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EVALUATION OF 2-CELL RC BOX CULVERTS

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EVALUATION OF 2-CELL RC BOX CULVERTS

THESIS

A thesis submitted in partial fulfilment of the
requirement for the degree of Master of Science in Civil Engineering in the
College of Engineering
at the University of Kentucky

By

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Director: Dr. Issam Harik, Professor of Civil and Environmental Engineering

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2018

ABSTRACT OF THESIS

EVALUATION OF 2-CELL RC BOX CULVERTS

Reinforced Concrete Box Culverts (RCBCs) are an integral part of the national and international transportation infrastructure. The National Bridge Inventory Standards (NBIS) requires that all bridges, which include culverts with spans $\geq$ 20 ft. (6.1 m), be load rated for safe load carrying capacity in accordance with the AASHTO Manual for Bridge Evaluation (MBE). In Kentucky, the Transportation Cabinet manages more than 15,500 bridges, of which almost 1,400 are bridge size culverts. Of the 1241 bridge size RCBCs that were being evaluated in Kentucky between 2015 and 2018, 846 were 2-cell culverts (or 68%). The objective in this study is to evaluate 2-cell RCBCs using the finite element (FE) method and to propose dead load and live load demand equations that can be used to determine the capacity demand ratio (C/D) and the load rating. The results indicate that the maximum dead load forces (positive and negative moments, and shear) vary linearly with respect to an increase in fill height, while the variation is bi-linear for the maximum live load forces. The proposed equations are derived in terms of the clear span and fill height. The results also indicated that, for fill heights greater than 10 ft (3 m), the maximum live load positive bending moments are less than 10% of their dead load counterparts. The primary advantage of the proposed equations lies in their simple formulation when analyzing and designing 2-cell culverts, which in turn alleviates the need to conduct a detailed finite element analysis to determine the maximum forces in 2-cell RCBCs.

KEYWORDS: REINFORCED CONCRETE, BOX CULVERT, FINITE ELEMENT METHOD, LIVE LOADS, DEAD LOADS, FILL HEIGHT

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04/24/2018

EVALUATION OF 2-CELL RC BOX CULVERTS

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To my Azimeh, supportive parents, and the only sister.

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I would like to acknowledge all the people who have assisted and inspired me throughout this research. I would like to admire my knowledgeable advisor, Dr. Issam Harik, who trusted on my abilities and provided me a great opportunity to conduct my research. My second appreciation also goes to Dr. Abheetha Peiris who has openly assisted me with his brilliant ideas and thoughts. Without the instructions and advices of these two wonderful persons, this research would not be even possible to be accomplished.

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1. Introduction

1.1. Problem Statement

Bridges have always played a significant role in transportation systems by allowing us to cross over natural obstacles, such as rivers and valleys. One of the main classes of bridge structures is culverts. Culverts with span lengths of 20 feet (6 m) or larger are classified as bridge sized culverts. The behavior of buried culverts is different from above-ground bridges. There is a large number of factors and variables that play a role in the complexity of a culvert structure.

From a quantitative point of view, culverts have been growing in numbers due to the growth of population and the associated necessity for continuing accommodations. According to the National Bridge Inventory Standard (NBIS, 2015) database, there are roughly 134,000 bridge sized culverts (or 22% of the 611,845 inventoried bridges in the United States), which is a significant number to be considered.

Additionally, a large proportion of culverts are old and were built decades ago. Any culvert after many years of operation could lose some of its initial capacity due to over loading, material deterioration etc. Old culverts won't have the same serviceability over time due to heavier truck weights and higher material strengths utilized in new codes of practice. In addition, changes to the culvert could occur over time resulting in changes to the culvert loading. These include changes in fill height and pavement thickness due to modifications to the roadway elevation.

Furthermore, since culverts are considered buried structures, the exact assessment of the soil-structure interaction behavior of existing culverts is complex. This is not just because of uncertainty about the type and design parameters of soil-surrounded culverts, but also because of the gradual alteration in the soil's parameter, like saturation condition, change in modulus with compaction, etc. Moreover, the choice between structural analysis approaches varies from practical formulas to sophisticated 3D finite element analysis. Choosing the optimal approach has always been a matter of balancing cost vs. accuracy. As an illustration, simplified methods are time effective but their results may not to be the most accurate and most of the time are more conservative than required. On the other hand, the 3D analysis is not time effective enough, but provides more reliable results. Mostly, this decision depends on the culverts' constitutive material (concrete, steel, or fiber-glass composites), geometry, and culvert type (box, arch, pipe, etc.).

All of these aforementioned reasons prove that the issues of design, evaluation, and inspection of culverts during their lifetime are very important tasks for Departments of Transportation (DOTs). First, all culverts need to be field inspected every couple of years in order to assess whether there are any obvious changes in the condition of the culvert like cracks, deterioration, excessive deflection, etc. Then, they need to be load rated by calculating the demand loads and the capacity of the structure for moment, shear, and thrust loads.

1.2. Literature Review

Bridge sized culverts need to be designed and maintained according to AASHTO specification. AASHTO introduced the bridge design specification based on the load and resistance factor design (LRFD) methodology in 1994. It is a standard code that is more reliable than the previous load factor design (LFD) standard specification (McGrath et al. 2005)

Field inspection of culverts is the next concern after designing a culvert. The Federal Highway Administration (FHWA 2009) requires bridge-sized culverts to be inspected at regular intervals. During the inspection, qualified bridge inspector carefully examine the culvert structure, and note any structural damage or deterioration. (AASHTO 2013). Frequently, older, in-service culverts including RC box culverts show little structural damage from field inspection, but the calculated load ratings indicate that such culverts do not have adequate strength (NCHRP 2015; Wood et al. 2016). Bridge and highway professionals, at both the state and federal levels, have always been looking for resolving the apparent disconnect between field inspections and calculated load-rating results for culverts (Lawson et al. 2009; Han et al. 2013; Orton et al. 2015; NCHRP 2015; Wood et al. 2016). AASHTO MBE (AASHTO 2013) introduces the general equation for load rating as:

$$RF = \frac{C - A_1 D}{A_2 L (1 + I)} \quad \text{Eq. 1}$$

where RF is the rating factor; C is structural capacity of the member; D is dead-load effect on the member; L is live-load effect on the member; I is the impact factor; A1 value is 1.3 (factor for dead loads from MBE 6B.4.2 and 6B.4.3); and A2 value is 2.17 for inventory level (factor for live loads from MBE 6B.4.3) and 1.3 for operating level (factor for live loads from MBE 6B.4.3).

During load rating, RC box culvert structural members are evaluated for flexure, shear, and axial thrust, as noted in the AASHTO Manual for bridge evaluation (MBE) (AASHTO

2013). The lowest rating factor from all sections and all load effects governs the load rating of the structure (AASHTO 2013). Load rating could be carried by different approaches from the simplest method to the more sophisticated ones. But for RC box culverts, AASHTO (2013) recommends the demand-prediction model to achieve “consistent and repeatable” load ratings and specifies a structural-frame model as a common approach.

The dead load effects for a culvert comes from the soil and pavement above the culvert and the self-weight of the culvert. The type of culvert installation, culvert foundation, and side fill compaction has significant effects on the dead-load contribution in the culvert (Lawson et al. 2010; Acharya 2012; Yoo et al. 2005). Many parameters could affect the live load effect on members of a culvert. To estimate the live load for load rating of a culvert buried at a shallow depth (i.e., a shallow cover), a reasonably accurate three-dimensional (3D) analysis is needed to evaluate the effect of these loads (Abdel-Karim et al. 1993).

The response of the culvert to a live load significantly increases when the depth of the cover above the culvert decreases (Abdel-Karim et al. 1990, 1993). Abdel-Karim et al. (1990) further suggested the live load effects on shear force, moment, etc. be neglected if they contribute less than 5% of the total load effects. Also, Gilliand (1986) suggested the cut-off point to be considered as the fill height at which the live-load pressures are less than 10% of the pressures due to the dead load only. Yeau et al. (2009) concluded that the effect of the live load is negligible when the cover depth is greater than 6.5 ft. (2 m) on the basis of a study of 39 metal culverts. Awwad et al. (2000) also reached a similar conclusion that the live loads were negligible after 7 ft. (2.1 m) of fill, using finite element analysis. Orton et al. (2015) suggested the cut off point for neglecting the effect of live load to be 6 ft. (1.82 m) by carrying out field testing on 10 in-service RC box culverts in Missouri.

Although the guidelines provided by the code or specification are useful for culvert design, they are conservative for load rating of culverts that are under either rigid or flexible pavements. The problem pertaining to load distribution through a pavement is not explicitly taken into account by AASHTO (Abdel-Karim et al. 1990). They also found that the effect of the pavement diminished when the fill depth was over 8.8 ft. (2.7 m), which is very close to AASHTO's current guideline of 8 ft. (2.4 m) fill for a single-span culvert. Peterson et al. (2010) conducted 3D numerical analyses of culverts with and without a pavement and found that the pavement thoroughly spread the load. However, they suggested that the unpaved case should dominate the design loads because live loads are applied before paving and during roadway rehabilitation. Lawson et al. (2010) also conducted an instrumented load test on three in-service culverts in Texas to compare the measured demands with the predicted values using analytical tools. They suggested the possibility of reducing live loads by considering the pavement stiffness. Park et al (2013) found that the pavement distress decreased as the depth of the fill cover increased. AASHTO (2013) acknowledges that "pavement/subgrade to the underlying culvert" influences the live-load distribution, although it does not provide guidance. NCHRP (2015) also specifically identifies accounting for "the effect of pavement" as a requirement for improved load-rating specifications in the request for research proposal.

1.3. Significance of the Study

The significance of this study lies in providing a comprehensive analysis of the performance of 2-cell RC Box Culverts, which is helpful for future design and load rating.

1.4. Research Objective and Tasks

The objective of this research is to evaluate the effect of varying a number of geometrical parameters such as clear span length, clear height, and fill height on the soil-structure performance of Reinforced Concrete Box Culverts (RCBCs).

In order to achieve the objective of this study, the following tasks were carried out:

1- **Culvert Survey:** Conducting a comprehensive survey on all in-service culverts in the state of Kentucky (approximately 1200) in an effort to identify the characteristics of all culverts such as culvert's type, design year, number of cells, clear spans, clear height, fill depth, and etc.

2- **Finite Element Model Verification:** Verifying the accuracy of the FEM computer program CANDE (**C**ulvert **AN**alysis and **De**sign), first with a hand calculation example, and then with an experimental field-tested culvert.

3- **Finite Element Evaluation:** Obtaining a number of finite element analyses to evaluate the effect of varying geometrical parameters such as clear span length, clear height, and fill depth on the structural performance of RC Box Culverts (RCBCs).

4- **Conclusions and Recommendations:** Develop comprehensive conclusions on structural performance of 2-cell RC Box Culverts and propose recommendations for future studies.

2. Culverts in Kentucky

A three months long survey was compiled on all existing bridge size culverts in Kentucky using data provided by the Kentucky Transportation Cabinet (KYTC). After collecting data, a set of bar charts were plotted to evaluate the characteristic of in-service culverts in Kentucky.

2.1. Structures Type

In the following bar chart, the number of bridge size culverts under each culvert category is shown. Approximately 94 percent of all 1378 in-service bridge size culverts in Kentucky are RC Box Culverts (1241). This abundance of RC Box Culverts (RCBCs) could be because of their easy construction and cost effectiveness rather than other type of culverts.

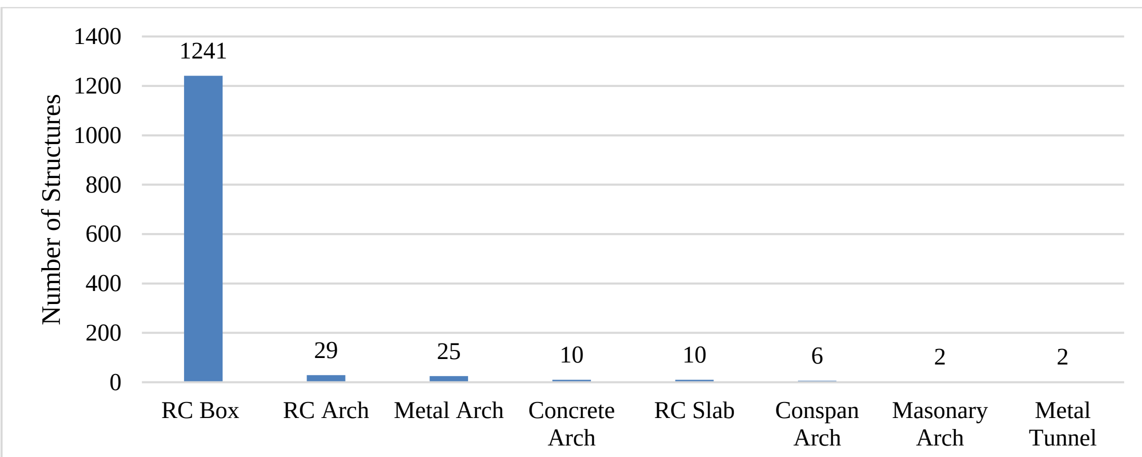

Figure 2.1. Structure Types

2.2. Design year of RCBCs

The next chart classifies the numbers of RCBCs based on their design decades from the beginning of the 19th century. The design year is a very important parameter, when bridge plans are unavailable, in approximating the compressive strength of concrete (F'_c) and yield strength of steel (F_y) based on the AASHTO standard for the process of load rating. It is obvious 427 of all RCBCs, nearly 34 percent, were designed between years 1950 and 1959, which is the largest number in quantity for a decade. Also, it is noticeable that 182 of all RCBCs were designed before the beginning of World War II (1939). This depicts how much load rating of existing culverts for current loading is important.

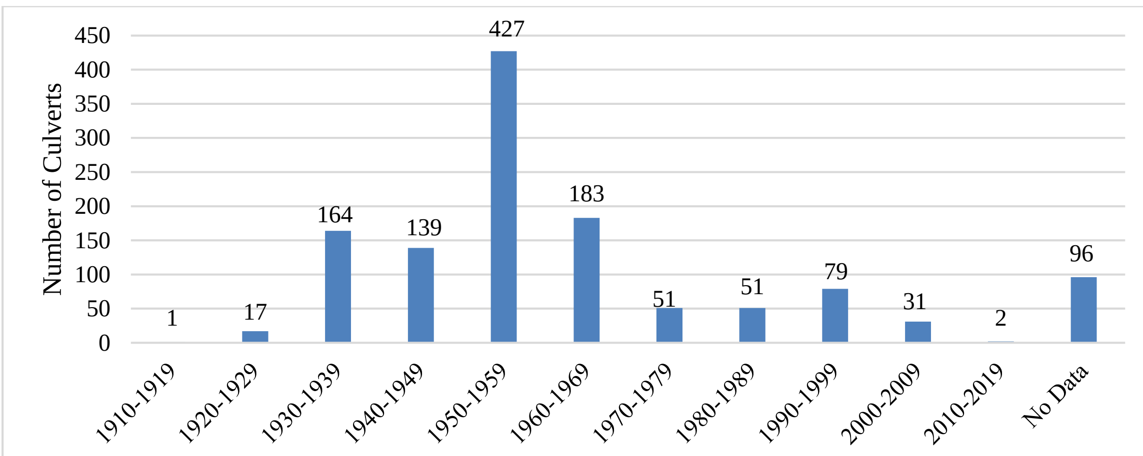

Figure 2.2. Design Year for RC Box Culverts

2.3. Number of Cells for RCBCs

The next bar chart describes the quantity of RCBCs based on their number of cells. About 87 percent of all RCBCs (1079 out of 1241) have more than one cell and about 68 percent

(846 out of 1241) have just two cells. These numbers accentuate the necessity of focusing of this study on double cell RCBCs.

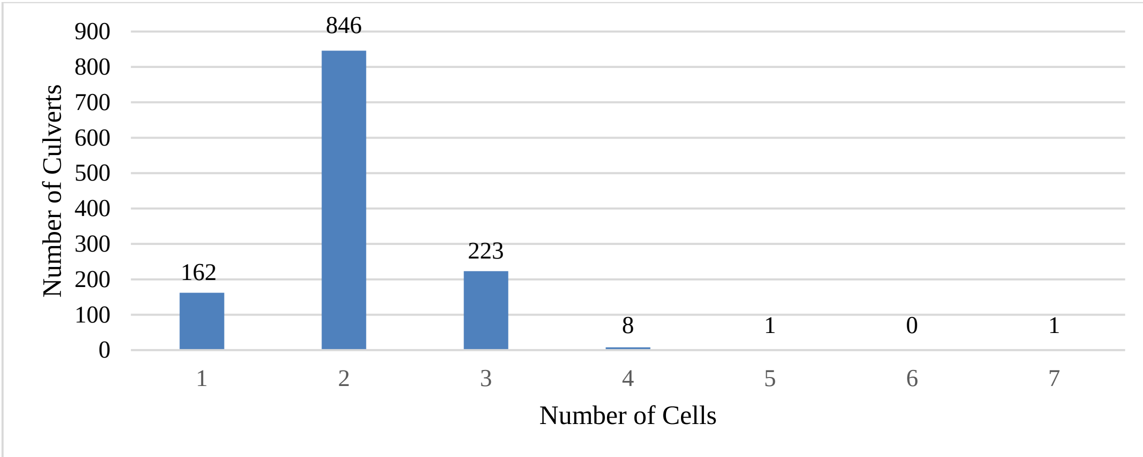

Figure 2.3. Number of Cells for RC Box Culverts

2.4. Cell's Dimensions of RCBCs

From cell's dimensions point of view, nearly 86 percent of all 2-cell RC box culverts (727 out of 846) have clear span in range of 10 ft. (3.05 m) to 14 ft. (4.27 m), and approximately 66 percent of all RC box culverts (566 out of 846) possess cell clear height in range of 6 ft. (1.83m) to 10 ft. (3.05m). Thus, these ranges of cell dimensions would be proper for being used in all case studies.

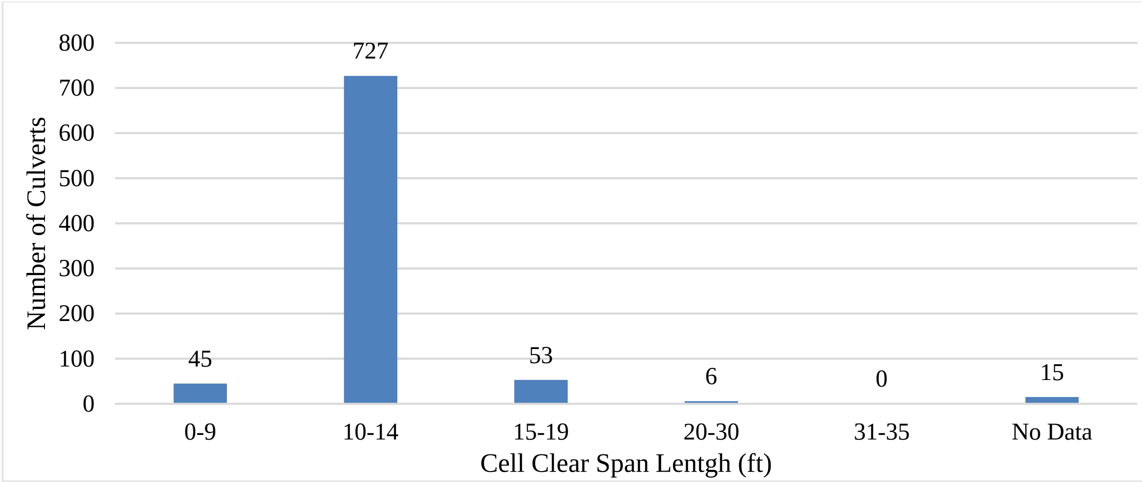

Figure 2.4. Cell’s Clear Span for 2-cell RC Box Culverts

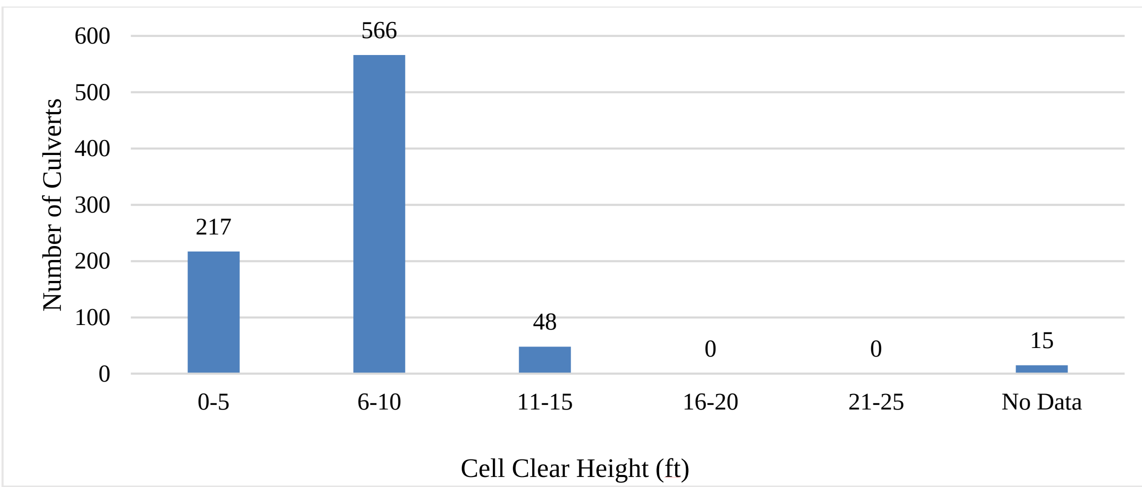

Figure. 2.5. Cell’s Clear Height for 2-cell RC Box Culverts

2.5. Fill Height for RCBCs

One of the most crucial parameters that have a considerable effect on the behavior of RCBCs is the fill height above the culvert. This parameter plays an essential role in distribution of live loads over the top slab of RCBCs. Basically, the depth and the stiffness of soil in backfill zone determine how the live load get distributed over the structure.

Therefore, this parameter needs to clearly be studied to reach a better understanding regarding the soil-structure interaction of RCBCs. The LRFD AASHTO (2012) bridge design specification suggests neglecting the effect of the live load for analyzing and load rating of culverts with fill heights greater than one of the followings: 8 ft. (2.4m), the clear span of a single-cell box culvert, or when it exceeds the distance between faces of outer walls for a multiple-cell culvert. The below bar chart denotes approximately 88 percent (741 out of 846) of all 2-cell RC box culverts in Kentucky is under a fill height less than 12 ft. (3.66 m), also 10 percent of all RC box culverts are labeled by value of -1 by KTC (Kentucky Transportation Center), which is basically because of uncertainty in their measurement in field inspection. But all of them were assumed to be 2 ft. (0.61m) during load rating in order to be more conservative. Therefore, the range of 1 ft. – 12 ft. was selected for case studies to investigate the effective fill depth for considering the live load effects.

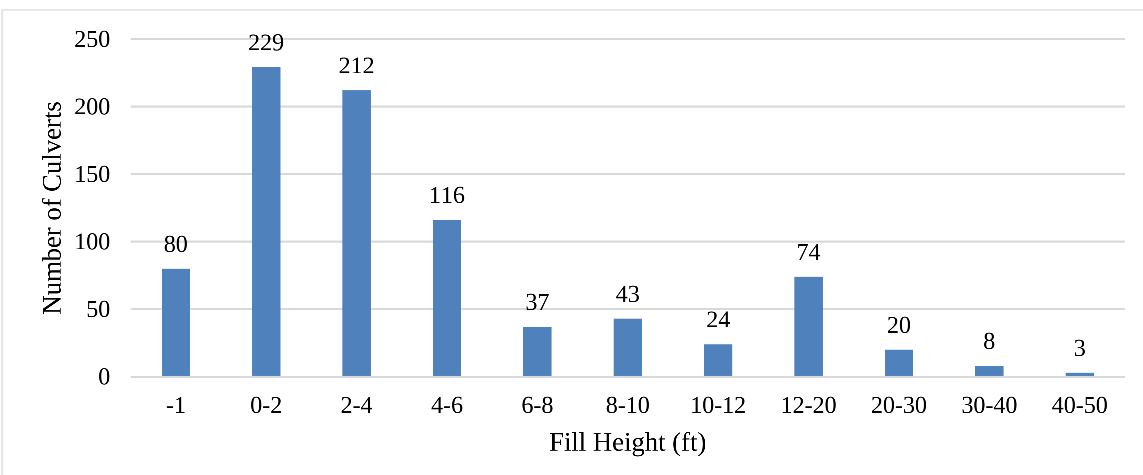

Figure 2.6. Fill Height for 2-cell RC Box Culverts

2.6. Presence of Bottom Slab

Bottom slab brings effective influence into the structural stability of RCBCs. As shown in the charts below, 66 percent of all 2-cell RC Box Culverts include a bottom slab.

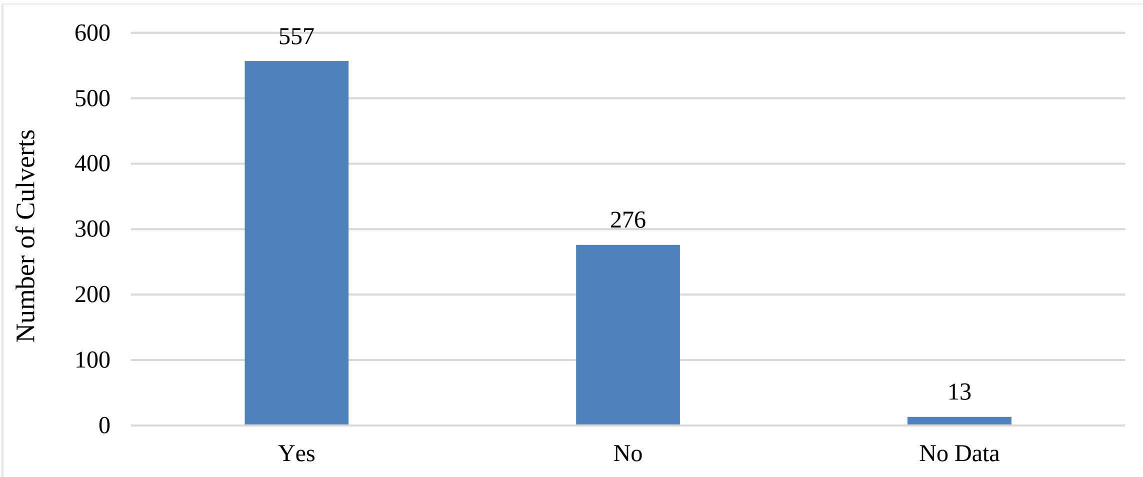

Figure 2.7. Bottom Slab for 2-cell RC Box Culverts

2.7. Moment Continuity in Top Slab

The moment continuity of top slabs drastically affects the behavior of top slab and consequently, the performance of whole structure. As it is shown in in 96 percent of all 2-cell RCBCs, the top slabs were built with simple connections and thereby it must be considered as one of the important characteristics.

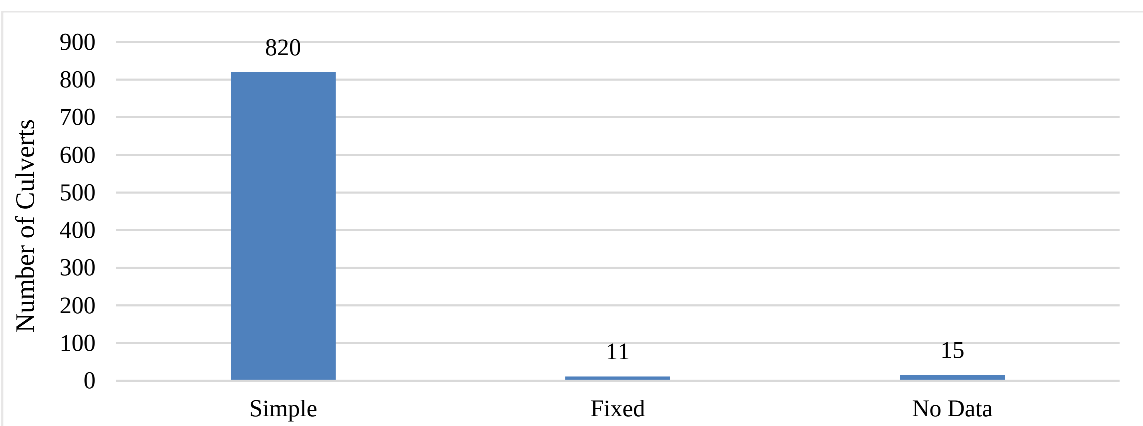

Figure 2.8. Moment Continuity for 2-cell RC Box Culverts

2.8. Case Studies

Based on the above arguments, the selected characteristics for the set of case studies in this research is given in Table 2.1.

Table 2.1. Characteristics of case studies

Characteristics	**Identified range**
Number of Cells	2
Clear Span length (ft.)	10 to 14
Clear Height (ft.)	6 to 10
Fill Height (ft.)	1 to 12
Presence of Bottom Slab	Yes
Moment Continuity of Top Slab	Simple Connection

3. Finite Element Modeling and Analysis

To reach a better understanding regarding the performance of RCBC's, it was necessary to conduct finite element analyses on the selected cases to investigate the effect of varying cell's dimensions and fill height on the maximum forces that occur in the top slab. Generally, finite element analysis is a comprehensive approach for analyzing every type of structures from macro structures to very large full-scale models. In the FEA, constitutive elements of a structure get divided into smaller simple elements with specific boundary conditions and the required analysis would be performed for all small elements over the whole structure. Therefore, this approach would be a time and energy consuming method particularly in the case of large 3D structures like culverts. But by considering some assumptions (e.g. assuming constant sections along the length of the culvert and etc.), the FEA could be simplified to a 2D model. In order to serve this purpose, a software named Culvert Analysis and Design (CANDE-2017) was used to perform FEA in this study.

3.1. CANDE Description

CANDE stands for **C**ulvert **AN**alysis and **DE**sign that is a computer program developed for structural design and analysis of buried structures (mostly culverts and pipes). CANDE is a 2-dimensional finite element modeling program which is able to model unit (1 inch) thickness of any shape of buried structures with any constitutive materials as a soil-structure system and design them based on design criteria. CANDE is capable of providing a condition for imposing incremental construction loading and moving loads to illustrate a real condition that can happen for a culvert during its lifetime.

The most distinguished feature of CANDE is the capability of accurately obtaining soil-structure interaction finite element analysis with different type of nonlinear soils. The reason behind choosing CANDE as the FEA performer of this study was its trustworthiness among engineers and researchers over last 30 years and its open source coding language. This computer program was designed with the forethought that future additions and modifications would always continue.

3.2. CANDE Verification

In every research study, one of the most important chapters is the verification of the proposed method in the research. This section must be taken into account before utilizing the method for the whole research because it could result in waste of time, energy, and money.

Thus, before using CANDE in this study, it was essential to make sure about its calculation engine and generated output results. First, a Manual Verification (Appendix A) was done to make sure about CANDE's calculated outputs in general, and then its performance in calculating stresses and displacement were verified by the results of an existing culvert. The details about the process of verification is described in the following sections.

3.2.1. Field Test Verification

After verifying CANDE with hand calculations, it was still required to verify CANDE with the results of field tested culverts. Sarah L. Orton et al. (2015) field tested and measured the strain and displacement of a group of in-service RC Box Culverts in Missouri with different range of fill depth due to a static truck load. Each culvert was heavily instrumented with strain transducers and linear variable displacement transducers (LVDTs) to monitor their strain and displacement for each position of truck load over the culvert. After finding the critical position for the live load, a set of displacement and strain profiles across all culverts' cross section were plotted. These profiles which were only due to live load provided proper basis for verification of CANDE.

Culvert L0525 was selected to be modeled and analyzed in CANDE in order to investigate the accuracy of the computer program. The input details such as dimensions and material properties are given in Table 3.1 and 3.2. Since there was no information about the amount of rebar in the culvert, minimum amount of rebar was assigned to the model in order to be assured that the culvert would not fail during the analysis in CANDE.

Table 3.1. Characteristics of the verification model

Culvert ID	**Cell**	**Clear Span(ft.)**	**Clear Height(ft.)**	**Year Built**	**Actual Fill (ft.)**	**Slab Thickness(in)**	**Wall Thickness(in)**
L0525	2	12	9.5	1953	2.75	11	11.5

Table 3.2 Material Properties

Material Type	**Module of Elasticity(psi)**	**Poisson ratio**	**Density(lb/ft^3)**
Concrete	3600000	0.17	150
Pavement	2900000	0.3	150
Bedrock	1000000	0.35	0.13
Soil/Fill	2900	0.3	125

Since all the strain transducers and linear variable displacement transducers (LVDTs) measured only the effect of live load in field testing, the effect of dead load was excluded during the 2D FE modeling in CANDE. The live load used in the field testing was two point-loads spaced 4 feet (1.22 m) away from each other with magnitude of 9-kip.

However, in the FE modeling in CANDE the magnitude of load had to be divided by width of each wheel (i.e. 20 inches) which came up to 450 lb/in, since all the elements in CANDE are modeled with unit thickness (1 inch) in out of plane direction.

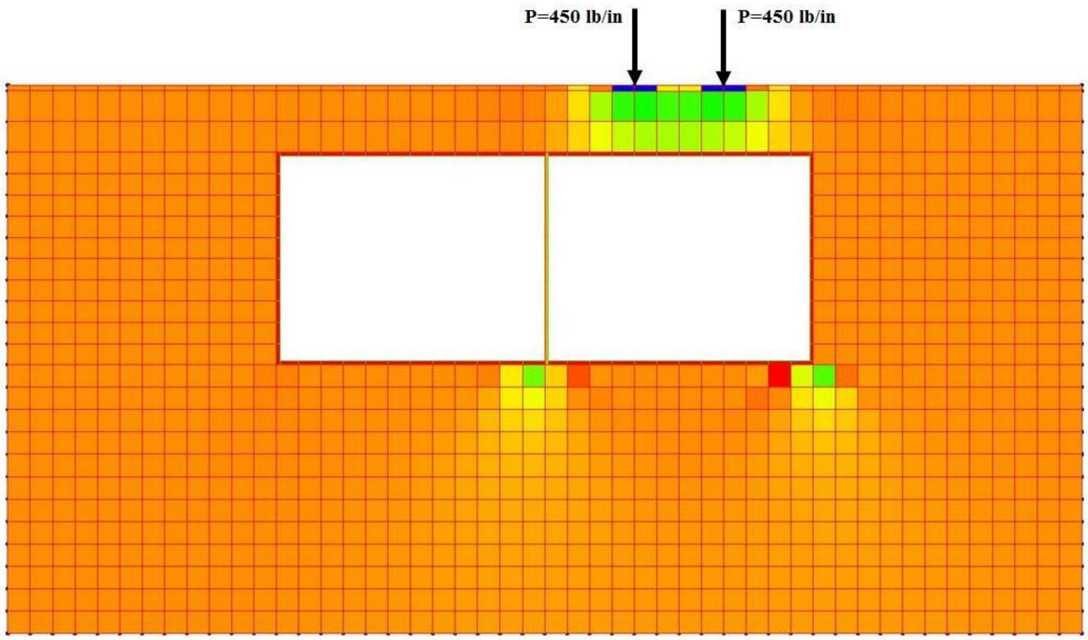

Figure 3.1. The FE model used for field testing verification

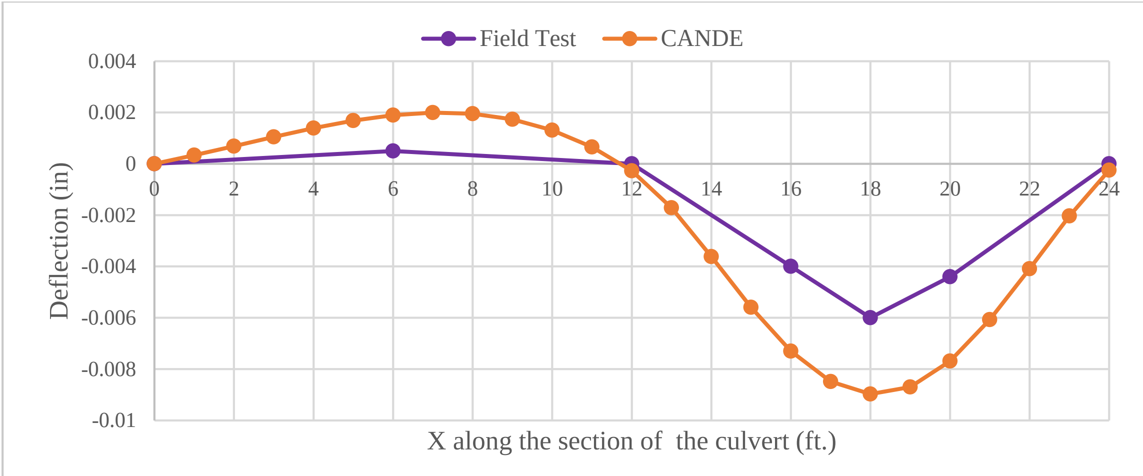

Figure 3.2. Deflection occurred at the top slab

By comparing the results of FE model in CANDE and the field-tested culvert, it was discernable that the both deflection diagrams were remarkably close to each other. Accordingly, CANDE is accurate enough to be used for the rest of this study.

3.3. CANDE Modeling and Analysis

CANDE includes two different solution methods for culverts and pipe structures. The first one is named Level 1 and is defined on the Burns and Richard (1964) elasticity solution which is proper for circular culverts deeply buried in homogenous soil subjected to gravity loading. The second one is based on the finite element methodology. Based on the method of inputting for finite element analyses, two sub-levels titled Level 2 and Level 3 are defined. The Level 2 is totally automated in mesh generation and time effective, but it is limited to simple and symmetric culverts. On the other hand, the Level 3 is not restricted to any specific shape, but all the process of mesh generation must be manually carried out by the user.

For the purpose of this study, in order to able to model the whole soil-structure system of 2-cells RC Box Culverts (RCBCs) in CANDE, Level 3 had to be carried out. In this method all nodes, elements, and meshes must be manually inputted. Admittedly, this method was the most time consuming, but it was the only possible method for modeling the whole soil-structure system in CANDE.

Thus, to ease the process of finite element modeling and mesh generation, a MATLAB programming code was written and used. This code in particular was written to provide the required nodes (points) and plane elements for meshing with proportioned labels and coordinates. This program noticeably reduced the required time for modeling of a 2-cell RCBC from a couple days to a couple hours, which was time effective.

3.3.1. Soil-Structure System

Generally, culverts are considered as buried structures since they are surrounded by soil and fill. The surrounding soil plays a significant role in soil-structure behavior of culverts by generating different types of dead load pressures and live load distribution over the culverts. Therefore, in order to reach an accurate conclusion regarding the performance of RCBCs, the effect of surrounding fill had to be considered. To do so, a specific area of soil-structure system was used in modeling of each case study. The effective section of each case study was restricted against horizontal and vertical movement by assigning special boundary conditions to the outermost layers of nodes. The bottommost nodes were assigned pinned connections by restricting their movement along X and Y axes and allowing them to rotate freely about Z axis. Additionally, nodes on the sides of the effective section were only limited against horizontal displacement, but they were allowed to be deflected along Y axis and freely rotated about the Z axis (Figure 3.3.).

For the whole soil-structure system a set of predefined soil materials were considered to be used in order to provide a constant condition for all case studies. Because of uncertainty regarding the behavior of soil materials and also to provide more conservative results, all soil materials were considered as linear elastic (isotropic) materials in which their behaviors are characterized by Young's modulus and Poisson's ratio.

All the case studies (RCBCs) were assumed to be placed on very stiff layers of bedrocks (red color zone in Figure 3.3.) in order to prevent the culverts from foundation settlement. From the first layer above the bedrock to the last layer beneath the road pavement (orange zone in fig 3.3.), all elements around the culvert was assumed to be compacted backfill. And finally, the last layer of soil underneath the asphalt pavement was assumed to be a dense grade layer to prevent the pavement from local deflection. All the required material properties for surrounding soil are given in the following table.

Table 3.3 Soil Material Properties

Soil Material	**Resilient Modulus(psi)**	**Poisson's Ratio**	**Density (lb/ft^3)**
Asphalt Pavement	300,000	0.3	150
Dense Grade	60,000	0.35	135
Compacted Backfill	20,000	0.35	125
Bedrock	1,000,000	0.3	0.13

3.3.2. Mesh Generation

CANDE similar to other finite element modeling computer programs, uses basic elements for meshing a structure as follows.

- Quadrilateral and Triangle elements: These types of elements are proper for defining soil and fill elements around a culvert.
- Beam – Column elements: They are suitable for defining culvert and asphalt pavement elements.
- Interface elements: They are mostly used for the interface elements between culvert's elements and soil, also for defining different types of connections between pipe elements.
- Link elements: They often get used for special nodal connection along with death option.

For the soil-structure system models in this study, three types of elements were used. First, the quadrilateral elements were used for the bedding and backfill with size of mostly 1ft. by 1ft. for elements close to the culverts, and 2ft. by 2ft. for elements away from the culvert. Each quadrilateral element was formed by four nodes at corners with two degrees of freedom per node (i.e. horizontal and vertical displacements). Second, beam elements were implemented for culvert's elements and asphalt pavement with relative sizes to the surrounding quadrilateral elements. Beam elements consisted of two nodes at either end with three degrees of freedom per node (i.e. horizontal and vertical displacements and rotation). Finally, interface elements were employed to define the pinned connection at wall-slab joints.

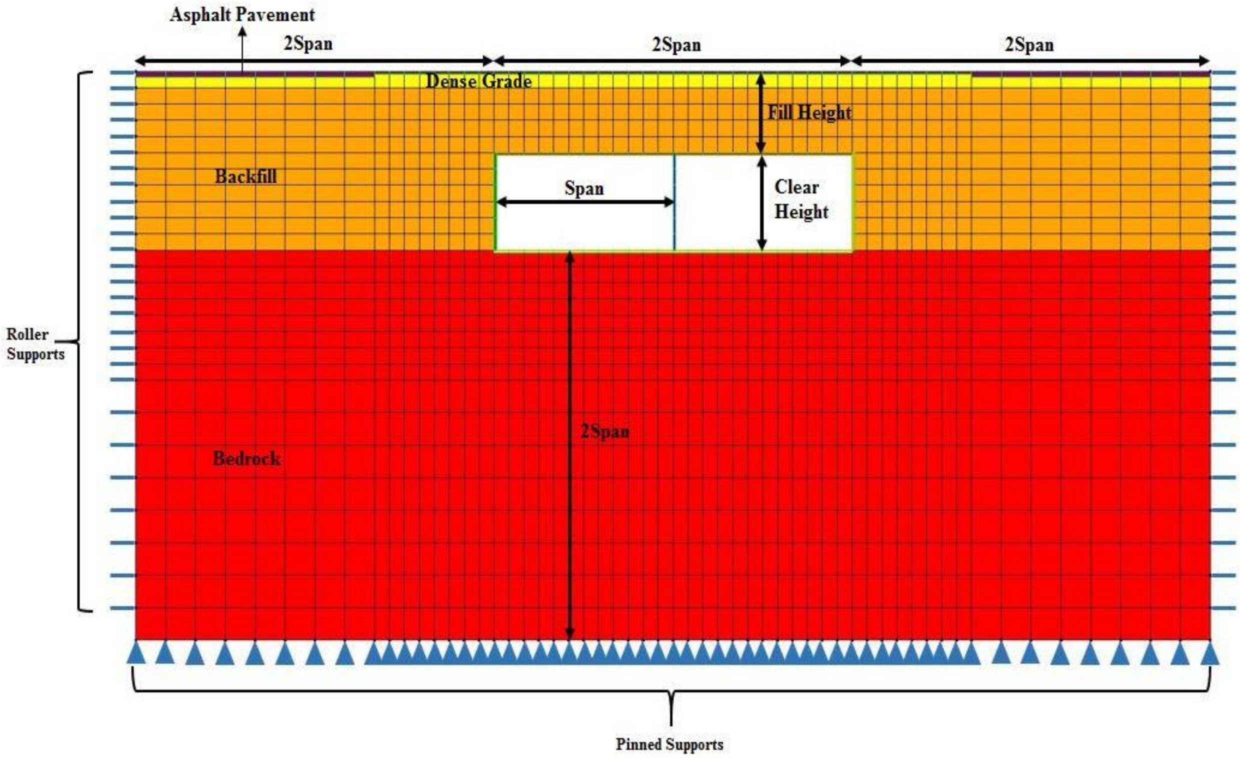

Figure 3.3. Mesh generation in CANDE

3.3.3. Case Studies in CANDE

The focus of this study was on the responses of RCBCs to the demand loads. In order to achieve this, it was required that all culverts under all case studies were adequately strong to resist the loadings and not fail during the FE analyses. To fulfill this aim, the physical design parameters (e.g. slabs thickness, walls thickness, etc.) of case studies were selected to represent similar in-service culverts in Kentucky (Table A.1.).

3.3.4. Loading

Culverts have been designed to resist both dead load and live load. Dead loads are admittedly calculated by density of constitutive materials times their occupied volume. For the live load, the popular standard truck load of HS-20 was used in this study in order to provide more reliable and generic results for the performance of RCBCs. More details about the live load and its distribution through the soil in CANDE are given at Appendix B.

4. FE Evaluation Results for RCBCs

The influence of varying geometrical dimensions on the maximum forces in the top slab of RC Box Culverts (RCBCs) were carried out by performing a number of FEA on the case studies. The behavior of all 54 RCBCs specified in table A.1. were separately investigated for dead and live loadings, and the maximum effects (i.e. positive and negative bending moments and shear force) that occurred in the top slab were determined. The reasons behind selecting the top slab as the subject of this study was that the likelihood of failure in the top slab is more than the other members in RCBCs. In the following figure the proposed geometrical dimensions in this study are explained.

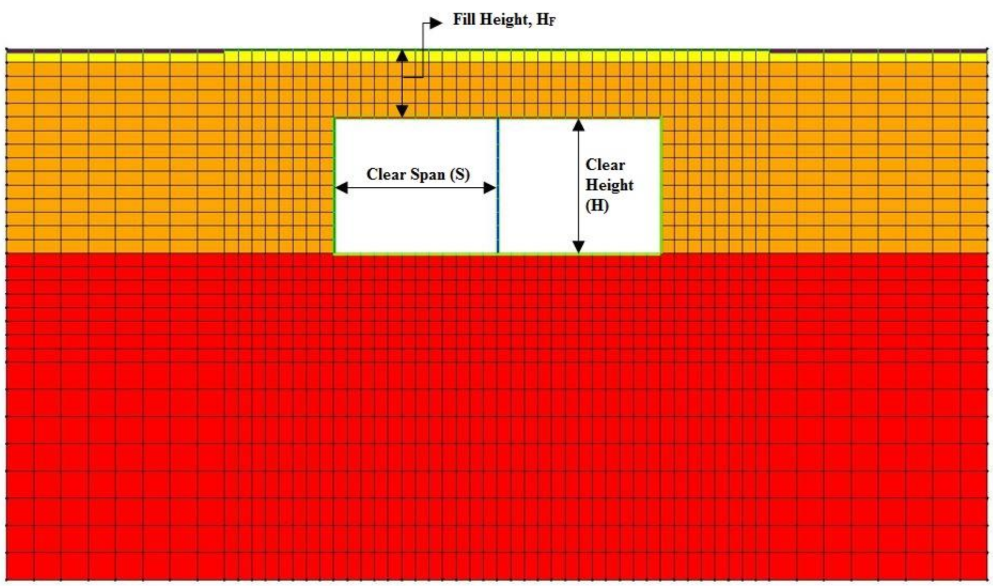

Figure 4.1. Proposed geometrical dimensions in this study

4.1. Dead Load Effects

In Figures. 4.2-4.4 the maximum dead load effects in the top slab of 2-cell RCBCs are depicted. Each figure shows a maximum dead load force (i.e., positive bending moment, negative bending moments or shear force) calculated by CANDE for specific range of clear height and clear span lengths versus the fill heights. As shown in all figures, the varying of the clear height does not affect the maximum dead load effects when the clear span length and fill height are constant. This could be because of the support conditions (i.e., simple connection) that were considered at the wall-slab joints. Therefore, the effects of clear height on the maximum dead load forces are noticeably negligible. However, with an increment in the clear span length, the maximum dead load forces in the top slab would remarkably increase with respect to the fill height. Generally, maximum dead load forces in the top slab increase linearly with respect to the fill height with a specific slope and Y-intercept (Figure 4.5.).

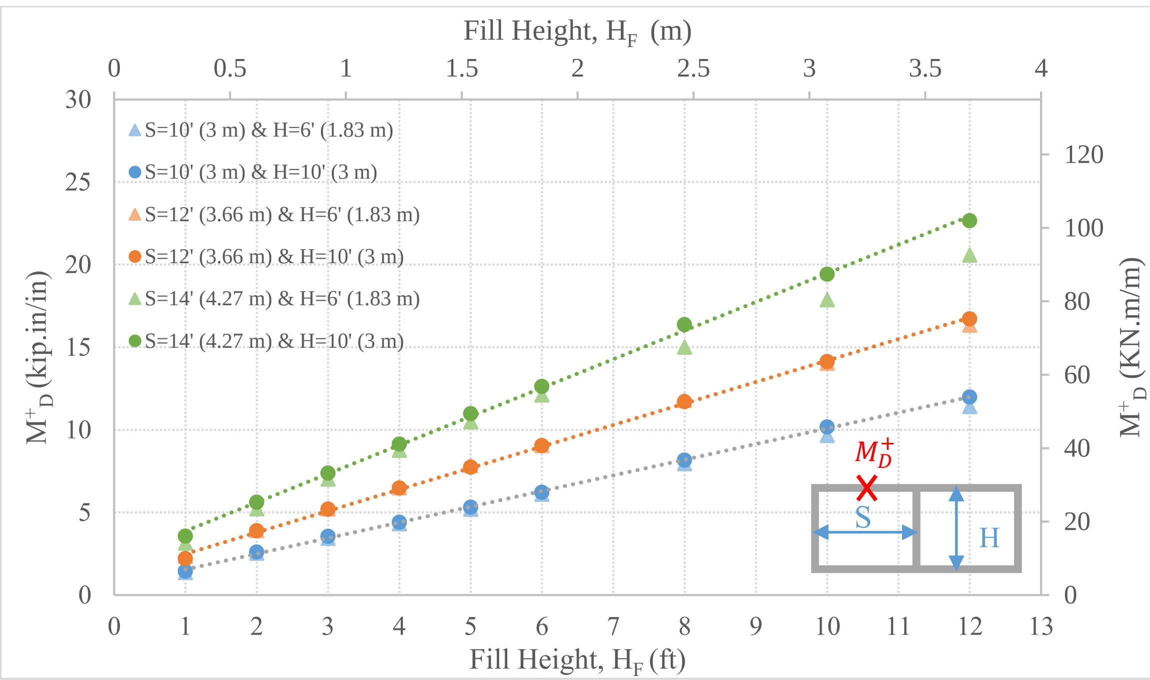

Figure 4.2. Maximum positive dead load bending moment (M_D^+) in the top slab

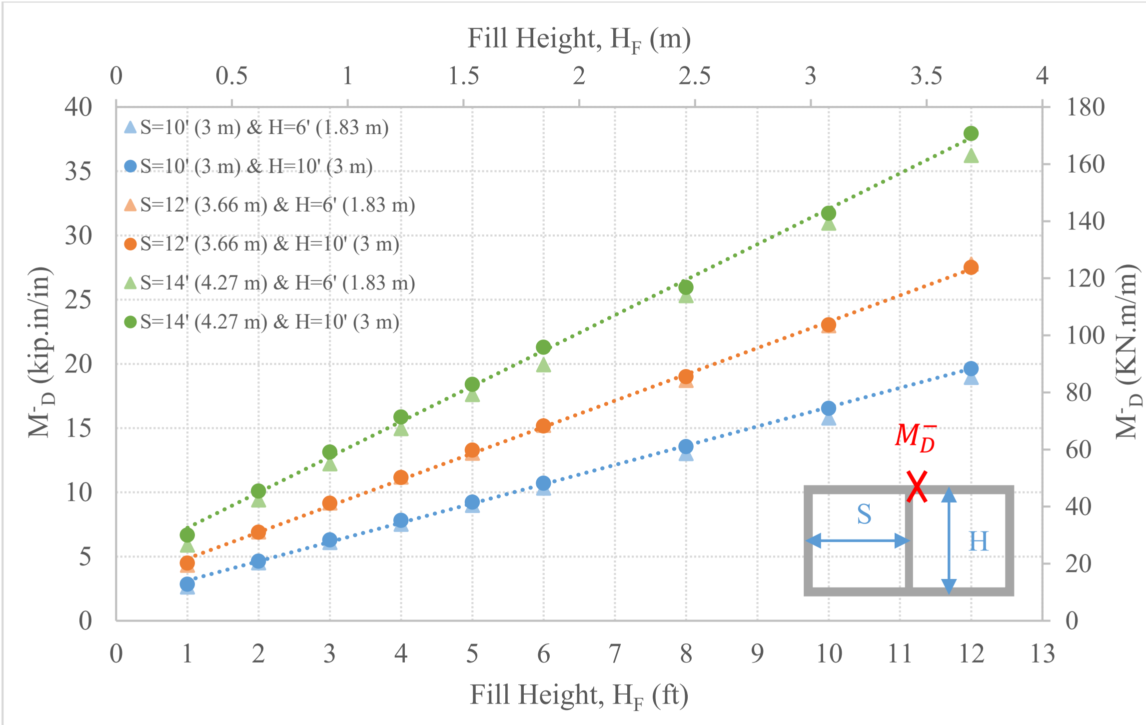

Figure 4.3. Maximum negative dead load bending moment (M_D^-) in the top slab

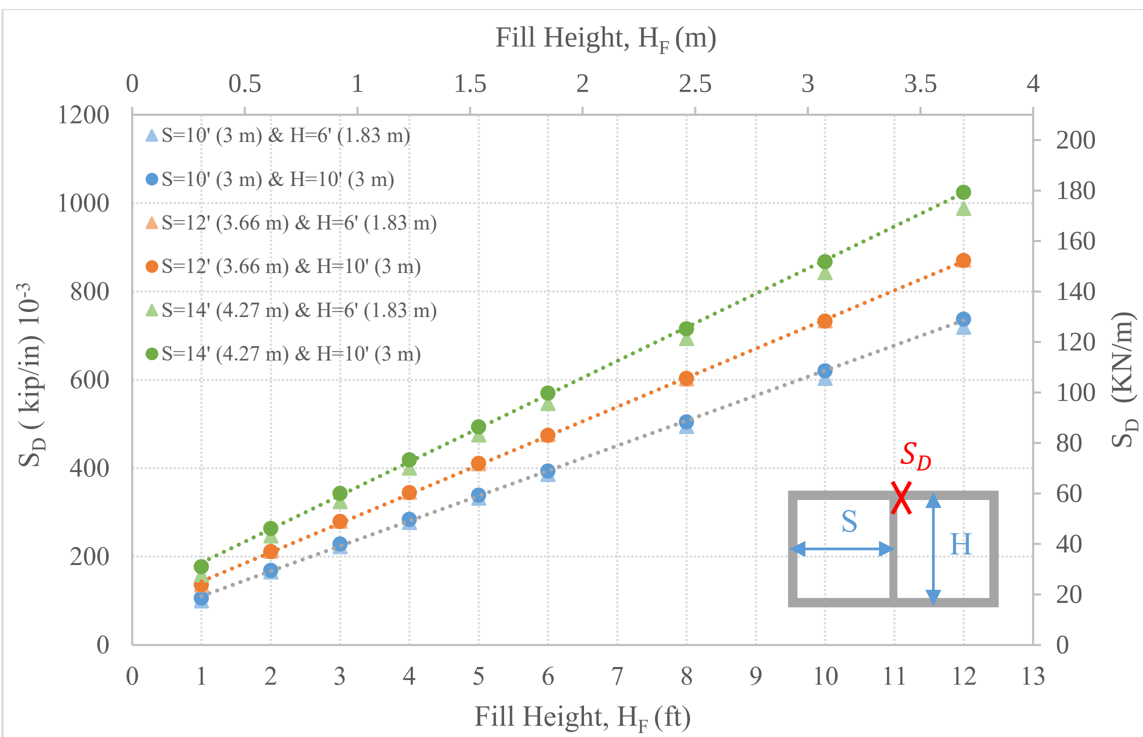

Figure 4.4. Maximum dead load shear force (S_D) in the top slab

The general form of linear equation for estimating the maximum dead load forces (i.e., maximum bending moments or shear due to dead load) in the top slab of 2-cell RCBCs is given in Figure 4.5.

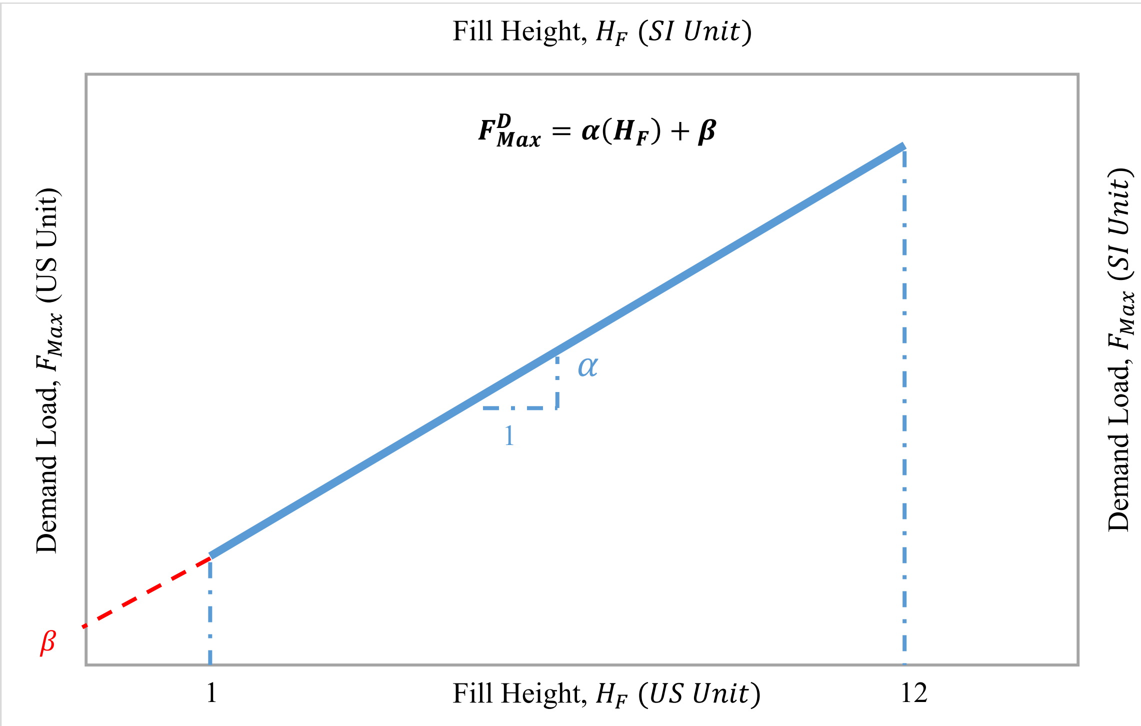

Figure 4.5. General dead load demand equation

Where F^D_{Max} is the maximum dead load force, α and β are the relevant slope and Y-intercept of the linear regression respectively, H_F is the fill height. By comparing the values of coefficients (i.e., α and β) with respect to the clear span lengths, a set of linear equations for determining these coefficients were derived. (Appendix C).

The linear equations for determining the maximum dead load forces in the top slab of RCBCs are summarized in the table 5.1. An individual can easily determine the maximum dead load effects for a specific 2-cell RCBC by plugging the clear span length and fill height into the respective equation.

Table 4.1. Dead load demand equations

Demand Force / Equation Type	Maximum Positive Bending Moment (MPBM) (kip.in/in)	Maximum Negative Bending Moment (MNBM) (kip.in/in)	Maximum Shear Force (MSF) [(kip/in) 10^{-3}]
Equation F_{Max}	$M_D^+ = \alpha_{PD}(\frac{H_F}{12}) + \beta_{PD}$	$M_D^- = \alpha_{ND}\left(\frac{H_F}{12}\right) + \beta_{ND}$	$S_D = \alpha_{SD}\left(\frac{H_F}{12}\right) + \beta_{SD}$
Slope α	$\alpha_{PD}\left(\frac{kip.in}{in^2}\right) = 0.1961\left(\frac{S}{12}\right) - 1.0253$	$\alpha_{ND}\left(\frac{kip.in}{in^2}\right) = 0.3152\left(\frac{S}{12}\right) - 1.6804$	$\alpha_{SD}\left(\frac{kip}{in^2}\right)10^{-3} = 4.84\left(\frac{S}{12}\right) + 8.1737$
Y-intercept β	$\beta_{PD}\left(\frac{kip.in}{in}\right) = 0.3869\left(\frac{S}{12}\right) - 3.334$	$\beta_{ND}\left(\frac{kip.in}{in}\right) = 0.7084\left(\frac{S}{12}\right) - 5.5298$	$\beta_{SD}\left(\frac{kip}{in}\right)10^{-3} = 14.003\left(\frac{S}{12}\right) - 87.622$

Where:

H_F is the fill height above the culvert (in) and S is the clear span length of the culvert (in)

4.2. Live Load Effects

Live load effects on the top slab of 2-cell RCBCs were determined by imposing the HS-20 truck on the pavement surface above the culverts, while the effects of dead load were excluded. For each case study, the axle loads were moving from left side of soil-structure system to the right side in sequence of load steps. In each load step the live load effects (i.e. positive bending moment, negative bending moment, and shear force) in the top slab were calculated and at the end the maximum of them were recorded. Figures. 4.6-4.8 show the maximum live load effects in the top slab of 2-cell RCBCs for specific range of clear span lengths and clear height versus the fill height. In contrast to the dead load effects, live load effects decrease bi-linearly with respect to the fill height.

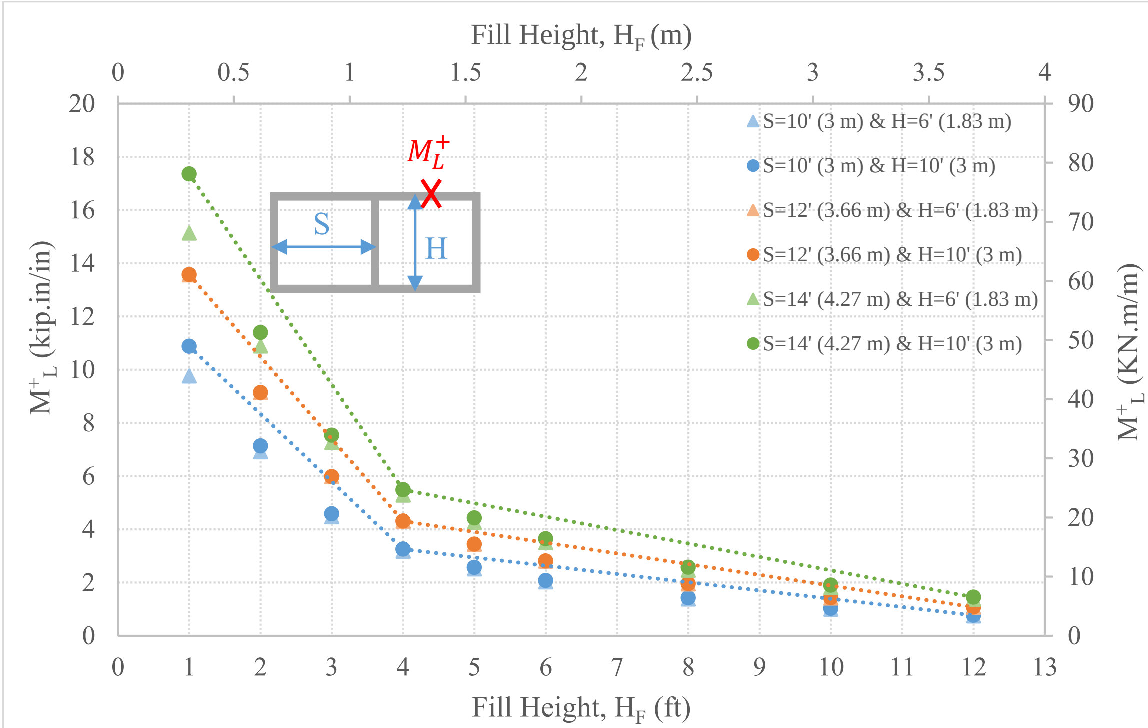

Figure 4.6. Maximum positive live load bending moment (M_L^+) in the top slab

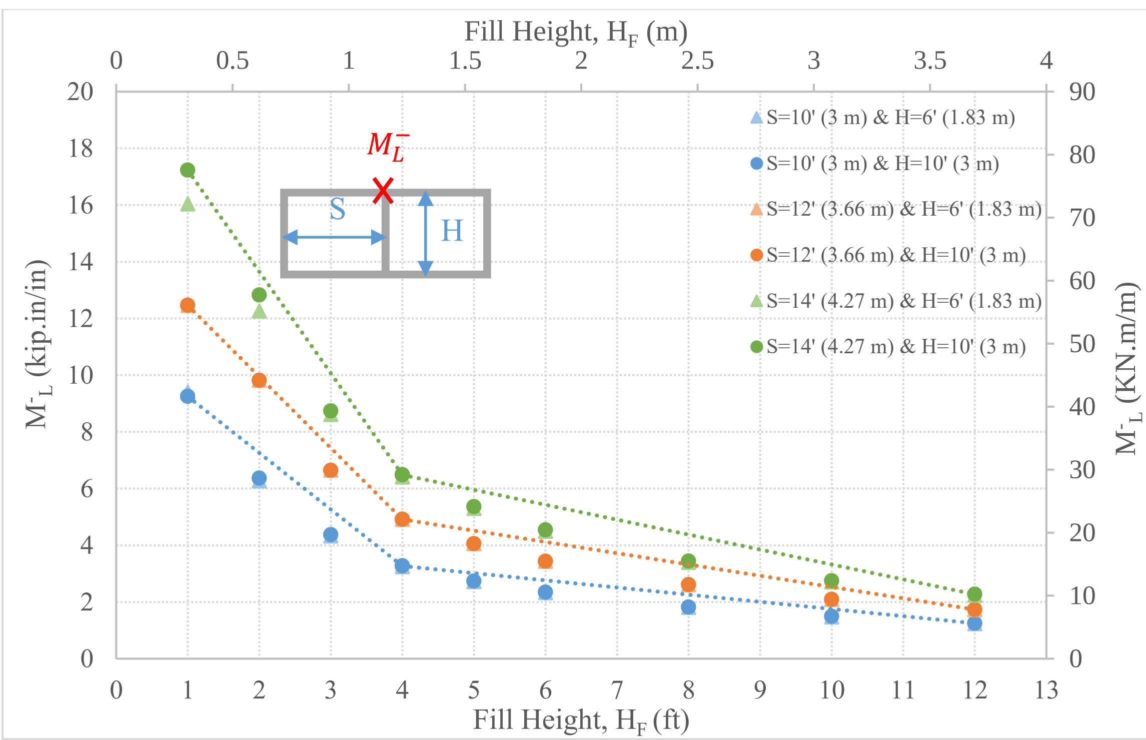

Figure 4.7. Maximum live load negative bending moment (M_L^-) in the top slab

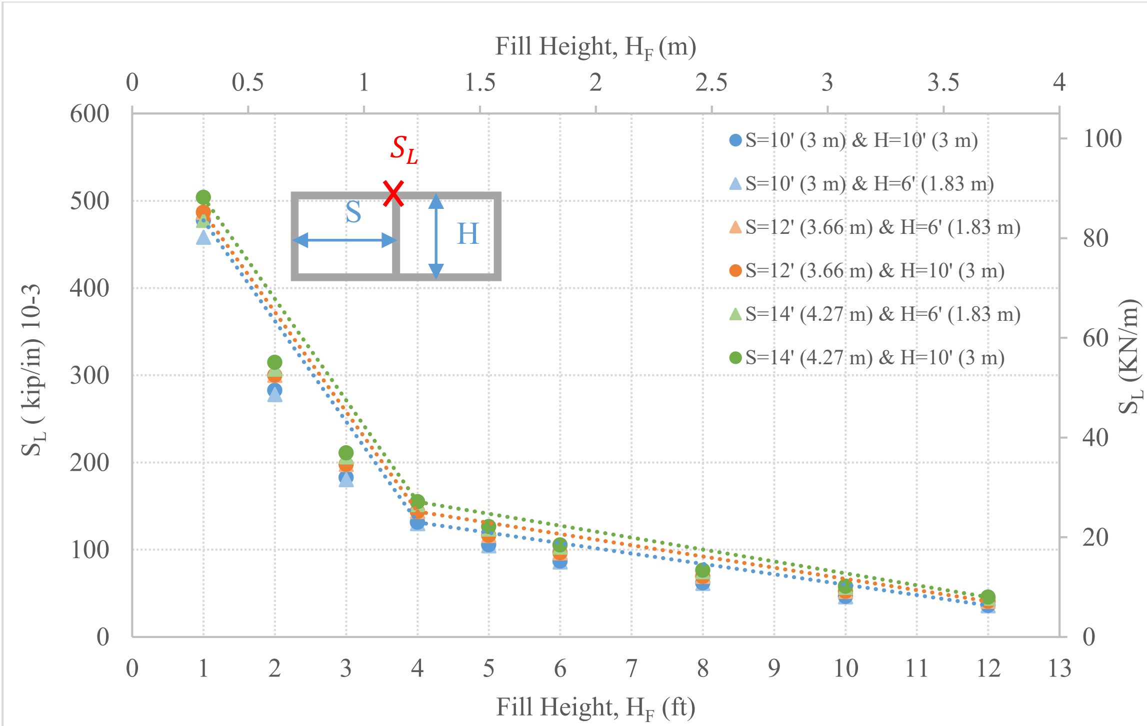

Figure 4.8. Maximum live load shear force (S_L) in the top slab

Similar to the dead load effects, variation in clear height does not significantly affect the maximum live load forces in the top slab of 2-cell RCBCs. In general, its influence for shallow fills is only 3 percent and it vanish with respect to the fill height's increment.

The general form of bi-linear equations for determining the maximum live load forces (i.e., maximum bending moments or shear due to dead load) in the top slab of 2-cell RCBCs is depicted in Figure 4.9. The first part of the bi-linear diagram, which includes the live load effects for fill height lesser than 4 feet (1.22 m), descends with a sharper slope than the second part. In this part, the dispersion of calculated results by CANDE from the trend line is more noticeable than the second part, which could be because of less distribution of the live load trough the shallow fills. Basically, the live load mostly acts as a sort of concentrated point load applying above the top slab for shallow fills. But for deep fills, live loads get distributed through the soil and mostly acts as uniform load. Also, in the first part (shallow fill height) the effect of varying in clear span length is more considerable for maximum bending moments than the second part. As opposed to the first part, the second part of the bi-linear curve has a smoother slope and the effect of varying clear span decreases with respect to the fill height. The bi-linear equations for determining the maximum un-factored live load forces in the top slab of 2-cell RCBCs are demonstrated in Tables 4.2. Similar to the dead load effects, the values of α and β for bi-linear equations vary linearly with respect to the clear span length (Appendix D).

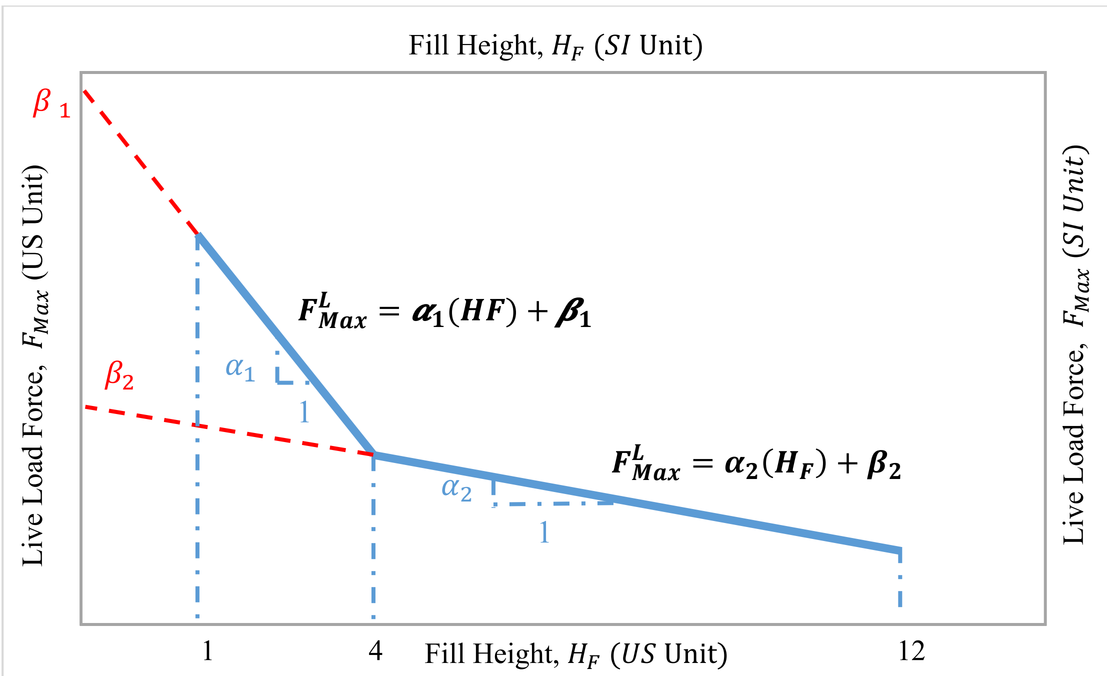

Figure 4.9. Figure 4.5. General live load demand equation

Where, F^L_{Max} is the maximum live load force which is occurred in the top slab of 2-cell RCBCs, α_i and β_i are the relevant slope and Y-intercept of the bi-linear regression respectively, and H_F is the fill height.

Table 4.2 Live load demand equations

Demand Force / Equation Type	**Maximum Positive Bending Moment (MPBM) (kip.in/in)**	**Maximum Negative Bending Moment (MNBM) (kip.in/in)**	**Maximum Shear Force (MSF) [(kip/in) 10^{-3}]**
Equations F_{max}	$M_L^+ = \alpha_{iPL}\left(\frac{H_F}{12}\right) + \beta_{iPD}$	$M_L^- = \alpha_{iNL}\left(\frac{H_F}{12}\right) + \beta_{iND}$	$S_L = \alpha_{iSL}\left(\frac{H_F}{12}\right) + \beta_{iSL}$
Slope α_1	$\alpha_{1PL}\left(\frac{kip.in}{in^2}\right) = -0.3539\left(\frac{S}{12}\right) + 1.0514$	$\alpha_{1NL}\left(\frac{kip.in}{in^2}\right) = -0.397\left(\frac{S}{12}\right) + 2.0664$	$\alpha_{1SL}\left(\frac{kip}{in^2}\right)10^{-3} = -0.2375\left(\frac{S}{12}\right) - 113.05$
Y-intercept β_1	$\beta_{1PL}\left(\frac{kip.in}{in}\right) = 1.9733\left(\frac{S}{12}\right) - 6.549$	$\beta_{1NL}\left(\frac{kip.in}{in}\right) = 2.3918\left(\frac{S}{12}\right) - 13.024$	$\beta_{1SL}\left(\frac{kip}{in}\right)10^{-3} = 6.83\left(\frac{S}{12}\right) + 522.83$
Slope α_2	$\alpha_{2PL}\left(\frac{kip.in}{in^2}\right) = -0.0486\left(\frac{S}{12}\right) + 0.1763$	$\alpha_{2NL}\left(\frac{kip.in}{in^2}\right) = 1.0779\left(\frac{S}{12}\right) - 6.4772$	$\alpha_{2SL}\left(\frac{kip}{in^2}\right)10^{-3} = -0.4398\left(\frac{S}{12}\right) - 7.5407$
Y-intercept β_2	$\beta_{2PL}\left(\frac{kip.in}{in}\right) = 0.7516\left(\frac{S}{12}\right) - 3.0465$	$\beta_{2NL}\left(\frac{kip.in}{in}\right) = 1.0779\left(\frac{S}{12}\right) - 6.4772$	$\beta_{2SL}\left(\frac{kip}{in}\right)10^{-3} = 7.6375\left(\frac{S}{12}\right) + 103$

Where:

H_F is the fill height above the culvert (in) and S is the clear span length of the culvert (in).

The presented equations in this study are highly recommended to be used for 2-cell RCBCs with the clear span range of 10 feet (3m) to 14 feet (4.27 m).

4.3. Demand Loads in Top Slab of 2-Cell RCBCs

By determining the maximum un-factored dead and live loads forces in the top slab of 2-cell RCBCs with the proposed equations, the desired factored demand loads can be yielded in the following equations.

$D = \emptyset_D F_{Max}^D + \emptyset_L F_{1Max}^L$ for $H_F \leq 4\ ft.$

$D = \emptyset_D F_{Max}^D + \emptyset_L F_{2Max}^L$ for $H_F > 4\ ft.$

Where:

D is the demand force for the top slab of 2-cell RCBCs, $\emptyset_D$ and $\emptyset_L$ are the dead and live loads factors respectively based on the desired design method (LRFD, LFD, and ASD), F_{Max}^D is the maximum un-factored dead load forces, F_{1Max}^L is the maximum un-factored live load forces when fill height is lesser than 4 feet, and F_{2Max}^L is the maximum un-factored live load forces when fill height is greater than 4 feet.

Finally, the capacity (C) of culverts can be determined based on the section properties of the structure (i.e., section's thickness, compression strength of the concrete, the yielding stress of steel, amount of rebar, etc.) and then by comparing the values of demand forces with the capacity, the safety of the structure would be evaluated. In general, the ratio of $\frac{Capacity}{Demand}$ must be greater than unity in order to have a safe culvert. By expanding the above ratio, the load rating factor can be presented in the following:

$$\frac{Capacity}{Demand} = \frac{C}{D} = \frac{C}{\emptyset_D F_{Max}^D + \emptyset_L F_{Max}^L} > 1$$

$$C > \emptyset_D F_{Max}^D + \emptyset_L F_{Max}^L \rightarrow C - \emptyset_D F_{Max}^D > \emptyset_L F_{Max}^L$$

Then: $Rating\ Factot\ (RF) = \frac{C - \emptyset_D F_{Max}^D}{\emptyset_L F_{Max}^L} > 1$

Having the rating factor greater than unity for a specific truck load assures that the truck can safely pass over the culvert.

4.4. Effective Fill Height for Live Load's Effects

By comparing the effects of live load and dead load on RCBCs, the cut off point for neglecting the effect of live load can be judged. Gilliand (1986) suggested the point that the effect of live load could be neglected as the fill height that live load pressure would be less than 10% of dead load pressure. Abdel-Karim et al. (1990) further suggested the live load effects could be neglected if they contribute less than 5% of the total load effects. Figure 4.10. shows the ratio of live load effects to dead load effects for the maximum positive bending moment because it was the most critical demand force than the other types (Appendix F).

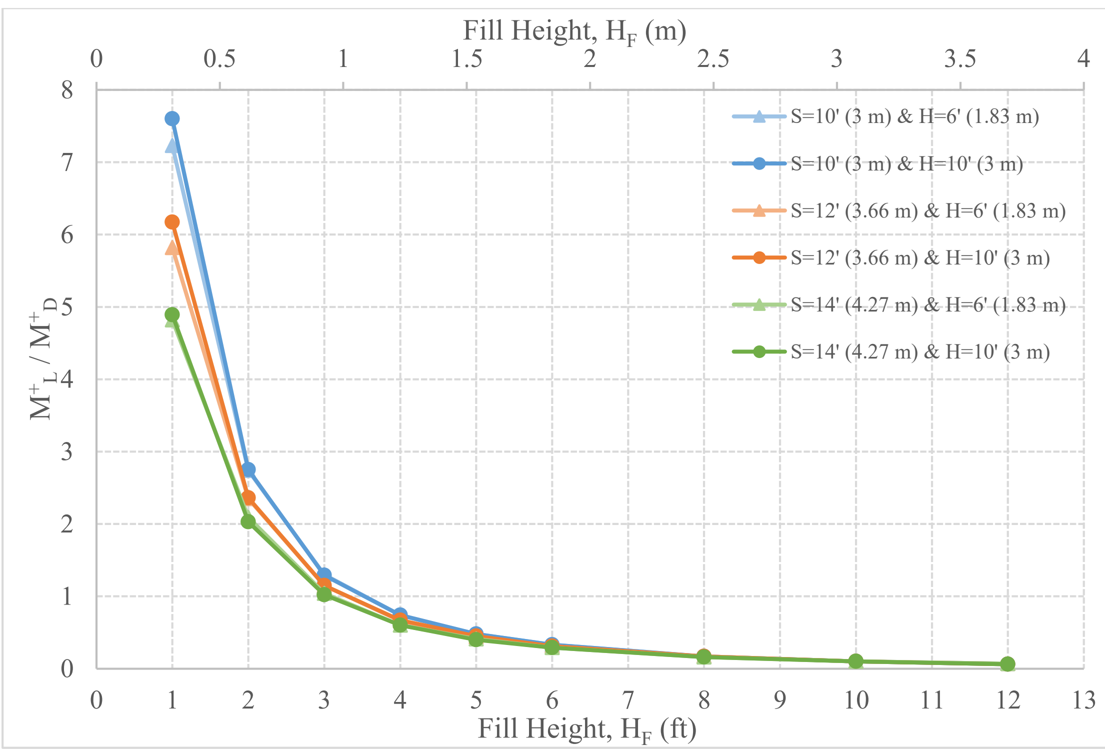

Figure 4.10. Ratio of live load effects to dead load effects (M^+_L / M^+_D)

Obviously, for shallow fill heights, the live load effects seem to be completely dominant for RCBCs. However, the ratio of live load effects to the dead load effects drastically decreases by increasing the fill height. In such a way that the influence of live load for fill height of 5 feet (1.5 m) would be less than 50% of dead load effect and for fill height of 10 feet (3 m), the ratio would be less than 10%. Additionally, the effect of changing in clear span length on the ratio of live load demand to the dead load demand completely vanishes for fill height greater than 6 feet (1.82 m).

5. Conclusions

In this research, the effect of varying geometrical dimensions on the performance of RCBCs were investigated for dead loads and live loads. The following are the conclusions of this thesis:

- The maximum dead load forces in the top slab increase linearly with increasing fill heights.
- The maximum live load forces in the top slab decrease bi-linearly with increasing fill heights.
- The clear height of the culvert has negligible effect on the dead load and live load maximum forces.
- Demand equations are proposed in terms of the clear span and fill height.
- The proposed Demand equations can be used in place of detailed finite element models to determine the maximum applied forces on the top slab.
- For fill heights greater than or equal to 10 ft. (3 m), the maximum live load force is less than 10% of the maximum dead load force.

Appendices

Appendix A: Manual Verification

In order to verify the calculation engine of CANDE by hand calculation, a 2 cells RC Box Culvert (RCBC) was modeled in the software without any fill above it, and a point load of 800lb/in (equal to the half axle load of HS-20 divided by the tire width) was applied at the middle point of one of the cells. This model in the hand calculation was assumed as a continuous beam placed on three simple connections and a point load with the same magnitude used in CANDE at the same location was applied. After comparing the both results (i.e. shear force and bending moment diagrams), it was noticed that the calculated results from both method were pretty close. The results of both methods (computer program and the hand calculation) are shown in follows:

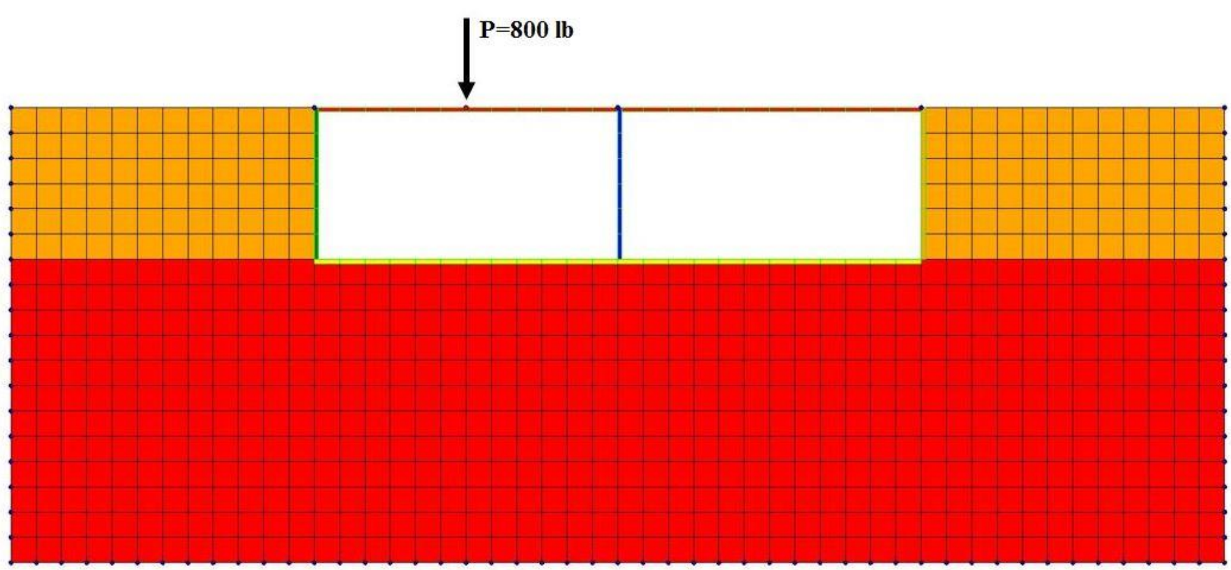

Figure A.1. CANDE model used for manual verification

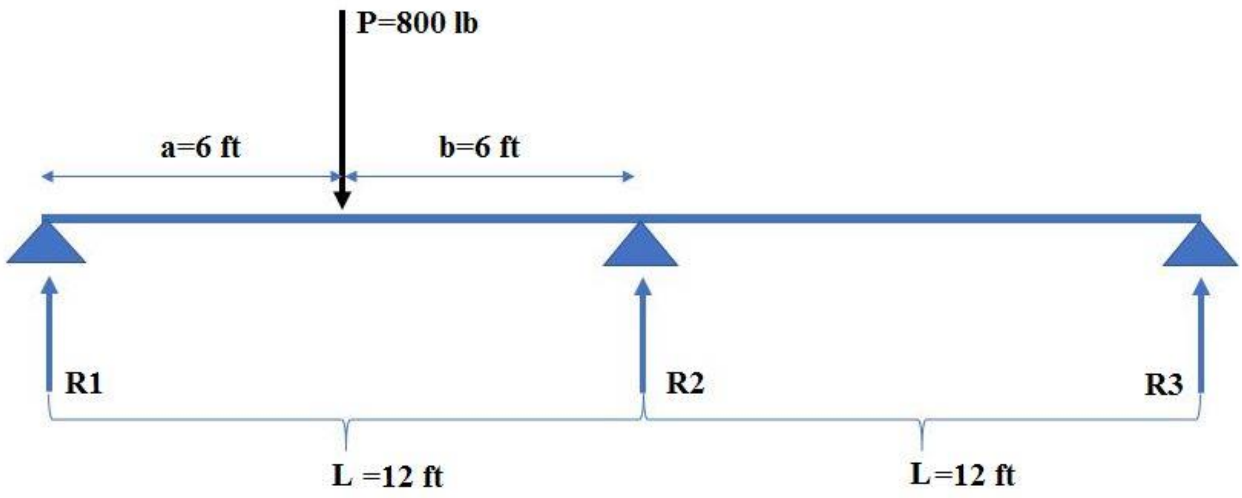

Fig. A.2. Simply supported continuous beam (as an illustration for the top slab)

$$R1 = \frac{Pb}{4L^3}\left(4L^2 - a(L+a)\right) = \frac{(800)(6)}{4(12)^3}\left(4(12)^2 - 6(12+6)\right) = 325\ lb$$

$$R2 = \frac{Pb}{2L^3}\left(2L^2 + b(L+a)\right) = \frac{(800)(6)}{2(12)^3}\left(2(12)^2 + 6(12+6)\right) = 550\ lb$$

$$R3 = -\frac{Pab}{4L^3}(L+a) = -\frac{(800)(6)(6)}{4(12)^3}(12+6) = -75\ lb$$

$M_{max} = \frac{Pab}{4L^3}\left(4L^2 - a(L+a)\right) = \frac{(800)(6)(6)}{4(12)^3}\left(4(12)^2 - 6(12+6)\right) = 1950\ lb.ft = 23400 lb.in$ (at loading point)

$$M_2 = -\frac{Pab}{4L^2}(L+a) = -\frac{(800)(6)(6)}{4(12)^2}(12+6) = -900 lb.f = -10800 lb.in\ (at\ middle\ support)$$

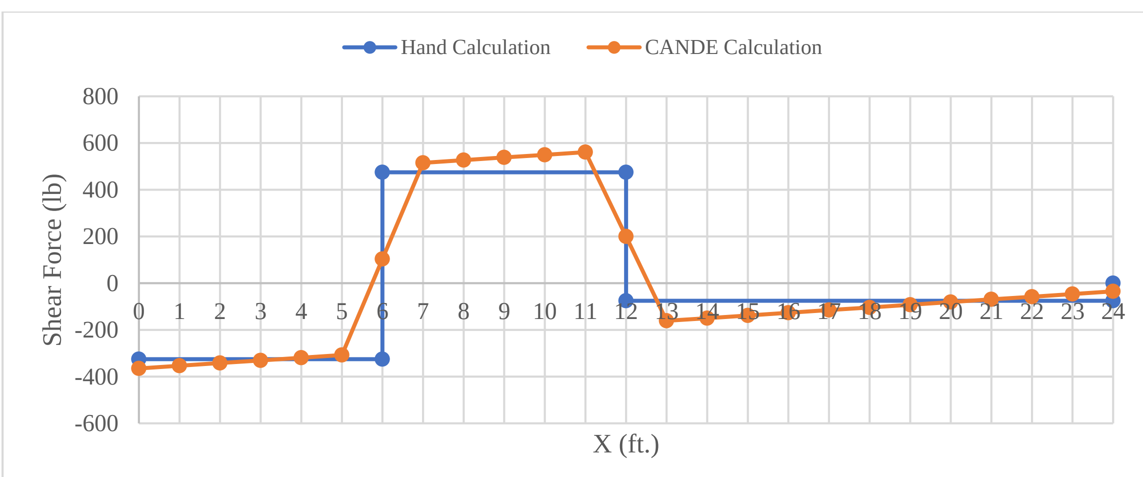

Figure A.3. Shear force diagram (CANDE vs. Hand Calculation)

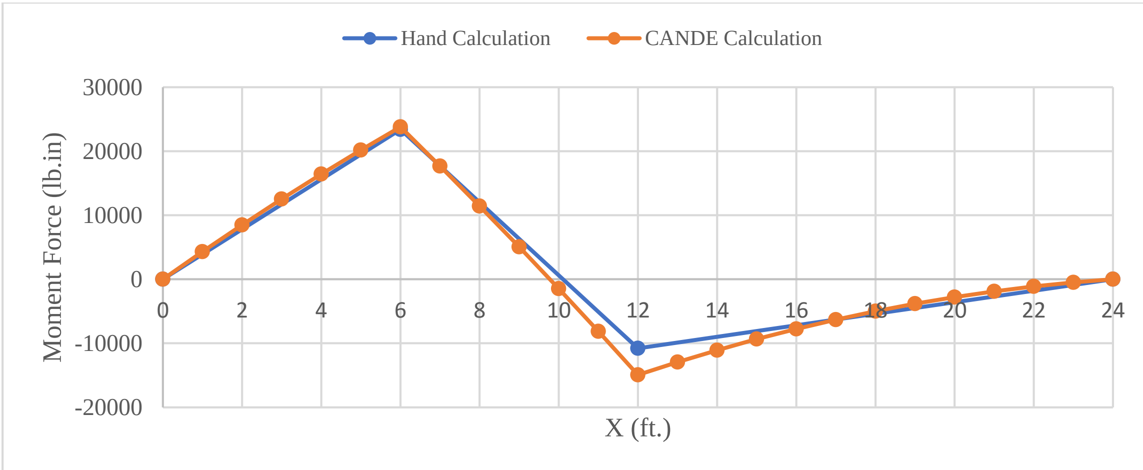

Figure A.4. Bending moment diagram (CANDE vs. Hand Calculation)

Appendix B: Case Studies

Table A.1. Characteristics parameters of case studies

Case Study Number	Model's ID	Number of Cells	Clear Span Length (Ft.)	Clear Height(Ft.)	Fill Height(Ft.)	Similar Existing Culvert's ID	Walls Thickness(in.)	Top Slab Thickness(in.)	Bottom Slab Thickness(in.)
1	2C-10x6-1FH	2	10	6	1	088B013N	12	11	13
2	2C-10x6-2FH	2	10	6	2	088B015N	12	11	13
3	2C-10x6-3FH	2	10	6	3	060B038N	12	9	11
4	2C-10x6-4FH	2	10	6	4	004B054N	10	9	11
5	2C-10x6-5FH	2	10	6	5	095B018N	12	11	13
6	2C-10x6-6FH	2	10	6	6	067B062N	12	12	14
7	2C-10x6-8FH	2	10	6	8	111B042N	12	10	12
8	2C-10x6-10FH	2	10	6	10	024B158N	10	12	14
9	2C-10x6-12FH	2	10	6	12	092B066N	10	12	14
10	2C-10x10-1FH	2	10	10	1	097C043N	12	12	14
11	2C-10x10-2FH	2	10	10	2	056B275N	10	11	13
12	2C-10x10-3FH	2	10	10	3	037B030N	12	11	13
13	2C-10x10-4FH	2	10	10	4	058B019N	10	9	11
14	2C-10x10-5FH	2	10	10	5	087B029N	12	12	14
15	2C-10x10-6FH	2	10	10	6	017B030N	10	10	12
16	2C-10x10-8FH	2	10	10	8	054B035N	12	15	18
17	2C-10x10-10FH	2	10	10	10	014B045N	12	10	12

18	2C-10x10-12FH	2	10	10	12	102B030N	12	13	15
19	2C-12x6-1FH	2	12	6	1	088B006N	12	13	13
20	2C-12x6-2FH	2	12	6	2	015B019N	12	12	14
21	2C-12x6-3FH	2	12	6	3	056B312N	12	13	15
22	2C-12x6-4FH	2	12	6	4	035B064N	12	10	12
23	2C-12x6-5FH	2	12	6	5	119C018N	10	11	13
24	2C-12x6-6FH	2	12	6	6	025B053N	12	11	13
25	2C-12x6-8FH	2	12	6	8	099B066N	12	11	13
26	2C-12x6-10FH	2	12	6	10	022B093N	12	14	16
27	2C-12x6-12FH	2	12	6	12	001B043N	10	12	13
28	2C-12x10-1FH	2	12	10	1	074B013N	12	11	13
29	2C-12x10-2FH	2	12	10	2	026B043N	12	11	13
30	2C-12x10-3FH	2	12	10	3	033B028N	12	11	13
31	2C-12x10-4FH	2	12	10	4	022B109N	12	10	12
32	2C-12x10-5FH	2	12	10	5	090B060N	12	15	17
33	2C-12x10-6FH	2	12	10	6	089B083N	12	12	20
34	2C-12x10-8FH	2	12	10	8	007B023N	12	16	18
35	2C-12x10-10FH	2	12	10	10	090B026N	12	16	18
36	2C-12x10-12FH	2	12	10	12	088B057N	12	13	15
37	2C-14x6-1FH	2	14	6	1	055B016N	12	14	16
38	2C-14x6-2FH	2	14	6	2	026B023N	12	13	15
39	2C-14x6-3FH	2	14	6	3	090B084N	12	12	14
40	2C-14x6-4FH	2	14	6	4	075B011N	10	10	12
41	2C-14x6-5FH	2	14	6	5	008B012N	10	11	13
42	2C-14x6-6FH	2	14	6	6	036B029N	10	15	17
43	2C-14x6-8FH	2	14	6	8	036B029N	10	15	17
44	2C-14x6-10FH	2	14	6	10	036B029N	10	15	17
45	2C-14x6-12FH	2	14	6	12	036B029N	10	15	17
46	2C-14x10-1FH	2	14	10	1	118B001N	12	13	15
47	2C-14x10-2FH	2	14	10	2	077B031N	12	12	14
48	2C-14x10-3FH	2	14	10	3	110B003N	12	12	15
49	2C-14x10-4FH	2	14	10	4	067B055N	12	13	15
50	2C-14x10-5FH	2	14	10	5	043B028N	10	13	15
51	2C-14x10-6FH	2	14	10	6	099B021N	12	13	15
52	2C-14x10-8FH	2	14	10	8	036B027N	10	14	16
53	2C-14x10-10FH	2	14	10	10	039B009N	12	15	17
54	2C-14x10-12FH	2	14	10	12	047B106N	10	14	16

Appendix C: Live Load Distribution

HS-20 is one of the most popular type of trucks that must be considered in design of all bridge type structures. The loading details for this truck is schematically illustrated as follows (Figure A.4.).

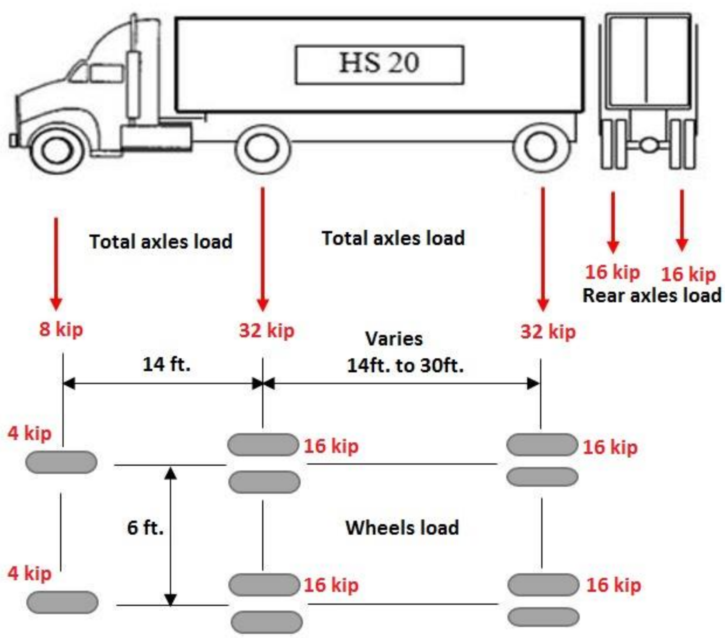

Figure A.4. HS-20 Standard Truck Loading

CANDE similar to the other 2D finite element modeling computer programs, confronts with a deficiency in comparison with 3D modeling programs. In general, 2D modeling software consider everything including the entire structural system and the loading condition as a 2D modeling. The raised problem here is that, if the 2D model gets extended in the out of plane direction to form the real 3D model, the live load would be extended too. However, the vehicular loads are finite pressure patch with footprint dimensions of $L \times W$ that do not conform to long prismatic loading (Fig. 5.10). Hence, 2D live load modeling could result in overestimating the stress in the culvert because it accounts for infinite longitudinal load spreading.

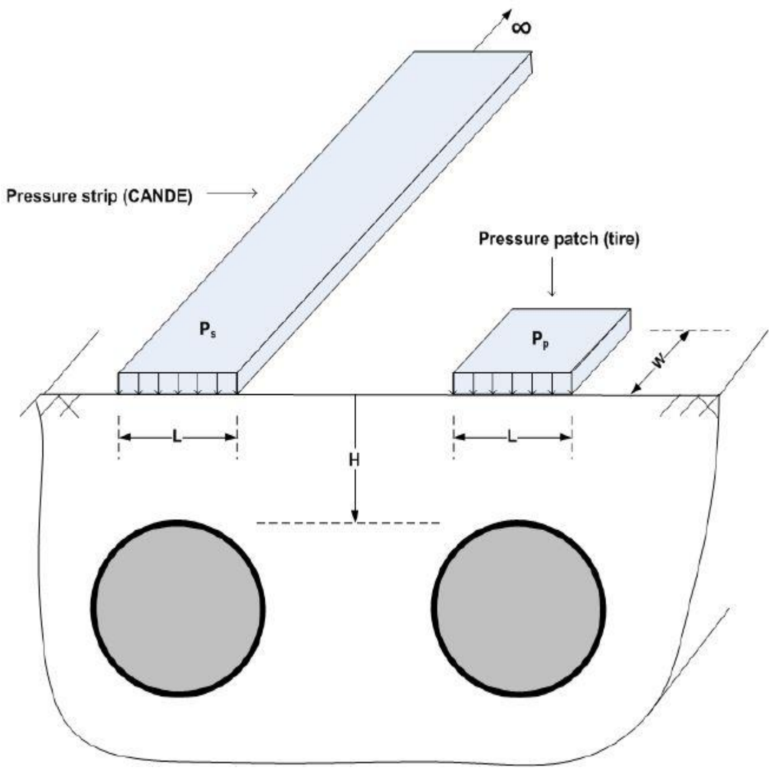

Figure. A.5. 2D Live load in CANDE vs. real 3D live load

Basically, live loads get distributed in CANDE based on the AASHTO method. In this method, live loads get spread uniformly within a 3D trapezoidal shape. The top surface of the trapezoid is the occupied area by the wheel and the bottom face is an area with linearly increase of the top plane's dimensions by the soil depth at a constant angle wherein the total force on any base-plane remains constant.

Fortunately, CANDE unlike the other 2D modeling software considers the effect of live load distribution in 3D, which results in more reasonable outputs. For resolving this issue two methods have been taken into accounts. First approach is Reduced Surface Load (RSL) that reduce the amount of load in 2D modeling in a way that the total amount of load would be equal to the 3D loading. In this method, the magnitude of live loads gets modified by a reduction factor, r_H.

$P_s = r_H P_P$

Where:

P_s = Reduced pressure on infinite strip $L \times \infty$

P_p = Actual pressure on footprint patch $L \times W$

The second approach which is the newest one is named Continuous Load Scaling (CLS). In this method, rather than reducing the magnitude of load vector, an equivalent but reverse procedure is obtained to increase the global stiffness matrix of the unit thickness of the plane-strain slice as a continuous function of soil depth. In this method the user is not worried anymore about modifying the actual load, since there is no need to calculate the reduction factor. A user can simply input the actual magnitude of load and footprint dimensions and let the software be responsible for amplifying the unit thickness of the plane-strain slice along the depth of soil. This approach was taken into aacount for this study.

Appendix D: Dead Load Responses

In the following the slope and Y-intercept diagrams are given for determining dead load effects.

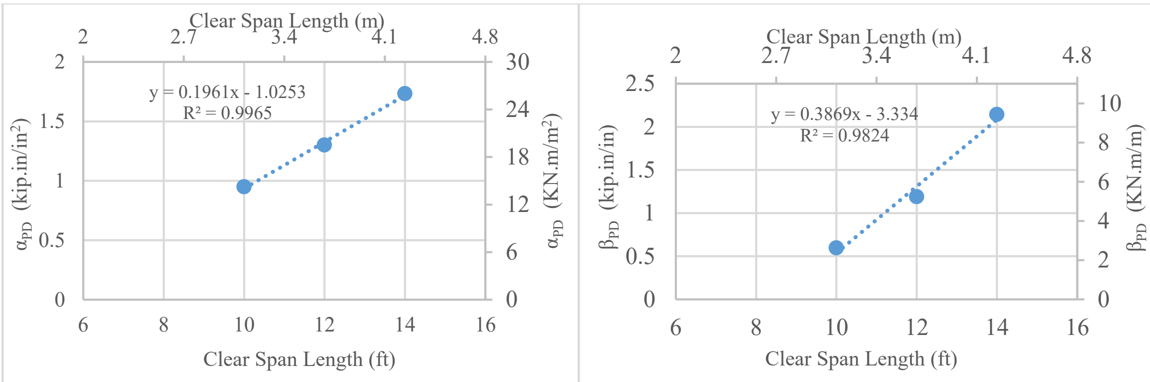

Figure. A.7. Slope and Y-intercept diagrams for maximum positive bending moment

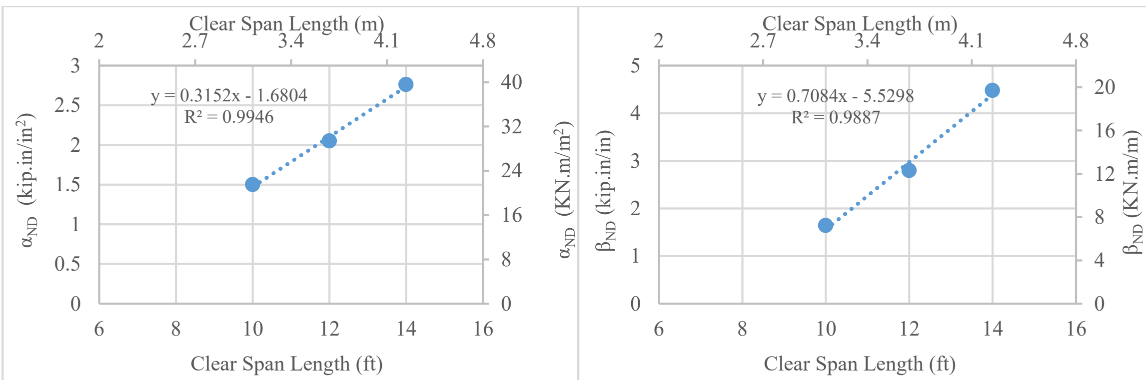

Figure. A.8. Slope and Y-intercept diagrams for maximum negative bending moment

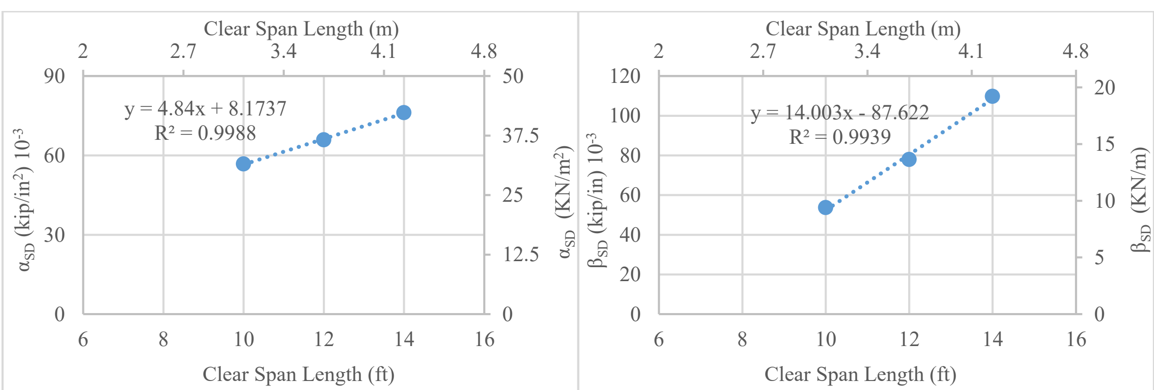

Figure. A.9. Slope and Y-intercept diagrams for maximum shear force

Appendix E: Live Load Responses

In the following the slope and Y-intercept diagrams are given for determining Live load effects.

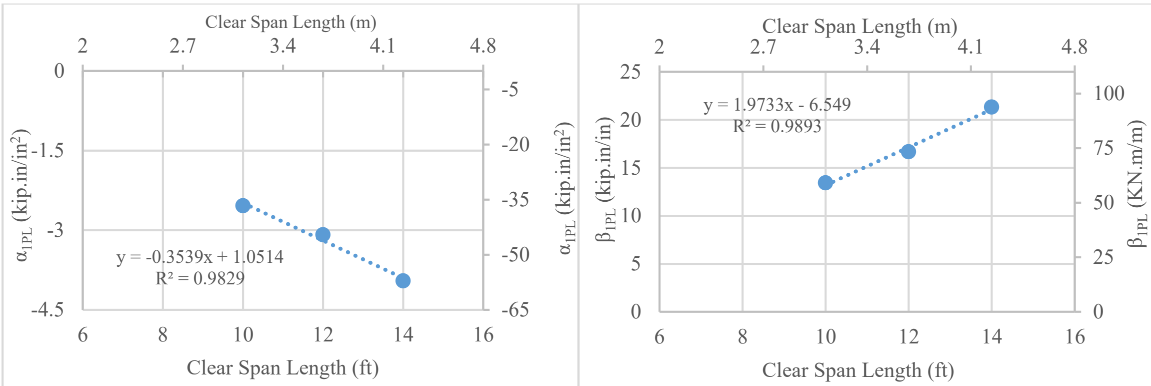

Figure A.10. Slope and Y-intercept diagrams for maximum positive bending moment for fill height less than 4 feet (1.22 m)

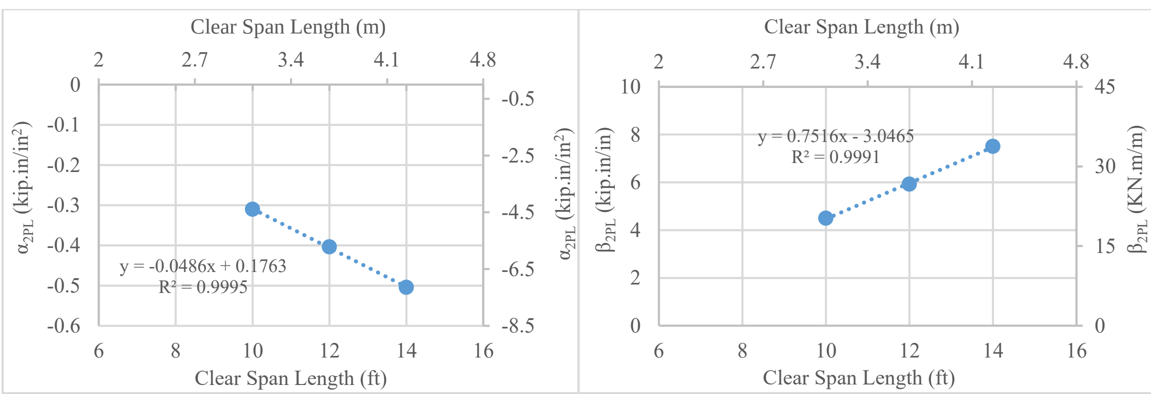

Figure A.11. Slope and Y-intercept diagrams for maximum positive bending moment for fill height greater than 4 feet (1.22 m)

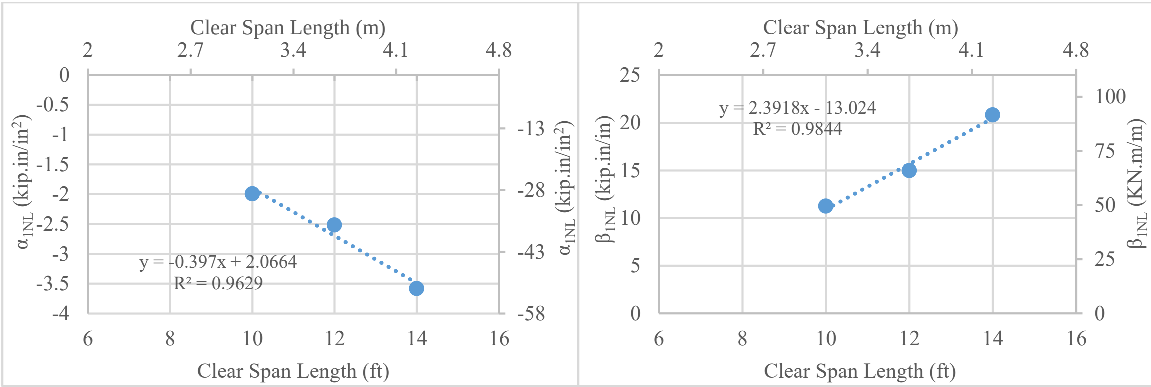

Figure A.12. Slope and Y-intercept diagrams for maximum negative bending moment for fill height less than 4 feet (1.22 m)

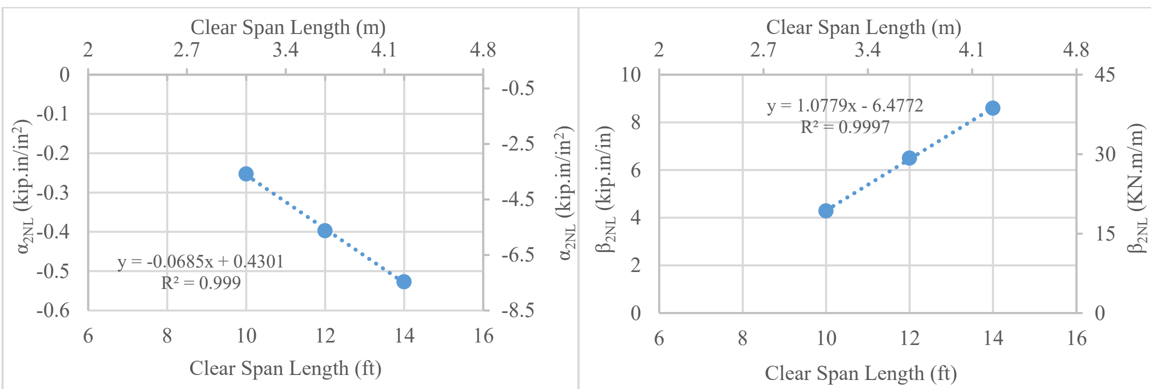

Figure A.13. Slope and Y-intercept diagrams for maximum negative bending moment for fill height greater than 4 feet (1.22 m)

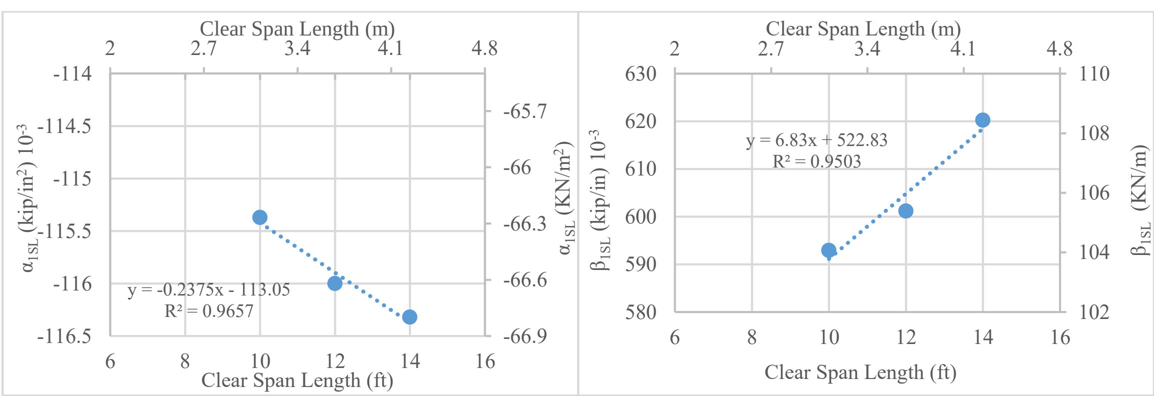

Figure A.14. Slope and Y-intercept diagrams for maximum shear force for fill height less than 4 feet (1.22 m)

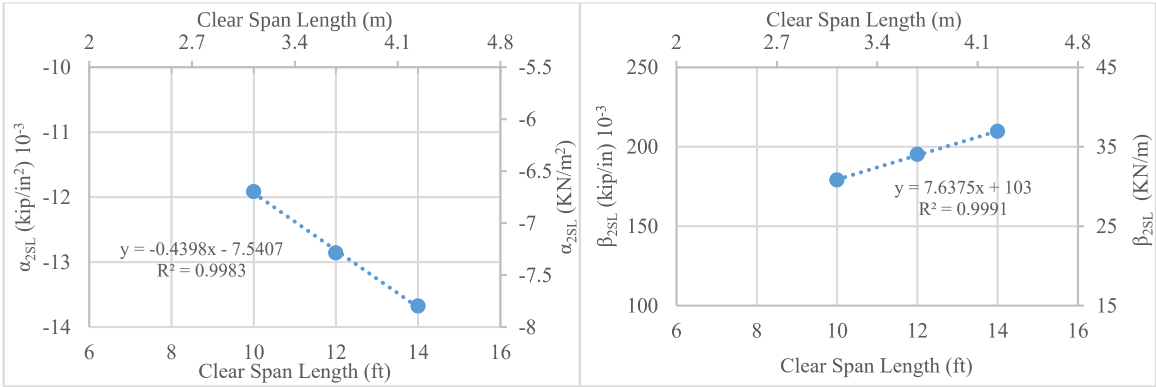

Figure A.14. Slope and Y-intercept diagrams for maximum shear force for fill height greater than 4 feet (1.22 m)

Appendix F: Effective fill height for live load effects

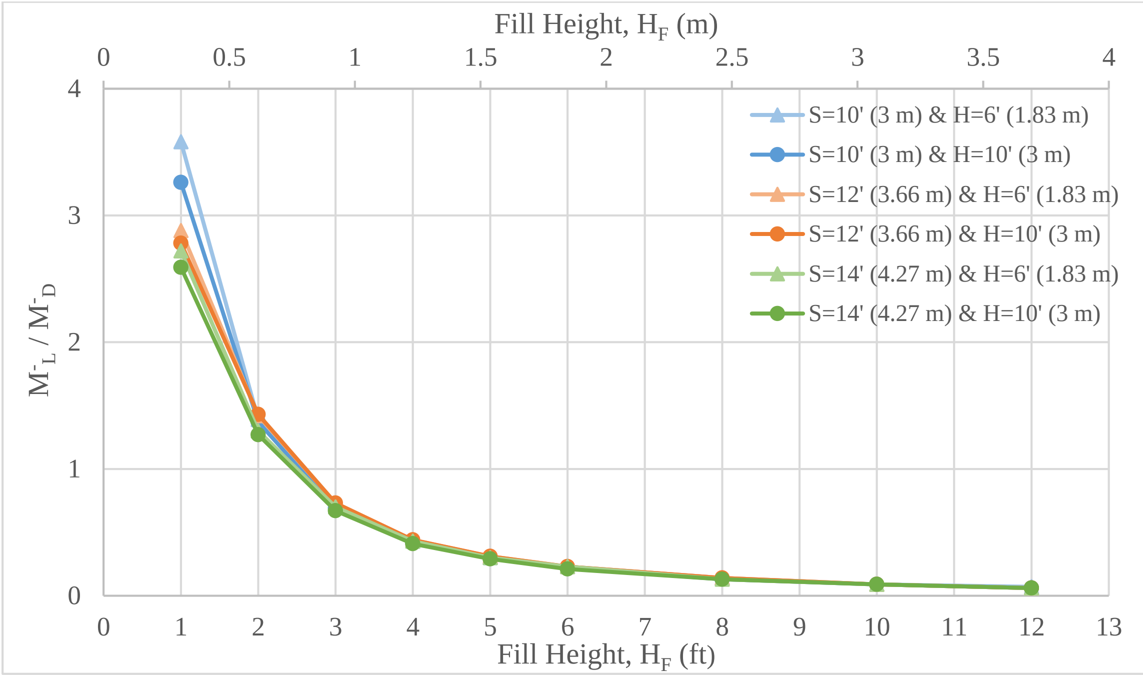

Figure A.15. Ratio of live load effects to dead load effects (M^{-}_{L} / M^{-}_{D})

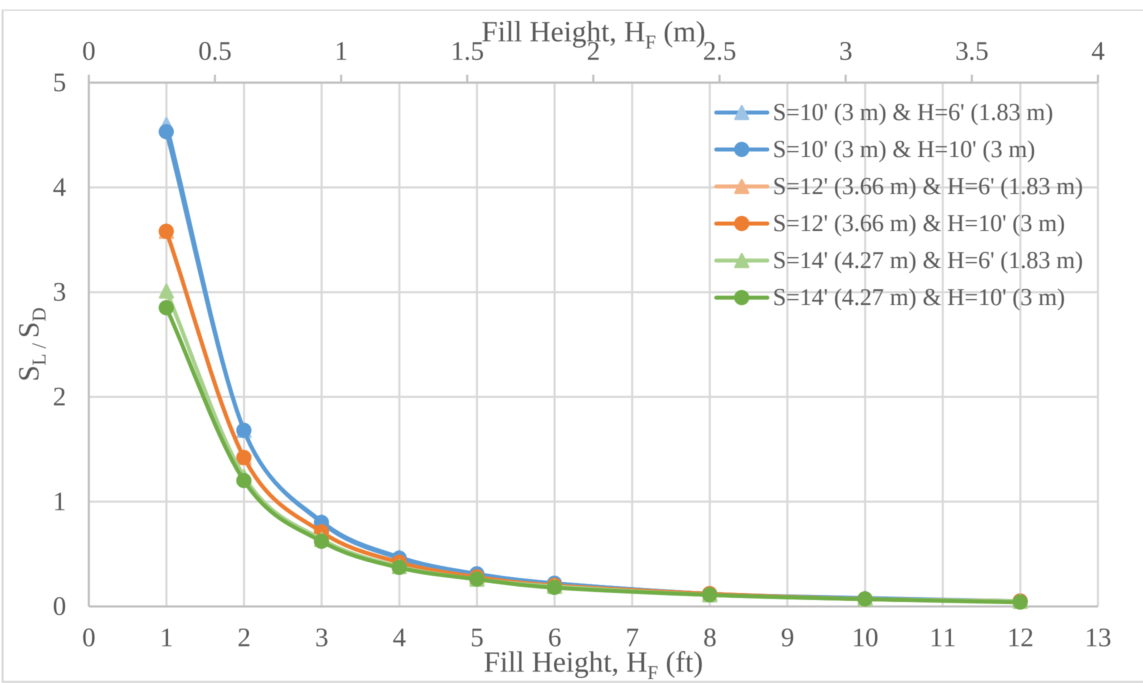

Figure A.16. Ratio of live load effects to dead load effects (S_L / S_D)

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  Spring 2017 *(National Civil Engineering Honor Society)* by the Department of Civil Engineering, University of Kentucky.
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