines the balanced steel ratio of the culvert member. The balanced steel ratio of the culvert member is calculated by using the following equation [4,17]:

$$\rho_b = \left(\frac{0.85 f_c' \beta_1}{F_y}\right)\left(\frac{87000}{87000 + F_y}\right) + \frac{A_s' F_b'}{b d F_y} \qquad \textit{Equation 3.11}$$

In this equation, Equation 3.11, ρ_b is the balanced ratio of the tensile reinforcement, f_c' is the 28 compressive strength of the concrete in psi, F_y is the yield strength of the steel reinforcement in psi, F_b' is the stress in the compression steel at balanced conditions calculated from Equation 3.10 in psi, A_s' is the area of the compression reinforcement in square inches, d is the distance from

the extreme compression fiber to the centroid of the tension reinforcement in inches, b is the width of the culvert member (the one foot design width) in inches, and β_1 is the factor relating the depth of the equivalent rectangular compressive stress block to the neutral axis depth calculated from Equations 3.6, 3.7, and 3.8.

The fifth capacity step calculation checks the balanced steel ratio of the culvert member. The check of the balanced steel ratio of the culvert member is performed by using the following equation [4,17]:

$$\rho = \frac{A_s}{bd} \leq 0.75\rho_b \qquad \textit{Equation 3.12}$$

In this equation, Equation 3.12, ρ is the ratio of the tensile reinforcement, A_s is the area of the tensile reinforcement in square inches, d is the distance from the extreme compression fiber to the centroid of the tension reinforcement in inches, b is the width of the culvert member (the one foot design width) in inches, and ρ_b is the balanced ratio of the tensile reinforcement calculated from Equation 3.11. The ratio of the tensile reinforcement, ρ, must be less than or equal to three-fourths of the balanced ratio of the tensile reinforcement, ρ_b.

The sixth and final capacity step calculation determines the moment capacity of the culvert member. The moment capacity of the culvert member is calculated by using the following equations [4,17]:

$$M_{n1} = A_s F_y - A'_s F'_s \qquad \textit{Equation 3.13}$$

$$M_{n2} = d - \frac{A_s F_y - A'_s F'_s}{2\left(0.85 f'_c b\right)} \qquad \textit{Equation 3.14}$$

$$M_{n3} = A'_s F'_s (d - d') \qquad \textit{Equation 3.15}$$

$$\phi M_n = \phi\left[(M_{n1} \times M_{n2}) + M_{n3}\right]\left(\frac{1}{12}\right)\left(\frac{1}{1000}\right) \qquad \textit{Equation 3.16}$$

In these equations, Equations 3.13, 3.14, 3.15, and 3.16, ϕM_n is the flexural capacity of the culvert member in kip-feet, ϕ is the strength reduction factor, f_c' is the 28 compressive strength of the concrete in psi, F_y is the yield strength of the steel reinforcement in psi, F_s' is the stress in the compression steel calculated from Equation 3.9 in psi, A_s is the area of the tensile reinforcement in square inches, A_s' is the area of the compression reinforcement in square inches, d' is the distance from the extreme compression fiber to the centroid of the compression reinforcement in inches, d is the distance from the extreme compression fiber to the centroid of the tension reinforcement in inches, and b is the width of the culvert member (the one foot design width) in inches. According to the SSHB in Article (16.6.4.6), the strength reduction factor, ϕ, is taken as 0.9 for flexure [4].

If the culvert member being analyzed does not have tensile reinforcement, the flexural capacity of the member may be conservatively taken as the minimum cracking moment capacity of the member [17]. The minimum cracking moment for the culvert member is calculated by using the following equation [17]:

$$\phi M_n = \frac{\phi h^2 \sqrt{f_c'}}{1000} \qquad \textit{Equation 3.17}$$

In this equation, Equation 3.17, ϕM_n is the flexural capacity of the culvert member in kip-feet, ϕ is the strength reduction factor, f_c' is the 28 compressive strength of the concrete in psi, and h is total thickness of the culvert member in inches. This equation is derived and simplified from the typical moment calculation equation involving the stress and section modulus properties of a member. The strength reduction factor, ϕ, is taken as 0.9 for flexure according to Article (16.6.4.6) of the SSHB [4].

3.3 Shear Capacity

The capacity term (C) in the rating factor equation can be determined for both flexure and shear, depending on whether flexure or shear rating factors are to be calculated, respectively. While flexural capacity equations are based on theoretical approaches, equations for shear capacity are based on experimental results. Shear capacity equations do present a fair approximation of test results; however, some cases produce shear capacities well below test results. This section presents current methods used to calculate nominal shear capacity as per ACI, LFD, and LRFD Specifications.

3.3.1 Background

Near the beginning of shear capacity equation development for reinforced concrete members, there were two general theories. Before 1900, one theory was based on horizontal shear forces as was already commonly used in conjunction with shear design of web rivets in steel girders. The other theory, commonly used and accepted today, based shear failures on diagonal tension instead of horizontal shear forces. Around 1910, work presented by E. Mörsch solidified the diagonal tension theory as being the main cause of shear failures. Since that time, equations for shear stress based on diagonal tension have continued to develop. The calculations for shear capacity in reinforced concrete members used today came from the test results presented in ACI-ASCE Committee 326's report on shear and diagonal tension [7].

3.3.2 ACI [8]

ACI 318-99/318R-99 presents equations for determining shear capacity (V_c) of non-prestressed concrete members in Section (11.3). The units used are pounds for force and inches for dimensions. The first equation presented in the ACI Specification is Equation (11-3),

$$V_c = 2\sqrt{f_c'}b_w d \qquad Equation\ 3.18$$

where f'_c is the 28 day compressive strength of concrete, b_w is the web width of the member, and d is the distance from the extreme compression fiber to the centroid of the longitudinal tensile reinforcement. This is the simplest of the equations available to compute shear capacity for members subjected to shear and flexure only [8].

ACI Equation (11-4) applies to members subjected to axial compression. The equation is,

$$V_c = 2\left(1 + \frac{N_u}{2000A_g}\right)\sqrt{f_c'}b_w d \qquad Equation\ 3.19$$

where f'_c, b_w, and d have the same definitions as they did in ACI Equation (11-3). The N_u term is the factored axial compression force at the section of the member being considered, and A_g is the gross area of the same section [8].

ACI Equation (11-5) presents a more detailed method of computing shear strength. The equation is,

$$V_c = (1.9\sqrt{f_c'} + 2500\rho_w \frac{V_u d}{M_u})b_w d \qquad Equation\ 3.20$$

where f'_c, b_w, and d stay the same from ACI Equation (11-3). The ρ_w term is a ratio of non-prestressed tension reinforcement to the effective area of concrete. ρ_w equals the area of non-prestressed tension reinforcement (A_s) divided by both the web width (b_w) and the distance from the extreme tensile fiber of the member to the center of the tensile reinforcement (d). The other

two terms, V_u and M_u, are the factored shear and moment forces at the section of interest, respectively. The equation is limited to,

$$V_c \leq 3.5\sqrt{f_c'}b_w d \qquad Equation\ 3.21$$

and the value of $V_u d/M_u$ is limited to 1 [8].

The final equation, ACI Equation (11-6), is an expansion of (11-5). The M_u term of Equation (11-5) is replaced with M_m. The equation for M_m is,

$$M_m = M_u - N_u \frac{(4h - d)}{8} \qquad Equation\ 3.22$$

where h is the member's thickness, d is the distance from the extreme tensile fiber of the member to the center of the tensile reinforcement, N_u is the factored axial force at the section, and M_u is the factored moment. $V_u d/M_m$ is not limited to 1, and the shear capacity (V_c) is now limited to,

$$V_c \leq 3.5\sqrt{f_c'}b_w d\sqrt{1 + \frac{N_u}{500A_g}} \qquad Equation\ 3.23$$

where the terms f'_c, b_w, d, N_u, and A_g have the same meanings as previously mentioned [8].

3.3.3 AASHTO LFD [4]

The Load Factor Design (LFD) method of determining shear capacity for reinforced concrete members is presented in AASHTO's Standard Specification for Highway Bridges Section (8.16.6.2). AASHTO LFD Equations (8-50) and (8-51) are presented in terms of shear strength, and units are inches for dimensions and pounds for force. AASHTO LFD Equations (8-48) and (8-49) are also mentioned in Section (8.16.6.2). They are the same as Equations 3.18 and 3.20, respectively [4].

AASHTO LFD Equation (8-50) is for compression members. The equation for shear strength (V_c) is,

$$V_c = 2\left(1 + \frac{N_u}{2000A_g}\right)\sqrt{f_c'}(b_w d) \qquad Equation\ 3.24$$

where f'_c is the 28 day compressive strength of concrete, N_u is the design axial load at the section, A_g is the gross area of the member's cross section, b_w is the web width of the member, and d is the distance from the extreme compression fiber to the centroid of the longitudinal tensile reinforcement. Shear strength from this equation is limited to [4],

$$V_c \leq 3.5\sqrt{f_c'}b_w d \qquad Equation\ 3.25$$

AASHTO LFD Equation (8-51) is an alternative to Equation (8-50). AASHTO's LFD simplified shear strength (V_c) Equation (8-51) is,

$$V_c = 2\sqrt{f_c'}b_w d \qquad Equation\ 3.26$$

where f'_c , b_w , and d are the same as in Equation 3.24 [4].

3.3.4 AASHTO LRFD [1]

Section (5.8.3.3) of AASHTO's Load and Resistance Factor Design (LRFD) Bridge Design Specification presents an equation for shear resistance (V_n) that considers the strength of concrete (V_c), transverse reinforcement steel (V_s), and prestressing steel (V_p). Only concrete strength (V_c) is applicable for slabs and walls of culverts, and is therefore the focus of this section. Units for equations in this section are kilo-pounds (kips) for force and inches for dimensions [1].

AASHTO LRFD Equation (5.8.3.3-3) defines the shear strength of concrete based on methods used in the modified compression field theory. The equation is,

$$V_c = 0.0316\beta\sqrt{f_c'}b_v d_v \qquad Equation\ 3.27$$

where f'_c is the 28 day compressive strength of concrete, b_v is the effective web width, d_v is the effective shear depth of the member, and β is a factor indicating the ability of diagonally cracked concrete to transmit tension and shear. Section (5.8.3.4.2) of the Specification covers the general method of shear design. By AASHTO LRFD Equation (5.8.3.4.2-2) for members that do not contain the minimum amount of transverse reinforcement steel, β is defined as,

$$\beta = \frac{4.8}{(1 + 750\varepsilon_s)} \frac{51}{(39 + s_{xe})} \qquad Equation\ 3.28$$

where ε_s is the shear strain and s_{xe} is the crack spacing parameter [1].

The shear strain (ε_s) is computed by,

$$\varepsilon_s = \frac{(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps}f_{po})}{(E_sA_s + E_pA_{ps})} \qquad Equation\ 3.29$$

where M_u is the factored moment, N_u is the factored axial force, V_u is the factored shear force, V_p is the applied shear of the prestressing force, d_v is the effective shear depth, f_{po} is a prestressing parameter, A_{ps} is the area of prestressing steel on the flexural tension side of the member, A_s is the area of non-prestressing steel on the flexural tension side of the member, and E_s and E_{ps} are the modulus of elasticity for the non-prestressed and prestressed steel, respectively. The shear stain is limited to 0.003. The crack spacing parameter (s_{xe}) is computed as,

$$s_{xe} = s_x \frac{1.38}{(a_g + 0.63)} \qquad Equation\ 3.30$$

where s_x is taken as the effective shear depth (d_v) and a_g is the maximum aggregate size. s_{xe} is limited to the range of 12 to 80 inches [1].

AASHTO LRFD Equation (5.14.5.3-1) is designed for use with the slabs of box culverts. The equation is,

$$V_c = (0.0676\sqrt{f_c'} + 4.6\frac{A_s}{bd_e}\frac{V_u d_e}{M_u})bd_e \qquad Equation\ 3.31$$

where f'_c is the 28 day compressive strength of concrete, b is the design width, d_e is the depth of the member from the extreme compression fiber to the centroid of the tensile steel, A_s is the area of reinforcing steel in the design width, and V_u and M_u are the factored shear and moment at the section, respectively. The equation is limited to a shear capacity (V_c) of,

$$V_c \leq 0.126\sqrt{f_c'}bd_e \qquad Equation\ 3.32$$

Additionally, the equation may be multiplied by the quantity $(1 + 0.04\, N_u/V_u)$ to account for axial forces, where N_u and V_u are the factored axial and shear force, respectively at the section being considered [1].

3.3.5 Summary of Shear Capacity Equations

Eight types of equations were shown in Section 3.3 for shear capacity calculation from the ACI, AASHTO LFD, and AASHTO LRFD Specifications. The shear analysis uses Equations 3.20 (ACI Eq. 11-5), 3.22 (ACI Eq. 11-6), 3.24 (LFD Eq. 8-50), 3.26 (LFD Eq. 8-51), 3.27 (LRFD Eq. 5.8.3.3-3), and 3.31 (LRFD Eq. 5.14.5.3-1) with the optional axial force term applied for comparison purposes. The comparison of the shear capacity equations to shear capacity by tests is presented in Chapter 7.

3.4 Determining Forces Needed to Calculate Shear Capacity

Aside from the basic properties and dimensions of a reinforced concrete member, some of the equations mentioned in Section 3.3 require factored shear, bending, and axial forces for the calculation of shear capacity. To acquire these forces for a structure, a model can be made with

appropriate dead and live loads and then analyzed. This section presents ways to acquire these dead and live loads for a 2D model, and Section 4.3 illustrates how the loaded models are analyzed for their internal forces.

3.4.1 Dead Loads

Once the unit weights of materials are determined, a calculation of volume multiplied by unit weight determines dead loads. In AASHTO's LFD (Equation 17-17) and LRFD (Equation 12.11.2.2.1-2) Specifications, the vertical soil pressure must be magnified by multiplying a soil structure interaction factor (SSIF). The calculation for F_e (SSIF) for embankment instillations is,

$$F_e = 1 + 0.2\frac{H}{B_c} \qquad Equation\ 3.33$$

where H is the height of fill and B_c is the width of the structure or unit-width considered. From AASHTO LRFD Equation (12.11.2.2.1-1), the vertical weight of the soil (W_e) is then calculated by,

$$W_e = F_e \gamma_s B_c H \qquad Equation\ 3.34$$

where F_e is the SSIF, γ_s is the unit weight of the soil, B_c is the width or unit-width being considered, and H is the height of fill. For AASHTO Specifications, the unit weight of the soil (γ_s) is taken as 120 pounds per cubic foot (pcf).

For culverts, the dead loads typically consist of both a vertical and a horizontal load. The vertical dead load consists of the weight of the structure, soil, and future wearing surface. The horizontal dead load consists of a linear load that increases with depth created by the horizontal soil pressure. The horizontal dead loads for a certain depth are calculated by multiplying the depth of the location by the horizontal soil pressure by the width or unit-width of the culvert. Horizontal soil pressure is set to a minimum of 30 pcf in AASHTO's Standard Specifications for Highway

Bridges in Section (3.20.1), and 60 pcf in AASHTO's LRFD Bridge Design Specifications for typical backfill materials. Figure 3.1 represents a typical loading case for dead loads acting on a box culvert [1, 4].

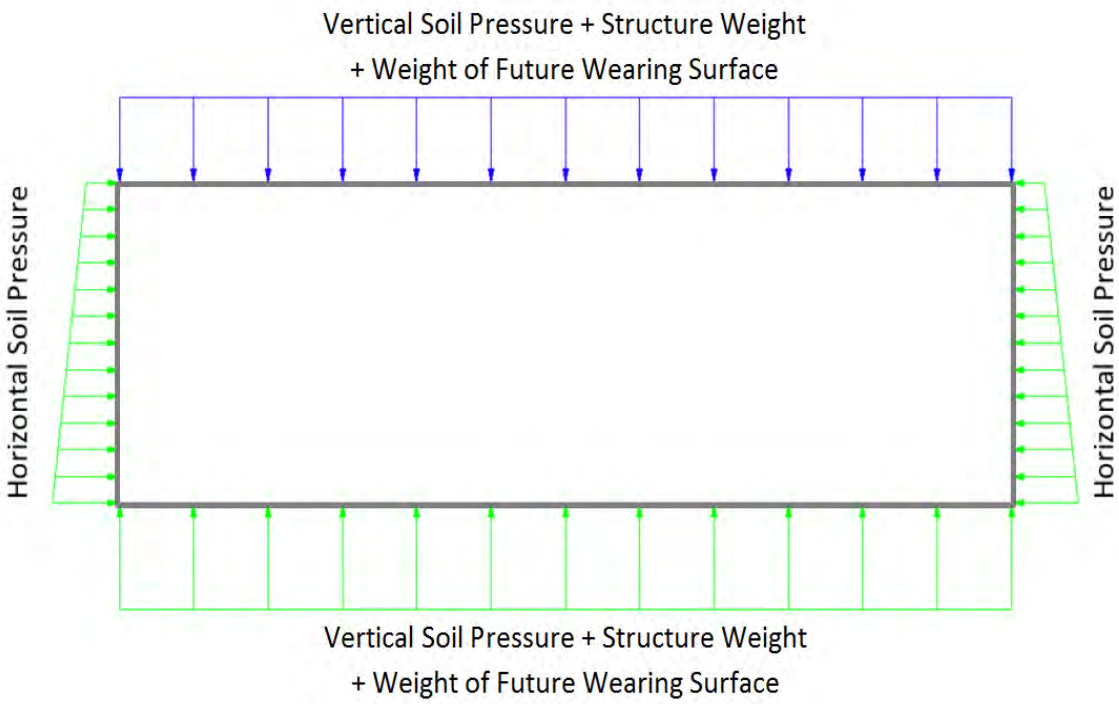


Figure 3.1: Typical Dead Load Case from STAAD Pro

3.4.2 Centipede Modeled Live Loads and Live Load Surcharge

There are generally two sets of live loads that are applied to culvert models when determining the bending, shear, and axial forces in a member. One is live load surcharge, which is applied to culverts' exterior walls. Live loads may be ignored for one cell culverts when the depth of fill is greater than both 8 feet and the clear span, and may be ignored for two or more cell culverts when the depth of fill is greater than the distance between faces of end walls. By AASHTO Specifications; live load surcharge (Δ_p) for a one foot unit width is,

$$\Delta_p = \gamma_s h_{eq} 1 \qquad Equation\ 3.35$$

where γ_s is the horizontal soil pressure, h_{eq} is the equivalent height of soil for vehicular load, and the unit width is one foot. The other is the live load created by vehicles on the top slab. The vehicular live load can be modeled as a 'centipede truck load' for culverts under fill. This type of loading consists of uniform loads generated by the distribution of vehicular load through soil being converted into a series of point loads. A centipede truck load is then moved across the structure so that the max forces along a member can be determined. Note, only an HS20 was used for the shear comparisons of Chapter 7, although more are mentioned below. Live load surcharge and the creation of a centipede truck load are clarified for both LFD and LRFD methods in the following subsections.

3.4.2.1 AASHTO LFD. Live load surcharge is calculated with h_{eq} equal to 2 feet for all cases by the LFD method. The vehicular load is calculated for at least an HS20 truck and a tandem load with the addition of a lane load for both trucks. A centipede truck load is used to represent the distribution of live load through the soil for cases of 2 feet or more of fill. To create the centipede truck load for both the HS20 and tandem truck along with the lane load, each axle and uniform lane load must be distributed based on the depth of fill above the top slab of the culvert, and then converted into a series of point loads. By Section (6.4.1) of the AASHTO Standard Specifications, the length of the load distribution is equal to the depth of fill multiplied by 1.75 when the depth of fill is 2 feet or more. Each axle load is then divided by the distribution length and width and multiplied by the multi presence factor and the impact factor to create a uniform load to be placed on the top slab of the culvert model. The uniform truck load can then be converted into a series of point loads with uniform spacing equal to or less than the distribution length. This is done by multiplying the uniform load by its length and then dividing that amount

by the number of point loads [4]. Figure 3.2 shows the load of a tire being distributed through fill to the top slab of a culvert and the resultant centipede load.

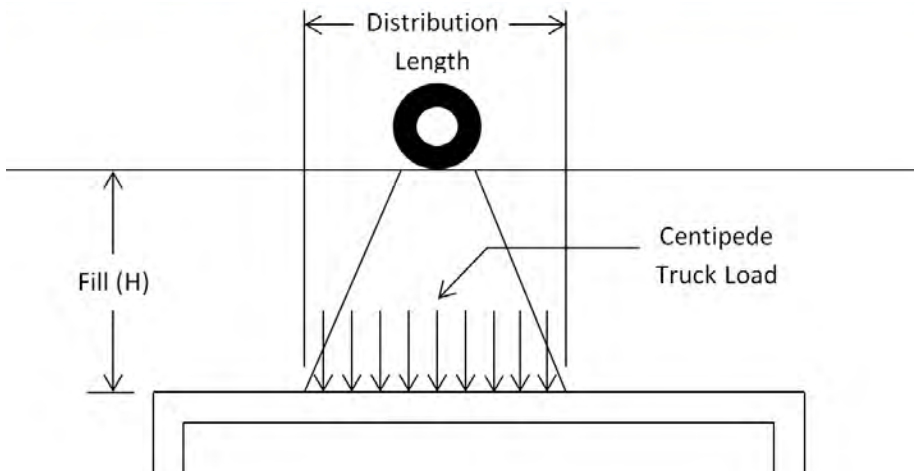


Figure 3.2: Typical Centipede Load

3.4.2.2 AASHTO LRFD. To calculate live load surcharge with Equation 3.35 above, h_{eq} is determined by Table (3.11.6.4-1) of the AASHTO LRFD Bridge Design Specifications for vehicular loading on abutments perpendicular to traffic. This table can be seen below in Table 3.1, where the abutment height is defined as the distance from the top of the fill to the bottom of the structure. The AASHTO LRFD vehicular live load consists of a truck, tandem, and lane load. For most culverts, lane load is not applied. A centipede vehicular live load is created in the same fashion by LRFD Specifications as with LFD Specifications. By Section (3.6.1.2.6) of the AASHTO LRFD Bridge Design Specifications, the distribution length for fills greater than 2 feet is equal to 10 inches (a tire's contact length and width) plus 1.15 times the depth of fill in select granular backfills [1]. Figure 3.3 is a diagram of an HS20. Figure 3.4 represents a typical loading case for live loads acting on a box culvert.

Table 3.1: AASHTO LRFD Table (3.11.6.4-1) [1]

Abutment Height (ft)	h_{eq} (ft)
5.0	4.0
10.0	3.0
≥20.0	2.0

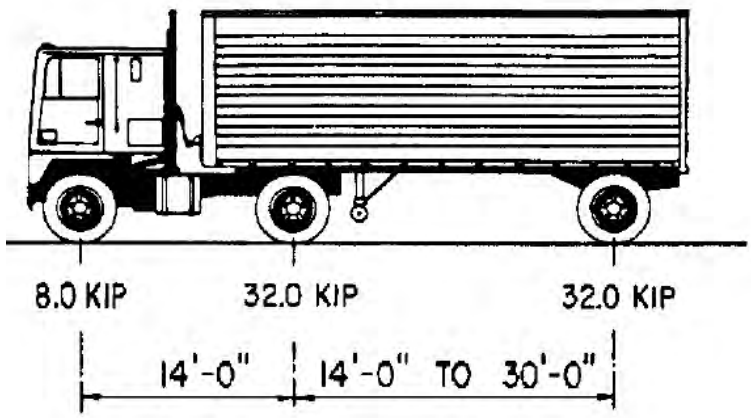


Figure 3.3: AASHTO LRFD HS20-44 Load Example [1]

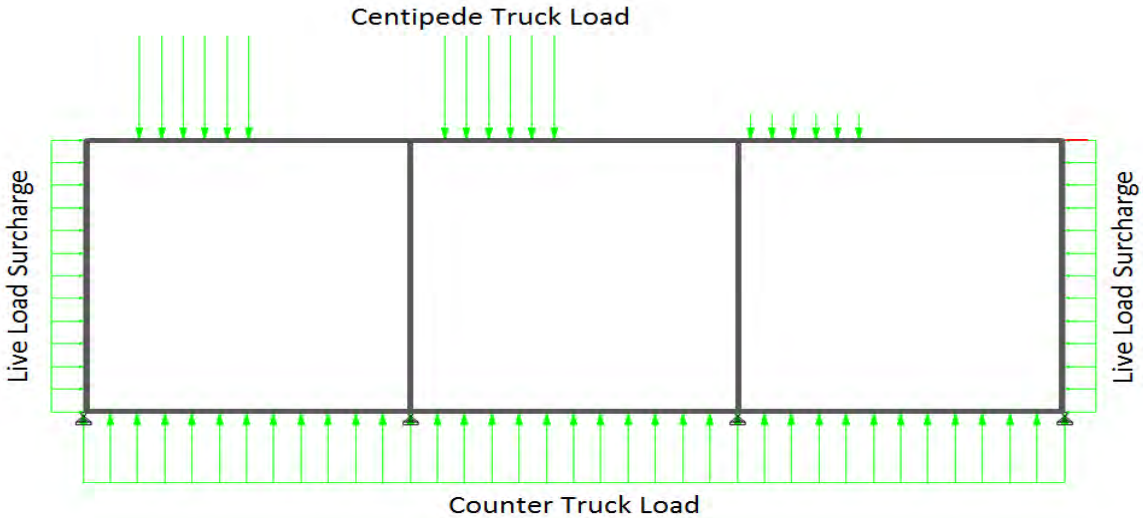


Figure 3.4: Typical Live Load Case from STAAD Pro

CHAPTER 4

CULVERT MODELING

A combined database of fifty culverts was selected for the shear analysis. Twenty culverts were chosen from TDOT's standard drawings for box and twenty for slab type culverts for the database titled the "TDOT Database." The remaining ten culverts came from past tests performed by Burns [11] and both Abolmaali and Garg [5], and the database was labeled the "Verification Database." Twenty culverts were used in the "TDOT Dump Truck Rating Factor Analysis Database." One hundred and fifty eight culverts were selected for the "Moment Continuity Analysis Database," and thirty one culverts were selected for the "Horizontal Soil Pressure Analysis Database." The culverts were modeled and analyzed by BRASS Culvert (Version 2.3.6), STAAD Pro, and Response-2000. This chapter describes the thought processes behind the selection of culverts for the databases, covers the process by which the dead and live loads for the models were attained, and explains the modeling process of the culverts in each program.

4.1 Database Selection

Five culvert databases were required to perform the analyses in Chapters 5, 6, 7, and 8.

4.1.1 TDOT Dump Truck Rating Factor Analysis Database

The TDOT dump truck analysis culverts were chosen to have a varied set of parameters. Those parameters were the number of cells, clear height, clear width, fill, and design year. The box culverts can be seen in Table 4.2, and the slab culverts can be seen in Table 4.3.

Table 4.1: Box Culverts for TDOT Dump Truck Rating Factor Analysis

Box Culverts					
No.	Model	Cell	Size Clr Width x Clr Ht (ft)	Fill (ft)	Year
1	B-2-36	2	8 x 4	0-6	1934
2	C-4-26	3	10 x 10	0	1942
3	C-10-14	1	10 x 5	0-5	1946
4	C-10-113	2	10 x 8	0-9	1948
5	D-4-199	3	8 x 3	0	1926
6	E-4-100	4	10 x 7	0	1950
7	E-8-119	2	15 x 8	0	1951
8	E-12-36	1	10 x 6	0-5	1952
9	G-5-62	3	12 x 6	0-9	1958
10	G-10-86	4	10 x 5	0-11	1959

Table 4.2: Slab Culverts for TDOT Dump Truck Rating Factor Analysis

Slab Culverts					
No.	Model	Cell	Size Clr Width x Clr Ht (ft)	Fill (ft)	Year
1	C-2-84	2	10 x 6	0-12	1940
2	D-0-62	2	10 x 3	0-5	1920
3	D-0-64	3	10 x 3	0-5	1920
4	D-0-295	4	10 x 5.5	0	1924
5	D-4-71	2	8 x 6	0-6	1925
6	F-2-55	3	15 x 10	0-6	1954
7	G-5-27	4	10 x 8	0-11	1957
8	G-5-28	2	12 x 6	0-9	1958
9	G-5-64	1	15 x 5	0-8	1958
10	G-10-54	3	12 x 10	0-9	1959

4.1.2 Horizontal Soil Pressure Analysis Database

The horizontal soil pressure culvert database consisted of two databases, one for a flexure analysis and one for a rating factor analysis. The flexure analysis database consisted of a group of culverts with typical dimensions and properties. Due to this database being used for moment comparisons and not rating factor comparisons, the culvert capacities were not required and therefore TDOT culverts were not needed. The standard culverts were selected to show how and if span length, wall height, number of cells, and fill depth affected the moments from the five load and load factor comparison tasks. The span lengths that were selected for these culverts were 8, 12, and 18 feet. The wall heights that were selected for these culverts were 4, 12, and 18 feet. There were one, two, and three celled culverts selected. Most of the culverts in this database were analyzed for zero, two, five, eight, and ten feet of fill. These fill depths were selected due to the fact that in the preliminary research, TDOT specified that these fills be used to analyze their culverts; this fill depth selection was just a continuation of that request. A list of these culverts with their properties can be seen in Table 4.3.

Table 4.3: Culverts for Horizontal Soil Pressure Flexure Analysis

Horizontal Soil Pressure Flexure Analysis Culvert Database			
Size (ft.)	Cell	Fill (ft.)	Member Thickness
8 x 4	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
8 x 12	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
8 x 18	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
12 x 4	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
12 x 12	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
12 x 18	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
18 x 4	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
18 x 12	1, 2, 3	0, 2, 5, 8, 10	All 1 foot
18 x 18	1, 2, 3	0, 2, 5, 8, 10	All 1 foot

The culverts used for the rating factor comparison of the horizontal soil pressure task are shown in Table 4.4. These culverts had varying span lengths, wall heights, fill depths, and number of cells. The span lengths ranged from ten feet to 15 feet, the wall heights ranged from four feet to 15 feet, the fill depths ranged from zero feet to 20 feet, and the number of cells ranged from one to three.

Table 4.4: Culverts for Horizontal Soil Pressure Rating Factor Comparison

Horizontal Soil Pressure Rating Factor Comparison Culverts				
Name	Cell	Size (ft.)	Year	Fill (ft.)
G-10-151	3	10 x 4	1960	0, 2, 5
B-2-92	2	10 x 8	1935	0, 2, 5, 6
K-15-8	1	12 x 12	1962	20
M-21-105	3	15 x 15	1981	2, 5, 8, 10

4.1.3 Shear Analysis Databases

The Verification Database consists of ten culverts. Four of the culverts are from a study performed by Jarrod Burns, which was mentioned in Section 2.2.2. The other six culverts are from a study by Ali Abolmaali and Anil Garg, which was covered in Section 2.2.1. Each of these culverts was tested to failure, and shear capacities were determined. This database was created so that the test results could be compared to shear capacities determined through equations from the ACI, AASHTO LRFD, and AASHTO LFD Specifications, as well as the shear capacities computed by the programs BRASS Culvert and Response-2000. Since the shear rating factor equation gives a value of 1 when dead loads are insignificant and live loads meet the capacity (failure), shear rating factors were not calculated for the Verification Database. The Verification Database can be seen in Tables 4.5 and 4.6.

Table 4.5: Verification Database Culverts by Burns [11]

No.	Specimen Name	Number of Cells	Skew°	Clear Width (ft)	Clear Height (ft)	Fill (ft)	Load Location (in)
1	S-SB-444-WB-5	1	0	4	4	0	5
2	S-SB-444-NB-5	1	0	4	4	0	5
3	S-SB-444-NB-6.5	1	0	4	4	0	6.5
4	S-SB-444-NB-11.5	1	0	4	4	0	11.5

Table 4.6: Verification Database Culverts by Abolmaali and Garg [5]

No.	Specimen Name	Number of Cells	Skew°	Clear Width (ft)	Clear Height (ft)	Fill (ft)	Load Location (in)
5	SP_2438-1219-1219_N_d	1	0	8	4	0	7
6	SP_2438-1219-1219_Y_d	1	0	8	4	0	7
7	BL_2438-1219-1219_N_d	1	0	8	4	0	7
8	BL_2438-1219-1219_Y_d	1	0	8	4	0	7
9	SP_2438-1219-1219_Y_1.5d	1	0	8	4	0	10.5
10	SP_2438-1219-1219_Y_2d	1	0	8	4	0	14

The culverts in this database consist of two sets of dimensions and various loading parameters. The four culverts from Burns had clear heights, clear spans, and widths of 4 feet. These four culverts were only loaded with a 20 by 10 inch plate on their top slab to simulate a truck wheel load with no fill. Two of the culverts were loaded towards the exterior wall, before their critical shear location. The shear force at failure is taken at the loading location for these two culverts in this thesis. All other culverts in the Verification Database are analyzed at their critical shear location. One of the two remaining culverts from Burns' test was loaded at the critical shear location and the other was loaded a few inches past it (away from the exterior wall). The six culverts from Abolmaali and Garg had clear heights and widths of 4 feet, and had clear spans of 8 feet. These culverts were loaded in a similar manner as the four culverts tested by Burns, with two of the six loaded beyond the critical shear location [5,11].

The TDOT Database consists of 20 box and 20 slab culverts from TDOT's standard drawings. As there were over 1000 standard culvert drawings to choose from, it was not difficult to find culverts with a broad range of different parameters. Specifically, a range of different drawing years, skews, clear heights, clear spans, fills, and number of cells was used to build the TDOT Database. The drawing years range from 1920 to 1990, the skew angles are between 0° and 60°, the clear heights vary between 3 and 15 feet, the clear spans are between 8 and 18 feet, the fill depths vary between 0 and 70 feet, and the number of cells ranges between 1 and 6. Culverts were also chosen to have a few lower rating factors to see the effects of increasing shear capacity. The TDOT Database can be seen if Tables 4.7 and 4.8.

Table 4.7: TDOT Database of Box Culverts for Shear Analysis

No.	TDOT Drawing	Number of Cells	Skew°	Clear Width (ft)	Clear Height (ft)	Fill (ft)	Year
1	C-4-141	1	All	10	3	40	1945
2	D-0-225	2	0	10	4	2	1929
3	D-0-294	6	0	10	7.5	0	1924
4	D-4-283	5	33	10	7	0	1927
5	G-10-86	4	45	10	5	10	1959
6	G-10-120	2	15	12	9	8	1959
7	H-5-116	2	All	8	8	20	1960
8	H-5-117	3	30	8	6	20	1960
9	H-5-150	1	All	8	3	12	1961
10	K-15-144	2	15	15	13	8	1963
11	K-38-14	3	0	10	10	13	1963
12	K-38-21	3	45	12	6	8	1964
13	K-38-128	2	45	8	5	0	1964
14	M-1-47	3	15	18	5	10	1984
15	M-1-62	3	0	15	15	5	1985
16	M-1-72	2	30	15	3	10	1985
17	M-1-91	3	60	12	4	2	1986
18	M-1-109	4	0	12	12	2	1988
19	M-1-142	1	30	18	15	2	1989
20	M-1-144	1	45	15	8	5	1990

Table 4.8: TDOT Database of Slab Culverts for Shear Analysis

No.	TDOT Drawing	Number of Cells	Skew°	Clear Width (ft)	Clear Height (ft)	Fill (ft)	Year
1	A-6-98	4	45	10	5	0	1930
2	D-0-62	2	90	10	4	2	1920
3	E-4-103	5	45	18	9	0	1950
4	F-10-93	3	45	12	6	8	1957
5	G-5-61	2	15	12	9	8	1958
6	H-5-53	3	90	10	10	11	1959
7	H-5-118A	2	All	8	8	20	1974
8	H-5-119	3	All	8	6	20	1960
9	H-5-151	1	All	8	3	20	1962
10	H-5-151A	1	All	10	3	70	1990
11	K-15-24	2	45	8	5	0	1961
12	K-15-34	5	30	10	6	13	1963
13	K-62-1	3	90	15	15	10	1967
14	M-1-47	3	15	18	5	10	1984
15	M-1-72	2	30	15	3	10	1985
16	M-1-91	3	60	12	4	2	1986
17	M-1-109	4	90	12	12	10	1988
18	M-1-142	1	30	18	15	2	1989
19	M-1-144	1	45	15	8	5	1990
20	M-82-142	2	15	15	13	10	1981

4.1.4 Moment Continuity Analysis Database

All the box and slab culverts chosen for the moment continuity task had zero negative moment reinforcement at the exterior wall connections. There were 124 box culvert drawings and 34 slab culvert drawings that did not have negative moment reinforcement at the exterior wall connections in the TDOT culvert inventory. These culverts had varying span lengths, wall heights, and number of cells. The span lengths ranged from six feet to 15 feet, the wall heights ranged from three feet to 15 feet, and the number of cells ranged from one to six. In total, the moment continuity culvert database contained 158 culvert drawings.

4.2 Determining Dead and Live Loads for Models

Once the TDOT Database and the Verification Database were decided, all 50 culverts were modeled in STAAD Pro to attain forces for shear capacity calculations. Although the dimensions and properties of the culverts could be taken from the drawings, dead and live loads had to be determined before the culverts could be modeled. The dead and live loads were calculated for both AASHTO's LFD and LRFD Specifications as described in Section 3.4. Mathcad was used to quicken the process.

Mathcad is a program that allows free-form entering of variables and equations to produce desired values. The program reads the values and equations from left to right and top to bottom. One of the distinguishing features of the program is its ability to persistently update all fields. Once equations from the Specifications are entered along with culverts dimensions and properties, Mathcad is able to produce final load values, lengths, and spacings (point loads or centipede loads). To acquire live and dead loads for different culverts, only the different dimensions and properties have to be changed. For cases of no fill, point loads were calculated. When fill was sufficiently deep enough to consider load distribution, each axle had the individual centipede loads calculated for 1 foot spacings. For cases of deep fill when axle loads overlapped, the loads were distributed into a single centipede load over the combined overlapping length of all axles.

Basic programing logic, such as an "if statement", was required in the Mathcad files since the solution for dead and live loads diverged based on some of the variables. For instance, live loads can be ignored in both AASHTO LFD [4] and LRFD [1] Specifications if a culvert has a single span and is under more than 8 feet of fill with the fill depth being greater than the clear span. The Specifications also state that culverts with two or more spans can ignore live loads if the depth of fill is greater than the distance between exterior walls of the culvert. This portion of the Mathcad

file uses an “if statement” that is based on the number of cells with two nested “if statements” questioning whether live loads can be ignored based on fill depth for the case of a single span, and fill depth and total span length for the case of multiple spans. Appendix B contains the full Mathcad file used for TDOT’s box culvert, C-4-141, for both AASHTO LFD [4] and LRFD [1] Specifications. Again, although more loads were calculated, only the HS20 was used in the analysis and comparisons of Chapter 7.

4.3 Modeling Culverts

After the dead and live loads were determined, the models could be completed. This section details the modeling process of each program and states what parts of the output were used for the analyses in Chapters 5, 6, 7, and 8. A brief explanation of each program is also be given.

4.3.1 STAAD Pro

STAAD Pro is a structural engineering program. Since the program was not designed for use with culverts specifically, dead and live loads are needed to complete the models in STAAD Pro. As mentioned in Section 4.2, Mathcad was used with Specification equations to determine appropriate dead and live loads for 2D models with 1 foot sections. Once modeled, the structures can be analyzed for their internal forces at any location along a specified member. To create a model in STAAD Pro, members must be created and loaded before the analysis can begin.

Once the culvert model analysis was completed, member forces were taken for use with the analyses in Chapters 5, 7, and 8. STAAD Pro allowed member forces to be determined at the desired location along a member for a predetermined load case. The extracted member forces were used with the various capacity equations that required them so that an analysis between Specification calculations of shear capacity and program based ones could be performed.

Appendix C details the process behind modeling in STAAD Pro, and Appendix D goes over the steps taken to verify the results of BRASS Culvert with STAAD Pro. The two following sections explain the two programs used to determine shear capacity directly.

4.3.2 BRASS Culvert

BRASS Culvert is a culvert modeling program designed to produce engineering values such as: member forces, shear capacity, rating factors, and more. For this thesis, BRASS Culvert was used to directly attain shear capacity values for the comparison analysis in Chapter 7 as well as produce the rating factors for the TDOT Rating Aids as mentioned in Chapter 9. At various locations for each member, the output contains: moment, axial, and shear forces; shear and moment capacity; and inventory and operating rating factors for both flexure and shear. A detailed explanation on how to use BRASS Culvert can be found in Appendix E.

4.3.3 Response-2000

Response-2000 allows an analysis of slabs and beams based on the Modified Compression Field Theory (MCFT). It allowed results to be generated in a similar manner to the test results in Chapter 7, as it uses the MCFT. These Sectional Response values were taken directly from Response-2000 and used as shear capacities for the analysis of Chapter 7. Appendix F goes through the steps used to model in Response-2000.

4.4 Modeling Summary

Chapter 4 went through the process used to attain forces and some capacities for the analyses of Chapters 5, 6, 7, and 8. In doing so, five programs were used. First, Mathcad was used to quickly run the equations necessary for calculating dead and live loads based on measurements

and properties determined from the drawings. STAAD Pro was used to model the culverts and their load cases in order to attain the forces at desired sections, and BRASS Culvert and Response-2000 were used to attain capacities and forces directly. Finally, Microsoft Excel was used to store and work with the forces necessary to calculate capacities based on Specifications and rating factors. A diagram of the process for attaining and using internal forces for the analyses of Chapters 5, 7, and 8 can be seen in Figure 4.1.

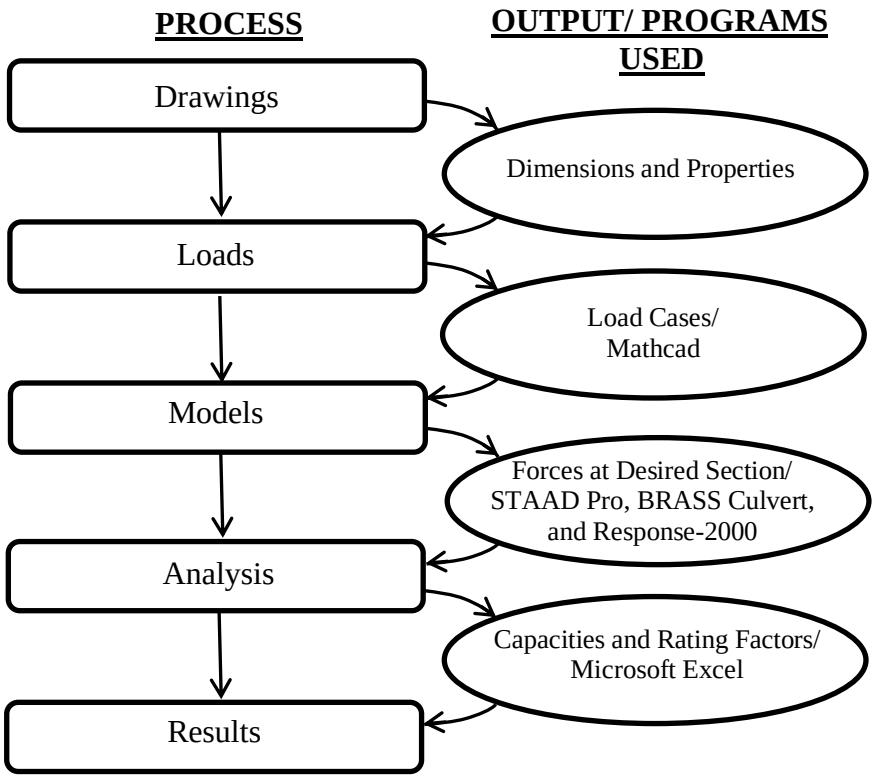


Figure 4.1: STAAD Pro Modeling and Rating Process

CHAPTER 5

HORIZONTAL SOIL PRESSURE ANALYSIS

The magnitude of lateral earth pressure, also known as horizontal earth pressure (EH), generated upon culverts' exterior walls is calculated based on soil densities and depth below the surface. The horizontal soil pressure analysis involved changing the unit weight of the soil used to calculate the horizontal soil pressure acting on the exterior walls of a culvert for the LFR method. The goal of this study was to determine the effects on the rating factors of reinforced concrete culverts created by using different values of lateral earth pressure.

5.1 Background

This study was formed because according to the SSHB in Article 6.2.1 a unit weight of horizontal soil of either 30 or 60 pounds per cubic foot can be used to calculate the horizontal soil pressure acting on the exterior walls of a culvert, and it is unknown how this difference in soil pressure affects the moments acting on the members of a culvert and the rating factors for the culvert members [4]. This difference could have either small or large effects on the moments acting on the culvert and therefore the rating factors for the culvert.

The LFR method was used to calculate the rating factors for this task. This method was used because it is the rating method that TDOT uses to rate their existing culverts.

Members of a culvert are separated into different sections for any type of analysis procedure. The slab members are separated into left, middle, and right sections and the wall members are separated into top and bottom sections. These different sections can be seen in Figure 5.1. The left side of a slab member represents the area towards the exterior wall and the right side

of a slab member represents the area towards the interior wall. For one cell culverts, the left and right sides of a slab member are the same section.

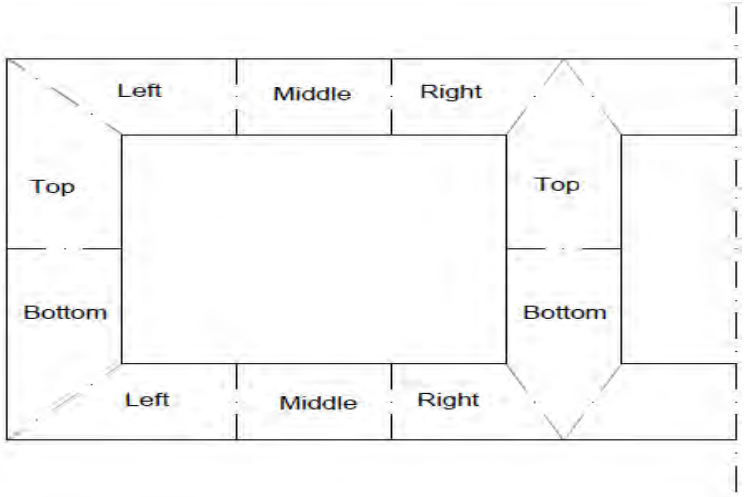


Figure 5.1: Culvert Section Labels

5.2 Flexure Analysis Results

Figures 5.2 and 5.3 are the moment plot graphs for the top of the exterior wall and the right side of the bottom slab for this particular load and load factor comparison task. For the figures, the vertical axis represents the moments produced by using a 60 pcf unit weight and the horizontal axis represents the moments produced by using a 30 pcf unit weight. If a data point is below the even line, the 60 pcf unit weight produced a negative moment larger than the 30 pcf unit weight for that point. If a data point is above the even line, the 30 pcf unit weight produced a negative moment larger than the 60 pcf for that point. If a data point is on the even line, the negative moments produced from the 30 pcf and 60 pcf unit weights are the same. In these figures, blue diamonds are for zero feet of fill moments, red squares are for two feet of fill moments, green triangles are for five feet of fill moments, purple squares are for eight feet of fill moments, and orange circles are for ten feet of fill moments. Each moment plot graph has a one-to-one ratio line

extending through the plot area. This line is referred to as the even line and represents the line at which the two items of comparison are equal in moment. These graphs help depict which item of the comparison produced the larger moment.

Figure 5.2 shows the moments on the top of the exterior wall from having all the dead loads act on the culvert. Figure 5.3 shows the moments on the right side of the bottom slab from having all the dead loads act on the culvert. Only the top of the exterior wall and the right side of the bottom slab are shown because the other culvert members follow their trends. The bottom of the exterior wall had the same trends as the top of the exterior wall. The middle of the bottom slab and the middle and right side of the top slab had the same trends as the right side of the bottom slab.

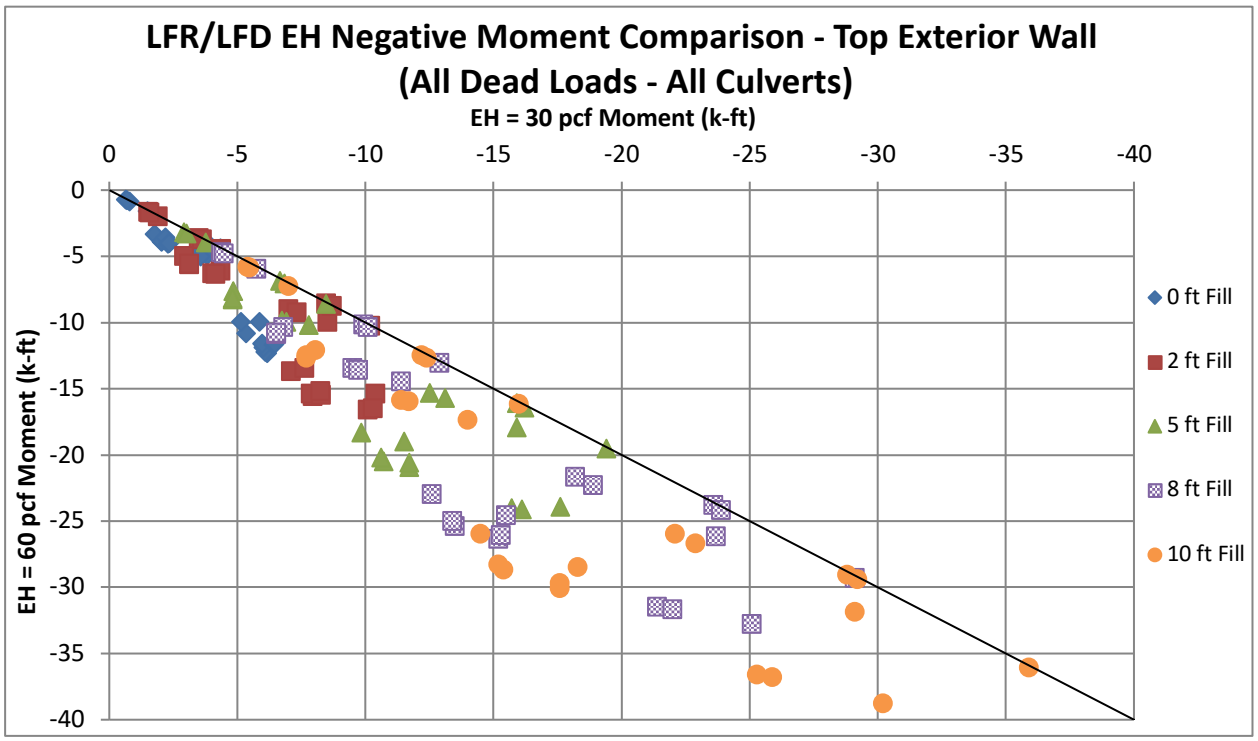


Figure 5.2: Top Exterior Wall LFR/LFD EH Moment Comparison

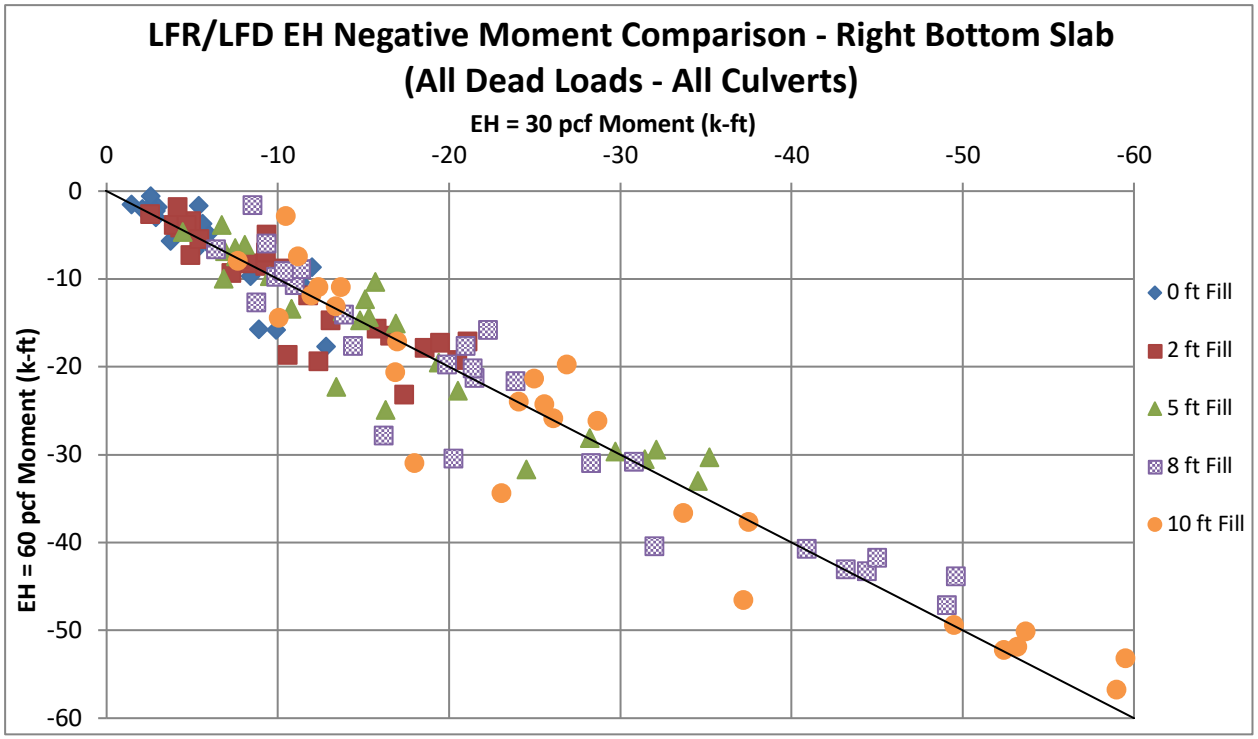


Figure 5.3: Right Bottom Slab LFR/LFD EH Moment Comparison

Since all the moments acting on the top and bottom of the exterior wall were below the even line, it was determined that the 60 pcf unit weight always produced a negative moment larger than the 30 pcf unit weight when all the dead loads were acting on the culvert. This indicates that no matter the properties of a culvert or the fill depth on a culvert, the top and bottom of the exterior wall always experienced larger negative moments when 60 pcf was used as the unit weight for the horizontal soil.

Since all the moments acting on the right side of the slabs were not below the even line, it was determined that the 60 pcf unit weight did not always produced a negative moment larger than the 30 pcf unit weight when all the dead loads were acting on the culvert. The 60 pcf unit weight only produced a negative moment larger than the 30 pcf unit weight for one cell culverts. The 30

pcf unit weight produced a negative moment larger than the 60 pcf unit weight for two and three cell culverts.

The one cell culverts had negative moment acting on the right side of their slabs, while the two and three cells had positive moment acting on the right side of their slabs when only the horizontal soil pressure was acting on the culvert. The one cells had negative moment acting on the right side of their slabs because the left and right sides of the top and bottom slabs for a one cell culvert are the same. Since, the right side of the top and bottom slabs for a one cell culvert are the same as the left side of the top and bottom slabs, there is always negative moment acting on it when only the horizontal soil pressure is acting on the culvert.

The 60 pcf unit weight controlled for the one cell culverts because it produced a larger negative moment when only the horizontal soil pressure was acting on the one cell culverts. Since all the other dead loads produced a negative moment for this part of the slab when they were added to the culvert, producing a larger negative moment value from having only the horizontal soil pressure act on the culvert at the start will result in a larger negative moment when all the other dead loads are added to the culvert at the end. Therefore, the 60 pcf unit weight controlled because it produced a larger negative moment when only the horizontal soil pressure was acting on the one cell culverts.

The 30 pcf unit weight controlled for the two and three cell culverts because the 60 pcf unit weight produced a larger positive moment when only the horizontal soil pressure was acting on the two and three cell culverts. Since all the other dead loads produced a negative moment for this part of the slab when they were added to the culvert, producing a larger positive moment value from having only the horizontal soil pressure act on the culvert at the start will result in a smaller negative moment when all the other dead loads are added to the culvert at the end. Therefore, the

30 pcf unit weight controlled because it produced a smaller positive moment when only the horizontal soil pressure was acting on the two and three cell culverts.

It was determined that certain span lengths, wall heights, cell types, and fill depths produce larger differences in moment than others. This indicates that the unit weight of the horizontal soil has a direct impact on the applied moments for the top and bottom of the exterior wall and the right side of the top and bottom slabs for certain types of culverts. Some of the moment differences between the unit weights were large and significant, while others were small and insignificant.

It was determined that the eight foot span lengths produced the largest differences, while the 18 foot span lengths produced the smallest differences. This indicates that the moment acting on the exterior wall and the right side of the slabs is more influenced by the horizontal soil pressure for culverts that have short spans rather than culverts that have long spans. This is due to the shorter span culverts having less applied vertical force than the longer span culverts, thus the horizontal force would contribute more to the moments acting on the exterior wall and the right side of the slabs. Therefore, the variation in the moments caused by the difference in the unit weights intensified.

It was determined that the 18 foot wall heights produced the largest differences, while the four foot wall heights produced the smallest differences. This indicates that the moment acting on the exterior wall and the right side of the slabs is more influenced by the horizontal soil pressure for culverts that have large wall heights rather than culverts that have small wall heights. This is due to the larger wall culverts having more applied horizontal force than the smaller wall culverts, thus the horizontal force would contribute more to the moments acting on the exterior wall and the right side of the slabs. Thus, the variation in the moments caused by the difference in the unit weights intensified.

It was determined that the ten foot fill depth produced the largest differences, while the zero foot fill depth produced the smallest differences. This indicates that the moment acting on the exterior wall and the right side of the slabs is more influenced by the horizontal soil pressure for culverts that have larger fill depths rather than culverts that have smaller fill depths. This is due to the force exerted by the horizontal soil pressure depending on the fill depth. The horizontal soil pressure increases as the fill depth increases, along with most of the other dead loads. This increase in the magnitude of the forces increases the moments acting on the exterior wall and the right side of the slabs, thus increasing the difference between the moments produced by the 60 pcf and 30 pcf unit weights.

The cell type of a culvert only affects the moments acting on the right side of the slabs; the cell type of a culvert does not affect the moments acting the exterior wall. If a culvert had one cell, the right side of the slabs always experienced larger negative moments when 60 pcf was used as the unit weight for the horizontal soil. If a culvert had two or three cells, the right side of the slabs always experienced larger negative moments when 30 pcf was used as the unit weight for the horizontal soil. It was determined that the two cell culverts produced the largest negative differences, while the three cell culverts produced the smallest negative differences. The one cell culvert moment differences were larger than the two cell culvert moment differences when the positive and negative differences were compared. This indicates that the moment acting on the right side of the slabs is more influenced by the horizontal soil pressure for culverts that have one cell rather than culverts that have two or three cells.

Table 5.1 shows the largest and smallest moment differences for the top and bottom of the exterior wall and the right side of the top and bottom slabs for this analysis. The table shows the

moment difference between the 60 pcf and 30 pcf unit weights, and which culverts these moment differences were recorded.

Table 5.1: LFR/LFD EH Difference Comparison

Largest and Smallest Moment Differences for the Horizontal Soil Pressure Load and Load Factor Comparison Task						
Top of the Exterior Wall						
Difference	Type	Value (k-ft)	Controlling Unit Weight	Culvert Size	Cell Type	Fill Depth (ft.)
Positive	Largest	13.3	60 pcf	8 x 18	2	10
	Smallest	0.05	60 pcf	18 x 4	1	0
Bottom of the Exterior Wall						
Difference	Type	Value (k-ft)	Controlling Unit Weight	Culvert Size	Cell Type	Fill Depth (ft.)
Positive	Largest	15.6	60 pcf	8 x 18	2	10
	Smallest	0.06	60 pcf	18 x 4	1	0
Right Side of the Top Slab						
Difference	Type	Value (k-ft)	Controlling Unit Weight	Culvert Size	Cell Type	Fill Depth (ft.)
Positive	Largest	11.5	60 pcf	8 x 18	1	10
	Smallest	0.05	60 pcf	18 x 4	1	0
Negative	Largest	6.12	30 pcf	8 x 18	2	10
	Smallest	0.03	30 pcf	18 x 4	3	0
Right Side of the Bottom Slab						
Difference	Type	Value (k-ft)	Controlling Unit Weight	Culvert Size	Cell Type	Fill Depth (ft.)
Positive	Largest	13	60 pcf	8 x 18	1	10
	Smallest	0.06	60 pcf	18 x 4	1	0
Negative	Largest	7.58	30 pcf	8 x 18	2	10
	Smallest	0.03	30 pcf	18 x 4	3	0

From the table, it can be seen that the 8 x 18 culvert with a ten foot fill depth had the largest differences because it had the smallest span length analyzed, the largest wall height analyzed, and

a ten foot fill depth. Also, the 18 x 4 culvert with a zero foot fill depth had the smallest differences because it had the longest span length analyzed, the smallest wall height analyzed, and a zero foot fill depth.

5.3 Rating Factor Results

Table 5.2 shows the operating rating factors for a few culverts that were analyzed for a rating factor comparison. This table reinforces the observations that were stated in the previous section about the effects of changing the unit weight of the horizontal soil pressure.

The rating factors for the G-10-151 culvert were not affected by the change in the unit weights because the culvert had a small wall height, four feet. The rating factors for the B-2-92 culvert were affected by the change in the unit weights due to it having a larger wall height, eight feet. The change in the rating factors for this culvert became greater as the fill depth increased. This is also true for the K-15-8 culvert and the M-21-105 culvert due to these culverts having larger wall heights and fill depths. The K-15-8 culvert had the largest change in rating factors because it had the largest fill depth that was analyzed for this part of the horizontal soil pressure comparison task, 20 feet.

5.4 Summary

Using different unit weights for the horizontal soil does affect the moments acting on a culvert. This in turn affects the rating factors for the culvert. The top and bottom of the exterior wall always experienced larger moments when 60 pcf was used as the unit weight of the horizontal soil. This indicates that the rating factors would be lower for the exterior wall if 60

Table 5.2: Comparison of Operating Rating Factors vs Horizontal Soil Pressure

Operating Rating Factors from the Horizontal Soil Pressure Comparison							
G-10-151; 10 x 4, 3 Cell		Exterior Wall		**K-15-8; 12 x 12, 1 Cell**		Exterior Wall	
		Bottom	Top			Bottom	Top
0 ft. Fill	30 pcf	18.2	2.3	20 ft. Fill	30 pcf	11.8	16.9
	60 pcf	18.2	2.3		60 pcf	0	3.3
2 ft. Fill	30 pcf	16.3	1.7	**M-21-105; 15 x 15, 3 Cell**		Exterior Wall	
	60 pcf	16.3	1.7			Bottom	Top
5 ft. Fill	30 pcf	16.5	3.4	2 ft. Fill	30 pcf	9.1	2.2
	60 pcf	16.5	3.4		60 pcf	5.1	1.4
B-2-92; 10 x 8, 2 Cell		Exterior Wall		5 ft. Fill	30 pcf	7.5	3.4
		Bottom	Top		60 pcf	1.9	1.5
0 ft. Fill	30 pcf	9.9	1.7	8 ft. Fill	30 pcf	5.2	3.3
	60 pcf	8.9	1.5		60 pcf	0	0.3
6 ft. Fill	30 pcf	8.9	2.9	10 ft. Fill	30 pcf	3.4	2.6
	60 pcf	5.7	2.0		60 pcf	0	0

pcf was used as the unit weight instead of 30 pcf. However, this was not always the case for the right side of the top and bottom slabs. The right side of the slabs always experienced larger moments when 60 pcf was used as the unit weight if the culvert being analyzed had only one cell. This section of the slabs always experienced larger moments when 30 pcf was used as the unit weight if the culvert being analyzed had more than one cell. This indicates that the rating factors for the right side of the slabs would be lower if the 60 pcf unit weight was used instead of the 30 pcf unit weight if the culvert had one cell. The opposite would be true if the culvert had more than one cell. Even though the two and three cell culverts had a reduction in value for the middle and right side of the slabs, this reduction was small when compared to the increase in value for the exterior wall and left side of the slabs.

The wall height and the fill depth affect the variation in the rating factors the most, while the span length and the cell type have a smaller influence. The cell type of a culvert only affects the rating factors for the right side of the slabs. The variation intensifies as the wall height

increases, fill depth increases, span length decreases, and the number of cells decreases. Culverts with four foot wall heights would not experience any change in rating factors. However, culverts with larger wall heights would experience variation in the rating factors.

The variation in the moments between the two unit weights can be large, thus the variation in the rating factors for a particular culvert can be large. From this analysis, it was concluded that using different unit weights for the horizontal soil could potentially turn either a satisfactory rating factor into an unsatisfactory rating factor or vice versa.

CHAPTER 6

RATING FACTOR ANALYSIS FOR TDOT DUMP TRUCK

It was questioned how much of a change in rating factors could be achieved for reinforced concrete culverts by using a TDOT dump truck live load instead of a standard HS20 or H15 truck. To assess this query, a database of 10 box and 10 slab culverts were modeled from TDOT's standard drawing database. Flexural and shear, operating rating factor values were recorded from the culvert analysis program known as BRASS Culvert (Version 2.3.6) for each of the 20 models. The comparison was done for a range of various skews, number of cells, clear heights, clear spans, fills, and design years. Once the analysis was completed, the lesser rating factor value between the HS20 and H15 trucks was compared to the TDOT dump truck's rating factor for each member location and fill depth. The rating factors were compared graphically to get a better sense of the results.

6.1 Background

TDOT will sometimes use a TDOT dump truck instead of standard truck loads when rating culverts. To test the results of doing so, BRASS Culvert was used to analyze multiple culverts with various conditions for standard truck loads and the TDOT dump truck. By changing only the live load, the resultant changes in rating factors should illustrate the differences clearly. If rating factors tend to increase, then using a TDOT dump truck load instead of a standard truck load would be a helpful solution towards raising rating factors.

6.2 Comparison by Changing Truck Live Load

For this analysis, standard H15 and HS20 truck's rating factors were compared to those based on a TDOT dump truck load. Since H15 trucks have the same spacing between front and rear axles as HS20 trucks do between front and mid axles and the HS20 truck has greater loads in both locations, it stands to reason that HS20 truck loads should produce lower rating factors than H15 trucks. This means that the controlling truck load will likely be the HS20 in most cases in this comparison. It is also important to note that the TDOT dump truck is 2 kips heavier when compared to the HS20 truck, as well as 8'-10" shorter overall at a minimum. At a cursory glance, the primary thing that would allow a TDOT dump truck load to produce better rating factors than an HS20 truck would be that the load per axel tends to be less for the dump truck. At greater fill depths, the weight per axels is likely not to be as significant due to load distribution, and the heavier TDOT dump truck load may produce lower rating factors overall. Figure 6.1 contains diagrams of the H15, HS20, and TDOT dump truck load cases.

6.3 Flexural Results

The comparison of flexural rating factors can be seen below in Figures 6.2 to 6.3. The rating factors reported are only for the operating level. The rating factors are reported with the controlling truck value on the y-axis and the TDOT dump truck values on the x-axis. The line drawn with the equation y = x is used to determine whether the rating factors tended to be larger for the controlling truck or the TDOT dump truck. When values lie above the line, the controlling truck produced a greater rating factor. When values lie below the line, the TDOT dump truck produced larger rating factors. The distance that the grouping of values lies away from the line

indicates the amount of change between using a TDOT dump truck or the controlling truck. The tighter the points are grouped around the line, the less the change seen by

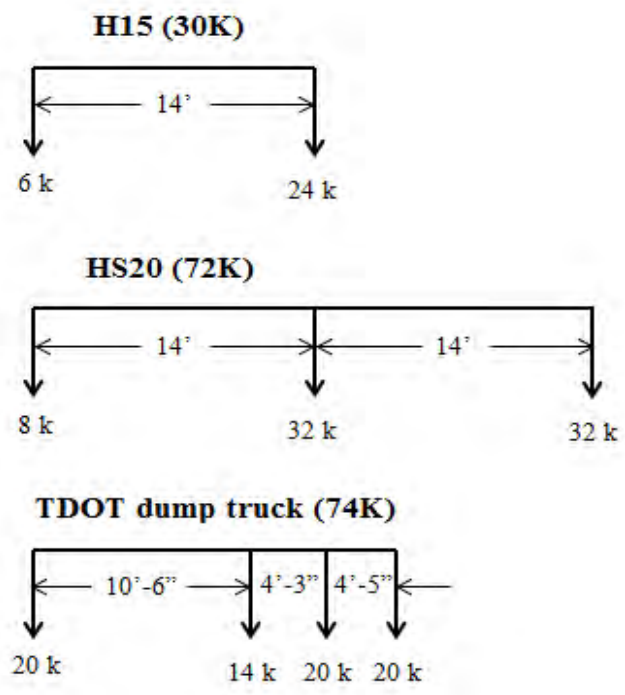


Figure 6.1: Truck Load Configurations

varying between the live loads. The overall trend was little to no change in rating factors between the controlling truck load and the TDOT dump truck load.

Appendix G1 contains the full set of flexural rating factors for the 10 box culverts, and Appendix G2 contains values of the 10 slab culverts. Values less than 1 represent culvert's members that are unsuitable to withstand their loads. Values of 99 or n/a represent member locations that are considered not to be impacted by the live loads, or possibly were considered to have no moment continuity. The term 'exterior' represents spans on the ends of culverts, and 'interior' represents the inside spans of culverts with 3 cells or more. Two and one cell culvert's slabs are all considered as 'exterior'. The term 'left' refers to a slab's location towards the exterior wall, and 'right' refers to a location towards the interior wall or the other exterior wall as

applicable. The Controlling Rating Factor column contains the lowest rating factor in that row of values. The Controlling Truck load implies that the lowest rating factor between the HS20 and H15 trucks was selected for these rows.

For the box culverts, comparison graphs were made for top slabs of interior and exterior spans, bottom slabs of interior and exterior spans, the exterior and interior walls of exterior spans, and interior walls of interior spans. The graph for the exterior wall of the exterior span shows little to no change in rating factors. The graph for the top slab of the exterior span shows that sometimes the controlling truck produced greater rating factors, and sometimes the TDOT dump truck did. In all instances, the change tended to be very small. The graph for the interior wall of the exterior span rating factors showed a few values produced by the TDOT dump truck were lower than those produced by the controlling truck. However, the trend tended to be little to no change overall once again. The graph for the bottom slab of the exterior span had some rating factors greater for the controlling truck load, some greater for the TDOT dump truck load, and the majority had little to no change. The same trend occurred again for the top slab of the interior span. The graphs of the interior wall and the bottom slab of the interior span both produced little to no change overall; with all changes having the controlling truck load produce the greater rating factors.

The same trends can be seen in the graphs for the slab culverts in Figures 6.4 to 6.5. The slab culvert comparison graphs were made for top slabs of interior and exterior spans, the exterior and interior walls of exterior spans, and interior walls of interior spans. Most of the changes in rating factors for the exterior wall of the exterior span were negligible. The majority of the changes in the top slab of the exterior and interior span were varied and small. The values of the interior wall of the interior and exterior span both demonstrated very little change towards the controlling truck producing higher rating factors in most of the values.

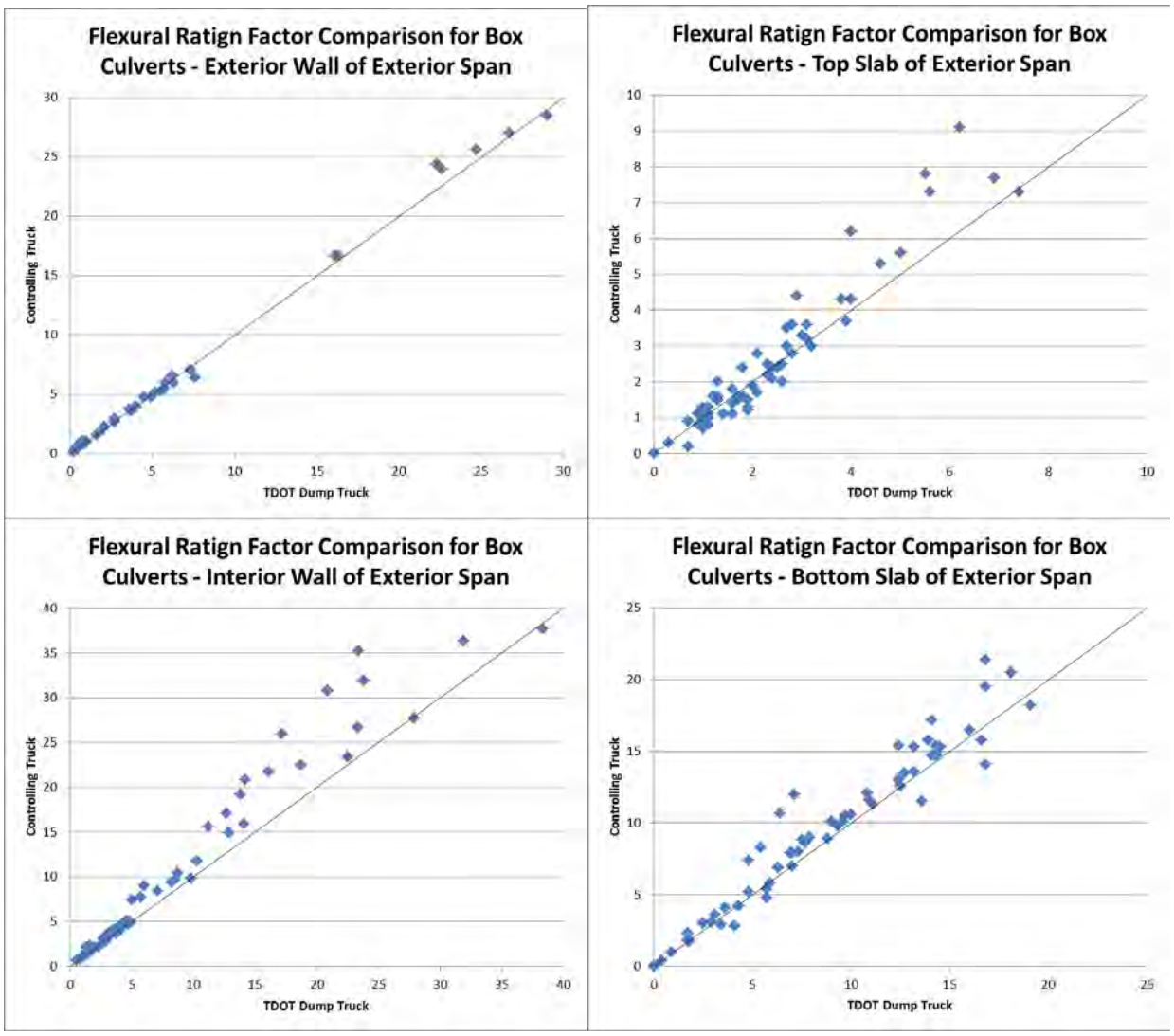


Figure 6.2: Flexural Rating Factor Comparison for Box Culverts- Exterior Span

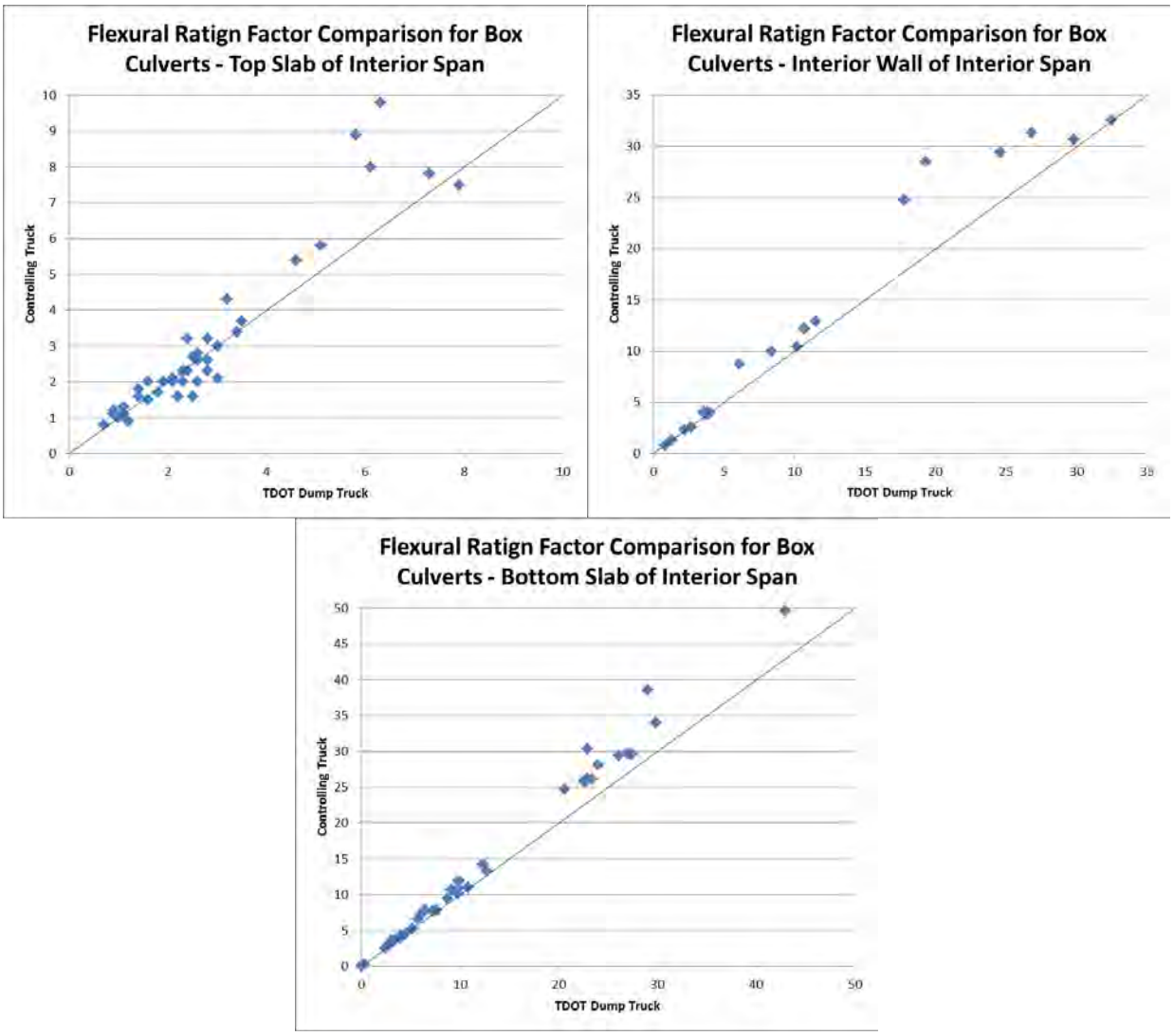


Figure 6.3: Flexural Rating Factor Comparison for Box Culverts- Interior Span

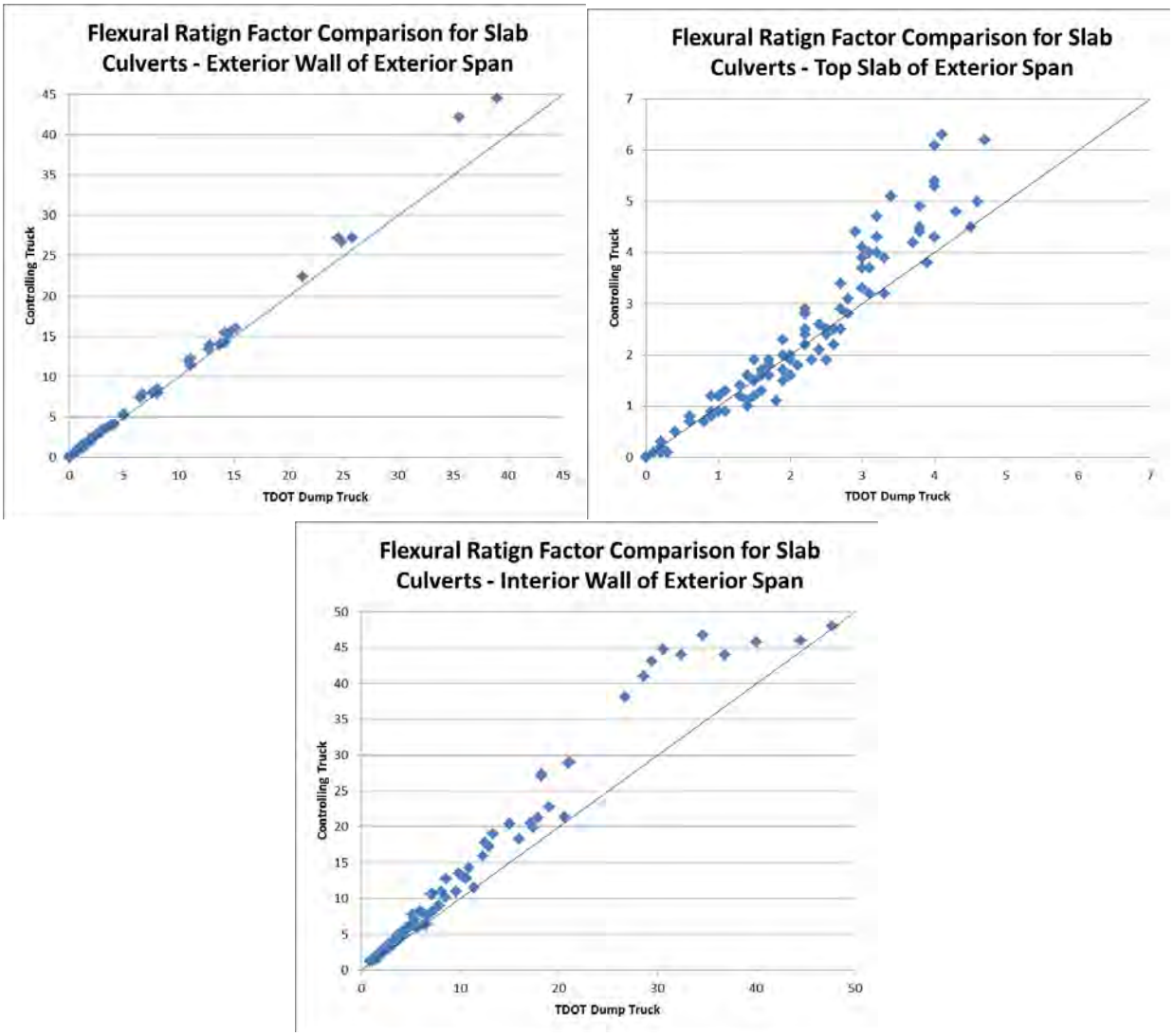


Figure 6.4: Flexural Rating Factor Comparison for Slab Culverts- Exterior Span

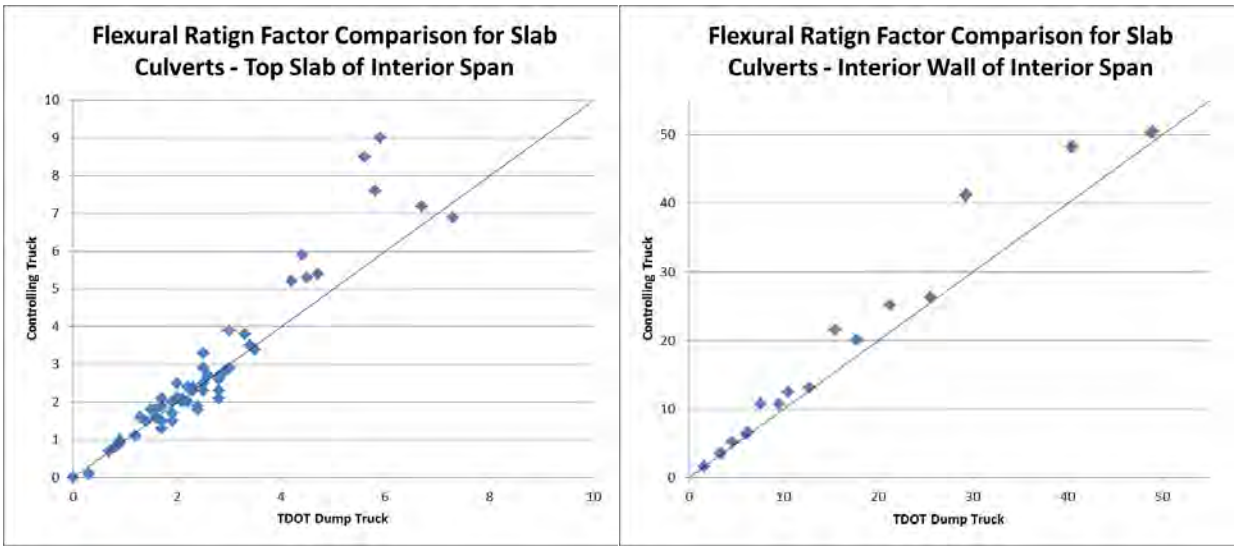


Figure 6.5: Flexural Rating Factor Comparison for Slab Culverts- Interior Span

6.4 Shear Results

Similarly, Appendix G3 contains the full set of shear rating factors for the 10 box culverts, and Appendix G4 contains the shear values of the 10 slab culverts. Shear rating factors were also used to perform a comparison between the TDOT Dump truck and the HS20. The shear results tended to show the same trends as were observed with the flexural rating factors.

6.5 TDOT Dump Truck Analysis Summary

As was assumed based on the similarities of the HS20 and TDOT dump truck, little variation was seen in the rating factors of reinforced concrete culverts. The TDOT dump truck never tended to produce greater rating factors than the HS20 as a whole for most members of the culverts. The exception being the bottom slabs and interior walls, in which case the HS20 tended to have slightly greater rating factors than the TDOT dump truck.

CHAPTER 7

SHEAR ANALYSIS

Once the top slab forces at the critical shear location for the 50 culverts were determined through STAAD Pro, an Excel file was used to store and process the values. Shear rating factors and nominal shear capacities were calculated for each culvert of the TDOT Database by Specification equations. Shear capacity values were also taken for each culvert from the programs BRASS Culvert and Response-2000. Comparison graphs were created to group the nominal shear capacity values. For the Verification Database culverts, test based shear capacities were compared to the equation and program based values. The TDOT Database was used to compare shear capacities produced by the Specification equations, BRASS Culvert, and Resoponse-2000. For the TDOT Database culverts, shear rating factors determined by shear capacities from BRASS Culvert and Response-2000 were compared to determine how sensitive the shear rating factor equation is to changes in capacity for various types of culverts.

7.1 Shear Capacity Analysis

This section explains the processes used for computing nominal shear capacities in Excel and other programs, and includes the general arrangement of the values stored in Excel.

7.1.1 General Layout and Input

An Excel spread sheet was created to contain culvert properties, dimensions, and forces in top slabs at the critical shear location. Forces were determined through STAAD Pro as outlined in Section 4.3.1, STAAD Pro models were created based on Mathcad output, and Mathcad files

were created from Specification equations and logic. When transferring values, units were used to match the intended equations. Table 7.1 shows properties and dimensions of culverts in the Verification Database. Similar tables were used for the properties and dimensions of the culverts in the TDOT Database. The values in the table include: the compressive strength of concrete (f'_c), the width of the member taken for one foot sections (b_w = 1'), the thickness of the member (h), the distance from the outer fiber of compression to the centroid of the tensile steel (d or d_e), the effective shear depth (d_v), the gross cross-sectional area (A_g), the area of steel (A_s), the maximum size of aggregate (a_g), and the steel's modulus of elasticity (E_s). Table 7.1 also shows values calculated based on these properties, dimensions, and forces.

The calculated values in Table 7.1 are the reinforcement ratio of the tensile steel area and the concrete above it (ρ_w), the length to depth ratio term ($V_u d/M_u$), the modified moment used to account for axial forces (M_m), the modified length to depth ratio term ($V_u d/M_m$), the shear strain term (ε_s), and the factor indicating the ability of diagonally cracked concrete to transmit tension and shear (β). The last three columns in Table 7.1 are the limits assigned to AASHTO LRFD and ACI shear strength equations. These values and limits are calculated as specified in Section 3.3.

Table 7.2 shows the forces determined through STAAD Pro in top slabs at the critical shear location for the box culverts of the TDOT Database by AASHTO LRFD methods. For two culverts in the Verification Database, S-SB-444-WB-5 and S-SB-444-NB-5, the forces are taken at the location of loading because they were loaded before their critical shear locations. All other culvert's forces in the Verification and TDOT Databases are taken at the critical shear location. The portion of the forces shown in Table 7.2 contains the unfactored forces of the live and dead loads. The live load values were taken for an HS20, shown in Figure 3.3, in all cases. The

Table 7.1: Culvert Properties and Dimensions for Shear Analyses

	Verification Culverts / Culvert Model	Design Values																		
		f'_c (ksi)	b, b_w, b_v (in)	h (in)	d, d_e (in)	d_v (in)	ρ_w	$V_u d/M_u$	M_m (lb-in)	$V_u d/M_m$	A_g (in^2)	A_s (in^2)	a_g (in)	ε_s	s_{xe} (in)	E_s (ksi)	β	$V_{c\ Lim.}$ (k) (Eq. 3.9.1)	$V_{c\ Lim.}$ (lb) (Eq. 3.4.1)	$V_{c\ Lim.}$ (lb) (Eq. 3.5.1)
1	S-SB-444-WB-5	8.5	12	7.5	6.5	4.5	0.003	1	178911	1.11	90	0.24	0.75	0.003	12	29000	1.5	28.65	25169	25478
2	S-SB-444-NB-5	8.5	12	7.5	6.5	4.5	0.003	0.95	257918	0.96	90	0.24	0.75	0.003	12	29000	1.5	28.65	25169	25454
3	S-SB-444-NB-6.5	8.4	12	7.5	6.5	4.5	0.003	0.80	340587	0.81	90	0.24	0.75	0.003	12	29000	1.5	28.48	25021	25281
4	S-SB-444-NB-11.5	7.9	12	7.5	6.5	4.5	0.003	0.89	227500	0.89	90	0.24	0.75	0.003	12	29000	1.5	27.62	24265	24345
5	SP_2438-1219-1219_N_d	5	12	8	7	5	0.003	1	200219	1.07	96	0.24	0.75	0.003	12	29000	1.5	23.67	20789	21065
6	SP_2438-1219-1219_Y_d	5	12	8	7	5	0.003	1	253753	1.07	96	0.24	0.75	0.003	12	29000	1.5	23.67	20789	21138
7	BL_2438-1219-1219_N_d	6	12	8	7	5	0.003	1	240363	1.07	96	0.24	0.75	0.003	12	29000	1.5	25.93	22773	23136
8	BL_2438-1219-1219_Y_d	5	12	8	7	5	0.003	1	200219	1.07	96	0.24	0.75	0.003	12	29000	1.5	23.67	20789	21065
9	SP_2438-1219-1219_Y_1.5d	5	12	8	7	5	0.003	1	213596	1.07	96	0.24	0.75	0.003	12	29000	1.5	23.67	20789	21083
10	SP_2438-1219-1219_Y_2d	5	12	8	7	5	0.003	1	106086	1.76	96	0.24	0.75	0.003	12	29000	1.5	23.67	20789	20822

factored live load moment, shear, and axial forces were calculated for an HS20 as well. The factors applied were based on the method used to calculate shear capacity.

For the AASHTO LRFD and ACI shear capacity equations, LRFD factors were applied to the forces as per AASHTO LRFD Bridge Design Specifications Table (3.4.1-2) seen in Table 7.3 below. LRFD and ACI live loads were multiplied by a factor of 1.75 for Strength I, and dead loads were multiplied by a factor of 1.5. To make the analysis simpler, 1.5 was conservatively used for all LRFD and ACI dead loads because it is the max load factor for dead loads considered as per AASHTO LRFD Bridge Design Specifications Page (3-12) of Section (3.4.1) for reinforced concrete culverts. AASHTO LFD factors were applied to the forces for use with LFD shear capacity equations as per AASHTO Standard Specifications (Table 3.22.1A) seen in Table 7.4 below. The factors are determined by multiplying γ to the β factor. The last line in the table is for culverts used with LFD equations. So, dead loads were multiplied by a factor of 1.3 and live loads were multiplied by a factor of 2.17 [1, 4].

7.1.2 Shear Capacity Specifications

Equations 3.20 through 3.31 were used to calculate nominal shear capacities for the analysis based on combined member forces from dead loads and an HS20. The shear capacities that had limits were compared to their limiting values. The limiting values of shear capacity were reported if the calculated shear capacity exceeded the limiting values. Equations 3.20 and 3.22 were reported as ACI Equations 1 and 2, respectively, Equations 3.24 and 3.26 were reported as LFD Equations 1 and 2, respectively, and Equations 3.27 and 3.31 were reported as LRFD Equations 1 and 2, respectively. Equation 3.31 was multiplied by the additional term containing axial force as mentioned in Section 3.3.4.

Table 7.2: Forces in the Top Slab at the Critical Shear Location

Slab Culverts		Unfactored LRFD Forces								
		Top Slab (Critical Shear Location)								
		HS20			LL Surcharge			Dead		
No.	Culvert Model	Mom. (k*ft)	Shear (k)	Axial (k)	Mom. (k*ft)	Shear (k)	Axial (k)	Mom. (k*ft)	Shear (k)	Axial (k)
1	A-6-98	3.04	5.08	0.785	0.058	0.007	0.227	0.203	0.664	0.546
2	D-0-62	4.14	3.75	0.023	0	0	0.169	1.68	1.28	0.354
3	E-4-103	2.17	5.28	0.791	0.276	0.021	0.359	1.49	1.47	1.22
4	F-10-93	0.171	1.16	0.369	0.1	0.011	0.203	1.07	5.76	3.57
5	G-5-61	0.069	1.15	0.215	0.254	0.035	0.276	1.66	5.73	3.88
6	H-5-53	0.138	0.621	0.081	0.303	0.041	0.284	2.87	6.57	4.89
7	H-5-118A	0	0	0	0	0	0	0.557	8.34	6.46
8	H-5-119	0.062	0.18	0.04	0.089	0.015	0.169	1.43	8.08	5.58
9	H-5-151	0	0	0	0	0	0	0.083	9.47	6.53
10	H-5-151A	0	0	0	0	0	0	35.9	32.7	28.8
11	K-15-24	2.85	5.01	0.643	0.111	0.023	0.263	0.067	0.466	0.391
12	K-15-34	0.004	0.387	0.101	0.082	0.011	0.164	0.755	7.22	4.37
13	K-62-1	0.08	1.06	0.16	0.596	0.054	0.415	9.55	9.69	7.61
14	M-1-47	0.201	1.18	0.612	0.046	0.003	0.156	0.997	10.7	7.53
15	M-1-72	0.059	1.02	0.726	0.01	0.001	0.102	1.79	8.31	6.92
16	M-1-91	5.1	3.76	0.887	0.058	0.006	0.187	2.67	1.99	1.32
17	M-1-109	0.189	0.865	0.169	0.289	0.034	0.32	4.93	7.43	5.88
18	M-1-142	4.3	4.48	0.408	0.755	0	0.444	4.35	4.06	3.69
19	M-1-144	2.71	2.31	0.383	0.284	0.001	0.294	4.35	5.75	3.37
20	M-82-142	0.064	1.06	0.176	0.478	0.052	0.367	5.58	9.18	6.77

Table 7.3: AASHTO LRFD Bridge Design Specifications Table (3.4.1-2) [1]

Type of Load, Foundation Type, and Method Used to Calculate Downdrag		Load Factor	
		Maximum	Minimum
DC: Component and Attachments		1.25	0.90
DC: Strength IV only		1.50	0.90
DD: Downdrag	Piles, α Tomlinson Method	1.4	0.25
	Piles, λ Method	1.05	0.30
	Drilled shafts, O'Neill and Reese (1999) Method	1.25	0.35
DW: Wearing Surfaces and Utilities		1.50	0.65
EH: Horizontal Earth Pressure			
• Active		1.50	0.90
• At-Rest		1.35	0.90
• *AEP* for anchored walls		1.35	N/A
EL: Locked-in Construction Stresses		1.00	1.00
EV: Vertical Earth Pressure			
• Overall Stability		1.00	N/A
• Retaining Walls and Abutments		1.35	1.00
• Rigid Buried Structure		1.30	0.90
• Rigid Frames		1.35	0.90
• Flexible Buried Structures other than Metal Box Culverts		1.95	0.90
• Flexible Metal Box Culverts and Structural Plate Culverts with Deep Corrugations		1.50	0.90
ES: Earth Surcharge		1.50	0.75

Table 7.4: AASHTO Standard Specifications Table (3.22.1A) [4]

TABLE 3.22.1A Table of Coefficients γ and β

Col. No.		1	2	3	3A	4	5	6	7	8	9	10	11	12	13	14	
			β FACTORS														
GROUP		γ	D	$(L+I)_n$	$(L+I)_p$	CF	E	B	SF	W	WL	LF	R+S+T	EQ	ICE	%	
SERVICE LOAD	I	1.0	1	1	0	1	β_E	1	1	0	0	0	0	0	0	100	
	IA	1.0	1	2	0	0	0	0	0	0	0	0	0	0	0	150	
	IB	1.0	1	0	1	1	β_E	1	1	0	0	0	0	0	0	**	
	II	1.0	1	0	0	0	1	1	1	1	0	0	0	0	0	125	
	III	1.0	1	1	0	1	β_E	1	1	0.3	1	1	0	0	0	125	
	IV	1.0	1	1	0	1	β_E	1	1	0	0	0	1	0	0	125	
	V	1.0	1	0	0	0	1	1	1	1	0	0	1	0	0	140	
	VI	1.0	1	1	0	1	β_E	1	1	0.3	1	1	1	0	0	140	
	VII	1.0	1	0	0	0	1	1	1	0	0	0	0	1	0	133	
	VIII	1.0	1	1	0	1	1	1	1	0	0	0	0	0	1	140	
	IX	1.0	1	0	0	0	1	1	1	1	0	0	0	0	1	150	
	X	1.0	1	1	0	0	β_E	0	0	0	0	0	0	0	0	100	Culvert
LOAD FACTOR DESIGN	I	1.3	β_D	1.67*	0	1.0	β_E	1	1	0	0	0	0	0	0	Not Applicable	
	IA	1.3	β_D	2.20	0	0	0	0	0	0	0	0	0	0	0		
	IB	1.3	β_D	0	0	1.0	β_E	1	1	0	0	0	0	0	0		
	II	1.3	β_D	0	0	0	β_E	1	1	1	0	0	0	0	0		
	III	1.3	β_D	1	0	1	β_E	1	1	0.3	1	1	0	0	0		
	IV	1.3	β_D	1	0	1	β_E	1	1	0	0	0	1	0	0		
	V	1.25	β_D	0	0	0	β_E	1	1	1	0	0	1	0	0		
	VI	1.25	β_D	1	0	1	β_E	1	1	0.3	1	1	1	0	0		
	VII	1.3	β_D	0	0	0	β_E	1	1	0	0	0	0	0	0		
	VIII	1.3	β_D	1	0	1	β_E	1	1	0	0	0	0	0	1		
	IX	1.20	β_D	0	0	0	β_E	1	1	1	0	0	0	0	1		
	X	1.30	1	1.67	0	0	β_E	0	0	0	0	0	0	0	0		Culvert

7.1.3 Shear Capacity by BRASS Culvert

Shear capacity was taken directly from the output file of BRASS Culvert for an HS20, as seen in Figure 6.1, and divided by the shear strength reduction factor of 0.85 to produce nominal shear capacities. This was done in order to allow a comparison to be made between BRASS Culvert's and the tested culverts' shear capacities. All equations that BRASS Culvert uses to calculate strength based shear capacity are mentioned in Section 3.3. For culverts under 2 feet of fill, BRASS Culvert uses the lesser of Equations 3.26 and Equation 3.20. For culverts with 2 feet

or more of fill, BRASS Culvert uses Equation 3.31 without the optional axial term to calculate shear capacity.

The following methods were used to create models when BRASS Culvert gave multiple options for an input. If corner bar reinforcement existed, moment continuity was assumed and vice-versa. Since the number of cells in the program did not go above 4, all culverts with more than 4 cells were analyzed as 4 cells. Also, culverts designed with LFD methods (before 1984) were analyzed with a horizontal dead load of 30 pcf. Culverts designed with LRFD methods (after 1984) were analyzed with a maximum horizontal dead load of 60 pcf and a minimum of 30 pcf. Lastly, the future wearing surface was added as a uniform load instead of letting the program automatically calculate it based on material densities and thickness. All other input came directly from the drawings for the TDOT Database culverts and from the papers for the Verification Database culverts.

	Moment Kft	Coin. Axial Force Kips	Shear Force Kips	Shear Cap Kips	Resistance Po Cap Kips	Mu Cap Kft	Mbal Cap Kft	Pbal Cap Kips	Steel Area In2	Mom. Cap Kft	Des. Thk in	Flexure Ratings Inv	Flexure Ratings Oper	Shear Ratings Inv	Shear Ratings Oper
Member No. = 2 TOP SLAB					Thickness = 18.00 (in)										
					Clear cover at end = 2.00 (in)										
					Clear cover at middle = 1.00 (in)										
					Bar diameter (lt) = 0.88 (in)										
					Bar diameter (mid) = 0.88 (in)										
					Bar diameter (rt) = 0.88 (in)										
LT	-21.6	2.7	12.7	26.1	438.2	84.1	101.1	112.7	1.3091	84.5	15.56	8.2	13.7	2.8	4.7
MID	49.2	2.7	3.4	27.8	438.2	90.0	106.5	123.5	1.3091	90.4	16.56	2.4	3.9	NA	NA
RT	-21.8	2.7	12.7	26.1	438.2	84.1	101.1	112.7	1.3091	84.5	15.56	8.2	13.6	2.6	4.4

Figure 7.1: Brass Culvert Partial Output

7.1.4 Shear Capacity by Response-2000

Each culvert's top slab was modeled in Response-2000 as a one foot cross section. Top slab forces used in Response-2000 from the TDOT Database were attained at the critical shear location through STAAD Pro with a load case consisting of the dead loads combined with a

downward 100 kip point load located at the same location. This type of loading was used to partially represent the original load case with the dead loads and to create a load case that would be most likely to cause shear failure. The load case used was able to determine shear capacities in a manner similar to the 10 tested culverts. Doing so allowed the use of the 40 TDOT Database culverts to further support the findings from the 10 Verification Database culverts. Since Response-2000 was not designed specifically for culverts, only the top slabs of the culverts were analyzed in STAAD Pro. The forces determined by STAAD Pro for dead loads and an HS20 were used to load the sections in Response-2000. The "Control: V-Gxy" graph from the "Sectional Response" analysis was used to attain shear capacity from Response-2000. In this graph, the y-axis is the maximum shear capacity calculated for a section.

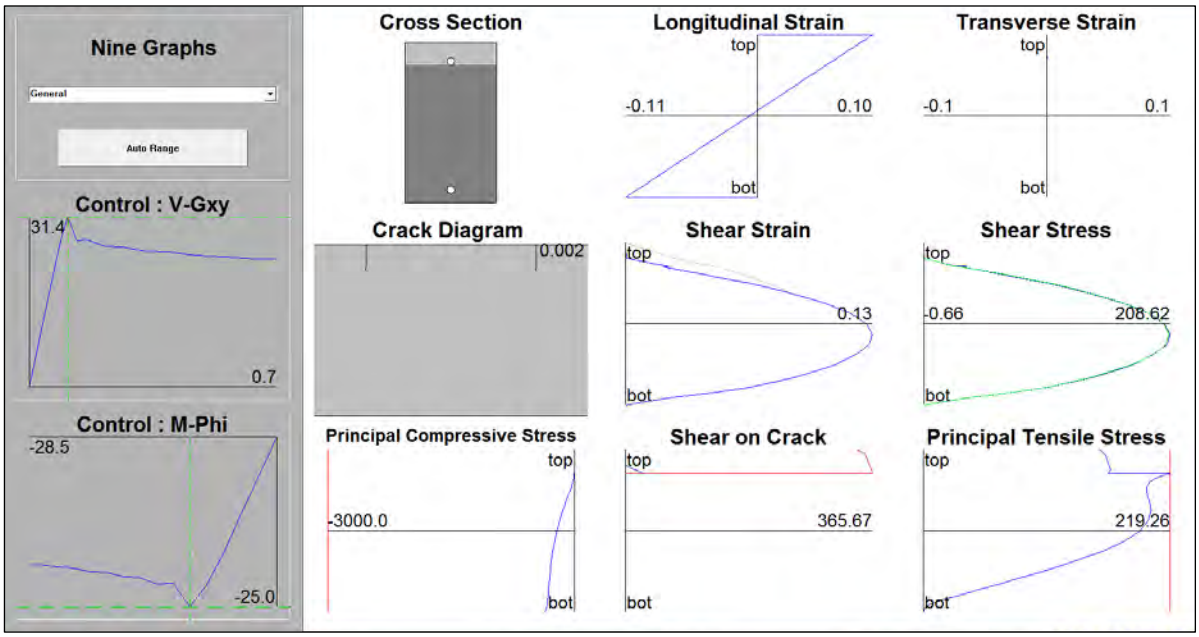


Figure 7.2: Response-2000 Sectional Response Output

7.2 Shear Capacity Results

This section contains the nominal shear capacities calculated for the Verification Database and the TDOT Database. The TDOT Database shear capacity results are broken up into box and slab type culverts. Figures 7.1 through 7.2 show the results of the nominal shear capacity comparison visually.

7.2.1 Verification Database

Table 7.5 is a reference table to link the Specifications' equations to the equations in this thesis. Specimens 1 through 4 come from the tests performed by Jarrod Burns [11]. Specimens 5 through 10 come from the tests performed by Abolmaali and Garg [5]. Figure 7.3 shows the visual results of the comparison, and Table 7.6 contains the numerical results of the comparison. The most important trend to note is the difference between the shear capacities from BRASS Culvert, and ones from Response-2000. On average, shear capacities from Response-2000 were approximately 1.25 times as great as those from BRASS Culvert. When comparing the shear capacities of BRASS Culvert to those of the test results, the test based shear capacities were more than 1.5 times as great on average. The same trend between Response-2000 and BRASS Culvert can be seen, to a lesser degree, with the TDOT Database in Sections 7.2.2 and 7.2.3. This trend is used to show that shear rating factors from BRASS Culvert can be overlooked.

In this analysis, Specimens 1 and 2 were evaluated at their load location, not their critical shear location. It is also important to remember that the forces used to calculate shear capacity for the culverts of the Verification Database are based on failure loads, not standard dead and live loads. This type of loading skews the differences in shear capacities between Specification equations, as opposed to what the differences would be if the culverts had been loaded with

standard dead and live loads. In particular, the shear capacities from AASHTO LRFD Equation 1 were all taken at their limit (ε_s = 0.003) due to the relatively large magnitude of the internal forces at failure. The differences in shear capacity from Specification equations are better represented with the TDOT Database culverts.

Most of the test specimens' actual (test results) shear capacity was the highest value out of all the methods used. The second highest shear capacity on average was computed by AASHTO LRFD Equation 2, which accounted for axial load by the addition of an optional factor to scale the equation by. On average, the third highest shear capacity was calculated by Response-2000. Response-2000 produced the second highest shear capacity for Specimens 9 and the highest shear capacity prediction for Specimen 10. In the case of Specimen 10, Response-2000 predicted a shear capacity higher than the actual shear capacity. This anomaly could be due to the specimens' load cases, as Specimens 9 and 10 were loaded away from the critical shear location by a factor of 1.5 and 2, respectively. Compared to the other culverts in the Verification Database, the axial forces from Response-2000 for Specimens 9 and 10 were larger, the flexural forces were smaller, and the shear forces were similar. Between the 10 culverts, the lowest calculated shear capacities came from AASHTO LRFD Equation 1, followed by BRASS Culvert.

Table 7.5: Various Equations for Shear Strength

Specification	Thesis	Results
LRFD Eq. (3.8.3.3-1 to 3)	Eq. 3.27	LRFD Eq. 1
LRFD Eq. (5.14.5.3-1)	Eq. 3.31	LRFD Eq. 2
ACI Eq. (11-5)	Eq. 3.20	ACI Eq. 1
ACI Eq. (11-6)	Eq. 3.22	ACI Eq. 2
LFD Eq. (8-50)	Eq. 3.24	LFD Eq. 1
LFD Eq. (8-51)	Eq. 3.26	LFD Eq. 2

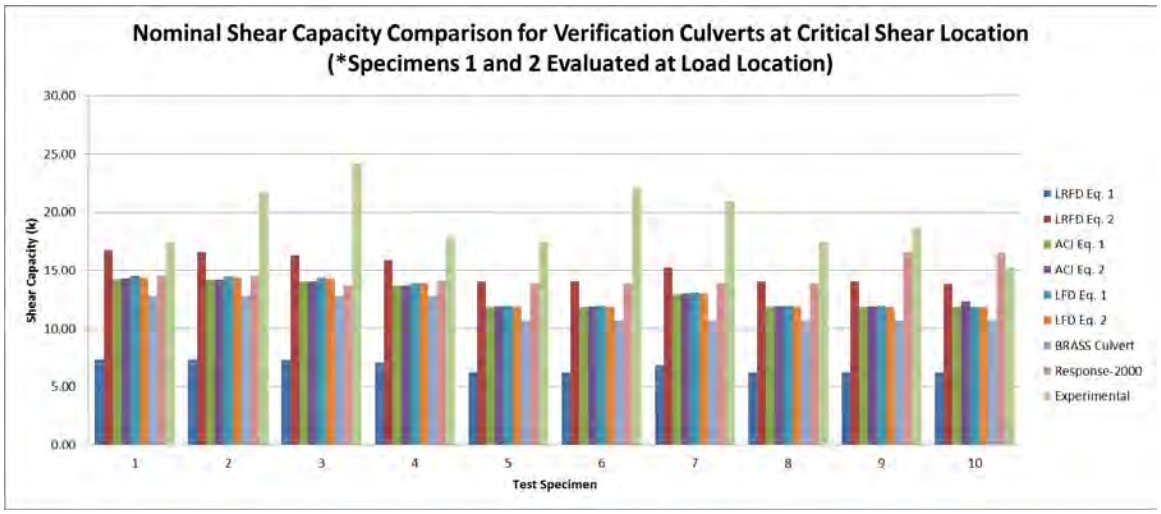


Figure 7.3: Verification Database- Nominal Shear Capacity Comparison

Table 7.6: Verification Database- Nominal Shear Capacities

No.	Model	Nominal Shear Capacities (k)								
		LRFD Eq 1	LRFD Eq 2	ACI Eq 1	ACI Eq 2	LFD Eq 1	LFD Eq 2	BRASS	R2000	Test
1	S-SB-444-WB-5	7.35	16.72	14.26	14.33	14.49	14.38	12.82	14.50	17.40
2	S-SB-444-NB-5	7.35	16.60	14.23	14.24	14.48	14.38	12.82	14.50	21.75
3	S-SB-444-NB-6.5	7.30	16.31	14.06	14.07	14.39	14.30	12.82	13.70	24.23
4	S-SB-444-NB-11.5	7.08	15.86	13.70	13.71	13.89	13.87	12.82	14.10	17.80
5	SP_2438-1219-1219_N_d	6.26	14.03	11.89	11.93	11.98	11.88	10.71	13.90	17.48
6	SP_2438-1219-1219_Y_d	6.26	14.03	11.89	11.93	12.00	11.88	10.71	13.90	22.13
7	BL_2438-1219-1219_N_d	6.86	15.27	12.96	13.00	13.14	13.01	10.71	13.90	20.95
8	BL_2438-1219-1219_Y_d	6.26	14.03	11.89	11.93	11.98	11.88	10.71	13.90	17.48
9	SP_2438-1219-1219_Y_1.5d	6.26	14.03	11.89	11.93	11.98	11.88	10.71	16.60	18.65
10	SP_2438-1219-1219_Y_2d	6.26	13.83	11.89	12.34	11.89	11.88	10.71	16.60	15.28

7.2.2 TDOT Database of Box Culverts

As with the Verification Database, Table 7.5 links the equations used to their references. Figure 7.4 shows the comparison bar graph of the nominal shear capacities for the box culverts of the TDOT Database, and Table 7.7 contains the same shear capacities as values. Like the results from the Verification Database, the most important trend is the one between the shear capacities from BRASS Culvert and those from Response-2000. For the box culverts of the TDOT Database,

the shear capacities were higher for Response-2000 on average. In Figure 7.4, BRASS Culvert produced marginally greater shear capacities than Response-2000 in Specimens 1, 9, 17, 19, and 20. As seen in Equation 3.1, the shear rating factor equation is divided by zero for cases of no live load shear force. So, Specimens 1 and 9 will not be seen in the rating factor comparison for box culverts because the live loads were assumed to be 0 as per AASHTO LRFD Section (3.6.1.2.6) [1]. The shear rating factor comparison of Section 7.4 demonstrates that the three cases of BRASS Culvert producing higher shear capacities in Specimens 17, 19, and 20 can be considered inconsequential overall. Section 7.4 also shows how the resultant shear rating factors of the TDOT Database culverts were used to conclude in part that shear rating factors produced by BRASS Culvert can be overlooked.

The magnitude of shear capacity between the 20 specimens was less important as some models were designed for higher shear loads. The trends to consider were those that were seen among the specimens individually. It was also worth noting trends seen among specimens individually that tended to be true for the 20 culverts as a whole. These trends are explained in the following paragraph.

Unlike the Verification Database, the box culverts of the TDOT Database produced reasonable shear capacities for AASHTO LRFD Equation 1. Since the TDOT Database used forces for the Specification equations produced by standard dead and live loads, the shear capacities produced by AASHTO LRFD Equation 1 are not skewed. This allowed AASHTO LRFD Equation 1 to be the second or third highest shear capacity on average, tied with ACI Equation 2. AASHTO LRFD Equation 2 produced the largest shear capacities for a majority of the Specimen. One thing in common between these three top shear capacities is that each equation considers axial force in addition to shear and bending forces. For the box culverts, AASHTO LFD

Equations 1 and 2, ACI Equation 1, and BRASS Culvert produced the lowest shear capacities of the group. The fact that BRASS Culvert produced some of the lower shear rating factors is explained by the fact that it can use ACI Equation 1, AASHTO LRFD Equation 2 without the axial term applied, or AASHTO LFD Equation 2. This means that axial forces are not being considered to contribute to shear capacity in BRASS Culvert's computations. Response-2000 produced values in between all other shear capacities on average.

Table 7.7: TDOT Database of Box Culverts- Nominal Shear Capacities

No.	Model	Nominal Shear Capacities (k)							
		LRFD Eq 1	LRFD Eq 2	ACI Eq 1	ACI Eq 2	LFD Eq 1	LFD Eq 2	BRASS	R2000
1	C-4-141	29.81	38.69	27.65	39.63	23.57	23.40	34.12	33.3
2	D-0-225	11.21	14.67	11.38	11.45	10.53	10.50	13.18	13.5
3	D-0-294	19.58	20.74	15.85	15.97	15.05	15.00	14.24	16.7
4	D-4-283	14.47	18.38	13.61	13.98	12.08	12.00	11.53	16.4
5	G-10-86	18.29	19.40	13.45	21.33	11.92	11.83	14.12	16.4
6	G-10-120	21.93	23.49	15.52	25.12	13.94	13.80	16.47	16.8
7	H-5-116	21.99	24.19	14.90	24.52	13.34	13.15	15.76	17.3
8	H-5-117	19.18	23.00	14.90	24.22	13.32	13.15	15.76	17.5
9	H-5-150	22.68	24.70	17.36	20.83	14.51	14.46	20.71	19.9
10	K-15-144	21.23	27.86	17.36	20.18	14.68	14.46	17.06	19.2
11	K-38-14	16.35	22.06	13.65	20.00	12.04	11.83	14.00	16.2
12	K-38-21	20.64	21.66	14.87	22.49	12.58	12.49	14.94	17.5
13	K-38-128	10.72	14.60	10.95	11.11	9.24	9.20	8.71	12.8
14	M-1-47	31.39	32.89	24.51	36.90	22.46	22.35	27.88	28.5
15	M-1-62	31.54	38.04	24.24	26.94	22.59	22.35	26.59	27.8
16	M-1-72	32.56	32.58	24.51	30.77	22.42	22.35	27.88	28.4
17	M-1-91	40.37	40.11	29.56	30.34	26.38	26.29	34.35	29.6
18	M-1-109	16.91	21.83	15.12	15.70	13.95	13.80	15.41	17.8
19	M-1-142	28.80	35.37	24.17	24.85	22.56	22.35	30.71	26.8
20	M-1-144	37.50	40.44	28.90	31.05	26.43	26.29	36.47	31.3

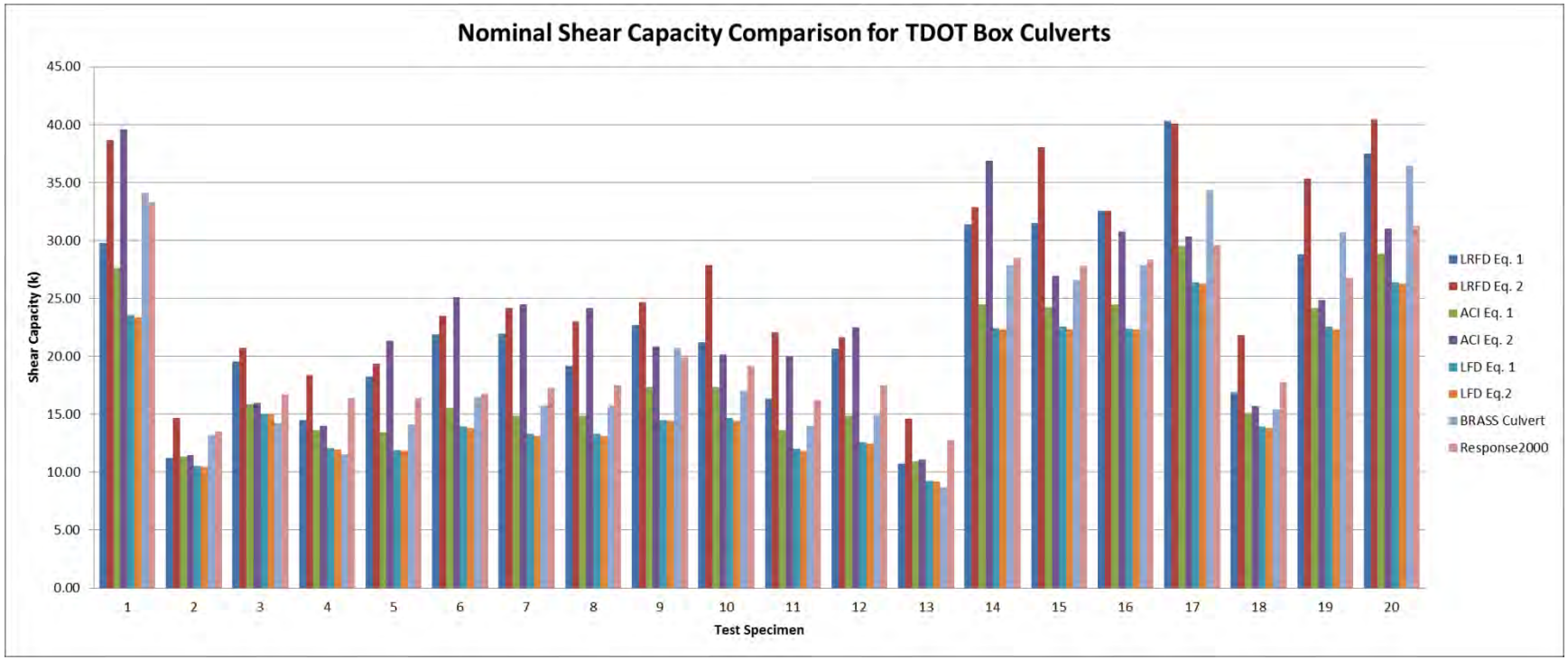


Figure 7.4: TDOT Database of Box Culverts- Nominal Shear Capacity Comparison

7.2.3 TDOT Database of Slab Culverts

The results of the TDOT Database for slab culverts were very similar to those of box culverts. Table 7.5 contains the guide to the equation references used in the result figure for slab culverts. Figure 7.5 contains a bar graph comparison of the nominal shear capacities for the 20 slab culverts of the TDOT Database, and Table 7.8 contains the nominal shear capacity values. The shear capacities computed with Response-2000 were larger than capacities by BRASS Culvert on average. Specimens 9, 10, 16, 18, and 19 produced higher shear capacities by BRASS Culvert. As with the box culverts, Specimens 9 and 10 of the slab culverts will not appear in the shear rating factor comparison of Section 7.4 due to their live loads being considered to be 0.

It is important that Response-2000 compute the larger shear capacities as the program is based on the Modified Compression Field Theory, which also incorporates contributions to shear capacity from axial compression. Since BRASS Culvert does not account for axial compression or use the Modified Compression Field Theory when calculating shear capacity, it should produce lower capacities than Response-2000 based on the findings in this thesis. Again, the fact that Specimens 16, 18, and 19 had higher shear capacities predicted by BRASS Culvert when compared to Response-2000 is shown to be insignificant overall with the shear rating factor results in Section 7.4.

Like the box culverts of the TDOT Database, the slab culverts produced larger shear capacities for AASHTO LRFD Equation 2 and ACI Equation 2 on average, followed by AASHTO LRFD Equation 1 and Response-2000. Generally, the lowest shear capacities came from AASHTO LFD Equations 1 and 2, BRASS Culvert, and ACI Equation 1. These results were expected as equations and programs that considered axial load's contribution to shear strength produced the highest values. It was also interesting to note that, of the higher results, the equation

and program (LRFD Eq. 1 and Response-2000, respectively) that used the Modified Compression Field Theory did not produce the highest shear capacities of the examined methods.

Table 7.8: TDOT Database of Slab Culverts- Nominal Shear Capacities

No.	Model	Nominal Shear Capacities (k)							
		LRFD Eq 1	LRFD Eq 2	ACI Eq 1	ACI Eq 2	LFD Eq 1	LFD Eq 2	BRASS	R2000
1	A-6-98	13.64	17.60	12.75	14.08	11.25	11.10	10.71	15
2	D-0-62	10.27	13.65	10.78	10.82	9.92	9.90	11.65	13
3	E-4-103	18.60	23.00	16.12	19.98	13.99	13.80	12.71	17.4
4	F-10-93	20.30	22.16	14.38	23.00	12.79	12.60	14.59	15.2
5	G-5-61	19.83	22.38	14.38	23.05	12.77	12.60	14.71	14.8
6	H-5-53	16.38	21.55	13.45	19.05	12.04	11.83	13.65	14.3
7	H-5-118A	19.02	21.74	13.63	23.40	12.73	12.49	14.35	14.9
8	H-5-119	20.48	23.67	14.90	24.42	13.39	13.15	15.76	17.5
9	H-5-151	19.36	22.65	14.01	22.26	12.17	11.83	16.94	16.6
10	H-5-151A	27.83	50.37	29.95	41.80	27.99	26.29	37.29	36.7
11	K-15-24	13.67	16.73	12.46	13.33	11.31	11.17	10.71	14.7
12	K-15-34	18.62	21.24	13.65	21.83	12.04	11.83	13.29	15.1
13	K-62-1	19.45	29.14	17.99	20.04	16.10	15.77	17.88	20
14	M-1-47	35.36	38.27	24.51	41.33	22.85	22.35	25.18	27.3
15	M-1-72	36.95	39.85	24.51	41.19	22.82	22.35	26.82	27.7
16	M-1-91	41.27	42.43	29.56	31.98	26.47	26.29	34.47	29.6
17	M-1-109	17.64	24.97	15.74	18.93	14.74	14.46	14.82	18.1
18	M-1-142	30.85	35.96	24.51	26.93	22.59	22.35	30.71	26.8
19	M-1-144	39.47	42.29	28.90	35.88	26.51	26.29	36.47	31.3
20	M-82-142	23.53	29.98	19.01	28.41	17.39	17.09	19.41	20.4

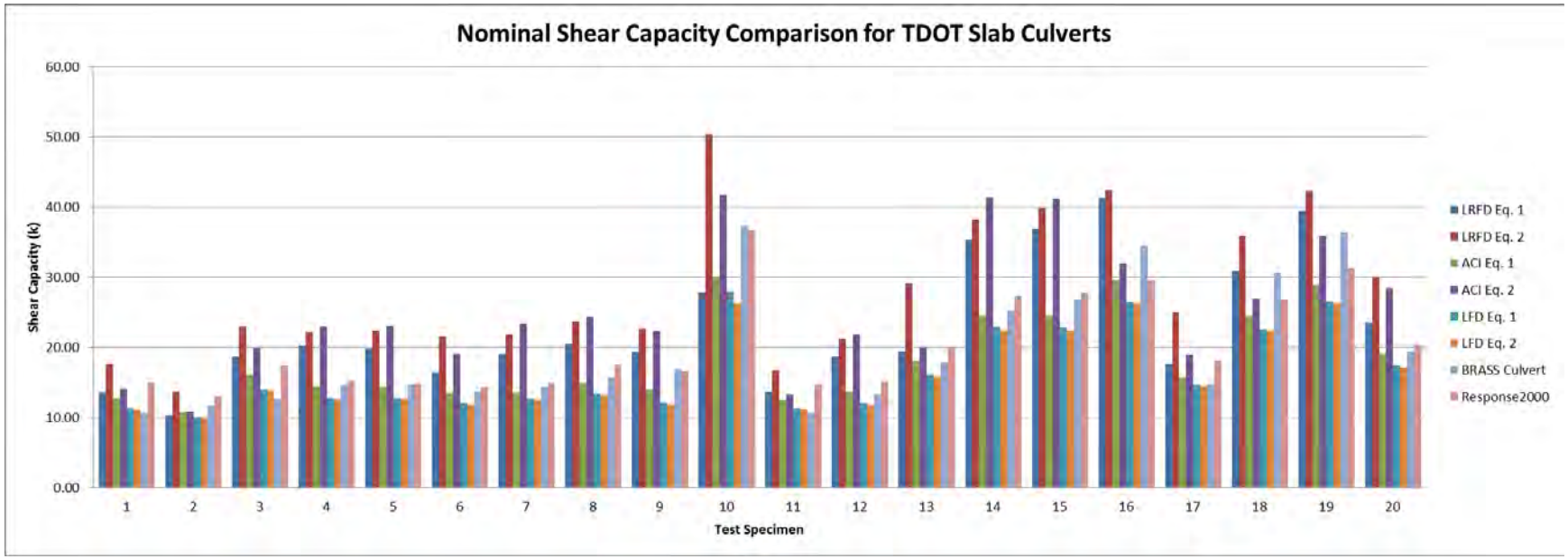


Figure 7.5: TDOT Database of Slab Culverts- Nominal Shear Capacity Comparison

7.3 Shear Rating Factor Analysis

A comparison was performed to test the impact that changing shear capacity had on shear rating factors. Specifically, this was accomplished by comparing the shear rating factors from BRASS Culvert to those from Response-2000 for the TDOT Database culverts. The culverts from the Verification Database were not used in the shear rating factor analysis as their loads were those present at failure. Since the dead loads of the Verification Database were essentially 0, and the shear live loads were equal to the shear capacity, the shear rating factors should theoretically all be less than 1. The goal of this analysis was to see an improvement in shear rating factors when using shear capacities from Response-2000, which is based on the Modified Compression Field Theory, compared to shear rating factors based on results from BRASS Culvert.

Shear rating factors were calculated with Equation 3.1 at the operating rating level as specified in Section 3.1.2 for appropriate dead loads and an HS20 with (1+IM) already factored in to the live load. A shear strength reduction factor of 0.85 was applied to the nominal shear capacities of Response-2000 before being used in the shear rating factor equation. Since the shear capacities from BRASS Culvert were already factored in the output file, they were used in the rating factor equation as produced by BRASS Culvert.

7.4 Shear Rating Factor Results

Once the shear capacities were calculated, Equation 3.1 was used to calculate shear rating factors for the BRASS Culvert and Response-2000 shear capacities of the TDOT Database. The rating factor comparisons are broken up into box and slab type culverts.

Figures 7.6 and 7.7 show the results of the shear rating factor comparison between BRASS Culvert and Response-2000.

7.4.1 Box Culverts

Figure 7.6 contains the rating factor comparison results of the TDOT Database box culverts in the form of a graph, and Table 7.9 contains the same rating factors as values. The values of "NA" in Table 7.9 are for cases where live load shear forces were equal to 0, or assumed to be so based on AASHTO LRFD Specifications [1]. The line "y = x" in Figure 7.6 shows where values from Response-2000 and BRASS Culvert are equal. Values above the line indicate that Response-2000 produced a higher shear rating factor for that model, and values below the line represent models that produced a higher shear rating factor from BRASS Culvert. The further a value is away from the line, the greater the difference in the shear rating factor for that model.

In Figure 7.6, the data generally lies above the line. This means that Response-2000 produced greater rating factors overall when compared to BRASS Culvert as can be expected based on similar trends from the shear capacity analysis. Shear rating factors that were less than 1 (unsatisfactory) from BRASS Culvert were always greater than 1 for Response-2000 for all culverts in the TDOT Database. Out of the twenty box culverts in the TDOT Database, BRASS Culvert only had higher shear rating factors for three models. On average for the cases, the difference in shear rating factors from the two programs was less than 20%, and the rating factors in all three cases were greater than 1 for both programs. The rest of the points on the graph clearly indicate that Response-2000 produced higher shear rating factors than BRASS Culvert, even having satisfactory rating factors

where BRASS Culvert did not. Considering the differences in shear capacity between Response-2000 and BRASS Culvert, even relatively small differences in shear capacity can lead to noticeable increases in shear rating factors.

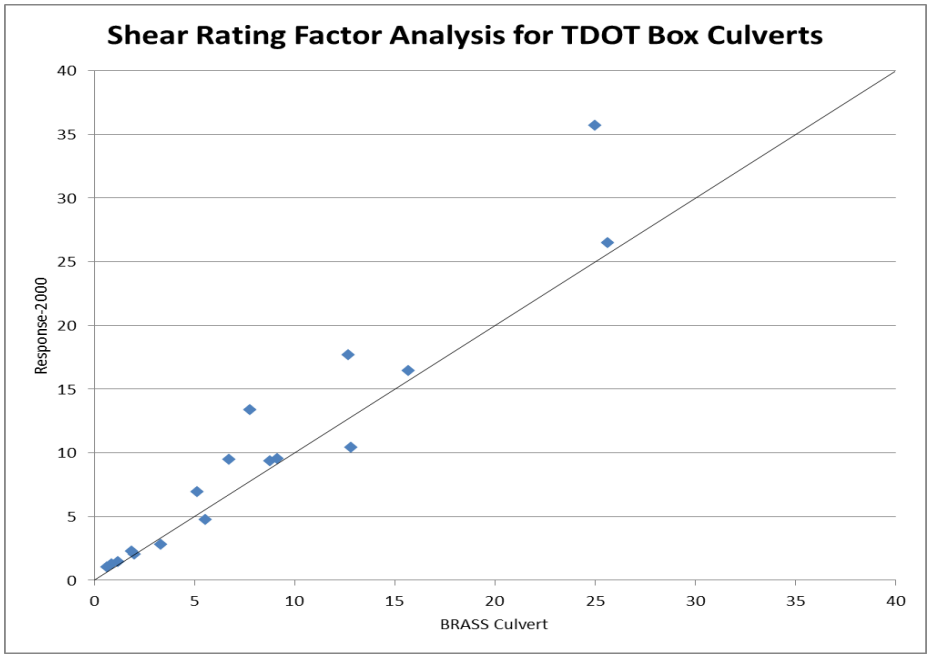


Figure 7.6: Box Culvert Shear Rating Factor Comparison

7.4.2 Slab Culverts

The slab culverts of the TDOT Database produced results similar to the box culverts. Figure 7.7 is the comparison graph of slab culverts between shear rating factors from BRASS Culvert and Response-2000. Table 7.10 contains the shear rating factor values from the comparison. Like the box culverts, values of "NA" in Table 7.10 indicate that the live load was 0, and the comparison graph in Figure 7.7 is set up in the same manner as Figure 7.6. Figure 7.7 has a general trend of shear rating factors being greater for

Response-2000. As with Figure 7.6, there were a few cases where the shear rating factors were below 1 for BRASS Culvert but not Response-2000.

Table 7.9: Box Culvert Shear Rating Factors

No.	Model	BRASS Culvert Shear RFs	R2000 Shear RFs
1	C-4-141	NA	NA
2	D-0-225	2.00	2.06
3	D-0-294	1.19	1.41
4	D-4-283	0.86	1.26
5	G-10-86	12.68	17.67
6	G-10-120	9.14	9.50
7	H-5-116	NA	NA
8	H-5-117	24.98	35.68
9	H-5-150	NA	NA
10	K-15-144	5.14	6.91
11	K-38-14	7.81	13.38
12	K-38-21	6.74	9.47
13	K-38-128	0.64	1.02
14	M-1-47	15.67	16.47
15	M-1-62	8.78	9.34
16	M-1-72	25.65	26.49
17	M-1-91	5.57	4.73
18	M-1-109	1.89	2.26
19	M-1-142	3.35	2.82
20	M-1-144	12.82	10.42

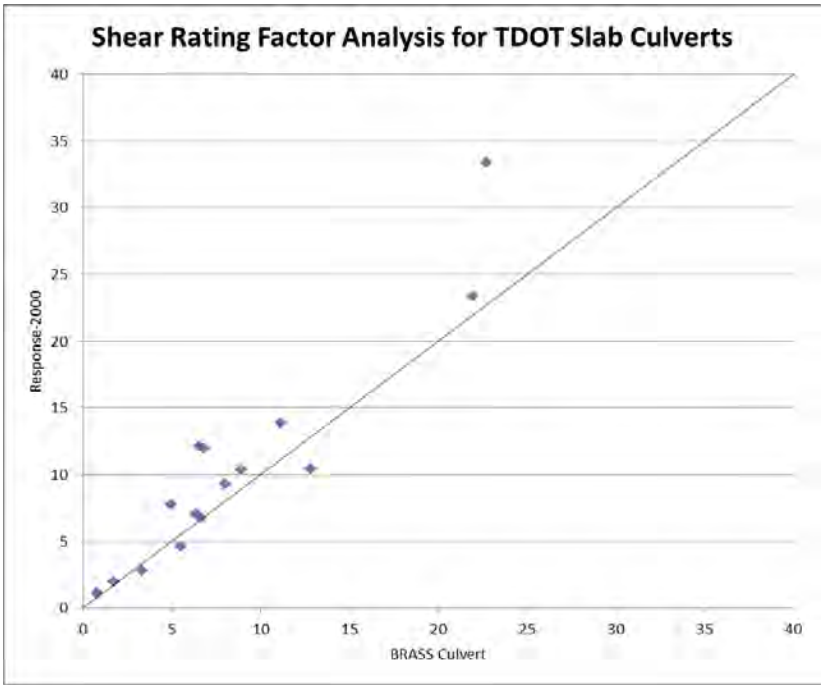


Figure 7.7: Slab Culvert Shear Rating Factor Comparison

Table 7.10: Slab Culvert Shear Rating Factors

No.	Method	BRASS Culvert Shear RFs	R2000 Shear RFs
1	A-6-98	0.77	1.10
2	D-0-62	1.75	1.99
3	E-4-103	0.80	1.15
4	F-10-93	6.39	7.06
5	G-5-61	6.64	6.74
6	H-5-53	8.91	10.33
7	H-5-118A	NA	NA
8	H-5-119	22.71	33.42
9	H-5-151	NA	NA
10	H-5-151A	NA	NA
11	K-15-24	0.80	1.12
12	K-15-34	6.82	11.98
13	K-62-1	4.98	7.79
14	M-1-47	11.17	13.86
15	M-1-72	21.97	23.34
16	M-1-91	5.51	4.65
17	M-1-109	6.58	12.14
18	M-1-142	3.35	2.82
19	M-1-144	12.83	10.43
20	M-82-142	8.01	9.32

7.5 Shear Analysis Summary

The shear analysis was comprised of the shear capacity comparison between Specification equations as well as programs and the shear rating factor comparison between BRASS Culvert and Response-2000. In the shear capacity comparison, it was determined that Equations 3.22 and 3.31 produced the highest shear capacities on average between the 6 equations used. Also, it was noted that BRASS Culvert produced lower shear capacities on average when compared to Response-2000. For the shear rating factor comparison, BRASS Culvert produced lower shear rating factors on average when compared to Response-2000. In this comparison, all shear rating factors for the culverts analyzed that were less than 1 for BRASS Culvert were greater than 1 for Response-2000. The data indicates that BRASS Culvert conservatively estimates shear capacities on average,

resulting in lower shear rating factors. It was also noted that small increases in shear capacity could cause shear rating factors to improve from being unsatisfactory (less than 1) to having values greater than 1.

CHAPTER 8

MOMENT CONTINUITY ANALYSIS

The moment continuity analysis involved changing the moment continuity of the connections of the top and bottom of the exterior walls with the slabs for culverts that did not have negative moment reinforcement for these regions. Since these connections have zero negative moment reinforcement to resist the negative moment being applied, the connection should not have full continuity but should have zero continuity.

8.1 Background

The continuity of both the top and bottom of the exterior walls were changed. Rating factors from culverts with full continuity at the exterior walls were compared to the rating factors from culverts with zero continuity at the exterior walls. While the continuity of the exterior wall connections with the slabs was changed, all the other connections of the culvert remained at full continuity.

The LFR method was used to calculate the rating factors for this task. This method was used because it is the rating method that TDOT uses to rate their existing culverts. In the capacity calculation of a member, the strength of the reinforcement and concrete is not always known. The positive and negative capacities were taken for each section of the culvert members. This was done since changing the moment continuity might change the controlling moment from either negative to positive or positive to negative. If a particular section did not have reinforcement, the cracking moment of the section was used to calculate the moment capacity. For example, this was done for the negative moment

capacities of the top and bottom of the exterior walls and the left side and middle of the top and bottom slabs.

This task was accomplished by using STAAD's ability to set the moment continuity at connections from full to zero. Once the loads were calculated from this sheet, they were manually transferred to STAAD and applied to the culvert. STAAD's regular load definition was used to represent the static loads; the dead and surcharge loads. STAAD's load generation was used to represent the HS20 truck moving across the top slab of the culverts. Only the HS20 truck was used to calculate the rating factors for the culverts. Two load generations were used for each culvert in this analysis. The first was used to represent the truck moving from left to right across the culvert and the second was used to represent the truck moving from right to left across the culvert. This was done in order to determine the worst case positive and negative moment being applied by the live load vehicle.

The rating factors for the interior walls of the culverts with more than one cell were not analyzed. This was done because interior walls typically have high rating factors and therefore are not considered to be a critical member when rating the culvert. The only sections and members rated in this analysis were the top and bottom of the exterior walls, the left, middle, and right sides of the outside top and bottom slabs.

8.2 Rating Factor Results

Only the operating rating factors are shown for the results of the moment continuity task. This was done since the trends of the inventory and operating rating factors were the

exactly the same. The only difference between the rating types was that the inventory rating factors had lower values than the operating rating factors.

Furthermore, only the two cell culverts are shown in this chapter for the moment continuity task. This was done because all the cell types showed the same trends for each member of the culverts when the continuity was changed. The two cells were chosen to be shown in this chapter because the two cells had the largest amount of culverts which assisted in showing the trends of the rating factors.

Only the top and bottom of the exterior wall and the right side of the top and bottom slabs are shown for the results of the load and load factor comparison tasks. This was done since the trends for the left side of the top slab were the same as the ones for the top of the exterior wall, and the trends for the left side of the bottom slab were the same as the ones for the bottom of the exterior wall. Also the trends for the middle of the slabs were the same as the ones for the right side of the slabs.

Figures 8.1 and 8.2 are the operating rating factors for the top and bottom of the exterior wall for the two cell culverts. Figure 8.1 shows the rating factors for the top of the exterior wall for the culverts evaluated at zero and five feet of fill. Figure 8.2 shows the rating factors for the right side of the top slab for the culverts evaluated at zero and five feet of fill. Only the top of the exterior wall and the right side of the top slab are shown because the other culvert members follow their trends. The bottom of the exterior wall had the same trends as the top of the exterior wall. The middle of the top slab and the middle and right side of the bottom slab had the same trends as the right side of the bottom slab.

These graphs show different types of data points for each fill depth and continuity type that was analyzed. Each scatter plot graph has a bold and black horizontal line

extending through the plot area. This line is referred to as the reference line and represents the line at which a rating factor has a value of one. For example, if a data point is above the reference line, the rating factor is greater than one, and if a data point is below the reference line, the rating factor is less than one. In the figures, blue diamonds represent rating factors for culverts analyzed at full continuity with zero feet of fill, red diamonds represent rating factors for culverts analyzed at full continuity with five feet of fill, orange circles represent rating factors for culverts analyzed at zero continuity with zero feet of fill, and light blue circles represent rating factors for culverts analyzed at zero continuity with five feet of fill. Overall, the diamond data points represent rating factors for culverts analyzed as having full moment continuity at the exterior wall connections, and the circle data points represent the rating factors for culverts analyzed as having zero moment continuity at the exterior wall connections.

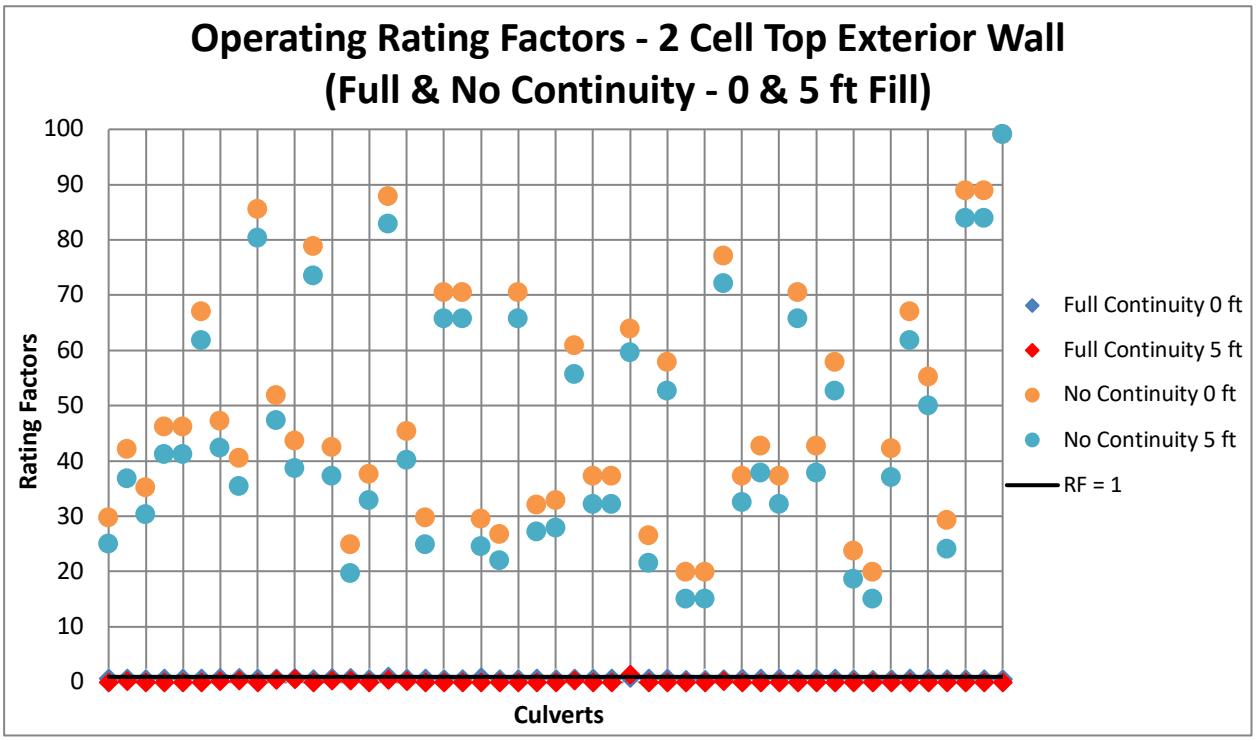


Figure 8.1: Top Exterior Wall Rating Factors – Zero & Five Feet Fill

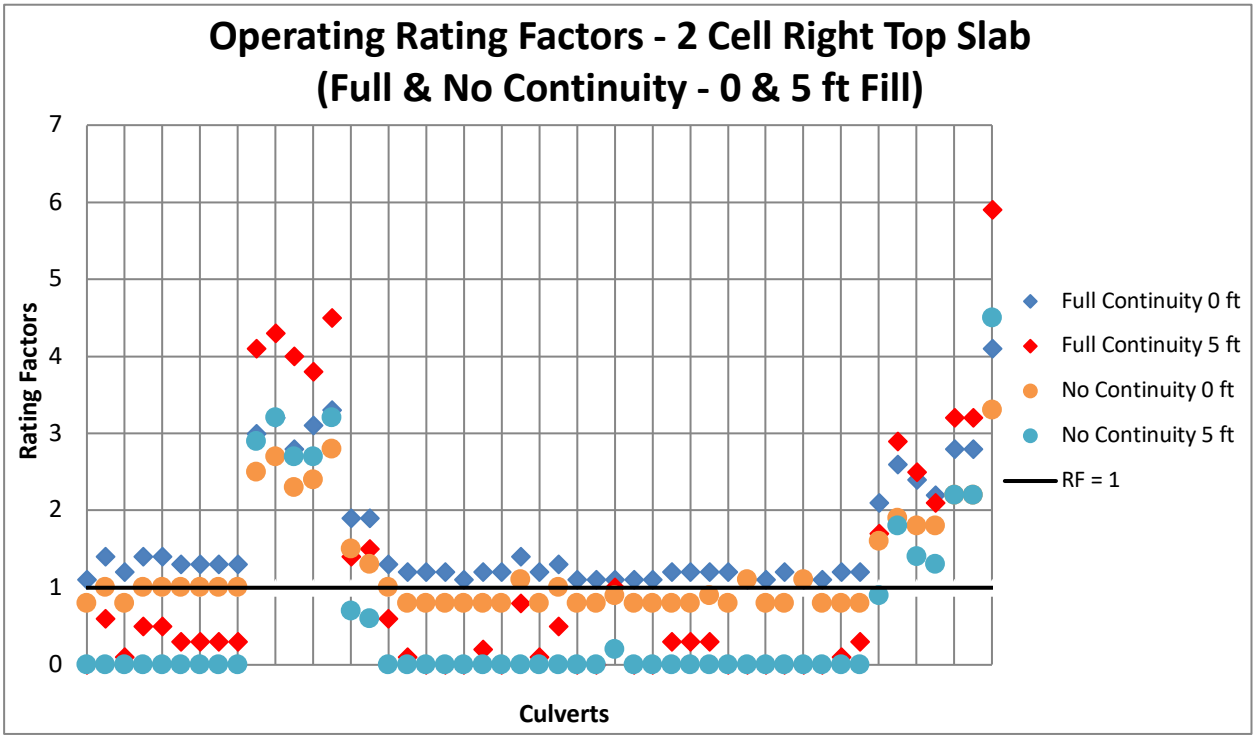


Figure 8.2: Right Top Slab Rating Factors – Zero & Five Feet Fill

From the figures, it can be seen that all the culvert rating factors for the top of the exterior wall at zero and five feet of fill increased in value when the culverts were modeled as having zero moment continuity. The opposite is true for the right side of the top slab. From this, it was determined that modeling culverts as having zero moment continuity at the exterior wall connections always improves the rating factors for the top and bottom of the exterior wall and the left side of the slabs, and reduces the rating factors for the middle and right side of the slabs.

The rating factors for the exterior wall and the left side of the slabs increased because the positive moment controlled over the negative moment. Since these sections had zero negative moment reinforcement, the rating factors were very low, mainly below than one, when the negative moment controlled. The negative moment only controlled

when the culverts were modeled as having full continuity. When the culverts were modeled as having zero continuity, the positive moment was larger than the negative moment, thus the positive moment controlled. The rating factors were higher when the positive moment controlled because these sections had positive moment reinforcement. Due to this, the rating factors were higher because the positive moment capacities were larger than the negative moment capacities.

The rating factors for the middle and right side of the slabs decreased because the positive moments acting on these sections increased due to there being zero negative moment acting at the connections of the slabs with the exterior wall. Thus, the moment that was previously acting at these connections was distributed to the other sections of the slabs. This process is shown in Figures 8.3 and 8.4. Figure 8.3 shows the moment graph for the top slab of a two cell culvert that was modeled as having full moment continuity at the exterior wall connections. Figure 8.4 shows the moment graph for the top slab of the same culvert being modeled as having zero moment continuity at the exterior wall connections. In both of these figures, the left side of the graphs represent the connection point of the top slab with the exterior wall, and the right side of the graphs represents the connection point of the top slab with the interior wall. From the figures, it can be seen that having zero negative moment at the connections of the slabs with the exterior wall increases the moments acting on the middle and the right side of the slabs, thus lowering the rating factors for the middle and right side of the top and bottom slabs.

There were patterns for the rating factors of right side of the slabs. The following figure, Figure 8.5, distinguishes these patterns by circling each rating factor cluster. Only the rating factors for the zero foot fill depth culverts are shown in this figure to help display

and explain the trend. The purple cluster represents the A type culvert models, the red cluster represents the B type culvert models, the green cluster represents the C type culvert models, the black cluster

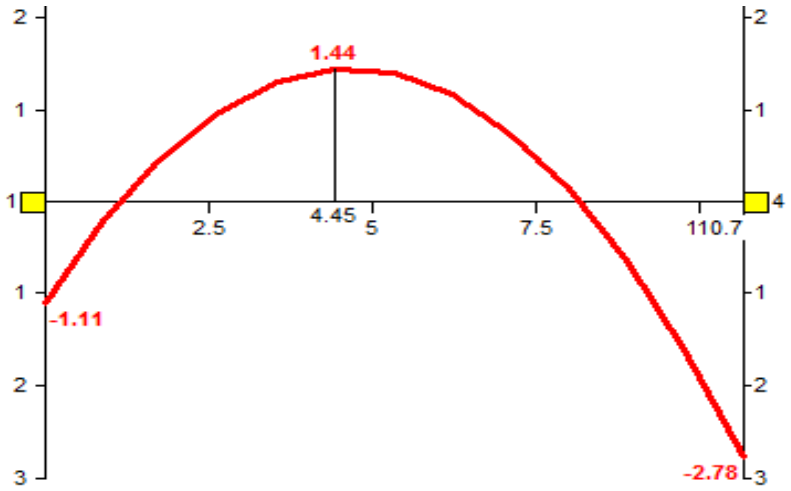


Figure 8.3: Top Slab Moments from Modeling with Full Continuity

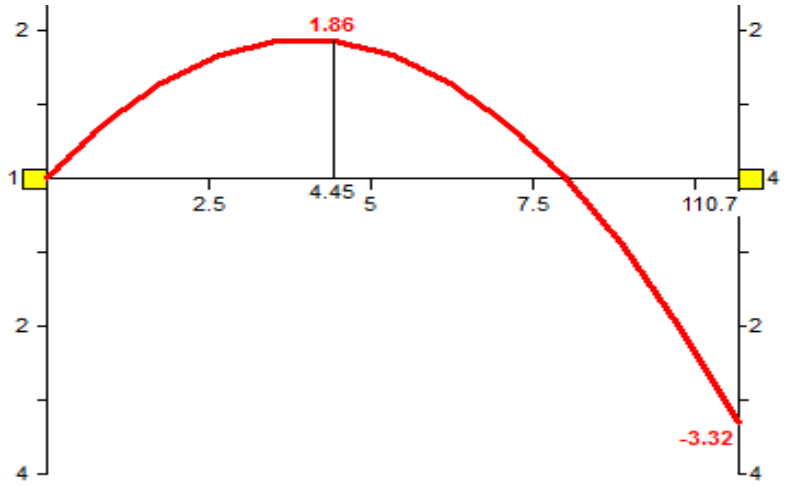


Figure 8.4: Top Slab Moments from Modeling with Zero Continuity

represents the D type culvert models, and the blue cluster represents the E, F, G, and H type culvert models. From these five clusters, two types of rating factor groups can be

recognized based on their rating factor value. The first group has their rating factor values below one. This group consists of the A and D type culvert models. The second group has their rating factor values above one. This group consists of the B, C, E, F, G, and H type culvert models. The rating factors for the second group were higher than the first group mainly because the second group had an extra negative moment reinforcement bar in the slabs at the interior wall connections. This extra reinforcement provided larger capacities for these culverts which resulted in higher rating factors.

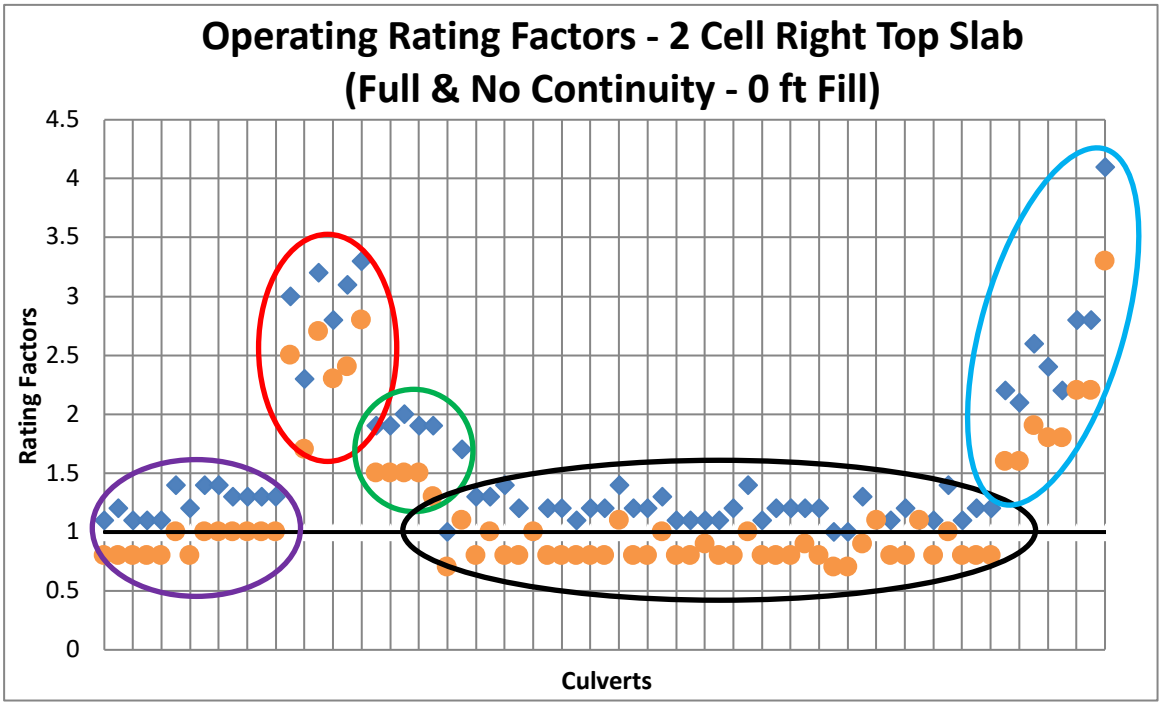


Figure 8.5: Distinguished Rating Factor Patterns – Right Top & Bottom Slabs

An example of a B type TDOT culvert drawing is shown in Figure 8.6, and an example of a D type TDOT culvert drawing is shown Figure 8.7. In Figure 8.6, the extra negative reinforcement for the slabs are the hooked bars encompassed by green ovals. It

can be seen in Figure 8.7 that these bars are nonexistent. The lack of these bars in Figure 8.8 is shown by red ovals.

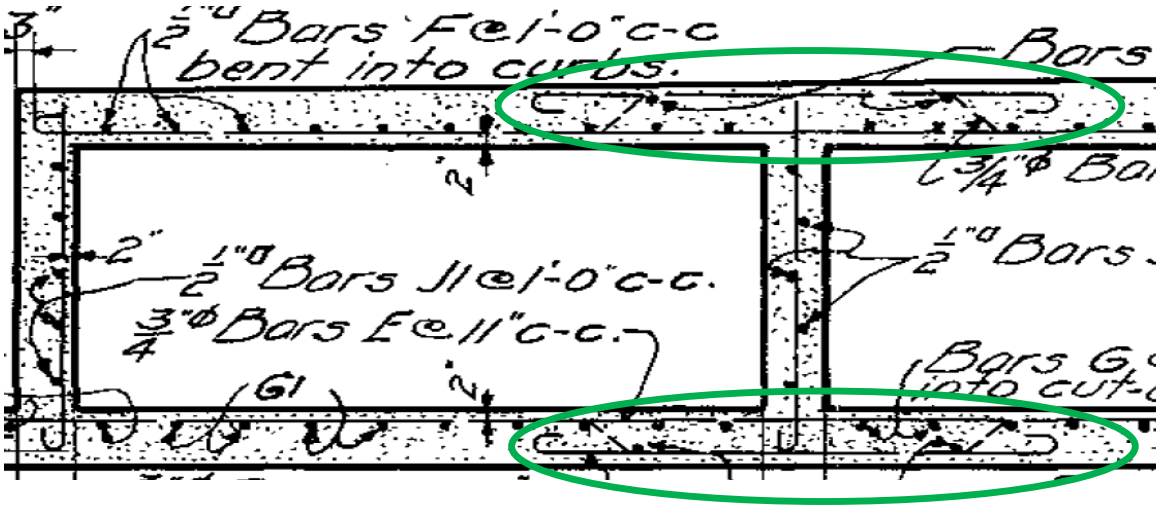


Figure 8.6: Extra Negative Reinforcement Added at Interior Wall Connections

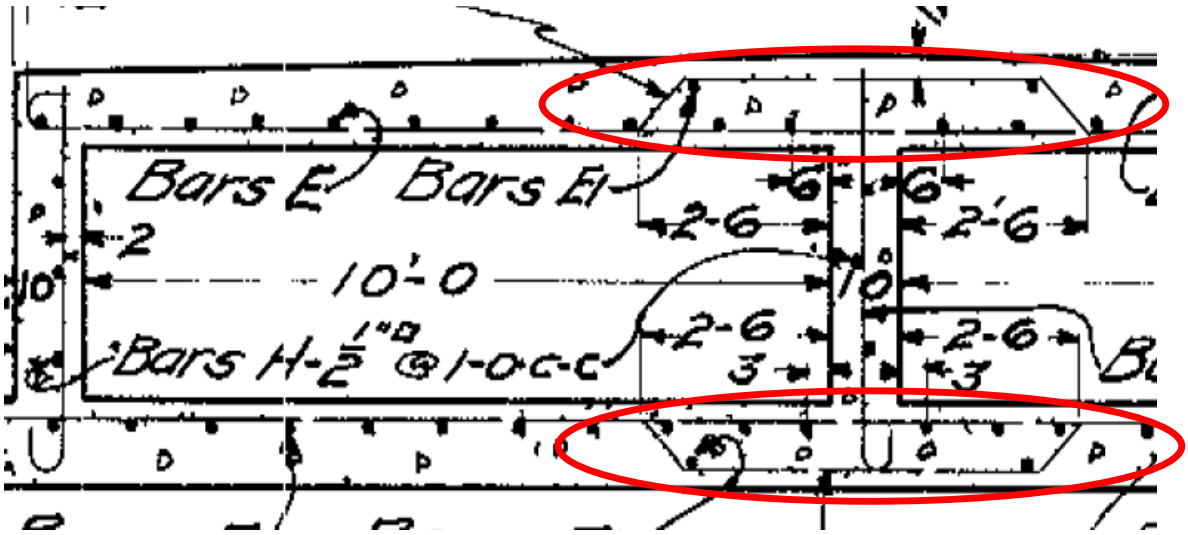


Figure 8.7: No Extra Negative Reinforcement at Interior Wall Connections

8.3 Summary

It was determined that modeling culverts as having zero moment continuity at the exterior wall connections drastically improves the rating factors for the top and bottom of the exterior wall and the left side of the top and bottom slabs. However, this modeling technique slightly reduces the rating factors for the middle and right side of the top and bottom slabs. This reduction was small when compared to the increase in value for the exterior wall and the left side of the slabs.

CHAPTER 9

RATING AIDS

A set of "Rating Aids," one for box culverts and one for slab, was created for TDOT to facilitate the rating process of reinforced concrete culverts in Tennessee. The Rating Aids are a pair of Excel files that contain sets of rating factors for all (over 800) of TDOT's standard drawings of culverts. The rating factors were determined with the culvert analysis program, BRASS Culvert, as described in Section 4.3.2 for the conditions and properties specified in the standard drawings. From the conception of the TDOT Rating Aids, to where they stand now, multiple graduate students have made their contributions. These contributions include sorting through TDOT's standard drawings to pick out culverts, general formatting of the rating factor pages, compiling and updating the rating factors, and creating and developing the way that the culvert drawings are searched for within the TDOT Rating Aids. This chapter covers the development of the TDOT Rating Aids, the creation of the "Search Page," and how the Rating Aids are to be used currently.

9.1 Development of the TDOT Rating Aids

Tennessee Tech graduate alumni, Caleb Jones, Michael Bednarcyk, and Kyle Zhang, laid the ground work for the TDOT Rating Aids. Through their efforts, pages were created to store the rating factors in an orderly manner. Also, a page of hyperlinks was developed to allow a method of searching for various drawings based on clear width by clear height and design year. The initial rating factors were stored in the Rating Aids, and a collection of BRASS Culvert files for every rated culvert was formed. The culvert

selection page for one cell box culverts can be viewed in Figure 9.1, and a rating factor page including flexure and shear can be seen in Figure 9.2. The rating factors were grouped by members, location along members, shear or flexure, fill depth, truck load, and rating level.

1 Cell →	Size →	8' x 3'	8' x 4'	8' x 5'	8' x 6'	8' x 7'	8' x 8'	10' x 3'	10' x 4'	10' x 5'	10' x 6'	10' x 7'	10' x 8'	10' x 9'	10' x 10'
Year	Skew°														
1922	15										D-0-199; 16°				
1927	30										D-7-47; 30°				
1930	All							A-6-95; ALL°	A-6-95; ALL°	A-6-95; ALL°	A-6-95; ALL°	A-6-95; ALL°	A-6-95; ALL°	A-6-95; ALL°	A-6-95; ALL°
1945	All	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°	C-4-141; ALL°
1946	30									C-10-14; 30°					
1950	25												E-4-57; 25°		
1952	30										E-12-36; 30°				
1960	90											K-15-38; 90°	K-15-38; 90°	K-15-38; 90°	K-15-38; 90°
1961	All	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°	H-5-150; ALL°
1962	90														
1962	75														
1962	60														
1962	45														
1962	30														
1965	All										K-54-39; ALL°				
1989	60														
1989	60														
1990	45														

Figure 9.1: Partial One Cell Box Culvert Selection Page

M-1-144: 1990, 1@15x14, 0-10 ft fill				⌂ - 1 CELL																			
Skew Angle = 45 Degrees				Exterior Wall								Top Slab						Bottom Slab					
∀-Search				Flexure				Shear				Flexure			Shear			Flexure			Shear		
Fill (ft)			Controling RF	Bottom	Middle (+)	Middle (-)	Top	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
0	H 15 Truck	Inventory	3.2	22.7	n/a	99	8.6	5.8	NA	NA	6	23.7	5.2	23.6	3.5	NA	3.2	41.5	42.8	40.2	40.1	NA	39.8
		Operating	5.3	37.8	n/a	99	14.3	9.7	NA	NA	10	39.5	8.6	39.4	5.8	NA	5.3	69.2	71.3	67	66.8	NA	66.4
	HS 20 Truck	Inventory	2.4	20.3	n/a	99	7	5.6	NA	NA	5.4	20.2	3.9	20.1	2.6	NA	2.4	39	26.5	39	19.3	NA	19.1
		Operating	3.9	33.9	n/a	99	11.6	9.3	NA	NA	9.1	33.6	6.5	33.6	4.3	NA	3.9	65.1	44.1	65	32.1	NA	31.8
2	H 15 Truck	Inventory	3.7	21.9	n/a	99	6.5	9.6	NA	NA	8.4	20	4	20	4	NA	3.7	41.9	33.6	41.8	59.1	NA	59.7
		Operating	6.1	36.6	n/a	99	10.8	16.1	NA	NA	14	33.3	6.7	33.3	6.7	NA	6.1	69.8	56.1	69.7	98.5	NA	99
	HS 20 Truck	Inventory	2.7	21.3	n/a	99	5.2	9.6	NA	NA	7.6	16.7	3	16.7	3	NA	2.7	41.4	25	41.4	31.8	NA	32.1
		Operating	4.6	35.5	n/a	99	8.6	16	NA	NA	12.6	27.9	5	27.9	5	NA	4.6	69	41.7	69	53	NA	53.5
5	H 15 Truck	Inventory	7.9	16.1	n/a	99	10.1	7.9	NA	NA	9.3	30.1	9.1	30.1	9.3	NA	8.6	38.1	22.7	38.1	24.6	NA	24.6
		Operating	13.1	26.8	n/a	99	16.8	13.1	NA	NA	15.4	50.2	15.2	50.2	15.5	NA	14.3	63.6	37.9	63.5	41	NA	41
	HS 20 Truck	Inventory	6.4	14.4	n/a	99	8.6	7.8	NA	NA	8.9	27	6.8	27	7	NA	6.4	36.2	14.8	36.1	15.7	NA	15.7
		Operating	10.7	24	n/a	99	14.3	13	NA	NA	14.8	45	11.4	45	11.6	NA	10.7	60.3	24.6	60.3	26.2	NA	26.2
8	H 15 Truck	Inventory	6.1	13.8	n/a	99	10.4	6.1	NA	NA	8.2	33.5	12.8	33.5	14.2	NA	12.7	37.8	22.1	37.8	23.5	NA	23.5
		Operating	10.2	23.1	n/a	99	17.4	10.2	NA	NA	13.6	55.8	21.3	55.9	23.7	NA	21.2	63	36.9	63	39.1	NA	39.1
	HS 20 Truck	Inventory	6.1	12.9	n/a	99	9.1	6.1	NA	NA	8	30.9	9.4	30.9	10.6	NA	9.5	36.6	15.2	36.6	16	NA	15.9
		Operating	10.1	21.5	n/a	99	15.2	10.1	NA	NA	13.3	51.5	15.7	51.5	17.7	NA	15.8	61.1	25.3	61.1	26.6	NA	26.6
10	H 15 Truck	Inventory	4.9	11.5	n/a	99	9.9	4.9	NA	NA	7.2	34.8	14.9	34.8	15.7	NA	14.1	36.5	22.4	36.5	22.7	NA	22.7
		Operating	8.2	19.2	n/a	99	16.6	8.2	NA	NA	12	57.9	24.9	57.9	26.2	NA	23.5	60.9	37.3	60.9	37.8	NA	37.8
	HS 20 Truck	Inventory	4.9	10.5	n/a	99	8	4.9	NA	NA	6.9	30.5	8.5	30.5	9.3	NA	8.4	34.9	14.5	34.9	14.6	NA	14.6
		Operating	8.1	17.5	n/a	99	13.4	8.1	NA	NA	11.5	50.9	14.2	50.9	15.6	NA	14	58.2	24.2	58.2	24.3	NA	24.3

Figure 9.2: Typical Box Culvert Rating Factor Page

Current Tennessee Tech graduate students, Brandon Bartrom and Heath Kaufman, updated the rating factors in the TDOT Rating Aids with both a newer version of BRASS

Culvert (2.3.6) and refined analyses, and also added more features. The skew angels in the culvert selection page seen in Figure 9.1 and the purple and blue buttons that return to the search pages in Figure 9.2 were some of the added features. Heath performed a moment continuity analysis [13] to further refine the flexural rating factors of some culverts within the Rating Aids. Based on the finding in this thesis, the shear rating factors from BRASS Culvert were removed from the TDOT Rating Aids. The author of this thesis, under the leadership of Dr. Sharon Huo, further improved the usability of the TDOT Rating Aids by developing an Excel sheet, titled the “Search Page," that would allow a search to be made for culverts based on number of cells, skew angle, clear width by clear height, and design year.

As seen in Figure 1.2, BRASS Culvert uses the AASHTO definition of skew angle, which is the “Angle between the centerline of a support and a line normal to the roadway centerline.” TDOT drawings use a skew angle between the centerline of a support and the roadway centerline. To stay consistent with TDOT drawings, TDOT’s definition of skew angle was used in the Rating Aids.

9.2 Search Page

The search page was created to facilitate a more fluid manner of browsing desired culverts’ rating factors. This page allows a culvert to be searched for based on the number of cells, skew angle between the centerline of the road way and the length of the culvert’s walls, cell size, and design year. Once the search is performed, a list of hyperlinks is created for the appropriate culvert drawings.

9.2.1 Operation and Details

To begin a search, the user must select the number of cells. This should be the easiest thing to determine as long as the culvert is visible. The search can then be further refined by selecting any or none of skew angle, cell size, and design year. Figure 9.3 shows the way the Search Page appears when the Box Culvert Rating Aid is opened. Once the desired parameters are selected, clicking the "Search" button begins the search by running the search macro. If any of the optional parameters do not match up to the culverts in the selected cell size of the Rating Aid, those parameters are removed from the search. This allows a refined search to be made even if the user is only sure of the number of cells. If the search completes without making any modifications to the search parameters, the "Warnings" box remains blank. If one or more of the optional parameters was removed from the search, the box turns yellow, and displays the text "Search Modified." In addition, text boxes tell which parameters were removed.

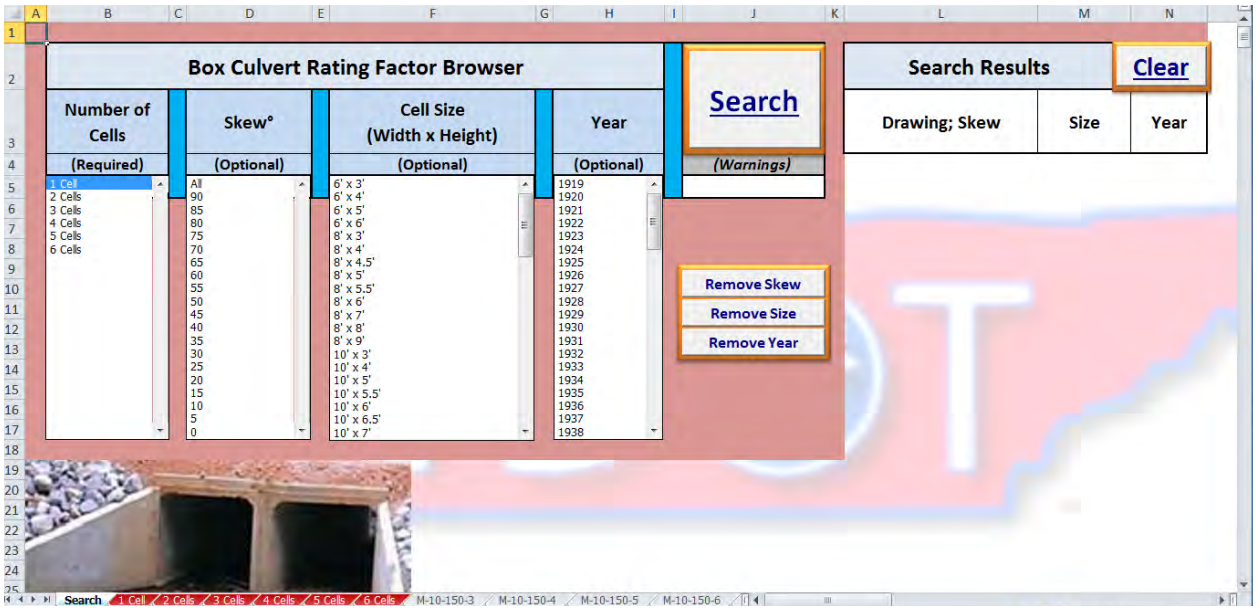


Figure 9.3: Box Culvert Search Page

The program removes any optional search parameter that does not exist for the selected number of cells. Next, the program removes cell size and year until matching culverts are found. The search first removes the year parameter, followed by the cell size, and finally removes the cell size and the year if no results are found. As the design year is the least known factor when inspecting a culvert, it was chosen to be removed from the search first. Cell size was chosen to be removed from the search next as it could be less known than the skew angle if sediment covers the bottom of a culvert. In this manner, a list of culvert models is always created, and is as short as possible based on the selected parameters. Figure 9.4 demonstrates what the Search Page looks like after searching with all four parameters and the year parameter being removed.

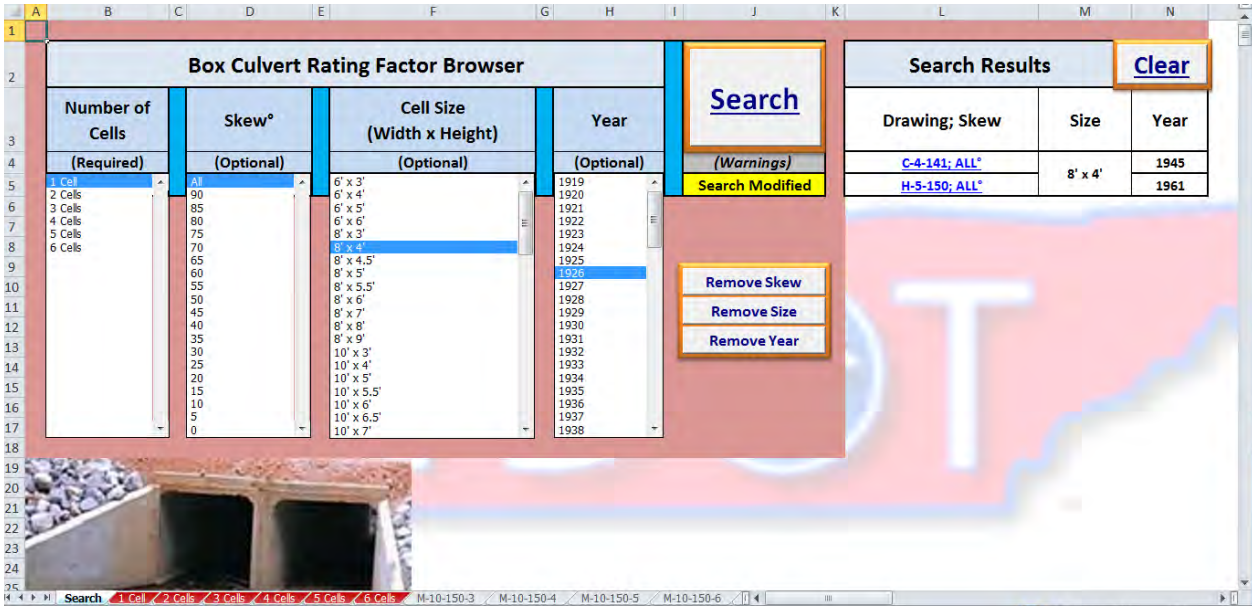


Figure 9.4: Search Page in Use - Year Parameter Removed

Once a culvert is selected from the search results, that hyperlink leads to a rating factor page similar to Figure 9.2. When finished viewing the rating factor page, the blue button with the search icon can be clicked to return to the Search Page. Once back on the Search Page, more results can be viewed, parameters can be changed and the search can be rerun, or the results can be cleared. Clicking the Remove Skew, Size, or Year buttons removes the corresponding parameters from the search. Clicking the Search button again clears the old results, and reruns the search with the new parameters. The "Clear Results" button can be used to remove the list of drawings and clear the Warnings box.

9.2.2 Search Code

Appendix H contains the full VBA code used in Excel to run the culvert search. The culvert Search program can be broken up into 4 main processes. Those processes are: the pre-setup and formatting, checking and adjusting search parameters, compiling and displaying results, and post-formatting. The key steps used in each process are listed in Appendix H.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

The conclusions presented in this chapter are drawn from the results of the studies performed in this report.

10.1 Conclusions

10.1.1 Horizontal Soil Pressure

The conclusions for the moment continuity study are as follows:

- A change in the unit weight of the horizontal soil from 60 pcf to 30 pcf can significantly change the rating factors for culverts depending on certain properties.
- The wall height and the fill depth affect the variation in the rating factors the most, while the span length and the cell type have a smaller influence. The variation intensifies as the wall height increases, fill depth increases, span length decreases, and the number of cells decreases. It was observed that the one cell 8 x 18 culvert with a ten foot fill depth had the largest variation because it had the largest wall height analyzed, the largest fill depth analyzed, the smallest span length analyzed, and the smallest number of cells analyzed.
- The exterior wall and the left side of the slabs for any culvert and the middle and right side of the slabs for one cell culverts experience larger flexure values when 60 pcf is used as the unit weight of the horizontal soil. The middle and right side of the slabs for culverts that have more than one cell experience larger flexure

values when 30 pcf is used as the unit weight. Based on this study, culverts designed with a unit weight of 30 pcf are not recommended to be rated with a unit weight of 60 pcf.

- Culverts with four foot wall heights would not experience any change in rating factors. However, culverts with larger wall heights would experience larger variation in the rating factors, which could potentially lead to lower rating factors.

10.1.2 TDOT Dump Truck Rating Factor Analysis

The conclusions for the TDOT dump truck rating factor analysis are as follows:

- Rating factors change very little for flexure or shear when comparing an HS20 and a TDOT dump truck.

10.1.3 Shear Analysis

The findings in this thesis were used to justify the removal of shear rating factors, as determined by BRASS Culvert, from the TDOT Culvert Rating Aids. Reasons shear rating factors from BRASS Culvert may be ignored include:

- Based on the scholarly papers mentioned in Chapter 2 and many others, shear capacity is conservatively underestimated by current code equations based on their empirical nature. As shown with the shear capacity analysis graphs in Chapter 5 for the two databases, some equations tend to underestimate shear capacity more than others.

- In Section 5.1, AASHTO LRFD Equation (5.14.5.3-1) [1] and ACI Equation (11-6) [8] tended to produce the least conservative shear capacities of the six equations used. These equations, as used in this thesis, are not used by BRASS Culvert to calculate shear capacity.
- Based on past tests, axial compression was shown to contribute towards reinforced concrete members' shear strength. AASHTO LRFD Equation (5.14.5.3-1) [1] and ACI Equation (11-6) [8] include axial force terms.
- Response-2000, which is based on the MCFT, produced larger shear capacities than BRASS Culvert on average. Also, test results from the Verification Culvert Database indicated that actual shear capacities were even greater than the values calculated by Response-2000 on average.
- Increases in shear rating factors were noted for even the smaller increases in shear capacity when comparing results from Response-2000 and BRASS Culvert for the TDOT Culvert Database.

10.1.4 Moment Continuity

The conclusion for the moment continuity study is as follows:

- Modeling culverts as having zero moment continuity at the exterior wall connections drastically improves the rating factors for the top and bottom of the exterior wall and the left side of the top and bottom slabs. However, this modeling technique slightly reduces the rating factors for the middle and right side of the top and bottom slabs.

10.1.5 TDOT Culvert Rating Aids

The conclusion on the TDOT Culvert Rating Aids as they now stand is:

- With the current iteration of the TDOT Culvert Rating Aids, engineers will be able to quickly search through TDOT's reinforced concrete culvert database and find the desired standard drawing's initial rating factors, as well as update the Rating Aids based on the current condition of the existing culvert.

10.2 Recommendations

Future work recommendations include:

- A larger database of culverts that have been tested to failure could be compiled and analyzed to reinforce the precision of the theoretical values of shear capacity predicted by Response-2000. More variation in clear height, clear span, and number of cells should be included.
- It is recommended that a different type of moment continuity analysis be performed for the exterior and interior wall connections based on percentages of continuity instead of a full to zero continuity study.

REFERENCES

1. AASHTO. *AASHTO LRFD Bridge Design Specifications.* 5th Edition. Washington D.C.: American Association of State Highway and Transportation Officials, 2010.

2. AASHTO. *Manual for Bridge Evaluation.* 2nd Edition, with 2011 Interim Revisions. Washington D.C.: American Association of State Highway and Transportation Officials, 2011.

3. AASHTO. *Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) Highway Bridges*. With 2005 Interim Revisions. American Association of State Highway and Transportation Officials. Washington, D.C., 2003.

4. AASHTO. *Standard Specifications for Highway Bridges.* 16th Edition. Washington D.C.: American Association of State Highway and Transportation Officials, 1996.

5. Abolmaali, Ali and Garg, Anil K. *Effect of Wheel Live Load on Shear Behavior of Precast Reinforced Concrete Box Culverts.* ASCE, Journal of Bridge Engineering, February 2008.

6. Abolmaali, Ali and Garg, Anil K. *Finite-Element Modeling and Analysis of Reinforced Concrete Box Culverts*. ASCE, Journal of Transportation Engineering, March 2009.

7. ACI-ASCE. *Shear and Diagonal Tension: Report of ACI-ASCE Committee 326.* American Concrete Institution and American Society of Civil Engineers, 1962.

8. ACI Committee 318. *Building Code Requirements for Structural Concrete (318-99) and Commentary (318R-99).* American Concrete Institute, 1999.

9. Baron, M. J. and Siess, C. P. *Effect of Axial Load on the Shear Strength of Reinforced Concrete Beams.* Urbana, IL: University of Illinois, 1956.

10. Bentz, Evan; Vecchio, Frank; and Collins, Michael. *Simplified Modified Compression Field Theory for Calculating Shear Strength of Reinforced Concrete Elements.* ACI Structural Journal, Technical Paper: Title no. 103-S65, August 2006.

11. Burns, Jarrod C. *Experimental Investigation of Shear Capacity of Precast Reinforced Concrete Box Culverts.* Arlington, TX: University of Texas, December 2006.

12. FHWA. *National Bridge Inspection Standards (NBIS).* Department of Transportation Federal Highway Administration, 2004.

13. Kaufman, Heath. *Analysis and Rating of Reinforced Concrete Box Culverts under Various Loading and Modeling Conditions.* Cookeville, TN: Tennessee Technological University, 2014.

14. Lawson W., Wood T., Newhouse C., and Jayawickrama P.. (2010). *Evaluating Existing Culverts for Load Capacity Allowing for Soil Structure Interaction*. Texas Technological University Multidisciplinary Research in Transportation Department.

15. LGAM. < *http:// www.lgam.info/reinforced-concrete-box-culvert* >. The Local Government & Municipal Knowledge Database, 2014.

16. Rahal, Khaldoun. *Shear Strength of Reinforced Concrete: Part II- Beams Subjected to Shear, Bending Moment, and Axial Load.* ACI Structural Journal, Technical Paper: Title no. 97-S23, 2000.

17. TxDOT. (2009). *Culvert Rating Guide.* Texas Department of Transportation.

18. Wu, X. Y. *Shear Resistance of Axially Loaded Reinforced Concrete Sections.* London, Imperial College London, June 2012.

APPENDIX A

EXAMPLE CALCULATIONS OF SHEAR RATING FACTORS

To start the process, TDOT standard drawing M-1-91 was used to determine basic properties and dimensions of the culvert. Figure A1.1 displays TDOT standard drawing M-1-91. From the drawing and based on LRFD Specification, the following items were determined to be used:

- f'_c = 3 ksi
- f_y = 60 ksi
- Clear Span = 12 ft
- Clear Height = 4 ft
- Number of Cells = 3
- Top Slab Thickness = 21 in
- Bottom Slab Thickness = 21 in
- Exterior Wall Thickness = 12 in
- Interior Wall Thickness = 12 in
- Future Wearing Surface Thickness = 3 in
- Vertical Soil Density = 120 pcf
- Horizontal Soil Density = 60 pcf
- Concrete Density = 150 pcf
- Future Wearing Surface Density = 140 pcf
- Modulus of Concrete = 3150 ksi
- Modulus of Steel = 29000 ksi
- Soil Structure Interaction Factor = 1.15
- Multiple Presence Factor = 1.2
- Fill Depth = 2 ft
- Skew Angle = 60° (from centerline of road to centerline of walls)
- Equivalent Height for Live Load Surcharge = 2 ft

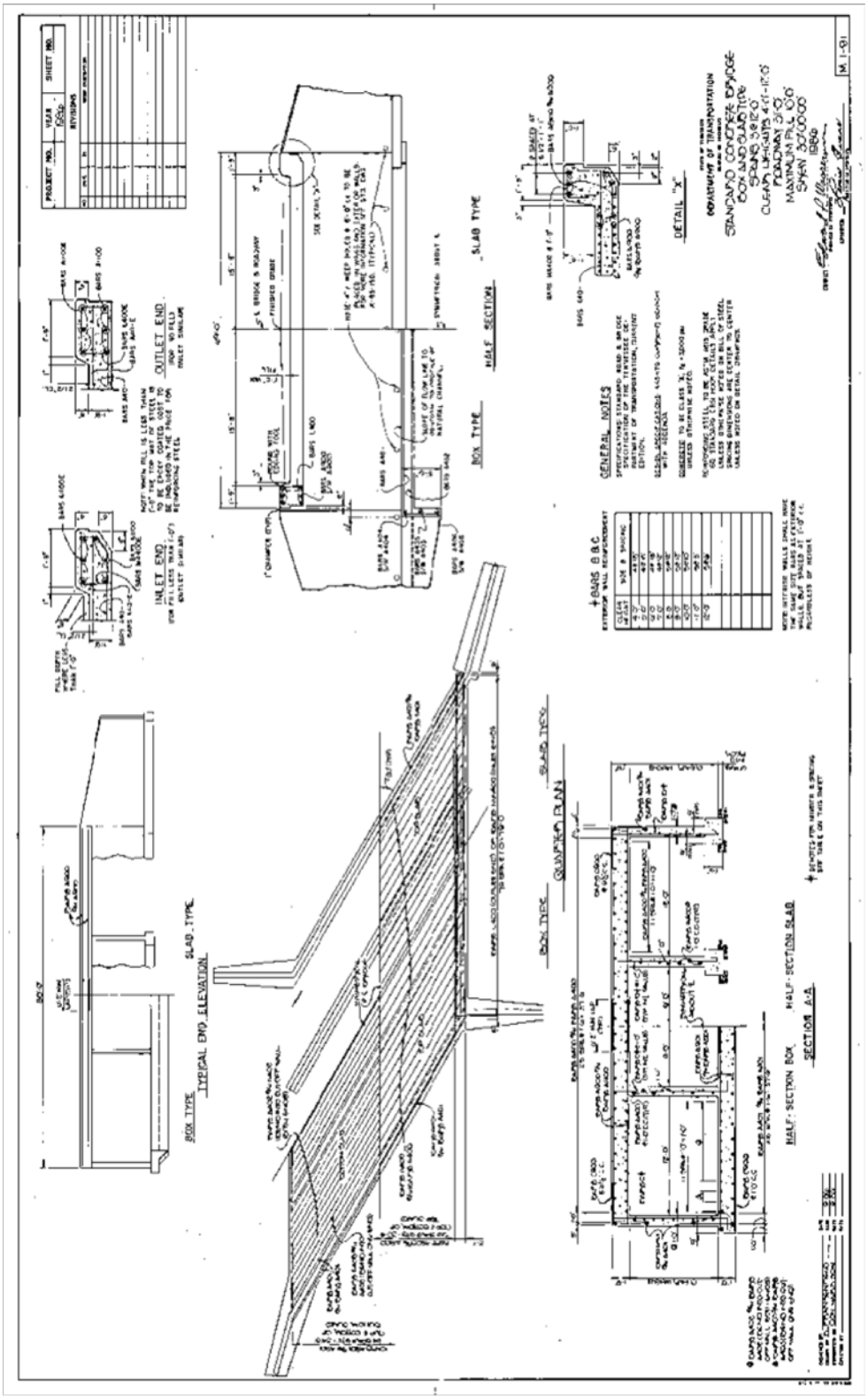


Figure A.1: TDOT Standard Drawing M-1-91

The next step was to use the Mathcad file seen in Appendix B2 to determine appropriate dead and live loads. The input and output from the Mathcad file for a 1 foot section can be seen in Figures A.2 and A.3, respectively.

$\gamma\_soil := 0.120$

$\gamma\_soil\_H := 0.060 \ \frac{k}{ft^3}$

$\gamma\_c := 0.150$

$\gamma\_ws := 0.140$

$E\_c := 3150 \ ksi$

$E\_s := 29000 \ ksi$

$mpf := 1.2$

$D\_E := H$

(Depth of Earth fill)

$F\_e := 1.15$ (SSIF)

$H\_ := 2 \ ft$ (Fill)

$Skew := 0$

$f\_c := 3 \ ksi$

$f\_y := 60 \ ksi$

$Clr\_Span := 12 \ ft$

$Clr\_Ht := 12 \ ft$

$BW := 1$ ft (Base Width)

$Num\_Cell := 4$

$Type := 1$

(Type 1 = Box Culvert and Type 2 = Slab Culvert)

$ST := \frac{12}{12}$ ft (Top Slab Thickness)

$SB := \frac{12}{12}$ ft (Bottom Slab Thickness)

$WT := \frac{12}{12}$ ft (Exterior Wall Thickness)

$IT := \frac{12}{12}$ ft (Interior Wall Thickness)

$t\_ws := \frac{3}{12}$ ft (Wearing Surface Thickness)

Figure A.2: LRFD Mathcad File Input

Dead Loads

Top Slab

$W\_TopSlab = 0.461 \ \frac{k}{ft}$

Exterior Walls

At Center of Top Slab

$W\_EH = 0.15 \ \frac{k}{ft}$

At Center of Bottom Slab

$W\_EH2 = 0.93 \ \frac{k}{ft}$

Live Loads

1 = YES, Ignore LL
2 = NO

$ILL = 2$

Live Load Surcharge

$\Delta p = 0.072 \ \frac{k}{ft}$

Lane Load

$LaneL = 0 \ \frac{k}{ft}$

$Counter\_LL = 0$

HS20 Truck

$HS20\_Load\_1 = 0.42288 \ kips$

$HS20\_Load\_2 = 1.69153 \ kips$

$HS20\_Load\_3 = 1.69153 \ kips$

$HS20\_gap = 12 \ ft$

$HS20\_Set = 3$

$HS20\_Length = 3 \ ft$ (also = # of loads)

(With 1 foot spacings)

$Counter\_Load\_HS20 = 0.23787 \ \frac{k}{ft}$

Tandem

$Tandem\_Load\_1 = 1.3215 \ kips$

$Tandem\_Load\_2 = 1.3215 \ kips$

$Tandem\_gap = 2 \ ft$

$Tandem\_Set = 2$

$Tandem\_Length = 3 \ ft$ (also = # of loads)

(With 1 foot spacings)

$Counter\_Load\_Tandem = 0.16519 \ \frac{k}{ft}$

Figure A.3: LRFD Mathcad File Output

Based on the output seen in Figure A.3, dead loads and centipede truck loads were entered into STAAD Pro models. Figure A.4 shows an HS20 truck being moved along the top slab of the culvert in STAAD Pro to determine controlling forces. After the controlling forces were determined for the HS20, they were entered into the Excel sheet used to calculate shear capacities and shear rating factors. The factored controlling shear forces based on the inventory level of AASHTO LFD methods were 8.01 kips for the live load and 2.48 kips for the dead load based on a live load factor of 2.17 and a dead load factor of 1.3. These are the forces that were used to calculate shear rating factors as is shown at the end of Appendix A. Although this method of determining forces was used with the Specification equations for determining shear capacity, different forces were used in Response-2000.

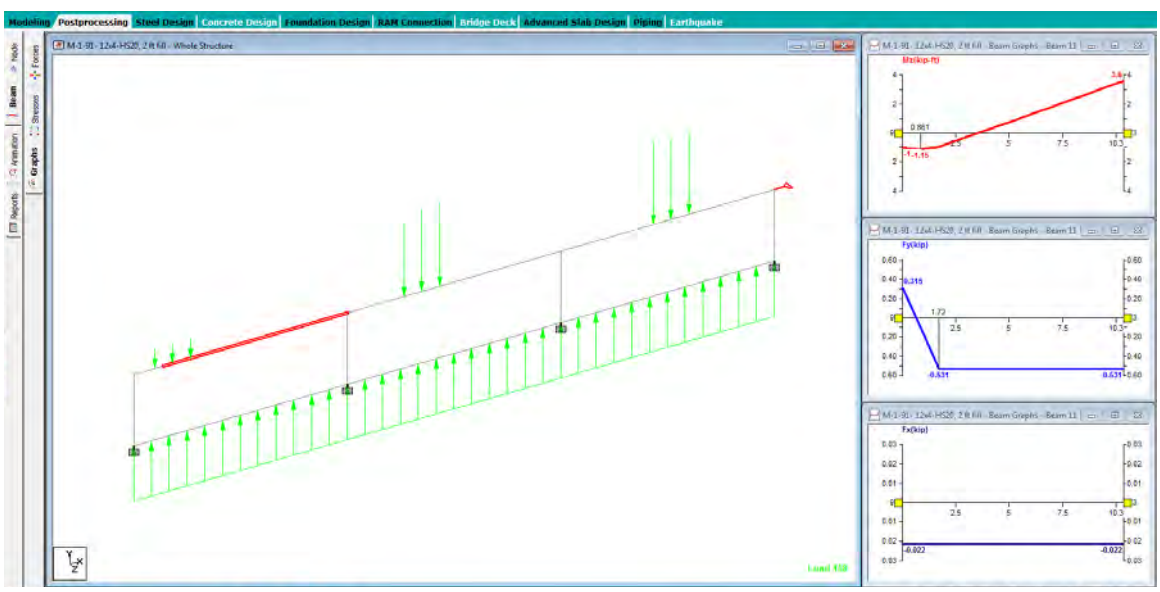


Figure A.4: HS20 Truck Moving along the Top Slab in STAAD Pro

When determining shear capacity through Response-2000 specifically, the live loads were ignored. The live loads were replaced with a 100 kip point load placed directly at the critical shear location to create a load case that would be most likely to induce shear based failure. The point load and appropriate dead loads were used to determine the forces most likely to occur during shear failure. Since Response-2000 uses a ratio of bending to shear forces when determining shear capacity, the magnitude of the point load does not skew the results. In STAAD Pro, the dead loads were kept in the load case to leave some similarities to culverts in use. The 100 kip load at the critical shear location was chosen to allow the load that is most likely to cause shear failure to overshadow the dead loads in magnitude. Figure A.5 shows the STAAD Pro output of the critical shear location forces used to determine shear capacity from Response-2000.

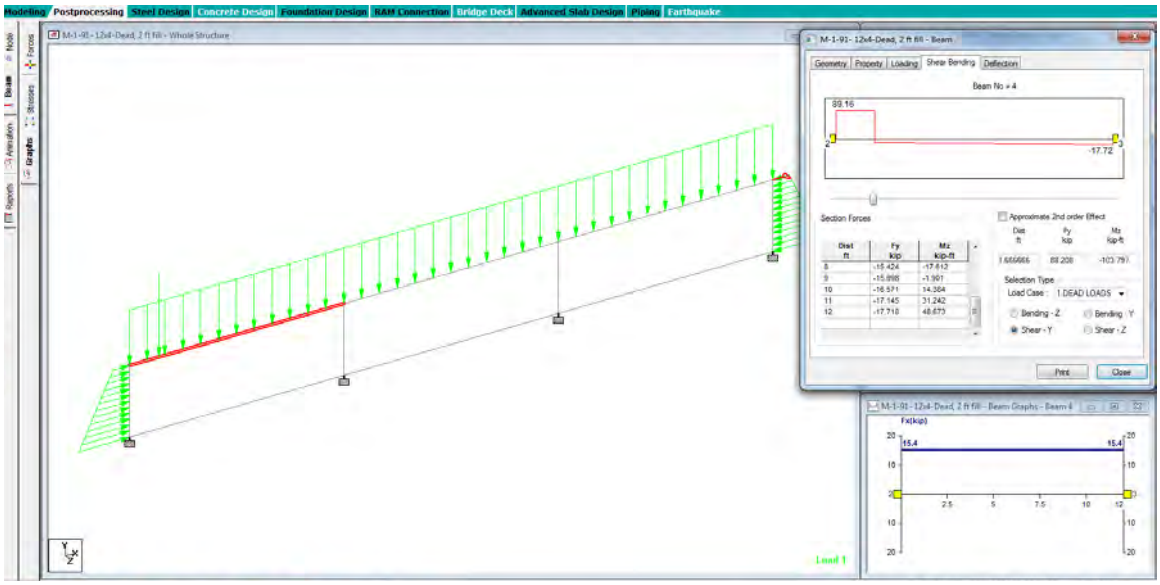


Figure A.5: Response-2000 Forces Determined for the Top Slab in STAAD Pro

The forces were determined to be an axial compression of 15.4 kips, a bending force of 103.8 kip-ft, and a shear force of 88.2 kips. Figure A.6 shows the model of culvert M-1-91 in Response-2000. As mentioned previously, the model is for a 1 foot section. Once analyzed with Response-2000, the nominal shear capacity was determined to be 29.6 kips, as seen in Figure A.7.

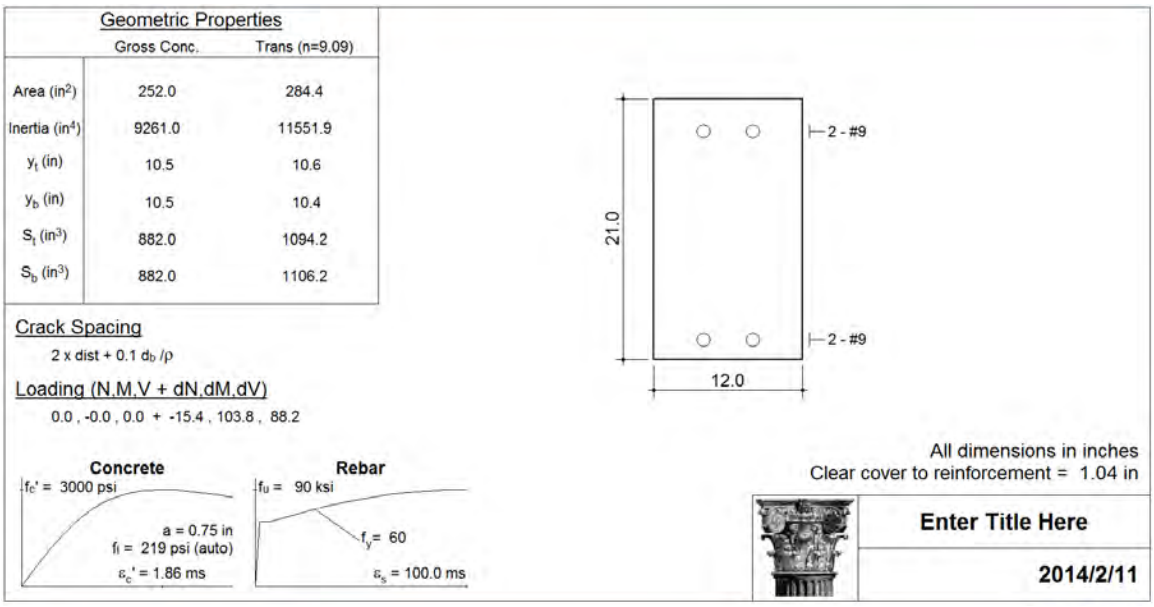


Figure A.6: Response-2000 Model with Critical Shear Location Forces Applied

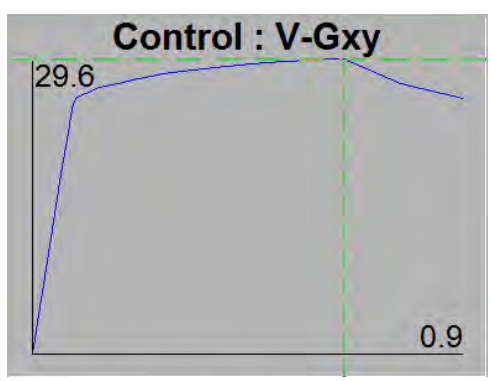


Figure A.7: Shear Capacity as Calculated by Response-2000

Once the shear capacity was determined, shear rating factors were calculated by Equation 3.1 at the operating level as follows,

$$RF = \frac{C - \gamma_{DL} DL}{\gamma_{LL} LL(1 + IM)}$$

where C is the structural member's capacity, IM is the impact factor, DL and LL are dead and live loads, respectively, and γ_{DL} and γ_{LL} are dead and live load factors, respectively. (1 + IM) was factored into the live load term when determining live load models in Mathcad. The capacity is equal to the nominal capacity multiplied by the shear strength reduction factor, 0.85. So, C = 0.85 * 29.6 = 25. 16.

For operating level calculations of shear rating factors, the dead loads were multiplied by the operating level dead load factor, γ_{DL} = 1.3. For the operating rating level, γ_{LL} also equals 1.3. It is important to note that the live loads used in the rating factor equation were for the controlling truck load, not the 100 kip point load. So, the shear rating factor for the critical shear location of the top slab of culvert M-1-91 by the Response-2000 shear capacity is 4.73 kips, as seen in the equation below. The term (1.3 / 2.17) is used to convert the inventory level live load to an operating one. As mentioned previously, the factored dead and live load shear forces at the inventory rating level from the HS20 were 2.48 kips and 8.01 kips, respectively.

$$RF = \frac{25.16 - 2.48}{8.01 * \left(\frac{1.3}{2.17}\right)} = 4.73\ kips$$

APPENDIX B

MATHCAD CODE FOR LOAD DETEMINATION

Appendix B1: Mathcad Code used to Determine AASHTO LFD [4] Dead and Live Loads

(TDOT Box Culvert C-4-141)

Input

$\gamma\_soil := 0.120$

$\gamma\_soil\_H := 0.030$

[min EH (3.20.1)]

$\gamma\_c := 0.150 \ \frac{k}{ft^3}$

$\gamma\_ws := 0.140$

$E\_c := 3150 \ ksi$

$E\_s := 29000 \ ksi$

$F\_e := 1.15$ (SSIF)

$D\_E := H\_$

(Depth of Earth fill)

$mpf := 1.0$

[for one lane loaded (3.12.1)]

$H\_ := 40 \ ft$ (Fill)

$Skew := 0$

$f\_c := 2.5 \ ksi$

$f\_y := 33 \ ksi$

$Clr\_Span := 10 \ ft$

$Clr\_Ht := 3 \ ft$

$BW := 1$ ft (Base Width)

$Num\_Cell := 1$

$ST := \frac{21.5}{12}$ ft (Top Slab Thickness)

$SB := \frac{21.5}{12}$ ft (Bottom Slab Thickness)

$WT := \frac{18.0}{12}$ ft (Exterior Wall Thickness)

$IT := \frac{0}{12}$ ft (Interior Wall Thickness)

$t\_ws := \frac{3}{12}$ ft (Wearing Surface Thickness)

$Type := 1$

(Type 1 = Box Culvert and Type 2 = Slab Culvert)

$h\_eq := 2.0 \ ft$

[LL Surcharge (3.20.3)]

$$IM := \begin{cases} [30\cdot(1 - 0.333\cdot D\_E)] & \text{if } 30\cdot(1 - 0.333\cdot D\_E) > 1 \\ 0 & \text{otherwise} \end{cases}$$

$IM = 0 \ \%$

[Dynamic Load Allowance(3.8.2.3)]

LOADS for 1' Sections

Dead Loads

Top Slab

Soil Weight - EV

$W\_EV := F\_e\cdot H\_\cdot\gamma\_soil\cdot 1$

$W\_EV = 5.52 \ \frac{k}{ft}$

Top Slab Wt. - DC

$W\_DC := \gamma\_c\cdot ST\cdot 1$

$W\_DC = 0.268 \ \frac{k}{ft}$

Future Wearing Surface - DW

$W\_DW := \gamma\_ws\cdot t\_ws\cdot 1$

$W\_DW = 0.035 \ \frac{k}{ft}$

Totals

$W\_TopSlab := W\_EV + W\_DC + W\_DW$

$W\_TopSlab = 5.82375 \ \frac{k}{ft}$

Exterior Walls

Soil Weight - EH

At Center of Top Slab

$W\_EH := \left(H\_ + \frac{ST}{2}\right)\cdot\gamma\_soil\_H\cdot 1$

$W\_EH = 1.22687 \ \frac{k}{ft}$

At Center of Bottom Slab

$W\_EH2 := \left(H\_ + ST + Clr\_Ht + \frac{SB}{2}\right)\cdot\gamma\_soil\_H\cdot 1$

$W\_EH2 = 1.37062 \ \frac{k}{ft}$

Live Loads

IGNORE LIVE LOADS??? (6.4.2)

$$ILL := \begin{cases} \begin{cases} 1 & \text{if } D\_E > 8 \\ 2 & \text{otherwise} \end{cases} & \text{if } Num\_Cell = 1 \\ \begin{cases} 1 & \text{if } D\_E > [Num\_Cell \cdot Clr\_Span + (Num\_Cell - 1) \cdot IT] \\ 2 & \text{otherwise} \end{cases} & \text{if } Num\_Cell > 1 \\ 3 & \text{otherwise} \end{cases}$$

1 = YES, Ignore LL
2 = NO

$ILL = 1$

Live Load Surcharge

$\Delta p := \gamma\_soil\_H \cdot h\_eq \cdot 1$ [LL Surcharge (3.20.3)]

$\Delta p = 0.06 \ \frac{k}{ft}$

Lane Load (Stand-Alone Load) (Figure 3.7.6B)

$Full\_Span := Clr\_Span \cdot Num\_Cell$ $Width := 10$

$F\_S\_Prime := 1.75 \cdot H\_ + Full\_Span$ $Width\_Prime := 1.75 \cdot H\_ + Width$

$$LaneL := \left(\frac{Full\_Span}{F\_S\_Prime} \cdot \frac{Width}{Width\_Prime} \cdot 0.64 \right)$$

$ConcLoadLengthAndNumber := floor(1.75 \cdot H\_)$

$$ConcLoad\_1 := \begin{cases} \left\lceil \frac{26}{\left\lfloor (ConcLoadLengthAndNumber)^2 \right\rfloor} \right\rceil & \text{if } ConcLoadLengthAndNumber > 0 \\ 26 & \text{otherwise} \end{cases}$$

$$ConcLoad\_2 := \frac{26}{(4 + 0.06 \cdot Clr\_Span)}$$

$$ConcLoad := \begin{cases} ConcLoad\_2 & \text{if } D\_E < 2 \\ \begin{cases} \left(\frac{ConcLoad\_2}{ConcLoadLengthAndNumber} \right) & \text{if } \left(\frac{ConcLoad\_2}{ConcLoadLengthAndNumber} \right) < ConcLoad\_1 \\ ConcLoad\_1 & \text{otherwise} \end{cases} & \text{if } D\_E \geq 2 \\ 101 & \text{otherwise} \end{cases}$$

$LaneL = 0.01 \ \frac{k}{ft}$ $ConcLoadLengthAndNumber = 70 \ ft$

+ 26 kip Concentrated Load the Thickness of the Member Away form the start. $ConcLoad = 5.30612 \times 10^{-3}$

$$LaneL\_Fill := \begin{cases} 0 & \text{if } D\_E < 2 \\ (LaneL + ConcLoad) & \text{otherwise} \end{cases}$$

$LaneL\_Fill = 0.01531 \ \frac{k}{ft}$ (When not equal to 0, use LaneL_Fill instead of LaneL w/o Concentrated Load)

$$Num\_CL := \begin{cases} 2 & \text{if } Num\_Cell > 1 \\ 1 & \text{otherwise} \end{cases}$$

$$Counter\_LL := \begin{cases} \left(LaneL + \frac{ConcLoad \cdot Num\_CL}{Full\_Span} \right) & \text{if } D\_E < 2 \\ LaneL\_Fill & \text{otherwise} \end{cases}$$

Live Load Vehicles

$S\_ := Clr\_Span$

$$E\_noFill := \begin{cases} (4 + 0.06 \cdot S\_) & \text{if } (4 + 0.06 \cdot S\_) < 7 \\ 7 & \text{otherwise} \end{cases}$$ (3.24.3.2)

$E\_noFill = 4.6 \ ft$

$E\_fill\_noOverlap := (1.75 \cdot D\_E) \cdot 2$ (6.4.1)

$E\_fill\_noOverlap = 140$ ft

$$E\_fill\_overlap := \left(\frac{E\_fill\_noOverlap}{2}\right) + 6$$

$E\_fill\_overlap = 76$ ft

$$E\_fill := \begin{cases} E\_fill\_noOverlap & \text{if } E\_fill\_noOverlap < E\_fill\_overlap \\ E\_fill\_overlap & \text{otherwise} \end{cases}$$

$E\_fill = 76$ ft

$$E := \begin{cases} E\_noFill & \text{if } D\_E < 2 \\ \begin{cases} E\_noFill & \text{if } E\_noFill > E\_fill \\ E\_fill & \text{otherwise} \end{cases} & \text{if } D\_E \geq 2 \\ 101 & \text{otherwise} \end{cases}$$

$E = 76$ ft

$$LLDF := \left(\frac{1}{E}\right) \cdot mpf \cdot \left(1 + \frac{IM}{100}\right)$$

$LLDF = 0.01316$

$l\_d := floor(1.75 \cdot D\_E)$

$l\_d = 70$ ft

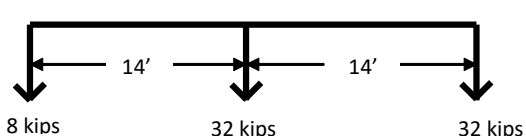
(length of distribution for one axel)

(also equals the number of centipede loads for one axel)

H15 Truck

Not required for minimum loading cases (3.7.4).

HS20 Truck



$HS20\_1 := 8$ kips

$$HS20\_centLoad\_1 := \begin{cases} \frac{HS20\_1}{l\_d} & \text{if } l\_d > 0 \\ HS20\_1 & \text{otherwise} \end{cases}$$

$HS20\_2 := 32$ kips

$$HS20\_centLoad\_2 := \begin{cases} \frac{HS20\_2}{l\_d} & \text{if } l\_d > 0 \\ HS20\_2 & \text{otherwise} \end{cases}$$

$HS20\_3 := 32$ kips

$$HS20\_centLoad\_3 := \begin{cases} \frac{HS20\_3}{l\_d} & \text{if } l\_d > 0 \\ HS20\_3 & \text{otherwise} \end{cases}$$

$HS20axel := 3$

$HS20\_noOverlap := (l\_d) \cdot HS20axel$ $\quad HS20\_noOverlap = 210 \quad ft$

$HS20\_overlap := l\_d + 28$ $\quad HS20\_overlap = 98 \quad ft$ (both also equal number of loads)

$$HS20\_gap := \begin{cases} \begin{cases} (14 - l\_d + 1) & \text{if } (14 - l\_d + 1) > 0 \\ 0 & \text{otherwise} \end{cases} & \text{if } l\_d > 0 \\ 14 & \text{otherwise} \end{cases}$$

(gap between sets of loads)

$$HS20\_Length := \begin{cases} l\_d & \text{if } HS20\_noOverlap \le HS20\_overlap \\ HS20\_overlap & \text{otherwise} \end{cases}$$

$$HS20\_Set := \begin{cases} 3 & \text{if } HS20\_gap > 0 \\ 1 & \text{otherwise} \end{cases}$$

$$HS20\_Load\_1 := \begin{cases} (HS20\_centLoad\_1 \cdot LLDF) & \text{if } HS20\_gap > 0 \\ \left\lceil \frac{(HS20\_centLoad\_1 + HS20\_centLoad\_2 + HS20\_centLoad\_3)}{3} \cdot \frac{HS20\_noOverlap}{HS20\_overlap} \cdot LLDF \right\rceil & \text{otherwise} \end{cases}$$

$$HS20\_Load\_2 := \begin{cases} (HS20\_centLoad\_2 \cdot LLDF) & \text{if } HS20\_gap > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$HS20\_Load\_3 := \begin{cases} (HS20\_centLoad\_3 \cdot LLDF) & \text{if } HS20\_gap > 0 \\ 0 & \text{otherwise} \end{cases}$$

$HS20\_Load\_1 = 9.66702 \cdot kips^{-3}$ $\quad HS20\_Load\_2 = 0 \quad kips$ $\quad HS20\_Load\_3 = 0 \quad kips$

$HS20\_gap = 0 \quad ft$

$HS20\_Set = 1$

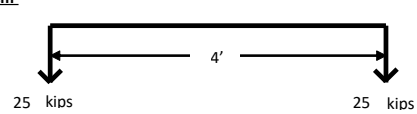
$HS20\_Length = 98 \quad ft$ (also = # of loads)

(With 1 foot spacings)

$$Counter\_Load\_HS20 := \begin{cases} (HS20\_Load\_1 + HS20\_Load\_2 + HS20\_Load\_3) \cdot \frac{HS20\_Length}{Full\_Span} & \text{if } l\_d > 0 \\ \frac{(HS20\_Load\_1 + HS20\_Load\_2 + HS20\_Load\_3)}{Full\_Span} & \text{otherwise} \end{cases}$$

$Counter\_Load\_HS20 = 0.09474 \quad \frac{k}{ft}$

Tandem



$Tandem\_1 := 25 \quad kips$ $\qquad Tandem\_2 := 25 \quad kips$

$$Tandem\_centLoad\_1 := \begin{cases} \frac{Tandem\_1}{l\_d} & \text{if } l\_d > 0 \\ Tandem\_1 & \text{otherwise} \end{cases} \qquad Tandem\_centLoad\_2 := \begin{cases} \frac{Tandem\_2}{l\_d} & \text{if } l\_d > 0 \\ Tandem\_2 & \text{otherwise} \end{cases}$$

$Tandemaxel := 2$

$Tandem\_noOverlap := (l\_d) \cdot Tandemaxel$ $\quad Tandem\_noOverlap = 140 \quad ft$

$Tandem\_overlap := l\_d + 4$ $\quad Tandem\_overlap = 74 \quad ft$ (both also equal number of loads)

$$Tandem\_gap := \begin{cases} \begin{cases} (4 - l\_d + 1) & \text{if } (4 - l\_d + 1) > 0 \\ 0 & \text{otherwise} \end{cases} & \text{if } l\_d > 0 \\ 4 & \text{otherwise} \end{cases}$$

(gap between sets of loads)

$$Tandem\_Length := \begin{cases} l\_d & \text{if } Tandem\_noOverlap \le Tandem\_overlap \\ Tandem\_overlap & \text{otherwise} \end{cases}$$

$$Tandem\_Set := \begin{cases} 2 & \text{if } Tandem\_gap > 0 \\ 1 & \text{otherwise} \end{cases}$$

$$Tandem\_Load\_1 := \begin{cases} (Tandem\_centLoad\_1 \cdot LLDF) & \text{if } Tandem\_gap > 0 \\ \left[\left(Tandem\_centLoad\_1 \cdot \frac{Tandem\_noOverlap}{Tandem\_overlap}\right) \cdot LLDF\right] & \text{otherwise} \end{cases}$$

$$Tandem\_Load\_2 := \begin{cases} (Tandem\_centLoad\_2 \cdot LLDF) & \text{if } Tandem\_gap > 0 \\ 0 & \text{otherwise} \end{cases}$$

$Tandem\_Load\_1 = 8.89047 \times 10^{3}\ kips$ $\quad Tandem\_Load\_2 = 0\ kips$

$Tandem\_gap = 0\ ft$

$Tandem\_Set = 1$

$Tandem\_Length = 74\ ft$ (also = # of loads)

(With 1 foot spacings)

$$Counter\_Load\_Tandem := \begin{cases} (Tandem\_Load\_1 + Tandem\_Load\_2) \cdot \frac{Tandem\_Length}{Full\_Span} & \text{if } l\_d > 0 \\ \frac{(Tandem\_Load\_1 + Tandem\_Load\_2)}{Full\_Span} & \text{otherwise} \end{cases}$$

$Counter\_Load\_Tandem = 0.06579\ \frac{k}{ft}$

Output

Dead Loads

Top Slab

$W\_TopSlab = 5.82375\ \frac{k}{ft}$

Exterior Walls

At Center of Top Slab

$W\_EH = 1.22687\ \frac{k}{ft}$

At Center of Bottom Slab

$W\_EH2 = 1.37062\ \frac{k}{ft}$

Live Loads

1 = YES, Ignore LL
2 = NO

$ILL = 1$

Live Load Surcharge

$\Delta p = 0.06\ \frac{k}{ft}$

Lane Load

$LaneL = 0.01\ \frac{k}{ft}$ $\quad ConcLoad = 5.30612 \times 10^{-3}$

$LaneL\_Fill = 0.01531\ \frac{k}{ft}$ $\quad Counter\_LL = 0.01531\ \frac{k}{ft}$

(When LaneL_Fill not equal to 0, use LaneL_Fill instead of LaneL w/o Concentrated Load)

HS20 Truck

$HS20\_Load\_1 = 9.66702 \times 10^{-3}\ kips$

$HS20\_Load\_2 = 0\ kips$

$HS20\_Load\_3 = 0\ kips$

$HS20\_gap = 0\ ft$

$HS20\_Set = 1$

$HS20\_Length = 98\ ft$ (also = # of loads)

(With 1 foot spacings)

$Counter\_Load\_HS20 = 0.09474\ \frac{k}{ft}$

Tandem

$Tandem\_Load\_1 = 8.89047 \times 10^{3}\ kips$

$Tandem\_Load\_2 = 0\ kips$

$Tandem\_gap = 0\ ft$

$Tandem\_Set = 1$

$Tandem\_Length = 74\ ft$ (also = # of loads)

(With 1 foot spacings)

$Counter\_Load\_Tandem = 0.06579\ \frac{k}{ft}$

Appendix B2: Mathcad Code used to Determine AASHTO LRFD [1] Dead and Live Loads

(TDOT Box Culvert C-4-141)

Input

$\gamma\_soil := 0.120$

$\gamma\_soil\_H := 0.060 \ \frac{k}{ft^3}$

$\gamma\_c := 0.150$

$\gamma\_ws := 0.140$

$E\_c := 3150 \ ksi$

$E\_s := 29000 \ ksi$

$mpf := 1.2$

$D\_E := H$ (Depth of Earth fill)

$F\_e := 1.15$ (SSIF)

$H\_ := 40 \ ft$ (Fill)

$Skew := 0$

$f\_c := 2.5 \ ksi$

$f\_y := 33 \ ksi$

$Clr\_Span := 10 \ ft$

$Clr\_Ht := 3 \ ft$

$BW := 1$ ft (Base Width)

$Num\_Cell := 1$

$Type := 1$

(Type 1 = Box Culvert and Type 2 = Slab Culvert)

$ST := \frac{21.5}{12}$ ft (Top Slab Thickness)

$SB := \frac{21.5}{12}$ ft (Bottom Slab Thickness)

$WT := \frac{18.5}{12}$ ft (Exterior Wall Thickness)

$IT := \frac{0}{12}$ ft (Interior Wall Thickness)

$t\_ws := \frac{3}{12}$ ft (Wearing Surface Thickness)

$$IM := \begin{cases} [33\cdot(1 - 0.125\cdot D\_E)] & \text{if } 33\cdot(1 - 0.125\cdot D\_E) > 1 \\ 0 & \text{otherwise} \end{cases}$$

$IM = 0$ %

(Dynamic Load Allowance)

(Table 3.11.6.4-1)

$wall\_ht := D\_E + ST + Clr\_Ht + SB$

$$h\_eq := \begin{cases} 4.0 & \text{if } wall\_ht \le 5 \\ \left[4.0 - \left(\frac{wall\_ht - 5}{5}\right)\right] & \text{if } 5 < wall\_ht < 10 \\ 3.0 & \text{if } wall\_ht = 10 \\ \left[3.0 - \left(\frac{wall\_ht - 10}{10}\right)\right] & \text{if } 10 < wall\_ht < 20 \\ 2.0 & \text{otherwise} \end{cases}$$

$h\_eq = 2$ ft

(LL Surcharge height)

Assume:

$k := 0.5$

LOADS for 1' Sections

Dead Loads

Top Slab

Soil Weight - EV

$W\_EV := F\_e\cdot H\_\cdot\gamma\_soil\cdot 1$

$W\_EV = 5.52 \ \frac{k}{ft}$

Top Slab Wt. - DC

$W\_DC := \gamma\_c\cdot ST\cdot 1$

$W\_DC = 0.2687 \ \frac{k}{ft}$

Future Wearing Surface - DW

$W\_DW := \gamma\_ws\cdot t\_ws\cdot 1$

$W\_DW = 0.035 \ \frac{k}{ft}$

Totals

$W\_TopSlab := W\_EV + W\_DC + W\_DW$

$W\_TopSlab = 5.82375 \ \frac{k}{ft}$

Exterior Walls

Soil Weight - EH

At Center of Top Slab

$$W\_EH := \left(H\_ + \frac{ST}{2}\right) \cdot \gamma\_soil\_H \cdot 1$$

$$W\_EH = 2.45375 \quad \frac{k}{ft}$$

At Center of Bottom Slab

$$W\_EH2 := \left(H\_ + ST + Clr\_Ht + \frac{SB}{2}\right) \cdot \gamma\_soil\_H \cdot 1$$

$$W\_EH2 = 2.74125 \quad \frac{k}{ft}$$

Live Loads

IGNORE LIVE LOADS??? (3.6.1.2.6)

$$ILL := \begin{cases} \begin{cases} 1 & \text{if } D\_E > 8 \\ 2 & \text{otherwise} \end{cases} & \text{if } Num\_Cell = 1 \\ \begin{cases} 1 & \text{if } D\_E > [Num\_Cell \cdot Clr\_Span + (Num\_Cell - 1) \cdot IT] \\ 2 & \text{otherwise} \end{cases} & \text{if } Num\_Cell > 1 \\ 3 & \text{otherwise} \end{cases}$$

1 = YES, Ignore LL
2 = NO

$$ILL = 1$$

Live Load Surcharge

$$\Delta p := k \cdot \gamma\_soil\_H \cdot h\_eq \cdot 1$$

$$\Delta p = 0.06 \quad \frac{k}{ft}$$

Lane Load

$$Full\_Span := Clr\_Span \cdot Num\_Cell \qquad Width := 10$$

$$F\_S\_Prime := 1.15 \cdot H\_ + Full\_Span \qquad Width\_Prime := 1.75 \cdot H\_ + Width$$

$$LaneL := \begin{cases} 0 & \text{if } Skew > 45 \\ 0 & \text{if } Clr\_Span \le 15 \\ 0 & \text{if } Type = 1 \\ \left(\frac{Full\_Span}{F\_S\_Prime} \cdot \frac{Width}{Width\_Prime} \cdot 0.64\right) & \text{otherwise} \end{cases}$$

(Type 1 = Box Culvert)

$$LaneL = 0 \quad \frac{k}{ft}$$

$$Counter\_LL := LaneL$$

***Note: Lane load only applys to slab culverts with clear spans greater than 15 feet and skews less than or equal to 45°.**

Live Load Vehicles

Perpendicular to Span

$S\_ := Clr\_Span$

$E\_noFill := \frac{(96 + 1.44 \cdot S\_)}{12}$

$E\_noFill = 9.2 \quad ft$

$E\_fill\_noOverlap := \left[\left(\frac{20}{12}\right) + F\_e \cdot D\_E\right] \cdot 2$

$E\_fill\_noOverlap = 95.33333 \quad ft$

$E\_fill\_overlap := \left(\frac{E\_fill\_noOverlap}{2}\right) + 6$

$E\_fill\_overlap = 53.66667 \ ft$

$$E\_fill := \begin{cases} E\_fill\_overlap & \text{if } E\_fill\_overlap < E\_fill\_noOverlap \\ E\_fill\_noOverlap & \text{otherwise} \end{cases}$$

$E\_fill = 53.66667 \quad ft$

$$E := \begin{cases} E\_noFill & \text{if } D\_E < 2 \\ \begin{cases} E\_noFill & \text{if } E\_noFill > E\_fill \\ E\_fill & \text{otherwise} \end{cases} & \text{if } D\_E \geq 2 \\ 101 & \text{otherwise} \end{cases}$$

$E = 53.66667 \ ft$

$LLDF := \left(\frac{1}{E}\right) \cdot mpf \cdot \left(1 + \frac{IM}{100}\right)$

$LLDF = 0.02236$

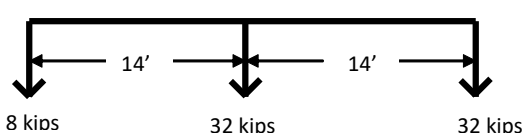
$l\_d := floor\left(\frac{10}{12} + F\_e \cdot D\_E\right)$

$l\_d = 46 \quad ft$

(length of distribution for one axel)

(also equals the number of centipede loads for one axel)

HS20 Truck



$HS20\_1 := 8 \quad kips$

$$HS20\_centLoad\_1 := \begin{cases} \left(\frac{HS20\_1}{l\_d}\right) & \text{if } l\_d > 0 \\ HS20\_1 & \text{otherwise} \end{cases}$$

$HS20\_2 := 32 \quad kips$

$$HS20\_centLoad\_2 := \begin{cases} \left(\frac{HS20\_2}{l\_d}\right) & \text{if } l\_d > 0 \\ HS20\_2 & \text{otherwise} \end{cases}$$

$HS20\_3 := 32 \quad kips$

$$HS20\_centLoad\_3 := \begin{cases} \left(\frac{HS20\_3}{l\_d}\right) & \text{if } l\_d > 0 \\ HS20\_3 & \text{otherwise} \end{cases}$$

$HS20axel := 3$

$HS20\_noOverlap := (l\_d) \cdot HS20axel \qquad HS20\_noOverlap = 138 \quad ft$

$HS20\_overlap := l\_d + 28 \qquad HS20\_overlap = 74 \quad ft$ (both also equal number of loads)

$$HS20\_gap := \begin{cases} \begin{cases} (14 - l\_d + 1) & \text{if } (14 - l\_d + 1) > 0 \\ 0 & \text{otherwise} \end{cases} & \text{if } l\_d > 0 \\ 14 & \text{otherwise} \end{cases}$$

(gap between sets of loads)

$$HS20\_Length := \begin{cases} l\_d & \text{if } HS20\_noOverlap \le HS20\_overlap \\ HS20\_overlap & \text{otherwise} \end{cases}$$

$$HS20\_Set := \begin{cases} 3 & \text{if } HS20\_gap > 0 \\ 1 & \text{otherwise} \end{cases}$$

$$HS20\_Load\_1 := \begin{cases} (HS20\_centLoad\_1 \cdot LLDF) & \text{if } HS20\_gap > 0 \\ \left[\frac{(HS20\_centLoad\_1 + HS20\_centLoad\_2 + HS20\_centLoad\_3)}{3} \cdot \frac{HS20\_noOverlap}{HS20\_overlap} \cdot LLDF\right] & \text{otherwise} \end{cases}$$

$$HS20\_Load\_2 := \begin{cases} (HS20\_centLoad\_2 \cdot LLDF) & \text{if } HS20\_gap > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$HS20\_Load\_3 := \begin{cases} (HS20\_centLoad\_3 \cdot LLDF) & \text{if } HS20\_gap > 0 \\ 0 & \text{otherwise} \end{cases}$$

$HS20\_Load\_1 = 0.02176 \quad kips \qquad HS20\_Load\_2 = 0 \quad kips \qquad HS20\_Load\_3 = 0 \quad kips$

$HS20\_gap = 0 \quad ft$

$HS20\_Set = 1$

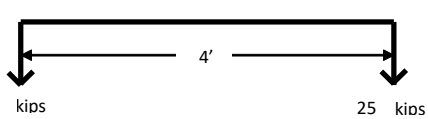
$HS20\_Length = 74 \quad ft$ (also = # of loads)

(With 1 foot spacings)

$$Counter\_Load\_HS20 := \begin{cases} (HS20\_Load\_1 + HS20\_Load\_2 + HS20\_Load\_3) \cdot \frac{HS20\_Length}{Full\_Span} & \text{if } l\_d > 0 \\ \frac{(HS20\_Load\_1 + HS20\_Load\_2 + HS20\_Load\_3)}{Full\_Span} & \text{otherwise} \end{cases}$$

$Counter\_Load\_HS20 = 0.16099 \quad \frac{k}{ft}$

Tandem



$Tandem\_1 := 25 \quad kips$

$$Tandem\_centLoad\_1 := \begin{cases} \left(\frac{Tandem\_1}{l\_d}\right) & \text{if } l\_d > 0 \\ Tandem\_1 & \text{otherwise} \end{cases}$$

$Tandem\_2 := 25 \quad kips$

$$Tandem\_centLoad\_2 := \begin{cases} \left(\frac{Tandem\_2}{l\_d}\right) & \text{if } l\_d > 0 \\ Tandem\_2 & \text{otherwise} \end{cases}$$

$Tandemaxel := 2$

$Tandem\_noOverlap := (l\_d) \cdot Tandemaxel$ $\qquad Tandem\_noOverlap = 92 \quad ft$

$Tandem\_overlap := l\_d + 4$ $\qquad Tandem\_overlap = 50 \quad ft$ (both also equal number of loads)

$$Tandem\_gap := \begin{cases} \begin{cases} (4 - l\_d + 1) & \text{if } (4 - l\_d + 1) > 0 \\ 0 & \text{otherwise} \end{cases} & \text{if } l\_d > 0 \\ 4 & \text{otherwise} \end{cases}$$

(gap between sets of loads)

$$Tandem\_Length := \begin{cases} l\_d & \text{if } Tandem\_noOverlap \le Tandem\_overlap \\ Tandem\_overlap & \text{otherwise} \end{cases}$$

$$Tandem\_Set := \begin{cases} 2 & \text{if } Tandem\_gap > 0 \\ 1 & \text{otherwise} \end{cases}$$

$$Tandem\_Load\_1 := \begin{cases} (Tandem\_centLoad\_1 \cdot LLDF) & \text{if } Tandem\_gap > 0 \\ \left[\left(Tandem\_centLoad\_1 \cdot \frac{Tandem\_noOverlap}{Tandem\_overlap}\right) \cdot LLDF\right] & \text{otherwise} \end{cases}$$

$$Tandem\_Load\_2 := \begin{cases} (Tandem\_centLoad\_2 \cdot LLDF) & \text{if } Tandem\_gap > 0 \\ 0 & \text{otherwise} \end{cases}$$

$Tandem\_Load\_1 = 0.02236 \quad kips$ $\qquad Tandem\_Load\_2 = 0 \quad kips$

$Tandem\_gap = 0 \quad ft$

$Tandem\_Set = 1$

$Tandem\_Length = 50 \quad ft$ (also = # of loads)

(With 1 foot spacings)

$$Counter\_Load\_Tandem := \begin{cases} (Tandem\_Load\_1 + Tandem\_Load\_2) \cdot \frac{Tandem\_Length}{Full\_Span} & \text{if } l\_d > 0 \\ \frac{(Tandem\_Load\_1 + Tandem\_Load\_2)}{Full\_Span} & \text{otherwise} \end{cases}$$

$Counter\_Load\_Tandem = 0.1118 \quad \frac{k}{ft}$

Output

Dead Loads

Top Slab

$W\_TopSlab = 5.82375 \ \frac{k}{ft}$

Exterior Walls

At Center of Top Slab

$W\_EH = 2.45375 \ \frac{k}{ft}$

At Center of Bottom Slab

$W\_EH2 = 2.74125 \ \frac{k}{ft}$

Live Loads

1 = YES, Ignore LL
2 = NO

$ILL = 1$

Live Load Surcharge

$\Delta p = 0.06 \ \frac{k}{ft}$

Lane Load

$LaneL = 0 \ \frac{k}{ft}$

$Counter\_LL = 0$

HS20 Truck

$HS20\_Load\_1 = 0.02176$ kips

$HS20\_Load\_2 = 0$ kips

$HS20\_Load\_3 = 0$ kips

$HS20\_gap = 0$ ft

$HS20\_Set = 1$

$HS20\_Length = 74$ ft (also = # of loads)

(With 1 foot spacings)

$Counter\_Load\_HS20 = 0.16099 \ \frac{k}{ft}$

Tandem

$Tandem\_Load\_1 = 0.02236$ kips

$Tandem\_Load\_2 = 0$ kips

$Tandem\_gap = 0$ ft

$Tandem\_Set = 1$

$Tandem\_Length = 50$ ft (also = # of loads)

(With 1 foot spacings)

$Counter\_Load\_Tandem = 0.1118 \ \frac{k}{ft}$

APPENDIX C

CULVERT MODELING IN STAAD PRO

The first step in creating a 2D model is positioning nodes for the ends of members and connecting them to form members. Node and member input for a 2 cell slab type culvert with a clear height of 4 feet and a clear span of 10 feet, along with its pictorial representation, is illustrated in Figure C.1. Material and spatial properties are defined as seen in Figure C.2 and then assigned to the appropriate members. The next step is to create and assign supports to the model, such as fixed or pinned. Figure C.3 shows a custom support being defined that only releases force in the horizontal direction. In the same figure, the box shaped supports on the culvert represent fixed end types, and the triangular shaped support represents the custom type.

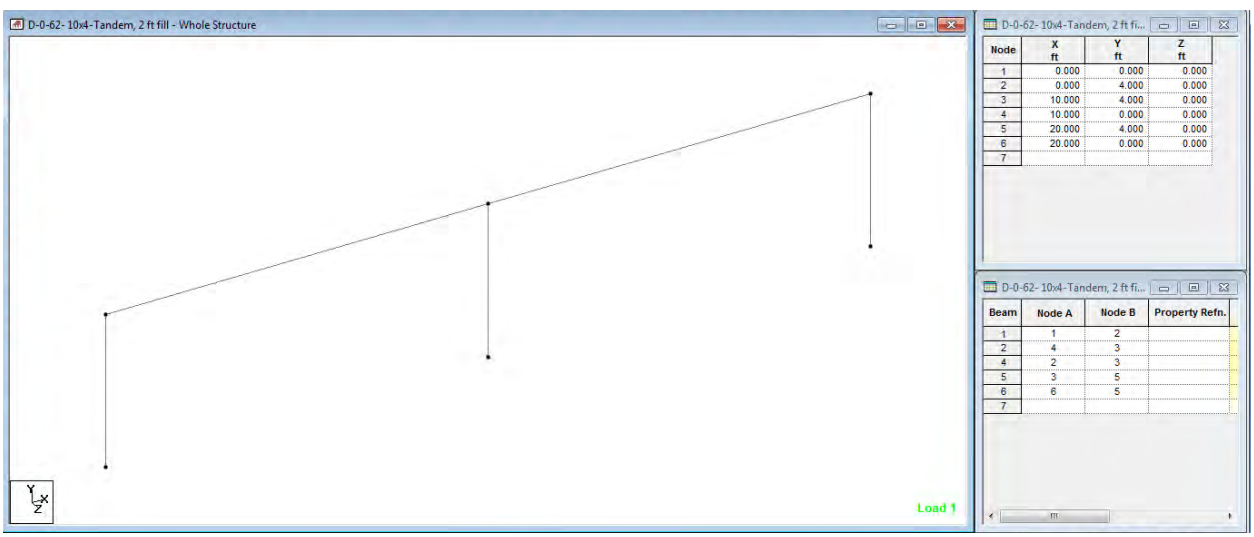


Figure C.1: STAAD Pro- Node and Member Creation

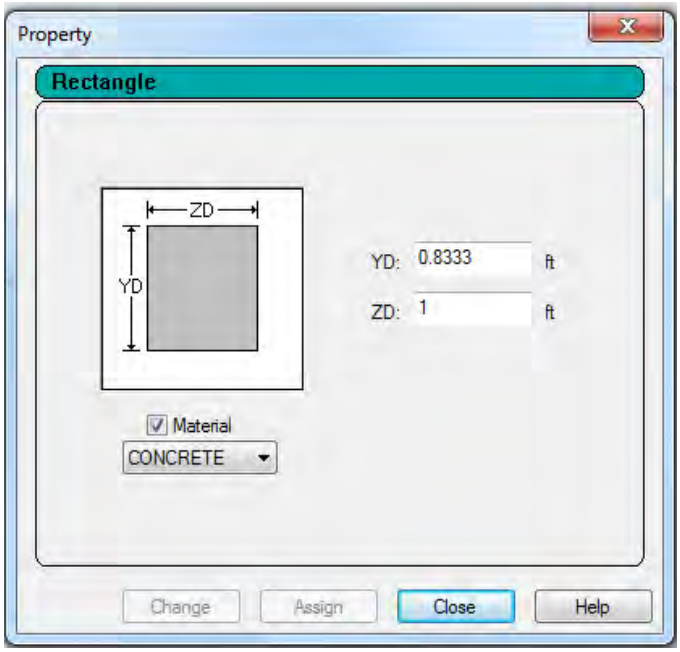


Figure C.2: STAAD Pro- Defining Spatial and Material Properties

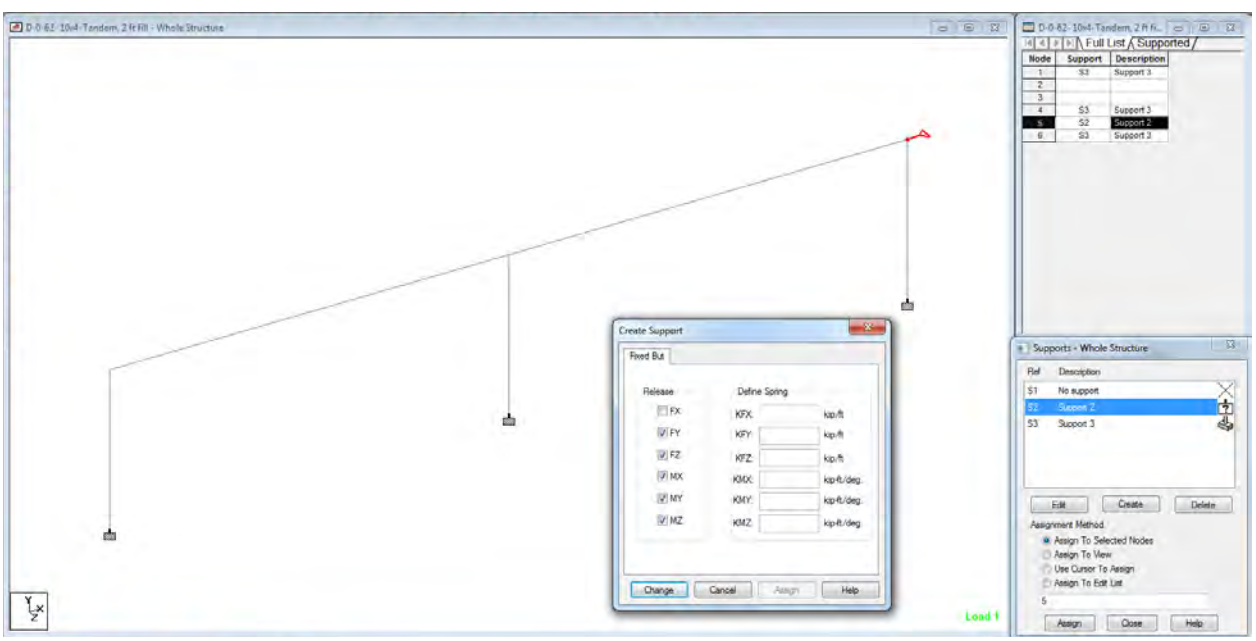


Figure C.3: STAAD Pro- Custom Supports Creation

The last step required before analyzing the structure is to define load cases. Types of loads can include self-weight of members, point loads, uniform loads, linear loads, moving loads, and more. Figure C.4 shows a uniform dead load being defined. This load is modeled with a uniform member load applied downward in the vertical direction. Once all desired load cases are created and positioned, models can be analyzed for everything from deformation of members to determining internal forces in the model. The internal forces of the top slab for this culvert model can be viewed in Figure C.5.

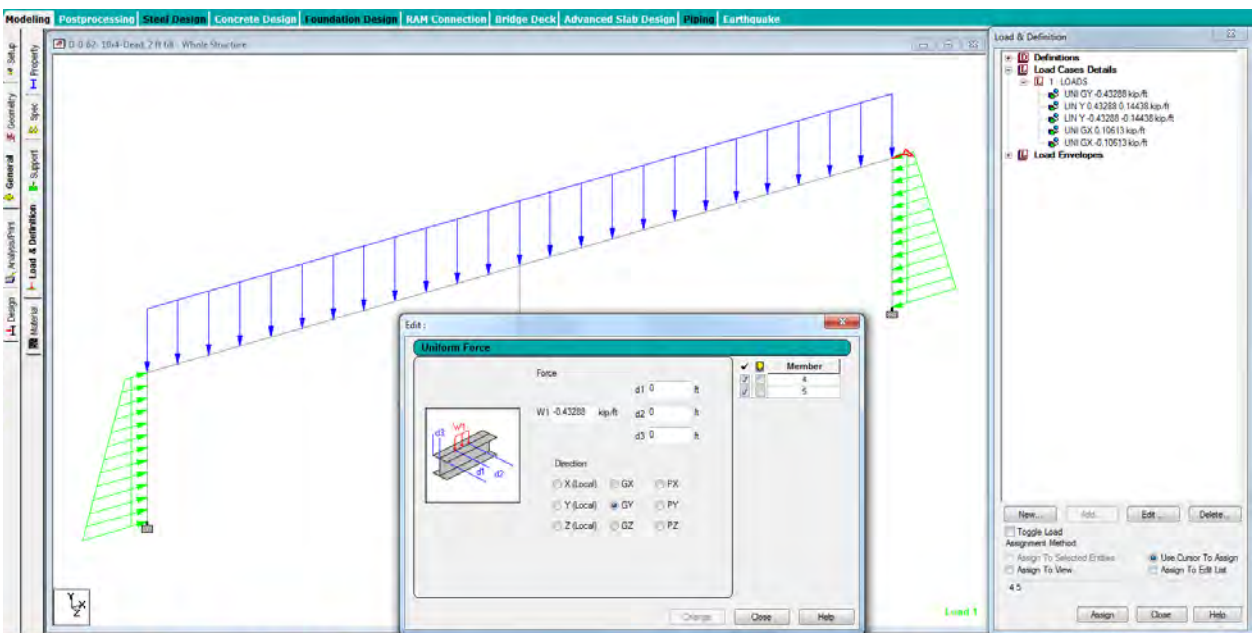


Figure C.4: STAAD Pro- Defining Load Cases

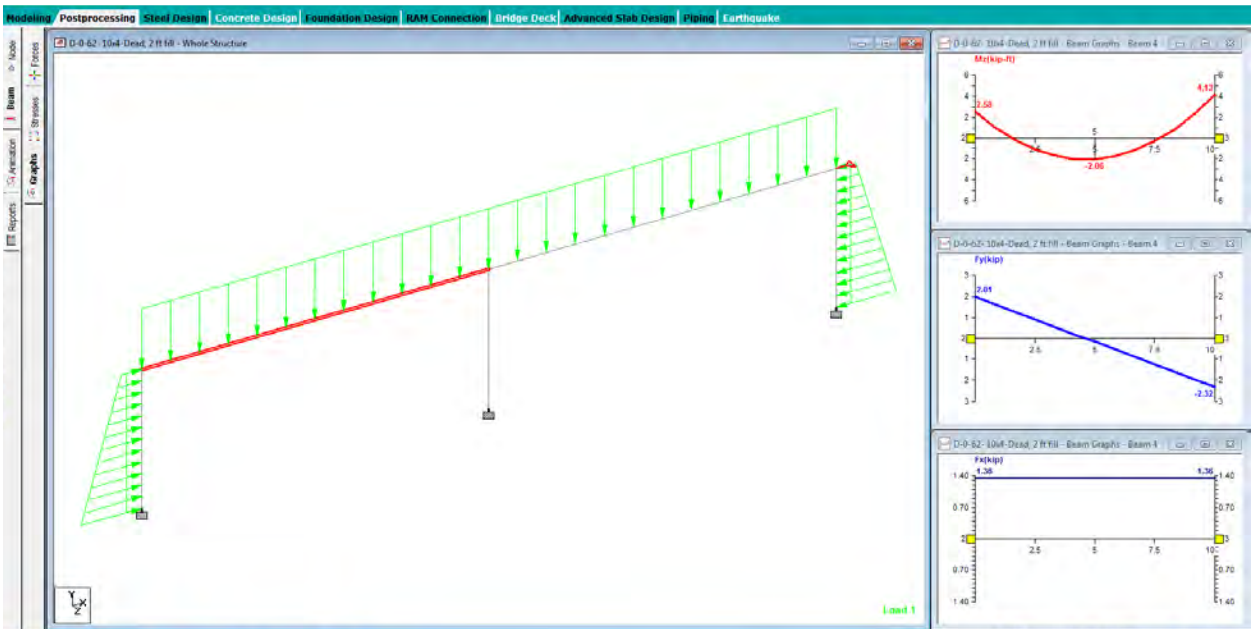


Figure C.5: STAAD Pro- Analysis Results of Forces for a Top Slab Member

APPENDIX D

STAAD PRO VERIFICATION

To verify the output information produced from STAAD, the moments produced by STAAD were compared to the moments produced by BRASS Culvert.

Two culverts each with two different fill depths were used in the moment verification. These culverts each had two cells with a clear span of 18 feet. The first culvert had a clear height of four feet and was analyzed with zero and eight feet of fill. The second culvert had a clear height of 18 feet and was analyzed with zero and ten feet of fill. Tables were created that show the combined dead load moments, the positive and negative live load moments caused by the HS20 truck, and the surcharge moments acting on the culvert members.

Tables, Table D.1, D.2, D.3, and D.4, were created that show the combined dead load moments, the positive and negative live load moments caused by the HS20 truck, and the surcharge moments acting on the members of the previously stated culverts. The top part of the tables show the unfactored moments calculated from STAAD, and the bottom part of the tables show the unfactored moments calculated from BRASS Culvert. Table D.1 shows the moments from the first culvert, the 18 x 4 culvert, with zero feet of fill. Table D.2 shows the moments from the first culvert, the 18 x 4 culvert, with eight feet of fill. Table D.3 shows the moments from the second culvert, the 18 x 18 culvert, with zero feet of fill. Table D.4 shows the moments from the second culvert, the 18 x 18 culvert, with ten feet of fill. From these tables, it can be seen that the dead load moments and the live load moments calculated by the two programs are very close to being the same moment values.

Table D.1: 18 x 4 Zero Feet Fill STAAD Pro and BRASS Culvert Comparison

18 x 4, 0 ft fill					
Unfactored Moments (k-ft) – STAAD Pro					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-2.7	0.67	-0.74	-0.15
	Top	-2.26	0.99	-3.42	-0.15
Top Slab	Left	-2.26	0.99	-3.42	-0.15
	Right	-13.8	0	-13.50	0.07
Interior Wall	Bottom	0.05	0.88	-0.88	0
	Top	-0.05	2.46	-2.46	0
Bottom Slab	Left	-2.7	0.67	-0.74	-0.15
	Right	-15.8	0	-3.50	0.07
Unfactored Moments (k-ft) – BRASS Culvert					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-2.60	0.90	-0.70	-0.15
	Top	-2.22	0.94	-3.45	-0.15
Top Slab	Left	-2.22	0.94	-3.45	-0.15
	Right	-13.83	0.01	-13.60	0.07
Interior Wall	Bottom	0.05	0.90	-0.97	0
	Top	-0.05	2.55	-2.48	0
Bottom Slab	Left	-2.60	0.90	-0.70	-0.15
	Right	-15.96	0	-3.55	0.07

Table D.2: 18 x 4 Eight Feet Fill STAAD Pro and BRASS Culvert Comparison

18 x 4, 8 ft fill					
Unfactored Moments (k-ft) – STAAD Pro					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-8.86	0.1	-0.65	-0.15
	Top	-8.76	0.64	-1.33	-0.15
Top Slab	Left	-8.76	0.64	-1.33	-0.15
	Right	-54.9	0	-5.68	0.07
Interior Wall	Bottom	0.04	0.38	-0.38	0
	Top	0.04	1.11	-1.11	0
Bottom Slab	Left	-8.86	0.1	-0.65	-0.15
	Right	-57.5	0	-4.29	0.07
Unfactored Moments (k-ft) – BRASS Culvert					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-8.68	0.14	-0.63	-0.15
	Top	-8.64	0.54	-1.42	-0.15
Top Slab	Left	-8.64	0.54	-1.42	-0.15
	Right	-55.22	0	-5.70	0.07
Interior Wall	Bottom	0.04	0.42	-0.43	0
	Top	-0.04	1.16	-1.14	0
Bottom Slab	Left	-8.68	0.14	-0.63	-0.15
	Right	-58.01	0	-4.22	0.07

Table D.3: 18 x 18 Zero Feet Fill STAAD Pro and BRASS Culvert Comparison

18 x 18, 0 ft fill					
Unfactored Moments (k-ft) – STAAD Pro					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-25.0	0.95	-0.33	-1.80
	Top	-17.5	0.64	-2.61	-1.77
Top Slab	Left	-17.5	0.65	-2.61	-1.77
	Right	-6.47	0	-13.2	0.83
Interior Wall	Bottom	0.06	0.43	-0.43	0
	Top	-0.06	0.97	-0.97	0
Bottom Slab	Left	-25.0	0.95	-0.33	-1.80
	Right	-13.9	0	-1.35	0.88
Unfactored Moments (k-ft) – BRASS Culvert					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-24.9	1.02	-0.30	-1.80
	Top	-17.47	0.66	-2.63	-1.78
Top Slab	Left	-17.47	0.66	-2.63	-1.78
	Right	-6.35	0.49	-13.31	0.85
Interior Wall	Bottom	0.06	0.43	-0.43	0
	Top	-0.06	0.97	-0.97	0
Bottom Slab	Left	-24.9	1.02	-0.30	-1.80
	Right	-14.16	0	-1.40	0.90

Table D.4: 18 x 18 Ten Feet Fill STAAD Pro and BRASS Culvert Comparison

18 x 18, 10 ft fill					
Unfactored Moments (k-ft) – STAAD Pro					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-46.5	0.28	-0.37	-1.80
	Top	-40.2	0.34	-0.98	-1.77
Top Slab	Left	-40.2	0.34	-0.98	-1.77
	Right	-50.7	0	-4.73	0.83
Interior Wall	Bottom	0.06	0.16	-0.16	0
	Top	-0.06	0.38	-0.38	0
Bottom Slab	Left	-46.6	0.28	-0.37	-1.80
	Right	-60.5	0	-2.41	0.88
Unfactored Moments (k-ft) – BRASS Culvert					
Member	Location	Dead Loads (DC+EV+EH+WS)	LL(+) HS20 Truck	LL(-) HS20 Truck	LS Surcharge
Exterior Wall	Bottom	-46.53	0.29	-0.27	-1.80
	Top	-40.1	0.32	-1.04	-1.78
Top Slab	Left	-40.1	0.32	-1.04	-1.78
	Right	-50.74	0.03	-4.75	0.85
Interior Wall	Bottom	0.06	0.18	-0.18	0
	Top	-0.06	0.41	-0.41	0
Bottom Slab	Left	-46.53	0.29	-0.27	-1.80
	Right	-60.98	0	-2.39	0.90

To help as a visual aid and to further prove the verification of STAAD's moments from the HS20 truck, graphs were produced showing the moments from the two programs at the tenth points of each member of the 18 x 18 culvert zero feet of fill. Figures D.1, D.3, D.5, and D.7 show the values of the positive moments acting on the tenth points of each member for the 18 x 18 culvert at zero feet of fill. Figures D.2, D.4, D.6, and D.8 show the values of the negative moments acting on the tenth points of each member for the 18 x 4 culvert at zero feet of fill. In these figures the STAAD moments are represented in blue and the BRASS Culvert moments are represented in red. When only the red is shown on the graphs, the moments are the same between the two programs for the particular point along the length of the member. For the exterior and interior walls, the zero tenth point represents the bottom of the wall and the ten tenth point represents the top of the wall. For the top and bottom slabs, the zero tenth point represents the left side of the slab and the ten tenth point represents the right side of the slab.

From the information presented in the tables and the graphs presented in this appendix, it was determined that the culvert modeling process in STAAD produces the correct dead and live load moments acting on the culvert be analyzed.

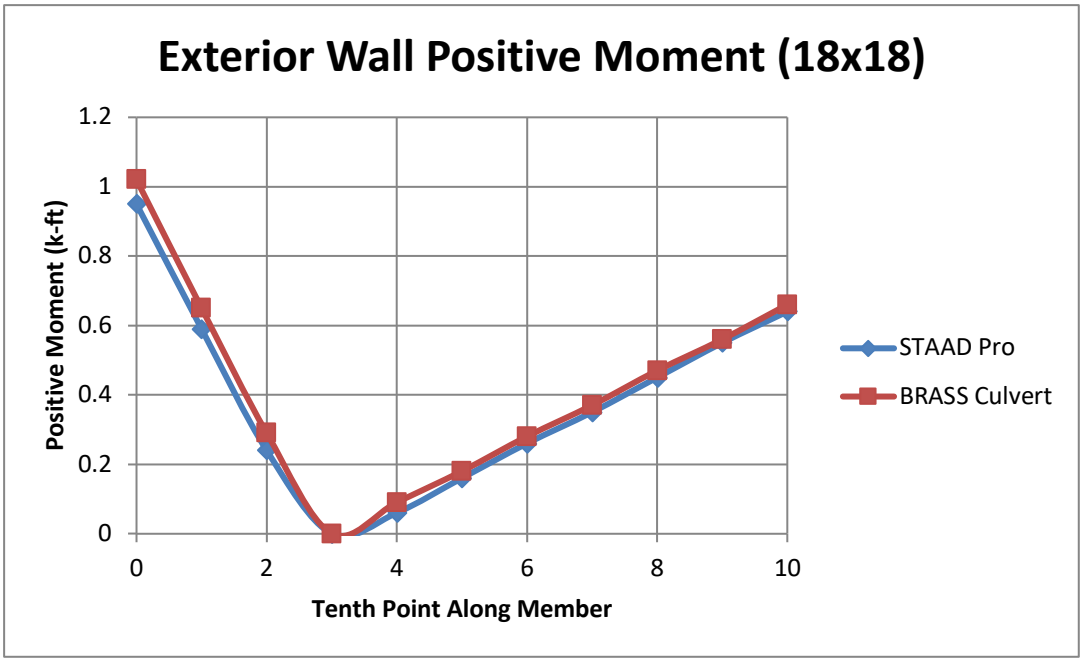


Figure D.1: 18 x 18 Zero Feet of Fill Positive Moment for Exterior Wall

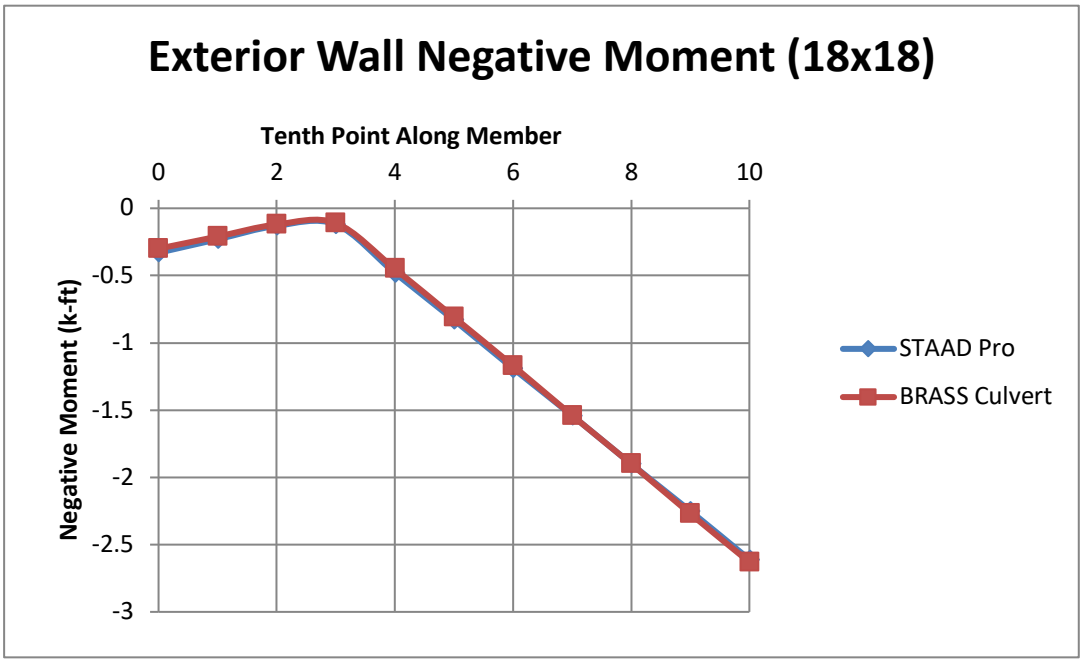


Figure D.2: 18 x 18 Zero Feet of Fill Negative Moment for Exterior Wall

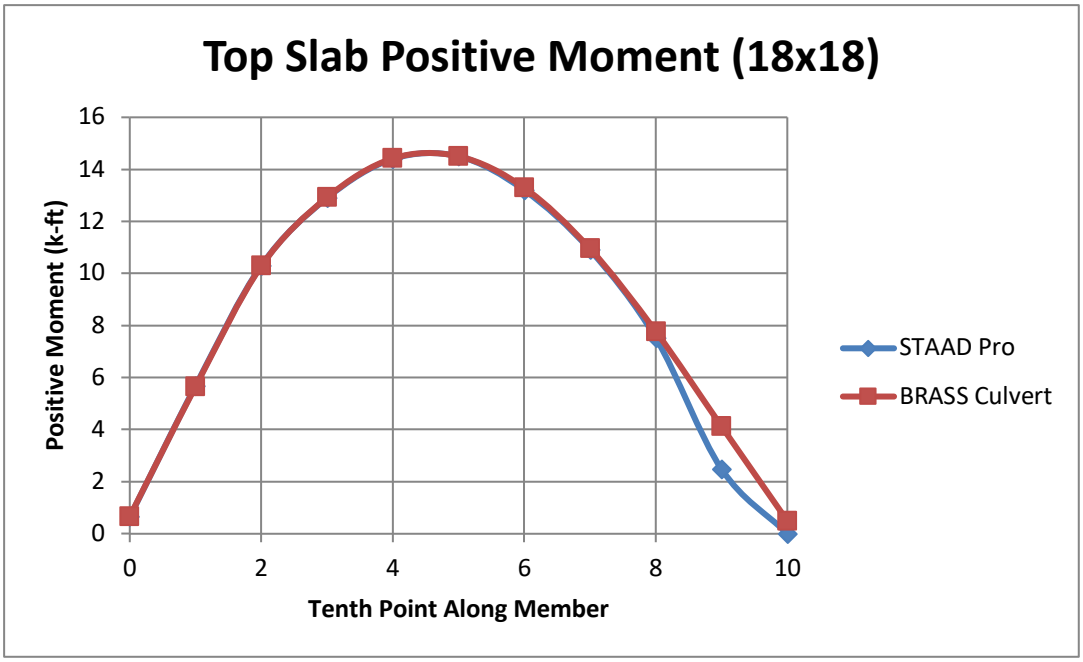


Figure D.3: 18 x 18 Zero Feet of Fill Positive Moment for Top Slab

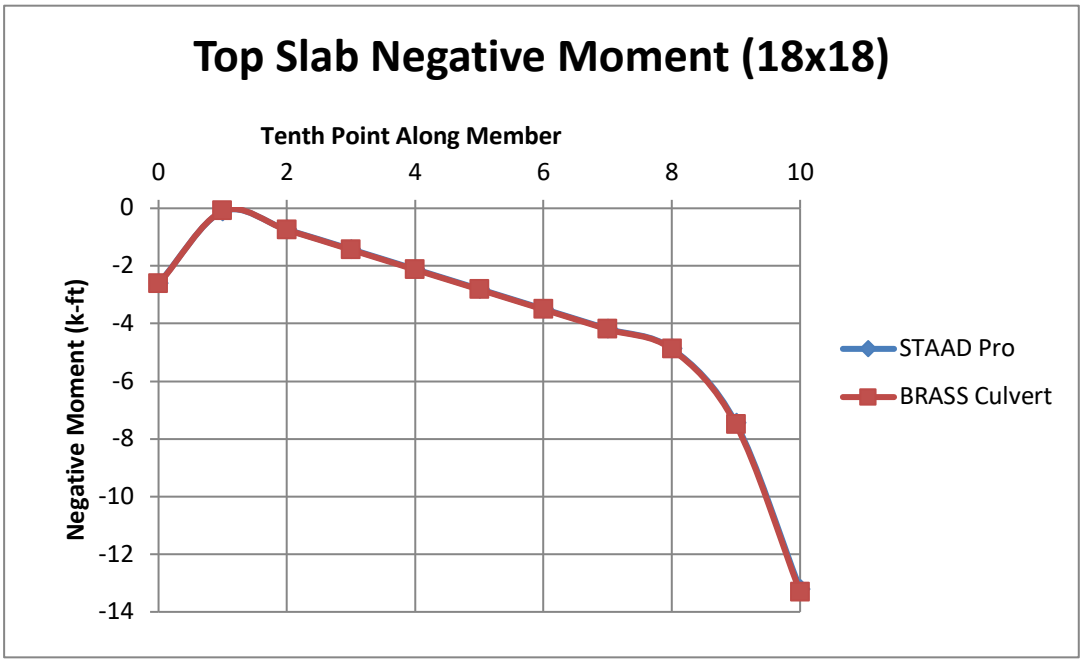


Figure D.4: 18 x 18 Zero Feet of Fill Negative Moment for Top Slab

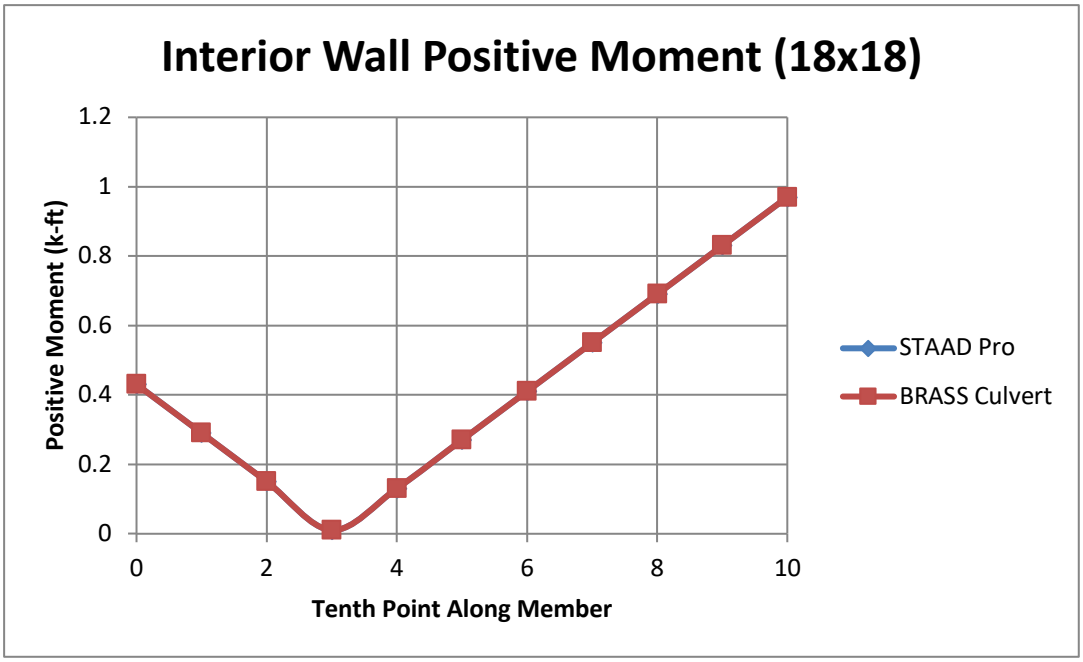


Figure D.5: 18 x 18 Zero Feet of Fill Positive Moment for Interior Wall

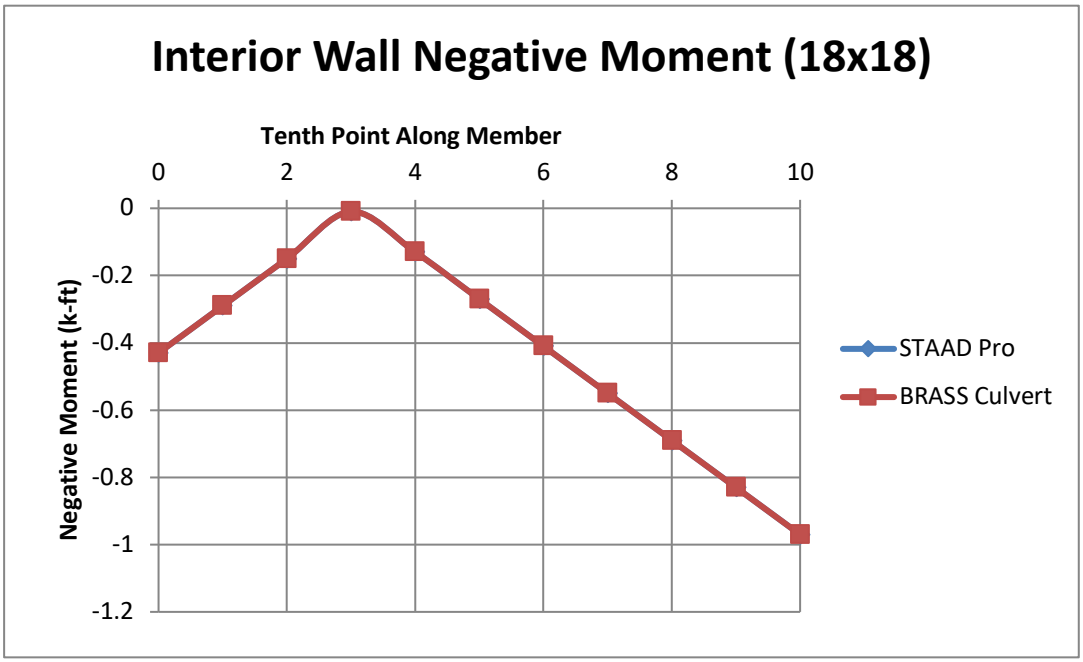


Figure D.6: 18 x 18 Zero Feet of Fill Negative Moment for Interior Wall

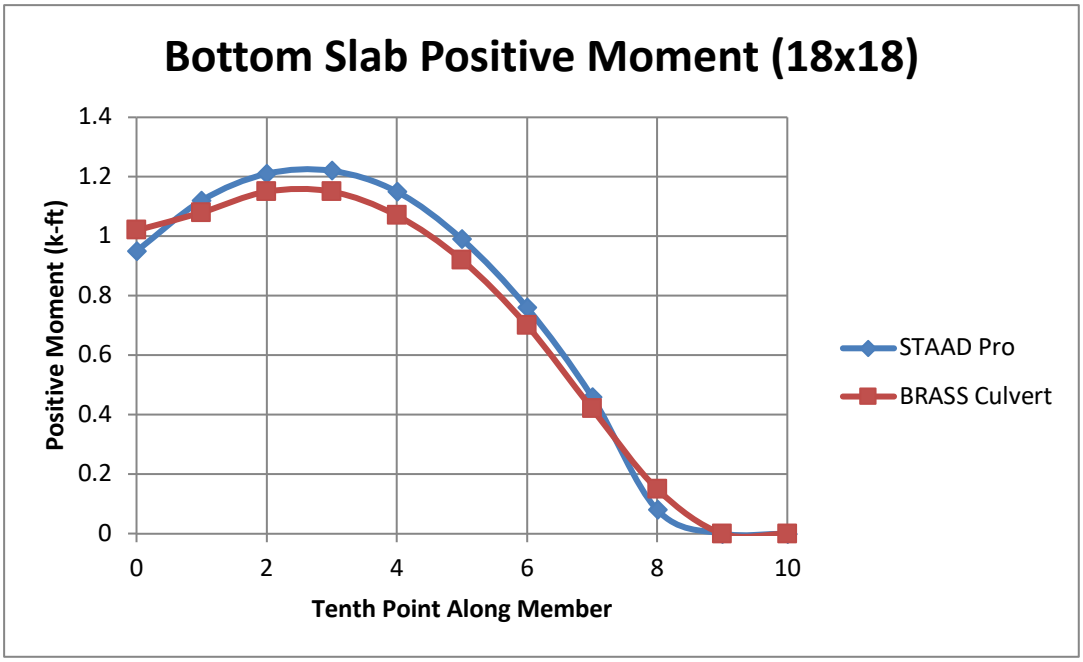


Figure D.7: 18 x 18 Zero Feet of Fill Positive Moment for Bottom Slab

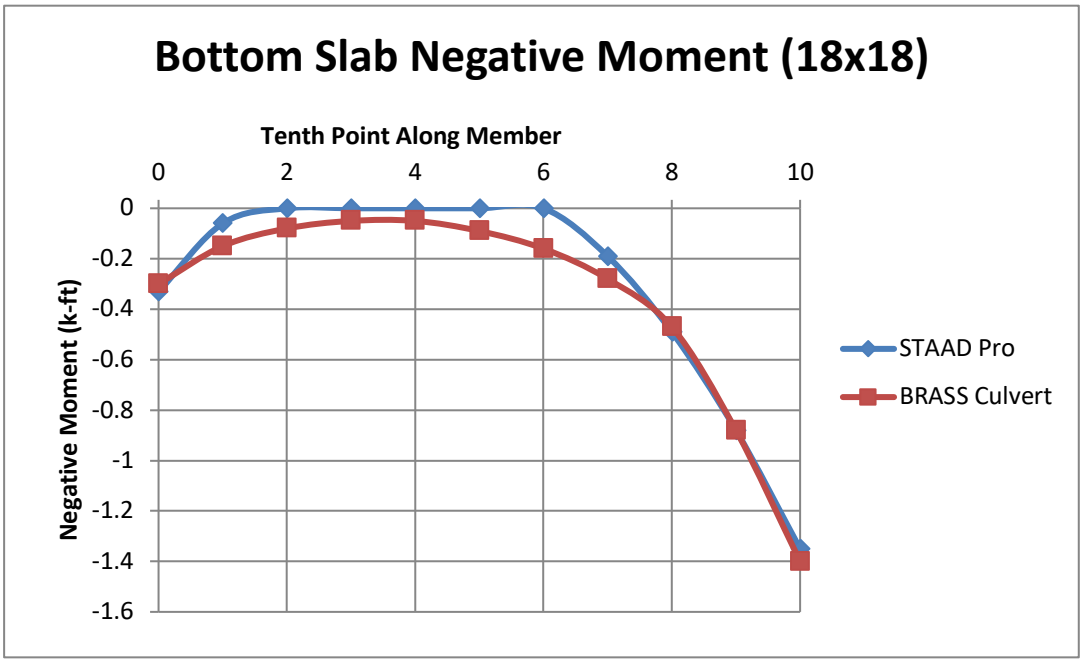


Figure D.8: 18 x 18 Zero Feet of Fill Negative Moment for Bottom Slab

APPENDIX E

CULVERT MODELING IN BRASS CULVERT

Figures E.1 to E.6 cover the method used to input values into BRASS Culvert. Figure E.1 shows the "Analysis Control" input tab. This tab allows the choice of cast in place vs. precast construction, the analysis method, whether or not a bottom slab exists, full or no moment continuity, the design method, including shear in the analysis or not, and a few more details. Figure E.2 shows the "Material Properties" tab where values for concrete compressive strength, steel strength, and densities can be entered. Figure E.3 contains the "Box Geometry" input tab. In addition to lengths and thicknesses, this tab is where the number of cells is entered. The "Skew" and "Concrete Cover" tab are shown in Figures E.4 and E.5, respectively. The skew angle is entered as the angle between the centerline of the walls and a line normal to the centerline of the roadway, which can be seen as the 45° angle labeled in Figure E.4. Figure E.6 shows the "Reinforcement Review" tab. This tab allows the entering of steel rebar size and spacing for positive and negative steel of the slabs and exterior walls, corner bar reinforcement, and interior wall reinforcement.

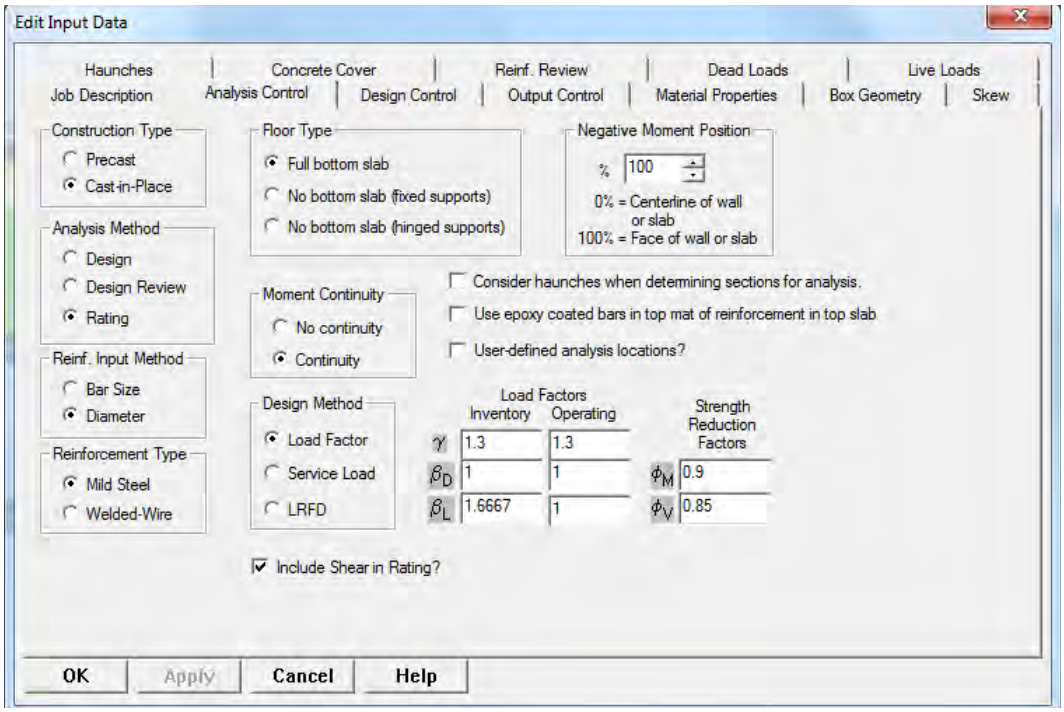


Figure E.1: BRASS Culvert- Analysis Control Input

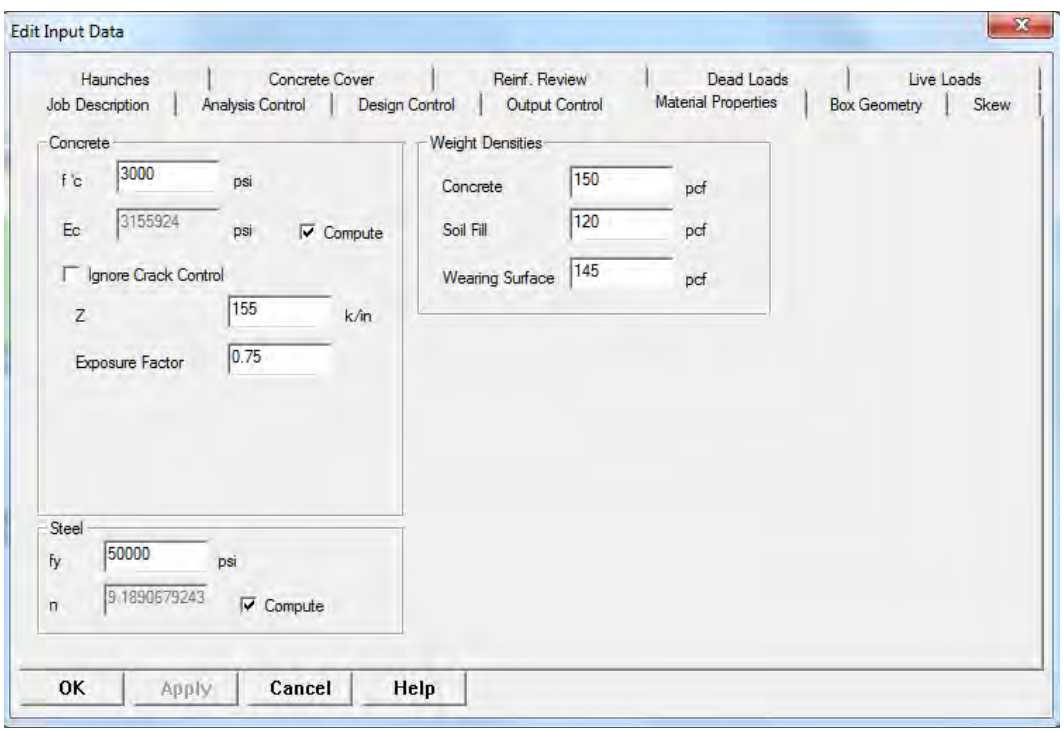


Figure E.2: BRASS Culvert- Material Properties Input

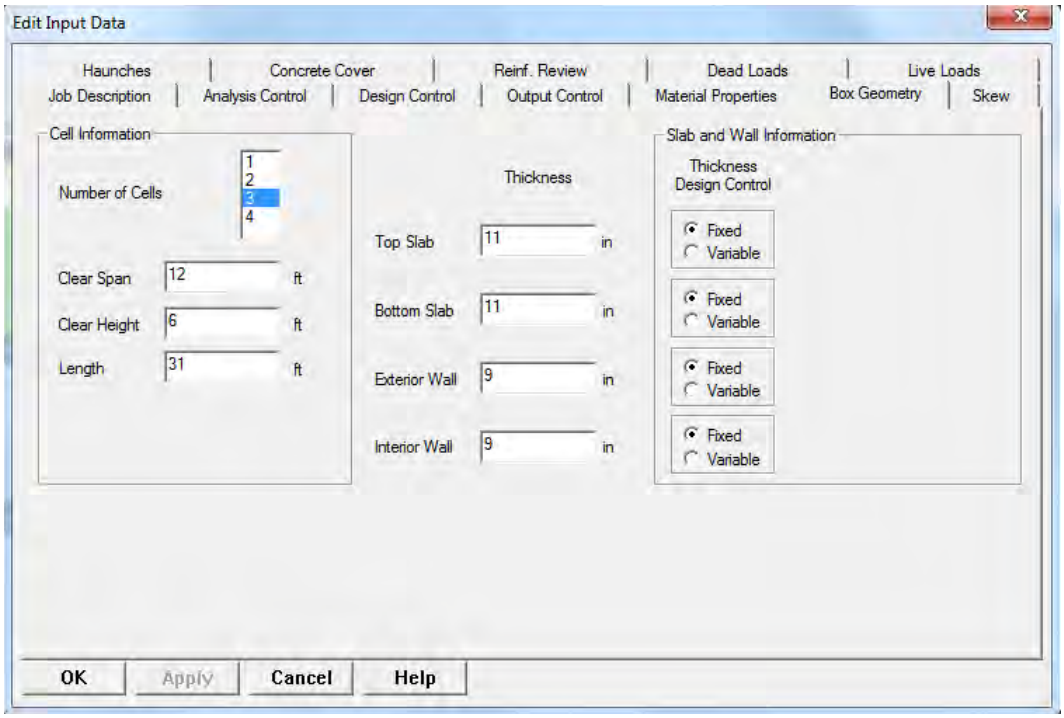


Figure E.3: BRASS Culvert- Culvert Geometry Input

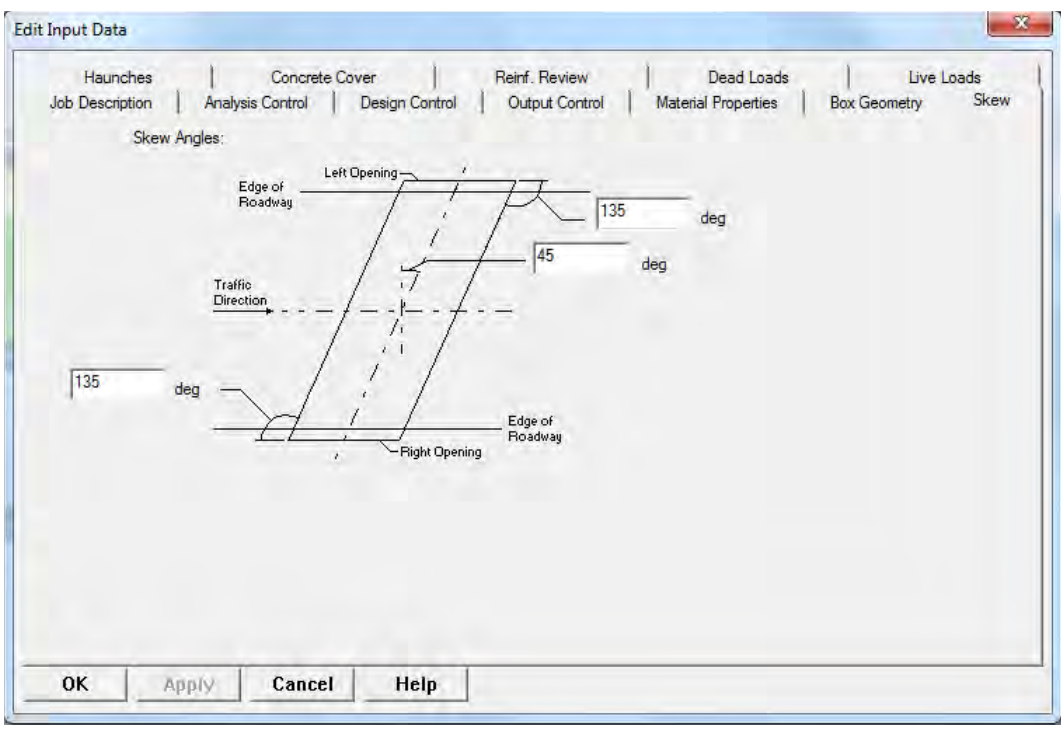


Figure E.4: BRASS Culvert- Skew Angle Input

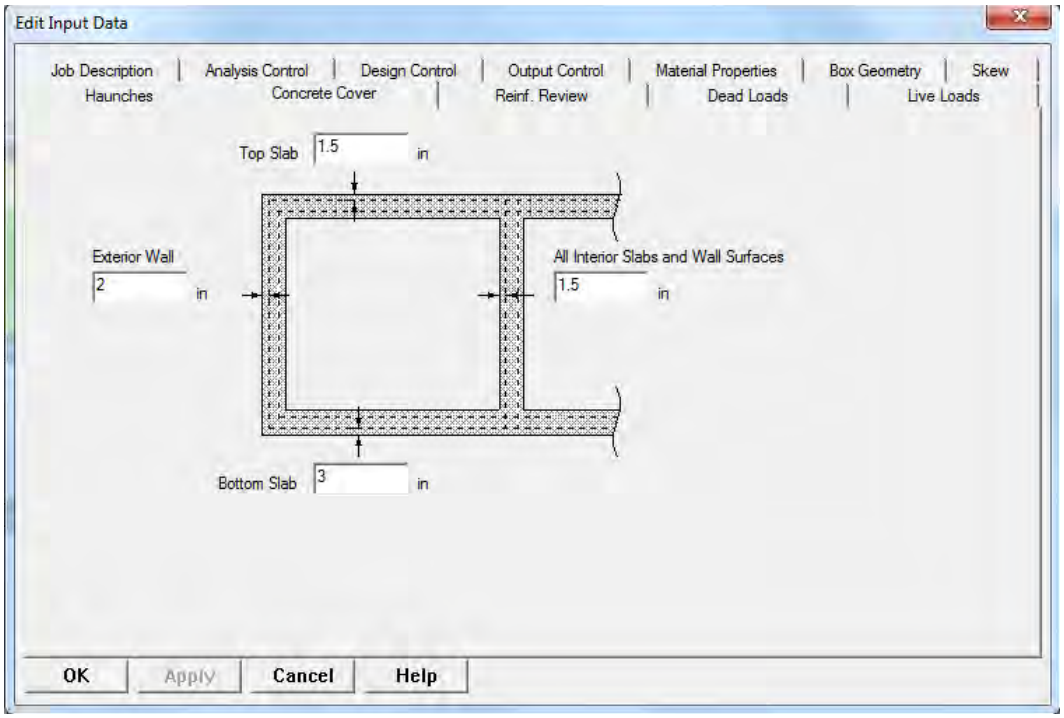


Figure E.5: BRASS Culvert- Concrete Cover Input

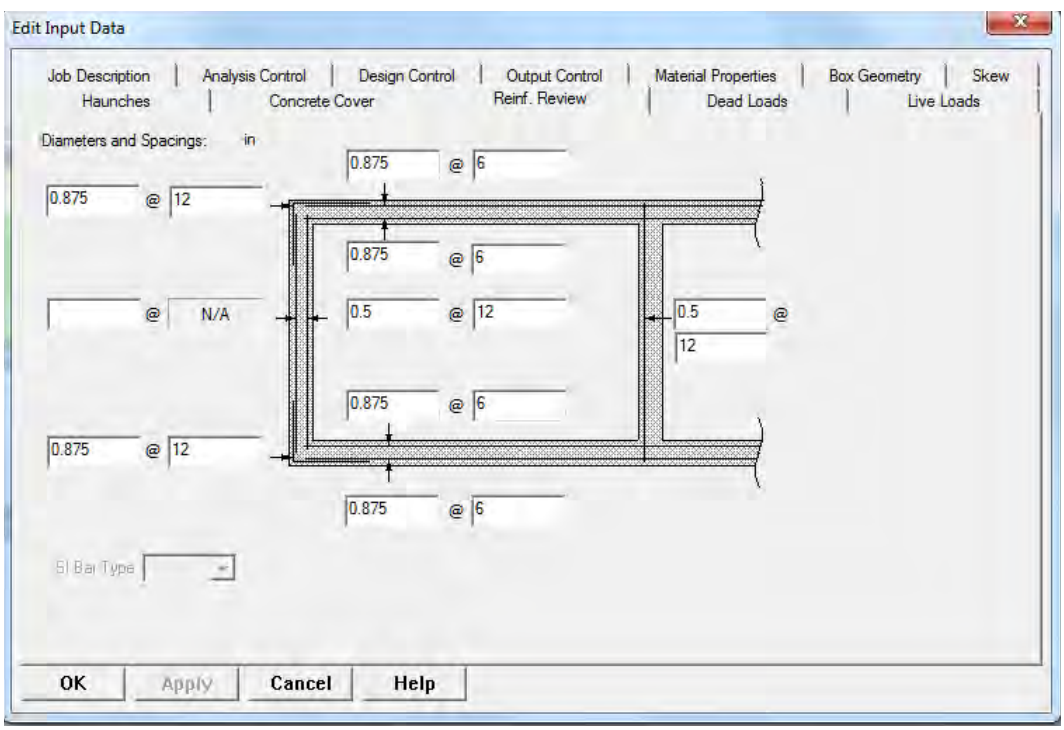


Figure E.6: BRASS Culvert- Steel Reinforcement Size and Spacing Input

The last two remaining tabs are for the dead and live load input. Figure E.7 shows the "Dead Loads" tab. Under the concentrated loads section, magnitudes and positions of point loads can be entered. The pressures section is for assigning the minimum and maximum soil pressure, along with the unit weight of water. Below the pressures section, the soil-structure interaction factor can be automatically computed for compacted or uncompacted soil, or can be overridden with a set value. The diagram to the bottom left allows the user to enter additional uniform dead loads, the thickness of the wearing surface, and the fill depth. Figure E.8 shows the "Live Loads" input tab. In addition to the vehicular live loads, live load surcharge can also be assigned as well as choosing whether to model the tire loads as concentrated or patch loads.

Figure E.9 is a picture of the scale model automatically generated for the input case shown in Figures E.1 to E.8. This figure shows the member and haunch thicknesses, clear distances, fill depth, wearing surface thickness and weight, uniform dead loads, soil pressures, and live load surcharge. Finally, Figure E.10 represents a portion of the output file pertaining to the H15 truck load.

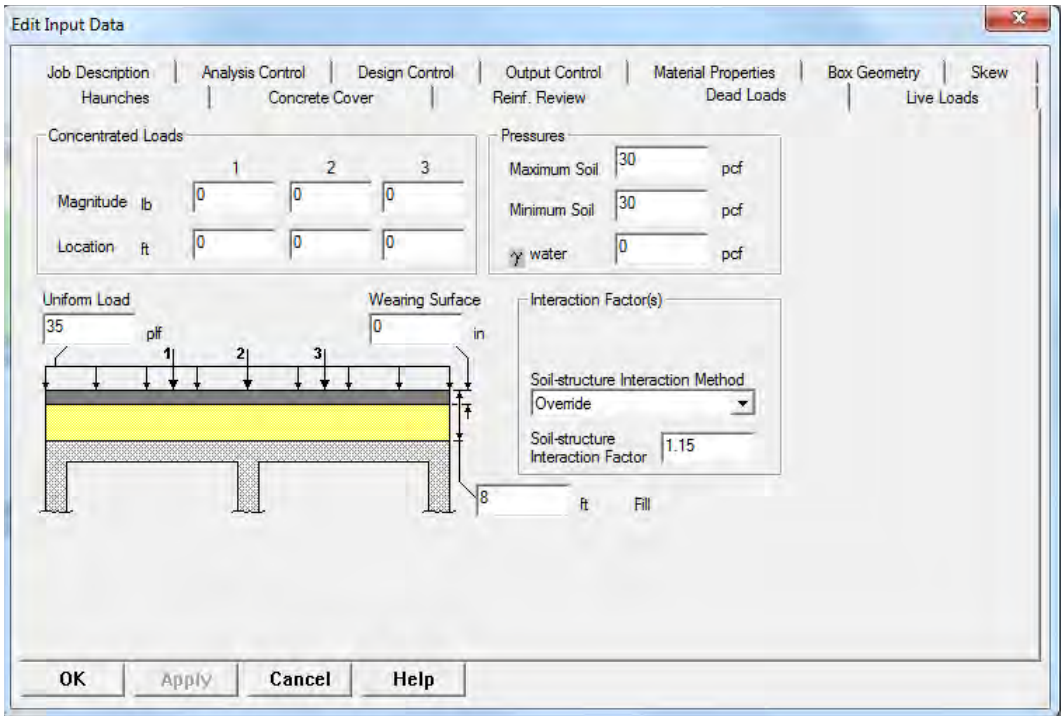


Figure E.7: BRASS Culvert- Dead Load Input

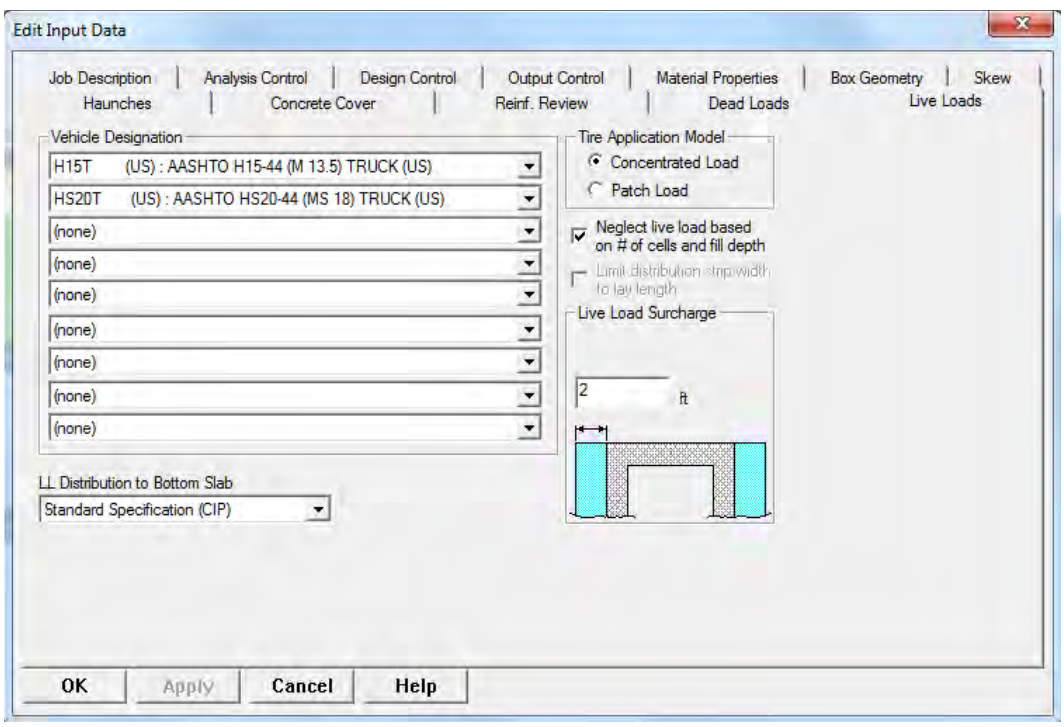


Figure E.8: BRASS Culvert- Live Load Input

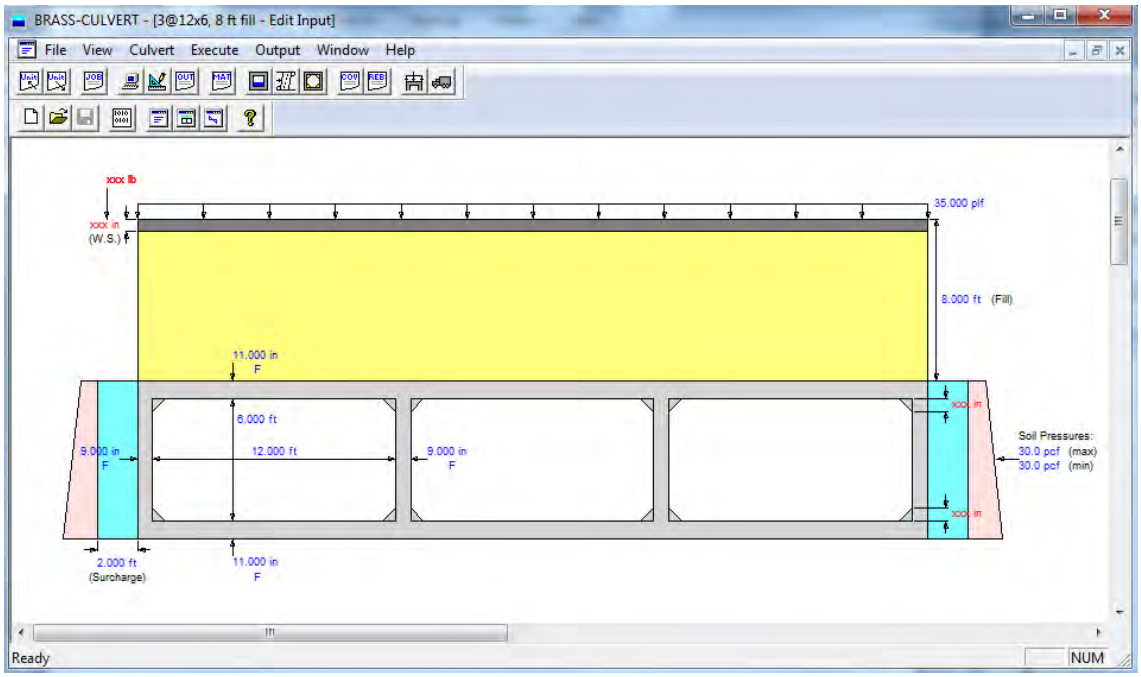


Figure E.9: BRASS Culvert- Generated Model Diagram

Output at Critical Sections (per unit design width)

Member No. = 1 EXTERIOR WALL

Thickness	= 10.00 (in)
Clear cover at end	= 2.00 (in)
Clear cover at middle	= 1.50 (in)
Bar diameter (bot)	= 0.00 (in)
Bar diameter (mid+)	= 0.56 (in)
Bar diameter (mid-)	= 0.00 (in)
Bar diameter (top)	= 0.00 (in)

	Moment Kft	Coin. Axial Force Kips	Shear Force Kips	Shear Cap Kips	Resistance Po Cap Kips	Resistance Mu Cap Kft	Mbal Cap Kft	Pbal Cap Kips	Steel Area In2	Mom. Cap Kft	Des. Thk in	Flexure Ratings Inv	Flexure Ratings Oper	Shear Ratings Inv	Shear Ratings Oper
BOT	0.0	n/a	0.3	10.2	178.5	0.0	n/a	n/a	0.0000 S	0.0	8.00	99.0	99.0	68.8	99.0
MID	0.5	1.5	0.0	10.5	183.9	5.0	20.1	84.6	0.2498	5.2	8.22	n/a	n/a	NA	NA
MID-	0.3	n/a	0.0	10.2	178.5	0.0	n/a	n/a	0.0000	0.0	8.00	99.0	99.0	NA	NA
TOP	0.1	n/a	0.2	10.2	178.5	0.0	n/a	n/a	0.0000 S	0.0	8.00	99.0	99.0	99.0	99.0

Member No. = 2 TOP SLAB

Thickness	= 9.75 (in)
Clear cover at end	= 2.00 (in)
Clear cover at middle	= 1.50 (in)
Bar diameter (lt)	= 0.00 (in)
Bar diameter (mid)	= 0.75 (in)
Bar diameter (rt)	= 0.75 (in)

LT	0.5	n/a	8.0	9.9	174.0	0.0	n/a	n/a	0.0000 S	0.0	7.75	99.0	99.0	1.3	2.2
MID	21.6*	0.3	1.6	10.0	194.0	16.6	23.0	65.3	0.9220	16.6	7.88	0.7	1.2	NA	NA
RT	-16.2*	0.3	10.9*	9.4	184.0	8.1	19.8	70.5	0.4610	8.1	7.38	0.1	0.2	0.8	1.3

Member No. = 3 INTERIOR WALL

Thickness	= 10.00 (in)
Clear cover at end	= 1.50 (in)
Clear cover at middle	= 1.50 (in)
Bar diameter (bot)	= 0.56 (in)
Bar diameter (mid+)	= 0.56 (in)
Bar diameter (mid-)	= 0.56 (in)
Bar diameter (top)	= 0.56 (in)

BOT	-0.0	7.6	0.0	10.5	183.9	5.0	20.1	84.6	0.2498	6.3	8.22	n/a	n/a	99.0	99.0
MID	0.0	7.6	0.0	10.5	183.9	5.0	20.1	84.6	0.2498	6.3	8.22	n/a	n/a	NA	NA
MID-	-0.0	7.6	0.0	10.5	183.9	5.0	20.1	84.6	0.2498	6.3	8.22	n/a	n/a	NA	NA
TOP	-0.0	7.6	0.0	10.5	183.9	5.0	20.1	84.6	0.2498	6.3	8.22	n/a	n/a	99.0	99.0

Figure E.10: BRASS Culvert- Partial Output File

APPENDIX F

CULVERT MODELING IN RESPONSE-2000

Figures F.1 through F.4 cover the "Quick Define" process for creating a cross section in Response-2000. The first step to creating a new model is shown in Figure F.1. The concrete strength, longitudinal and transverse steel yield strength, and the prestressed steel type are entered as needed. The second step is covered in Figure F.2. The second step involves the choosing of an appropriate cross sectional shape and dimensions. Figure F.3 shows the third step, which involves choosing the size and amount of steel rebar to be considered in the top and bottom of the section. The final step is shown in Figure F.4. This field allows the entering of stirrups and prestressing steel. As neither existed in either culvert database used in this thesis, this page was left unchanged. Once completed, a representation of the cross section and other material properties is displayed as shown in Figure F.5.

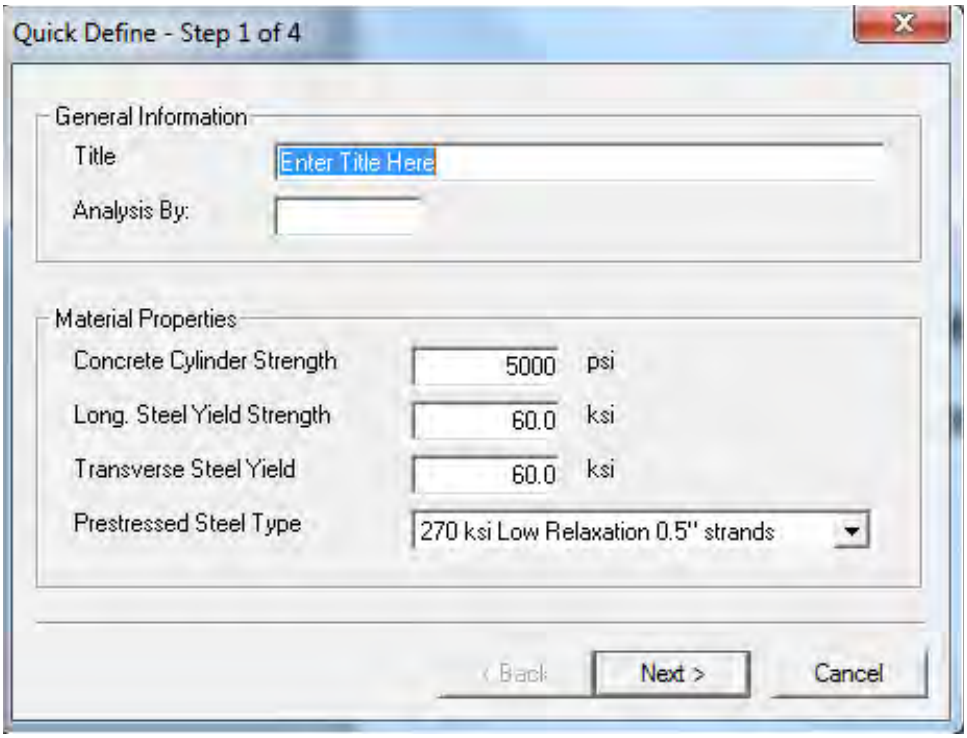


Figure F.1: Response-2000- Material Properties

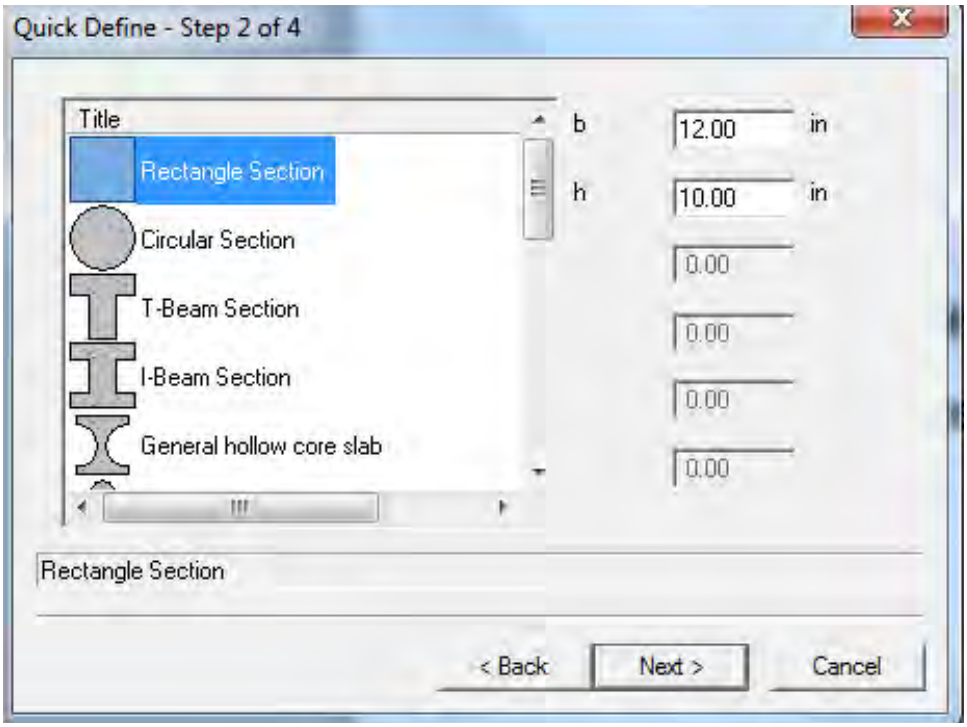


Figure F.2: Response-2000- Cross Sections

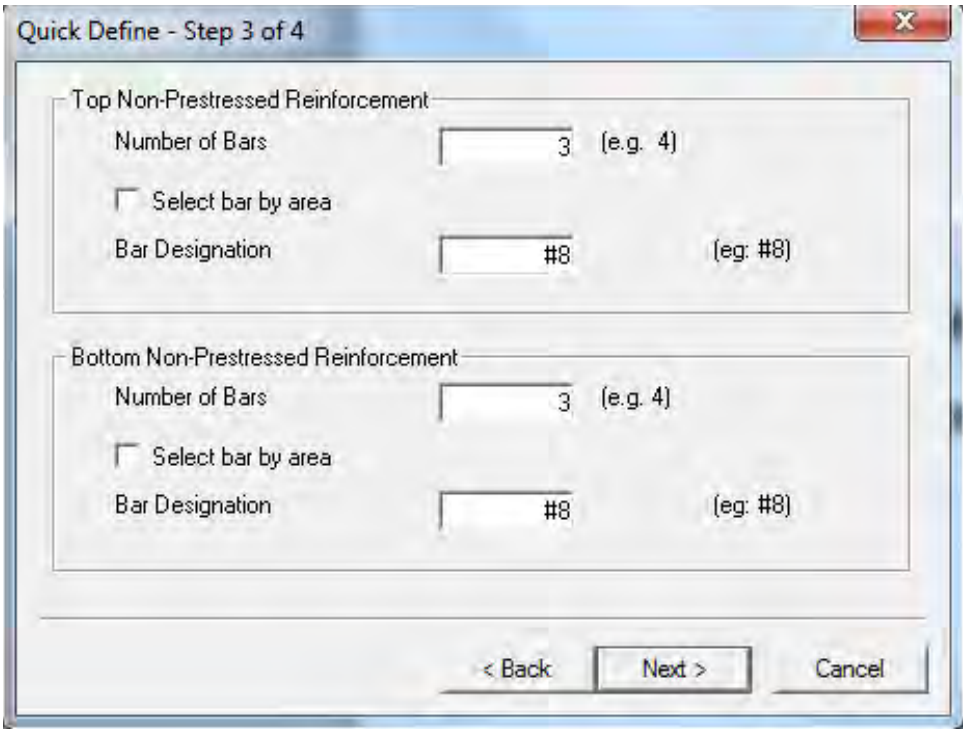


Figure F.3: Response-2000- Top and Bottom Steel Size and Spacing

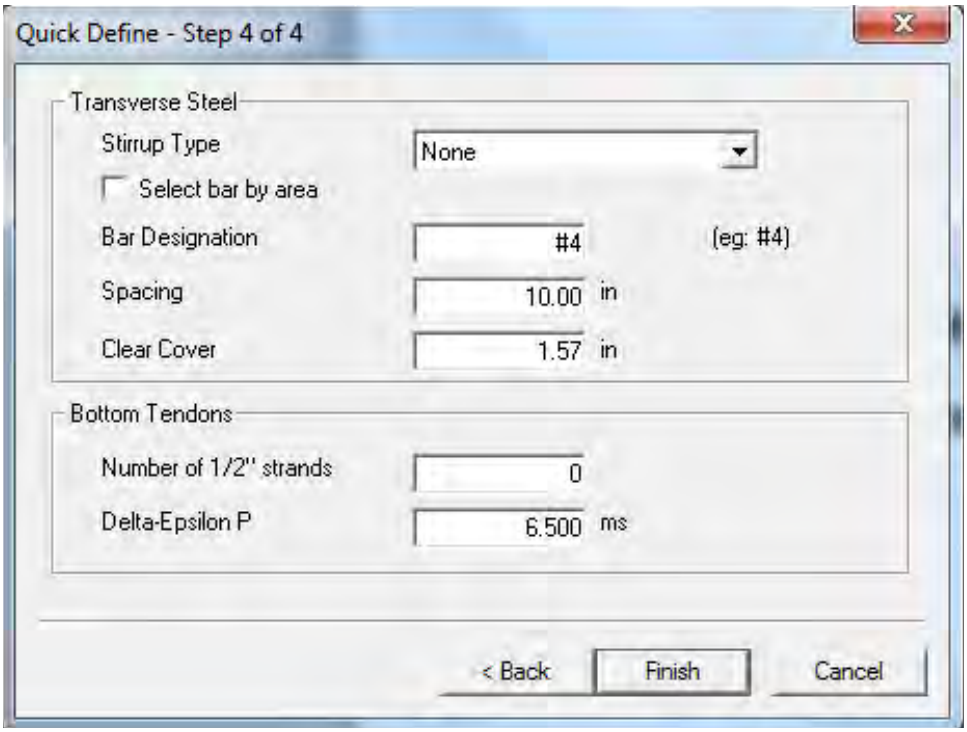


Figure F.4: Response-2000- Transverse Steel and Bottom Tendons

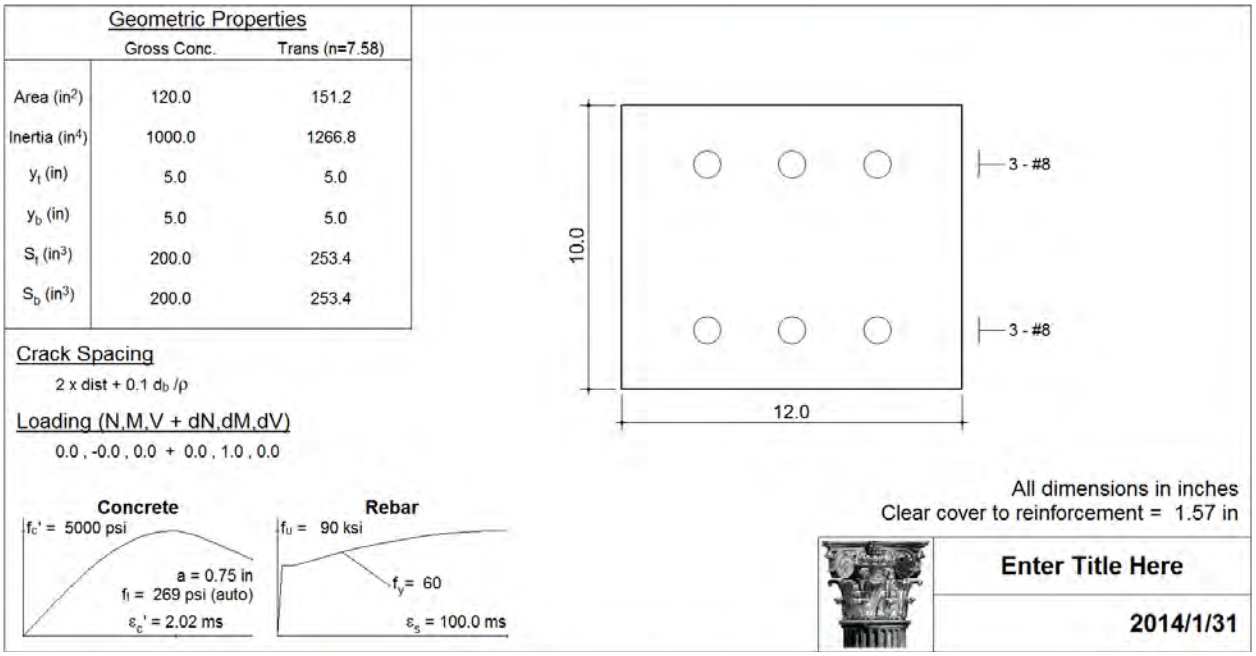


Figure F.5: Response-2000- Cross Section View

The last step before an analysis can be made is the entering of the loads. Figure F.6 shows the load definition window. To perform a "One Time" analysis and attain cracking strengths, the left handed "Constant" column is used. This type of analysis does not consider any values under the "Increment" column. To perform a "Sectional Response" analysis and attain ultimate values, the Constant column should be left blank and the loads should be entered under the Increment column. Figure F.7 contains a Controlling Shear-Shear Strain graph from a Sectional Response type analysis. The highest value of 15.9 indicates the analyzed section's ultimate shear strength.

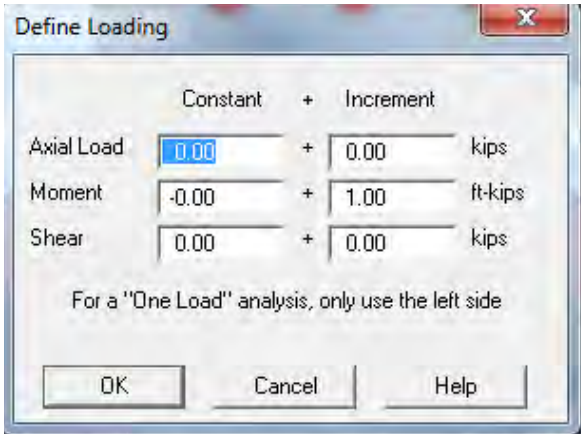


Figure F.6: Response-2000- Load Case Definition

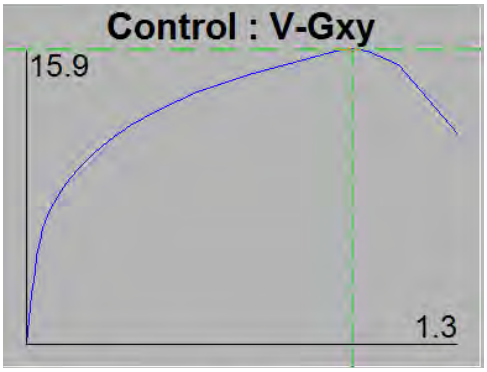


Figure F.7: Response-2000- Control Plot of Shear-Shear Strain

APPENDIX G

TDOT DUMP TRUCK RATING FACTOR ANALYSIS RESULTS

Appendix G1: Box Culvert Flexural Rating Factor Tables

C-10-14: 1946, 1@10x5, 0-5 ft Fill				1-Cell									
Skew Angle = 30 Degrees				Exterior Wall				Top Slab			Bottom Slab		
				Flexure				Flexure			Flexure		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.4	99	n/a	99	99	99	1.4	99	99	10.7	99
	Dump Truck	Operating	1.6	99	n/a	99	99	99	1.6	99	99	6.4	99
2	Cntrl. Truck	Operating	1	99	n/a	99	99	99	1	99	99	7.4	99
	Dump Truck	Operating	1.1	99	n/a	99	99	99	1.1	99	99	4.8	99
5	Cntrl. Truck	Operating	1.5	99	n/a	99	99	99	1.5	99	99	2.3	99
	Dump Truck	Operating	1.3	99	n/a	99	99	99	1.3	99	99	1.7	99

E-12-36 :1952, 1@10x6, 0-5 ft Fill				1-Cell									
Skew Angle = 30 Degrees				Exterior Wall				Top Slab			Bottom Slab		
				Flexure				Flexure			Flexure		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.4	99	n/a	99	99	99	1.4	99	99	12	99
	Dump Truck	Operating	1.6	99	n/a	99	99	99	1.6	99	99	7.1	99
2	Cntrl. Truck	Operating	1	99	n/a	99	99	99	1	99	99	8.3	99
	Dump Truck	Operating	1.1	99	n/a	99	99	99	1.1	99	99	5.4	99
5	Cntrl. Truck	Operating	1.5	99	n/a	99	99	99	1.5	99	99	2.3	99
	Dump Truck	Operating	1.3	99	n/a	99	99	99	1.3	99	99	1.7	99

B-2-36: 1934, 2@8x4, 0-6 ft Fill				2-Cell													
Skew Angle = 35 Degrees				Exterior Wall				Top Slab			Interior Wall				Bottom Slab		
				Flexure				Flexure			Flexure				Flexure		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	1.2	99	n/a	99	99	99	1.2	2.4	n/a	n/a	n/a	n/a	99	14.1	4.8
	Dump Truck	Operating	1.8	99	n/a	99	99	99	1.9	1.8	n/a	n/a	n/a	n/a	99	16.8	5.7
2	Cntrl. Truck	Operating	1.1	99	n/a	99	99	99	1.1	1.6	n/a	n/a	n/a	n/a	99	11.5	2.9
	Dump Truck	Operating	1.2	99	n/a	99	99	99	1.6	1.2	n/a	n/a	n/a	n/a	99	13.6	3.4
5	Cntrl. Truck	Operating	0.4	99	n/a	99	99	99	3	1.6	n/a	n/a	n/a	n/a	99	8.6	0.4
	Dump Truck	Operating	0.4	99	n/a	99	99	99	2.7	1.3	n/a	n/a	n/a	n/a	99	7.7	0.4
6	Cntrl. Truck	Operating	0	99	n/a	99	99	99	3.6	1.1	n/a	n/a	n/a	n/a	99	8.8	0
	Dump Truck	Operating	0	99	n/a	99	99	99	2.8	0.9	n/a	n/a	n/a	n/a	99	7.5	0

C-10-113: 1948, 2@10x8, 0-9 ft Fill				2-Cell													
Skew Angle = 90 Degrees				Exterior Wall				Top Slab			Interior Wall				Bottom Slab		
				Flexure				Flexure			Flexure				Flexure		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	1.1	n/a	n/a	99	n/a	31.5	1.1	1.5	n/a	n/a	n/a	n/a	n/a	19.5	7.9
	Dump Truck	Operating	1.4	n/a	n/a	99	n/a	30.9	1.4	1.7	n/a	n/a	n/a	n/a	n/a	16.8	6.9
2	Cntrl. Truck	Operating	0.7	n/a	n/a	99	n/a	n/a	0.9	0.7	n/a	n/a	n/a	n/a	n/a	15.3	2.8
	Dump Truck	Operating	1	n/a	n/a	99	n/a	24.3	1	1	n/a	n/a	n/a	n/a	n/a	14.5	4.1
5	Cntrl. Truck	Operating	0	n/a	n/a	99	n/a	n/a	1.8	0.2	n/a	n/a	n/a	n/a	n/a	5.4	0
	Dump Truck	Operating	0	n/a	n/a	99	n/a	n/a	1.6	0.7	n/a	n/a	n/a	n/a	n/a	5.7	0
8	Cntrl. Truck	Operating	0	n/a	n/a	99	n/a	n/a	2	0	n/a	n/a	n/a	n/a	n/a	4.1	0
	Dump Truck	Operating	0	n/a	n/a	99	n/a	n/a	1.3	0	n/a	n/a	n/a	n/a	n/a	3.6	0
9	Cntrl. Truck	Operating	0	n/a	n/a	99	n/a	n/a	1.3	0	n/a	n/a	n/a	n/a	n/a	3	0
	Dump Truck	Operating	0	n/a	n/a	99	n/a	n/a	1	0	n/a	n/a	n/a	n/a	n/a	2.5	0

E-8-119: 1951, 2@15x8, no fill				2-Cell														
Skew Angle = 90 Degrees				Exterior Span														
			Controlling RF	Exterior Wall				Top Slab			Interior Wall				Bottom Slab		
				Flexure				Flexure			Flexure				Flexure		
Fill (ft)				Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	0.7	1.5	12.4	99	1	1.3	1.6	1	2.3	2.1	2.1	0.7	1.8	n/a	1
	Dump Truck	Operating	0.5	1.4	12.6	99	0.7	1.1	1.8	1	1.6	1.3	1.3	0.5	1.8	n/a	0.9

D-4-199: 1926, 3@8x3, No Fill				3-Cell																			
Skew Angle = 75 Degrees				Exterior Span														Interior Span					
				Exterior Wall				Top Slab			Interior Wall				Bottom Slab			Top Slab			Bottom Slab		
				Flexure				Flexure			Flexure				Flexure			Flexure			Flexure		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.1	99	n/a	99	99	99	1.3	1.1	n/a	n/a	n/a	n/a	99	15.3	3.6	1.1	1.6	1.1	3.6	49.6	3.6
	Dump Truck	Operating	0.9	99	n/a	99	99	99	1.9	0.9	n/a	n/a	n/a	n/a	99	13.2	3.1	0.9	2.5	0.9	3.1	42.9	3.1

C-4-26: 1942, 3@10x10, No Fill				3-Cell																			
Skew Angle = 90 Degrees				Exterior Span														Interior Span					
				Exterior Wall				Top Slab			Interior Wall				Bottom Slab			Top Slab			Bottom Slab		
				Flexure				Flexure			Flexure				Flexure			Flexure			Flexure		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.4	6.7	8.1	99	1.4	2.4	1.5	2.2	4.7	4.6	4.9	1.7	7	17.2	11.3	2.3	1.6	2	10.8	26.2	9.5
	Dump Truck	Operating	1.4	6.6	8.2	99	1.4	2.5	1.9	2.3	4.7	4.2	4.9	1.7	7	14.1	11.1	2.4	2.2	2.1	9.8	22.9	8.7

G-5-62(63) :1958, 3@12x6 0-9 ft Fill — 3-Cell

Skew Angle = 60 Degrees

Fill (ft)			Controlling RF	Exterior Span: Exterior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Top Slab Flexure Left	Middle	Right	Interior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Flexure Left	Middle	Right	Interior Span: Top Slab Flexure Left	Middle	Right	Bottom Slab Flexure Left	Middle	Right
0	Cntrl. Truck	Operating	1.4	10.9	8.7	99	1.4	3.3	2.1	2.5	5.1	3.5	3.9	1.4	16.5	21.4	12.1	2.6	2.3	2.3	11.9	38.6	10.7
	Dump Truck	Operating	1.3	10.3	8.6	99	1.3	3	2.4	2.6	4.6	3	3.4	1.3	16	16.8	10.8	2.8	2.8	2.4	9.9	29	9.1
2	Cntrl. Truck	Operating	0.9	8	10	99	0.9	2.5	1.6	1.6	4.6	3.1	3.5	1.3	13.6	15.4	7.9	1.7	2	1.5	7.9	30.3	7.1
	Dump Truck	Operating	0.8	7.4	9.7	99	0.8	2.3	1.8	1.7	4.1	2.7	3.1	1.1	13.2	12.4	7	1.8	2.3	1.6	6.5	22.9	6
5	Cntrl. Truck	Operating	1.5	3.9	27.9	99	1.5	5.3	3.6	2.4	14.9	8.4	10.4	3.7	10.5	10.1	3.1	2.6	5.4	2.3	3.8	24.7	3.3
	Dump Truck	Operating	1.3	3.5	27.2	99	1.3	4.6	3.1	2.4	12.9	7.1	8.7	3.1	9.7	9	2.9	2.6	4.6	2.3	3.4	20.6	3
8	Cntrl. Truck	Operating	0	1.7	40.1	99	1.2	7.8	4.4	1.6	30.8	15.6	20.8	7.4	10.1	8	0	2	8.9	1.8	0.3	25.9	0.3
	Dump Truck	Operating	0	1.6	37.7	99	0.8	5.5	2.9	1.3	20.9	11.2	14.2	5	9.6	7.3	0	1.6	5.8	1.4	0.3	22.6	0.3
9	Cntrl. Truck	Operating	0	0.8	42.7	99	0.7	7.3	3.5	0.9	31.9	17.1	21.7	7.7	9.8	6.9	0	1.3	8	1.2	0	25.7	0
	Dump Truck	Operating	0	0.8	41.1	99	0.5	5.6	2.7	0.7	23.8	12.7	16.1	5.7	9.3	6.3	0	1.1	6.1	0.9	0	22.6	0

E-4-100 : 1950, 4@10x7, 0 ft Fill — 4-Cell

Skew Angle = 60 Degrees

Fill (ft)			Controlling RF	Exterior Span: Exterior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Top Slab Flexure Left	Middle	Right	Interior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Flexure Left	Middle	Right	Interior Span: Top Slab Flexure Left	Middle	Right	Interior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Flexure Left	Middle	Right
0	Cntrl. Truck	Operating	0.5	4.5	6	99	0.5	0.8	0.8	1.1	2.8	2.1	2.2	0.8	5.8	9	4.2	1.1	0.9	1	2.6	2.3	2.3	0.8	3.9	14.2	4.6
	Dump Truck	Operating	0.5	4.6	6.2	99	0.5	0.9	1.1	1.1	2.9	1.9	2.3	0.8	5.9	7.9	4.3	1.1	1.2	1	2.7	2.2	2.2	0.8	3.9	12.3	4.5

G-10-86(87) :1959, 4@10x5, 0-11 ft Fill — 4-Cell

Skew Angle = 45 Degrees

Fill (ft)			Controling RF	Exterior Span: Exterior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Top Slab Flexure Left	Middle	Right	Interior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Flexure Left	Middle	Right	Interior Span: Top Slab Flexure Left	Middle	Right	Interior Wall Flexure Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Flexure Left	Middle	Right
0	Cntrl. Truck	Operating	1.3	11.8	8.9	99	1.3	3	2	2.8	5	3.6	3.9	1.4	18.2	20.5	12.6	3	2.1	2.8	4	4	4	1.3	11.1	34	13.3
	Dump Truck	Operating	1.3	12.2	9.3	99	1.3	3.2	2.6	2.8	4.8	3.3	4	1.4	19.1	18.1	12.5	3	3	2.6	4	3.8	3.8	1.3	10.8	29.8	12.7
2	Cntrl. Truck	Operating	0.9	9.2	10	99	0.9	2.4	1.7	1.9	4.7	3.3	3.7	1.3	15.8	15.8	8.9	2.1	2	2	3.9	3.8	3.8	1.3	7.8	28.1	10.1
	Dump Truck	Operating	0.9	9.5	10.4	99	0.9	2.5	2.1	2	4.6	3.1	3.7	1.3	16.6	13.9	8.8	2.1	2.6	1.9	3.9	3.7	3.7	1.3	7.6	24	9.7
5	Cntrl. Truck	Operating	1.7	6.3	27.8	99	1.7	5.6	4.3	3.2	15.9	9.7	11.8	4.1	14.7	13.5	5.2	3.4	5.8	3.7	12.9	12.2	12.2	4.1	5.3	26.1	7.7
	Dump Truck	Operating	1.5	6	26.9	99	1.5	5	3.8	3.1	14.1	8.5	10.3	3.6	14.1	12.7	4.8	3.4	5.1	3.5	11.5	10.7	10.7	3.6	5.2	23.4	7.2
8	Cntrl. Truck	Operating	1.8	5	40.6	99	1.8	9.1	6.2	2.8	35.2	19.2	25.9	9	15.4	13	1.8	3.2	9.8	4.3	28.5	24.8	24.8	8.7	2.5	29.4	6.6
	Dump Truck	Operating	1.2	4.6	37.2	99	1.2	6.2	4	2.1	23.4	13.8	17.2	6	14.3	12.4	1.7	2.4	6.3	3.2	19.3	17.8	17.8	6.1	2.4	26.1	5.7
10	Cntrl. Truck	Operating	0	3.5	45	99	0.8	7.7	4.3	1.2	36.3	22.5	26.7	9.4	14.9	11.6	0	1.6	7.8	3.2	31.3	29.4	29.4	10	0	29.7	4.2
	Dump Truck	Operating	0	3.3	44.6	99	0.7	6.9	4	1	31.9	18.7	23.3	8.2	14.3	10.9	0	1.4	7.3	2.8	26.8	24.6	24.6	8.4	0	27	4
11	Cntrl. Truck	Operating	0	2.7	47.6	99	0.3	7.3	3.7	0.3	37.7	23.4	27.7	9.8	14.7	10.6	0	0.8	7.5	2.7	32.6	30.7	30.7	10.4	0	29.6	2.9
	Dump Truck	Operating	0	2.6	48.4	99	0.3	7.4	3.9	0.3	38.3	22.5	27.9	9.8	14.3	10	0	0.7	7.9	2.5	32.5	29.8	29.8	10.2	0	27.4	2.8

Appendix G2: Slab Culvert Flexural Rating Factor Tables

G-5-64: 1958, 1@15'x5', 0-8 ft Fill				1-Cell							
Skew Angle = 45 Degrees					Exterior Wall				Top Slab		
					Flexure				Flexure		
Fill (ft)				Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Rating Factor	Cntrl. Truck	Operating	1.4	99	n/a	99	99	99	1.4	99
		Dump Truck	Operating	1.3	99	n/a	99	99	99	1.3	99
2	Rating Factor	Cntrl. Truck	Operating	0.7	99	n/a	99	99	99	0.7	99
		Dump Truck	Operating	0.6	99	n/a	99	99	99	0.6	99
5	Rating Factor	Cntrl. Truck	Operating	0.2	99	n/a	99	99	99	0.2	99
		Dump Truck	Operating	0.2	99	n/a	99	99	99	0.2	99
8	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	0	99
		Dump Truck	Operating	0	99	n/a	99	99	99	0	99

D-4-71: 1925, 2@8x6, 0-6 ft fill				2-Cell											
Skew Angle = 45 Degrees					Exterior Wall				Top Slab			Interior Wall			
					Flexure				Flexure			Flexure			
Fill (ft)				Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Rating Factor	Cntrl. Truck	Operating	0.8	99	n/a	99	99	99	1.1	0.8	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0.6	99	n/a	99	99	99	1.8	0.6	n/a	n/a	n/a	n/a
2	Rating Factor	Cntrl. Truck	Operating	0.1	99	n/a	99	99	99	1	0.1	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0.1	99	n/a	99	99	99	1.4	0.1	n/a	n/a	n/a	n/a
5	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	2.5	0	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0	99	n/a	99	99	99	2.2	0	n/a	n/a	n/a	n/a
6	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	2.9	0	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0	99	n/a	99	99	99	2.2	0	n/a	n/a	n/a	n/a

C-2-84: 1940, 2@10x6, 0-12 ft fill				2-Cell											
Skew Angle = 45 Degrees					Exterior Wall				Top Slab			Interior Wall			
					Flexure				Flexure			Flexure			
Fill (ft)				Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Rating Factor	Cntrl. Truck	Operating	1.6	99	n/a	99	99	99	1.6	1.9	n/a	n/a	n/a	n/a
		Dump Truck	Operating	2	99	n/a	99	99	99	2	2.3	n/a	n/a	n/a	n/a
2	Rating Factor	Cntrl. Truck	Operating	1.1	99	n/a	99	99	99	1.3	1.1	n/a	n/a	n/a	n/a
		Dump Truck	Operating	1.4	99	n/a	99	99	99	1.6	1.4	n/a	n/a	n/a	n/a
5	Rating Factor	Cntrl. Truck	Operating	1.2	99	n/a	99	99	99	3.1	1.2	n/a	n/a	n/a	n/a
		Dump Truck	Operating	1.3	99	n/a	99	99	99	2.8	1.3	n/a	n/a	n/a	n/a
8	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	4.4	0	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0	99	n/a	99	99	99	2.9	0	n/a	n/a	n/a	n/a
10	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	2.9	0	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0	99	n/a	99	99	99	2.7	0	n/a	n/a	n/a	n/a
13	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	2	0	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0	99	n/a	99	99	99	2	0	n/a	n/a	n/a	n/a

G-5-28 :1958, 2@12'x6', 0-9 ft Fill				2-Cell											
Skew Angle = 45 Degrees					Exterior Wall				Top Slab			Interior Wall			
					Flexure				Flexure			Flexure			
Fill (ft)				Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Rating Factor	Cntrl. Truck	Operating	1.2	3.5	12	99	1.2	2.6	2.2	2.5	2.1	4.3	4.3	1.3
		Dump Truck	Operating	1.1	3.1	10.9	99	1.1	2.4	2.6	2.6	1.8	3.8	3.8	1.1
2	Rating Factor	Cntrl. Truck	Operating	0.7	2.4	12.2	99	0.7	1.9	1.8	1.6	2	4.2	4.2	1.2
		Dump Truck	Operating	0.6	2.1	11.1	99	0.6	1.7	2.1	1.6	1.8	3.7	3.6	1.1
5	Rating Factor	Cntrl. Truck	Operating	0.8	2.8	27.2	99	0.8	3.7	4.4	2.2	6.1	12.8	12.7	3.7
		Dump Truck	Operating	0.7	2.5	24.5	99	0.7	3.1	3.8	2.2	5	10.6	10.6	3
8	Rating Factor	Cntrl. Truck	Operating	0	1.6	42.2	99	0	4.7	6.3	1.2	12.7	27.3	27.1	7.8
		Dump Truck	Operating	0	1.3	35.5	99	0	3.2	4.1	0.9	8.6	18.3	18.2	5.2
9	Rating Factor	Cntrl. Truck	Operating	0	1	44.5	99	0	4.1	5.3	0.3	13.5	29	28.8	8.3
		Dump Truck	Operating	0	0.8	39	99	0	3	4	0.2	9.9	21.1	21	6

D-0-62 :1920, 2@10'x3', 0-5 ft Fill — 2-Cell

Skew Angle = 90 Degrees

Fill (ft)				Controling RF	Exterior Wall Flexure Bottom	Exterior Wall Flexure Middle (+)	Exterior Wall Flexure Middle (-)	Exterior Wall Flexure Top	Top Slab Flexure Left	Top Slab Flexure Middle	Top Slab Flexure Right	Interior Wall Flexure Bottom	Interior Wall Flexure Middle (+)	Interior Wall Flexure Middle (-)	Interior Wall Flexure Top
0	Rating Factor	Cntrl. Truck	Operating	0.7	99	n/a	99	99	99	1.2	0.7	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0.8	99	n/a	99	99	99	1.5	0.8	n/a	n/a	n/a	n/a
2	Rating Factor	Cntrl. Truck	Operating	0.1	99	n/a	99	99	99	0.9	0.1	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0.2	99	n/a	99	99	99	1.1	0.2	n/a	n/a	n/a	n/a
5	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	1.9	0	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0	99	n/a	99	99	99	1.7	0	n/a	n/a	n/a	n/a

D-0-64: 1920, 3@10'x3', 0-5 ft Fill — 3-Cell

Skew Angle = 90 Degrees

Fill (ft)				Controlling RF	Exterior Span: Exterior Wall Flexure Bottom	Exterior Span: Exterior Wall Flexure Middle (+)	Exterior Span: Exterior Wall Flexure Middle (-)	Exterior Span: Exterior Wall Flexure Top	Exterior Span: Top Slab Flexure Left	Exterior Span: Top Slab Flexure Middle	Exterior Span: Top Slab Flexure Right	Exterior Span: Interior Wall Flexure Bottom	Exterior Span: Interior Wall Flexure Middle (+)	Exterior Span: Interior Wall Flexure Middle (-)	Exterior Span: Interior Wall Flexure Top	Interior Span: Top Slab Flexure Left	Interior Span: Top Slab Flexure Middle	Interior Span: Top Slab Flexure Right
0	Rating Factor	Cntrl. Truck	Operating	0.7	99	n/a	99	99	99	1.2	0.8	n/a	n/a	n/a	n/a	0.8	1.5	0.7
		Dump Truck	Operating	0.7	99	n/a	99	99	99	1.5	0.9	n/a	n/a	n/a	n/a	0.8	1.9	0.7
2	Rating Factor	Cntrl. Truck	Operating	0.1	99	n/a	99	99	99	0.9	0.1	n/a	n/a	n/a	n/a	0.1	1.3	0.1
		Dump Truck	Operating	0.3	99	n/a	99	99	99	1	0.3	n/a	n/a	n/a	n/a	0.3	1.7	0.3
5	Rating Factor	Cntrl. Truck	Operating	0	99	n/a	99	99	99	1.6	0	n/a	n/a	n/a	n/a	0	3.8	0
		Dump Truck	Operating	0	99	n/a	99	99	99	1.4	0	n/a	n/a	n/a	n/a	0	3.3	0

F-2-55 : 1954, 3@15'x10', 0-6 ft Fill — 3-Cell

Skew Angle = 90 Degrees

Fill (ft)				Controlling RF	Exterior Span: Exterior Wall Flexure Bottom	Exterior Span: Exterior Wall Flexure Middle (+)	Exterior Span: Exterior Wall Flexure Middle (-)	Exterior Span: Exterior Wall Flexure Top	Exterior Span: Top Slab Flexure Left	Exterior Span: Top Slab Flexure Middle	Exterior Span: Top Slab Flexure Right	Exterior Span: Interior Wall Flexure Bottom	Exterior Span: Interior Wall Flexure Middle (+)	Exterior Span: Interior Wall Flexure Middle (-)	Exterior Span: Interior Wall Flexure Top	Interior Span: Top Slab Flexure Left	Interior Span: Top Slab Flexure Middle	Interior Span: Top Slab Flexure Right
0	Rating Factor	Cntrl. Truck	Operating	1.4	2.4	7.4	99	1.5	3.4	2.4	2.6	2.3	4.9	5.3	1.4	2.7	2.7	2.4
		Dump Truck	Operating	1	2.1	6.5	99	1.2	2.7	2.5	2.4	1.8	3.8	4.1	1	2.6	2.8	2.3
2	Rating Factor	Cntrl. Truck	Operating	0.8	2.3	7.8	99	0.8	2.3	1.8	1.5	2.1	4.4	4.9	1.2	1.6	2.1	1.5
		Dump Truck	Operating	0.6	2	6.7	99	0.6	1.9	1.7	1.5	1.6	3.5	3.7	0.9	1.6	2.1	1.4
5	Rating Factor	Cntrl. Truck	Operating	0.6	2.4	13.9	99	0.6	4	3.7	2	5.9	13	14.2	3.1	2.3	5.2	2.1
		Dump Truck	Operating	0.5	2.2	12.8	99	0.5	3.2	3	1.9	4.6	10.3	10.9	2.4	2.3	4.2	2
6	Rating Factor	Cntrl. Truck	Operating	0.2	2.2	15.5	99	0.2	4	3.9	1.7	7.1	15.9	17.2	3.7	2.1	5.9	1.9
		Dump Truck	Operating	0.2	2	14.2	99	0.2	3.1	3	1.6	5.4	12.3	12.9	2.8	2	4.4	1.7

G-10-54 : 1959, 3@12'x10', 0-9 ft Fill — 3-Cell

Skew Angle = 60 Degrees

Fill (ft)				Controlling RF	Exterior Span											Interior Span		
					Exterior Wall				Top Slab			Interior Wall				Top Slab		
					Flexure				Flexure			Flexure				Flexure		
					Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Rating Factor	Cntrl. Truck	Operating	1.4	5.2	16	99	1.4	3.3	2.1	2.5	4.1	8.4	9	2.4	2.6	2.3	2.3
		Dump Truck	Operating	1.2	5	15.2	99	1.2	3	2.4	2.7	3.6	7.4	7.9	2.1	2.8	2.8	2.5
2	Rating Factor	Cntrl. Truck	Operating	0.8	5.3	15.3	99	0.8	2.4	1.7	1.6	3.6	7.5	8.1	2.1	1.7	2	1.5
		Dump Truck	Operating	0.7	5	14.5	99	0.7	2.2	1.9	1.7	3.2	6.6	7.1	1.8	1.9	2.2	1.7
5	Rating Factor	Cntrl. Truck	Operating	1	8	22.4	99	1	4.5	3.9	2.5	10.1	21.3	22.8	5.6	2.8	5.3	2.5
		Dump Truck	Operating	0.8	7.6	21.3	99	0.8	3.8	3.3	2.5	8.5	17.9	19	4.6	2.9	4.5	2.5
8	Rating Factor	Cntrl. Truck	Operating	0	8.5	26.7	99	0	5.4	5.1	1.9	19	41	44.8	10.6	2.5	8.5	2.1
		Dump Truck	Operating	0	8	24.8	99	0	4	3.4	1.5	13.3	28.6	30.6	7.2	2	5.6	1.7
9	Rating Factor	Cntrl. Truck	Operating	0	8.4	27.2	99	0	4.9	4.3	1.2	20.4	44	46.7	11	1.8	7.6	1.6
		Dump Truck	Operating	0	8	25.8	99	0	3.8	3.2	1	15	32.4	34.6	8.1	1.5	5.8	1.3

D-0-295: 1924, 4@10x5.5, no fill — 4-Cell

Skew Angle = 75 Degrees

Fill (ft)				Controlling RF	Exterior Span											Interior Span						
					Exterior Wall				Top Slab			Interior Wall				Top Slab			Interior Wall			
					Flexure				Flexure			Flexure				Flexure			Flexure			
					Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Rating Factor	Cntrl. Truck	Operating	0.9	99	n/a	99	99	99	1.5	0.9	n/a	n/a	n/a	n/a	0.9	1.8	1.1	n/a	n/a	n/a	n/a
		Dump Truck	Operating	0.9	99	n/a	99	99	99	1.9	0.9	n/a	n/a	n/a	n/a	0.9	2.4	1.2	n/a	n/a	n/a	n/a

G-5-27 : 1957, 4@10'x8', 0-11 ft Fill — 4-Cell

Skew Angle = 60 Degrees

Fill (ft)				Controlling RF	Exterior Span											Interior Span						
					Exterior Wall				Top Slab			Interior Wall				Top Slab			Interior Wall			
					Flexure				Flexure			Flexure				Flexure			Flexure			
					Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Rating Factor	Cntrl. Truck	Operating	1.2	1.9	8	99	1.2	3.2	1.9	2.8	3	6.1	6.4	1.7	2.9	2.1	2.7	3.6	6.6	6.6	1.7
		Dump Truck	Operating	1.3	1.9	8.1	99	1.3	3.3	2.5	2.8	2.8	5.7	6.6	1.7	3	2.8	2.6	3.4	6.2	6.2	1.6
2	Rating Factor	Cntrl. Truck	Operating	0.8	1.9	7.9	99	0.8	2.5	1.6	1.9	2.9	5.9	6.3	1.6	2	1.9	2	3.4	6.3	6.3	1.6
		Dump Truck	Operating	0.8	1.9	8	99	0.8	2.5	2	2	2.7	5.6	6.3	1.6	2.1	2.4	1.9	3.3	6.1	6.1	1.6
5	Rating Factor	Cntrl. Truck	Operating	1	3	11.4	99	1	4.8	4.2	3.2	8.7	18.3	19.9	4.9	3.4	5.4	3.5	10.7	20.1	20	5.2
		Dump Truck	Operating	0.9	2.9	11.1	99	0.9	4.3	3.7	3.1	7.6	16	17.4	4.3	3.5	4.7	3.4	9.5	17.7	17.7	4.6
8	Rating Factor	Cntrl. Truck	Operating	0.2	3.7	13.4	99	0.2	6.2	6.1	2.8	17.8	38.1	43.1	10.6	3.3	9	3.9	21.5	41.3	41.1	10.7
		Dump Truck	Operating	0.1	3.5	12.7	99	0.1	4.7	4	2.2	12.5	26.7	29.4	7.1	2.5	5.9	3	15.5	29.3	29.2	7.6
10	Rating Factor	Cntrl. Truck	Operating	0	4	14	99	0	5	4.3	1.3	20.5	44	45.8	11	1.8	7.2	2.9	25.1	48.3	48.1	12.5
		Dump Truck	Operating	0	3.9	13.7	99	0	4.6	4	1.1	17.1	36.8	40	9.6	1.6	6.7	2.5	21.2	40.5	40.4	10.5
11	Rating Factor	Cntrl. Truck	Operating	0	4.1	14.2	99	0	4.5	3.8	0.5	21.4	46	48	11.5	1	6.9	2.4	26.3	50.5	50.3	13.1
		Dump Truck	Operating	0	4.1	14.2	99	0	4.5	3.9	0.4	20.6	44.5	47.7	11.4	0.9	7.3	2.2	25.5	49	48.8	12.7

Appendix G3: Box Culvert Shear Rating Factor Tables

C-10-14: 1946, 1@10x5, 0-5 ft Fill				1-Cell									
Skew Angle = 30 Degrees				Exterior Wall				Top Slab			Bottom Slab		
				Shear				Shear			Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.9	43.7	NA	NA	43.4	2	NA	1.9	15.7	NA	15.7
	Dump Truck	Operating	1.9	43.7	NA	NA	43.4	2.1	NA	1.9	9.3	NA	9.3
2	Cntrl. Truck	Operating	2.1	57.2	NA	NA	56.7	2.2	NA	2.1	17.4	NA	17.4
	Dump Truck	Operating	2.2	57.2	NA	NA	56.7	2.4	NA	2.2	10.3	NA	10.3
5	Cntrl. Truck	Operating	5	55.7	NA	NA	55.2	5.5	NA	5	8.8	NA	8.8
	Dump Truck	Operating	4.5	55.7	NA	NA	55.2	5	NA	4.5	6.3	NA	6.3

E-12-36 :1952, 1@10x6, 0-5 ft Fill				1-Cell									
Skew Angle = 30 Degrees				Exterior Wall				Top Slab			Bottom Slab		
				Shear				Shear			Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.9	33.9	NA	NA	34	2	NA	1.9	17.6	NA	17.6
	Dump Truck	Operating	1.9	33.9	NA	NA	34	2.1	NA	1.9	10.4	NA	10.4
2	Cntrl. Truck	Operating	2.1	44.3	NA	NA	44.3	2.2	NA	2.1	19.8	NA	19.8
	Dump Truck	Operating	2.2	44.3	NA	NA	44.3	2.4	NA	2.2	11.7	NA	11.7
5	Cntrl. Truck	Operating	5	42.8	NA	NA	42.8	5.5	NA	5	9.1	NA	9.1
	Dump Truck	Operating	4.5	42.8	NA	NA	42.8	5	NA	4.5	6.6	NA	6.6

B-2-36: 1934, 2@8x4, 0-6 ft Fill				2-Cell													
Skew Angle = 35 Degrees				Exterior Wall				Top Slab			Interior Wall				Bottom Slab		
				Shear				Shear			Shear				Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	1.3	48.3	NA	NA	48.2	1.6	NA	1.3	99	NA	NA	99	13.6	NA	6.5
	Dump Truck	Operating	1.3	48.3	NA	NA	48.2	2	NA	1.3	99	NA	NA	99	16.1	NA	7.6
2	Cntrl. Truck	Operating	1.4	63	NA	NA	62.9	2.1	NA	1.4	99	NA	NA	99	15.4	NA	6.1
	Dump Truck	Operating	1.5	63	NA	NA	62.9	2.8	NA	1.5	99	NA	NA	99	18.2	NA	7.3
5	Cntrl. Truck	Operating	3.1	61.5	NA	NA	61.4	6.9	NA	3.1	99	NA	NA	99	12.3	NA	3.5
	Dump Truck	Operating	2.8	61.5	NA	NA	61.4	6.2	NA	2.8	99	NA	NA	99	10.9	NA	3.1
6	Cntrl. Truck	Operating	3.1	61	NA	NA	60.9	8.8	NA	3.4	99	NA	NA	99	13	NA	3.1
	Dump Truck	Operating	2.6	61	NA	NA	60.9	6.8	NA	2.7	99	NA	NA	99	11.1	NA	2.6

C-10-113: 1948, 2@10x8, 0-9 ft Fill				2-Cell													
Skew Angle = 90 Degrees				Exterior Wall				Top Slab			Interior Wall				Bottom Slab		
				Shear				Shear			Shear				Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	1.3	16	NA	NA	16.4	1.6	NA	1.3	99	NA	NA	99	21	NA	9
	Dump Truck	Operating	1.2	16	NA	NA	16.4	1.7	NA	1.2	99	NA	NA	99	18.1	NA	7.8
2	Cntrl. Truck	Operating	1	19.2	NA	NA	19.2	1.6	NA	1	99	NA	NA	99	21.2	NA	8
	Dump Truck	Operating	1	19.2	NA	NA	19.2	1.8	NA	1	99	NA	NA	99	20.2	NA	7.6
5	Cntrl. Truck	Operating	1.6	17.7	NA	NA	17.7	4.2	NA	1.6	99	NA	NA	99	8.5	NA	1.6
	Dump Truck	Operating	1.4	17.7	NA	NA	17.7	3.7	NA	1.4	99	NA	NA	99	8.9	NA	1.7
8	Cntrl. Truck	Operating	0	16.2	NA	NA	16.2	6.6	NA	0.7	99	NA	NA	99	8.5	NA	0
	Dump Truck	Operating	0	16.2	NA	NA	16.2	4.3	NA	0.5	99	NA	NA	99	7.3	NA	0
9	Cntrl. Truck	Operating	0	15.7	NA	NA	15.7	5.5	NA	0	99	NA	NA	99	7.5	NA	0
	Dump Truck	Operating	0	15.7	NA	NA	15.7	4.2	NA	0	99	NA	NA	99	6.4	NA	0

E-8-119: 1951, 2@15x8, no fill				2-Cell													
Skew Angle = 90 Degrees				Exterior Span													
				Exterior Wall				Top Slab			Interior Wall				Bottom Slab		
			Controlling RF	Shear				Shear			Shear				Shear		
Fill (ft)				Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	1.2	5.9	NA	NA	5.1	1.5	NA	1.2	7.4	NA	NA	7.4	31.7	NA	5.2
	Dump Truck	Operating	1	5.2	NA	NA	4.6	1.3	NA	1	5.9	NA	NA	5.9	32.6	NA	5

D-4-199: 1926, 3@8x3, No Fill				3-Cell																			
Skew Angle = 75 Degrees				Exterior Span														Interior Span					
				Exterior Wall				Top Slab			Interior Wall				Bottom Slab			Top Slab			Bottom Slab		
				Shear				Shear			Shear				Shear			Shear			Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.3	93.8	NA	NA	93.6	1.7	NA	1.3	99	NA	NA	99	15.9	NA	8.6	1.5	NA	1.4	11.2	NA	11.2
	Dump Truck	Operating	1.3	93.8	NA	NA	93.6	2.1	NA	1.3	99	NA	NA	99	13.8	NA	7.4	1.7	NA	1.5	9.7	NA	9.7

C-4-26: 1942, 3@10x10, No Fill				3-Cell																			
Skew Angle = 90 Degrees				Exterior Span														Interior Span					
				Exterior Wall				Top Slab			Interior Wall				Bottom Slab			Top Slab			Bottom Slab		
				Shear				Shear			Shear				Shear			Shear			Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
0	Cntrl. Truck	Operating	1.6	14.9	NA	NA	9.1	1.8	NA	1.6	24.7	NA	NA	24.7	26.3	NA	15.9	1.8	NA	1.7	20.2	NA	20.3
	Dump Truck	Operating	1.6	14.9	NA	NA	9.3	2	NA	1.6	23.5	NA	NA	23.5	23.6	NA	17	1.9	NA	1.7	19.9	NA	19.9

G-5-62(63) :1958, 3@12x6 0-9 ft Fill — 3-Cell

Skew Angle = 60 Degrees

Fill (ft)			Controlling RF	Exterior Span: Exterior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Top Slab Shear Left	Middle	Right	Interior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Shear Left	Middle	Right	Interior Span: Top Slab Shear Left	Middle	Right	Bottom Slab Shear Left	Middle	Right
0	Cntrl. Truck	Operating	1.7	6	NA	NA	5.2	1.9	NA	1.7	10.8	NA	NA	10.8	21.4	NA	12.1	1.8	NA	1.8	14.8	NA	14.9
	Dump Truck	Operating	1.5	5.4	NA	NA	4.8	1.9	NA	1.5	9.5	NA	NA	9.5	20.2	NA	12.1	1.8	NA	1.6	13.9	NA	14
2	Cntrl. Truck	Operating	1.4	5.4	NA	NA	4.7	1.9	NA	1.4	10.2	NA	NA	9.5	21.7	NA	9.9	1.6	NA	1.5	12.7	NA	12.8
	Dump Truck	Operating	1.4	4.8	NA	NA	4.3	2	NA	1.4	8.9	NA	NA	8.4	19.3	NA	9.9	1.7	NA	1.5	11.8	NA	12
5	Cntrl. Truck	Operating	2.4	13.9	NA	NA	9.7	4.3	NA	2.4	25	NA	NA	24.5	9.4	NA	3.6	3	NA	2.8	5.5	NA	5.5
	Dump Truck	Operating	2.1	12.1	NA	NA	8.7	3.8	NA	2.1	20.9	NA	NA	20.1	8.8	NA	3.5	2.9	NA	2.6	5.2	NA	5.2
8	Cntrl. Truck	Operating	0	15.1	NA	NA	13.4	6.1	NA	1.8	42.4	NA	NA	46	6.6	NA	0	3.3	NA	3	2	NA	2
	Dump Truck	Operating	0	14.1	NA	NA	10.6	4	NA	1.3	28.9	NA	NA	29.9	6.2	NA	0	2.3	NA	2.1	1.9	NA	1.9
9	Cntrl. Truck	Operating	0	15.3	NA	NA	13.1	5.1	NA	1	42.8	NA	NA	45.2	5.3	NA	0	2.5	NA	2.3	0.5	NA	0.5
	Dump Truck	Operating	0	14.2	NA	NA	11	3.9	NA	0.8	31.4	NA	NA	34	5	NA	0	1.9	NA	1.8	0.5	NA	0.5

E-4-100 : 1950, 4@10x7, 0 ft Fill — 4-Cell

Skew Angle = 60 Degrees

Fill (ft)			Controlling RF	Exterior Span: Exterior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Top Slab Shear Left	Middle	Right	Interior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Shear Left	Middle	Right	Interior Span: Top Slab Shear Left	Middle	Right	Interior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Shear Left	Middle	Right
0	Cntrl. Truck	Operating	1	4.7	NA	NA	4	1.1	NA	1	8.9	NA	NA	8.9	15.8	NA	8.9	1	NA	1	9.2	NA	NA	9.2	10.4	NA	11.6
	Dump Truck	Operating	1	4.9	NA	NA	4.1	1.1	NA	1	8.6	NA	NA	8.6	15.9	NA	9.9	1.1	NA	1	8.9	NA	NA	8.9	10.9	NA	12

G-10-86(87) :1959, 4@10x5, 0-11 ft Fill — 4-Cell

Skew Angle = 45 Degrees

Fill (ft)			Controling RF	Exterior Span: Exterior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Top Slab Shear Left	Middle	Right	Interior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Shear Left	Middle	Right	Interior Span: Top Slab Shear Left	Middle	Right	Interior Wall Shear Bottom	Middle (+)	Middle (-)	Top	Bottom Slab Shear Left	Middle	Right
0	Cntrl. Truck	Operating	1.6	5.3	NA	NA	4.6	1.8	NA	1.6	9.8	NA	NA	9.8	24.2	NA	13.6	1.7	NA	1.7	10.4	NA	NA	10.4	15.6	NA	18
	Dump Truck	Operating	1.6	5.5	NA	NA	4.8	2	NA	1.6	9.2	NA	NA	9.2	23.8	NA	14.6	1.8	NA	1.7	9.8	NA	NA	9.8	15.9	NA	18.2
2	Cntrl. Truck	Operating	1.5	4.9	NA	NA	4.3	1.8	NA	1.5	9.4	NA	NA	8.9	24.4	NA	11.8	1.7	NA	1.6	9.6	NA	NA	9.4	13.8	NA	16.6
	Dump Truck	Operating	1.6	5.1	NA	NA	4.4	2.1	NA	1.6	8.9	NA	NA	8.5	23.8	NA	12.7	1.8	NA	1.7	9.3	NA	NA	9.1	14.2	NA	16.8
5	Cntrl. Truck	Operating	2.9	13.7	NA	NA	9.4	4.9	NA	2.9	25.4	NA	NA	23.5	13.7	NA	5.9	3.6	NA	3.6	25.1	NA	NA	24.4	7.7	NA	9.8
	Dump Truck	Operating	2.6	12.1	NA	NA	8.7	4.3	NA	2.6	22.3	NA	NA	20.6	13.5	NA	5.9	3.3	NA	3.3	22.2	NA	NA	21.6	7.7	NA	9.4
8	Cntrl. Truck	Operating	2.4	17.5	NA	NA	13.8	7.7	NA	3.1	43.5	NA	NA	46.3	11.6	NA	2.4	4.4	NA	4.8	45.5	NA	NA	44.2	4.6	NA	7
	Dump Truck	Operating	2.1	16.5	NA	NA	10.6	5.1	NA	2.1	30.4	NA	NA	30.1	11.1	NA	2.3	3	NA	3.2	31.7	NA	NA	30.9	4.5	NA	6.6
10	Cntrl. Truck	Operating	0	17.9	NA	NA	12.7	5.4	NA	1.3	44.5	NA	NA	48.2	9.3	NA	0	2.5	NA	3.1	47.3	NA	NA	46.1	1.5	NA	4.1
	Dump Truck	Operating	0	17	NA	NA	11.8	5.3	NA	1.2	37.8	NA	NA	40.7	8.8	NA	0	2.4	NA	2.9	40.2	NA	NA	39.1	1.4	NA	4
11	Cntrl. Truck	Operating	0	18.1	NA	NA	12.4	4.8	NA	0.6	44.5	NA	NA	48.3	7.9	NA	0	1.8	NA	2.5	47.4	NA	NA	46.2	0	NA	2.5
	Dump Truck	Operating	0	17.3	NA	NA	12.6	5.3	NA	0.6	43.6	NA	NA	47.3	7.5	NA	0	1.9	NA	2.7	46.6	NA	NA	45.4	0	NA	2.4

Appendix G4: Slab Culvert Shear Rating Factor Tables

G-5-64: 1958, 1@15'x5', 0-8 ft Fill			1-Cell							
Skew Angle = 45 Degrees				Exterior Wall				Top Slab		
				Shear				Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	2	99	NA	NA	99	2.1	NA	2
	Dump Truck	Operating	1.6	99	NA	NA	99	1.7	NA	1.6
2	Cntrl. Truck	Operating	1.9	99	NA	NA	99	1.9	NA	1.9
	Dump Truck	Operating	1.6	99	NA	NA	99	1.7	NA	1.6
5	Cntrl. Truck	Operating	3.4	99	NA	NA	99	3.6	NA	3.4
	Dump Truck	Operating	2.7	99	NA	NA	99	2.9	NA	2.7
8	Cntrl. Truck	Operating	3.1	99	NA	NA	99	3.3	NA	3.1
	Dump Truck	Operating	2.2	99	NA	NA	99	2.3	NA	2.2

D-4-71: 1925, 2@8x6, 0-6 ft fill			2-Cell											
Skew Angle = 45 Degrees				Exterior Wall				Top Slab			Interior Wall			
				Shear				Shear			Shear			
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Cntrl. Truck	Operating	1.1	99	NA	NA	99	1.4	NA	1.1	99	NA	NA	2.2
	Dump Truck	Operating	1.1	99	NA	NA	99	1.8	NA	1.1	99	NA	NA	2.8
2	Cntrl. Truck	Operating	1.1	99	NA	NA	99	1.7	NA	1.1	99	NA	NA	2.6
	Dump Truck	Operating	1.2	99	NA	NA	99	2.3	NA	1.2	99	NA	NA	3.5
5	Cntrl. Truck	Operating	2.2	99	NA	NA	99	5.6	NA	2.2	99	NA	NA	9.1
	Dump Truck	Operating	2	99	NA	NA	99	5	NA	2	99	NA	NA	8.3
6	Cntrl. Truck	Operating	2.3	99	NA	NA	99	6.9	NA	2.3	99	NA	NA	11.7
	Dump Truck	Operating	1.9	99	NA	NA	99	5.4	NA	1.9	99	NA	NA	9

C-2-84: 1940, 2@10x6, 0-12 ft fill			2-Cell											
Skew Angle = 45 Degrees				Exterior Wall				Top Slab			Interior Wall			
				Shear				Shear			Shear			
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Cntrl. Truck	Operating	1.5	45.7	NA	NA	61.3	2	NA	1.5	99	NA	NA	99
	Dump Truck	Operating	1.5	45.7	NA	NA	61.3	2.3	NA	1.5	99	NA	NA	99
2	Cntrl. Truck	Operating	1.5	59.8	NA	NA	80.2	2.3	NA	1.5	99	NA	NA	99
	Dump Truck	Operating	1.5	59.8	NA	NA	80.2	2.7	NA	1.5	99	NA	NA	99
5	Cntrl. Truck	Operating	2.8	58.3	NA	NA	78.7	6.8	NA	2.8	99	NA	NA	99
	Dump Truck	Operating	2.6	58.3	NA	NA	78.7	6.1	NA	2.6	99	NA	NA	99
8	Cntrl. Truck	Operating	2.8	56.8	NA	NA	77.2	11.9	NA	2.8	99	NA	NA	99
	Dump Truck	Operating	1.9	56.8	NA	NA	77.2	7.8	NA	1.9	99	NA	NA	99
10	Cntrl. Truck	Operating	1.1	55.8	NA	NA	76.2	9	NA	1.1	99	NA	NA	99
	Dump Truck	Operating	1	55.8	NA	NA	76.2	9	NA	1	99	NA	NA	99
13	Cntrl. Truck	Operating	0	54.8	NA	NA	75.2	8.7	NA	0	99	NA	NA	99
	Dump Truck	Operating	0	54.8	NA	NA	75.2	9.1	NA	0	99	NA	NA	99

G-5-28 :1958, 2@12'x6', 0-9 ft Fill			2-Cell											
Skew Angle = 45 Degrees				Exterior Wall				Top Slab			Interior Wall			
				Shear				Shear			Shear			
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Cntrl. Truck	Operating	1.7	3.5	NA	NA	3	1.9	NA	1.7	6.1	NA	NA	6.1
	Dump Truck	Operating	1.5	3.1	NA	NA	2.7	1.9	NA	1.5	5.3	NA	NA	5.3
2	Cntrl. Truck	Operating	1.4	2.8	NA	NA	2.5	1.8	NA	1.4	5.5	NA	NA	5.4
	Dump Truck	Operating	1.4	2.5	NA	NA	2.2	1.8	NA	1.4	4.8	NA	NA	4.7
5	Cntrl. Truck	Operating	2.4	6	NA	NA	4.5	3.9	NA	2.4	13.4	NA	NA	13.3
	Dump Truck	Operating	2.2	5	NA	NA	3.8	3.4	NA	2.2	11.1	NA	NA	11
8	Cntrl. Truck	Operating	1.9	9.2	NA	NA	5.4	5.3	NA	1.9	23.7	NA	NA	23.4
	Dump Truck	Operating	1.3	6.1	NA	NA	3.9	3.5	NA	1.3	16	NA	NA	15.8
9	Cntrl. Truck	Operating	1.1	8.6	NA	NA	4.8	4.3	NA	1.1	23.8	NA	NA	23.5
	Dump Truck	Operating	0.8	6.3	NA	NA	3.7	3.3	NA	0.8	17.4	NA	NA	17.2

D-0-62 :1920, 2@10'x3', 0-5 ft Fill — 2-Cell

Skew Angle = 90 Degrees

Fill (ft)			Controling RF	Exterior Wall Shear Bottom	Exterior Wall Shear Middle (+)	Exterior Wall Shear Middle (-)	Exterior Wall Shear Top	Top Slab Shear Left	Top Slab Shear Middle	Top Slab Shear Right	Interior Wall Shear Bottom	Interior Wall Shear Middle (+)	Interior Wall Shear Middle (-)	Interior Wall Shear Top
0	Cntrl. Truck	Operating	1.1	99	NA	NA	99	1.5	NA	1.1	99	NA	NA	99
	Dump Truck	Operating	1	99	NA	NA	99	1.6	NA	1	99	NA	NA	99
2	Cntrl. Truck	Operating	1	99	NA	NA	99	1.6	NA	1	99	NA	NA	99
	Dump Truck	Operating	1	99	NA	NA	99	1.9	NA	1	99	NA	NA	99
5	Cntrl. Truck	Operating	1.4	99	NA	NA	99	4.3	NA	1.4	99	NA	NA	99
	Dump Truck	Operating	1.2	99	NA	NA	99	3.9	NA	1.2	99	NA	NA	99

D-0-64: 1920, 3@10'x3', 0-5 ft Fill — 3-Cell

Skew Angle = 90 Degrees

Fill (ft)			Controlling RF	Exterior Span: Exterior Wall Shear Bottom	Exterior Span: Exterior Wall Shear Middle (+)	Exterior Span: Exterior Wall Shear Middle (-)	Exterior Span: Exterior Wall Shear Top	Exterior Span: Top Slab Shear Left	Exterior Span: Top Slab Shear Middle	Exterior Span: Top Slab Shear Right	Exterior Span: Interior Wall Shear Bottom	Exterior Span: Interior Wall Shear Middle (+)	Exterior Span: Interior Wall Shear Middle (-)	Exterior Span: Interior Wall Shear Top	Interior Span: Top Slab Shear Left	Interior Span: Top Slab Shear Middle	Interior Span: Top Slab Shear Right
0	Cntrl. Truck	Operating	1.1	94.8	NA	NA	99	1.5	NA	1.1	99	NA	NA	99	1.3	NA	1.2
	Dump Truck	Operating	1.1	94.8	NA	NA	99	1.6	NA	1.1	99	NA	NA	99	1.3	NA	1.2
2	Cntrl. Truck	Operating	1	99	NA	NA	99	1.6	NA	1	99	NA	NA	99	1.2	NA	1.2
	Dump Truck	Operating	1	99	NA	NA	99	1.9	NA	1	99	NA	NA	99	1.4	NA	1.2
5	Cntrl. Truck	Operating	1.5	99	NA	NA	99	4.2	NA	1.5	99	NA	NA	99	2.3	NA	2.2
	Dump Truck	Operating	1.3	99	NA	NA	99	3.7	NA	1.3	99	NA	NA	99	2.3	NA	2

F-2-55 : 1954, 3@15'x10', 0-6 ft Fill — 3-Cell

Skew Angle = 90 Degrees

Fill (ft)			Controlling RF	Exterior Span: Exterior Wall Shear Bottom	Exterior Span: Exterior Wall Shear Middle (+)	Exterior Span: Exterior Wall Shear Middle (-)	Exterior Span: Exterior Wall Shear Top	Exterior Span: Top Slab Shear Left	Exterior Span: Top Slab Shear Middle	Exterior Span: Top Slab Shear Right	Exterior Span: Interior Wall Shear Bottom	Exterior Span: Interior Wall Shear Middle (+)	Exterior Span: Interior Wall Shear Middle (-)	Exterior Span: Interior Wall Shear Top	Interior Span: Top Slab Shear Left	Interior Span: Top Slab Shear Middle	Interior Span: Top Slab Shear Right
0	Cntrl. Truck	Operating	1.9	6.4	NA	NA	5	2.1	NA	1.9	12.1	NA	NA	12.1	1.9	NA	1.9
	Dump Truck	Operating	1.5	5	NA	NA	4	1.9	NA	1.5	9.6	NA	NA	9.6	1.8	NA	1.6
2	Cntrl. Truck	Operating	1.5	5.6	NA	NA	4.1	1.9	NA	1.5	10.1	NA	NA	10.1	1.6	NA	1.6
	Dump Truck	Operating	1.3	4.3	NA	NA	3.2	1.7	NA	1.3	8	NA	NA	7.9	1.5	NA	1.4
5	Cntrl. Truck	Operating	2.1	13.6	NA	NA	6.4	3.6	NA	2.1	23.2	NA	NA	23	2.7	NA	2.5
	Dump Truck	Operating	1.8	10.4	NA	NA	5.3	3	NA	1.8	18.4	NA	NA	18.2	2.4	NA	2.2
6	Cntrl. Truck	Operating	1.9	14.8	NA	NA	6.5	3.8	NA	1.9	26.3	NA	NA	26.1	2.6	NA	2.5
	Dump Truck	Operating	1.6	11.4	NA	NA	5.3	3	NA	1.6	20.4	NA	NA	20.2	2.3	NA	2.1

G-10-54 : 1959, 3@12'x10', 0-9 ft Fill 3-Cell

Skew Angle = 60 Degrees

				Exterior Span											Interior Span		
				Exterior Wall				Top Slab			Interior Wall				Top Slab		
				Shear				Shear			Shear				Shear		
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right
0	Cntrl. Truck	Operating	1.9	7.5	NA	NA	5.7	2.1	NA	1.9	15.8	NA	NA	15.8	2	NA	1.9
	Dump Truck	Operating	1.6	6.5	NA	NA	5.2	2.1	NA	1.6	13.8	NA	NA	13.8	2	NA	1.8
2	Cntrl. Truck	Operating	1.6	7	NA	NA	5	2.1	NA	1.6	14	NA	NA	13.8	1.8	NA	1.7
	Dump Truck	Operating	1.6	6.1	NA	NA	4.5	2.1	NA	1.6	12.3	NA	NA	12.1	1.9	NA	1.7
5	Cntrl. Truck	Operating	2.9	16.6	NA	NA	8.1	4.5	NA	2.9	33.7	NA	NA	33.3	3.5	NA	3.3
	Dump Truck	Operating	2.6	15.1	NA	NA	7.2	4	NA	2.6	28.4	NA	NA	28.1	3.3	NA	3
8	Cntrl. Truck	Operating	2.8	17.8	NA	NA	9.1	6.3	NA	2.8	56.6	NA	NA	56.1	4.3	NA	3.9
	Dump Truck	Operating	2	17	NA	NA	7.5	4.2	NA	2	39.7	NA	NA	39	3	NA	2.7
9	Cntrl. Truck	Operating	2	17.7	NA	NA	8.5	5.4	NA	2	58.5	NA	NA	58	3.4	NA	3.1
	Dump Truck	Operating	1.5	17.1	NA	NA	7.3	4.1	NA	1.5	43.1	NA	NA	42.9	2.7	NA	2.4

D-0-295: 1924, 4@10x5.5, no fill 4-Cell

Skew Angle = 75 Degrees

				Exterior Span											Interior Span						
				Exterior Wall				Top Slab			Interior Wall				Top Slab			Interior Wall			
				Shear				Shear			Shear				Shear			Shear			
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Cntrl. Truck	Operating	1.5	99	NA	NA	99	1.9	NA	1.5	99	NA	NA	2.8	1.8	NA	1.7	99	NA	NA	2.3
	Dump Truck	Operating	1.4	99	NA	NA	99	2.2	NA	1.4	99	NA	NA	3.5	1.9	NA	1.7	99	NA	NA	2.8

G-5-27 : 1957, 4@10'x8', 0-11 ft Fill 4-Cell

Skew Angle = 60 Degrees

				Exterior Span											Interior Span						
				Exterior Wall				Top Slab			Interior Wall				Top Slab			Interior Wall			
				Shear				Shear			Shear				Shear			Shear			
Fill (ft)			Controlling RF	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top	Left	Middle	Right	Bottom	Middle (+)	Middle (-)	Top
0	Cntrl. Truck	Operating	1.4	6.6	NA	NA	4.9	1.6	NA	1.4	16.1	NA	NA	16.1	1.5	NA	1.5	17.6	NA	NA	17.6
	Dump Truck	Operating	1.4	6.8	NA	NA	4.9	1.8	NA	1.4	15	NA	NA	15	1.6	NA	1.5	16.4	NA	NA	16.4
2	Cntrl. Truck	Operating	1.4	6.4	NA	NA	4.4	1.7	NA	1.4	14.7	NA	NA	14.6	1.5	NA	1.5	16.1	NA	NA	15.9
	Dump Truck	Operating	1.4	6.4	NA	NA	4.4	1.9	NA	1.4	13.8	NA	NA	13.7	1.7	NA	1.6	15.3	NA	NA	15.1
5	Cntrl. Truck	Operating	2.5	11	NA	NA	6.8	4	NA	2.5	36.7	NA	NA	36.4	3.1	NA	3.1	40.8	NA	NA	40.4
	Dump Truck	Operating	2.3	10.8	NA	NA	6.3	3.6	NA	2.3	32.1	NA	NA	31.8	2.9	NA	2.8	36	NA	NA	35.6
8	Cntrl. Truck	Operating	2.4	10.3	NA	NA	7.2	5.6	NA	2.4	64.6	NA	NA	66.3	3.5	NA	3.7	70.6	NA	NA	69.9
	Dump Truck	Operating	1.6	10.7	NA	NA	6.1	3.8	NA	1.6	45.4	NA	NA	45	2.4	NA	2.6	50.6	NA	NA	50.1
10	Cntrl. Truck	Operating	0.7	9.9	NA	NA	5.9	3.6	NA	0.7	68	NA	NA	67.7	1.7	NA	2.2	75.4	NA	NA	74.7
	Dump Truck	Operating	0.7	10	NA	NA	5.6	3.5	NA	0.7	56.9	NA	NA	57.2	1.7	NA	2	63.6	NA	NA	63
11	Cntrl. Truck	Operating	0	9.7	NA	NA	5.3	3	NA	0	67.9	NA	NA	67.6	1	NA	1.6	75.7	NA	NA	75
	Dump Truck	Operating	0	9.7	NA	NA	5.3	3.3	NA	0	65.7	NA	NA	65.4	1.1	NA	1.7	73.4	NA	NA	72.7

APPENDIX H

SEARCH CODE FOR TDOT RATING AIDS

```
Sub CreateList()
'
' CreateList Macro
'
' Keyboard Shortcut: Ctrl+Shift+L
'
```

Clears past results and removes previous formatting

```
    Sheets("Search").Range("L4", "O700") = ""
    With Sheets("Search").Range("L4", "O700")
        .UnMerge
        .Interior.Pattern = xlNone
        .Interior.TintAndShade = 0
        .Interior.PatternTintAndShade = 0
        .Borders(xlDiagonalDown).LineStyle = xlNone
        .Borders(xlDiagonalUp).LineStyle = xlNone
        .Borders(xlEdgeLeft).LineStyle = xlNone
        .Borders(xlEdgeTop).LineStyle = xlNone
        .Borders(xlEdgeBottom).LineStyle = xlNone
        .Borders(xlEdgeRight).LineStyle = xlNone
        .Borders(xlInsideVertical).LineStyle = xlNone
        .Borders(xlInsideHorizontal).LineStyle = xlNone
    End With
```

Displays that the program is processing the results in the Warnings cell and turns it orange

```
    Sheets("Search").Cells(5, 10) = "Processing..."
    With Sheets("Search").Cells(5, 10)
        .Interior.Pattern = xlSolid
        .Interior.PatternColorIndex = xlAutomatic
        .Interior.Color = 49407
        .Interior.TintAndShade = 0
        .Interior.PatternTintAndShade = 0
    End With
```

Creates and stores matrices for the Search Page and each page of hyperlinks

```
    Set SearchPage = Worksheets("Search").Range("A1")
    Set OneCell = Worksheets("1 Cell").Range("A1")
    Set TwoCells = Worksheets("2 Cells").Range("A1")
    Set ThreeCells = Worksheets("3 Cells").Range("A1")
    Set FourCells = Worksheets("4 Cells").Range("A1")
    Set FiveCells = Worksheets("5 Cells").Range("A1")
    Set SixCells = Worksheets("6 Cells").Range("A1")
```

Displays “Error” in the Warnings box and turns it red when number of cells is not selected

```
    If Worksheets("Search").Range("B5") = "" Then
        Sheets("Search").Cells(5, 10) = "Error"
        With Sheets("Search").Cells(5, 10)
            .Interior.Pattern = xlSolid
            .Interior.PatternColorIndex = xlAutomatic
            .Interior.Color = 255
            .Interior.TintAndShade = 0
            .Interior.PatternTintAndShade = 0
        End With
        MsgBox "Number of Cells Required!"
```

```
        Exit Sub
    End If
```

Sets the variables type

```
    Dim i As Integer
    Dim j As Integer
    Dim m As Integer
    Dim n As Integer
    Dim p As Integer
    Dim q As Integer
    Dim Count As Integer
    Dim TF As Integer
    Dim TF2 As Integer
    Dim Start As Integer
    Dim CheckYear As Integer
    Dim CheckSize As Integer
    Dim CheckSkew As Integer
    Dim Cell As Variant
    Dim Skew As Variant
    Dim Size As Variant
    Dim Year As Variant
    Dim CheckResults As Integer
    Dim Check1 As Integer
```

Sets variables to be used to determine the 4 search parameters

```
    m = Worksheets("Search").Range("B5")
    n = Worksheets("Search").Range("D5")
    p = Worksheets("Search").Range("F5")
    q = Worksheets("Search").Range("H5")
```

Sets variables to be used for the 4 search parameters (Located on 'Search Page' 419 cells down)

```
    Set Cell = Worksheets("Search").Cells(418 + m, 2)
    Set Skew = Worksheets("Search").Cells(418 + n, 4)
    Set Size = Worksheets("Search").Cells(418 + p, 6)
    Set Year = Worksheets("Search").Cells(418 + q, 8)
```

Zeroes variables

```
    Count = 0
    CheckSize = 0
    CheckYear = 0
    CheckSkew = 0
    CheckResults = 0
    Check1 = 0
```

Checks to see if skew, size, and year exist for chosen number of cells

```
    For i = 3 To 200
        If Cell = "1 Cell" Then
            If OneCell(i, 2) = Skew Or Skew = "" Then
                CheckSkew = 1
            End If
            If OneCell(1, i) = Size Or Size = "" Then
                CheckSize = 1
            End If
            If OneCell(i, 1) = Year Or Year = "" Then
                CheckYear = 1
```

```
    End If
End If
If Cell = "2 Cells" Then
    If TwoCells(i, 2) = Skew Or Skew = "" Then
        CheckSkew = 1
    End If
    If TwoCells(1, i) = Size Or Size = "" Then
        CheckSize = 1
    End If
    If TwoCells(i, 1) = Year Or Year = "" Then
        CheckYear = 1
    End If
End If
If Cell = "3 Cells" Then
    If ThreeCells(i, 2) = Skew Or Skew = "" Then
        CheckSkew = 1
    End If
    If ThreeCells(1, i) = Size Or Size = "" Then
        CheckSize = 1
    End If
    If ThreeCells(i, 1) = Year Or Year = "" Then
        CheckYear = 1
    End If
End If
If Cell = "4 Cells" Then
    If FourCells(i, 2) = Skew Or Skew = "" Then
        CheckSkew = 1
    End If
    If FourCells(1, i) = Size Or Size = "" Then
        CheckSize = 1
    End If
    If FourCells(i, 1) = Year Or Year = "" Then
        CheckYear = 1
    End If
End If
If Cell = "5 Cells" Then
    If FiveCells(i, 2) = Skew Or Skew = "" Then
        CheckSkew = 1
    End If
    If FiveCells(1, i) = Size Or Size = "" Then
        CheckSize = 1
    End If
    If FiveCells(i, 1) = Year Or Year = "" Then
        CheckYear = 1
    End If
End If
If Cell = "6 Cells" Then
    If SixCells(i, 2) = Skew Or Skew = "" Then
        CheckSkew = 1
    End If
    If SixCells(1, i) = Size Or Size = "" Then
        CheckSize = 1
    End If
    If SixCells(i, 1) = Year Or Year = "" Then
        CheckYear = 1
    End If
```

```
        End If
        If CheckSkew = 1 And CheckSize = 1 And CheckYear = 1 Then
            Exit For
        End If
    Next
```

Warns when skew, year, and/or size fail to match any values for the selected number of cells

```
    If CheckSkew = 0 Then
        Sheets("Search").Cells(5, 10) = "Search Modified"
        Sheets("Search").Cells(5, 10).Interior.Pattern = xlSolid
        Sheets("Search").Cells(5, 10).Interior.PatternColorIndex = xlAutomatic
        Sheets("Search").Cells(5, 10).Interior.Color = 65535
        Sheets("Search").Cells(5, 10).Interior.TintAndShade = 0
        Sheets("Search").Cells(5, 10).Interior.PatternTintAndShade = 0
        MsgBox "No Drawings with Selected Skew for Specified # of Cells, Skew Parameter Removed!"
        Skew = ""
    End If
    If CheckYear = 0 Then
        Sheets("Search").Cells(5, 10) = "Search Modified"
        Sheets("Search").Cells(5, 10).Interior.Pattern = xlSolid
        Sheets("Search").Cells(5, 10).Interior.PatternColorIndex = xlAutomatic
        Sheets("Search").Cells(5, 10).Interior.Color = 65535
        Sheets("Search").Cells(5, 10).Interior.TintAndShade = 0
        Sheets("Search").Cells(5, 10).Interior.PatternTintAndShade = 0
        MsgBox "No Drawings with Selected Year for Specified # of Cells, Year Parameter Removed!"
        Year = ""
    End If
    If CheckSize = 0 Then
        Sheets("Search").Cells(5, 10) = "Search Modified"
        Sheets("Search").Cells(5, 10).Interior.Pattern = xlSolid
        Sheets("Search").Cells(5, 10).Interior.PatternColorIndex = xlAutomatic
        Sheets("Search").Cells(5, 10).Interior.Color = 65535
        Sheets("Search").Cells(5, 10).Interior.TintAndShade = 0
        Sheets("Search").Cells(5, 10).Interior.PatternTintAndShade = 0
        MsgBox "No Drawings with Selected Size for Specified # of Cells, Size Parameter Removed!"
        Size = ""
    End If
```

Sets the Search page back to being the Active Page

```
    Sheets("Search").Activate
```

Searches are custom tailored to each available number of cells- All are set up in a similar manner

```
    If Cell = "1 Cell" Then
```

Used to look through columns of the selected number of cells' page of hyperlinks

```
        For i = 3 To 500
```

If no results are returned for valid parameters once the last culverts' Size parameter on the hyperlink page is checked, parameters are removed and the search is reset until results are found

```
            If Sheets("1 Cell").Cells(1, i) = "" Then
                If CheckResults = 0 Then
                    Check1 = Check1 + 1
```

If no results are returned for valid parameters, the Year parameter is removed first

```
                    If Check1 = 1 Then
                        Year = ""
                        i = 3
                        j = 3
```

```
                Check1 = Check1 + 1
            End If
```

If no results are returned a second time, the Year parameter is reassigned and Size is removed

```
            If Check1 = 3 Then
                Year = Worksheets("Search").Cells(418 + q, 8)
                Size = ""
                i = 3
                j = 3
                Check1 = Check1 + 1
            End If
```

If no results are returned a third time, the Year and Size parameter are removed

```
            If Check1 = 5 Then
                Size = ""
                Year = ""
                i = 3
                j = 3
                Check1 = Check1 + 1
            End If
        Else
```

If results were found, and the last culvert has been checked, the for loop is exited moving the program on to the the final phase (post process formatting)

```
            Exit For
        End If
    End If
```

Used to look through rows of the selected number of cells' page of hyperlinks

```
    For j = 3 To 500
```

If no results are returned for valid parameters once the last culverts' Year and Skew parameters on the hyperlink page is checked, the "j" for loop is exited, returning to the next "i" for loop

```
        If Sheets("1 Cell").Cells(j, 1) = "" Then
            Exit For
        End If
```

This section is used to decide whether to use the cell being looked at as part of the results
First, the cell is required to not have nothing in it, or to put it in normal terms, to have something in the cell (a hyperlink)

```
        If Sheets("1 Cell").Cells(j, i) <> "" Then
```

Secondly, the cell in question is required to have a matching year parameter, if the Year parameter is defined; if Year is not defined, then it also passes this check

```
            If Sheets("1 Cell").Cells(j, 1) = Year Or Year = "" Then
```

This is the same for the Skew

```
                If Sheets("1 Cell").Cells(j, 2) = Skew Or Skew = "" Then
```

and Year parameters

```
                    If Sheets("1 Cell").Cells(1, i) = Size Or Size = "" Then
```

Once a result has been found, CheckResults is set to 1 (1 = True, there was at least 1 result, 0 = False)

```
                        CheckResults = 1
```

Each time a match is found, the count goes up by 1; Count is used to decide which row to place the result in on the Search page and is used in the merging process

```
                        Count = Count + 1
```

The result is copied from the page of hyperlinks

```
                        Sheets("1 Cell").Cells(j, i).Copy
```

and pasted to the Search page

```
                        Sheets("Search").Cells(3 + Count, 12).PasteSpecial Paste:=xlPasteAllUsingSourceTheme
```

If a size parameter is currently being used, then that value is used in the Size column of the Results on the Search page

```
                        If Size <> "" Then
                            Sheets("Search").Cells(3 + Count, 13) = Size
```

```
                    Else
```

if not, then the size of the current result is used

```
                        Sheets("Search").Cells(3 + Count, 13) = Sheets("1 Cell").Cells(1, i)
                    End If
```

The same is done for the Year parameter and put in the year column of the Results List

```
                    If Year <> "" Then
                        Sheets("Search").Cells(3 + Count, 14) = Year
                    Else
                        Sheets("Search").Cells(3 + Count, 14) = Sheets("1 Cell").Cells(j, 1)
                    End If
                End If
            End If
        End If
    End If
Next
Next
End If
```

Similar processes are taken for each of the other number of cells when selecting which results to copy over to the Search page's Results section

```
If Cell = "2 Cells" Then
    For i = 3 To 500
        If Sheets("2 Cells").Cells(1, i) = "" Then
            If CheckResults = 0 Then
                Check1 = Check1 + 1
                If Check1 = 1 Then
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 3 Then
                    Year = Worksheets("Search").Cells(418 + q, 8)
                    Size = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 5 Then
                    Size = ""
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
            Else
                Exit For
            End If
        End If
        For j = 3 To 500
            If Sheets("2 Cells").Cells(j, 1) = "" Then
                Exit For
            End If
            If Sheets("2 Cells").Cells(j, i) <> "" Then
                If Sheets("2 Cells").Cells(j, 1) = Year Or Year = "" Then
                    If Sheets("2 Cells").Cells(j, 2) = Skew Or Skew = "" Then
```

```
                If Sheets("2 Cells").Cells(1, i) = Size Or Size = "" Then
                    CheckResults = 1
                    Count = Count + 1
                    Sheets("2 Cells").Cells(j, i).Copy
                    Sheets("Search").Cells(3 + Count, 12).PasteSpecial Paste:=xlPasteAllUsingSourceTheme
                    If Size <> "" Then
                        Sheets("Search").Cells(3 + Count, 13) = Size
                    Else
                        Sheets("Search").Cells(3 + Count, 13) = Sheets("2 Cells").Cells(1, i)
                    End If
                    If Year <> "" Then
                        Sheets("Search").Cells(3 + Count, 14) = Year
                    Else
                        Sheets("Search").Cells(3 + Count, 14) = Sheets("2 Cells").Cells(j, 1)
                    End If
                End If
            End If
        End If
    End If
    Next
  Next
End If

If Cell = "3 Cells" Then
  For i = 3 To 500
    If Sheets("3 Cells").Cells(1, i) = "" Then
      If CheckResults = 0 Then
        Check1 = Check1 + 1
        If Check1 = 1 Then
          Year = ""
          i = 3
          j = 3
          Check1 = Check1 + 1
        End If
        If Check1 = 3 Then
          Year = Worksheets("Search").Cells(418 + q, 8)
          Size = ""
          i = 3
          j = 3
          Check1 = Check1 + 1
        End If
        If Check1 = 5 Then
          Size = ""
          Year = ""
          i = 3
          j = 3
          Check1 = Check1 + 1
        End If
      Else
        Exit For
      End If
    End If
    For j = 3 To 500
      If Sheets("3 Cells").Cells(j, 1) = "" Then
        Exit For
      End If
```

```
            If Sheets("3 Cells").Cells(j, i) <> "" Then
                If Sheets("3 Cells").Cells(j, 1) = Year Or Year = "" Then
                    If Sheets("3 Cells").Cells(j, 2) = Skew Or Skew = "" Then
                        If Sheets("3 Cells").Cells(1, i) = Size Or Size = "" Then
                            CheckResults = 1
                            Count = Count + 1
                            Sheets("3 Cells").Cells(j, i).Copy
                            Sheets("Search").Cells(3 + Count, 12).PasteSpecial Paste:=xlPasteAllUsingSourceTheme
                            If Size <> "" Then
                                Sheets("Search").Cells(3 + Count, 13) = Size
                            Else
                                Sheets("Search").Cells(3 + Count, 13) = Sheets("3 Cells").Cells(1, i)
                            End If
                            If Year <> "" Then
                                Sheets("Search").Cells(3 + Count, 14) = Year
                            Else
                                Sheets("Search").Cells(3 + Count, 14) = Sheets("3 Cells").Cells(j, 1)
                            End If
                        End If
                    End If
                End If
            End If
        Next
    Next
End If

If Cell = "4 Cells" Then
    For i = 3 To 500
        If Sheets("4 Cells").Cells(1, i) = "" Then
            If CheckResults = 0 Then
                Check1 = Check1 + 1
                If Check1 = 1 Then
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 3 Then
                    Year = Worksheets("Search").Cells(418 + q, 8)
                    Size = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 5 Then
                    Size = ""
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
            Else
                Exit For
            End If
        End If
        For j = 3 To 500
```

```
            If Sheets("4 Cells").Cells(j, 1) = "" Then
                Exit For
            End If
            If Sheets("4 Cells").Cells(j, i) <> "" Then
                If Sheets("4 Cells").Cells(j, 1) = Year Or Year = "" Then
                    If Sheets("4 Cells").Cells(j, 2) = Skew Or Skew = "" Then
                        If Sheets("4 Cells").Cells(1, i) = Size Or Size = "" Then
                            CheckResults = 1
                            Count = Count + 1
                            Sheets("4 Cells").Cells(j, i).Copy
                            Sheets("Search").Cells(3 + Count, 12).PasteSpecial Paste:=xlPasteAllUsingSourceTheme
                            If Size <> "" Then
                                Sheets("Search").Cells(3 + Count, 13) = Size
                            Else
                                Sheets("Search").Cells(3 + Count, 13) = Sheets("4 Cells").Cells(1, i)
                            End If
                            If Year <> "" Then
                                Sheets("Search").Cells(3 + Count, 14) = Year
                            Else
                                Sheets("Search").Cells(3 + Count, 14) = Sheets("4 Cells").Cells(j, 1)
                            End If
                        End If
                    End If
                End If
            End If
        Next
    Next
End If

If Cell = "5 Cells" Then
    For i = 3 To 500
        If Sheets("5 Cells").Cells(1, i) = "" Then
            If CheckResults = 0 Then
                Check1 = Check1 + 1
                If Check1 = 1 Then
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 3 Then
                    Year = Worksheets("Search").Cells(418 + q, 8)
                    Size = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 5 Then
                    Size = ""
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
            Else
                Exit For
```

```
            End If
        End If
        For j = 3 To 500
            If Sheets("5 Cells").Cells(j, 1) = "" Then
                Exit For
            End If
            If Sheets("5 Cells").Cells(j, i) <> "" Then
                If Sheets("5 Cells").Cells(j, 1) = Year Or Year = "" Then
                    If Sheets("5 Cells").Cells(j, 2) = Skew Or Skew = "" Then
                        If Sheets("5 Cells").Cells(1, i) = Size Or Size = "" Then
                            CheckResults = 1
                            Count = Count + 1
                            Sheets("5 Cells").Cells(j, i).Copy
                            Sheets("Search").Cells(3 + Count, 12).PasteSpecial Paste:=xlPasteAllUsingSourceTheme
                            If Size <> "" Then
                                Sheets("Search").Cells(3 + Count, 13) = Size
                            Else
                                Sheets("Search").Cells(3 + Count, 13) = Sheets("5 Cells").Cells(1, i)
                            End If
                            If Year <> "" Then
                                Sheets("Search").Cells(3 + Count, 14) = Year
                            Else
                                Sheets("Search").Cells(3 + Count, 14) = Sheets("5 Cells").Cells(j, 1)
                            End If
                        End If
                    End If
                End If
            End If
        Next
    Next
End If

If Cell = "6 Cells" Then
    For i = 3 To 500
        If Sheets("6 Cells").Cells(1, i) = "" Then
            If CheckResults = 0 Then
                Check1 = Check1 + 1
                If Check1 = 1 Then
                    Year = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 3 Then
                    Year = Worksheets("Search").Cells(418 + q, 8)
                    Size = ""
                    i = 3
                    j = 3
                    Check1 = Check1 + 1
                End If
                If Check1 = 5 Then
                    Size = ""
                    Year = ""
                    i = 3
                    j = 3
```

```
                Check1 = Check1 + 1
            End If
        Else
            Exit For
        End If
    End If
    For j = 3 To 500
        If Sheets("6 Cells").Cells(j, 1) = "" Then
            Exit For
        End If
        If Sheets("6 Cells").Cells(j, i) <> "" Then
            If Sheets("6 Cells").Cells(j, 1) = Year Or Year = "" Then
                If Sheets("6 Cells").Cells(j, 2) = Skew Or Skew = "" Then
                    If Sheets("6 Cells").Cells(1, i) = Size Or Size = "" Then
                        CheckResults = 1
                        Count = Count + 1
                        Sheets("6 Cells").Cells(j, i).Copy
                        Sheets("Search").Cells(3 + Count, 12).PasteSpecial Paste:=xlPasteAllUsingSourceTheme
                        If Size <> "" Then
                            Sheets("Search").Cells(3 + Count, 13) = Size
                        Else
                            Sheets("Search").Cells(3 + Count, 13) = Sheets("5 Cells").Cells(1, i)
                        End If
                        If Year <> "" Then
                            Sheets("Search").Cells(3 + Count, 14) = Year
                        Else
                            Sheets("Search").Cells(3 + Count, 14) = Sheets("5 Cells").Cells(j, 1)
                        End If
                    End If
                End If
            End If
        End If
    Next
Next
End If
```

Sets the Search page back to being the ActiveSheet; at this point, all results are listed on the Search page

```
Sheets("Search").Activate
```

The Check1 variable is equal to 2 when all selected parameters existed for the chosen number of cells, but did not return any results until the year parameter was removed

```
If Check1 = 2 Then
    Sheets("Search").Cells(5, 10) = "Search Modified"
    Sheets("Search").Cells(5, 10).Interior.Pattern = xlSolid
    Sheets("Search").Cells(5, 10).Interior.PatternColorIndex = xlAutomatic
    Sheets("Search").Cells(5, 10).Interior.Color = 65535
    Sheets("Search").Cells(5, 10).Interior.TintAndShade = 0
    Sheets("Search").Cells(5, 10).Interior.PatternTintAndShade = 0
    MsgBox "No Results with Selected Skew, Size, and Year for Specified # of Cells; Year Parameter Removed!"
End If
```

The Check1 variable is equal to 4 when all selected parameters existed for the chosen number of cells, but did not return any results until the size parameter was removed

```
If Check1 = 4 Then
    Sheets("Search").Cells(5, 10) = "Search Modified"
    Sheets("Search").Cells(5, 10).Interior.Pattern = xlSolid
    Sheets("Search").Cells(5, 10).Interior.PatternColorIndex = xlAutomatic
```

```
        Sheets("Search").Cells(5, 10).Interior.Color = 65535
        Sheets("Search").Cells(5, 10).Interior.TintAndShade = 0
        Sheets("Search").Cells(5, 10).Interior.PatternTintAndShade = 0
        MsgBox "No Results with Selected Skew, Size, and Year for Specified # of Cells; Size Parameter Removed!"
    End If
```

The Check1 variable is equal to 6 when all selected parameters existed for the chosen number of cells, but did not return any results until the size and year parameters were removed

```
    If Check1 = 6 Then
        Sheets("Search").Cells(5, 10) = "Search Modified"
        Sheets("Search").Cells(5, 10).Interior.Pattern = xlSolid
        Sheets("Search").Cells(5, 10).Interior.PatternColorIndex = xlAutomatic
        Sheets("Search").Cells(5, 10).Interior.Color = 65535
        Sheets("Search").Cells(5, 10).Interior.TintAndShade = 0
        Sheets("Search").Cells(5, 10).Interior.PatternTintAndShade = 0
        MsgBox "No Results with Selected Skew, Size, and Year for Specified # of Cells; Size and Year Parameters Removed!"
    End If
```

This portion is used to determine if consecutive Size cells match in the Results section, and then merges them when they match

```
    TF = 0
    TF2 = 0
    Start = 0
    For i = 2 To Count
        If Sheets("Search").Cells(3 + i, 13) = Sheets("Search").Cells(3 + i - 1, 13) Then
            TF = TF + 1
            If TF = 1 Then
                Start = 3 + i - 1
            End If

            If Sheets("Search").Cells(3 + i, 13) <> Sheets("Search").Cells(3 + i + 1, 13) Or i = Count Then
                TF2 = 1
            End If
        End If

        If TF2 = 1 Then
            Sheets("Search").Range(Cells(Start + 1, 13), Cells(Start + TF, 13)) = ""
            Sheets("Search").Range(Cells(Start, 13), Cells(Start + TF, 13)).Merge
            TF = 0
            TF2 = 0
            Start = 0
        End If
    Next
```

This section puts borders around the results, bolds the text, removes fill color, and centers the text

```
    With Sheets("Search").Range(Cells(4, 12), Cells(3 + Count, 14))
        .Borders(xlEdgeLeft).LineStyle = xlContinuous
        .Borders(xlEdgeLeft).Weight = xlMedium
        .Borders(xlEdgeTop).LineStyle = xlContinuous
        .Borders(xlEdgeTop).Weight = xlMedium
        .Borders(xlEdgeBottom).LineStyle = xlContinuous
        .Borders(xlEdgeBottom).Weight = xlMedium
        .Borders(xlEdgeRight).LineStyle = xlContinuous
        .Borders(xlEdgeRight).Weight = xlMedium
        .Borders(xlInsideVertical).LineStyle = xlContinuous
        .Borders(xlInsideVertical).Weight = xlThin
```

```
        .Borders(xlInsideHorizontal).LineStyle = xlContinuous
        .Borders(xlInsideHorizontal).Weight = xlMedium
        .Interior.Pattern = xlSolid
        .Interior.PatternColorIndex = xlAutomatic
        .Interior.ThemeColor = xlThemeColorDark1
        .Interior.TintAndShade = 0
        .Interior.PatternTintAndShade = 0
        .Font.Bold = True
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlCenter
    End With
```

This removes the "Processing…" text and color from the Warnings cell on the Search page if no modifications were made or errors existed

```
    If Sheets("Search").Cells(5, 10) = "Processing..." Then
        Sheets("Search").Cells(5, 10) = ""
        With Sheets("Search").Cells(5, 10).Interior
            .Pattern = xlSolid
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark1
            .TintAndShade = 0
            .PatternTintAndShade = 0
        End With
    End If
```

The Search page is set as the ActiveSheet, and Cell A1 is selected to return to the top of the page

```
    Sheets("Search").Activate
    Sheets("Search").Range("A1").Select
End Sub
```