

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**SCHOOL OF CIVIL AND ENVIRONMENTAL**  
**ENGINEERING**



**DEVELOPMENT OF COMPREHENSIVE TOOL FOR THE**  
**STRUCTURAL ANALYSIS, DESIGN, AND DETAILING OF**  
**BURIED BOX CULVERTS**

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**A Thesis in Structural Engineering**

By Tewele Brhane

June 2023

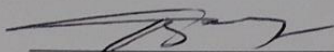
Addis Ababa

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled '**Development of Comprehensive Tool for the Structural Analysis, Design, And Detailing of Buried Box Culverts**' presented by **Tewele Brhane**, a candidate for the degree of **Master of Science in Civil Engineering (Structural)** and hereby certify that it is worthy of acceptance.

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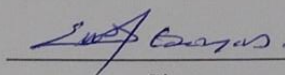


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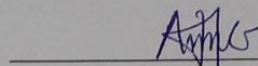


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## **UNDERTAKING**

I certify that research work titled “Development of Comprehensive Tool for the Structural Analysis, Design, And Detailing of Buried Box Culverts” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Tewele Brhane

## **ABSTRACT**

Box culvert design currently involves using a minimum of three software programs, including Microsoft Excel for load determination and structural analysis tools such as CSI SAP or MIDAS CIVIL for determining action effects. AutoCAD is then used for structural detailing. This approach can lead to project delays and an increased likelihood of mistakes.

Furthermore, the current design approach uses a two-dimensional plane frame model that assumes beam elements are centered in concrete members and that the model is externally supported by pinned and roller supports, resulting in uneconomical designs that may compromise safety. Moreover, the ERA standard drawing has restrictions that do not account for all potential culvert sizes and fill heights.

To address these issues, this research proposes a comprehensive software solution for structural analysis, design, and detailing of box culverts. The proposed software enables designers to analyze and design box culverts of any size and fill height while accounting for vertical displacement of the foundation soil using spring modeling. This approach streamlines the design process, saving time and increasing accuracy, while also improving safety.

The software program developed in this research is a web application. As a result, users can easily access the software from any location at any time, using any device with an internet connection, without the need for installation.

Design charts have been developed to illustrate how the bending moment varies at different locations for various opening sizes of a culvert. This is achieved by varying the fill height and number of openings.

## **ACKNOWLEDGMENTS**

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## CHAPTER 1 INTRODUCTION

### 1.1 Background

Buried structures serve a variety of purposes. They are typically used for conveying water. At other times, they are used to provide cattle underpasses, pedestrian underpasses, or conduits from one side to the other [1, 2]. The most widely used buried structures are pipes and box culverts. Box culverts are used in cases where the bearing capacity of the foundation material is poor and using pipe culverts is not appropriate [2, 3, 4].

Box culverts are required to be provided under the earth embankment for the crossing of watercourses like streams across the embankment, as road embankments cannot be allowed to obstruct the natural waterway. The culverts are also serving as utility tunnels that carry electricity, water, and sewer lines for passage of traffic, including usage as roads or as parking on top of the box culverts. Sometimes, they also carry communication lines, such as telephones and cable television. In addition to this, railroad construction and maintenance depend on the use of box culverts. They can replace small bridges or create crossings over creeks or other waterways. Undertrack culverts are vital to the success of modern railroads [1, 2, 3].

When compared to slab or arch culverts, box culverts have many benefits. The structure of the box is strong, stable, safe, and simple to assemble. The key benefit is that, unlike other types of culverts, it may be positioned at any elevation within the embankment with an adjustable cushion. It can be erected on soft soil without the need for a separate elaborate foundation by projecting an appropriate base slab that will lower the base pressure within the foundation soil's safe bearing capacity. In the event that the roadway needs to be widened in the future, it is simple to extend the current culvert without encountering any design or construction issues [2].

Box culverts are available in a number of sizes and forms and may be designed to handle a wide range of conditions and requirements, including high water flows, heavy loads, and special site conditions. One of the key advantages of box culverts is their strength and durability. Additionally, they are typically designed to provide a smooth, unobstructed

passage for water or other fluids, which can help minimize erosion and reduce the risk of flooding [2].

Soil-structure interaction is a term used to describe how buried structures carry vertical loads. This is achieved through a combination of the structure's internal capacity and the soil's arching around it. The method by which a buried structure carries vertical loads varies depending on its stiffness. Rigid culverts, such as concrete box culverts and rigid pipes, are assumed to carry design loads internally with limited reliance on the soil [4].

The hydrologist does hydraulic analysis to determine the culvert's size, whereas structural components of the culverts should be designed and detailed in accordance with the guidelines in the manual by a structural engineer. The reinforcement used in concrete box culverts can be either conventional bar reinforcement or welded wire fabric.

The collapse of culverts and bridges has a significant influence on the country's economic development, access to community facilities, and other daily activities because vehicle transportation is Ethiopia's primary and essential method of moving people and products [5].

This research will address the software development for the structural analysis, design, and detailing and generate design charts for box culverts using the Python programming language.

## **1.2 Statement of the problem**

In current design practice, the box culvert design mainly involves a minimum of three software. We use Microsoft Excel to determine the loads applied to our culvert and for the structural design of the culvert based on the action effects from the structural analysis tools, structural analysis tools such as CSI SAP, MIDAS CIVIL, and other relevant tools in order to determine the action effects, and AutoCAD for structural detailing. This practice leads to delays in project delivery, motivates the designer to detail them from past experience by assuming "Nothing will happen" rather than doing analysis. Altogether, using a number of tools makes our design tedious and increases the probability of making mistakes.

And since the structural analysis tools are cracked software, they are more likely to be infected with serious computer viruses, which can damage the user's computer system. Using cracked software is not fully reliable and is also illegal.

Furthermore, the current design approach uses a 2-Dimensional (2D) plane frame model to analyze the box culvert. Beam elements in the 2D model are assumed to be centered in the concrete members. The model is assumed to be externally supported by a pinned support on one end and a roller support on the other. This assumption implies that there is no vertical displacement. However, box culverts are recommended in cases when the bearing capacity of the foundation material is low and the vertical displacement of the foundation soil is significant. This type of modeling leads to uneconomical design, which is one of our primary concerns, along with safety.

In addition, the ERA standard drawing is restricted to span lengths of 3 and 4 meters, with a maximum fill height of 8 meters, but in practice, culvert sizes and even greater fill heights may be used that are not specified in the standard drawings.

### **1.3 Significance of the Study**

In current design practice, box culvert design mainly involves a minimum of three software programs. We use Microsoft Excel to determine the loads applied to the culvert and for the structural design of the culvert based on the action effects from the structural analysis tools, such as CSI SAP, MIDAS CIVIL, and other relevant tools, in order to determine the action effects, and AutoCAD for structural detailing. This practice leads to delays in project delivery and motivates the designer to detail them from past experience by assuming "nothing will happen" rather than doing analysis. Altogether, using a number of tools makes our design tedious and increases the probability of making mistakes.

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In addition, the ERA standard drawing is restricted to span lengths of 3.0 and 4.0 meters, with a maximum fill height of 8.0 meters, but in practice, culvert sizes and even greater fill heights may be used that are not specified in the standard drawings.

This research aims to address various issues in box culvert analysis, design, and detailing by developing a comprehensive software tool for structural analysis, design, and detailing. The software will offer solutions to the following issues:

- Enabling the design of box culverts of any size.
- Facilitating the design of culverts with varying span lengths between internal and external spans.
- Allowing the design of culverts with multiple openings.
- Encouraging designers to engage in the design process instead of relying on past experience.
- Providing the flexibility to design box culverts to accommodate any fill height.
- Incorporating spring-based modeling of foundation soil to account for vertical displacement.
- Reducing the time required for analysis, design, detailing, and design review of box culverts.

## **1.4 Research objectives**

### **1.4.1 General objective**

The general objective of this research is to develop a comprehensive and efficient software tool that can be used to perform structural analysis, design, and detailing of buried box culverts. Additionally, it seeks to generate design charts for buried box culverts in accordance with the AASHTO LRFD Bridge Design Specifications and the ERA Bridge Design Manual 2013.

### **1.4.2 Specific objective**

- To develop a software tool capable of performing structural analysis, design, and detailing of buried box culverts.
- To prepare a module for the graphical user interface.
- Generate design charts that facilitate the determination of design moments at various locations of the culvert.

## **1.5 Scope and Limitations**

### **1.5.1 Scope**

With the computer program developed, box culverts of any span length, height, and fill height can be analyzed, designed, and detailed accordingly.

With the software program developed, practicing engineers, design and supervision consultants, clients, and contractors will be able to design culverts that are safe, economical, and also save time during the design and design review of box culverts. The design charts will also be handy in the design review of box culverts.

### **1.5.2 Limitations**

Only the following factors were considered when developing the software program:

- The software has been developed with the purpose of exclusively accommodating the design of box culverts that possess uniform span lengths as well as those that have different span lengths between their internal and external cells. The software doesn't cover the design of culverts with non-uniform span lengths between the interior cells.

## **1.6 Methodology**

Python programming language is used in the software development process. The following Python libraries are used during software backend development:

- Openpyxl for Excel automation

- Pyautocad: write ActiveX automation scripts for AutoCAD.
- Numpy: to perform a wide variety of mathematical operations on arrays
- Matplotlib: for the data visualization

Since Python is an object-oriented programming language, the program is written in different modules for ease of debugging. Each module is imported whenever it is needed.

Finally, the frontend of the software is done using Hypertext Markup Language (HTML) and Cascading Style Sheets (CSS), and the backend of the software is done using the Flask Python web framework. Moreover, JavaScript is used for the creation of dynamic and interactive elements on the web page.

## **1.7 Content of the Thesis**

The thesis comprises seven chapters, starting with the first chapter that covers the introduction of the box culverts, its scope, limitations, and the objectives of the research.

The second chapter provides a comprehensive literature review of existing studies on the structural analysis and design of box culverts, including available software programs.

The third chapter focuses on the analysis and design of box culverts using the Load and Resistance Factor Design (LRFD) approach. This chapter discusses the principles of LRFD provisions for the structural analysis and design of box culverts.

The fourth chapter outlines the development of a computer program for the structural analysis, design, and detailing of box culverts, including the flow charts for the software.

The fifth chapter describes the development of design charts for reinforced concrete cast-in-place box culverts.

Chapter six showcases the application of the developed computer program and provides examples to verify the design of box culverts with the result from CSISAP2000v24.0.0, including validation of design results.

The final chapter presents the conclusions drawn from the outputs based on the developed computer program and the recommendations based on the findings discussed in this chapter.

## CHAPTER 2 LITERATURE REVIEW

### 2.1 General

Box culverts are typically built with two vertical and horizontal slabs monolithically casted [6, 7, 8]. These culverts are commonly used in the construction of road and railway bridges, especially where massive embankments or dikes cross over a stream with restricted flow. Box culverts are also an excellent choice when a small discharge channel needs to cross over a road drain. Furthermore, because of their monolithic design, box culverts are ideal for locations where the soil has a low bearing capacity [6, 7, 9, 10].

### 2.2 Construction Material Strength for Box Culverts

#### 2.2.1 Concrete

Concrete has a high compressive strength but a low tensile strength. When the tensile stress induced by temperature changes, shrinkage, or applied loads exceeds the concrete's tensile strength, it will experience cracking [11].

##### 2.2.1.1 *Compressive strength*

Concrete strength typically denotes the uniaxial compressive strength, which is determined through a compression test on a standard test cylinder. This method serves as a standard means of monitoring concrete strength for quality control or acceptance purposes. Therefore, compressive strength is used as a convenient way to refer to concrete strength [11]. Typically, the specified compressive strength of concrete is achieved 28 days after the concrete is cast. The minimum cube compressive strength that can be used for structural applications is 16 MPa [12].

##### 2.2.1.2 *Tensile Strength of Concrete*

Concrete's tensile strength ranges between 8 and 15% of its compressive strength the actual value is highly influenced by the type of tensile strength test used, the type of aggregate used, the compressive strength of the concrete, and the presence of a compressive stress transverse to the tensile stress [11].

The strength of concrete may vary depending on the type of tension test used, but typically, the strength decreases as the volume of concrete subjected to high tensile stress increases [11].

While the compressive strength and tensile strength of concrete are directly related, the ratio of these two strengths tends to decrease as the compressive strength increases. As a result, concrete's tensile strength is generally proportional to the square root of its compressive strength [11].

The tensile strength of concrete can be determined by [13] :

- Direct tension test
- A cylinder split test and
- Flexure (Modulus of rupture) Test.

### **2.2.1.3 Modulus of Elasticity**

The stress-strain relationship for concrete is not linear. As a result, the modulus of elasticity varies from point to point. Furthermore, its value varies with [14].

- Concrete strength
- Concrete ages
- Loading types, and
- Cement and aggregate properties

In the absence of recorded experimental data, it is possible to estimate the modulus of elasticity ( $E_c$ ) for concrete with unit densities ranging from 1440 to 2500 kg/m<sup>3</sup> and maximum specified compressive strengths of 105 MPa using the following relation [12] :

$$E_c = 0.043K_1\gamma_c^{1.5}\sqrt{f_c'} \quad (1)$$

Where:

- $K_1$  = correction factor for source of aggregate
- $\gamma_c$  = unit density of concrete (kg/m<sup>3</sup>)
- $f_c'$  = specified compressive strength of concrete

### **2.2.2 Reinforcement Bar**

Although modern approaches to design require the use of characteristic strength, which is usually the 5% fracture value, the strength grade for reinforcing steel is currently specified in terms of minimum guaranteed yield strength [13].

Reinforcements with yield strengths greater than 520 MPa shall not be used in the design. Also, the nominal yield strength must be the minimum specified for the selected steel grade. In addition to this, the modulus of elasticity of steel reinforcement is considered to be 200 000 MPa [12].

### **2.3 Soil Structure Interaction**

Soil-structure interaction models are used to calculate the forces exerted on the buried structure and to simultaneously evaluate the deformation and distress to the structure [15].

The analysis and design of box culverts should consider the potential impact of surface foundations, as these structures can generate significant induced earth pressure on the culvert. It is crucial to thoroughly investigate and incorporate the effect of surface foundations on soil pressures surrounding box culverts to ensure their structural integrity and durability [16]. It is important to note that before conducting design calculations, it is necessary to accurately determine the soil parameters for both the subgrade and the backfill [17].

Classical earth pressure theory may not accurately predict the loading on a buried conduit due to variations caused by the structure deflecting differently than the surrounding soil. This can lead to either a decrease or increase in pressure on the structure depending on the direction of soil stress produced by soil movement along a slippage plane [18].

To analyze the behavior of a RC box culvert under live loads, the soil properties must be determined and used to calculate hyperbolic parameters for a finite element method computer program. This involves obtaining representative soil samples from culvert backfill materials and conducting standard laboratory procedures to determine their properties [18].

The behavior of box culverts under static loads is controlled by soil arching which is a result of the complex interaction between the culvert and the surrounding soil. Soil arching is a critical consideration in the design of culverts as it is primarily influenced by the relative stiffness of the culvert and the soil. The height of the soil above the culvert, the geometrical configuration of the box culvert, and the properties of the surrounding soil are some of the factors that affect soil arching on box culverts. [19].

The phenomenon of soil arching, primarily induced by the presence of a rigid body within a deformable body, leads to the redistribution of stresses in a buried box culvert. Consequently, it is essential to consider soil-structure interaction when studying the behavior of box culverts for designing them safely and efficiently [8].

If the foundation is built on a hard material, it is not necessary to use an elastic, compressible support beneath the base slab for boxes. However, if an elastic, compressible support is used, the foundation will be regarded as "flexible". On the other hand, if the foundation is founded on a hard material, it will be considered rigid [20].

The modulus of subgrade reaction ( $k_s$ ) of the foundation material can be determined using the mathematical expression given by [8]:

$$k_s = q/S \quad (2)$$

Where:

- q = Soil pressure in kN/m<sup>2</sup>
- S = Settlement of the soil in meter

According to [21], the simplest approach to represent a foundation subgrade is by means of Winkler's model. This model employs linear springs to represent soils, and each spring are independently of the others. Mathematically Winkler model is given by [8]:

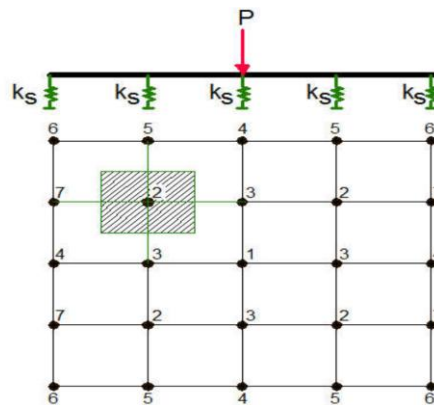
$$p(x, y) = k_s w_0(x, y) \quad (3)$$

Where:

- p (x, y) = is the vertical contact pressure at an arbitrary point (x, y)
- $k_s$  = is the coefficient of subgrade reaction

$w_o$  = corresponding vertical displacement at that point

The tributary area for node 2 of the plate is depicted schematically in **Figure 2-1** [8].



**Figure 2-1 Typical model of plate on grade supported on soil springs [8]**

Andrzej Helowicz [17] conducted a parametric analysis to compare the bending moment values and distribution for a box culvert designed with subgrade stiffness taken into account versus a model on rigid supports. The results showed that including subgrade elasticity in the numerical model was important as it prevented excessive deflections and surface cracking in various box culvert elements. It is crucial to determine the proper soil parameters for both the subgrade and backfill before designing a box culvert that considers subgrade stiffness. Close cooperation between geotechnical and structural engineers is required to ensure the accuracy of the design. Building a box culvert on a different subgrade than the target one can lead to over- or under-reinforcement of structural members.

## 2.4 Types of Box Culvert

Box culverts can be classified into cast-in-situ and precast box culvert based on their method of installation.

### 2.4.1 Cast-In-Situ Box Culvert

Box culverts that are made of reinforced in the field are considered cast-in-place. These structures are built with concrete and rebar at the project site. Forms are constructed to outline and create the dimensions and shape the box culvert, and concrete is poured into them [22, 23]. The performance of these structures over the years has been very good [4, 7].



**Figure 2-2 Cast in situ box culvert**

#### **2.4.2 Precast Box Culvert**

One of the most versatile and cost-effective precast concrete products are the precast concrete segmental box culverts, which are well-suited to meet the demands of fast-paced construction projects. These culverts are highly adaptable in terms of design and easy to install on site, resulting in significant cost savings. They are typically produced and transported as finished sections of the desired shape, either by captive manufacturers or commercial suppliers [3].



**Figure 2-3 Precast box culvert [24]**

### **2.5 Overview of Methods of Structural Analysis for Box Culverts**

To analyze box culverts, it is recommended to use closed rigid frames and carry out separate analyses for different loading conditions such as dead loads, superimposed earth loads, lateral earth pressure, and live loads intensity. Critical points, such as corners and areas with positive moment, require determining the maximum moment and shear, and this is achieved by combining the load effects obtained from the separate loading conditions [23].

There are several methods of analyzing rigid frames. They include [23];

- Displacement method.
- Method of force.
- Moment distribution method.

The computer program developed by [25, 26] uses the stiffness matrix method of analysis to calculate the design moments, thrusts, and shears. The box culverts are modeled as four member frames with a unit width. The member stiffness matrices are assembled to form a global stiffness matrix for a given frame. A load matrix is also assembled for the joints, and conventional matrix methods of structural analysis are used. To simplify the process, the fixed end force and flexibility coefficients for a member with linearly varying haunches are obtained through numerical integration.

## **2.6 Design Consideration of Box Culverts**

RC box culverts comprises three structural elements namely top slab, bottom slab and side wall. They are designed and cast monolithically to withstand various types of loads, including live loads, embankment loads, water pressure, and lateral earth pressure. Their unique construction and design make them an ideal choice for applications where hydraulic and other site-specific requirements need to be considered [2].

The top of the box culvert can either be at grade or at fill, depending on whether the road is in an embankment. The height and number of boxes required also vary depending on the specific site requirements. The box culvert's barrel shall have sufficient length to accommodate the carriageway and curbs to ensure the proper functioning of the culvert system [2]

RC box culverts provide several advantages over other types of culverts. Their monolithic design offers excellent durability and strength, making them capable of withstanding heavy loads and traffic. They also require minimal maintenance, making them a cost-effective option for infrastructure projects. The unique design of box culverts allows for a more efficient flow of water, preventing flooding and erosion.

Moreover, RC box culverts can be designed and built to meet specific site requirements, ensuring that they perform optimally in their intended location.

- The loads considered for the analysis of box culverts are Dead load, Live load, Soil pressure on side walls, Surcharge due to live load, and Water pressure from inside.
- The weight of embankment, deck slab and the track load are considered to be uniformly distributed loads on the top slab with the uniform soil reaction on the bottom slab. For live load distribution, the width of dispersion perpendicular to the span is computed first. Width of dispersion parallel to the span is also calculated. Then the maximum magnitude of load is divided by width of dispersion parallel to span and width of dispersion perpendicular to the span to get the load intensity on the top slab.
- The self-weight of two side walls acting as concentrated loads is assumed to produce uniform soil reaction on the bottom slab.
- The pressure distribution on side walls is assumed to be triangular with maximum pressure intensity. Designers need to consider two loading conditions:
  - The culvert is full of water, and
  - The culvert is empty.
- The earth pressure on the vertical side walls of the box culvert is computed according to the Coulomb's theory.

The following loading cases considered for the design of box culverts are as given below [2, 27, 28]:

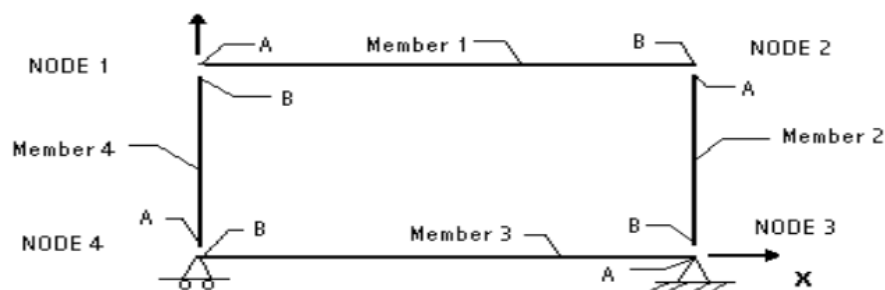
- Live load, dead load and earth pressure acting, with no water pressure from inside.
- Live load, dead load and earth pressure acting from outside and water pressure acting from inside.
- Dead load and earth pressure acting from outside and water pressure acting from inside.

## 2.7 Related Studies on Analysis and Design of Box Culvert

### 2.7.1 Existing Computer Programs

BOXCAR is a comprehensive and sophisticated computer program designed for structural analysis and reinforcement design of single cell reinforced concrete box culverts. As the name suggests, the program is primarily focused on the analysis and design of box culverts, with the goal of ensuring that the final structure meets all the required hydraulic and site-specific considerations [29].

As shown in **Figure 2-4**, BOXCAR's approach to model the culvert involves using a two-dimensional (2D) frame model, which assumes that the foundation soil is rigid and does not experience any vertical displacement.



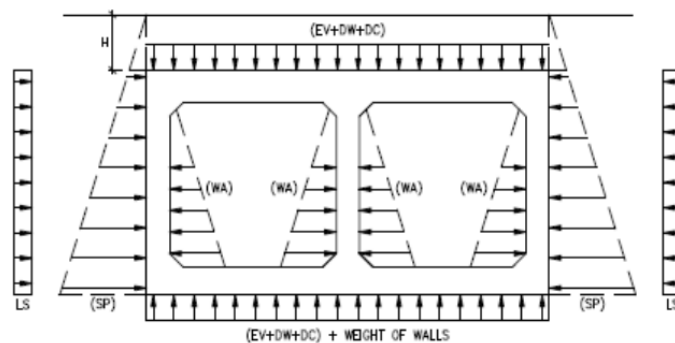
**Figure 2-4** Box culvert model using BOXCAR [29]

The software ESurvey Structure, developed by ESurveying Softech, is used to generate drawings of box culverts. It takes into account several input parameters including road type, box type, finished road level, number of cells, chainage, reinforcement template, invert level, downstream side, and template [30]. However, it is important to note that the software cannot perform structural analysis and design for the box culverts.

Eriksson Culvert is a software program designed for Microsoft Windows that facilitates the analysis or design of precast or cast-in-place concrete box culverts with either single or multiple cells. The software is able to determine the necessary side wall and slab thicknesses, as well as the required reinforcement for the culvert [31]. The program is compatible with various specifications such as the AASHTO LRFD Specifications, the AASHTO Standard Specifications, AREMA, or CHBDC.

Some of the limitations of Eriksson Culvert are:

- The maximum number of cells that can be designed using the software is four.
- It ignores the effect of vertical displacement. Instead, as shown in **Figure 2-5**, it considers soil pressure by applying an upward vertical reaction caused by the structure's self-weight, vertical earth pressure, live load, and water pressure.
- It doesn't generate drawings of the box culvert (AutoCAD drawings).



**Figure 2-5 Static Loading Diagram in Box culvert using Eriksson Culvert [31]**

CANDE is a public-domain computer program that was developed under the sponsorship of the Federal Highway Administration (FHWA) for the purpose of designing and analyzing buried culverts. The name CANDE is short for Culvert Analysis and Design, which reflects the program's focus. To model the interaction between the culvert structure and the surrounding soil, CANDE employs a finite-element methodology based on a two-dimensional slice of the culvert installation. This approach enables the program to simulate the behavior of the soil-structure system as a whole under incremental loading conditions, which makes it a powerful tool for analyzing the structural performance of culverts [32]. The shortcoming of this program is that it cannot generate structural drawings for the culverts.

Manmeetsingh Sethi, [33] attempted to automate the design of box culverts through design automation. The software analyzes and designs box culverts according to Indian Standard, but it is limited to the analysis and design of single cell box culverts despite its aim to automate the entire process.

### **2.7.2 Modeling of Box Culverts Using Commercially Available Software**

Midas Civil was utilized by [34] to analyze a dual cell box culvert located on a municipal road in Yunnan, China that crosses the Baita River. Based on beam element modeling, SHI determined that the top and bottom of the culvert satisfied the normal section bearing capacity of flexural members, crack width during the service stage, and various criteria in the construction stage. Furthermore, the web and side plates of the box culvert fulfilled the requirements for strength and stiffness of bearing capacity for axially eccentric compressive members.

Vasu Shekhar Tanwar, Dr. M. P. Verma, Sagar Jamle, [27] conducted an analysis of a single cell box culvert using STAAD Pro to reduce stress within the box by flaring the box partially.

Afzal Hanif Sharif, [28] conducted a study focused on developing the most effective and safe design for a box culvert. To achieve this goal, he used the moment distribution method and compared its results with those obtained from the STAAD PRO program method. Additionally, all structural elements of the box culvert were designed, and safety checks were performed to ensure the bridge met safety standards.

in order to enable the designer to decide the combination of various loading cases to arrive at the maximum design forces at the critical section, thus saving considerable design time and effort made a study to arrive at the coefficients for moments, shear forces, and axial thrusts for different loading cases and for different ratios of  $L/H = 1.0$ ,  $L/H = 1.25$ ,  $L/H = 1.5$ ,  $L/H = 1.75$ , and  $L/H = 2.0$  for a three-cell box culvert [35, 36].

Abdul Kareem, M.B. Al-Shammaa, [37] had done analysis and design of single cell box culvert by simplified method using the software "STAAD.Pro" taking one meter width of culvert to ACI-code 2011 with SI units to produce a plane structure instead of space structure. The structure is subjected to various types of loads and supported by a bed of springs instead of soil interaction according to Winkler's modeling. This paper finally concludes that there is no significant difference in the values and shape of the bending moment and shear force diagrams found using other methods.

## CHAPTER 3 ANALYSIS AND DESIGN OF RC BOX CULVERTS

### 3.1 General

The ERA Standard Detailing Drawing for Roadworks 2013 provides standard drawings for reinforced concrete single and double cell box culverts with spans of 3.0 m and 4.0 m and rises ranging from 2.0 to 4.0 m. However, if box culverts fall outside of these standard sizes, they must be designed according to the AASHTO LRFD Bridge Design Specifications and the ERA Bridge Design Manual 2013.

### 3.2 Design Standard

The primary design standard used for software development in this research is the AASHTO LRFD Bridge Design Specifications along with the ERA Bridge Design Manual 2013. The AASHTO LRFD Bridge Design Specifications are a widely recognized industry standard that offer detailed guidance on box culvert design, construction, and evaluation. By incorporating these standards, a comprehensive box culvert design tool was developed that prioritizes structural safety, efficiency, and sustainability.

### 3.3 Design Method

Culverts shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspect-ability, economy, and aesthetics.

The LRFD methodology shall be satisfied for all specified force effects and their combinations. In order to ensure compliance with each limit state, it is required that all components and connections satisfy:

$$\sum \eta_i \gamma_i Q_i \leq \phi R_n \quad (4)$$

Where:

$R_n$  = nominal resistance

$Q_i$  = force effect

$\eta_i$  = load modifier

$\gamma_i$  = load factor

$\phi_i$  = resistance factor

### 3.3.1 Load Modifier

For all box culverts, the force effects of the Strength I load combination shall be subjected to the application of load modifiers ( $\eta$ ) for ductility, redundancy, and operational classification [38].

The load modifier that corresponds to a maximum and minimum value of the load factor are given by [12]:

$$\eta_i = \eta_D \eta_R \eta_I \quad (5)$$

$$\eta_i = \frac{1}{\eta_D \eta_R \eta_I} \quad (6)$$

### 3.3.2 Load Factor

According to [12], the load factors shown in **Table 3-1** shall be used in the design of box culverts for the Strength I and Service I limit states.

**Table 3-1 Load Factors for Strength I and Service I Limit State [12]**

Load Type		Strength I		Service I
		Max.	Min.	
Dead Load-Components	DC	1.25	0.90	1.00
Dead Load-Wearing Surface	DW	1.50	0.65	1.00
Vertical Earth Pressure	EV	1.30	0.90	1.00
Horizontal Earth Pressure	EH	1.35	0.50	1.00
Live Load Surcharge	LS	1.75	1.75	1.00
Live Load Intensity	LL+IM	1.75	1.75	1.00

### 3.3.3 Resistance Factor

Resistance factor is to account for the variability of material properties, structural dimensions, workmanship, and uncertainty in predicting resistance, by reducing the computed nominal resistance of a structural element [39].

For cast-in-place reinforced concrete box culverts the resistance factors for the Strength Limit State for flexure and shear are 0.9 and 0.85, respectively [39].

### **3.4 Analysis and Design of RC Box culvert to AASHTO LRFD Bridge Design Specifications**

#### **3.4.1 Material Properties**

##### **3.4.1.1 Concrete**

The minimum specified concrete compressive strength shall not be less than 16 MPa [12].

##### **3.4.1.2 Reinforcement Bar**

The selected steel grade must have a nominal yield strength that meets the specified minimum requirement. However, for design purposes, yield strengths above 520 MPa should not be used. If bars with yield strengths below 420 MPa are to be used, the Owner's approval is necessary [12].

#### **3.4.2 Geometry**

In accordance with [12] and [40], the depth of the slab of box culvert should not be less than 175 mm and 185 mm, respectively. It is recommended to consider the minimum slab thickness given by [40] as a conservative approach.

As specified in [35], the minimum thickness of the structural elements of a box culvert shall be taken as:

- The slab's minimum thickness in millimeter must match 100 times the clear span meter.
- The minimum thickness of a wall in millimeter must correspond 100 times to the clear height in meter.
- In cast-in-place culverts, the bottom slab's thickness should exceed the top slab's thickness by 25 mm.

### 3.4.3 Limit States and Load Combinations

#### 3.4.3.1 Limit States

##### 3.4.3.1.1 Service Limit State

Box culverts shall be investigated at Service Load Combination I as specified in AASHTO LRFD Bridge Design Specifications **Table 3.4.1-1** [12].

##### 3.4.3.1.2 Strength Limit State

Box culverts shall be investigated at Strength Load Combination I and II, as specified AASHTO LRFD Bridge Design Specifications **Table 3.4.1-1** [12].

##### 3.4.3.1.3 Fatigue Limit State

Fatigue checks are not required in the analysis and design of box culverts.

#### 3.4.3.2 Load Combinations

According to [12], box culverts should be designed for the following strength I load combination.

- Strength Ia load combination: Maximum vertical load and maximum horizontal load.

$$1.25DC + (1.30)(\eta)EV + (1.75)(LL+IM) + (1.35)(\eta)EH_{max} + 1.75LS$$

- Strength Ib load combination: Maximum vertical load and minimum horizontal load.

$$1.25DC + (1.30)(\eta)EV + (1.75)(LL+IM) + 1.00WA + (0.9/\eta)EH_{min}$$

- Strength Ic load combination: Minimum vertical load and maximum horizontal load.

$$0.9DC + (0.90/\eta)EV + (1.35)(\eta)(EH_{max}) + 1.75LS$$

In the design of box culverts, load modifiers ( $\eta$ ) of 1.0 should be used for all loads except for earth EV and EH loads, where a load modifier of  $\eta = 1.05$  is used to account for the lack of redundancy [4].

In order to perform serviceability checks, it is required to use the load combinations specified below. It should be noted that a load factor of unity shall be used for these checks [38].

- Service Ia load combination: Maximum vertical load and maximum horizontal load.

$$1.00DC + 1.00EV + (1.00)(LL + IM) + 1.00EH_{max} + 1.00LS$$

- Strength Ib load combination: Maximum vertical load and minimum horizontal load.

$$1.00DC + 1.00EV + (1.00)(LL + IM) + 1.00WA + 1.00EH_{min}$$

- Strength Ic load combination: Minimum vertical load and maximum horizontal load.

$$1.00DC + 1.00EV + 1.00EH_{max} + 1.00LS$$

### 3.4.4 Loading

#### 3.4.4.1 Self-Weight (*Dc*)

The nominal dead load consists of the weight of the materials and parts of the structure that are structural elements [41]. The self-weight of the box culvert per linear meter of the culvert, considering the unit width of the culvert, can be taken as [26]:

$$W_{Dc} = t_s \gamma_c \tag{7}$$

Where:

- $W_{DC}$  = Self-weight (kN/m)
- $t_s$  = thickness of the structural element (m)
- $\gamma_c$  = Unit weight of concrete (kN/m<sup>3</sup>)

#### 3.4.4.2 Vertical Earth Pressure (*EV*)

The weight of the fill on top of the culvert develops the vertical earth pressure. Fill height is measured from the top slab to the surface of the pavement. Since the culvert walls are assumed to be frictionless, there is no vertical component of the earth's horizontal resultant force to be considered [4].

The soil-structure interaction factor is used to adjust the vertical earth load that a culvert can support. It aims to account for the arching effect of the soil above and around the culvert and consider installation conditions. Culverts constructed in trench conditions can carry less load than those built in embankment conditions because the soil in trench walls is usually stiffer than new embankment material. It is conservative to assume that culverts are installed in embankment conditions, and it is recommended not to exceed 1.15, which shall be computed using [4, 12]:

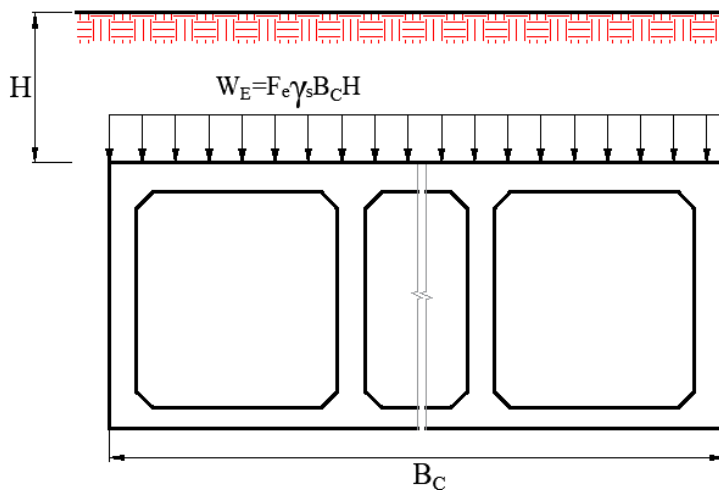
$$W_E = F_e \gamma_s B_c H \quad (8)$$

For an embankment installation, the soil-structure interaction factor shall be computed using [12]:

$$F_e = 1 + 0.20 \frac{H}{B_c} \quad (9)$$

Where:

- $F_e$  = Soil structure interaction factor
- $\gamma_s$  = Unit weight of the backfill above the culvert
- $B_c$  = Outside width of the box culvert
- $H$  = Depth of the backfill



**Figure 3-1 Vertical Erath Pressure Imposed Over a Box Culverts**

#### 3.4.4.3 Horizontal Earth Pressure (EH)

The equivalent fluid method shall be used for the purpose of the design and analysis of box culverts. The maximum lateral earth pressure on the external walls shall be determined based on the concept of at-rest earth pressure [3, 12, 35].

To determine the minimum force effects, it is assumed that the earth pressure acting on exterior walls from the submerged soil is equal to half the weight of the earth. And it is considered that the earth's horizontal force acts perpendicular to the walls of the culvert [4].

In cases where the equivalent-fluid method is used, the basic earth pressure can be taken as,  $p$  (in MPa) [12, 40].

$$p = \gamma_{eq}gH(x10^{-9}) \quad (10)$$

$$k_o = 1 - \sin \phi'_f \quad (11)$$

where:

- $\gamma_{eq}$  = equivalent fluid unit weight of soil, not less than 480 (kg/m<sup>3</sup>)
- $g$  = gravitational acceleration (m/sec<sup>2</sup>)
- $H$  = depth of the backfill (mm)
- $\phi'_f$  = effective angle of internal action of soil
- $k_o$  = coefficient of at-rest lateral earth pressure

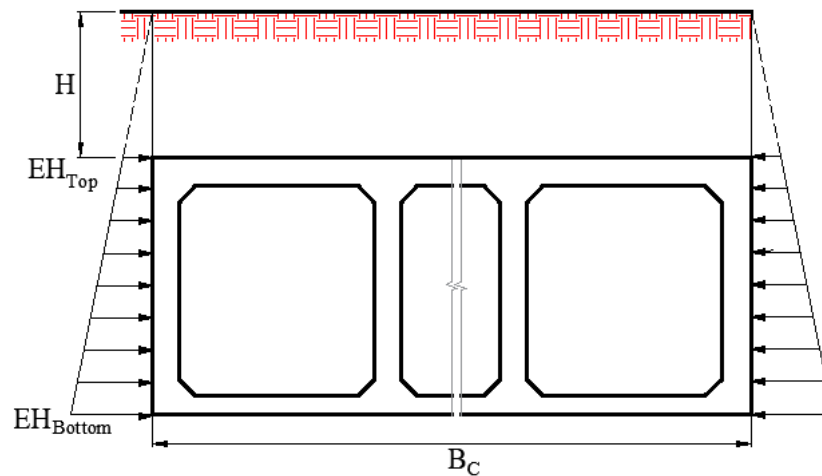


Figure 3-2 Horizontal Earth Pressure on the Walls

#### 3.4.4.4 Live Load Surcharge (Ls)

A live load surcharge should be applied in cases where vehicular loads are expected to act on the surface of the backfill within a distance equal to one-half the wall height behind the back face of the wall [12].

According to [12, 35], in order to determine the appropriate equivalent height of soil for vehicular loading, it is necessary to consider the distance from the bottom of the culvert to the roadway surface using **Table 3-2**. For intermediate wall heights, linear interpolation shall be used to determine the equivalent height of soil.

**Table 3-2 Equivalent Height of Soil for Vehicular Loading on Abutment Perpendicular to  
Traffic [12]**

Abutment height (mm)	$h_{eq}$ (mm)
1500	1200
3000	900
$\geq 6000$	600

The increase in horizontal pressure resulting from the live load surcharge may be taken as:

$$\Delta p = k\gamma_s h_{eq} \quad (12)$$

where:

- $\Delta p$  = horizontal earth pressure due to live load surcharge (MPa)
- $k$  = coefficient of lateral earth pressure
- $\gamma_s$  = total unit weight of soil ( $\text{kg/m}^3$ )
- $h_{eq}$  = equivalent height of soil for vehicular load ( $\text{m/sec}^2$ )

#### **3.4.4.5 Water Pressure (WA)**

To determine the water pressure inside the culvert, the height of the water pressure should be measured from the bottom of the culvert to the water level [39]. The water pressure should be considered in two conditions [4]:

- The culvert is full of water
- The culvert is empty

#### **3.4.4.6 Vehicular Live Load (LL)**

The approximate strip approach is used to design box culverts, in which a design strip of 1 m width is oriented parallel to the span. To ensure appropriate structural stability, the design live loads applied to the top slabs of box culverts include both the HL-93 truck and tandem loads, regardless of span length. Furthermore, lane loads are applied to the top slabs of box culverts with span lengths of 4600 mm or greater [4].

##### **3.4.4.6.1 Multiple Presence Factor (MPF)**

In order to account for traffic flow that runs parallel to the span, box culverts are designed to accommodate a single loaded lane with the application of the single lane multiple presence factor of 1.2 to the live load effect. This design consideration ensures that the box

culverts are capable of supporting the weight of traffic and maintaining their structural integrity [12].

#### 3.4.4.6.2 Dynamic Load Allowance (IM)

According to AASHTO LRFD Bridge Design Specifications, a dynamic load allowance shall be considered when the fill height is less than or equal to 2440 mm. The percentage value for the dynamic load allowance in culverts and other buried structures shall be considered as follows:

$$IM = 33(1.0 - 4.1 \cdot 10^{-4} D_E) \geq 0\% \quad (13)$$

where:

IM = Dynamic load allowance

$D_E$  = The minimum depth of earth cover above the structure (mm)

#### 3.4.4.6.3 Tire Contact Area

The tire contact area of a wheel with one or two tires can be considered as a single rectangle, where the width and length of the rectangle are assumed to be 510 mm and 250 mm, respectively [12].

#### 3.4.4.6.4 Live Load Distribution with Less Than 0.6 m of Fill

Where the depth of the fill is less than 600 mm and traffic primarily travels parallel to the span, the box culvert shall be analyzed based on a single loaded lane with a single lane multiple presence factor [12].

The axle load should be distributed on the top slab of the culvert as follows in order to determine moment, thrust, and shear [12]:

- Patch dimension perpendicular to the span:

$$E = 2440 + 0.12S \quad (14)$$

- Patch dimension parallel to span

$$E_{span} = L_T + LLDF(H) \quad (15)$$

Where:

E = equivalent distribution width perpendicular to span (mm)

$E_{span}$  = equivalent distribution length parallel to span (mm)

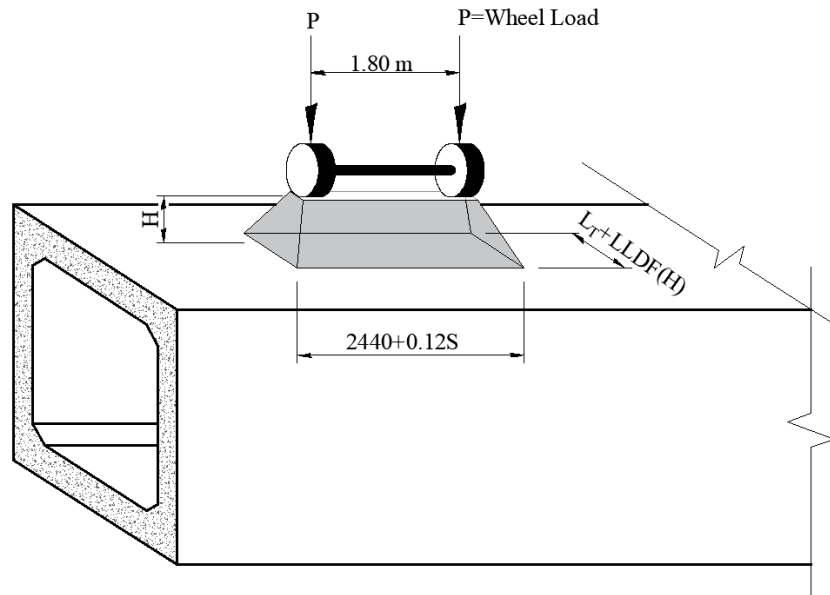
S = clear span (mm)

$L_T$  = length of tire contact area parallel to span (mm)

LLDF = factor for distribution of live load with depth of fill, 1.15 or 1.00

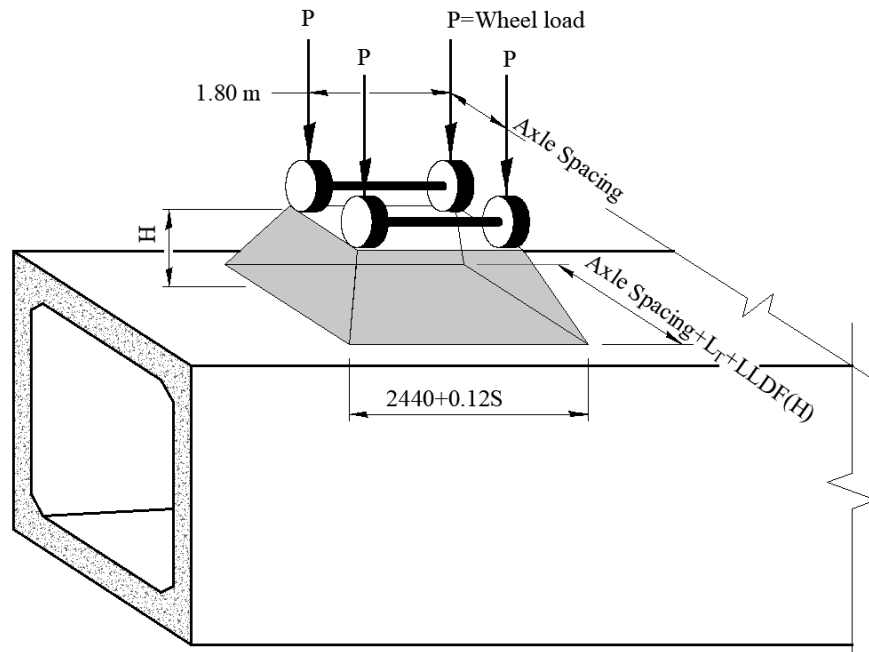
H = depth of fill from top of culvert to top of pavement (mm)

As shown in **Figure 3-3**, there is no possibility of overlapping of the load intensity of the distributed live load through the earth fill when the axel spacing is greater than the patch dimension parallel to span.



**Figure 3-3 Isometric View of Live Load Distribution for Fill Height When There is No Overlapping of Load Intensity [38]**

When the axel spacing is less than the distribution length the live load intensity will overlap, as shown in **Figure 3-4**.



**Figure 3-4 Isometric View of Live Load Distribution for Fill Height When There is Overlapping of Load Intensity [38]**

#### 3.4.4.6.5 Live Load Distribution with 0.6 m of Fill or Greater

If the depth of the fill is 600 mm or more, the wheel loads can be assumed to be uniformly distributed over a rectangular area with dimensions equivalent to the tire contact area, as specified in Article 3.4.4.6.3. Furthermore, this dimension is increased by either 1.15 times the depth of the fill in select granular backfill or the depth of the fill in all other cases [12].

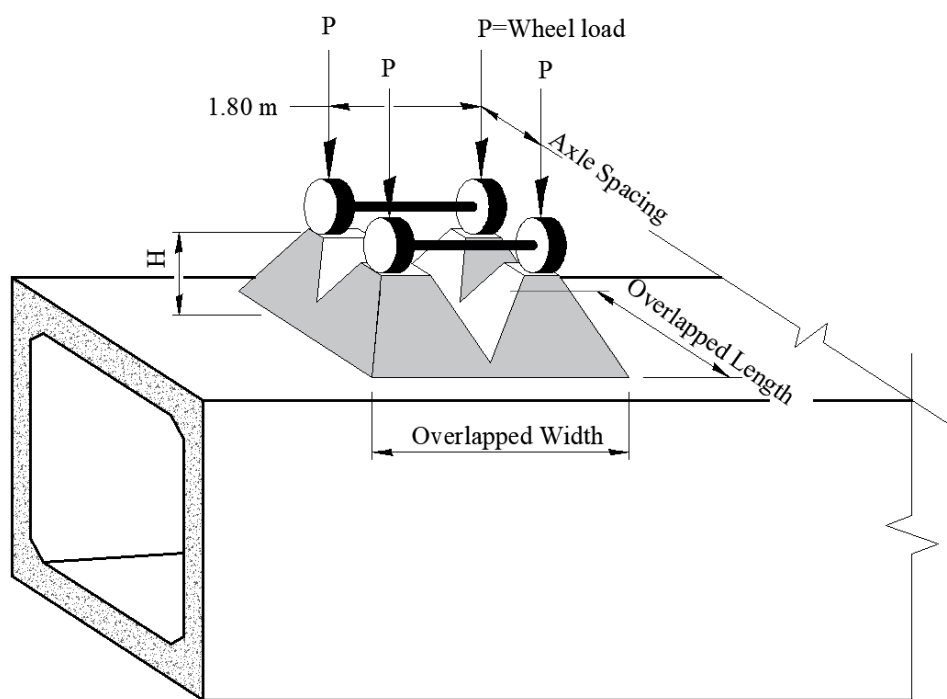
In the case of single-span culverts, if the depth of fill is greater than 2400 mm and spans the entire length of the culvert, the live load effect can be ignored. Similarly, for multiple-span culverts, if the depth of fill exceeds the distance between the end walls, the live load effect can be ignored [12].

In cases where the contact areas of multiple wheels overlap, the total load must be distributed uniformly over the overlapped area [12].

The extent of live load intensity overlap within an earth fill is determined by the fill height, with the likelihood of overlap increasing as the height of the fill increases. This likelihood gives rise to three potential scenarios:

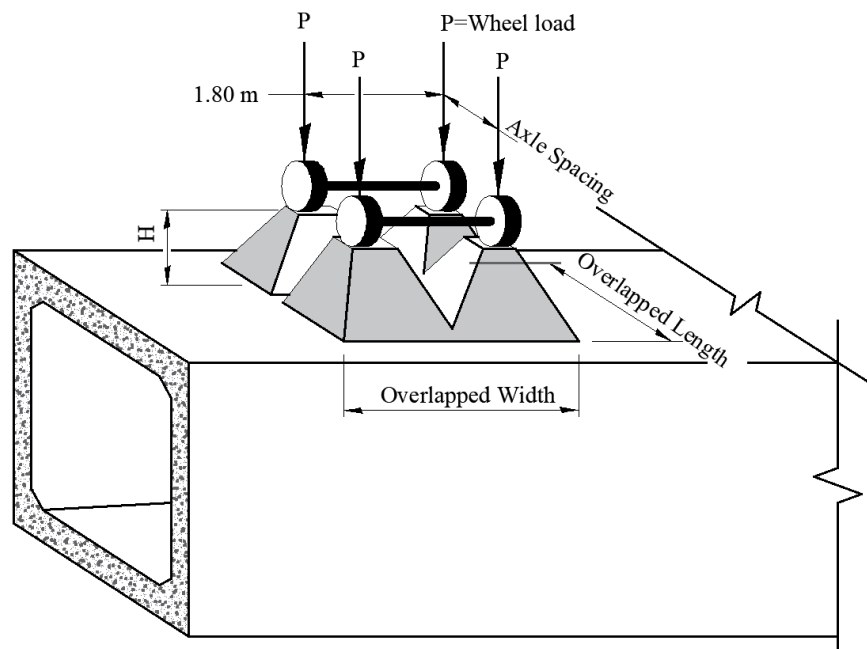
- no overlap of load projection,
- overlap of load projection from wheel loads on the same axle, and
- overlap of load projection when both the transverse and longitudinal patch dimensions are overlapped.

As illustrated in **Figure 3-5**, an overlap in load projection for live loads occurs when the overlapped length exceeds the axle spacing and the overlapped width is wider than the wheel spacing.

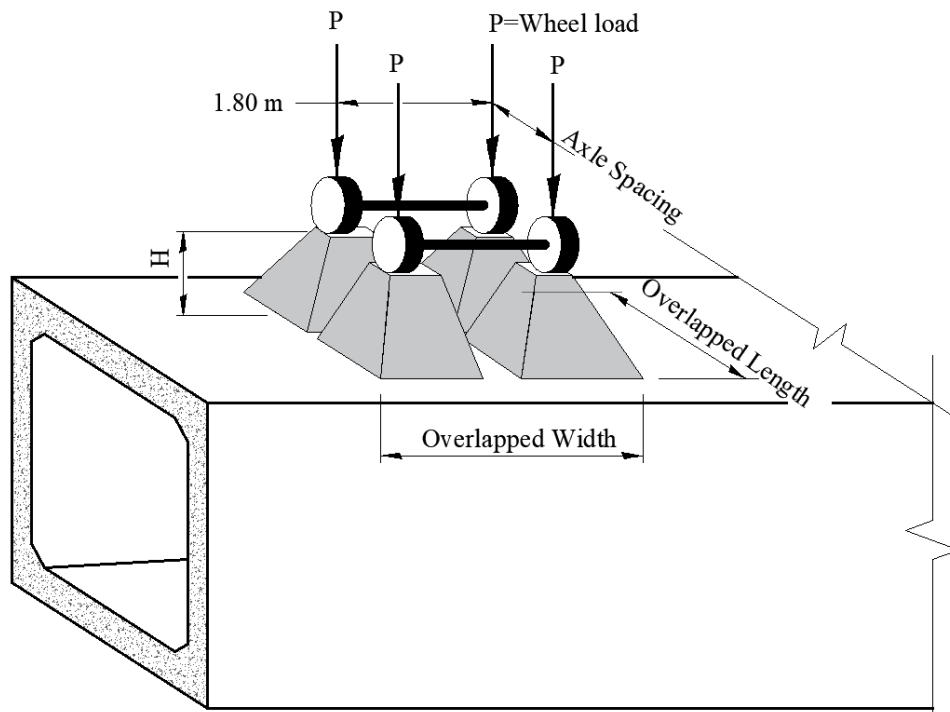


**Figure 3-5 Traffic Travelling Parallel to Span (600 mm of fill or greater show load projection overlap of four wheels) [38]**

In **Figure 3-6**, the overlapped width exceeds the wheel spacing, while the overlapped length is less than the axle spacing. If both the overlapped width and overlapped length are less than the wheel spacing and axle spacing, respectively, the distribution of live loads through earth fills can be illustrated as shown in **Figure 3-7**.



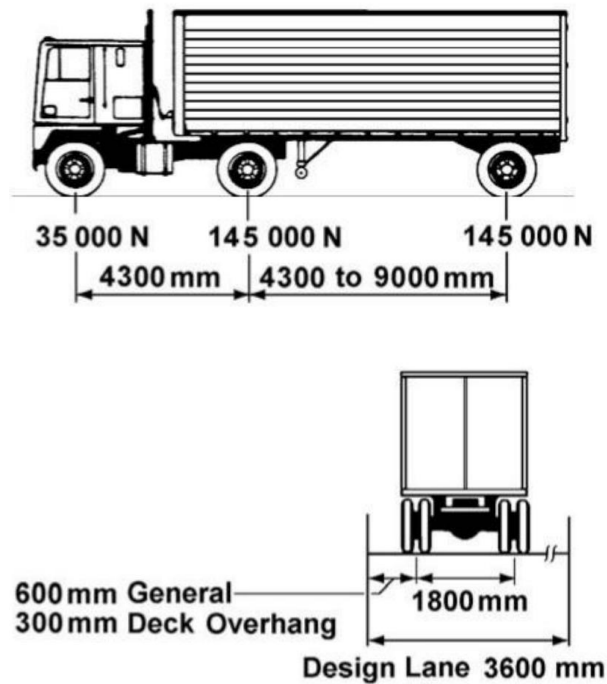
**Figure 3-6 Traffic Travelling Parallel to Span (600 mm of fill or greater showing load projection overlap of wheel loads in transverse direction) [38]**



**Figure 3-7 Traffic Travelling Parallel to Span (600 mm of fill or greater no load projection overlap) [38]**

#### 3.4.4.6.6 Truck Load

The weights and spacing of axels and wheels for the design truck shall be as specified in the **Figure 3-8** [12].



**Figure 3-8** AASHTO LRFD Figure 3.6.1.2.2-1 Characteristics of design truck [12]

#### 3.4.4.6.7 Tandem Load

The design tandem shall have a pair of 110 kN axels spaced 1200 mm apart. The transversal spacing of the wheels should be 1800 mm. A dynamic load allowance shall be considered as described in Article 3.4.4.6.2 [12].

#### 3.4.4.6.8 Lane Load

The design lane load should be a uniformly distributed load of 9.3 N/mm in the longitudinal direction. In the transverse direction, the design lane load should be uniformly distributed over a 3000-mm width. The force effects from the design lane load shall not be subject to a dynamic load allowance [12].

As specified in [12], for top slabs of box culverts of all spans, and in all other cases the lane load shall be considered when the span exceeds 4600 mm.

### 3.4.5 Structural Analysis

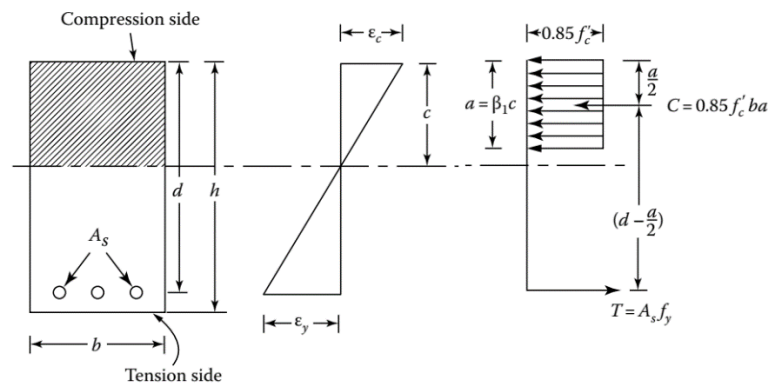
There are several methods for modeling culverts [4]. According to [12], box culverts shall be analyzed as two-dimensional frames. The foundation model shall be based on Winkler's unidirectional subgrade model and assumed that the structure was founded on it. Only compression-loaded elastic constraints shall be used to connect the bottom slab with the soil, which may cause certain parts of the structure to become detached from the surrounding soil. This approach enables the analysis to take into account the vertical displacement of the soil [17].

### 3.4.6 Structural Design

#### 3.4.6.1 Flexure

##### 3.4.6.1.1 Design Moment for Box Culverts

To determine the nominal flexural resistance of a beam, it is assumed that there is an equivalent rectangular stress distribution, as illustrated in **Figure 3-9**. The relationship between concrete stress and strain can be considered satisfied through the use of an equivalent rectangular concrete compressive stress block with a magnitude of  $0.85 f_c'$  over a zone that is bound parallel to the neutral axis and located at a distance of  $a = \beta_1 c$  from the extreme compression fiber [42].



**Figure 3-9 Equivalent rectangular stress distribution used for design [42]**

As specified in [39, 12, 42], The nominal and factored flexural resistances can be taken as:

$$M_r = \phi M_n \quad (16)$$

$$M_n = A_s f_s \left( d_s - \frac{a}{2} \right) \quad (17)$$

Where:

$M_r$  = factored flexural resistance

$M_n$  = nominal flexural resistance

$\phi$  = resistance factor specified in [12] Article 5.5.4.2

$A_s$  = area of non-prestressed tension reinforcement

$f_s$  = stress in the mild steel tension reinforcement at nominal flexural resistance

$d_s$  = distance from extreme compression fiber to the centroid of non-prestressed tensile reinforcement

$a$  = depth of the equivalent stress block

$\beta_1$  = stress block factor

- For concrete strength that does not exceed 28 MPa, the value of 0.5 must be used.
- When the concrete strength exceeds 28 MPa, the value must be reduced by 0.05 for each additional 7 MPa of strength.

In the case where inclined monolithic haunches at a 45-degree angle are specified, the negative reinforcement required for walls and slabs can be proportioned by considering the flexural moment at the intersection of the haunch and the uniform depth of the structural element [12].

#### 3.4.6.1.2 Minimum Reinforcement

Adequate amounts of tensile reinforcement must be provided to produce a factored flexural resistance that is not less than the lesser [12]:

- The factored flexural resistance, should be equal to or greater than the minimum value, which is the smaller of 1.2 times the cracking moment, calculated using an elastic stress distribution and the modulus of rupture, of the concrete [12].

$$M_{cr} = f_r \frac{I_g}{y_t} \quad (18)$$

Where:

$M_{cr}$  = cracking moment

$f_r$  = Modulus of rupture

$I_g$  = gross moment of inertia

$y_t$  = centroid of the section

- 1.33 times the factored moment required by the applicable strength load combination

#### 3.4.6.1.3 Maximum reinforcement

As stated in [12], to ensure that the section is under tension control, it is necessary to check the strain in the reinforcement. If a resistance factor of 0.9 is to be applied for flexure, then the reinforcement strain should be no less than 0.005 [4].

The condition can be considered satisfied if:

$$c/d \leq 0.42 \quad (19)$$

Where:

$$c = \frac{A_s f_y}{0.85 f_c \beta_1 b} \quad (20)$$

#### 3.4.6.1.4 Control of Cracking

In order to achieve an evenly distributed primary reinforcement, it is necessary to verify the crack control equations, which are influenced by various factors including the tensile stress in the steel reinforcement at the service limit state, the concrete cover, and the geometric relationship between the crack width at the tension face versus the crack width at the reinforcement level. Since culverts are exposed to water, the exposure factor of 0.75 for class 2 is shall be used [4].

The reinforcement spacing shall satisfy:

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c \quad (21)$$

In which:

$$\beta_s = 1 + \frac{d_c}{0.7(h - d_c)} \quad (22)$$

#### 3.4.6.1.5 Shrinkage and Temperature Reinforcement

In order to account for the effects of shrinkage and temperature stresses, it is important to provide reinforcement near the surfaces of concrete exposed to daily temperature changes. The amount of shrinkage and temperature reinforcement shall not be less than the value determined as [12]:

$$A_s \geq \frac{0.75bh}{2(b+h)f_y} \quad (23)$$

$$0.233 \leq A_s \leq 1.27 \quad (24)$$

Where:

- $A_s$  = area of reinforcement in each direction and each face ( $\text{mm}^2/\text{mm}$ )
- $b$  = least width of component section (mm)
- $h$  = least thickness of component section (mm)
- $f_y$  = specified yield strength of reinforcing (MPa)

#### 3.4.6.2 Shear

The factored shear resistance can be determined as [12]:

$$V_r = \phi V_n \quad (25)$$

Where:

- $V_r$  = factored shear resistance
- $V_n$  = Nominal shear resistance
- $\phi$  = resistance factor

For culverts without haunches, the critical shear section location shall be taken at a distance of the critical shear depth from the slab or wall face. Moreover, for culverts with haunches, the critical shear section shall be taken at a distance of critical shear depth from the end of the haunch [39].

##### 3.4.6.2.1 Depth of Fill Greater than or Equal to 600 mm

For box culvert slabs with 600 mm or more of fill, the shear resistance of concrete for one-way action shall be determined by [39, 12, 4]:

$$V_c = \min \left\{ \left( 0.178\sqrt{f'_c} + 32 \frac{A_s}{bd_e} \frac{V_u d_e}{M_u} \right) bd_e, 0.332\sqrt{f'_c} bd_e \right\} \quad (26)$$

As specified in [12], the quantity  $V_u d_e / M_u$  shall not exceed 1.0.

For single-cell box culverts where the slab is monolithically casted with the walls the shear resistance shall not be less than the value determined using [12]:

$$V_c = 0.25 \sqrt{f_c'} b d_e \quad (27)$$

Shear resistance for walls of box culverts shall be determined as [12]:

$$V_c = 0.083 \beta \sqrt{f_c'} b_v d_v \quad (28)$$

Where:

- $V_c$  = nominal shear resistance of concrete (N)
- $A_s$  = area of reinforcing steel in the design width (mm)
- $b$  = Design width (mm)
- $d_e$  = Effective depth from extreme compression fiber to the centroid of the tensile force in the tensile reinforcement (mm)
- $d_v$  = Effective shear depth (mm)
- $V_u$  = Shear from factored loads (N)
- $M_u$  = Moment from factored loads (N-mm)
- $\beta$  = The ability of diagonally cracked section to transmit tension

#### 3.4.6.2.2 Depth of Fill Less than 600 mm

For box culverts with less than 600 mm fill, the shear resistance of concrete for slabs and walls shall be determined as [12]:

$$V_c = 0.083 \beta \sqrt{f_c'} b_v d_v \quad (29)$$

#### 3.4.6.3 Axial Thrust

The factored compressive resistance of the walls of the box culvert shall be taken as [12, 43]:

$$P_r = \phi P_n \quad (30)$$

In which:

$$\phi P_n = 0.85(0.85 f_c' A_g) \quad (31)$$

Where:

$P_r$  = factored axial resistance (N)

$P_n$  = nominal axial resistance (N)

$f'_c$  = specified compressive strength of concrete at 28 days (MPa)

$A_g$  = gross area of section ( $\text{mm}^2$ )

$\phi$  = Resistance factor

In the design of box culverts, for the strength limit state, it is not recommended to consider the benefit of axial thrust [4].

## **CHAPTER 4      COMPUTER PROGRAM FOR STRUCTURAL ANALYSIS, DESIGN, AND DETAILING OF BOX CULVERTS**

### **4.1 General**

The main focus of this chapter is the development of a computer program designed to aid in the structural analysis, design, and detailing of box culverts. This chapter offers a comprehensive view of the software development process starting from the initial concept and leading up to the final implementation. The chapter provides a thorough explanation of the program's functions and highlights its key features and abilities.

### **4.2 Software Development Process**

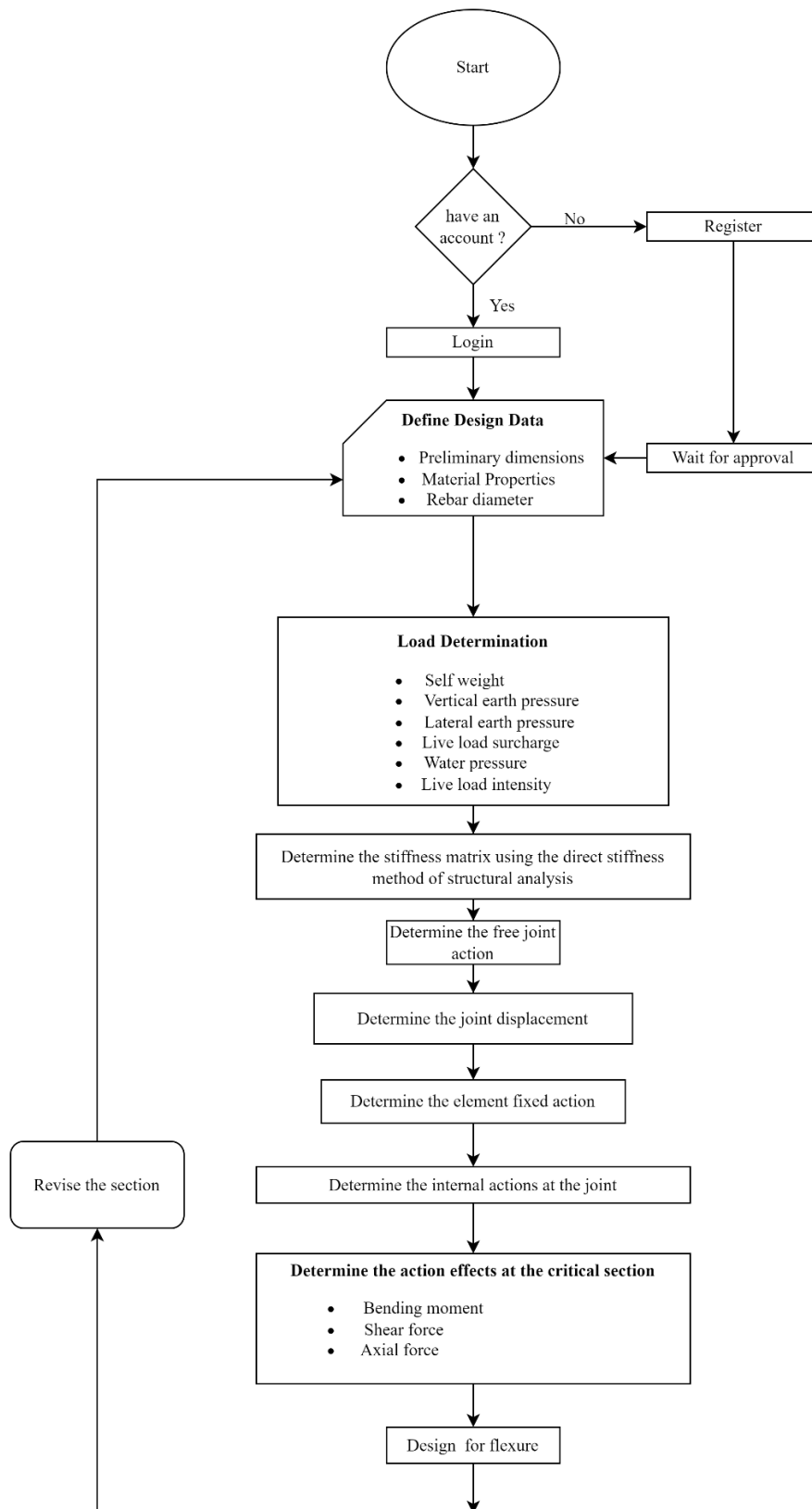
The following steps are followed in the software development process for the structural analysis, design, and detailing of box culverts.

- Requirement gathering is the first step in the software development process. This process aims to identify the software requirements that will be necessary to address the specific gap or problem that this research is aiming to solve.
- Once the requirements for the software have been identified, a blueprint outlining the architecture of the software is created. In order to ensure optimal backend development, four modules are designed for the load determination, structural analysis, structural design, and structural detailing of the box culvert. The Flask Python Web Framework is used as a web application for the backend, consisting of three modules these are routes for defining page URLs, models for adding user data to the database, and forms for creating user forms. The software is also equipped with a Frontend to enhance user experience, featuring HTML files for the Home Page, Login Page, User Data Definition Page, Analysis and Design Page, and Detailing Page.
- Once the design is finalized, the software development process has begun. In the case of developing box culvert structural analysis and design software, Python programming language is used to write the necessary code. The python code is

responsible to perform structural analysis, design and detailing of the culvert and provide accurate results. Furthermore, the software requires a user interface that enables users to interact with it easily. This is achieved through frontend development using HTML (Hyper Text Markup Language) code. The HTML code is responsible for structuring the software's layout and the placement of its different components. To add styling to the webpage and ensure that it is aesthetically pleasing, CSS (Cascading Styling Sheets) is employed. Finally, functionality for buttons and other interactive elements of the software is added using the JavaScript programming language. This allows the users to interact with the software.

- The software is thoroughly tested to ensure that it performs as expected. Conventional structural analysis tools along with manual testing are carried out to verify the output of the software is correct, producing accurate results for various input data sets.

### 4.3 Flow Chart for the Structural Analysis, Design, and Detailing of Box Culverts Using the Software



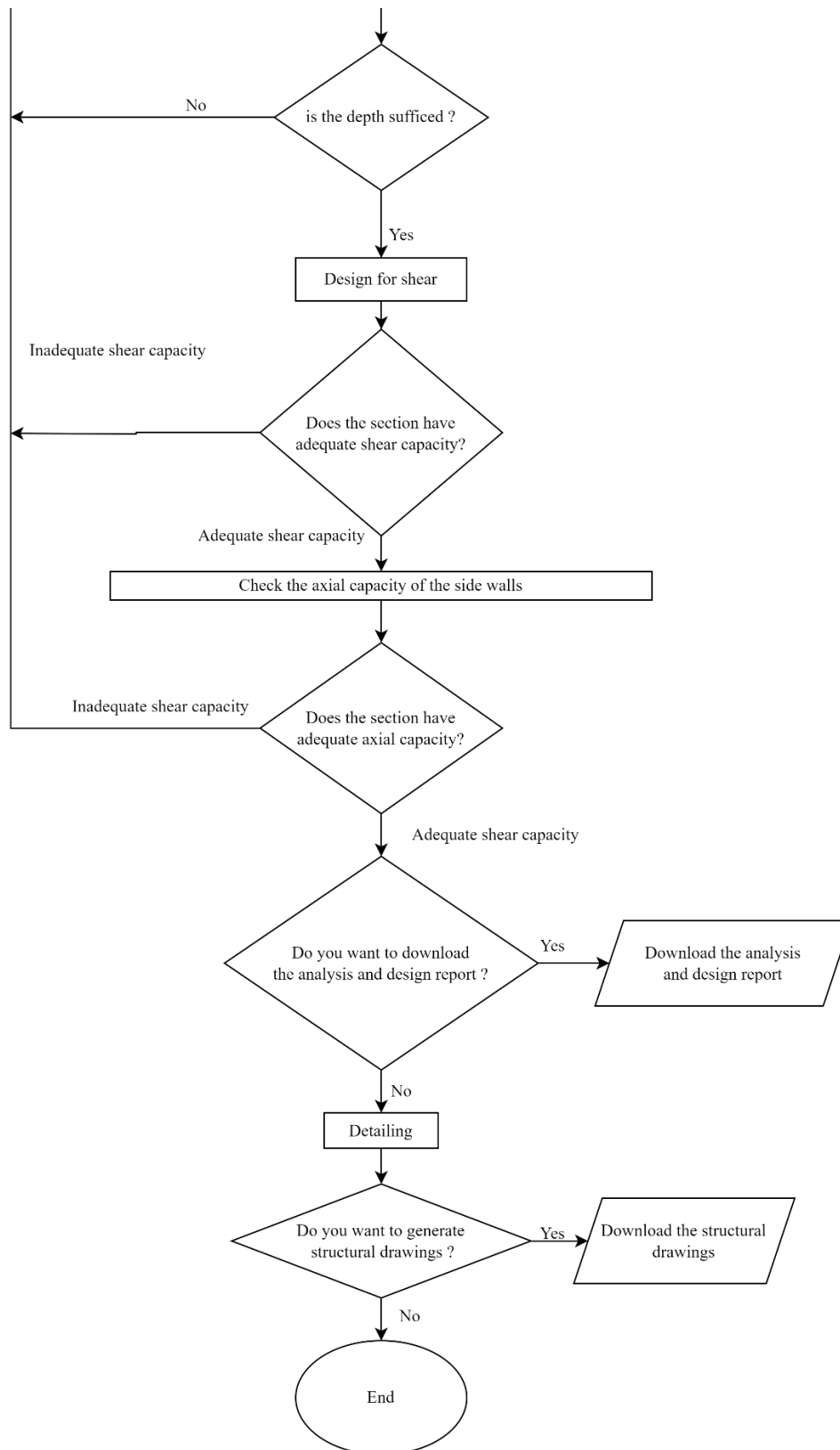


Figure 4-1 Flow chart for the analysis, design, and detailing of box culverts using the software

#### 4.4 Graphical User Interface (GUI)

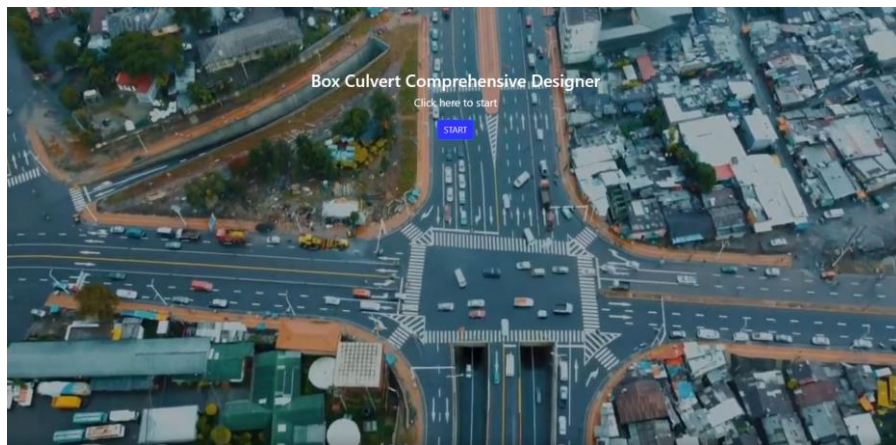
To create a visually appealing and functional user interface for the software, the frontend is designed using three core web technologies: HTML, CSS, and JavaScript.

HTML (Hyper Text Markup Language) is used to structure the frontend, laying the groundwork for the software's design and layout. HTML is responsible for defining the numerous frontend components such as text, pictures, buttons, and forms. It enables the design of a clean and ordered layout that helps users navigate through the software.

CSS (Cascading Style Sheets) is used to style HTML components, giving the frontend a consistent appearance. CSS specifies the visual attributes of HTML components including font, color, size, and spacing. It is in charge of the frontend's overall look, ensuring a consistent and pleasant user experience. JavaScript is used to provide functionality to the frontend making it interactive and responsive.

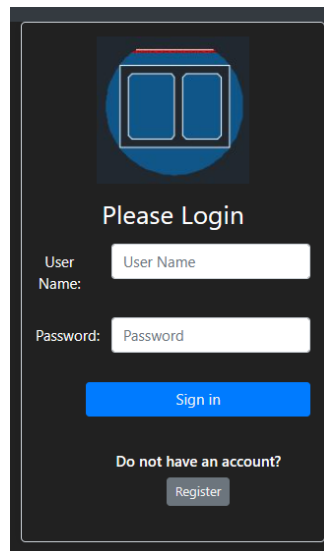
By combining HTML, CSS, and JavaScript the software is made visually pleasing, responsive, and easy to use.

The homepage is the first page displayed to the user when they open the software, shown in **Figure 4-2**. This page serves as the user's gateway point, providing an overview of the software's features and capabilities. The homepage provides a smooth and user-friendly experience with its intuitive structure and design, allowing users to swiftly and easily access the software's numerous capabilities.



**Figure 4-2 Homepage of the software**

Once the user clicks on the "START" button, the software will automatically redirect the user to the login page. If user does not have an existing account, the page will provide the option to register, as shown in **Figure 4-3**. This process ensures that users can easily create an account and access the software's features. By allowing users to register seamlessly, the software promotes a convenient user experience.



Please Login

User Name

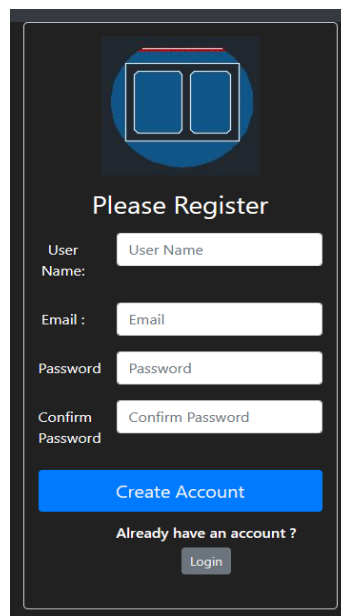
Password

Sign in

Do not have an account?

Register

**Figure 4-3** Login page of the software



Please Register

User Name

Email

Password

Confirm Password

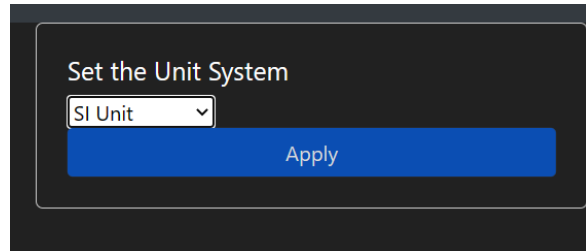
Create Account

Already have an account ?

Login

**Figure 4-4** Register page of the software

Once the user enters their password, the software will provide an option to select either the SI unit system or Imperial unit system for designing box culverts. This means that users can choose their preferred unit system for the design process.



**Figure 4-5 Unit system selection for design**

After the user selects an appropriate unit system, the software will redirect them to the page where the design data is defined. This page consists of three sections, which are the preliminary dimensions definition, material properties definition, and diameter of reinforcement bar definition for the design. The pages for these design definitions are shown in **Figure 4-6**, **Figure 4-7**, and **Figure 4-8** respectively.

- Preliminary Dimensions Definition Page: This page allows the user to input the preliminary dimensions for the culvert design, including the opening size and fill height.

Dimensions	Material	Rebar for design
Number of cells:		2
Clear height :		3 m
Clear span for interior cell		0 m
Clear span for exterior cell		3 m
Top slab thickness:		0.3 m
Bottom slab thickness:		0.325 m
Side wall thickness:		0.25 m
Haunch vertical dimension:		0 m
Haunch horizontal dimension:		0 m
Fill height:		4 m
Concrete cover:		0.05 m

Next

Figure 4-6 Preliminary dimensions definition page

- Material properties definition page

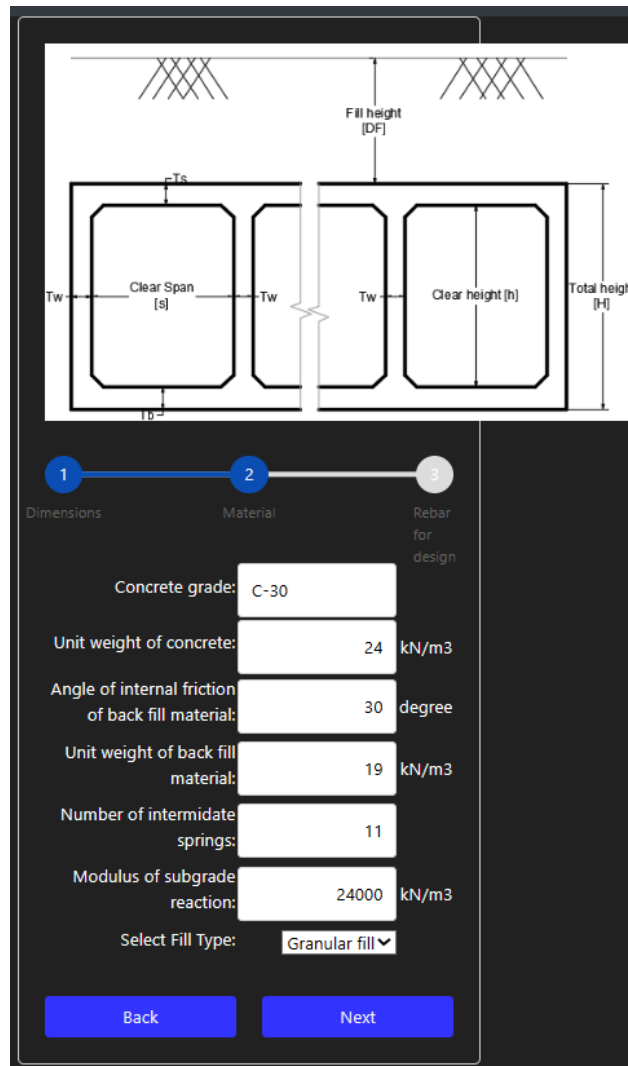
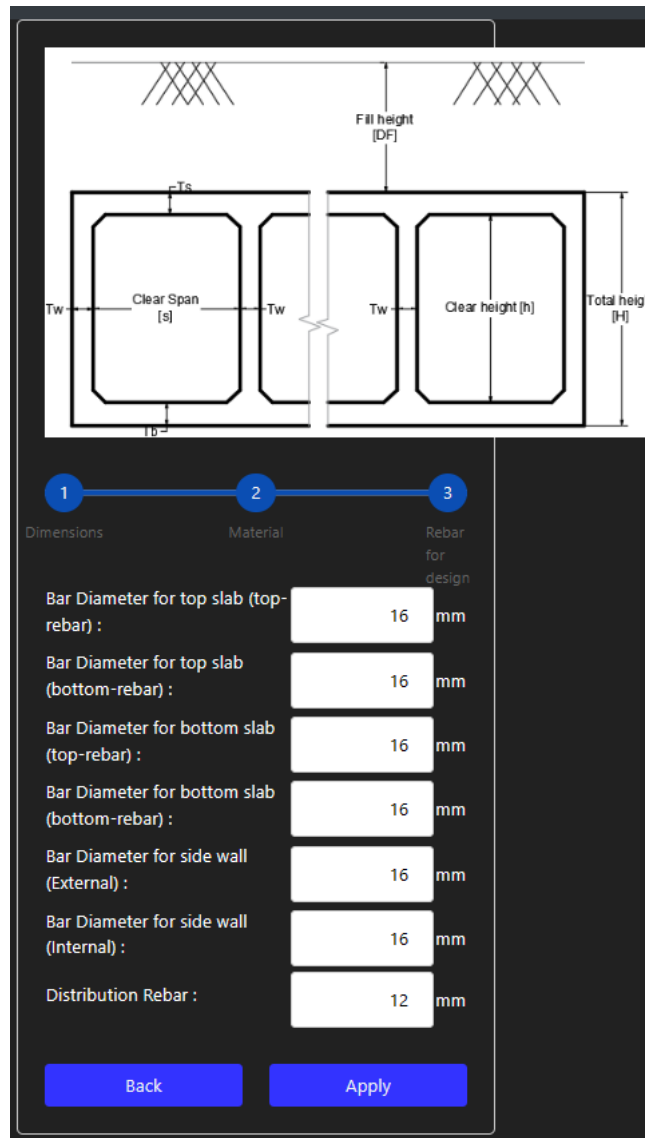


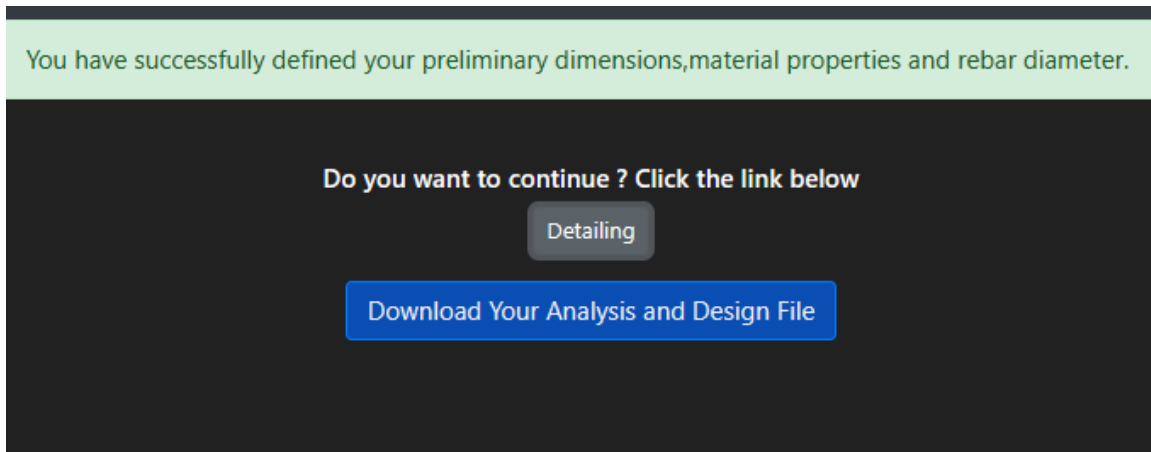
Figure 4-7 Material Properties definition page

- Diameter of reinforcement bar definition page



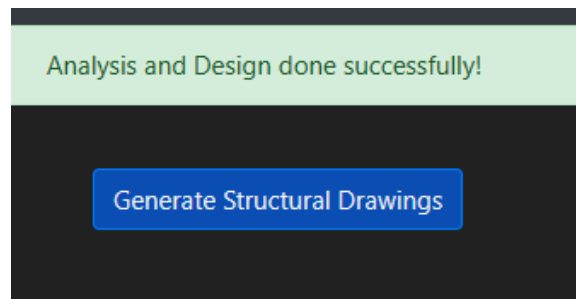
**Figure 4-8 Diameter of reinforcement bar definition page**

Upon specifying the preliminary dimensions, material properties, and rebar diameter by clicking the "Apply" button, the software performs the analysis and design phase for the box culvert. After performing the structural analysis and design, the software directs the user to the analysis and design page and prompts them to confirm their intention to download the analysis and design report. If the user chooses to acquire the report, they can do so by selecting the "Download your analysis and design file" button, as illustrated in **Figure 4-9**.



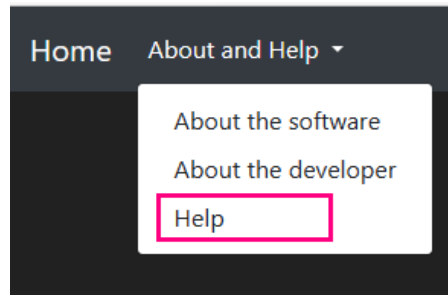
**Figure 4-9 Analysis and Design report generation page**

To proceed with the structural detailing the user can click the "Detailing" button, which will redirect them to the detailing page. On this page, they will be able to generate structural drawings of the box culvert by clicking the "Generate Structural Drawings" button, as depicted **Figure 4-10**.



**Figure 4-10 Structural detailing page**

Users who need assistance or additional information regarding the software's development, recommendations, or user guide can access the help feature in two ways. The first involves pressing the "F1" key on their keyboard, which will immediately redirect them to the help section. Alternatively, the user can click the help button featured in the figure below, which will direct them to the same help section. The help section offers users precise information, which can contribute to obtaining accurate results while using the software. Additionally, the help section simplifies the software's use by offering a comprehensive and user-friendly guide. Consequently, users can acquire support and guidance with ease and convenience while using the software.



**Figure 4-11** Help section of the software

#### **4.5 Structural Analysis of an Existing Box Culvert**

In cases where the design documents are available the software allows for a review of the adequacy of a box culvert by defining its dimension, material properties, and rebar diameter. The software is capable of analyzing and designing the box culvert based on this input data. Upon completion of the design the reinforcement can be checked for adequacy by comparing the amount obtained to the amount provided during the design. In addition to this, the adequacy of the section can be assessed.

## **CHAPTER 5      DESIGN CHARTS**

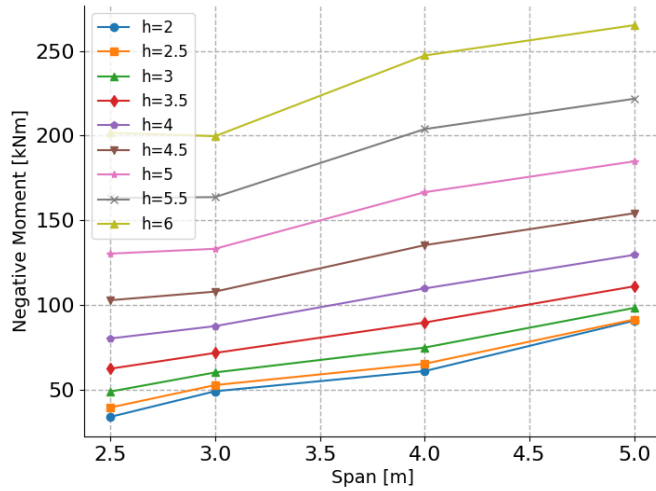
### **5.1    General Overview**

This research focuses on the development of a software program for the analysis, design, and detailing of box culverts. However, in cases where the software is not accessible, design charts have been developed to assist designers with their work.

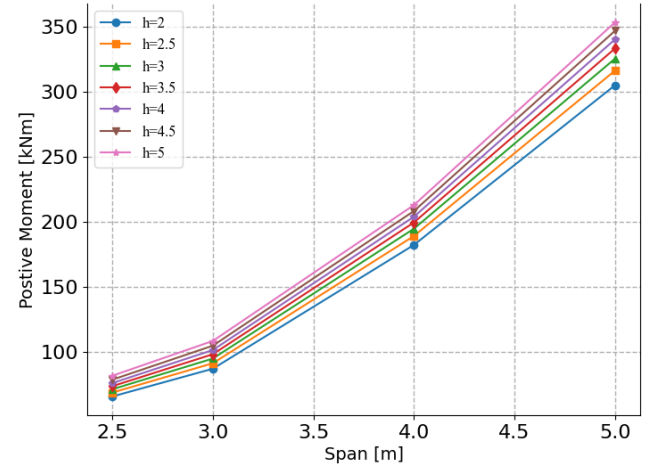
### **5.2    Design Charts Preparation for Box Culverts**

The design chart was developed to demonstrate the relationship between bending moment and span at different locations in box culverts. The culvert height is varied while keeping the fill height fixed to showcase how different heights can affect the bending moment distribution. The design chart is a valuable tool for designers to evaluate the bending moment at various locations in the box culvert under different culvert heights. This can help designers optimize the design.

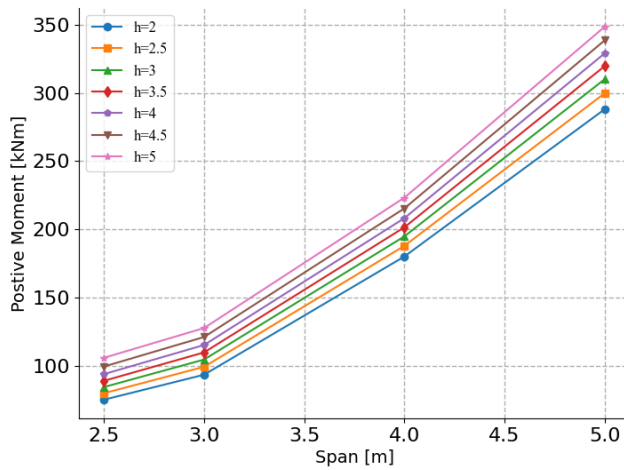
This chapter presents sample design charts for single-cell and double-cell box culverts, with opening sizes ranging from 2.5 m to 5.0 m and opening heights varying from 2.0 m to 5.0 m, while fixing the fill height and modulus of subgrade reaction at 3 m and 34,800 kN/m<sup>3</sup>, respectively. However, Python code has been developed to generate design charts for any opening size and fill height.



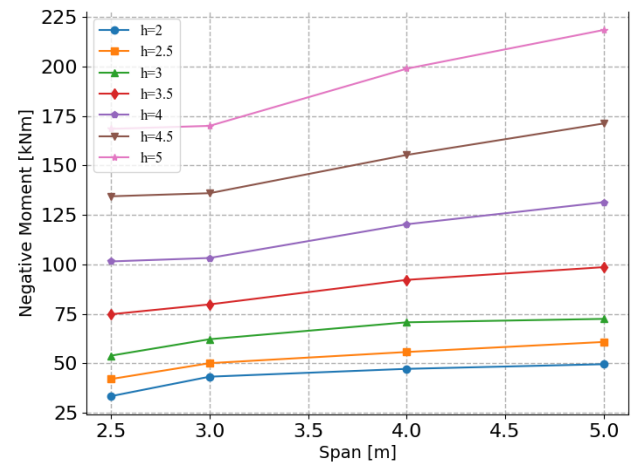
**Figure 5-1** Distribution of bending moment in the left end of the top slab of single cell box culvert



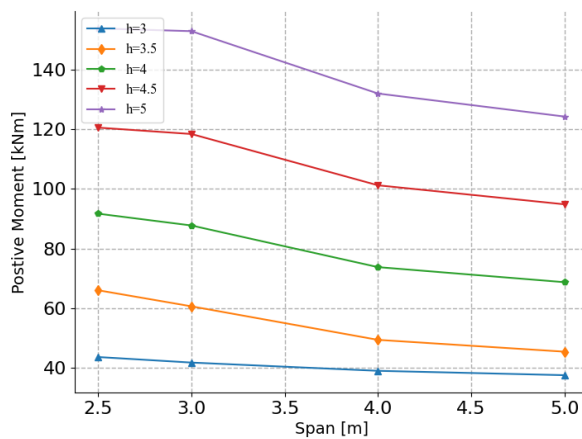
**Figure 5-3** Distribution of bending moment in the mid span of the top slab of single cell box culvert



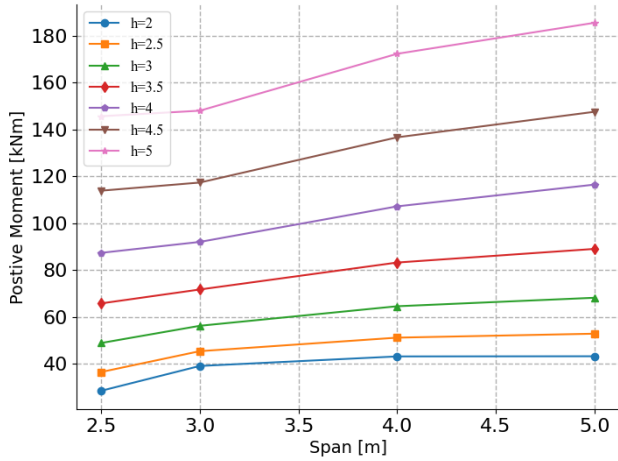
**Figure 5-2** Distribution of bending moment in the mid span of the bottom slab of single cell box culvert



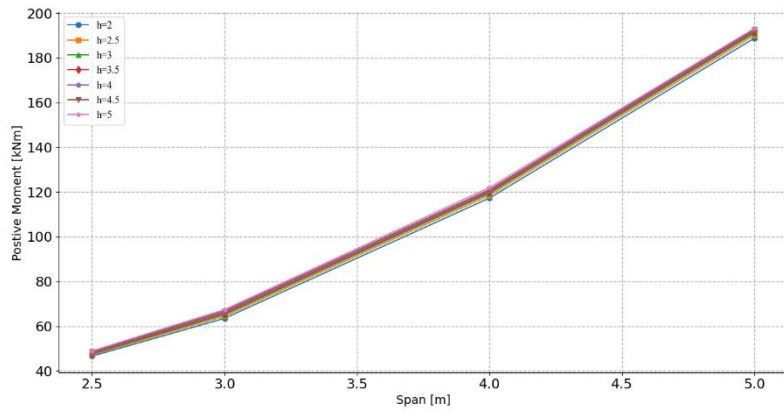
**Figure 5-4** Distribution of bending moment in the left end of the bottom slab of single cell box culvert



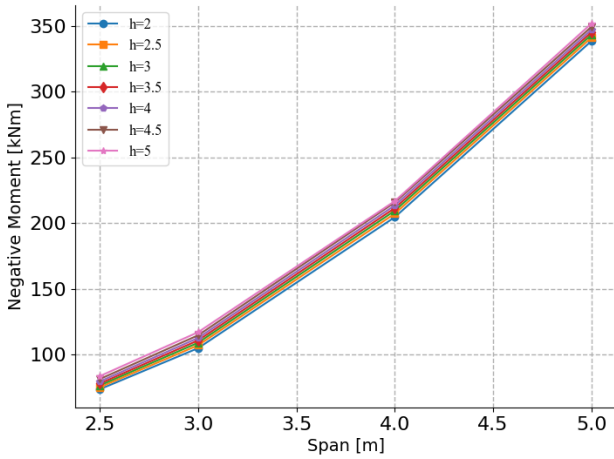
**Figure 5-5** Distribution of bending moment in the mid height of the side wall of single cell box culvert



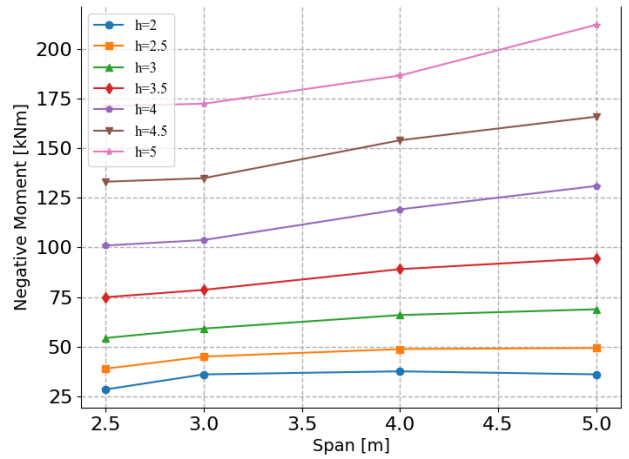
**Figure 5-6** Distribution of bending moment in the left end of the top slab of double cell box culvert



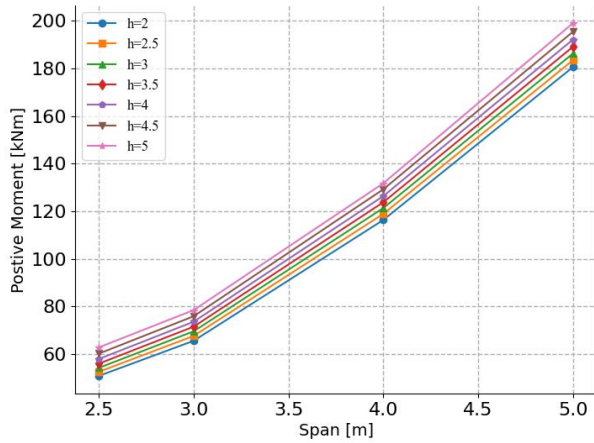
**Figure 5-8** Distribution of bending moment in the mid span of the top slab of double cell box culvert



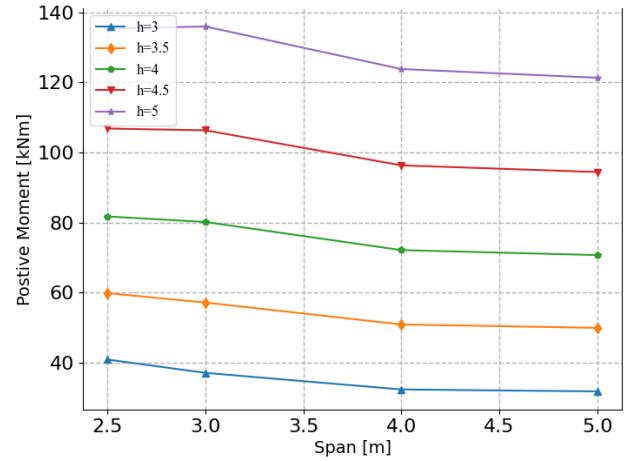
**Figure 5-7** Distribution of bending moment in the right end of the top slab of double cell box culvert



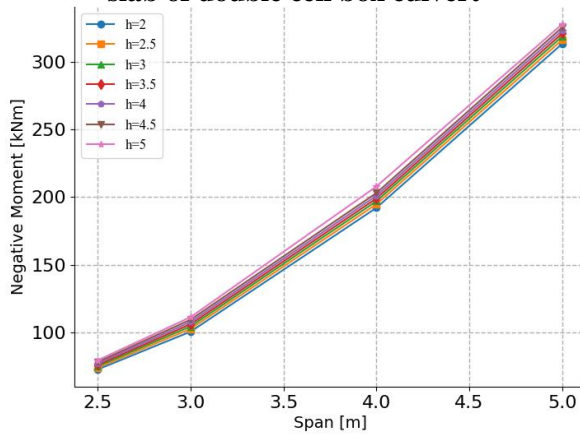
**Figure 5-9** Distribution of bending moment in the left end of the bottom slab of double cell box culvert



**Figure 5-10** Distribution of bending moment in the mid span of the bottom slab of double cell box culvert



**Figure 5-12** Distribution of bending moment in the mid height of the side wall of double cell box culvert



**Figure 5-11** Distribution of bending moment in the right end of the top slab of double cell box culvert

## CHAPTER 6 DESIGN EXAMPLES AND VALIDATION

### 6.1 General Overview

This chapter involves design examples using the software addressed in this research and conventional structural analysis tools. CSI SAP2000v24.0.0 is used as a conventional structural analysis tool in order to determine the action effects.

### 6.2 Design Example using the Comprehensive Tools for The Structural Analysis, Design, And Detailing of Buried Box Culverts

#### 6.2.1 Design of Single Cell Box Culvert

##### 6.2.1.1 Design Method

- Load and Resistance Factor Design (LRFD)

##### 6.2.1.2 Design Manual

- AASHTO LRFD Bridge Design Specifications, Fifth Edition, 2010
- ERA Bridge Design Manual 2013

##### 6.2.1.3 Design Data's

###### 6.2.1.3.1 Material properties

###### 6.2.1.3.1.1 Concrete Properties

Concrete grade	=	C-30	
Compressive strength, $f_c'$	=	24	MPa
Unit weight	=	24	kN/m <sup>3</sup>
Modulus of elasticity, $E_c$	=	25.49	GPa

###### 6.2.1.3.1.2 Reinforcement Bar

Grade 420 steel: For rebars diam. 20mm and above

$f_y$	=	420	MPa
$E_s$	=	200	GPa

Grade 300 steel: For rebars less than diam. 20

$$f_y = 300 \text{ MPa}$$

$$E_s = 200 \text{ GPa}$$

#### 6.2.1.3.1.3 Soil Properties

Angle of Internal Friction of Backfill Material, $\phi'$	= 30°
Unit Weight of Saturated Earth Fill	= 19 kN/m <sup>3</sup>
Modules of Subgrade Reaction of Foundation Material	= 34800 kN/m <sup>2</sup>

#### 6.2.1.3.2 Preliminary culvert dimension

Number of Cells	= 1	
Clear Height, h	= 3	m
Clear Span, s	= 3	m
Thickness of Side Walls, $t_w$	= 0.25	m
Thickness of Top Slab, $t_s$	= 0.25	m
Thickness of Bottom Slab, $t_{bs}$	= 0.275	m
Haunch Vertical Dimension, $t_v$	= 0	m
Haunch Horizontal Dimension, $t_h$	= 0	m
Fill height, H	= 3.0	m
Concrete Cover	= 50	m
Fill Type	= Granular Fill	
Number of Intermediate Springs	= 25	

#### 6.2.1.4 Load Determination

##### 6.2.1.4.1 Self-Weight

The self-weight of the culvert is determined using the equation given in Section 3.4.4.1.

- The self-weight of the top slab of the culvert is:

$$DC_{top} = t_s * \gamma_c = 0.25 \text{ m} \times 24 \text{ kN} / \text{m}^3 = 6 \text{ kN/m}$$

- The self-weight of the side wall is:

$$DC_{side\_wall} = h * t_w * \gamma_c = 3.0 \text{ m} \times 0.25 \text{ m} \times 24 \text{ kN} / \text{m}^3 = 19.58 \text{ kN}$$

- The self-weight of the bottom slab of the culvert is:

$$DC_{bottom} = t_b * \gamma_c = 0.275 \text{ m} \times 24 \text{ kN} / \text{m}^3 = 6.60 \text{ kN/m}$$

#### 6.2.1.4.2 Earth Pressure

##### a. Vertical Earth Pressure

The vertical earth pressure produced by the weight of the fill above the culvert can be determined using the equation given in Section 3.4.4.2.

A conservative assumption of embankment installation should be made, with consideration given to the interaction factor which is dependent on the fill height and outside width of the culvert:

$$F_e = 1 + 0.2 \frac{H}{B_c} \leq 1.15$$

$$F_e = 1 + 0.2 \times \frac{3.0 \text{ m}}{3.50 \text{ m}} = 1.17 \quad \text{Take } F_e = 1.15$$

The vertical earth pressure on the top slab of the box culvert is:

$$EV = F_e \gamma_s H = 1.15 \times 19 \text{ kN} / \text{m}^3 \times 3.0 \text{ m} = 65.55 \text{ kN} / \text{m}$$

##### b. Horizontal Earth Pressure

The method used to determine the lateral earth pressure on the culvert is based on the equivalent fluid method as described in Section 3.4.4.3. For at-rest conditions, a maximum equivalent fluid unit weight of  $9.60 \text{ kN/m}^3$  and a minimum equivalent fluid unit weight of  $4.80 \text{ kN/m}^3$  are used.

The lateral earth pressure at the top of the culvert is:

$$EH_{max} = \gamma_{eq} H = 9.6 \text{ kN} / \text{m}^3 \times 4.0 \text{ m} = 28.80 \text{ kN} / \text{m}$$

$$EH_{min} = \gamma_{eq} H = 4.8 \text{ kN} / \text{m}^3 \times 4.0 \text{ m} = 14.40 \text{ kN} / \text{m}$$

The lateral earth pressure at the bottom of the culvert is:

$$EH_{\max} = \gamma_{eq} x (H + t_s + h + t_{bs}) = 9.6 \text{ kN} / \text{m}^3 \times (3.0 \text{ m} + 0.25 \text{ m} + 3.0 \text{ m} + 0.275 \text{ m}) = 62.64 \text{ kN} / \text{m}$$

$$EH_{\min} = \gamma_{eq} x (H + t_s + h + t_{bs}) = 4.8 \text{ kN} / \text{m}^3 \times (3.0 \text{ m} + 0.25 \text{ m} + 3.0 \text{ m} + 0.275 \text{ m}) = 31.32 \text{ kN} / \text{m}$$

c. Live Load Surcharge

To determine the live load surcharge at the top of the culvert an equivalent fill height is obtained from **Table 3-2** which depends on the height measured from the top surface of the top slab to the pavement or fill.

The fill height at the top of the culvert is:

$$H_{\text{at\_top\_of\_culvert}} = H = 3.0 \text{ m}$$

From **Table 3-2**, the equivalent height for a fill depth of 3.0 m is:

$$h_{eq} = 0.90 \text{ m}$$

The lateral live load surcharge at the top of the culvert is:

$$k_o = 1 - \sin \phi = 1 - \sin 30 = 0.50$$

$$L_{s\_top} = k_o \gamma_s h_{eq} = 0.5 \times 19 \text{ kN} / \text{m}^3 \times 0.90 \text{ m} = 8.55 \text{ kN} / \text{m}$$

To determine the live load surcharge at the bottom of the culvert an equivalent fill height is obtained from **Table 3-2** which depends on the height measured from the bottom surface of the bottom slab to the pavement or fill.

$$H_{\text{at\_bottom\_of\_the\_culvert}} = H + t_s + h + t_{bs} = 3.0 \text{ m} + 0.25 \text{ m} + 3.0 \text{ m} + 0.275 \text{ m} = 6.53 \text{ m}$$

Since the height from the bottom surface of the bottom slab which is 6.53m the equivalent height of fill from **Table 3-2** shall be taken as:

$$h_{eq} = 0.60 \text{ m}$$

The lateral live load surcharge at the bottom of the culvert is:

$$k_o = 1 - \sin \phi = 1 - \sin 30 = 0.50$$

$$L_{s\_top} = k_o \gamma_s h_{eq} = 0.5 \times 19 \text{ kN} / \text{m}^3 \times 0.60 \text{ m} = 5.70 \text{ kN} / \text{m}$$

#### 6.2.1.4.3 Water Load

The lateral pressure exerted by water inside the culvert is:

$$WA_{top} = 0.00 \text{ kN/m}$$

$$WA_{bottom} = \gamma_w h = 9.81 \text{ kN/m}^3 \times 3.0\text{m} = 29.43 \text{ kN/m}$$

#### 6.2.1.4.4 Live Load

The live load effect shall be considered since the fill height equals the span of the culvert.

##### 6.2.1.4.4.1 Dynamic Load Allowance

The dynamic load allowance shall be determined using the equation given in Section 3.4.4.6.2.

$$IM = 33 \times (1.0 - 4.1 \times 10^{-4} D_E) \geq 0.00 \%$$

$$D_E = H = 3000 \text{ mm}$$

$$IM = 33 \times (1.0 - 4.1 \times 10^{-4} \times 3000 \text{ mm}) = -7.59\% \quad \text{Therefore, take } IM = 0.00 \%$$

##### 6.2.1.4.4.2 Live Load Distribution

Since the fill height is greater than 600 mm, the live load shall be distributed according to the provisions described in Section 3.4.4.6.5.

##### 6.2.1.4.4.2.1 Tandem Load Distribution

Dynamic load allowance	=	0.00	%
Wheel load	=	55.0	kN
Tire length	=	250	mm
Tire width	=	510	mm
Fill type	=	Granular fill	
Live load distribution factor	=	1.15	
Multiple presence factor	=	1.2	

- The distribution width and length for a fill height of 3.0m is:

$$W = \text{Tire width} + 1.15H = 510 \text{ mm} + 1.15 \times 3000 \text{ mm} = 3960 \text{ mm}$$

$$L = \text{Tire length} + 1.15H = 250 \text{ mm} + 1.15 \times 3000 \text{ mm} = 3700 \text{ mm}$$

Where:

W = width of distributed load (perpendicular to span)

L = length of distributed load (parallel to span)

- Check for overlap of load projection:

$$W = 3960 \text{ mm}$$

$$L = 3700 \text{ mm}$$

Since the width and length of the load projection are greater than 1800 mm and 1200 mm, respectively, there is an overlap in the load projection.

- Compute the overlapped area where the live load is distributed:

$$\text{Overlapped width} = W + 1800 \text{ mm} = 3960 \text{ mm} + 1800 \text{ mm} = 5760 \text{ mm}$$

$$\text{Overlapped length} = L + 1200 \text{ mm} = 3700 \text{ mm} + 1200 \text{ mm} = 4900 \text{ mm}$$

$$\text{Total contact area} = \text{Overlapped width} \times \text{Overlapped length}$$

$$\text{Total contact area} = 5760 \text{ mm} \times 4900 \text{ mm} = 2.83 \times 10^7 \text{ mm}^2$$

- The live load intensity is produced by a configuration of tandem truck:

$$LL + IM = \frac{4 \times P \times MPF \times (1 + IM)}{\text{Total contact area}} = \frac{4 \times 55 \text{ kN} \times 1.2 \times (1 + 0)}{28.22 \text{ m}^2} = 9.35 \text{ kN / m}^2$$

#### 6.2.1.4.4.2.2 Truck Load Distribution

Dynamic load allowance	=	0.00	%
Wheel load	=	72.5	kN
Tire length	=	250	mm
Tire width	=	510	mm
Fill type	=	Granular fill	
Live load distribution factor	=	1.15	
Multiple presence factor	=	1.2	

- The distribution width and length for a fill height of 3.0m is:

$$W = \text{Tire width} + 1.15 \times H = 510 \text{ mm} + 1.15 \times 3000 \text{ mm} = 3960 \text{ mm}$$

$$L = \text{Tire length} + 1.15 \times H = 250 \text{ mm} + 1.15 \times 3000 \text{ mm} = 3700 \text{ mm}$$

Where:

W = width of distributed load (perpendicular to span)

L = length of distributed load (parallel to span)

Check for overlap of load projection:

$$W = 3960 \text{ mm} > 1800 \text{ mm}$$

$$L = 3700 \text{ mm} < 4300 \text{ mm}$$

Since the width of the load projection is greater than 1800 mm and the length is less than 4300 mm, an overlap occurs in the transverse direction but not in the longitudinal direction.

Compute the overlapped area where the live load is distributed:

$$\text{Overlapped width} = W + 1800 \text{ mm} = 3960 \text{ mm} + 1800 \text{ mm} = 5760 \text{ mm}$$

$$\text{Overlapped length} = L = 3700 \text{ mm} = 3700 \text{ mm}$$

$$\text{Total contact area} = \text{Overlapped width} \times \text{Overlapped length}$$

$$\text{Total contact area} = 5760 \text{ mm} \times 3700 \text{ mm} = 2.13 \times 10^7 \text{ mm}^2$$

The live load intensity is produced by a configuration of tandem truck:

$$LL + IM = \frac{2 \times P \times MPF \times (1 + IM)}{\text{Total contact area}} = \frac{2 \times 72.5 \text{ kN} \times 1.2 \times (1 + 0)}{21.31 \text{ m}^2} = 8.16 \text{ kN / m}^2$$

#### 6.2.1.4.4.3 Lane Load

Lane load should be ignored since the span of the culvert is less than 4600 mm.

#### 6.2.1.5 Structural Analysis

The bending moment and shear force shown in **Table 6-1** and **Table 6-2** are taken at the critical sections defined in Section 3.4.6.1.1 and 3.4.6.2 respectively.

**Table 6-1 Bending Moment at Critical Sections**

Design Location	Dc (kNm)	EV (kNm)	LL+IM (kNm)	Ls (kNm)	EH <sub>max</sub> (kNm)	EH <sub>min</sub> (kNm)	WA (kNm)
Side Wall Top	-1.93	-30.10	-4.29	-1.62	-10.85	-5.42	3.67
Side Wall Center	-4.48	-25.40	-3.62	6.00	38.35	19.18	-12.29
Side Wall Bottom	-7.04	-20.70	-2.95	-2.56	-16.18	-8.09	5.13
Top Slab Left End	-0.54	-17.69	-2.52	-3.07	-18.48	-9.24	5.53
Top Slab Center	6.21	56.06	8.00	-3.07	-18.49	-9.25	5.53
Top Slab Right End	-0.54	-17.69	-2.52	-3.07	-18.50	-9.25	5.53
Bottom Slab Left End	-3.78	-7.73	-1.10	-3.89	-26.34	-13.17	9.00
Bottom Slab Center	13.96	55.52	7.92	-3.14	-21.27	-10.64	7.28
Bottom Slab Right End	3.78	7.73	1.10	3.89	26.34	13.17	-9.00

**Table 6-2 Shear Force at the Critical Sections**

Design Locations	Dc (kN)	EV (kN)	LL+IM (kN)	Ls (kN)	EH <sub>max</sub> (kN)	EH <sub>min</sub> (kN)	WA (kN)
Sidewall Top	-1.70	3.12	0.45	9.64	53.48	26.74	-14.49
Moment at the Critical Shear Location (kNm)	-2.24	-29.52	-4.21	0.16	-1.15	-0.56	1.14
Top Slab Right End	-7.94	-86.70	-12.37	0.00	0.01	0.00	5.53
Moment at the Critical Shear Location (kNm)	0.96	-1.29	-0.18	-3.07	-18.48	-9.24	0.00
Bottom Slab Left End	25.20	89.47	12.77	0.37	2.52	1.26	0.98
Moment at the Critical Shear Location (kNm)	0.65	3.47	0.49	3.89	26.35	13.17	-9.00

**Table 6-3 Bending Moment for Strength I and Service I Load Combinations**

Design Location	Strength Ia (kNm)	Strength Ib (kNm)	Strength Ic (kNm)	Service Ia (kNm)	Service Ib (kNm)	Service Ic (kNm)
Sidewall Top	69.21	51.99	48.38	48.78	38.07	44.49
Sidewall Center	18.24	42.47	36.82	10.84	26.62	14.47
Sidewall Bottom	69.64	44.02	53.31	49.43	33.65	46.48
Top Slab Left End	60.8	31.63	48.76	42.3	24.47	39.78
Top Slab Center	66.7	95.88	26.98	48.71	66.55	40.71
Top Slab Right End	60.83	31.63	48.8	42.32	24.47	39.8
Bottom Slab Left End	61.34	19.49	54.84	42.84	16.78	41.74
Bottom Slab Center	71.45	105.26	29.38	52.99	74.04	45.06
Bottom Slab Right End	61.35	19.5	54.85	42.84	16.78	41.74

**Table 6-4 Shear Force for Strength I and Service I Load Combinations**

Design Locations	Strength Ia (kN)	Strength Ib (kN)	Strength Ic (kN)	Service Ia (kN)	Service Ib (kN)	Service Ic (kN)
Sidewall top	93.56	11.59	91.70	65.59	14.42	64.96
Moment at critical shear Location (kNm)	50.47	49.69	29.92	36.04	35.22	31.83
Top slab left end	149.91	144.40	89.07	107.01	101.49	94.63
Moment at critical shear Location (kNm)	32.44	8.80	31.92	22.06	9.75	21.88
Bottom slab left end	180.20	178.04	111.46	130.34	129.69	117.57
Moment at critical shear Location (kNm)	61.36	19.50	54.85	42.85	16.79	41.74

### 6.2.1.6 Structural Design

#### 6.2.1.6.1 Top Slab

##### 6.2.1.6.1.1 Design for Flexure

The flexural design of the box culvert structural elements shall be designed according to the provisions defined in Section 3.4.6.1.

#### a. Bottom Reinforcement (Mid Span)

Design Data:

$$M_u = 95.88 \text{ kNm}$$

$$f_y = 300 \text{ MPa}$$

$$f_c' = 24 \text{ MPa}$$

$$d = 192 \text{ mm}$$

$$b = 1000 \text{ mm}$$

$$\text{bar diameter} = 16 \text{ mm}$$

$$\text{Concrete cover} = 50 \text{ mm}$$

$$\phi = 0.9$$

Assume  $a = 29.46 \text{ mm}$

$$A_s = \frac{M_u}{\phi f_y (d - \frac{a}{2})} = \frac{95.88 \times 10^6 \text{ Nmm}}{0.9 \times 300 \text{ N/mm}^2 (192 \text{ mm} - \frac{29.46 \text{ mm}}{2})} = 2003.24 \text{ mm}^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{2003.24 \text{ mm}^2}{0.85 \times 24 \text{ N/mm}^2 \times 1000 \text{ mm}} = 29.46 \text{ mm} \quad \text{Assumption is correct.}$$

$$s = \frac{b a_s}{A_s} = \frac{1000 \text{ mm} \times 201 \text{ mm}^2}{2003.24 \text{ mm}^2} = 100 \text{ mm}$$

- Check for minimum reinforcement

For cast-in-place box culverts the amount of flexural reinforcement shall satisfy the requirements described in Section 3.4.6.1.2.

$$f_r = 0.63 \sqrt{f_c'} = 0.63 \sqrt{24} = 3.09 \text{ MPa}$$

$$I_{cr} = \frac{b h^3}{12} = \frac{1000 \text{ mm} \times (250 \text{ mm})^3}{12} = 1.30 \times 10^9 \text{ mm}^4$$

$$M_{cr} = f_r \frac{I_{cr}}{y_t} = 3.09 \text{ N/mm}^2 \left( \frac{1.30 \times 10^9 \text{ mm}^4}{125 \text{ mm}} \right) = 32.15 \text{ kNm/m}$$

$$1.2M_{cr} = 38.58 \text{ kNm/m}$$

$$1.33M_u = 80.86 \text{ kNm/m}$$

$$M_u \geq \min \begin{cases} 1.2M_{cr} \\ 1.33M_u \end{cases} = \min \begin{cases} 38.58 \text{ kNm/m} \\ 127.52 \text{ kNm/m} \end{cases} = 38.58 \text{ kNm/m}$$

The requirement for minimum flexural reinforcement is satisfied.

- Check for maximum reinforcement

To satisfy the requirement stated in Section 3.4.6.1.3, it is necessary to ensure the ratio of the depth of the neutral axis to the effective depth of the section is less than or equal to 0.42.

$$c = \frac{a}{\beta} = \frac{29.46 \text{ mm}}{0.85} = 34.66 \text{ mm}$$

$$c/d = \frac{34.66 \text{ mm}}{192 \text{ mm}} = 0.18 < 0.42 \quad \text{The section is under reinforced.}$$

- Check crack control

It is required to check that the crack is controlled by the distribution of the flexural reinforcements in order to ensure that the main reinforcements are well distributed. The equations used for determining the minimum spacing of flexural reinforcement bars to satisfy crack control requirements depend on the tensile stress in steel reinforcement at the service limit state, the concrete cover, and the geometric relationship between the crack width at the tension face and the crack width at the reinforcement level. Since culverts are water-exposed substructures, an exposure factor of 0.75 should be used [4].

$$M_{service} = 66.55 \text{ kNm}$$

$$d_c = \text{concrete cover} + \frac{\text{bar diameter}}{2} = 58 \text{ mm}$$

$$\gamma_e = 0.75 \text{ (exposure factor for class 2 exposure class)}$$

$$\text{strain factor } \beta_s = 1 + \frac{0.7d_c}{(h + d_c)} = 1 + \frac{0.7 \times 58 \text{ mm}}{(250 \text{ mm} + 58 \text{ mm})} = 1.21$$

$$\rho = \frac{A_s}{A_c} = \frac{2003.24 \text{ mm}^2}{(250 \text{ mm} \times 250 \text{ mm})} = 0.008$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n = \sqrt{(0.008 \times 8)^2 + 2 \times 0.008 \times 8} - 0.008 \times 8 = 0.30$$

$$j = 1 - k/3 = 1 - 0.30/3 = 0.9$$

$$f_{ss} = \frac{M_{service}}{A_s j d} = \frac{66.55 \times 10^6 \text{ Nmm}}{2003.24 \text{ mm}^2 \times 0.9 \times 192 \text{ mm}} = 192.21 \text{ MPa}$$

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c = \frac{123000 \times 0.75}{1.21 \times 192.21 \text{ N/mm}^2} - 2 \times 58 \text{ mm} = 280 \text{ mm}$$

There is no problem of cracking.

Provide  $\phi$  16 c / c 100 (Bottom reinforcement)

b. Top Reinforcement (Left End or Right End)

Design Data:

$$M_u = 60.80 \text{ kNm}$$

$$f_y = 300 \text{ MPa}$$

$$f_c' = 24 \text{ MPa}$$

$$d = 192 \text{ mm}$$

$$b = 100 \text{ mm}$$

$$\text{bar diameter} = 16 \text{ mm}$$

$$\text{Concrete cover} = 50 \text{ mm}$$

$$\phi = 0.9$$

Assume  $a = 18.10 \text{ mm}$

$$A_s = \frac{M_u}{\phi f_y (d - \frac{a}{2})} = \frac{60.80 \times 10^6 \text{ Nmm}}{0.9 \times 300 \text{ N/mm}^2 (192 \text{ mm} - \frac{18.10 \text{ mm}}{2})} = 1230.82 \text{ mm}^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{1230.82 \text{ mm}^2}{0.85 \times 24 \text{ N/mm}^2 \times 1000 \text{ mm}} = 18.10 \text{ mm} \quad \text{Assumption is correct.}$$

$$s = \frac{b a_s}{A_s} = \frac{1000 \text{ mm} \times 201 \text{ mm}^2}{1230.82 \text{ mm}^2} = 160 \text{ mm}$$

- Check for minimum reinforcement:

$$f_r = 0.63 \sqrt{f_c'} = 0.63 \sqrt{24} = 3.09 \text{ MPa}$$

$$I_{cr} = \frac{b h^3}{12} = \frac{100 \text{ mm} \times (250 \text{ mm})^3}{12} = 1.30 \times 10^9 \text{ mm}^4$$

$$M_{cr} = f_r \frac{I_{cr}}{y_t} = 3.09 \text{ N/mm}^2 \left( \frac{1.30 \times 10^9 \text{ mm}^4}{125 \text{ mm}} \right) = 32.15 \text{ kNm/m}$$

$$1.2M_{cr} = 38.58 \text{ kNm/m}$$

$$1.33M_u = 80.86 \text{ kNm/m}$$

$$M_u \geq \min \begin{cases} 1.2M_{cr} \\ 1.33M_u \end{cases} = \min \begin{cases} 38.58 \text{ kNm/m} \\ 80.86 \text{ kNm/m} \end{cases} = 38.58 \text{ kNm/m}$$

The requirement for minimum flexural reinforcement is satisfied.

- Check for maximum reinforcement

$$c = \frac{a}{\beta} = \frac{18.10 \text{ mm}}{0.85} = 21.29 \text{ mm}$$

$$c/d = \frac{21.29 \text{ mm}}{192 \text{ mm}} = 0.11 < 0.42$$

The section is under reinforced.

- Check crack control:

$$M_{service} = 42.30 \text{ kNm}$$

$$d_c = \text{concrete cover} + \text{bar diameter} / 2 = 58 \text{ mm}$$

$$\gamma_e = 0.75 \text{ (exposure factor for class 2 exposure class)}$$

$$\text{strain factor } \beta_s = 1 + \frac{0.7d_c}{(h + d_c)} = 1 + \frac{0.7 \times 58 \text{ mm}}{(250 \text{ mm} + 58 \text{ mm})} = 1.21$$

$$\rho = \frac{A_s}{A_c} = \frac{1230.82 \text{ mm}^2}{(250 \text{ mm} \times 250 \text{ mm})} = 0.005$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n = \sqrt{(0.005 \times 8)^2 + 2 \times 0.005 \times 8} - 0.005 \times 8 = 0.24$$

$$j = 1 - k/3 = 1 - 0.24/3 = 0.92$$

$$f_{ss} = \frac{M_{service}}{A_s j d} = \frac{42.30 \times 10^6 \text{ Nmm}}{1230.82 \text{ mm}^2 \times 0.92 \times 192 \text{ mm}} = 194.84 \text{ MPa}$$

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c = \frac{123000 \times 0.75}{1.21 \times 194.86 \text{ N/mm}^2} - 2 \times 58 \text{ mm} = 270 \text{ mm}$$

There is no problem of cracking.

Provide  $\phi 16$  c/c 160 (Top reinforcement)

#### 6.2.1.6.1.2 Design for Shear

The shear resistance of the top slab of the culvert for fill height greater than or equal to 600 mm is given by:

$$V_c = \min \left\{ \left( 0.178\sqrt{f_c'} + 32 \frac{A_s}{bd_e} \frac{V_u d_e}{M_u} \right) bd_e, 0.332\sqrt{f_c'} bd_e \right.$$

Where the quantity  $\frac{V_u d_e}{M_u}$  shall be less than or equal to unity:

$$\frac{V_u d_e}{M_u} = \frac{149.91 \text{ kN} \times 0.192 \text{ m}}{32.44 \text{ kNm}} = 0.88 < 1.00 \quad \text{Use } \frac{V_u d_e}{M_u} = 0.88$$

$$V_c = \min \left\{ \left( 0.178\sqrt{24 \text{ N/mm}^2} + 32 \frac{1230.8 \text{ mm}^2}{1000 \text{ mm} \times 192 \text{ mm}} \times 0.88 \right) 1000 \text{ mm} \times 192 \text{ mm} = 206.81 \text{ kN} \right.$$

$$\left. 0.332\sqrt{24 \text{ N/mm}^2} \times 1000 \text{ mm} \times 192 \text{ mm} = 312.28 \text{ mm} \right.$$

$$V_c = 206.81 \text{ kN}$$

The nominal shear resistance of concrete for single-cell box culverts shall not be less than:

$$V_c = 0.25\sqrt{f_c'} bd_e = 0.25\sqrt{24 \text{ N/mm}^2} \times 1000 \text{ mm} \times 192 \text{ mm} = 235.15 \text{ kN}$$

Therefore, take nominal shear resistance of 235.15 kN.

The factored shear resistance of the top slab can be taken as:

$$V_r = \phi V_c = 0.85 \times 235.15 \text{ kN} = 199.9 \text{ kN}$$

From **Table 6-4** Shear Force for Strength I and Service I Load Combinations **Table 6-4**, the shear force at the critical section is determined to be 149.91kN.

$$V_r = 199.9 \text{ kN} > V_u = 149.91 \text{ kN}$$

As the factored shear resistance of the top slab of the box culvert is greater than the shear force at the critical section, it can be concluded that the section has adequate shear capacity.

### 6.2.1.6.2 Bottom Slab

#### 6.2.1.6.2.1 Design for Flexure

##### c. Top Reinforcement (Mid Span)

Design Data:

$$M_u = 105.26 \text{ kNm}$$

$$f_y = 300 \text{ MPa}$$

$$f_c' = 24 \text{ MPa}$$

$$d = 217 \text{ mm}$$

$$b = 1000 \text{ mm}$$

$$\text{bar diameter} = 16 \text{ mm}$$

$$\text{Concrete cover} = 50 \text{ mm}$$

$$\phi = 0.9$$

Assume  $a = 28.26 \text{ mm}$

$$A_s = \frac{M_u}{\phi f_y \left(d - \frac{a}{2}\right)} = \frac{105.26 \times 10^6 \text{ Nmm}}{0.9 \times 300 \text{ N/mm}^2 \left(217 \text{ mm} - \frac{28.26 \text{ mm}}{2}\right)} = 1921.60 \text{ mm}^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{1921.60 \text{ mm}^2}{0.85 \times 24 \text{ N/mm}^2 \times 1000 \text{ mm}} = 28.26 \text{ mm} \quad \text{Assumption is correct.}$$

$$s = \frac{b a_s}{A_s} = \frac{1000 \text{ mm} \times 201 \text{ mm}^2}{1921.60 \text{ mm}^2} = 100 \text{ mm}$$

- Check for minimum reinforcement

$$f_r = 0.63 \sqrt{f_c'} = 0.63 \sqrt{24} = 3.09 \text{ MPa}$$

$$I_{cr} = \frac{b h^3}{12} = \frac{100 \text{ mm} \times (275 \text{ mm})^3}{12} = 1.733 \times 10^9 \text{ mm}^4$$

$$M_{cr} = f_r \frac{I_{cr}}{y_t} = 3.09 \text{ N/mm}^2 \left( \frac{1.733 \times 10^9 \text{ mm}^4}{137.5 \text{ mm}} \right) = 38.90 \text{ kNm/m}$$

$$1.2 M_{cr} = 46.68 \text{ kNm/m}$$

$$1.33 M_u = 139.99 \text{ kNm/m}$$

$$M_u \geq \min \begin{cases} 1.2 M_{cr} \\ 1.33 M_u \end{cases} = \min \begin{cases} 46.68 \text{ kNm/m} \\ 139.99 \text{ kNm/m} \end{cases} = 46.68 \text{ kNm/m}$$

The requirement for minimum flexural reinforcement is satisfied.

- Check for maximum reinforcement

$$c = \frac{a}{\beta} = \frac{28.26 \text{ mm}}{0.85} = 33.25 \text{ mm}$$

$$c/d = \frac{33.25 \text{ mm}}{217 \text{ mm}} = 0.15 < 0.42$$

The section is under reinforced.

- Check crack control

$$M_{\text{service}} = 74.04 \text{ kNm}$$

$$d_c = \text{concrete cover} + \text{bar diameter} / 2 = 58 \text{ mm}$$

$$\gamma_e = 0.75 \text{ (exposure factor for class 2 exposure class)}$$

$$\text{strain factor } \beta_s = 1 + \frac{0.7d_c}{(h + d_c)} = 1 + \frac{0.7 \times 58 \text{ mm}}{(275 \text{ mm} + 58 \text{ mm})} = 1.18$$

$$\rho = \frac{A_s}{A_c} = \frac{1921.60 \text{ mm}^2}{(275 \text{ mm} \times 275 \text{ mm})} = 0.007$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n = \sqrt{(0.007 \times 8)^2 + 2 \times 0.007 \times 8} - 0.007 \times 8 = 0.28$$

$$j = 1 - k/3 = 1 - 0.28/3 = 0.9$$

$$f_{ss} = \frac{M_{\text{service}}}{A_s j d} = \frac{74.04 \times 10^6 \text{ Nmm}}{1921.60 \text{ mm}^2 \times 0.9 \times 217 \text{ mm}} = 1996.06 \text{ MPa}$$

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c = \frac{123000 \times 0.75}{1.18 \times 1996.06 \text{ N/mm}^2} - 2 \times 58 \text{ mm} = 280 \text{ mm}$$

There is no problem of cracking.

Provide  $\phi$  16 c / c 100 (Top reinforcement)

- d. Top Reinforcement (Left End or Right End)

Design Data:

$$M_u = 61.34 \text{ kNm}$$

$$f_y = 300 \text{ MPa}$$

$$f'_c = 24 \text{ MPa}$$

$$d = 217 \text{ mm}$$

$$b = 100 \text{ mm}$$

$$\text{bar diameter} = 16 \text{ mm}$$

$$\text{Concrete cover} = 50 \text{ mm}$$

$$\phi = 0.9$$

Assume  $a = 15.98 \text{ mm}$

$$A_s = \frac{M_u}{\phi f_y \left(d - \frac{a}{2}\right)} = \frac{61.34 \times 10^6 \text{ Nmm}}{0.9 \times 300 \text{ N/mm}^2 \left(217 \text{ mm} - \frac{15.98 \text{ mm}}{2}\right)} = 1087.06 \text{ mm}^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{1087.06 \text{ mm}^2}{0.85 \times 24 \text{ N/mm}^2 \times 1000 \text{ mm}} = 15.98 \text{ mm} \quad \text{Assumption is correct.}$$

$$s = \frac{b a_s}{A_s} = \frac{1000 \text{ mm} \times 201 \text{ mm}^2}{1087.06 \text{ mm}^2} = 180 \text{ mm}$$

- Check for minimum reinforcement:

$$f_r = 0.63 \sqrt{f_c'} = 0.63 \sqrt{24} = 3.09 \text{ MPa}$$

$$I_{cr} = \frac{b h^3}{12} = \frac{100 \text{ mm} \times (275 \text{ mm})^3}{12} = 1.73 \times 10^9 \text{ mm}^4$$

$$M_{cr} = f_r \frac{I_{cr}}{y_t} = 3.09 \text{ N/mm}^2 \left( \frac{1.73 \times 10^9 \text{ mm}^4}{137.5 \text{ mm}} \right) = 38.90 \text{ kNm/m}$$

$$1.2 M_{cr} = 38.90 \text{ kNm/m}$$

$$1.33 M_u = 81.59 \text{ kNm/m}$$

$$M_u \geq \min \begin{cases} 1.2 M_{cr} \\ 1.33 M_u \end{cases} = \min \begin{cases} 38.90 \text{ kNm/m} \\ 81.59 \text{ kNm/m} \end{cases} = 38.90 \text{ kNm/m}$$

The requirement for minimum flexural reinforcement is satisfied.

- Check for maximum reinforcement

$$c = \frac{a}{\beta} = \frac{15.98 \text{ mm}}{0.85} = 18.81 \text{ mm}$$

$$c/d = \frac{18.81 \text{ mm}}{217 \text{ mm}} = 0.09 < 0.42$$

The section is under reinforced.

- Check crack control:

$$M_{service} = 42.84 \text{ kNm}$$

$$d_c = \text{concrete cover} + \frac{\text{bar diameter}}{2} = 58 \text{ mm}$$

$$\gamma_e = 0.75 \text{ (exposure factor for class 2 exposure class)}$$

$$\text{strain factor } \beta_s = 1 + \frac{0.7 d_c}{(h + d_c)} = 1 + \frac{0.7 \times 58 \text{ mm}}{(275 \text{ mm} + 58 \text{ mm})} = 1.18$$

$$\rho = \frac{A_s}{A_c} = \frac{1087.06 \text{ mm}^2}{(275 \text{ mm} \times 275 \text{ mm})} = 0.004$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n = \sqrt{(0.004 \times 8)^2 + 2 \times 0.004 \times 8} - 0.004 \times 8 = 0.22$$

$$j = 1 - k/3 = 1 - 0.22/3 = 0.92$$

$$f_{ss} = \frac{M_{service}}{A_s j d} = \frac{42.84 \times 10^6 \text{ Nmm}}{1087.05 \text{ mm}^2 \times 0.92 \times 217 \text{ mm}} = 196.10 \text{ MPa}$$

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c = \frac{123000 \times 0.75}{1.21 \times 196.10 \text{ N/mm}^2} - 2 \times 58 \text{ mm} = 280 \text{ mm}$$

There is no problem of cracking.

Provide  $\phi$  16 c / c 180 (Bottom reinforcement)

#### 6.2.1.6.2.1.1 Design for Shear

The shear resistance of the bottom slab of the culvert for fill height greater than or equal to 600 mm is given by:

$$V_c = \min \left\{ \begin{array}{l} \left( 0.178 \sqrt{f_c'} + 32 \frac{A_s}{bd_e} \frac{V_u d_e}{M_u} \right) bd_e \\ 0.332 \sqrt{f_c'} bd_e \end{array} \right.$$

Where the quantity  $\frac{V_u d_e}{M_u}$  shall be less than or equal to unity:

$$\frac{V_u d_e}{M_u} = \frac{180.20 \text{ kN} \times 0.217 \text{ m}}{61.36 \text{ kNm}} = 0.64 < 1.00 \quad \text{Use } \frac{V_u d_e}{M_u} = 0.64$$

$$V_c = \min \left\{ \begin{array}{l} \left( 0.178 \sqrt{24 \text{ N/mm}^2} + 32 \frac{1087.10 \text{ mm}^2}{1000 \text{ mm} \times 217 \text{ mm}} \times 0.64 \right) 1000 \text{ mm} \times 217 \text{ mm} = 211.50 \text{ kN} \\ 0.332 \sqrt{24 \text{ N/mm}^2} \times 1000 \text{ mm} \times 217 \text{ mm} = 352.94 \text{ mm} \end{array} \right.$$

$$V_c = 211.50 \text{ kN}$$

The nominal shear resistance of concrete for single-cell box culverts shall not be less than:

$$V_c = 0.25 \sqrt{f_c'} bd_e = 0.25 \sqrt{24 \text{ N/mm}^2} \times 1000 \text{ mm} \times 217 \text{ mm} = 265.77 \text{ kN}$$

Therefore, take nominal shear resistance of 265.77 kN.

The factored shear resistance of the top slab can be taken as:

$$V_r = \phi V_c = 0.85 \times 265.77 \text{ kN} = 225.9 \text{ kN}$$

From **Table 6-4**, the shear force at the critical section is determined to be 180.20 kN.

$$V_r = 225.90 \text{ kN} > V_u = 180.20 \text{ kN}$$

As the factored shear resistance of the bottom slab of the box culvert is greater than the shear force at the critical section, it can be concluded that the section has adequate shear capacity.

### 6.2.1.6.3 Side Wall

#### 6.2.1.6.3.1 Design for Flexure

##### e. External Reinforcement

Design Data:

$$M_u = 69.64 \text{ kNm}$$

$$f_y = 300 \text{ MPa}$$

$$f'_c = 24 \text{ MPa}$$

$$d = 192 \text{ mm}$$

$$b = 1000 \text{ mm}$$

$$\text{bar diameter} = 16 \text{ mm}$$

$$\text{Concrete cover} = 50 \text{ mm}$$

$$\phi = 0.9$$

Assume  $a = 20.89 \text{ mm}$

$$A_s = \frac{M_u}{\phi f_y \left(d - \frac{a}{2}\right)} = \frac{69.64 \times 10^6 \text{ Nmm}}{0.9 \times 300 \text{ N/mm}^2 \left(192 \text{ mm} - \frac{20.89 \text{ mm}}{2}\right)} = 1921.60 \text{ mm}^2$$

$$a = \frac{A_s f_y}{0.85 f'_c b} = \frac{1420.64 \text{ mm}^2}{0.85 \times 24 \text{ N/mm}^2 \times 1000 \text{ mm}} = 20.89 \text{ mm} \quad \text{Assumption is correct.}$$

$$s = \frac{ba_s}{A_s} = \frac{1000 \text{ mm} \times 201 \text{ mm}^2}{1420.64 \text{ mm}^2} = 140 \text{ mm}$$

- Check for minimum reinforcement

$$f_r = 0.63 \sqrt{f'_c} = 0.63 \sqrt{24} = 3.09 \text{ MPa}$$

$$I_{cr} = \frac{bh^3}{12} = \frac{100 \text{ mm} \times (250 \text{ mm})^3}{12} = 1.30 \times 10^9 \text{ mm}^4$$

$$M_{cr} = f_r \frac{I_{cr}}{y_t} = 3.09 \text{ N/mm}^2 \left( \frac{1.30 \times 10^9 \text{ mm}^4}{137.5 \text{ mm}} \right) = 32.15 \text{ kNm/m}$$

$$1.2M_{cr} = 38.58 \text{ kNm/m}$$

$$1.33M_u = 92.62 \text{ kNm/m}$$

$$M_u \geq \min \begin{cases} 1.2M_{cr} \\ 1.33M_u \end{cases} = \min \begin{cases} 38.58 \text{ kNm/m} \\ 92.62 \text{ kNm/m} \end{cases} = 38.58 \text{ kNm/m}$$

The requirement for minimum flexural reinforcement is satisfied.

- Check for maximum reinforcement

$$c = \frac{a}{\beta} = \frac{20.89 \text{ mm}}{0.85} = 24.58 \text{ mm}$$

$$c/d = \frac{24.58 \text{ mm}}{192 \text{ mm}} = 0.13 < 0.42$$

The section is under reinforced.

- Check crack control

$$M_{service} = 49.43 \text{ kNm}$$

$$d_c = \text{concrete cover} + \text{bar diameter} / 2 = 58 \text{ mm}$$

$$\gamma_e = 0.75 \text{ (exposure factor for class 2 exposure class)}$$

$$\text{strain factor } , \beta_s = 1 + \frac{0.7d_c}{(h + d_c)} = 1 + \frac{0.7 \times 58 \text{ mm}}{(250 \text{ mm} + 58 \text{ mm})} = 1.21$$

$$\rho = \frac{A_s}{A_c} = \frac{1420.64 \text{ mm}^2}{(250 \text{ mm} \times 250 \text{ mm})} = 0.0057$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n = \sqrt{(0.0057 \times 8)^2 + 2 \times 0.0057 \times 8} - 0.0057 \times 8 = 0.26$$

$$j = 1 - k/3 = 1 - 0.26/3 = 0.91$$

$$f_{ss} = \frac{M_{service}}{A_s j d} = \frac{49.43 \times 10^6 \text{ Nmm}}{1420.64 \text{ mm}^2 \times 0.9 \times 192 \text{ mm}} = 198.38 \text{ MPa}$$

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c = \frac{123000 \times 0.75}{1.18 \times 198.38 \text{ N/mm}^2} - 2 \times 58 \text{ mm} = 270 \text{ mm}$$

There is no problem of cracking.

Provide  $\phi$  16 c/c 140 (External reinforcement)

f. Internal Reinforcement (Mid height)

Design Data:

$$M_u = 42.47 \text{ kNm}$$

$$f_y = 300 \text{ MPa}$$

$$f_c' = 24 \text{ MPa}$$

$$d = 192 \text{ mm}$$

$$b = 100 \text{ mm}$$

$$\text{bar diameter} = 16 \text{ mm}$$

$$\text{Concrete cover} = 50 \text{ mm}$$

$$\phi = 0.9$$

Assume

$$a = 12.45 \text{ mm}$$

$$A_s = \frac{M_u}{\phi f_y (d - \frac{a}{2})} = \frac{42.47 \times 10^6 \text{ Nmm}}{0.9 \times 300 \text{ N/mm}^2 (217 \text{ mm} - \frac{12.45 \text{ mm}}{2})} = 846.80 \text{ mm}^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{846.80 \text{ mm}^2}{0.85 \times 24 \text{ N/mm}^2 \times 100 \text{ mm}} = 12.45 \text{ mm} \quad \text{Assumption is correct.}$$

$$s = \frac{b a_s}{A_s} = \frac{100 \text{ mm} \times 201 \text{ mm}^2}{846.80 \text{ mm}^2} = 240 \text{ mm}$$

- Check for minimum reinforcement:

$$f_r = 0.63 \sqrt{f_c'} = 0.63 \sqrt{24} = 3.09 \text{ MPa}$$

$$I_{cr} = \frac{b h^3}{12} = \frac{100 \text{ mm} \times (250 \text{ mm})^3}{12} = 1.30 \times 10^9 \text{ mm}^4$$

$$M_{cr} = f_r \frac{I_{cr}}{y_t} = 3.09 \text{ N/mm}^2 \left( \frac{1.30 \times 10^9 \text{ mm}^4}{125 \text{ mm}} \right) = 32.15 \text{ kNm/m}$$

$$1.2 M_{cr} = 38.58 \text{ kNm/m}$$

$$1.33 M_u = 56.49 \text{ kNm/m}$$

$$M_u \geq \min \left\{ \begin{array}{l} 1.2 M_{cr} \\ 1.33 M_u \end{array} \right\} = \min \left\{ \begin{array}{l} 38.58 \text{ kNm/m} \\ 56.49 \text{ kNm/m} \end{array} \right\} = 38.58 \text{ kNm/m}$$

The requirement for minimum flexural reinforcement is satisfied.

- Check for maximum reinforcement

$$c = \frac{a}{\beta} = \frac{12.45 \text{ mm}}{0.85} = 14.65 \text{ mm}$$

$$c/d = \frac{14.65 \text{ mm}}{192 \text{ mm}} = 0.08 < 0.42 \quad \text{The section is under reinforced.}$$

- Check crack control:

$$M_{\text{service}} = 26.62 \text{ kNm}$$

$$d_c = \text{concrete cover} + \text{bar diameter}/2 = 58 \text{ mm}$$

$$\gamma_e = 0.75 \text{ (exposure factor for class 2 exposure class)}$$

$$\text{strain factor } \beta_s = 1 + \frac{0.7d_c}{(h + d_c)} = 1 + \frac{0.7 \times 58 \text{ mm}}{(250 \text{ mm} + 58 \text{ mm})} = 1.21$$

$$\rho = \frac{A_s}{A_c} = \frac{846.80 \text{ mm}^2}{(250 \text{ mm} \times 250 \text{ mm})} = 0.0034$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n = \sqrt{(0.0034 \times 8)^2 + 2 \times 0.0034 \times 8} - 0.0034 \times 8 = 0.20$$

$$j = 1 - k/3 = 1 - 0.20/3 = 0.93$$

$$f_{ss} = \frac{M_{\text{service}}}{A_s j d} = \frac{26.62 \times 10^6 \text{ Nmm}}{846.80 \text{ mm}^2 \times 0.93 \times 192 \text{ mm}} = 175.90 \text{ MPa}$$

$$s \leq \frac{123000 \gamma_e}{\beta_s f_{ss}} - 2d_c = \frac{123000 \times 0.75}{1.21 \times 175.90 \text{ N/mm}^2} - 2 \times 58 \text{ mm} = 320 \text{ mm}$$

There is no problem of cracking.

Provide  $\phi 16$  c/c 180 (Bottom reinforcement)

#### 6.2.1.6.3.2 Design for Shear

The shear resistance of the side wall of the culvert can be determined as:

$$V_c = 0.083 \beta \sqrt{f_c'} b_v d_v \quad (32)$$

In which:

$$d_v = \min \begin{cases} 0.72h \\ 0.9d_e \\ d_e - a/2 \end{cases} = \min \begin{cases} 0.72 \times 250 \text{ mm} \\ 0.9 \times 192 \text{ mm} \\ 192 \text{ mm} - 20.75 \text{ mm}/2 \end{cases} = 185.58 \text{ mm}$$

$$b_v = 1000 \text{ mm}$$

$$\beta = 2 \text{ (since the total thickness is less than 400 mm)}$$

The nominal shear resistance of side wall is:

$$V_c = 0.083 \times 2 \times \sqrt{24 \text{ N/mm}^2} \times 1000 \text{ mm} \times 185.58 \text{ mm} = 151.08 \text{ kN}$$

Therefore, take nominal shear resistance of 151.08 kN.

The factored shear resistance of the top slab can be taken as:

$$V_r = \phi V_c = 0.083 \times 151.08 \text{ kN} = 12.84 \text{ kN}$$

From **Table 6-4** Shear Force for Strength I and Service I Load Combinations **Table 6-4**, the shear force at the critical section is determined to be 80.75 kN.

$$V_r = 12.84 \text{ kN} > V_u = 80.75 \text{ kN}$$

As the factored shear resistance of the side wall of the box culvert is greater than the shear force at the critical section, it can be concluded that the section has adequate shear capacity.

#### 6.2.1.6.3.3 Axial Thrust

The axial capacity of sidewall members shall be checked since it has the maximum thrust value. The axial capacity of the wall can be determined as:

$$P_r = \phi P_n = \phi (0.85 f_c' A_g) = 0.85 \times (0.85 \times 24 \frac{\text{N}}{\text{mm}^2} \times 250 \text{ mm} \times 1000 \text{ mm}) = 433.5 \text{ kN}$$

The maximum axial loads on the side wall which is determined using the software is:

$$P_u = 206.52 \text{ kN}$$

The axial load capacity of the side wall of the box culvert is adequate since it is greater than the maximum axial load applied on the wall.

#### 6.2.1.6.4 Shrinkage and Temperature Reinforcement

The shrinkage and temperature reinforcement to be provided near the concrete surface can be determined as follows:

$$A_{S(T+SH)} \geq \frac{0.75bh}{2(b+h)f_y} = \frac{0.75 \times 1000 \text{ mm} \times 275 \text{ mm}}{2(1000 \text{ mm} + 275 \text{ mm}) \times 300 \frac{\text{N}}{\text{mm}^2}} = 0.27 \text{ mm}^2/\text{mm}$$

$$0.233 \text{ mm}^2/\text{mm} < A_{S(T+SH)} = 0.27 \text{ mm}^2/\text{mm} < 1.27 \text{ mm}^2/\text{mm}$$

Therefore, take  $A_{S(T+SH)} = 0.27 \text{ mm}^2/\text{mm}$

$$s = \frac{ba_s}{A_{S(T+SH)}} = \frac{1000 \text{ mm} \times 0.113 \frac{\text{mm}^2}{\text{mm}}}{0.27 \frac{\text{mm}^2}{\text{mm}}} = 410 \text{ mm}$$

$$S_{\max} = \begin{cases} 3h \\ 450 \text{ mm} \end{cases} = \begin{cases} 3 \times 250 \text{ mm} \\ 450 \text{ mm} \end{cases} = 450 \text{ mm}$$

Therefore, provide  $\phi 12 \text{ c/c } 400$  near the surface of the concrete.

## 6.2.2 Design of Double Cell Box Culvert

### 6.2.2.1 Design Method

- Load and Resistance Factor Design (LRFD)

### 6.2.2.2 Design Manual

- AASHTO LRFD Bridge Design Specifications, Fifth Edition, 2010
- ERA Bridge Design Manual 2013

### 6.2.2.3 Design Data

The design data used for the single-cell box culvert is being applied to the double-cell box culverts, except the top slab thickness, bottom slab thickness, and sidewall thickness are increased to 300 mm, 325 mm, and 300 mm, respectively.

### 6.2.2.4 Load Determination

The procedure used to determine the applied loads on the single-cell box culverts was adopted for the double-cell box culverts. A summary of the loads that have been applied to the box culverts is presented in **Table 6-5**.

**Table 6-5 Loads applied on the box culvert**

Load Type	Structural Element	Applied Load
Self-weight	Top slab	7.20 kNm
	Side wall	23.85 kN
	Bottom slab	7.80 kNm
Vertical earth pressure	At the top slab	61.96 kNm
Maximum Horizontal earth pressure	At the top	28.80 kNm
	At the bottom	63.60 kNm
Minimum Horizontal earth pressure	At the top	14.40 kNm
	At the bottom	31.80 kNm
Live load surcharge	At the top	8.55 kNm
	At the bottom	5.70 kNm
Water pressure	At the top	0.00 kNm
	At the bottom	29.43 kNm
Live load	At the top slab	12.45 kNm

### 6.2.2.5 Structural Analysis

The bending moment and shear force shown in **Table 6-6** and **Table 6-7** are taken at the critical sections defined in Section 3.4.6.1.1 and 3.4.6.2 respectively.

**Table 6-6 Bending Moment at the Critical Locations for Double Cell Box Culvert**

Design Location	Dc (kNm)	EV (kNm)	LL+IM (kNm)	Ls (kNm)	Eh <sub>max</sub> (kNm)	Eh <sub>min</sub> (kNm)	WA (kNm)
Exterior sidewall top	1.58	-20.25	-4.07	-2.65	-18.19	-9.09	5.57
Exterior sidewall center	-3.50	-16.99	-3.41	5.26	34.04	17.02	-10.70
Exterior sidewall bottom	-8.59	-13.73	-2.76	-3.01	-18.55	-9.28	6.40
Interior sidewall top	0.00	0.00	0.00	0.01	0.08	0.04	-0.01
Interior sidewall center	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Interior sidewall bottom	0.00	0.00	0.00	-0.01	-0.08	-0.04	0.01
Exterior top slab left end	3.08	-8.34	-1.68	-4.12	-25.75	-12.88	7.30
Exterior top slab center	4.08	37.25	7.49	-1.06	-6.26	-3.13	1.86
Exterior top slab right end	-11.13	-56.56	-11.37	2.01	13.22	6.61	-3.58
Exterior bottom slab left end	-5.06	-2.05	-0.41	-4.29	-28.89	-14.44	10.23
Exterior bottom slab center	10.79	35.74	7.18	-1.12	-7.90	-3.95	2.28
Exterior bottom slab right end	10.07	54.88	11.03	-1.69	-10.46	-5.23	3.42

**Table 6-7 Shear Force at the Critical Locations for Double Cell Box Culvert**

Design Location	Dc (kN)	EV (kN)	LL+IM (kN)	Ls (kN)	Eh <sub>max</sub> (kN)	Eh <sub>min</sub> (kN)	WA (kN)
Exterior Sidewall Top	-3.38	2.16	0.43	9.08	53.52	26.76	-14.74
Moment at the critical shear (kNm)	0.72	-19.69	-3.96	-0.04	-3.44	-1.72	1.73
Exterior Sidewall Bottom	-3.38	2.16	0.43	9.12	53.65	26.82	-14.74
Exterior Top Slab right end	-4.37	-62.27	-12.52	-2.04	-12.99	-6.50	3.62
Exterior Top Slab left end	13.89	94.82	19.06	-2.04	-12.99	-6.50	3.62
Moment at the critical shear (kNm)	-7.76	-33.22	-6.68	1.54	10.25	5.12	-2.75
Exterior Bottom Slab left End	24.14	65.56	13.18	2.20	14.29	7.14	-3.75
Moment at the critical shear (kNm)	-10.07	-54.88	-11.03	4.29	28.90	14.45	-3.42
Exterior Bottom Slab Right End	25.32	102.93	20.69	-1.97	-12.61	-6.30	5.81

**Table 6-8 Bending Moment for Strength I and Service I Load Combinations for Double  
Cell Box Culvert**

Design Locations	Strength Ia (kNm)	Strength Ib (kNm)	Strength Ic (kNm)	Service Ia (kNm)	Service Ib (kNm)	Service Ic (kNm)
Exterior sidewall top	63.19	35.00	48.12	43.57	26.25	39.50
Exterior sidewall center	23.91	29.66	38.24	15.39	17.59	18.80
Exterior sidewall bottom	65.88	35.85	52.27	46.64	27.95	43.88
Interior sidewall top	0.13	0.02	0.13	0.09	0.03	0.09
Interior sidewall center	0.00	0.00	0.00	0.00	0.00	0.00
Interior sidewall bottom	0.13	0.03	0.13	0.09	0.03	0.09
Exterior top slab left end	54.19	14.21	48.83	36.81	12.52	35.14
Exterior top slab center	58.31	68.21	28.14	41.49	47.54	34.00
Exterior top slab right end	88.77	108.93	41.22	63.83	76.03	52.47
Exterior bottom slab left end	58.31	12.00	54.95	40.71	11.74	40.29
Exterior bottom slab center	61.69	73.75	30.33	44.70	52.05	37.51
Exterior bottom slab right end	89.02	105.73	43.14	63.83	74.16	52.80

**Table 6-9 Shear Force for Strength I and Service I Load Combinations for Double Cell Box  
Culvert**

Design Locations	Strength Ia (kN)	Strength Ib (kN)	Strength Ic (kN)	Service Ia (kN)	Service Ib (kN)	Service Ic (kN)
Exterior sidewall top	91.25	7.69	90.76	61.82	11.24	61.39
Moment at the critical shear (kNm)	37.86	32.65	22.92	26.42	22.92	22.46
Exterior sidewall bottom	91.50	7.74	91.01	61.99	11.30	61.55
Exterior top slab left end	134.34	114.30	84.76	94.18	82.02	81.67
Moment at the critical shear (kNm)	49.52	65.09	21.16	35.87	45.28	29.20
Exterior top slab right end	158.15	178.20	80.11	112.73	124.89	93.67
Exterior bottom slab left end	166.83	145.10	107.78	119.36	106.27	106.19
Moment at the critical shear (kNm)	58.32	97.83	12.44	42.78	64.94	31.75
Exterior bottom slab right end	187.05	208.76	98.75	134.37	148.44	113.68

### 6.2.2.6 Structural Design

The design procedure, and equations for the double-cell box culvert is the same to that of the single-cell box culvert, with the exception that the double-cell box culvert has more design locations than single-cell box culvert.

#### 6.2.2.6.1 Design for Flexure

A summary of the reinforcement bars used for the double-cell box culvert is presented in **Table 6-10**.

**Table 6-10 Summary of Reinforcement Bar for Double Cell Box Culvert**

Structural Element	Design Location	Design Moment (kNm)	Depth (mm)	Provided Reinforcement Bar
Top Slab	Left End	54.45	300	φ 16 C/C 230.0
	Mid Span	68.70	300	φ 16 C/C 190.0
	Right End	114.68	300	φ 16 C/C 110.0
Bottom Slab	Left End	58.37	325	φ 16 C/C 220.0
	Mid Span	73.88	325	φ 16 C/C 190.0
	Right End	110.57	325	φ 16 C/C 130.0
Side wall	Top End	58.87	250	φ 16 C/C 200.0
	Mid Height	38.58	250	φ 16 C/C 250.0
	Bottom End	60.83	250	φ 16 C/C 190.0

#### 6.2.2.6.2 Design for Shear

A summary of the design shear force at the designated locations and the factored shear resistance of the various sections of the double-cell box culvert are provided in Table 6-11.

**Table 6-11 Summary of Shear Capacity Check of the Double Cell Box Culvert**

Structural Element	Design Location	Design Shear Force (kN)	Shear Resistance (kN)	Remark
Top Slab	Left End	134.34	183.46	Adequate Shear Capacity
	Right End	158.15	184.53	Adequate Shear Capacity
Bottom Slab	Left End	166.83	208.94	Adequate Shear Capacity
	Right End	208.76	222.33	Adequate Shear Capacity
Side Wall	Bottom End	91.25	161.99	Adequate Shear Capacity

#### 6.2.2.6.3 Axial Thrust

As described in Section 6.2.2.6.3, the axial capacity of sidewall members shall be checked since it has the maximum thrust value. The axial capacity of the wall can be determined as follows:

$$P_r = \phi P_n = \phi (0.85 f_c' A_g) = 0.85 \times (0.85 \times 24 \frac{N}{mm^2} \times 300 \text{ mm} \times 1000 \text{ mm}) = 520 \text{ kN}$$

The maximum axial loads on the side wall which is determined using the software is:

$$P_u = 468.92 \text{ kN}$$

The axial load capacity of the side wall of the box culvert is adequate since it is greater than the maximum axial load applied on the wall.

#### 6.2.2.6.4 Shrinkage and Temperature Reinforcement

The shrinkage and temperature reinforcement to be provided near the concrete surface can be determined as follows:

$$A_{S(T+SH)} \geq \frac{0.75bh}{2(b+h)f_y} = \frac{0.75 \times 1000 \text{ mm} \times 325 \text{ mm}}{2(1000 \text{ mm} + 325 \text{ mm}) \times 300 \frac{N}{mm^2}} = 0.307 \text{ mm}^2/mm$$

$$0.233 \text{ mm}^2/mm < A_{S(T+SH)} = 0.307 \text{ mm}^2/mm < 1.27 \text{ mm}^2/mm$$

$$\text{Therefore, take } A_{S(T+SH)} = 0.307 \text{ mm}^2/mm$$

$$s = \frac{ba_s}{A_{S(T+SH)}} = \frac{1000 \text{ mm} \times 0.113 \frac{mm^2}{mm}}{0.31 \frac{mm^2}{mm}} = 370 \text{ mm}$$

$$S_{\max} = \begin{cases} 3h \\ 450 \text{ mm} \end{cases} = \begin{cases} 3 \times 250 \text{ mm} \\ 450 \text{ mm} \end{cases} = 450 \text{ mm}$$

Therefore, provide  $\phi 12 \text{ c/c } 370$  near the surface of the concrete.

### 6.3 Analysis and Design of Box Culverts Using CSI SAP2000v24.0.0

#### 6.3.1 Design of Single Cell Box Culvert Using CSI SAP2000v24.0.0

##### 6.3.1.1 Design Method

- Load and Resistance Factor Design (LRFD)

##### 6.3.1.2 Design Manual

- AASHTO LRFD Bridge Design Specifications, Fifth Edition, 2010
- ERA Bridge Design Manual 2013

##### 6.3.1.3 Design Data's

The design data that were used for the single-cell box culvert in Section 6.2.1 are being used.

##### 6.3.1.4 Load Determination

The loads that were computed in Section 6.2.1 are being used in the modeling of the single-cell box culvert using CSISAP2000 v24.0.0.

##### 6.3.1.5 Structural Analysis

CSISAP2000 v24.0.0 was used to analyze the culvert, and action effects for the Strength I and Service I load combinations are depicted in the figure below.

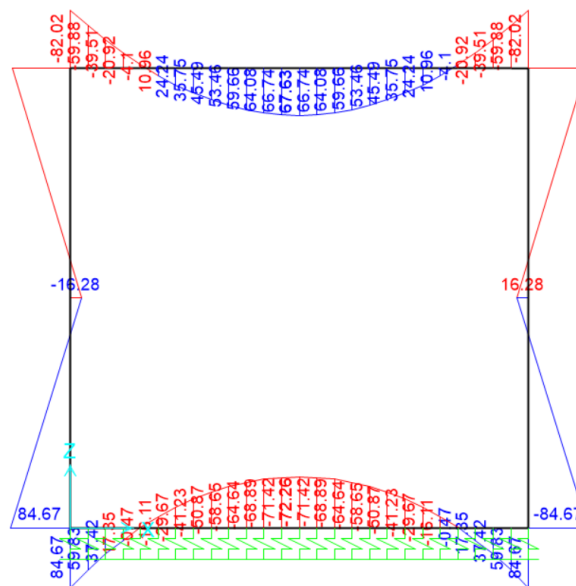


Figure 6-1 Bending Moment Diagram for Strength Ia Load Combination

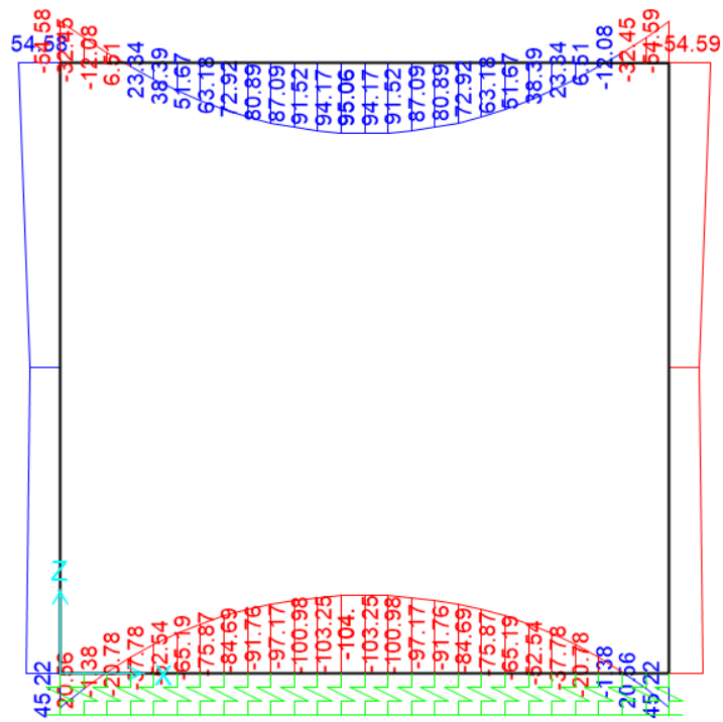


Figure 6-2 Bending Moment Diagram for Strength Ib Load Combination

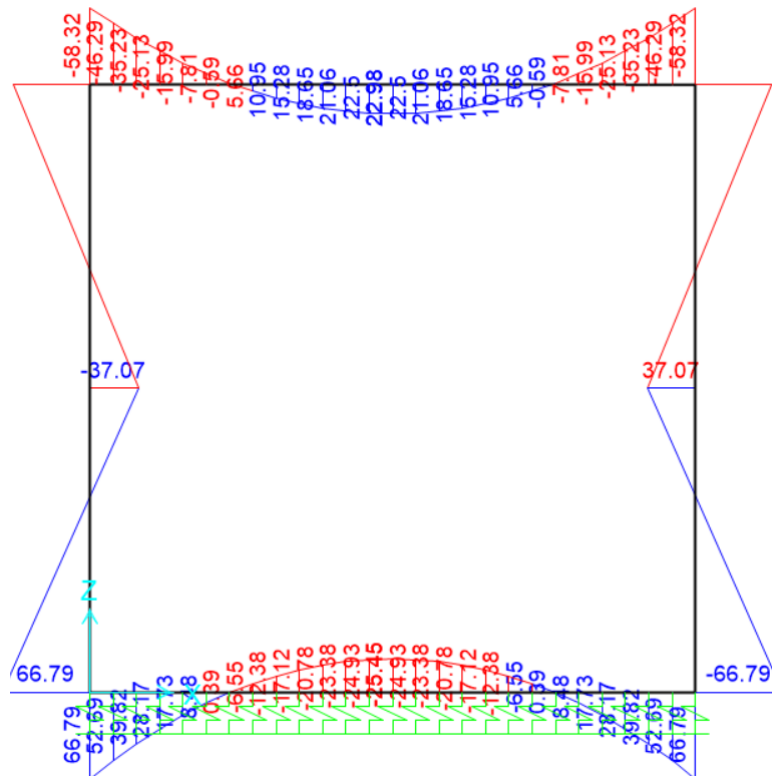


Figure 6-3 Bending Moment Diagram for Strength Ic Load Combination

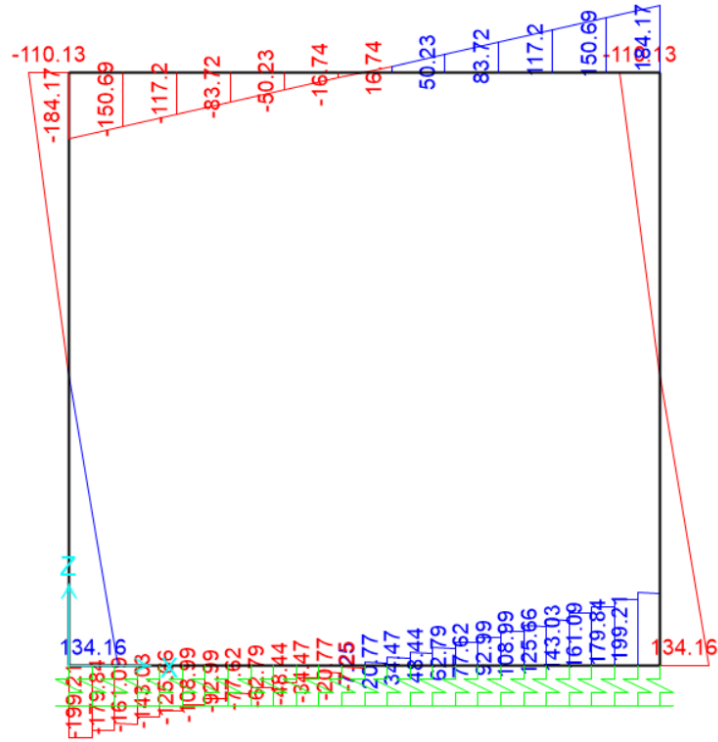


Figure 6-4 Shear Force Diagram for Strength Ia Load Combination

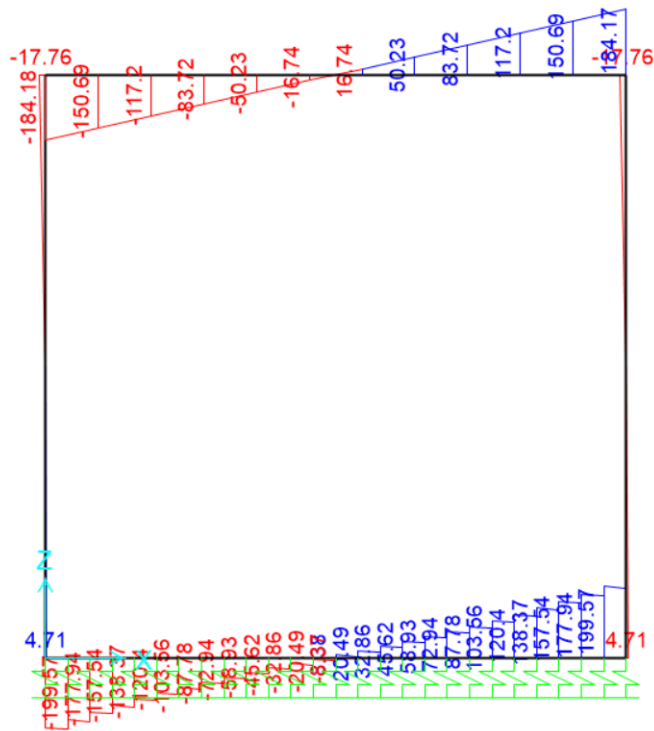
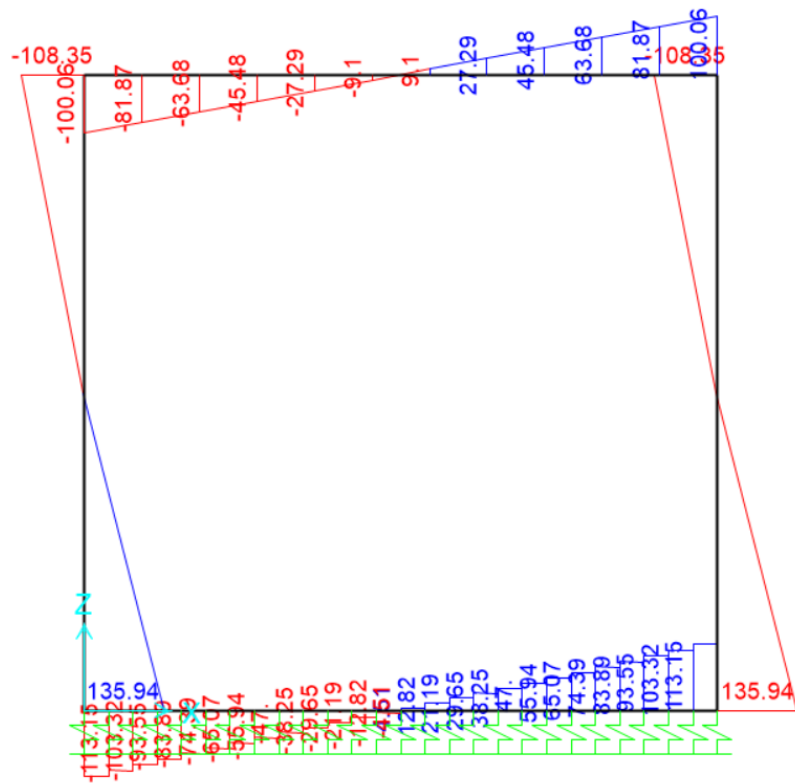


Figure 6-5 Shear Force Diagram for Strength Ib Load Combination



**Figure 6-6 Shear Force Diagram for Strength Ic Load Combination**

The action effects used for the structural elements of the box culvert under different load cases and combinations were extracted from the analysis performed using CSISAP2000v24.0.0 and are presented in tabular as shown below.

**Table 6-12 Bending Moment at the Critical Locations for Single Cell Box Culvert using CSISAP2000 v24.0.0**

Design Location	Dc (kNm)	EV (kNm)	LL+IM (kNm)	Ls (kNm)	EHmax (kNm)	EHmin (kNm)	WA (kNm)
Sidewall Top	-1.94	-30.08	-4.29	-1.61	-10.84	-5.42	3.67
Sidewall Center	-4.47	-25.37	-3.62	6.00	38.35	19.18	-12.29
Sidewall Bottom	-7.03	-20.67	-2.95	-2.55	-16.11	-8.05	5.10
Top Slab left end	-0.56	-17.67	-2.52	-3.07	-18.51	-9.26	5.53
Top Slab Center	6.19	56.07	8.00	-3.07	-18.51	-9.26	5.53
Top Slab right end	-0.56	-17.67	-2.52	-3.07	-18.51	-9.26	5.53
Bottom Slab left End	-3.75	-7.71	-1.10	-3.88	-26.31	-13.16	8.99
Bottom Slab Center	13.93	55.35	7.90	-3.14	-21.27	-10.64	7.27
Bottom Slab right End	-3.75	-7.71	-1.10	-3.88	-26.31	-13.16	8.99

**Table 6-13 Shear Force at the Critical Locations for Single Cell Box Culvert using  
CSISAP2000 v24.0.0**

Design Location	Dc (kN)	EV (kN)	LL+IM (kN)	Ls (kN)	EH <sub>max</sub> (kN)	EH <sub>min</sub> (kN)	WA (kN)
Sidewall Top	-1.68	3.13	0.45	9.64	53.95	26.97	-14.49
Moment at the critical shear (kNm)	-2.22	-29.55	-4.21	0.16	-1.15	-0.56	1.14
Top Slab right end	-7.99	-87.15	-12.43	0.00	0.01	0.00	0.00
Moment at the critical shear (kNm)	0.96	-1.29	-0.18	-3.07	-18.48	-9.24	0.00
Bottom Slab left End	25.17	89.37	12.75	0.37	2.52	1.26	0.98
Moment at the critical shear (kNm)	0.65	3.47	0.49	3.89	26.35	13.17	-8.88

**Table 6-14 Bending Moment for Strength I and Service I Load Combinations for Single  
Cell Box Culvert using CSISAP2000 v24.0.0**

Design Location	Strength Ia (kNm)	Strength Ib (kNm)	Strength Ic (kNm)	Service Ia (kNm)	Service Ib (kNm)	Service Ic (kNm)
Sidewall Top	-68.61	-51.98	-45.14	-48.76	-38.07	-44.47
Sidewall Center	16.28	-42.42	37.08	10.88	-26.58	14.51
Sidewall Bottom	-68.62	-43.97	-50.49	-49.31	-33.60	-46.36
Top Slab Left End	-59.86	-31.64	-46.28	-42.33	-24.49	-39.80
Top Slab Center	67.64	95.86	22.99	48.68	66.53	40.68
Top Slab Right End	-59.86	-31.64	-46.28	-42.33	-24.49	-39.80
Bottom Slab Left End	-59.85	-19.43	-52.69	-42.75	-16.73	-41.65
Bottom Slab Center	72.26	104.94	25.44	52.77	73.81	44.87
Bottom Slab Right End	-59.85	-19.43	-52.69	-42.75	-16.73	-41.65

**Table 6-15 Shear Force for Strength I and Service I Load Combinations for Single Cell Box  
Culvert using CSISAP2000 v24.0.0**

Design Locations	Strength Ia (kN)	Strength Ib (kN)	Strength Ic (kN)	Service Ia (kN)	Service Ib (kN)	Service Ic (kN)
Sidewall Top	93.46	11.57	91.68	65.49	14.37	65.04
Moment at the Critical Shear Location (kNm)	-51.77	-49.82	-28.61	-36.97	-35.40	-32.76
Top Slab Left End	-150.69	-150.70	-81.87	-107.56	-107.57	-95.13
Moment at the Critical Shear Location (kNm)	-31.47	-8.80	-30.83	-22.06	-9.75	-21.88
Bottom Slab Left End	179.85	177.83	103.33	130.18	129.53	117.43
Moment at the Critical Shear Location (kNm)	49.17	8.82	46.32	34.84	8.90	34.35

### 6.3.1.6 Structural Design

The design is performed following the same procedure as outlined Section 6.2.1.

#### 6.3.1.6.1 Design for Flexure

A summary of the reinforcement bars used for the single-cell box culvert analyzed using CSISAP2000v24.0.0 is presented in **Table 6-16**

**Table 6-16 Summary of Reinforcement Bar for Double-Cell Box Culvert Analyzed using CSISAP2000v24.0.0**

Structural Element	Design Location	Design Moment (kNm)	Depth (mm)	Provided Reinforcement Bar
Top Slab	Left End	-59.86	250	φ 16 C/C 160.0
	Mid Span	95.86	250	φ 16 C/C 100.0
Bottom Slab	Left End	-59.85	275	φ 16 C/C 180.0
	Mid Span	104.94	275	φ 16 C/C 100.0
Side wall	Top End	-68.61	250	φ 16 C/C 140.0
	Mid Height	37.08	250	φ 16 C/C 240.0
	Bottom End	-50.49	250	φ 16 C/C 140.0

#### 6.3.1.6.2 Design for Shear

A summary of the design shear force at the designated locations and the factored shear resistance of the various sections of the single-cell box culvert analyzed using CSISAP2000v24.0.0 are provided in **Table 6-17**.

**Table 6-17 Summary of Shear Capacity Check of the Double Cell Box Culvert**

Structural Element	Design Shear Force (kN)	Shear Resistance (kN)	Remark
Top Slab	150.70	199.87	Adequate Shear Capacity
Bottom Slab	179.85	225.90	Adequate Shear Capacity
Side Wall	93.46	128.42	Adequate Shear Capacity

#### 6.3.1.6.3 Axial Thrust

As described in Section 6.2.2.6.3, the axial capacity of sidewall members shall be checked since it has the maximum thrust value. The axial capacity of the wall can be determined as follows:

$$P_r = \phi P_n = \phi (0.85 f_c' A_g) = 0.85 \times (0.85 \times 24 \frac{N}{mm^2} \times 250 \text{ mm} \times 1000 \text{ mm}) = 433.5 \text{ kN}$$

The maximum axial loads on the side wall which is determined using the CSISAP2000v24.0.0 is:

$$P_u = 208.84 \text{ kN}$$

The axial load capacity of the side wall of the box culvert is adequate since it is greater than the maximum axial load applied on the wall.

#### 6.3.1.6.4 Shrinkage and Temperature Reinforcement

The shrinkage and temperature reinforcement to be provided near the concrete surface can be determined as follows:

$$A_{S(T+SH)} \geq \frac{0.75bh}{2(b+h)f_y} = \frac{0.75 \times 1000 \text{ mm} \times 275 \text{ mm}}{2(1000 \text{ mm} + 275 \text{ mm}) \times 300 \frac{\text{N}}{\text{mm}^2}} = 0.27 \text{ mm}^2/\text{mm}$$

$$0.233 \text{ mm}^2/\text{mm} < A_{S(T+SH)} = 0.27 \text{ mm}^2/\text{mm} < 1.27 \text{ mm}^2/\text{mm}$$

Therefore, take  $A_{S(T+SH)} = 0.27 \text{ mm}^2/\text{mm}$

$$s = \frac{ba_s}{A_{S(T+SH)}} = \frac{1000 \text{ mm} \times 0.113 \frac{\text{mm}^2}{\text{mm}}}{0.27 \frac{\text{mm}^2}{\text{mm}}} = 410 \text{ mm}$$

$$S_{\max} = \begin{cases} 3h \\ 450 \text{ mm} \end{cases} = \begin{cases} 3 \times 250 \text{ mm} \\ 450 \text{ mm} \end{cases} = 450 \text{ mm}$$

Therefore, provide  $\phi 12 \text{ c/c } 400$  near the surface of the concrete.

### 6.3.2 Design of Double Cell Box Culvert Using CSI SAP2000v24.0.0

#### 6.3.2.1 Design Method

- Load and Resistance Factor Design (LRFD)

#### 6.3.2.2 Design Manual

- AASHTO LRFD Bridge Design Specifications, Fifth Edition, 2010
- ERA Bridge Design Manual 2013

#### 6.3.2.3 Design Data's

The design data that were used for the double-cell box culvert in Section 6.2.2 are being used.

#### 6.3.2.4 Load Determination

The loads that were computed in Section 6.2.2 are being used in the modeling of the single-cell box culvert using CSISAP2000 v24.0.0.

#### 6.3.2.5 Structural Analysis

CSISAP2000 v24.0.0 was used to analyze the culvert, and action effects for the Strength I and Service I load combinations are depicted in the figure below.

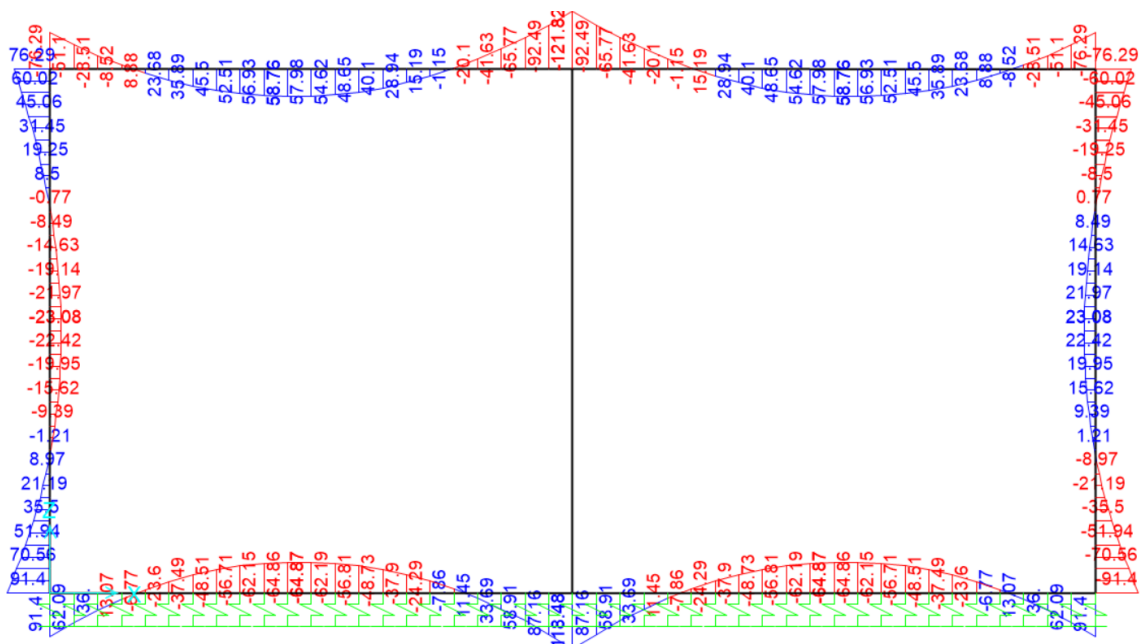


Figure 6-7 Bending Moment Diagram for Strength Ia Load Combination

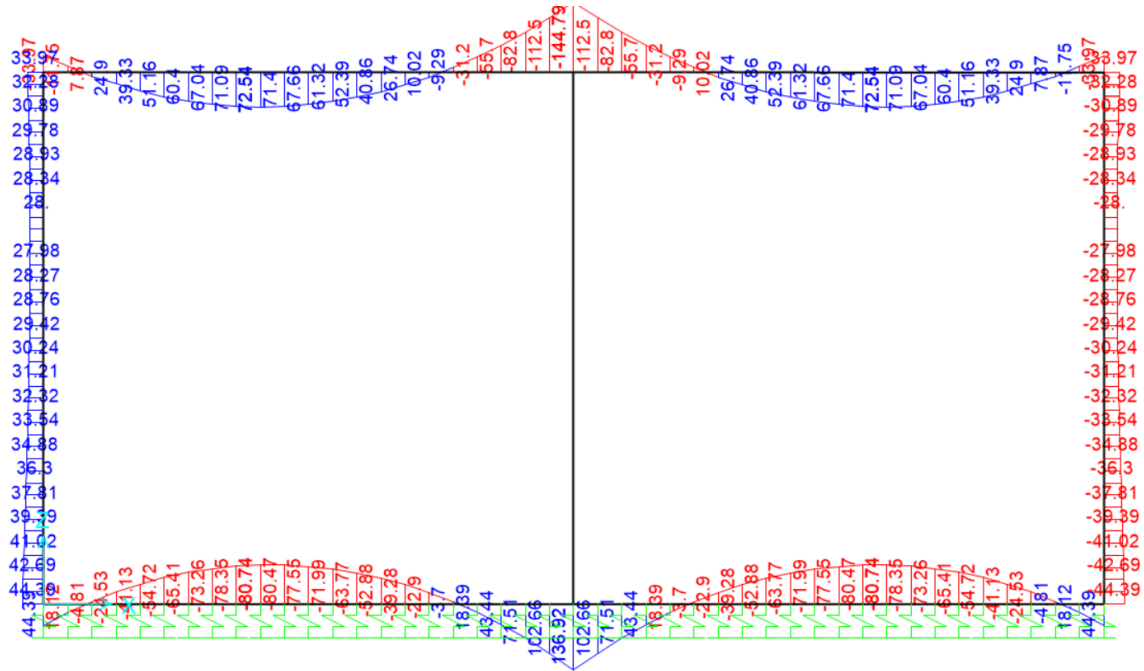


Figure 6-8 Bending Moment Diagram for Strength Ib Load Combination

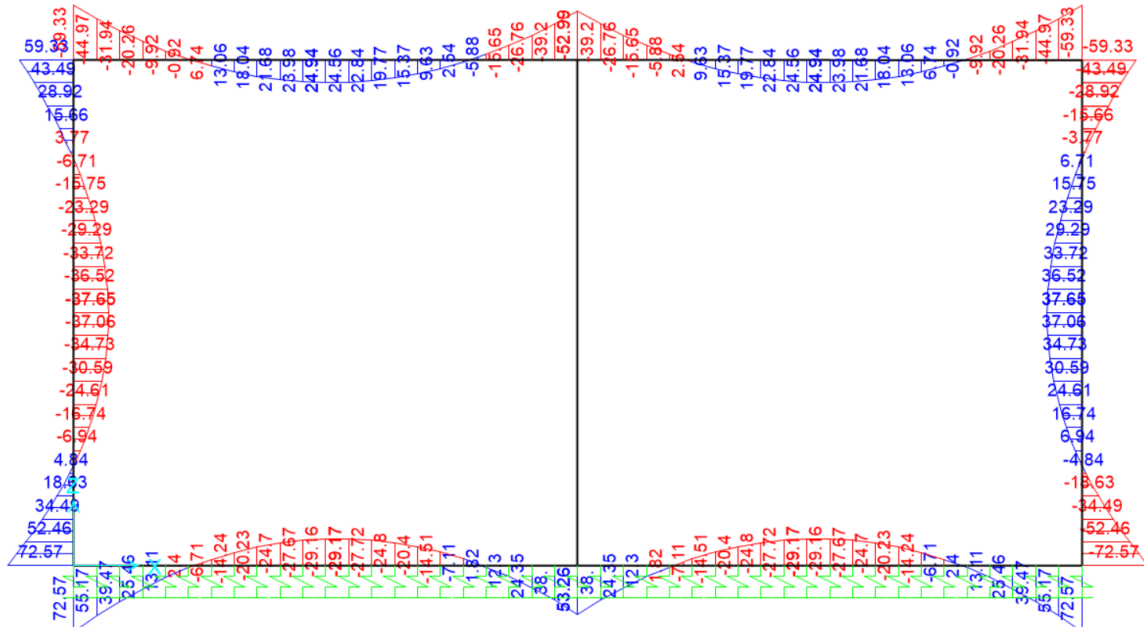


Figure 6-9 Bending Moment Diagram for Strength Ic Load Combination

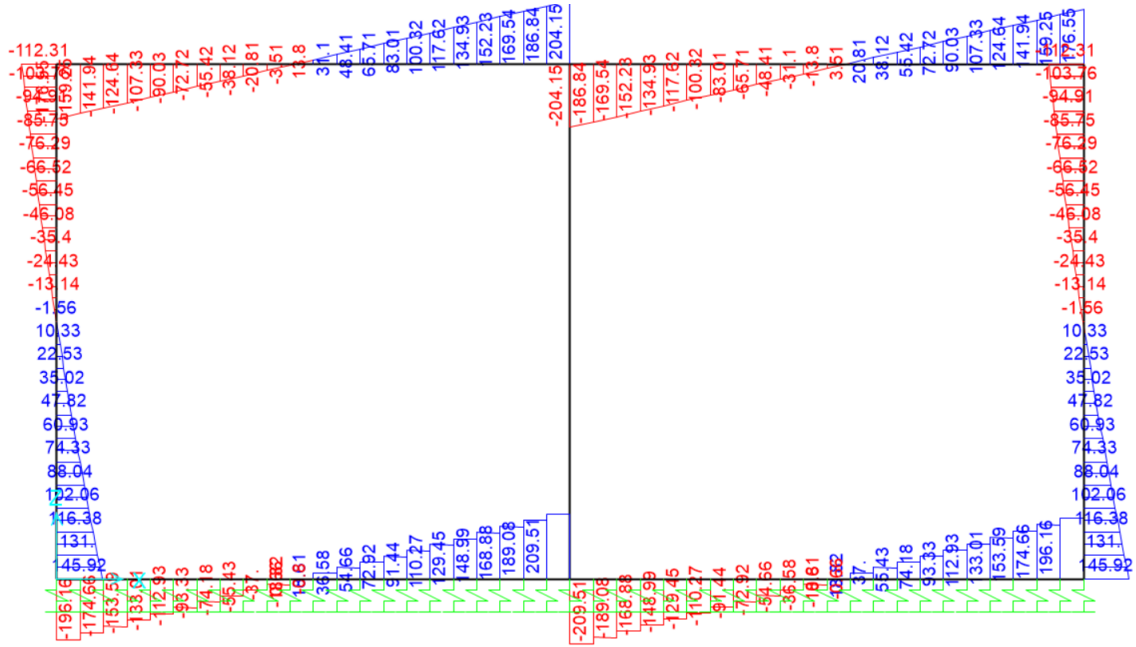


Figure 6-10 Shear Force Diagram for Strength Ia Load Combination

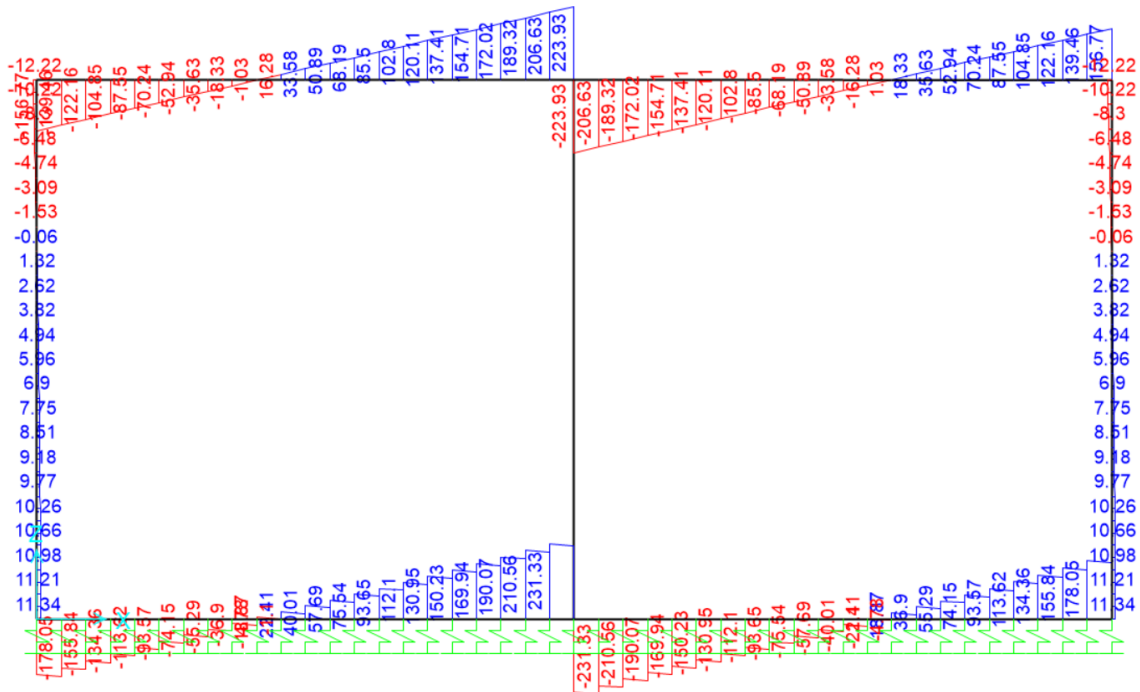
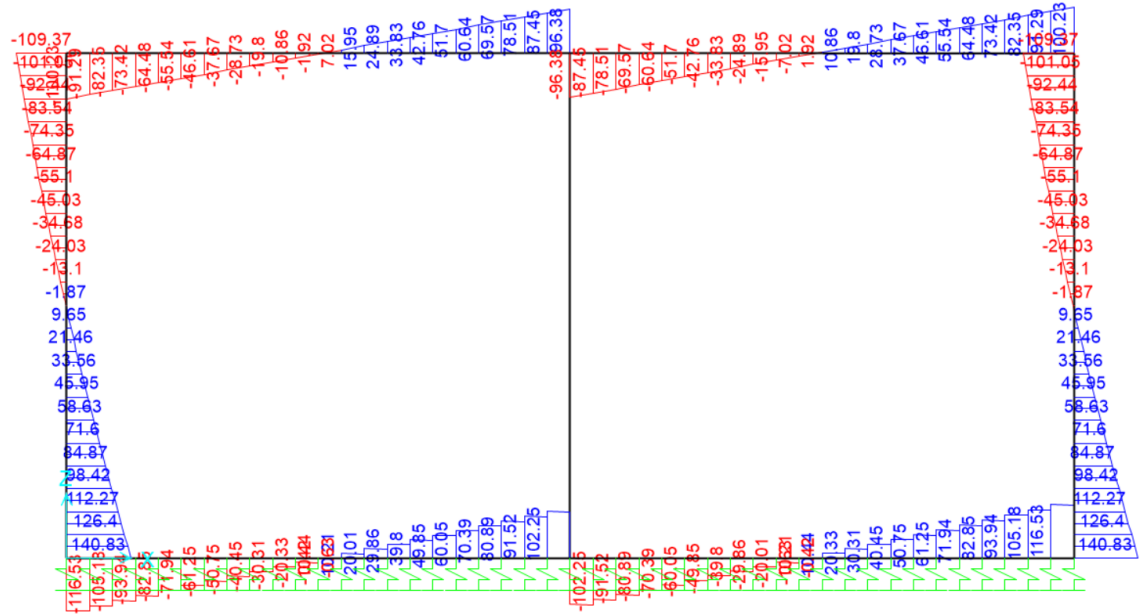


Figure 6-11 Shear Force Diagram for Strength Ib Load Combination



**Figure 6-12 Shear Force Diagram for Strength Ic Load Combination**

The action effects used for the structural elements of the box culvert under different load cases and combinations were extracted from the analysis performed using CSISAP2000v24.0.0 and are presented in tabular as shown below.

**Table 6-18 Bending Moment at the Critical Locations for Double Cell Box Culvert using CSISAP2000 v24.0.0**

Design Location	Dc (kNm)	EV (kNm)	LL+IM (kNm)	Ls (kNm)	Eh <sub>max</sub> (kNm)	Eh <sub>min</sub> (kNm)	WA (kNm)
Exterior sidewall top	1.79	-19.05	-3.96	-2.61	-18.04	-9.02	6.10
Exterior sidewall center	-3.68	-15.54	-3.52	5.28	34.24	17.12	-10.88
Exterior sidewall bottom	-8.59	-13.02	-2.98	-2.96	-18.20	-9.10	5.48
Interior sidewall top	0.00	0.00	0.00	0.01	0.08	0.04	-0.01
Interior sidewall center	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Interior sidewall bottom	0.00	0.00	0.00	-0.01	-0.08	-0.04	0.01
Exterior top slab left end	3.79	-7.10	-1.43	-4.11	-25.71	-12.85	7.83
Exterior top slab center	3.97	37.20	7.47	-1.07	-6.33	-3.17	1.81
Exterior Top Slab right end	-12.00	-57.88	-11.63	1.97	13.04	6.52	-4.24
Exterior bottom slab left end	-5.94	-2.83	-0.47	-4.25	-28.60	-14.30	9.50
Exterior bottom slab center	11.51	37.37	7.51	-1.16	-8.20	-4.10	2.89
Exterior bottom slab right end	9.50	53.95	10.84	-1.64	-10.17	-5.08	3.00

**Table 6-19 Shear Force at the Critical Locations for Double Cell Box Culvert using  
CSISAP2000 v24.0.0**

Design Location	Dc (kN)	EV (kN)	LL+IM (kN)	Ls (kN)	Eh <sub>max</sub> (kN)	Eh <sub>min</sub> (kN)	WA (kN)
Exterior sidewall top	-3.48	2.13	0.39	9.45	54.71	27.36	-15.15
Moment at the critical shear (kNm)	0.73	-18.84	-3.79	-0.04	-3.43	-1.72	1.76
Exterior sidewall bottom	-3.39	2.12	0.39	9.53	54.78	27.39	-16.36
Exterior top slab right end	-4.37	-62.27	-12.52	-2.04	-12.99	-6.50	3.62
Exterior top slab left end	13.89	94.82	19.06	-2.04	-12.99	-6.50	3.62
Moment at the critical shear (kNm)	-7.76	-33.22	-6.68	1.54	10.25	5.12	-2.75
Exterior bottom slab left end	25.76	69.49	13.96	2.12	13.72	6.86	-3.15
Moment at the critical shear (kNm)	-9.48	-53.94	-10.84	4.13	27.09	13.55	-3.00
Exterior bottom slab right end	25.77	103.77	20.85	-1.96	-12.60	-6.30	5.82

**Table 6-20 Bending Moment for Strength I and Service I Load Combinations for Double  
Cell Box Culvert using CSISAP2000 v24.0.0**

Design Locations	Strength Ia (kN-m)	Strength Ib (kN-m)	Strength Ic (kN-m)	Service Ia (kN-m)	Service Ib (kN-m)	Service Ic (kN-m)
Exterior sidewall top	60.83	32.33	46.91	41.87	24.14	37.91
Exterior sidewall center	25.80	28.18	39.35	16.78	16.50	20.30
Exterior sidewall bottom	64.70	36.04	48.91	45.75	28.21	42.77
Interior sidewall top	0.13	0.02	0.12	0.09	0.03	0.09
Interior sidewall center	0.00	0.00	0.00	0.00	0.00	0.00
Interior sidewall bottom	0.13	0.03	0.13	0.09	0.03	0.09
Exterior top slab left end	51.09	10.64	44.96	34.56	9.76	33.13
Exterior top slab center	57.97	67.91	26.94	41.24	47.28	33.77
Exterior Top Slab right end	92.43	113.01	39.16	66.50	79.23	54.87
Exterior bottom slab left end	60.09	14.87	54.25	42.09	14.04	41.62
Exterior bottom slab center	64.89	77.92	29.16	47.03	55.18	39.52
Exterior bottom slab right end	87.20	103.13	41.32	62.48	72.21	51.64

**Table 6-21 Shear Force for Strength I and Service I Load Combinations for Double Cell  
Box Culvert using CSISAP2000 v24.0.0**

Design Locations	Strength Ia (kN)	Strength Ib (kN)	Strength Ic (kN)	Service Ia (kN)	Service Ib (kN)	Service Ic (kN)
Exterior sidewall top	93.33	7.54	89.91	63.20	11.25	62.81
Moment at the critical shear (kNm)	36.36	31.15	20.23	25.37	21.86	21.58
Exterior sidewall bottom	93.67	6.45	90.22	63.43	10.15	63.04
Exterior top slab left end	134.34	114.30	78.60	94.18	82.02	81.67
Moment at the critical shear (kNm)	49.52	65.09	18.78	35.87	45.28	29.20
Exterior top slab right end	158.15	178.20	72.45	112.73	124.89	93.67
Exterior bottom slab left end	174.64	154.21	105.17	125.05	112.92	111.09
Moment at the critical shear (kNm)	58.82	95.84	10.55	43.04	63.72	32.20
Exterior bottom slab right end	189.06	210.76	91.49	135.83	149.91	114.98

### 6.3.2.6 Structural Design

The design is performed following the same procedure as outlined Section 6.2.2.

#### 6.3.2.6.1 Design for Flexure

A summary of the reinforcement bars used for the double-cell box culvert analyzed using CSISAP2000v24.0.0 is presented in **Table 6-22**.

**Table 6-22 Summary of Reinforcement Bar for Double-Cell Box Culvert Analyzed using  
CSISAP2000v24.0.0**

Structural Element	Design Location	Design Moment (kN-m)	Depth (mm)	Provided Reinforcement Bar
Top Slab	Left End	51.09	300	φ 16 C/C 220.0
	Mid Span	67.91	300	φ 16 C/C 190.0
	Right End	108.93	300	φ 16 C/C 110.0
Bottom Slab	Left End	65.20	325	φ 16 C/C 220.0
	Mid Span	73.74	325	φ 16 C/C 190.0
	Right End	113.01	325	φ 16 C/C 130.0
Side wall	Top End	60.83	300	φ 16 C/C 200
	Mid Height	50.83	300	φ 16 C/C 250.0
	Bottom End	64.70	300	φ 16 C/C 190.0

#### 6.3.2.6.2 Design for Shear

A summary of the design shear force at the designated locations and the factored shear resistance of the various sections of the double-cell box culvert analyzed using CSISAP2000v24.0.0 are provided in **Table 6-23**.

**Table 6-23 Summary of Shear Capacity Check of the Double Cell Box Culvert**

Structural Element	Design Location	Design Shear Force (kN)	Shear Resistance (kN)	Remark
Top Slab	Left End	-134.34	183.46	Adequate Shear Capacity
	Right End	-158.15	184.53	Adequate Shear Capacity
Bottom Slab	Left End	174.64	208.94	Adequate Shear Capacity
	Right End	210.76	222.33	Adequate Shear Capacity
Side Wall	Bottom End	93.33	162.00	Adequate Shear Capacity

#### 6.3.2.6.3 Axial Thrust

As described in Section 6.2.2.6.3, the axial capacity of sidewall members shall be checked since it has the maximum thrust value. The axial capacity of the wall can be determined as follows:

$$P_r = \phi P_n = \phi (0.85 f_c' A_g) = 0.85 \times (0.85 \times 24 \frac{N}{mm^2} \times 250 \text{ mm} \times 1000 \text{ mm}) = 520 \text{ kN}$$

The maximum axial loads on the side wall which is determined using the CSISAP2000v24.0.0 is:

$$P_u = 477.68 \text{ kN}$$

The axial load capacity of the side wall of the box culvert is adequate since it is greater than the maximum axial load applied on the wall.

#### 6.3.2.6.4 Shrinkage and Temperature Reinforcement

The shrinkage and temperature reinforcement to be provided near the concrete surface can be determined as follows:

$$A_{S(T+SH)} \geq \frac{0.75bh}{2(b+h)f_y} = \frac{0.75 \times 1000 \text{ mm} \times 325 \text{ mm}}{2(1000 \text{ mm} + 325 \text{ mm}) \times 300 \frac{N}{mm^2}} = 0.307 \text{ mm}^2/mm$$

$$0.233 \text{ mm}^2/mm < A_{S(T+SH)} = 0.307 \text{ mm}^2/mm < 1.27 \text{ mm}^2/mm$$

$$\text{Therefore, take } A_{S(T+SH)} = 0.307 \text{ mm}^2/mm$$

$$s = \frac{ba_s}{A_{S(T+SH)}} = \frac{1000 \text{ mm} \times 0.113 \frac{mm^2}{mm}}{0.31 \frac{mm^2}{mm}} = 370 \text{ mm}$$

$$S_{\max} = \begin{cases} 3h \\ 450 \text{ mm} \end{cases} = \begin{cases} 3 \times 250 \text{ mm} \\ 450 \text{ mm} \end{cases} = 450 \text{ mm}$$

Therefore, provide  $\phi 12$  c / c 370 near the surface of the concrete.

## 6.4 Validation of Results

### 6.4.1 Comparison of the Software Results with the CSISAP2000v24.0.0 and Hand Calculation

Section 6.2 and 6.3 of this research presents a comprehensive analysis and design of single cell and double cell box culverts using both the software program developed in this research and CSISAP200v24.0.0. The study shows that the action effects computed by both software programs are comparable. The analysis of the action effects obtained by the software programs is then used for the structural design of the culverts. Notably, the amount of flexural reinforcement obtained from both software programs is similar, indicating the reliability of the software program developed in this research for designing box culverts.

Moreover, the study checks the shear capacity of the culverts using both software programs. The results demonstrate that the shear capacity of the section is consistent, highlighting the reliability of the software program developed in this research. Additionally, the axial thrust capacity of the culverts is checked using both software programs, resulting in the same result. The research findings indicate that the software program developed in this research can be effectively used to review and design box culverts.

The study findings show that the software program developed in this research and CSISAP200v24.0.0 provide consistent result regarding the action effects, flexural reinforcement, shear capacity, and axial thrust capacity of the culverts. Therefore, it can be concluded that the software programs can be used for the structural design of box culverts, with confidence in the results obtained.

**Table 6-24 Comparisons of bending moments for the Strength I load combination of a single-cell box culvert**

Design Location	Design Moment (kNm)		Deviation of Results in %
	Using the software program	Using CSISAP2000v24.0.0	
Sidewall Top	68.61	69.21	0.861
Sidewall Center	42.42	42.47	0.116
Sidewall Bottom	68.62	69.64	1.459
Top Slab Left End	59.86	60.8	1.54
Top Slab Center	95.86	95.88	0.018
Top Slab Right End	59.86	60.83	1.588
Bottom Slab Left End	59.85	61.34	2.436
Bottom Slab Center	104.94	105.26	0.3
Bottom Slab Right End	59.85	61.35	2.452

**Table 6-25 Comparisons of bending moments for the Service I load combination of a single-cell box culvert**

Design Location	Design Moment (kNm)		Deviation of Results in %
	Using the software program	Using CSISAP2000v24.0.0	
Sidewall Top	48.76	48.78	0.03
Sidewall Center	26.58	26.62	0.14
Sidewall Bottom	49.31	49.43	0.23
Top Slab Left End	42.33	42.3	0.06
Top Slab Center	66.53	66.55	0.04
Top Slab Right End	42.33	42.32	0.02
Bottom Slab Left End	42.75	42.84	0.20
Bottom Slab Center	73.81	74.04	0.31
Bottom Slab Right End	42.75	42.84	0.20

**Table 6-26 Comparisons of Shear Forces for the Strength I load combination of a single-cell box culvert**

Design Location	Design Shear Force (kN)		Deviation of Results in %
	Using the software program	Using CSISAP2000v24.0.0	
Sidewall Top	90.75	93.46	2.90
Top Slab Left End	149.91	150.70	0.52
Bottom Slab Left End	180.20	179.85	0.19

**Table 6-27 Comparison of Flexural Reinforcements for single cell box culvert**

Structural Element	Design Location	Provided Reinforcement Bar Using the Software Program	Provided Reinforcement Bar Using the CSISAP2000v24.0.0
Top Slab	Left End	φ 16 C/C 160.0	φ 16 C/C 160.0
	Mid Span	φ 16 C/C 100.0	φ 16 C/C 100.0
Bottom Slab	Left End	φ 16 C/C 180.0	φ 16 C/C 180.0
	Mid Span	φ 16 C/C 100.0	φ 16 C/C 100.0
Side wall	Top End	φ 16 C/C 140.0	φ 16 C/C 140.0
	Mid Height	φ 16 C/C 240.0	φ 16 C/C 240.0
	Bottom End	φ 16 C/C 140.0	φ 16 C/C 140.0

**Table 6-28 Comparisons of bending moments for the Strength I load combination of a double-cell box culvert**

Design Locations	Design Moment (kNm)		Deviation of results (%)
	Using the software	Using CSISAP2000v24.0.0	
Exterior Sidewall Top	63.19	60.83	3.73
Exterior Sidewall Center	38.24	39.35	2.81
Exterior Sidewall Bottom	65.88	64.70	1.78
Interior Sidewall Top	0.13	0.13	0.00
Interior Sidewall Center	0.00	0.00	0.00
Interior Sidewall Bottom	0.13	0.13	0.00
Exterior Top Slab Left End	54.19	51.09	5.71
Exterior Top Slab Center	68.21	67.91	0.45
Exterior Top Slab Right End	108.93	113.01	3.61
Exterior Bottom Slab Left End	58.31	60.09	2.96
Exterior Bottom Slab Center	73.75	77.92	5.35
Exterior Bottom Slab Right End	105.73	103.13	2.45

**Table 6-29 Comparisons of bending moments for the Service I load combination of a  
double-cell box culvert**

Design Locations	Design Moment (kNm)		Deviation of results (%)
	Using the software	Using CSISAP2000v24.0.0	
Exterior Sidewall Top	43.57	41.87	3.90
Exterior Sidewall Center	18.80	20.30	7.37
Exterior Sidewall Bottom	46.64	45.75	1.91
Interior Sidewall Top	0.09	0.09	0.00
Interior Sidewall Center	0.00	0.00	0.00
Interior Sidewall Bottom	0.09	0.09	0.00
Exterior Top Slab Left End	36.81	34.56	6.12
Exterior Top Slab Center	47.54	47.28	0.54
Exterior Top Slab Right End	76.03	79.23	4.04
Exterior Bottom Slab Left End	40.71	42.09	3.29
Exterior Bottom Slab Center	52.05	55.18	5.67
Exterior Bottom Slab Right End	74.16	72.21	2.63

**Table 6-30 Comparisons of Shear Forces for the Strength I load combination of a double-  
cell box culvert**

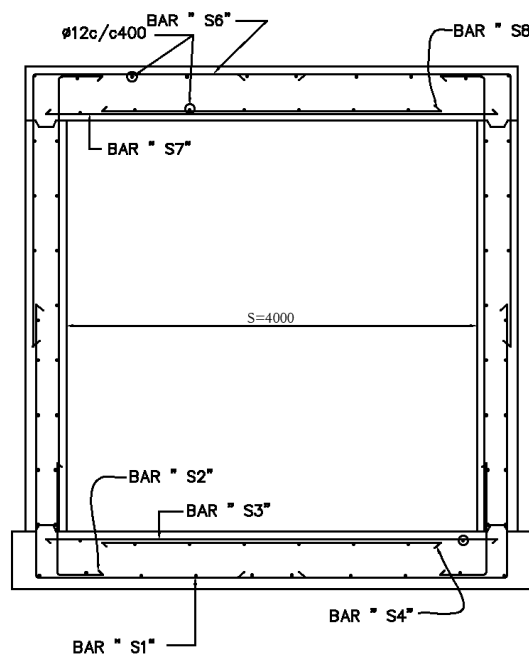
Design Locations	Design Moment (kNm)		Deviation of results (%)
	Using the software	Using CSISAP2000v24.0.0	
Exterior sidewall top	91.25	93.33	2.23
Exterior sidewall bottom	91.50	93.67	2.32
Exterior top slab left end	134.34	134.34	0.00
Exterior top slab right end	178.20	178.20	0.00
Exterior bottom slab left end	166.83	174.64	4.47
Exterior bottom slab right end	208.76	210.76	0.95

**Table 6-31 Comparison of Flexural Reinforcements for double-cell box culvert**

Structural Element	Design Location	Provided Reinforcement Bar Using the Software Program	Provided Reinforcement Bar Using the CSISAP2000v24.0.0 Program
Top Slab	Left End	φ 16 C/C 220.0	φ 16 C/C 220.0
	Mid Span	φ 16 C/C 190.0	φ 16 C/C 190.0
	Right End	φ 16 C/C 110.0	φ 16 C/C 110.0
Bottom Slab	Left End	φ 16 C/C 220.0	φ 16 C/C 220.0
	Mid Span	φ 16 C/C 190.0	φ 16 C/C 190.0
	Right End	φ 16 C/C 130.0	φ 16 C/C 130.0
Side wall	Top End	φ 16 C/C 200.0	φ 16 C/C 200.0
	Mid Height	φ 16 C/C 250.0	φ 16 C/C 250.0
	Bottom End	φ 16 C/C 190.0	φ 16 C/C 190.0

#### 6.4.2 Comparison between ERA Standard Drawing and the Software Output

In order to compare the ERA Standard Drawing with the software output, an analysis and design were performed for a single cell box culvert. The culvert has a clear height of 4 meters and a clear span of 4 meters. The fill height ranges from 2 meters to 6 meters. The assumed modulus of subgrade reaction for the analysis is 24000 kN/m<sup>3</sup>.



**Figure 6-13 Box culvert designation for single cell box culvert**

**Table 6-32 Comparison of reinforcement bars between ERA Standard Drawing and Software Output for Bottom Slab of Single Cell Box Culvert**

CLEAR SPAN [m]	WALL HEIGHT [m]	FILL HEIGHT, Hf [m]	TOP SLAB THICKNESS [mm]	WALL THICKNESS, W [mm]	ERA Standard Drawing						Software Output					
					BAR -S1		BAR -S3		BAR -S4		BAR -S1		BAR -S3		BAR -S4	
					φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]
4	4	2	270	250	20	125	20	250	20	250	20	180	20	320	20	320
		3	270	250	20	125	20	250	20	250	20	160	20	280	20	280
		4	400	250	20	125	20	250	20	250	20	140	20	280	20	280
		5	400	250	20	125	20	250	20	250	20	120	20	240	20	240
		6	460	250	20	125	20	250	20	250	20	110	20	220	20	220

**Table 6-33 Comparison of reinforcement bars between ERA Standard Drawing and Software Output for Top Slab of Single Cell Box Culvert**

CLEAR SPAN [m]	WALL HEIGHT [m]	FILL HEIGHT, Hf [m]	TOP SLAB THICKNESS [mm]	WALL THICKNESS, [mm]	ERA Standard Drawing						Software Output					
					BAR -S6		BAR -S7		BAR -S8		BAR -S6		BAR -S7		BAR -S8	
					φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]	φ	Spacing [mm]
4	4	2	270	250	20	125	20	250	20	250	20	190	20	300	20	300
		3	270	250	20	125	20	250	20	250	20	160	20	240	20	240
		4	400	250	20	125	20	250	20	250	20	150	20	260	20	260
		5	400	250	20	125	20	250	20	250	20	130	20	220	20	220
		6	460	250	20	125	20	250	20	250	20	120	20	220	20	220

The observed variation in results between the ERA Standard Drawing and the software output can be attributed to several factors, including:

- The ERA Standard Drawing does not provide specific details about the properties of the backfill material.
- ERA Standard Drawing does not mention the specific modeling technique employed during its preparation. Different modeling techniques can yield different results due to variations in assumptions.
- The ERA Standard Drawing does not specify the type of foundation material involved. Different types of foundation soils possess varying properties, including bearing capacity and settlement characteristics. Additionally, the rebar amount specified in the ERA Standard Drawing does not vary with different types of foundation soils. In contrast, the software output considers the type of foundation material, resulting in more accurate and customized results.

Considering these factors, it is expected that the lack of backfill material properties, unspecified modeling technique, and non-consideration of different foundation materials can contribute to variations in the results obtained from the ERA Standard Drawing compared to the software output.

## **CHAPTER 7      CONCLUSIONS AND RECCOMENDATIONS**

### **7.1 Conclusion**

In conclusion, the development of a comprehensive software program for the analysis, design, and detailing of box culverts is presented in this thesis. The software allows for the analysis and design of box culverts of any size and fill height while accounting for vertical displacement of the foundation soil using spring modeling. The proposed solution streamlines the design process, saving time and increasing accuracy while improving safety. The software generates analysis and design reports, as well as structural drawings.

The research findings also indicate that the software program developed in this research is reliable and provides comparable results to the widely used CSISAP200v24.0.0 software for the analysis and design of box culverts. The study shows that the amount of flexural reinforcement obtained from both software programs is similar. This provides confidence in the use of the software programs for the analysis and design of box culverts.

In conclusion, design charts have been prepared to illustrate the bending moment at various locations of the box culvert. However, due to the complexity of designing box culverts and the numerous parameters involved, it is challenging to account for all potential scenarios and non-dimensionalize the design charts. Nonetheless, the design charts presented in this study can serve as a valuable resource for designers seeking to understand the bending moment variations of box culverts with varying opening sizes and fill heights.

## **7.2 Recommendation**

Based on the research presented in this thesis, the following recommendations are made:

- The proposed solution accounts for the vertical displacement of foundation soil using spring modeling, which results in more accurate and reliable results. Therefore, it is recommended that this feature be used in the analysis and design processes.
- The software program generates detailed analysis and design reports, as well as structural drawings, which streamline the design process and save time. It is recommended that the generated reports and drawings be used in the design process to improve efficiency and accuracy.
- To enhance the accuracy and efficiency of the design process, it is recommended to use the software program developed in this research rather than relying on the design charts. The software program provides more flexibility in adjusting various design parameters.

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## **APPENDIX A: SAMPLE STRUCTURAL DRAWINGS**

This section presents sample structural drawings double cell box culvert. The drawing has been generated using the software developed in this study, showcasing the dimensions, reinforcement details, and general notes for each type of box culvert.



