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REVIEW OF CODES OF PRACTICE FOR THE DESIGN OF BOX CULVERTS FOR RECOMMENDATION FOR SOUTH AFRICAN BUREAU OF STANDARDS (SABS)

Written by

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ABSTRACT

The study is a comparative desk study of the application of the vertical earth load, traffic live load and the nominal earth pressure in the design methodology of culverts as outlined in TMH7 – Code of Practice for the design of highways bridges and culverts in South Africa Part 2, AASHTO LRFD Bridge Design specification and the DMRB volume 2 section 2 part 12 - BD31/01. It involves the theoretical design and analysis of five single cell reinforced concrete box culverts ranging from 2.1m to 6.0m under different fill depths ranging from 0 to 8.0m by applying load obtained using the three design manuals.

The objective of this study is to analyze the methodology involved in estimating vertical earth load on a culvert as outlined in the design manuals to ascertain relevance of the formulae and procedure in TMH7 or/and to recommend the most effective approach for evaluating the vertical earth load on box culverts specific and appropriate for South Africa. By comparing the load derivation methodology outlined in ASHTO LRFD and BD 31/01 and analyzing the load forces obtained from the analysis.

Box culverts are designed as rigid monolithic structures to withstand the maximum bending moment and shear force. The design involves the analysis of the various loads acting on the culvert with the weight of the overhead earth embankment being the most significant. The vertical earth load, live load and the lateral earth pressure acting on the culverts at various fill depth are manually derived from equations as outlined in the three design manuals. The culverts are modelled and analyzed in Prokon as two-dimensional plane frame structures using the frame analysis module by applying this load to determine maximum positive hogging moments, maximum negative sagging moments and maximum positive shear forces for each span for the top slab.

The load forces obtained for each span are then plotted against the soil cover depth to illustrate the discrete load effect of the vertical earth load and live load on the culverts at varying fill height and to determine the relationship between the culvert geometry, soil cover depth and the applied load. The result of the analysis shows that an increasing non-linear relationship exists between the load effects, the soil cover depth, and the span length. The dead load effect increases with increasing fill depth and culvert span while the live load effect diminishes with increasing fill height and culvert span i.e., for culverts buried at shallow depths, the traffic live load is the most critical load but as the height of the soil cover increases the dead load becomes more significant until a point is reached where the live load is totally insignificant.

The vertical earth loads obtained from TMH7 and BD31/01 are constant at a particular fill depth for each culvert despite the different span length. The vertical earth load for these two manuals is estimated from the soil cover depth and density, the load tabulated clearly is independent of the culvert geometry. The load obtained from AASHTO LFRD is the lowest and less than 20% of the load obtained from the other two design manuals. Unlike TMH7 and BD31/01, AASHTO LFRD considers the effect of the soil-structure interaction to adjust the vertical earth load on the structure which automatically reduces the load value. The vertical earth load values obtained from TMH7 and BD31/01 are generally more conservative as compared to those obtained from AASHTO LFRD.

Keywords: TMH7, AASHTO LFRD, BD31/01, culvert, vertical earth load, live load, span length, load effects.

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DEDICATION

To the Holy Spirit my helper, without whom am nothing. To my late brother Maurice Mpeta-Phiri Jnr, you will always be in my heart Jnr.

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List of acronyms

TMH7	Code of Practice for the Design of Highway Bridges and Culverts in South Africa
AASHTO LFRD	American Association of State Highway and Transportation Officials Load and Resistance Factor Design Bridge Design Specifications
BD31/01	The Design Manual for Roads and Bridges Volume 2 Section 2 Part 12: The Design of Buried Concrete Box and Portal Frame Structures
FEM	Fixed End Moment
MSM	Mid Span Moment
SF	Shear Force
UDL	Uniformly Distributed Load

CHAPTER ONE

INTRODUCTION

1.1 General Background

The design of culverts consists of five general steps; the hydrological design to determine the design flow, the hydraulic design to determine the geometric dimensions, size determination of available factory sizes when dealing with precast culverts, the structural design to determine reinforcement bar details and lastly the general culvert layout to determine the section type which is either single or multiple. The focus of this paper is solely on the structural design aspect.

The Manual for the visual assessment of road structures - TMH9 is the recommended guide in South Africa used when visually assessing culverts. A culvert is thus described as a buried structure consisting of a cellular unit or an opening/s within the structure used to convey water. Culverts are classified into two main types: major and lesser culverts in accordance with the clear span length and the total cross-sectional area of the opening. The major culvert has a rectangular or square opening with a clear span length equal to or greater than 2.1m but less than 6m or a diameter equal to or greater than 2.1m when circular. In all these cases the total cross-sectional opening is equal to or larger than 5m^2. The manual does not give dimensions for the lesser culverts but defines them as culverts smaller than major culverts.

The structural design of a culvert is performed to ensure that the culvert withstands any dead, live or earth loads acting on it. The applicable methodology for load specification in South Africa is outlined in the Code of Practice for the Design of Highway Bridges and Culverts in South Africa - TMH7 Part 2 (1981). The strength of a culvert is greatly influenced by the material composition of the culvert and the geometric properties such as the shape. Culverts are of different shapes – box, arch, circular and slap and are made from different material – reinforced concrete, stones, steel, plastic, aluminum and High-density polyethylene, at times materials are combined to form composite structures. The most widely used culverts in South Africa are reinforced concrete box culverts; rectangular or square in shape which are precast or cast in-situ.

Box culverts consists of the top slab, vertical side walls and the bottom slab all monolithically connected. The top slab depending on the site condition can be at the road level or buried below the road level. The bottom slab reduces pressure on the soil by acting as a mat foundation and can be used on weak soils hence requires no separate foundation. The top slab is designed to withstand dead loads (self-weight and imposed dead loads) and traffic live load, the sidewalls the earth and water pressure while the bottom slab is required to withstand dead loads (the culvert total self-weight and imposed loads) and imposed pressure loads.

Box culverts are designed as rigid monolithic structures to withstand the maximum bending moment and shear force. The design involves the analysis of the various loads acting on the culvert with the weight of the overhead earth embankment being the most significant, Kim and Yoo (2000) considers the effect from live load insignificant in deeply buried culverts. The TMH7 part 2 outlines ways of computing the vehicular loading, vertical earth loading, and the nominal pressure caused by soil filling on the side walls of the culvert. The effect of seismic activity is ignored in the code and found irrelevant since the culvert span is considered to be less than 6.1m.

The TMH7 part 1 and 2 was first published in 1981 and uses a simple design approach requiring the use of increased partial safety factors for the determination of vertical earth loading on culverts. The revisions and errata for the TMH7 Part I and 2 were issued in 1988 (Anderson,2006) with no changes made to the culvert design section. When compared to other design codes used in culvert design for instance the ASHTO LRFD Bridge Design Specifications and the DMRB volume 2 section 2 part 12 - BD 31/01, TMH7 is the least revised and updated.

Most parts of the bridge design section in TMH7 are based on the British Standard BS5400 which has since been superseded by the Eurocode 1 Part 2 (EN 1991-2) in 2010. Eurocodes are pan European design codes and like the British Standard codes apply the limit state design. Since the codes are used in different countries in Europe, each country is at liberty to publish country specific safety related parameters in the form of Nationally Determined Parameters (NDPs) used in conjunction with the Eurocode of interest. The design of buried concrete structures subjected to traffic loading is covered in DMRB volume 2 section 2 part 12 - BD 31/01. This document sets the Standard requirements for and gives advice on the design of buried concrete box and portal frame structures of precast and cast in-situ construction up to 15 meters long from abutment to abutment and with up to 11m of fill above the roof slab.

This dissertation analyses the methodology involved in determining the culvert’s vertical earth load as outlined in TMH7 part 2 to ascertain relevance of the formulae and procedure or/and to recommend an update to the methodology. This is achieved by analyzing the methodologies as presented in ASHTO LRFD and BD 31/01, and then comparing with what is outlined in TMH7.

1.2 Purpose of the study

The purpose of this study is to review the computation methodology for the design of culverts as outlined in TMH7 – Code of Practice for the design of highways bridges and culverts in South Africa Part 2, sections 2.33 to 2.4 (vertical earth loading on culverts and earth pressure on retaining structures) and in AASHTO LRFD Bridge Design specification (section 12.11- Reinforced concrete cast in place and precast box culverts and reinforced cast in place arches) and the DMRB volume 2 section 2 part 12 - BD 31/01 (section 3 – Loading).

A 2d structural frame analysis will be carried out in Prokon for various single span culverts at various soil cover depths by applying the above design manuals. The maximum bending moment and shear forces obtained are used to establish a comparison in the methodologies presented and to determine the most effective methodology for culvert load analysis and to establish need for updating the TMH7 culvert load section.

1.3 Objective of the study

The main objective of this research is to recommend the most effective methodology to determine the vertical earth load acting on box culverts specific and appropriate for South Africa and to determine need for updating the TMH7.

Specifically, this study reviews.

i. The vertical earth load and the vehicular live load formulae on culverts due to earth embarkments.
ii. Application and effect of the vertical earth load on concrete box culverts at varying soil depth.
iii. Relationship between the culvert span and the soil cover depth.
iv. Relationship between the vehicular live load and the soil cover depth.

1.4 Scope and Limitation of the study

The study is a comparative desk study of the application of the vertical earth load, vehicular live load and the nominal earth pressure in the design methodology of box culverts as outlined in the TMH7 Part 2, the AASHTO LRFD and the BD31/01 with emphasis placed on the vertical earth load. It involves the theoretical design and analysis of five single span concrete box culverts ranging from 2.1m – 6.0m under different soil depths of 0 – 8.0m by applying load obtained using the three design manuals. The aim of the design is to compare the results obtained in terms of the maximum load forces i.e., end moments, mid span moments and shear forces.

Being a hypothetical design, the absence of field data offers a challenge in that since no testing was conducted on similar culverts, the study lacks actual field data obtained from instrumentation as a basis for result comparison but relies solely on other similar studies. Also, since the vertical earth load, vehicular traffic load and lateral earth pressure are the only loads considered in the design part of the study while ignoring any other factors the results obtained are conservative.

1.5 Outline of the study

Chapter 1: Introduction

Provides a background summary of culverts in general and a basic introduction of the TMH7 Part 2, the AASHTO LRFD and the BD31/01. The purpose and objectives of the study are defined, followed by the scope and limitation of the study.

Chapter 2: Literature Review

This chapter discusses the vertical earth load on buried structures as presented in literature discussing the load calculation, effects, and distribution. A review the methodology for the vertical and lateral earth load as outlined in the three design manuals is presented.

Chapter 3: Methodology – Load Application

Details the analytical methods applied to determine the position and values for the dead, live and lateral earth load applied in the analysis depending on the design manual. The results obtained are presented in tables and graphs. The section also describes the design analysis methodology of the culverts in Prokon.

Chapter 4: Analysis and Discussion

This section presents the 2d analysis of concrete box culverts various depth and the results obtained in Prokon for the TMH7 Part 2, the AASHTO LRFD and the BD31/01. A comparison discussion regarding the obtained results is then presented.

Chapter 5: Summary and Conclusion

The main points of the study detailing the review, conclusion, and recommendations regarding the TMH7 - vertical earth loading on culverts are presented. Reasons for the recommendation are and the need for further detailed research in culvert design in South Africa are also presented.

CHAPTER TWO

LITERATURE REVIEW AND REVIEW OF THE CODES

2.1 Introduction

Culverts are buried structures constructed under roadways or railways. Culverts are designed to determine the configuration and strength of the concrete and the reinforcing bars to withstand maximum bending and shear force under the subjected loads. Generally, this load can be categorized into primary and secondary loading. The primary loads include the dead load, live load and the earth pressure. Secondary loads are sophisticated to come up with due to them being unpredictable and localized; several factors exist causing such kinds of loads, these factors include volume change in compressive soils due to change in moisture and soil pressure change due to plant roots among other factors.

The dead load comprises of self-weight of the earth fill cover acting on the culvert and any other super imposed dead load, the top and bottom slab of the culvert and the side walls of the structure while the live load is largely vehicular loading on the road surface. The significance of the load acting on the culvert is dependent on the geometry and stiffness of the culvert i.e., shape, thickness, material, roadway use and the general soil characteristic since this affects the stress redistribution in the surrounding soil.

The weight of the earth fill cover is the most significant design load, Kim and Yoo (2000) considers the effect from live load insignificant, with the live loads only becoming significant when the overhead earth cover is shallow. In a study by Orton et al. (2013) it was determined that at above 1.8m of cover soil depth, the measured effect of the live load was less than 10% of the dead load effect. This was thus considered as a point at which the effect of the live load on the culvert could be ignored during design. A shallow backfill cover on box culverts is an example where the effect of the live load is important.

Box culverts are four-sided reinforced concrete, closed rigid structures rectangular or square in shape built across road or train ways. Based on the hydraulic requirements the culverts are either single or multiple section (cell) and are determined from the required culvert height and area. Box culverts are composed of the top slab, bottom slab and two side walls monolithically built. The structural design is carried out with information obtained from a hydraulic report; information such as the culvert length, head water level, water velocity, head loss, side slope and the ground level is vital. This information for instance; the head water level is then used to determine whether the culvert should be designed as submerged or not with the determined design flow.

2.2 Vertical earth loading on culverts

Marton-Spangler was the first to propose and develop analytical solutions to determine vertical earth pressure on buried rigid conduits and culverts Marston and Anderson (1913). The theory recognizes that the amount of load taken by a pipe is affected by the relative movement between the backfill and the natural soil, as settlement of both the backfill and pipe occurs Cameron, D.A (1991). The formulae developed became the basis for most formulae currently applied in the design of buried structures.

The earth pressure acting on deeply buried culverts is significantly affected by arching (Vaslestad et al. 2011). For instance, when box culverts are designed as rigid structures the obtained vertical earth pressure is greater than the weight of the backfill material on the culvert resulting in a negative arching effect, unlike flexible culverts where the weight of the backfill material is less than the vertical earth pressure resulting in a positive arching effect. In a study by Yang (2000), it was observed that the magnitude and distribution of earth pressure was greatly influenced by the relative stiffness of the soil and the culvert, the modulus of the founding soil and the level of the compaction of the fill area around the culvert. The compactive effort seem to have a greater significant influence on the horizontal earth pressure distribution on the culvert walls.

2.2.1 Review of culvert vertical earth loads - TMH7 part 2

The specifications for loads on culverts in South Africa is documented in the Code of Practice for Bridges and Culverts in South Africa - TMH7 Part 2 (1981). The code comprises of two sections dedicated to culvert design loading. Sections 2.33 covers the vertical earth load and the effect of this loading due to earth embankments and section 2.4 which addresses the earth pressure on retaining structures including the side walls of the culvert.

The manual states three different approaches for evaluating the vertical earth load but puts emphasis on only one approach which is an extension of the AASHO and CPA formulae. This approach applies simple design rules to both rigid and flexible culverts using increased partial safety factors to allow for the approximate nature of the of the formulae.

2.2.1.1 History of the AASHO formula

The use of a formula within a condition and with material for which it was never intended for can lead to erroneous or even inconclusive results it is thus important to know the limitations and basic assumptions of any adopted formula. TMH7 does not state the AASHO and CPA formulae in reference making it hard for the writer to determine the relevance of the mentioned formulae.

The AASHO formula was obtained from the AASHO road tests carried out in the 1950s by the American Association of State Highway and Transportation Officials (AASHTO). The tests involved monitoring moving loads of a known magnitude on a highway pavement or bridge structures of known thickness and studying the performance of the pavement to the applied loads. This information was then applied to improve the design and construction of pavements and bridges. According to the AASHO road test report 4 (1962) the bridge experiment was included in the AASHO Road Test to determine the significant effects of specified axle loads and gross vehicle loads when applied at known frequency on bridges of known design and characteristics.

2.2.1.2 Simple Design Approximate Method for Vertical Earth Loading

TMH7 manual mentions three approaches used to determine the vertical earth pressure, but as a way of simplifying the load determining procedure only the first approach is covered in the manual. This approach offers four appropriate equations for use in determining the value of the vertical earth load. Below are the approaches as outlined in the manual.

i. The first approach applies simple design rules to both rigid and flexible culverts. This method though simple requires the use of increased partial safety factors due to the approximate nature of the formulae.

ii. The second approach is the use of sophisticated design rules to both rigid and flexible culverts. This method puts into consideration the culvert type, soil properties, trench size and the culvert projection. This method allows the use of reduced partial safety factors.

iii. The third approach is the use of sophisticated design rules to flexible and special type of culverts. This method uses a phenomenological approach.

Four equations used for calculating the unfactored vertical earth load are outlined in the manual. The manual does not cover negative projecting culverts as such the equations presented cannot be applied in the design of such culverts. Negative projecting culvert are culverts installed in a shallow trench so that the top slab of the culvert is below the natural ground level and then backfilled to a level above the natural ground level as shown in figure 1.1.

The equations mention a number of conditions to be applied; the first equation is used for culverts in a trench on unyielding foundation with no projection; this is a culvert placed in a narrow excavation and backfilled to the normal ground level on firm uncompressible founding material.

Culvert in trench on unyielding foundation with no projection:

$$g_1 = 10\rho h \, x \, 10^{-3} \; \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . \; 1$$

The second equation applies to an untrenched culvert on a yielding foundation which is a culvert laid on ground level and backfilled to the desired level founded on compressible material.

i. Culvert untrenched on yielding foundation:

$$g_2 = 10\rho h \, x \, 10^{-3} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2$$

The conditions for the third and fourth equations are similar to the second equation except that the height of the backfill material is also considered.

ii. Culvert untrenched on unyielding foundation for h >1.7b:

$$g_3 = \rho(18.83h - 8.54b)x \, 10^{-3} \; \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \; 3$$

iii. Culvert untrenched on unyielding foundation for h ≤ 1.7b:

$$g_4 = 25.4\rho b \, (e^{\alpha} - 1)x \, 10^{-3} \; \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . \, . \ldots \; 4$$

Where: α - $0.38\, h/b$

g_n - unit vertical loading due to low fill in $\frac{kN}{m}^2$ for cases n= 1 to 4

h - height of earth fill cover in meters

b - overall width of the trench or if untrenched the overall width of culvert in meters

ρ - effective density of fill material in $\frac{kg}{m}^3$

e - base of natural logarithm = 2.7183

From the four equations, the vertical earth load is a factor of density of the back fill material and the height of the backfill material. Since most box culverts are trenched, emphasis is placed on the first equation. The equation is a concise estimate of the vertical earth load ignoring the effect of the overall trench width or the culvert width which are considered in equations 3 and 4. The interaction between the culvert and the trench material or backfill material is ignored in the manual. Buried culverts

Buried conduits are classified according to the installation type which is in relation to the natural ground level. There are three common installation methods: trench/ditch, positive projection embankment and negative projection embankment. Trench/ditch conduits are installed in a trench with the top of the conduit below the natural ground level, positive projecting conduits are installed in such a way that the top of the conduit is above the natural ground level whereas the negative projecting conduit is installed in a shallow trench below the natural ground level which is then backfilled to a level higher than the natural ground level. Refer to figure 1.1 for a pictorial presentation of these three methods.

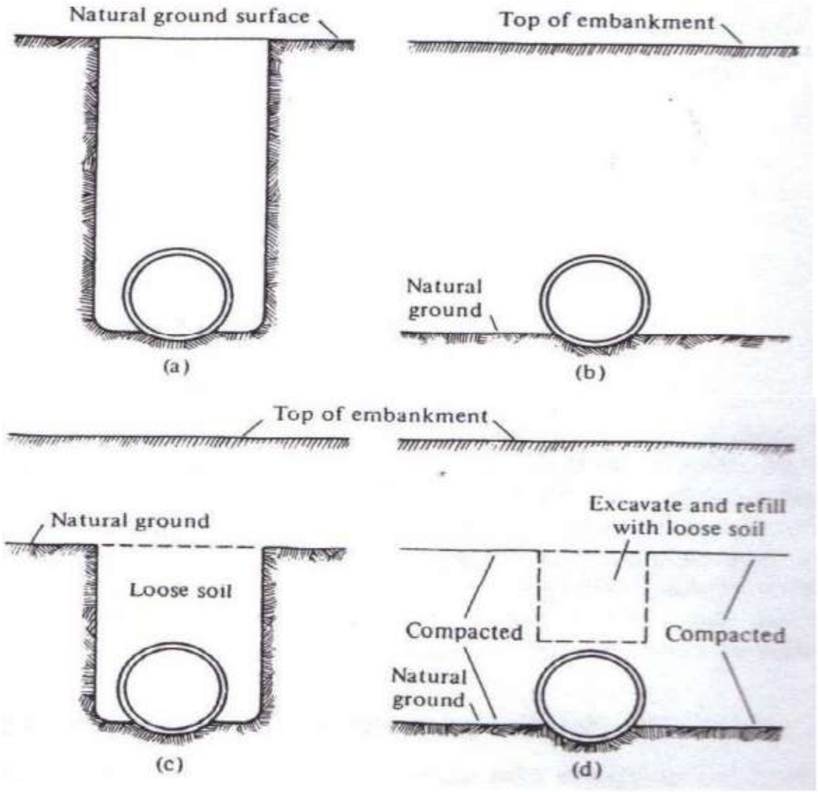


Figure 1.1: (a) Trench conduit, (b) Positive projection embankment (c) & (d) Negative projection embankment (Spangler, 1982)

As previously mentioned, the vertical earth loading is the most significant design load in buried structures. A. Goyns (2009) mentions four parameters which considerably influence the backfill load on buried conduits. These factors are the installation method, the backfill height over conduit, the density of the fill material and the effective trench/ditch width. The SANS 10102-1 adds cohesion of friction properties of the fill material, relative stiffnesses, settlements of the conduit, the fill and the in-situ material to this list.

The trench width seems to have a significant effect on the earth load acting on a buried conduit, for instance placing the conduit in a ditch way wider than it increases the earth load on the structure since the trench walls will not carry any load on behalf of the conduit. When the trench width is at a minimum, upward frictional forces develop from the interaction between the trench wall and the conduit thereby reducing the load carried by the conduit, thus reducing the weight of the fill material on the conduit. Two factors influence the density of the fill material - the degree to which the material has been compacted and the general nature of the material.

The Marston-Spangler formula employs the active earth pressure to compute the vertical earth load on buried conduits shows the effect of the trench width on the fill load i.e.

$$W = C_d w {B_d}^2 \ldots\ldots\ldots 5$$

Where: W - load on the conduit in kN/m

w - unit weight of backfill in kN/m^3

B_d - trench width on top of conduit in m

C_d - load coefficient which is a function of the backfill height to the trench width

(H/B$_d$) and of the friction coefficient between the backfill and the side of the trench.

The value for the load coefficient can be obtained from charts or calculated from the formula below i.e.

$$C_d = \frac{1-\exp(-2k\mu'.H/B_d)}{2k\mu'} \ldots\ldots\ldots 6$$

Where: k - coefficient of active pressure

μ' - $(\tan\varphi')$, φ' is the Angle of sliding friction between the backfill and trench sides. These values are given in charts for corresponding angles of friction.

2.2.2 Review of culvert vertical earth loads – AASHTO LRFD Bridge Design Specification

The National Highway Bridge Specifications used previously in the United States of America for bridge and culvert design were first published in 1931. Through extensive effort in the late 1980s and early 1990s, AASHTO was developed and later the LRFD for bridge design was adopted with its first publication in 1994. The final edition was eventually released in 2002 (Pierce,2015). This edition has been revised several times over the years and the one currently in use is the 9th edition which was released in 2020.

The AASHTO LRFD Bridge Design specification applies the load and resistance factor design in its design methodology. The code outlines two formulae in section 12.11.2.2 – modification of earth loads for soil – structure interaction, the formulae are for unfactored vertical earth load acting on the culvert in terms of the construction methods i.e. embankment and trench installations. In an embankment installation, the culvert has the top slab projecting above the natural ground level then covered with the fill material whereas in a trench installation the culvert in a narrow trench has the top slab below the natural ground level then covered with the fill material (Akbas & Yuksel,2015).

i. For embankment installation;

$$W_E = F_e \gamma_s B_c H \qquad \ldots 7$$

in which $F_e = 1 + 0.20\frac{H}{B_c}$ ……………………………………………8

ii. For trench installation.

$$W_E = F_t \gamma_s B_c H \qquad \ldots 9$$

in which $F_t = \frac{C_d {B_d}^2}{H B_c} \leq F_e$ ……………………………………………10

Where W_E - total unfactored earth load (kip/f)

B_c - outside width of culvert (ft)

H - depth of backfill (ft)

F_e - soil-structure interaction factor for embankment installation as specified by formula

F_t - soil-structure interaction factor for trench installation as specified by formula

γ_s - unit weight of backfill (kcf)

B_d = horizontal width of trench (ft)

C_d = load coefficient obtained from chart 1.

Both formulae take into consideration the trench width, the backfill height and the effective density of the fill material. Unlike the TMH7 formulae, the soil-structure interaction is considered which is a function of the height of backfill to the trench width. This function differs for the two installation methods in that the function for the trench installation considers the effect of the culvert width and load coefficient (C_d); this coefficient as previously mentioned is a factor of the active pressure and the angle of sliding friction between the backfill and trench sides.

2.2.3 Review of Culvert Vertical Earth Loads – BD 31/01 Volume 2

The United Kingdom uses the Design Manual for Roads and Bridges (DMRB) volume 2 section 2 Highway Structures Design: (Substructures, Special Structures and Materials) Special Structures part 12 BD 31/01-The Design of Buried Concrete Box and Portal Frame Structures design manual for roads and bridges BD 31/01 Volume 2, Section 2, Part 12 as the standard for design of buried concrete box and portal frame structures.

The manual classifies the weight of the backfill material and road construction material above buried structures as the nominal superimposed dead load applied as a uniformly distributed load. Positive arching which might reduce the backfill load is ignored in the manual but effects of consolidation of the backfill material adjacent to the buried structure is considered. Settlement of this material results in negative arching of the backfill material on top of the structure which increases the weight of the cover material. Two formulae are provided for determining the imposed dead load intensity in cases where it is not possible to determine the effects of settlement experienced between the buried structure and the adjacent fill material.

i. The minimum superimposed dead load intensity

$$SDL_{min} = \gamma H \quad \ldots\ldots 11$$

ii. The maximum superimposed dead load intensity

$$SDL_{max} = \beta\gamma H \quad \ldots\ldots 12$$

Where: H - backfill cover height in m

γ - average nominal bulk density of the fill and surfacing in kN/m^3

β - taken from Chart 1.2 and is a factor of the cover depth

From the two equations the SDL is a factor of the density of the fill material and the height of the backfill material. β is only considered when calculating the maximum SDL and from the figure β is constant for backfill cover depth of up to 8m.

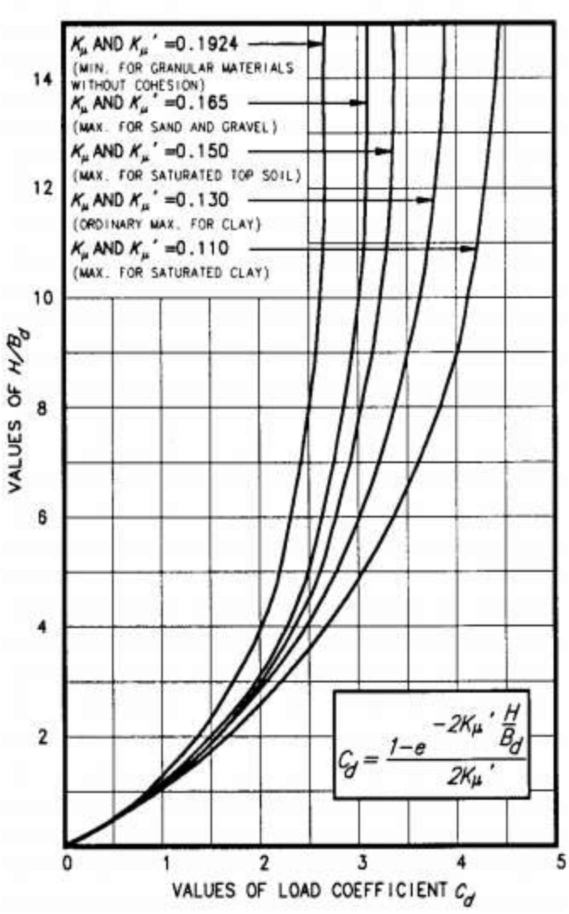


Chart 1.1: H/B_d v Cd (AASHTO, 2015)

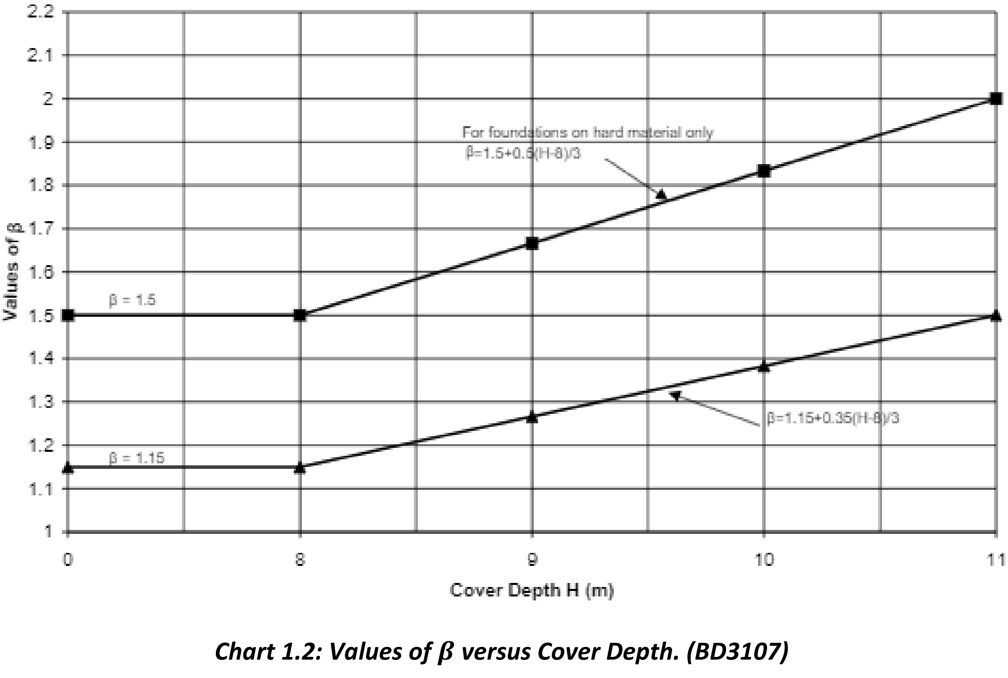


Chart 1.2: Values of β versus Cover Depth. (BD3107)

2.3 Review Earth pressure on culverts' side walls

The earth pressure on culverts side walls is determined from principles of soil mechanics of the backfill or adjacent material. The distribution of this pressure is influenced by the compaction level attained on the backfill material and the reaction of the structure to the applied load. An example is the deflection of the buried structure due to the loading. Culverts are designed as rigid structures as such the soil stiffness relative to the culverts' stiffness is not considered. Concrete and stony culverts are very stiff and experience no deflection such that the maximum lateral pressure experienced is the active earth pressure.

The Coulomb (1776) and Rankine (1857) theories are most commonly used to determine active and passive earth coefficients (Voitenko,2018). The Rankine theory relates the lateral earth pressure to the vertical earth pressure - the earth pressure coefficient is the ratio of the lateral earth pressure to the vertical earth pressure (Terzaghi et al. 1996). For culvert design the active pressure coefficient is of interest. The pressure is assumed to act on the vertical plane at an angle parallel to the backfill. The back slope angle β will influence the pressure coefficient as can be seen from the pressure coefficient formulae.

$$P_a = K_a \, \omega \quad \ldots\ldots 13$$

Where P_a - the lateral active earth pressure

K_a - Rankine active earth pressure coefficient

ω - vertical pressure on any horizontal plane in the backfill

For a level back slope (β = 0):

$$K_a = \frac{1 - Sin\emptyset}{1 + Sin\emptyset} \quad \ldots\ldots 14$$

$\emptyset$ - angle of the internal friction of the soil

And for a sloping back slope (β > 0):

$$K_a = \mathrm{Cos}\,\beta \, \frac{\mathrm{Cos}\,\beta - \sqrt{\mathrm{Cos}\,\beta^2 - \mathrm{Cos}\,\emptyset^2}}{\mathrm{Cos}\,\beta + \sqrt{\mathrm{Cos}\,\beta^2 - \mathrm{Cos}\,\emptyset^2}} \quad \ldots\ldots 15$$

The AASHTO LRFD Bridge Design manual states that the equivalent fluid method can be used to determine the Rankine earth pressure. This method is only recommended for free draining backfill material. The basic earth pressure p;

$$p = \gamma_{eq} z \quad \ldots\ldots 16$$

Where: γ_{eq} - equivalent fluid unit weight of soil, not less than 0.030 (kcf) z - depth below surface of soil (ft)

The manual also contains a table from which the values of equivalent fluid unit weights for walls not exceeding 20feet are present. For a sloping backfill surface, the vertical and horizontal pressure resultant are obtained from equations 17 and 18.

$$p_v = p_h tan\beta \quad \ldots\ldots 17$$

$$p_h = 0.5\gamma_{eq}H^2 \quad \ldots\ldots 18$$

Where H is the total wall height measured from the surface of the ground to the bottom of the footing

For the Coulomb theory the Rankine coefficient in equation 14 and 15 is replaced by the Coulomb's active earth pressure coefficient i.e.

$$K_a = \frac{\sin^2(\alpha+\emptyset)}{\sin^2\alpha \sin(\alpha-\delta)[1+\sqrt{\frac{\sin(\emptyset+\delta)\sin(\emptyset-\beta)}{\sin(\emptyset-\delta)\sin(\emptyset+\beta)}}]2} \quad \ldots\ldots 19$$

Where α - angle of the back of retaining wall

δ - friction angle between soil and back of retaining wall

2.3.1 Approximate theory for earth pressure - TMH7 part 2

Earth pressure acting on retaining structures including sides of culverts is covered in section 2.4 of the manual. It is mentioned that the earth pressure regarded as the nominal pressure shall be determined from principles of soil mechanics from the properties of the backfill or soil material.

The equivalent fluid pressure theory is commended for use as an approximation with defined horizontal earth pressure values given for two classes of fill material – type I material - coarse grained sands with a low sill/clay content and type II material – fine, silty sand. The recommended pressure values are as presented in table below.

Fill Material Type	***Horizontal Earth Pressure Per meter depth***
Type I	5.6 kN/m²
Type II	7.8 kN/m²

Table 2.1: Horizontal Earth Pressure Per meter depth values

Provision is made for backfill material at a slope, the horizontal and vertical earth pressure can then be estimated by multiplying the equivalent fluid pressure by a factor k_h and k_v to determine the horizontal and vertical component of the earth pressure respectively.

$k_h = 1 + (9 \text{ x } 10^{-10}\beta_s^6)$……………………………………………………………………………20

$k_v = (15 \text{ x } 10^{-3})\beta_s + (65 \text{ x } 10^{-11}\beta_s^6)$………………………………………………………………21

Where β_s - angle of surcharge in degrees but not exceeding 33°

Similarly, as previously mentioned in section 2.3 the equivalent fluid pressure is only recommended for free draining backfill material. Unlike equation 18 as presented in the AASHTO LRFD Bridge Design manual, the horizontal component is influenced by the angle of surcharge.

2.3.2 Lateral Earth Pressure – AASHTO LRFD Bridge Design Specification

The AASHTO LRFD Bridge Design specification applies both the Rankine and Coulomb theories to determine lateral earth pressure. The lateral earth pressure is covered in section 3.11.5.1 in the manual.

The lateral earth pressure is assumed to increase non-linearly proportional to the depth of earth:

$p = k\gamma_s z$ ……………………………………………………………………………………………22

Where: p - the lateral earth pressure (ksf)

k - coefficient of lateral earth pressure

γ_s - unit weight of soil (kcf)

z - depth below surface of soil (ft)

The resultant lateral earth pressure occurring due to the weight of a backfill material is assumed to act at a height of H/3 above the base of the wall. The coefficient of lateral pressure is obtained from the Coulomb earth pressure theory as presented in equation 17. The manual discourages the use of silt and lean clay as a backfill material and where drainage in retained earth is restricted the effect of hydrostatic water pressure should be considered.

2.3.3 Lateral Earth Pressure - BD 31/01 volume 2

The manual outlines several formulae for the lateral earth pressure acting on the walls of the culvert sides depending on the load combination applied during design. Three load types are mentioned in the code – permanent loads, vertical live loads and horizontal live loads with the horizontal earth pressure categorized as a permanent load. The manual outlines three load combinations namely, combination 1, combination 3 and combination 4. Combination 1 consists of permanent loads, vertical live loads and horizontal live load surcharge, combination 2 consists of combination 1 and temperature effects whereas combination 4 consists of permanent loads and horizontal live load surcharge and one other load i.e., traction, centrifugal, accidental load due to skidding or collision load.

For the culvert design, combination 1 is considered a disturbing earth pressure acting concurrently on both side walls is experienced. This pressure is equivalent to:

$K_a \gamma D$ ……………………………………………………………………………………………23

Where γ - average nominal bulk density of the fill and surfacing in kN/m^3

D - depth of the culvert side wall at which the pressure is applied below ground level in m

And a minimum earth pressure is also applied to act concomitantly on the side walls which is equivalent to;

$0.2\gamma D$ ……………………………………………………………………………………………24

2.4 Summary

The review of the design manuals demonstrates the lack of detail in the vertical earth load estimation formula presented in TMH7 especially for trenched culverts on unyielding foundation with no projection (g_1). The vertical earth load is based on the fill height and density only, a concise procedure which overestimates the earth pressure. In actual sense, the culvert-soil interaction plays a huge role in determining the actual earth load carried by the culvert. A few factors exist governing the interaction of box culverts with the surrounding soil (Abuhajar,2017). These factors include soil arching, culvert geometry, thickness of the box culvert, fill depth and the fill density.

Soil arching occurs due to settlement of soil columns on the sides of the culvert, this effect is more significant in embankment installation or wider trenches or generally in very compressible soils where the soil column on top of the culvert settles less as compared to the soil columns on the side. This differential settlement causes stress redistribution around the culvert area resulting in an increase or decrease in the soil pressure.

The vertical earth load formulae in AASHTO LFRD is incisive, similar to the Marston-Spangler formula and considers the effect of the soil – structure interaction i.e., due to the culverts' width, the fill height and the fill density. The trench width has a significant effect on the earth load acting on the culvert, a trench wider than the culvert acts as an embankment installation since the trench walls do not carry the earth load hence increasing the earth load similar to the action of soil arching. When the trench width is at a minimum, upward frictional forces develop from the interaction between the trench wall and the structure thereby reducing the earth load on the culvert. To account for this effect the soil-structure interaction factor as well as the outside width of the culvert are applied in the vertical earth load formula. As such the vertical earth load obtained when applying AASHTO LFRD formulae are minimal and specific to the culvert, depending on the culvert width.

The TMH7 vertical earth load tabulation is equivalent to the minimum superimposed dead load intensity in BD31/01. Unlike TMH7, BD31/01 presents two formulae for the general tabulation of the superimposed dead load intensity: one for the minimum load (SDL_{min}) and the other for the maximum load (SDL_{max}) which is basically the SDL_{min} multiplied by a factor of the cover depth (β) giving very high vertical earth load values.

Side walls of buried culverts act as retaining walls causing lateral pressure from the adjacent soil on the walls. The pressure is determined from principles of soil mechanics of the adjacent material using the Coulomb or Rankine earth pressure theories. The lateral earth pressure formulae for all three design manuals are the same.

CHAPTER THREE

METHODOLOGY – LOAD APPLICATION

3.1 Introduction

To analyze the effect of the vertical earth load (cushion from the earth fill) on the culvert a hypothetical box culvert analysis and design is carried out. The effect is analyzed in terms of the reaction of the culvert in form of bending moments and shear forces obtained after an applied load. Although the focus is on the vertical earth load, analyzing the culvert with this single load alone is impractical since culverts are subjected to other load types acting at the same time with the earth load in real life. These loads include vehicular loads, lateral earth pressure, hydrostatic pressure from ground water, uplift, braking and accelerating forces just to mention a few (Ubani et al. 2020). Apart from the load type, the reaction of the culvert to any applied load is also influenced by; how the load is dispersed on the culvert in terms of the load as a point load or a uniformly distributed load, the position of the applied load along the culvert span, the culvert geometry i.e., span, depth and material composition, the culvert – soil interaction, the site condition, and the soil arching among other factors.

A number of studies exist to determine the effect of the various load types on a culvert; Ubani et al. (2020) studied the effect of soil compressibility on the structural response of box culverts using finite element approach. The paper mentions that a culvert depth of lesser or greater than 0.6m from the roadway crown affects how the wheel load is dispersed on the culvert top slab. For a depth less than 0.6m the wheel load is applied directly on the carriageway as a point load on the other hand the load is dispersed as a uniformly distributed load on the culvert when the depth is greater than 0.6m.

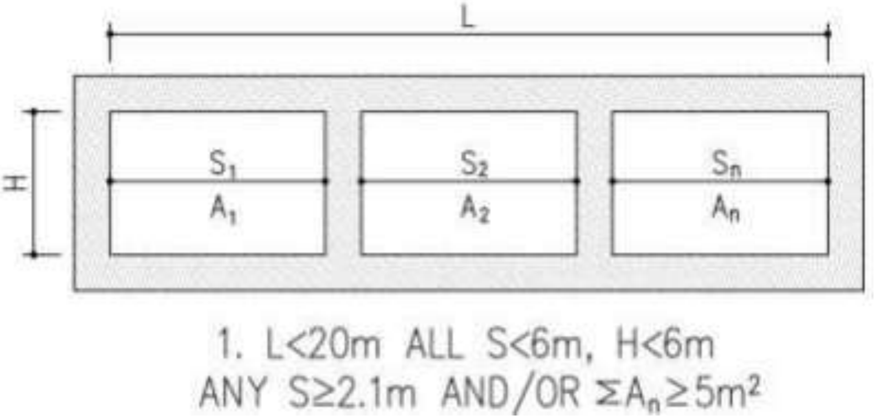
Orton et al. (2013) conducted a field study on ten existing reinforced box culverts with varying backfill cover depth ranging from around 0.8 to 4 meters to study how the live load was affected by the soil cover depth. The effect of the vehicular load; a truck load in this case on the culvert was then measured using strain transducers and linear variable differential transformers. It was concluded from the research that the effect of the live load was dependent on the soil cover depth; an increase in the cover depth diminished the effect of the live load. At a cover depth of greater than 1.8m the effect of the live load could be ignored since the measured effect at this depth was less than 10% of the dead load effect.

In another study Awwad et al. (2019) using finite element analysis, analyzed the wheel load distribution in four-sided concrete box culverts. A vehicular load - AASHTO HS20 wheel load and the vertical earth load were applied at the midspan of concrete box culverts of varying sizes and span lengths. The earth load was a factor of the cover depth which was varied between 0 and 3m and the wheel loads were projected on the culverts using the ASTM C890 procedure. The finite elements results showed among other things that the influence of the wheel load on the culvert top slab decreased significantly when the backfill cover was greater than 3m but for a single cell culvert the edge loading was more critical than the mid span loading for covers less than 0.9m.

Wood (2015) evaluated the influence of the cover soil depth, demand model sophistication and live load attenuation method – on the load rating of three cast-in place reinforced-concrete box culverts. Two demand models; structural-frame model and a soil-structure interaction model were analyzed in the study using data obtained from instrumentation mounted on culverts under varying cover fill depth. The writer observed that the structural-frame model was more simplified, produced conservative results and over predicted live loads in the bottom slab and side walls although the results for the top slab were reasonable. On the other hand, the soil-structure interaction model improved the live loading attenuation and impact more especially on the bottom slab and side walls.

3.2 Culvert Geometry

TMH19 defines a major culvert as a structure with a span of less than 20m and a height of not more than 6m refer to Figure 3.1a for a visual representation, any other culvert with dimensions lesser than those of a major culvert is classifies as a lesser culvert.



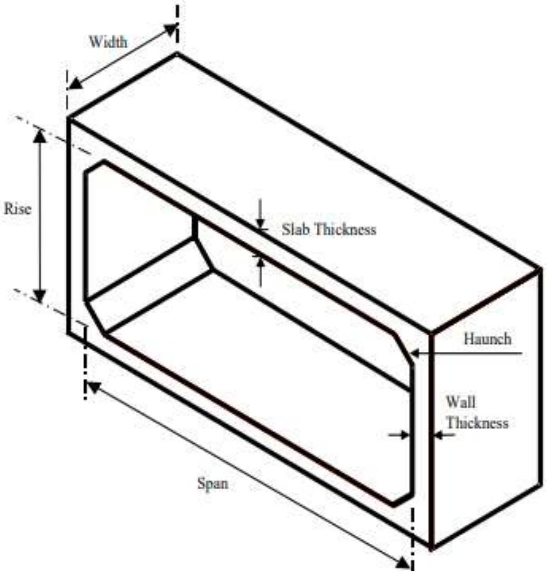


Figure 3.1: a) Major culvert visual representation (TMH7,1982) b) Box culvert geometric properties

Figure 3.1b shows the main geometric properties of a typical single unit box culvert. The culvert geometric design defines the design in terms of the span number (determined by the number of cellular units), the span length (S_1, S_2, S_n), box height/rise (H) and the aspect ratio which is the span over rise ratio (Wood,2015).

For the analysis, box culverts having the span length varying from 2.1m to 6m and varying heights are considered. According to the Rocla website - one of the leading precast concrete products manufacturers in South Africa, the standard culvert sizes available on the market have spans ranging from 0.45m to 3.6m and heights from 0.3m to 3m with culvert strength classes of 75S, 100S, 150S, 175S and 200S where S is the nominal span in meters. Proof loads for these strength classes are outlined in SANS 986. Since the maximum span length for a major culvert is 6m, other custom culvert sizes are considered for this study.

Table 3.1 below outlines the specifications for the culverts investigated in this study.

Span (m)	***Height (m)***	***Slab thickness (mm)***	***Wall thickness(mm)***	***Haunch (mm)***
2.1	2.1	200	200	200
3.0	3.0	250	250	250
4.0	3.0	275	275	275
5.0	3.0	300	300	300
6.0	3.0	350	350	350

Table 3.1: Single cell box culvert specifications

3.3 Dead Load

The culverts in this study are subjected to three load cases - dead load (DL), live vehicular load (LL)and a triangular earth pressure (EP) on the side walls. The dead load is a combination of the culvert self-weight and the earth fill, where the self -weight is a composition of the top slab, the side walls and the bottom slab dependent on the element under consideration.

The top slab is designed to withstand the self-weight, the weight of the vertical earth cover and any imposed load. The side walls are designed to withstand the earth pressure and the soil surcharge pressure while the bottom slab is designed to withstand the self-weight of the culvert as a whole and the weight of the earth fill. Calculation of the earth fill weight is specific to the design code as outlined in chapter 2.

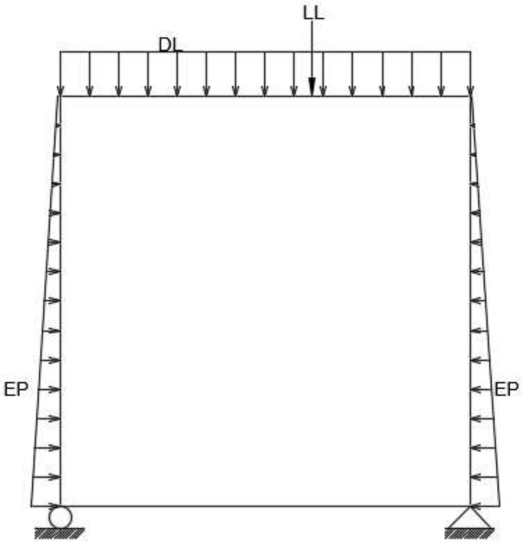


Figure 3.2a Load cases under consideration

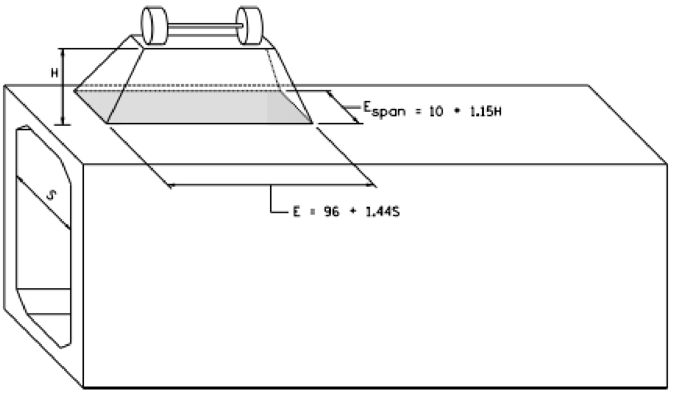


Figure 3.2b Traffic Traveling Parallel to Span for soil cover ≤ 0.6m

Adopted AASHTO (2014)

Earth pressure at rest is recommended for the analysis of the side walls Ubani et al. (2020).

3.4 Live Load

It is imperative that the vehicular load distribution through the earth fill be considered to attain a certain accuracy in the results obtained. The intensity of wheel loads is attenuated through the pavement layer, embankment soil, and the top slab of the culvert (Okeil et al. 2018). The depth of the cover soil directly influences the distribution of the live load on the culvert. AASHTO LRFD categorizes the soil fill heights into two categories, soil cover depth of less than 0.6m and soil cover depth greater or equal to 0.6m. For a fill cover depth of 0 to 0.6m the culvert is considered a direct traffic culvert (Wood,2015). At this depth the effect of the traffic load is more as a concentrated load on the culvert contrary to when the soil cover depth is greater or equal to 0.6m.

For direct traffic culverts, the traffic load is considered to be uniformly distributed over a rectangular area equal to E·Espan, as shown in figure 3.2b.

$E = 96 + 1.44S, \quad E_{span} = L_T + LLDF.(H)$ ………………………………………………………………25

Where E is equivalent distribution width perpendicular to span (ft)

S is clear span (ft)

E_{span} is equivalent distribution length parallel to span (in)

L_T length of tire contact area parallel to span (in)

LLFF = 1.15 factor of distribution of live load through soil cover depth

H is depth of soil cover (ft)

Where the soil cover depth is equal or greater than 0.6m the traffic loads may be considered to be uniformly distributed over a rectangular area with sides equal to the dimension of the tire contact area and increased by either 1.15 times the depth of the soil cover in select granular backfill, or the depth of the soil cover in all other cases. The load distribution area is shown in Figures 3.2c and 3.2d.

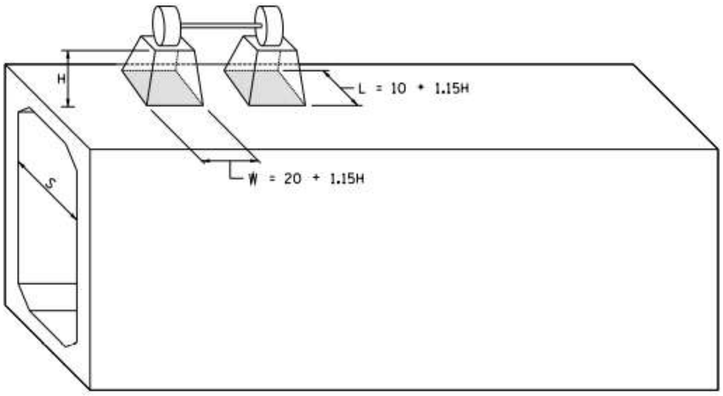


Figure 3.2c: Distribution load for traffic Traveling Parallel to Span for soil cover ≥ 0.6m for separate wheels Adopted AASHTO (2013)

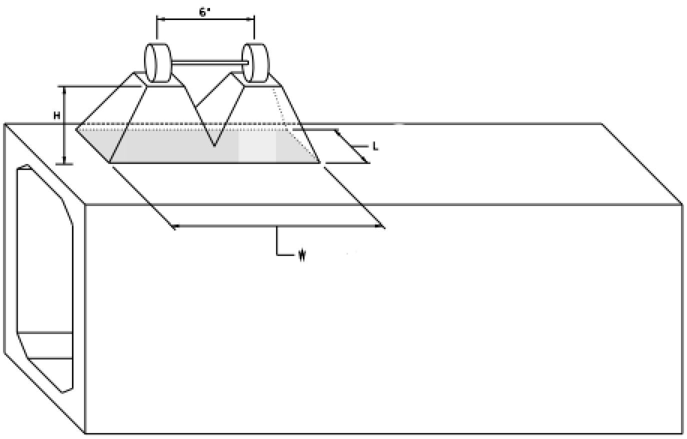


Figure 3.2d: Distribution load for traffic Traveling Parallel to Span for soil cover ≥ 0.6m for overlapping area Adopted AASHTO (2013)

The individual wheel distribution area through soil cover of greater or equal to 0.6m is L.W where;

$L = 10 + 1.15H$, $W = 20 + 1.15H$ ……………………..…………………………..…..……………..…*26*

when the distribution area is overlapping.

$L = 0.83 + 1.15H$, $W = \text{Axle spacing} + 1.67 + 1.15H$….……………………….…..………………..…*27*

with sides equal to the dimension of the tire contact area and 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.

For a single span culvert, the live load should be neglected when the soil cover depth is greater than 2.45m and exceeds the effective culvert span length i.e., the distance between inside faces of the end walls for multiple span culverts.

In TMH7 the traffic load consists of three components: Normal loading (NA), Abnormal Loading (NB) and Super Loading (NC). NA and NB loading are considered in this paper. The pressure of the on the culvert is assumed to spread out at approximately 45 degrees from the wheel point load to a uniformly distributed load with an increase in depth over a perimeter of area refer to figure 3.3.

a. NA Loading

The Na loading applied on rigid culverts consists of;

i. A uniformly distributed pressure applied on the surface area of the top slab q_{a1};

$$q_{a1} = \frac{36n}{b_r + 2h} \quad kN/m^2 \text{……………………………………………………………}28$$

where n is the number of nominal lanes,
b_r width of carriageway (m)
h soil cover to culvert (m)

ii. A uniformly distributed pressure strip (q_{a2}) which is superimposed on (q_{a1}) extended for a length of $(b_r + 2h)$ in the direction of the center line of the culvert applied to cause adverse effect.

$$q_{a2} = \frac{\sum_{i=1}^{n} \frac{120}{\sqrt{i}}}{(b_r + 2h)2h} \quad kN/m^2. \text{……………………………………………………}29$$

iii. Two 100kN wheel nominal loads not less than 1m apart applied separately of q_{a1} and q_{a2} loads above and distributed over two circular areas of π $(h + 0.2)^2 m^2$ applied anywhere on the top surface of the culvert to cause maximum effect.

b. NB Loading

The equivalent of 36 units of NB (NB36) is a single load (Q_b) applied over a contact area of 300 x 300 mm^2 on such positions as to cause maximum adverse effect spread through soil cover at 45 degrees. The load width b_h and length 1_h at the level of the top of the culvert are equal to (0.3 + 2h);

$Q_b = 1.25(90 + 12L_s^{1.8})kN$; L_s is the effective culvert span (m) ………………………………………30

For $b_h < (L_s + 0.3)$ the load width and Load length is increased by $0.7(L_s - b_h + 0.3)$ and $0.35(L_s - b_h + 0.3)$.

BD 31/01 considers two traffic load components – Normal load (HA) and Abnormal Load (HB) for culvert design. Unlike the TMH7, the fill cover determines the load combination.

c. HA Loading

i. For a fill cover of less or equal to 0.6m the HA load is not dispersed through the fill, HA is the combination HA UDL/KEL.

ii. For a fill cover of greater than 0.6m, the HA load is replaced by HB30 dispersed through the fill.

iii. A single 100kN HA wheel nominal load is dispersed through the fill, where this has a more severe effect on the member under consideration than the loads described in (i) or (ii) above.

d. HB Loading

i. For culverts on trunk and motor ways HB45 loading is applied whereas an HB30 loading is applied on other public highways.

ii. A loading of HB30 is also applied on all culverts on top of any HA loading only.

e. Wheel Load

At ground level the dispersion of the wheel load is assumed to be uniformly distributed spreading over a contact area, circular or square in shape, based on an effective pressure of 1.1N/mm

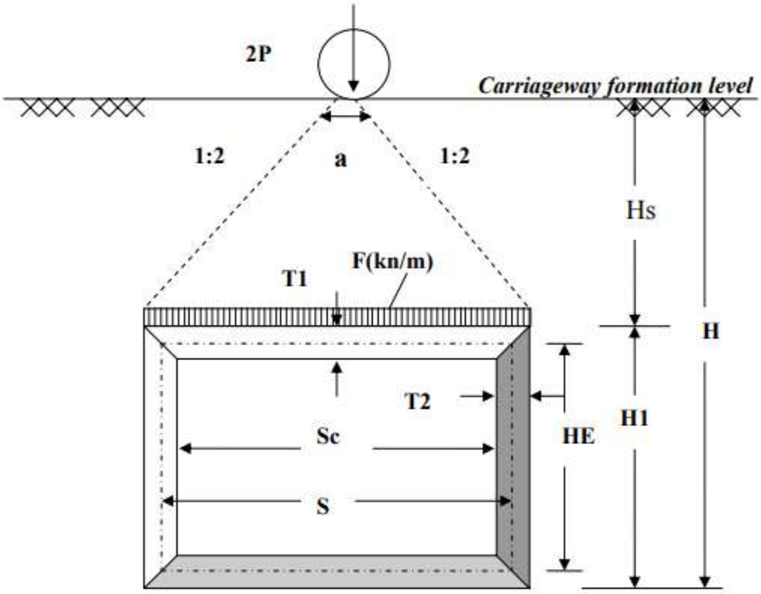


Figure 3.3 Live Loads distribution Adopted Ahmed (2006)

3.5 Overview of the design process

TMH7 does not specify analysis method for culvert design. The AASHTO Manual for Bridge Evaluations (MBE) recommends the use of a 2-Dimensional (2D) plane frame model to analyse culverts. The frame members are considered to be centred in the culvert members, with the frame supported at the bottom corners as a pin joint on one end and as a roller joint on the other with the forces in the model assumed to be in equilibrium. The approximate strip method is used for the design by considering a 1meter strip parallel to the culvert span. The structural-frame model is analysed with varying cover soil depth of 0, 0.6m, 1.0m, 1.5m, 2 m, 3m, 4.5m, 6and 8m with culverts span ranging from 2.1m to 6m as presented in Table 3.1.

As previously stated, the results are more conservative and the live load overpredicted for the bottom slab and side walls but since our focus is on the top slab, then the bending moments and shear forces obtained for the top slab should be sufficient for the comparison between the design codes of interest.

To simplify the design, the culverts are assumed to be empty and trenched on an unyielding foundation. The backfill material is a Type 1 material with a low silt or clay content and an effective density of 18kN/m^3. The coefficients of earth pressure Ka = 0.33 obtained from a repose angle of 30°, the rest of the material properties are listed overleaf.

Concrete Compressive Strength = 30 MPa

Reinforced Concrete Unit Weight = 24kN/m^3

Culvert Backfill Angle of Internal Friction = 30 degrees

The dead load considered is the culvert self-weight and weight of the soil cover fill over the culvert, the weight of the road surfacing is ignored. The live load considered are the NA and NB loads. Figure 3.4 shows the plan and axle arrangement of a unit NB load as presented in the code, the wheel axle and vehicle unit loading for the four-axle vehicle are presented in Table 3.2. Presented in the same table are load values by Anderson (2006) for an eight-axle wheel vehicle which were obtained from weigh-in-motion sensors on some South African toll roads. Figure 3.5 shows one of the recorded eight axle wheel configuration, the maximum vehicle weight recorded was 560kN.

		Non-steer (kN)
TMH7 ***Four-axle (1 unit)***	Per wheel Per Axle Per Vehicle	2.5 10 40
Anderson ***Eight-axle***	Per wheel Per Axle Per Vehicle	Varies Varies 560

Table 3.2 NB Loading Adopted TMH7 (1981) & Anderson (2015)

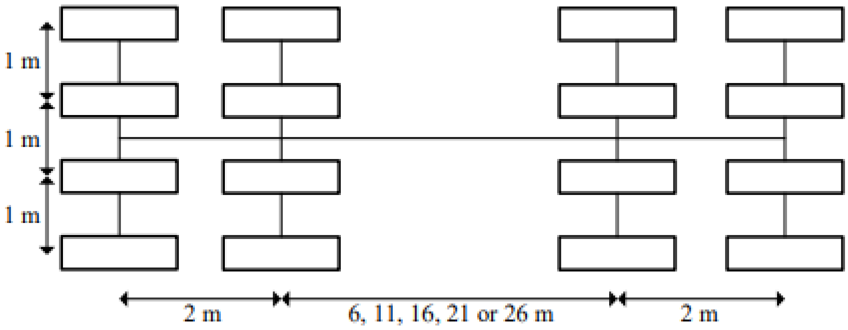


Figure 3.4 NB Loading Adopted TMH7 (1981)

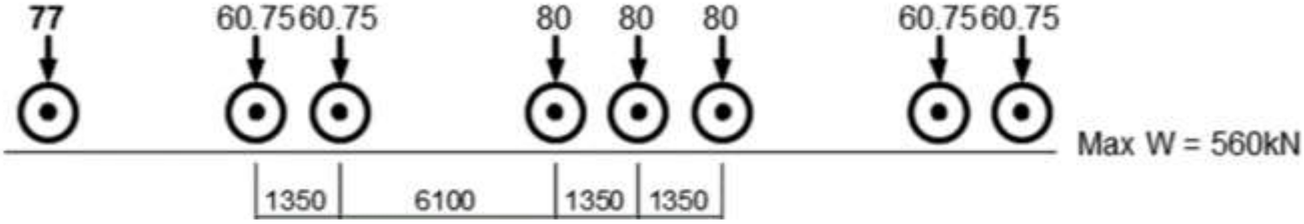


Figure 3.5 Eight-axle configuration Adopted Anderson (2006)

3.6 Structural-Frame Model Analysis

The Prokon frame analysis module is used in modelling the structural frames. Prokon is a finite element analysis software with various modules for structural analysis and design developed in 1989 (prokon.com, 2021). The module performs both static and dynamic analysis modes, the linear elastic frame analysis option will be considered for the frame models under consideration. In 2011 when Ahmed and Alarabi compared the results obtained from the manual analysis of several concrete box culverts using the moment distribution coefficients with those obtained from Prokon, it was concluded that the Prokon results were very close to the exact solution.

The relevance of this analysis is to determine the maximum bending moment and shear-force of the various single span (2.1m, 3m, 4m, 5m and 6m) culverts by applying the dead and live load obtained from the formulae in TMH7, AASHTO and the BD/31. The values obtained will then be compared against each other.

Box culverts are monolithic structures and normally analyzed as rigid frames with no consideration of sidesways. Depending on the founding material the culvert foundation is regarded as flexible on compressible support or rigid on hard material. For the analysis, the frame will be analyzed as having both top corner connections as fixed connections and having a pin joint on one bottom corner and a roller joint on the other as presented in figure 3.2a. The structure-soil interaction is not considered in the analysis since this is beyond Prokon’s jurisdiction.

3.6.1 Dead Load

The culverts' top slab dead load is the sum of the self-weight of the top slab, super imposed dead load and the weight of the soil at a particular depth obtained by using the formulae as per the code of interest. In this study the superimposed dead loads are ignored. The self- weight of the culverts' top slab are presented below, the vertical earth loads for the culverts at various depths are presented in Table 3.3. The obtained vertical earth loads are then plotted against the soil cover death.

Span (m)	2.1	3.0	4.0	5.0	6.0
Top slab self-weight (kN/m^2)	4.8	6.0	6.6	7.2	8.4

i. TMH7 part 2

All the culverts are assumed to be trenched on an unyielding foundation with no project. The unfactored unit vertical loading due to the earth fill was obtained using *equation 1* i.e. $g_1 = 10\rho h \; x \; 10^{-3}$. The unfactored vertical earth loads are presented in Table 3.3.

ii. AASHTO LFRD

The vertical unfactored load due to the earth fill for trench installation was obtained using *equation 9* i.e. $W_E = F_t \gamma_s B_c H$. The unfactored vertical earth loads are presented in Table 3.3.

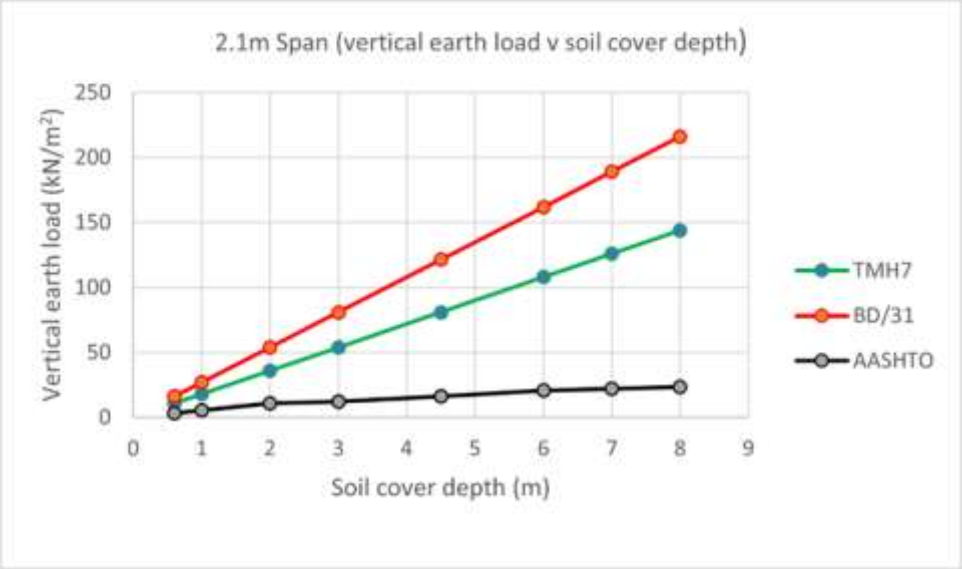
iii. BD31/01 - Minimum superimposed dead load intensity

The maximum superimposed dead load was obtained using *equation 1* i.e. $SDL_{min} = \gamma H$. The results obtained are presented in Table 3.3.

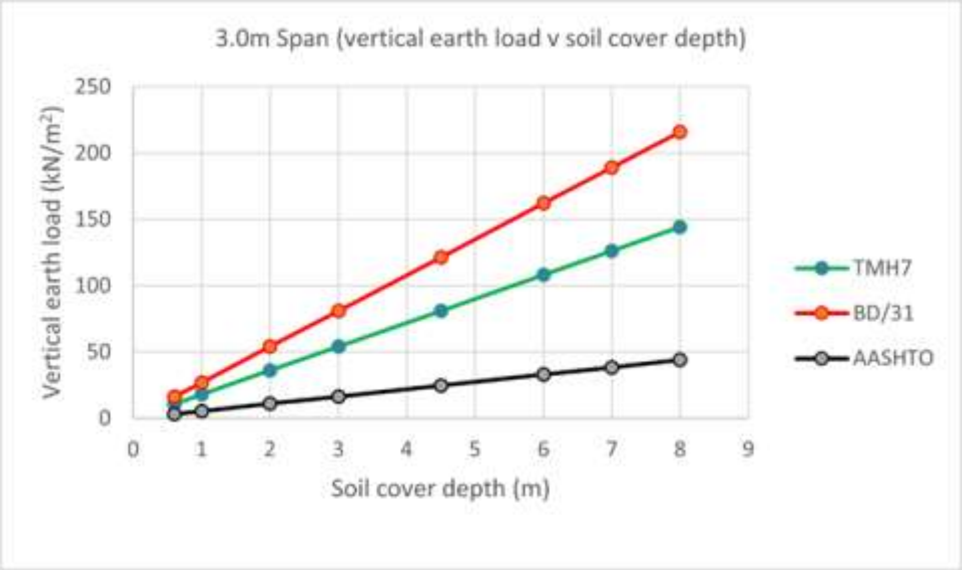
Soil cover depth (m)	***Vertical Earth Load for all spans (kN/m^2)***		***AASHTO Vertical Earth Load (kN/m^2) for span***				
	TMH7	***BD31/01***	**2.1**	**3.0**	**4.0**	**5.0**	**6.0**
0.6	10.8	16.2	3.3	3.3	3.3	3.3	3.3
1.0	18	27.0	5.5	5.5	5.5	5.5	5.5
2.0	36	54.0	11.0	11.0	11.0	11.0	11.0
3.0	54	81.0	12.3	16.5	16.5	16.5	16.5
4.5	81	121.5	16.5	24.7	24.7	24.7	24.7
6.0	108	162.0	20.6	32.9	32.9	32.9	33.1
7.0	126	189.0	21.9	38.4	38.4	38.4	33.1
8.0	144	216.0	23.3	43.9	43.9	43.9	33.1

Table 3.3 Vertical* Earth *Load (kN/m2) for spans

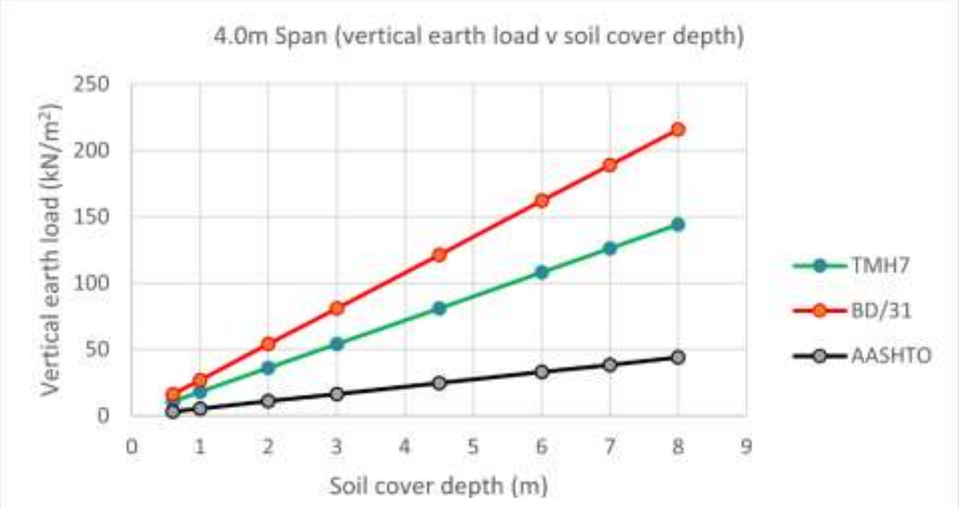
iv. Vertical earth load v soil cover depth graphs for spans



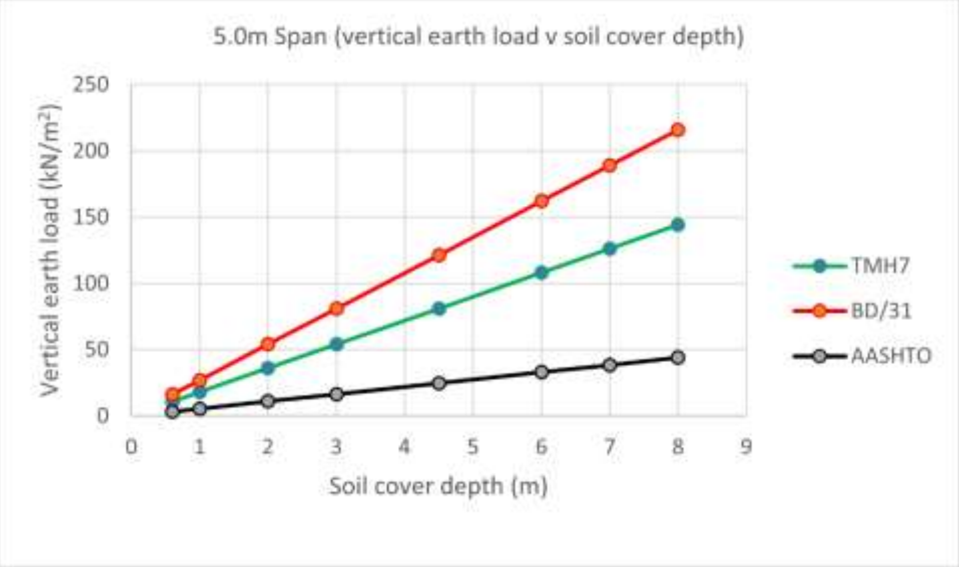
Graph 3.1: Vertical earth load v soil cover depth for 2.1m span



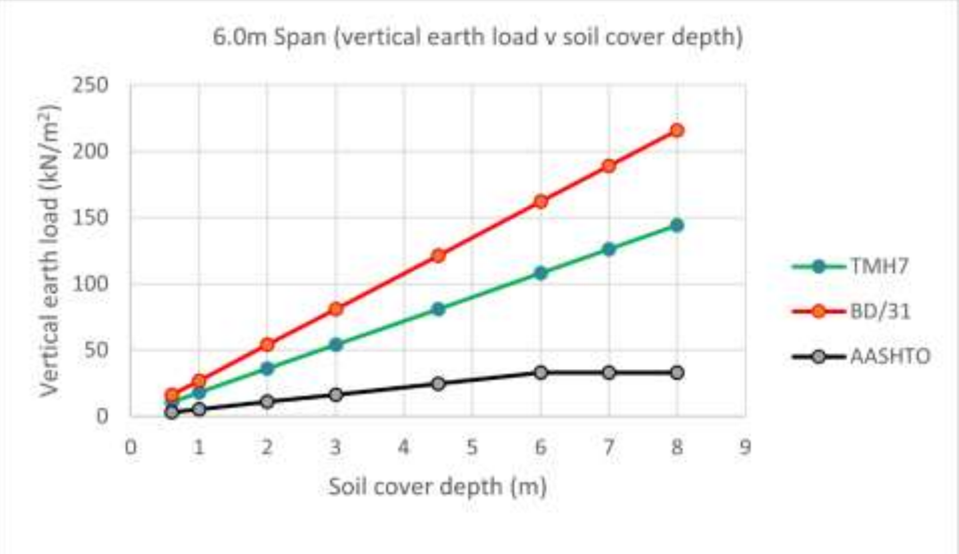
Graph 3.2: Vertical earth load v soil cover depth for 3.0m span



Graph 3.3: Vertical earth load v soil cover depth for 4.0m span



Graph 3.4: Vertical earth load v soil cover depth for 5.0m span



Graph 3.5: Vertical earth load v soil cover depth for 6.0m span

3.6.2 Traffic Live Load

a) TMH7 Live Load on culverts

i. NA Loading

Values for NA loading are obtained for q_{a1} and q_{a2} using *equation 25 and 26*.

$$q_{a1} = \frac{36n}{b_r+2h} \quad kN/m^2 \qquad q_{a2} = \frac{\sum_{i=1}^{n}\frac{120}{\sqrt{i}}}{(b_r+2h)2h} \quad kN/m^2$$

These two load components are uniformly distributed loads and act on the culvert spans at the same time. A third component consisting of two – 100kN concentrated load is then applied separately on the spans, this load is normally more severe than the two other loads on short spans. The position of the concentrated load causing maximum adverse reaction on the culvert span is obtained using the influence line theorem. The distribution and position of the NA load components on the surface are shown in figure 3.6 and the values presented in Table 3.4.

Soil cover depth (m)	q_{a1} (kN/m^2)	q_{a2} (kN/m^2)	Contact area for 100kN load (m^2)	UDL due to 100kN load (kN/m^2)
0	9.73	0.00	0.13	795.77
0.6	8.37	19.85	2.01	49.74
1	7.66	10.90	4.52	22.10
2	6.32	4.49	15.21	6.58
3	5.37	2.55	32.17	3.11
4.5	4.39	1.39	69.40	1.44
6	3.71	0.88	120.76	0.83
7	3.36	0.68	162.86	0.61
8	3.08	0.55	211.24	0.47

Table 3.4: **TMH7 NA load component values at various soil cover depth**

ii. NB Loading

The NB load (Q_b) is a single load oobtained from *equation 27;* $Q_b = 1.25(90 + 12L_s^{1.8})kN$. The spans under consideration range from 2.1m to 6m, hence from the equation it is clear that the Q_b value for the 6m span is way greater than that of the 2.1m span as can be seen in graph 3.6. Q_b is assumed to act at midspan hence causing maximum adverse effect on the span.

From this position a contact patch area of 300 x 300 mm^2 is established from which the pressure is spread through the soil cover at 45 degrees. The effect area at a particular depth is then determined for each span but since the frame is analyzed in 2D, emphasis is placed on the length rather than the area of this area. Figure 3.7 shows the position of $Q_b$on the 2.1m culvert, the contact length and pressure spread through the soil cover.

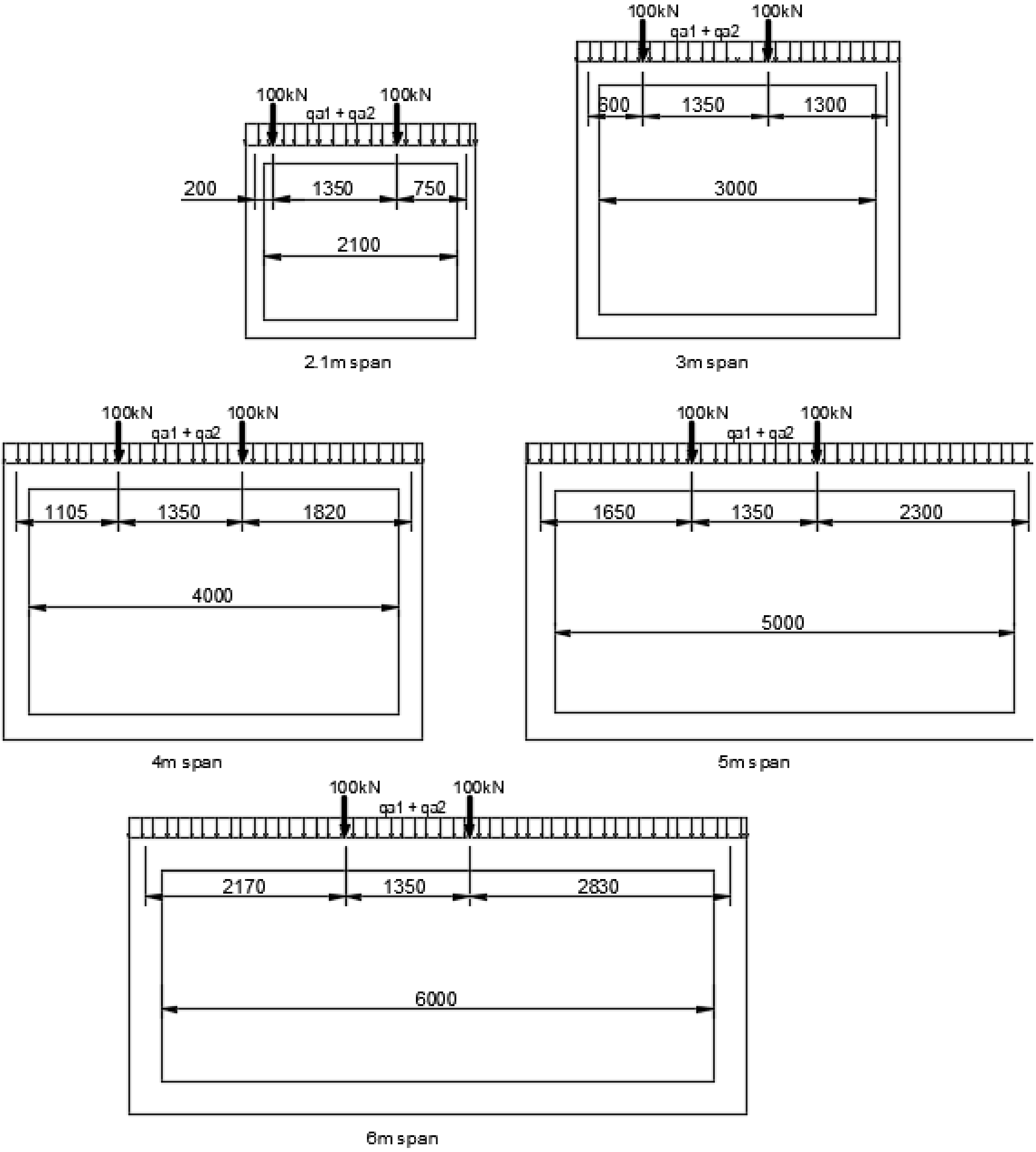
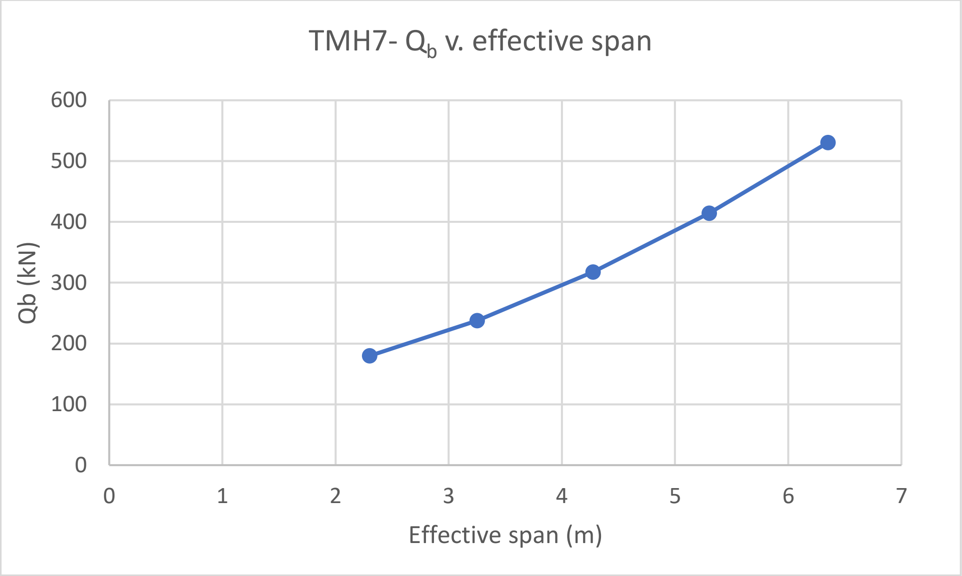


Figure 3.6 TMH7 NA load position on culverts with no soil cover

The concentrated load is dispersed through the soil cover depth at a slope of 2 vertically to 1 horizontally from a 0.3m patch length with Q_b acting at the midspan. Figures 3.7 shows the dispersion of Q_b through the soil cover for three culverts. From the figure, it can be observed that the effect of Q_b on the culvert is influenced by the culvert span and the soil cover; for instance, for the 2.1m span –Q_b

is only dispersed to a soil depth of 1.1m after which the dispersion zone no longer falls over the culvert width as such Q_b values drastically reduce after this depth.



Graph 3.6: TMH7 – Q_b v. effective span

Soil cover depth (m)	*Contact load length for span (m)*	*Qb (kN/m2)*				
		2.1	*3.0*	*4.0*	*5.0*	*6.0*
0.6	1.5	80.0	105.8	141.3	184.0	235.6
1.0	2.3	34.0	45.0	60.1	78.3	100.2
1.1	2.5	28.8	38.1	50.9	66.2	84.8
1.6	3.5	14.7	19.4	26.0	33.8	43.3
2.0	4.3	9.7	12.9	17.2	22.4	28.7
2.1	4.55	8.7	11.5	15.4	20.0	25.6
2.7	5.6	5.7	7.6	10.1	13.2	16.9
3.0	6.3	4.5	6.0	8.0	10.4	13.4
3.2	6.7	4.0	5.3	7.1	9.2	11.8
4.5	9.3	2.1	2.8	3.7	4.8	6.1
6.0	12.3	1.2	1.6	2.1	2.7	3.5
7.0	14.3	0.9	1.2	1.6	2.0	2.6
8.0	16.3	0.7	0.9	1.2	1.6	2.0

Table 3.5: TMH7 - Q_b Load values at various soil cover depth

Similarly, for the 6m span –Q_b is dispersed to a soil depth of 3.2m after which the dispersion zone exceeds the culvert width. The load contact length is used to determine the Q_b as a uniformly distributed load at various soil cover depth on the culvert, since a meter width strip of the culvert is considered for the analysis, the load contact width is one; the Q_b udl dispersed through the soil cover is tabulated in Table 3.5.

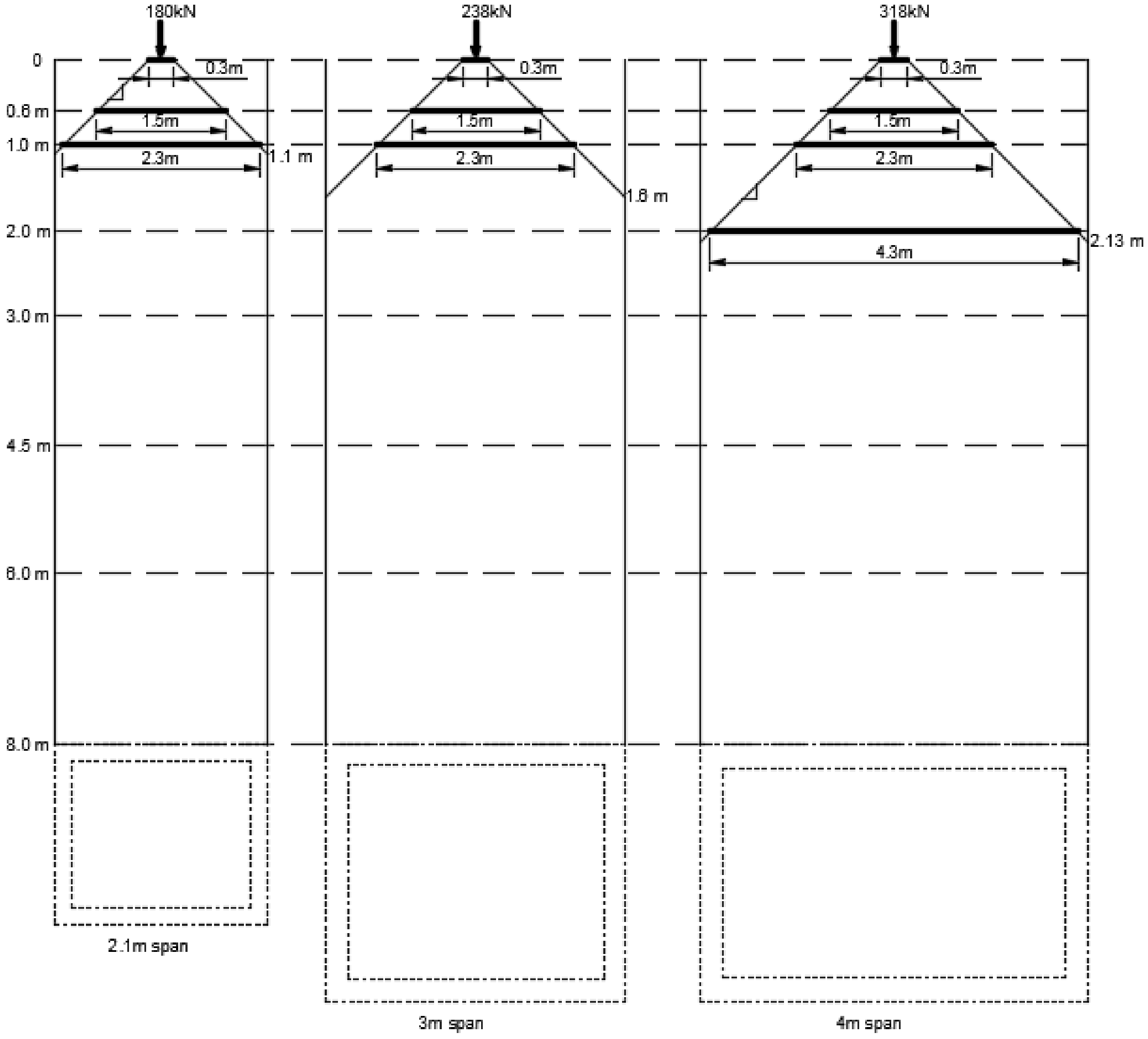


Figure 3.7: TMH7 - NB Load distribution through soil cover for spans 2.1m,3m and 4m

b) AASHTO LFRD Live load on culverts

The HL-93 truck tandem axle load is used as the design vehicular live load applied to the top slabs of box culverts in AASHTO LFRD. For this study, the load from an eight-axle wheel truck is used as the design live load. Figure 3.5 shows the configuration of an eight- axle truck with the axle loads. The road carriage width is assumed to be 7.4m. From the plan and axle arrangement in Figure 3.4, the distance between axles is 1.35m and the maximum distance is 6.1m, since the largest effective culvert span is 6.35m, the highest number of axles that can act on the span at the same time are the three axle loads of 80kN each. But the code mentions that for single box culverts with a typical span length, the maximum forces on the culvert are likely to be produced by a single design truck rear axle patch as such the two-end axle loads of 60.75kN each are considered in the design. The position of the axle loads causing maximum adverse reaction on the culvert is determined using influence line theory.

i. *Soil cover depth less than 0.6m;*

Dimensions for the patch load distribution dimensions are obtained using formulae in *equation 25* i.e. $E = 96 + 1.44S,\ \ E_{span} = L_T + 1.15H = L_T\ since\ H = 0, E_{span} = 1.6m$

$E\ and\ E_{span}$values obtained and used to determine the Live load pressure due to the tandem, Live load pressure due to tandem with impact and multiple presence factor is then obtained. The results are presented in Table 3.6.

The Dynamic Load factor (IM) $= 0.33(1 - 0.125D_E) \geq 0$; $D_E = H = 0$ hence IM = 0.33 and is only considered for fill heights up to 2.45m.

The Multiple Presence factor (MP) for a single lane = 1.2

$W_{LLtandem} = 2(60.75)/(E.E_{span})$ and $W_{LL+IMtandem} = W_{LLtandem}(1 + IM)MP$

Span (m)	E (m)	$W_{LLtandem}$(kN/m^2)	$W_{LL+Imtandem}$(kN/m^2)
2.1	32.4	2.34	2.90
3	33.9	2.24	2.77
4	35.4	2.14	2.66
5	36.9	2.06	2.55
6	38.4	1.98	2.45

Table 3.6: AASHTO LFRD Tandem Live Load for soil cover depth < 0.6m

ii. *Soil cover depth greater or equal to 0.6m;*

Dimensions for the patch load distribution dimensions are obtained using formulae *equation 27 and 28* i.e.

$L =$ 10 + 1.15H, W = 20 + 1.15H for a soil cover of 0.6m since the distributed load from each wheel is separate and

$L =$ 0.83 + 1.15H, W = Axle-spacing + 1.67 + 1.15H for the rest of the soil depth cover since the load distribution patches of the wheels overlap. Overlapping of the patch areas is determined by subtracting L from the axle spacing a negative answer means the areas overlap.

L *and* W values obtained are used to determine the Live load pressure due to the tandem, Live load pressure due to tandem with impact and multiple presence factor is then obtained. The results are presented in Table 3.7.

The Dynamic Load Allowance (IM) $= 0.33(1 - 0.125D_E) \geq 0$ and is only considered for fill heights up to 2.45m.

The Multiple Presence factor (MP) for a single lane = 1.2

$W_{LLtandem} = 2(60.75)/(L.W)$ and $W_{LL+IMtandem} = W_{LLtandem}(1 + IM)MP$

Soil cover depth (m)	W (m)	L (m)	$W_{LLtandem}$(kN/m^2)	$W_{LL+IMtandem}$(kN/m^2)
0.6	6.79	3.74	4.79	7.18
1.0	2.75	1.40	31.45	45.09
2.0	3.90	2.55	12.19	15.50
3.0	5.05	3.70	6.49	
4.5	6.78	5.43	3.30	
6.0	8.50	7.15	2.00	
7.0	9.65	8.30	1.52	
8.0	10.80	9.45	1.19	

Table 3.7: AASHTO LFRD Tandem Live Load for soil cover depth ≥ 0.6m

c) BD31/01 Live load on culverts

Carriage live loads are either HA or HB loading.

i. HA Loading

Three vertical loads are considered under this loading, the UDL and KEL, 30-unit HB load and a single 100kN load. The manual specifies that for HA loading, the dispersal of loads is not necessary if the soil cover depth is lower than 0.6m but for soil cover depth of greater than 0.6m 30 units of the HB loads adequately dispersed through the cover soil depth is used in place of the HA load. The single wheel load of 100 kN is also considered as an alternative when it has a more adverse effect on the member as opposed to the other two loads. On short span members the single 100kN load can produce more severe effects than the UDL and KEL.

- ***100 kN HA wheel load***

A single 100kN load is dispersed at a slope of 2 vertical to 1 horizontal from the edge of the load contact patch through the soil. The position of this load causing the most adverse reaction on the span is obtained using the influence line theorem, refer to figure for this position on the various culvert spans. The contact patch area for the load to produce an effective pressure of 1.1N/mm^2

$= \sqrt{(100000/1.1)} = 302 \times 302$ mm.

For a 0.6m soil cover depth (H). The load will be dispersed to the top slab of the culvert as below;

Dispersed area to top slab = 302 + (2 x (600/2) = 902 x 902 mm

Assume a neutral axis of 100mm for the 200mm top slab; the dispersed width on which the single wheel is dispersed to the neutral axis (h_{na}) of the top slab:

$= C + H + 2h_{na} = 302 + 600 + (2 \times 100) = 1102$mm

The wheel load on dispersed area = $100/1.102^2 = 82.34$kN/m^2

- ***HA UDL and KEL loading***

The magnitude of this load is dependent on the loaded length, in this case the culverts’ effective span length.

For H ≤ 0.6m no dispersal is allowed hence;

$UDL = 336\ (1/L)^{0.67}\ kN/m$ and $KEL = 120kN$

The UDL value is divided by the notional lane width to get the UDL in kN/m^2. When H is greater than 0.6m the HA UDL and KEL loading does not adequately model traffic loading so live loading is restricted to the 100kN wheel load and a minimum of 30 units of HB vehicle.

For H ≥ 0.6m

A minimum of 30 units HB vehicle or 45 units for Trunk Roads and Motorways is considered.

For a 30-unit HB vehicle;

Wheel load = 30 x (10/4) = 75kN

Contact patch area to produce an effective pressure of 1.1N/mm$^{2\ =}$ √ (75000/1.1) = 261× 261 mm.

An axle is dispersed over a total width of C + (n-1) S + H + 2h$_{na}$

Where *n* is the number of wheels on an axle and *S* is the wheel spacing.

For h$_{na}$ = 100mm the depth to the neutral axis = H + h$_{na}$ = 700mm

Assuming the wheels are spaced at 1m on each axle, the transverse dispersal lines overlap at a depth

= (1000 – 261) mm = 739 mm > 700mm hence the distributed patch load area does not overlap

The width over which the axle is dispersed over = 261 + 600 + (2x100) = 1061mm

For an axle spacing of 1.35m, the load dispersal line overlaps at a depth

= (1350 – 320) mm = 1030mm > 700mm hence no need to consider the front and rear axle pairs.

The longitudinal dispersal of axle load = 302 + 600 + (2 x 100) = 1102mm

Axle load on dispersed area = 80 / (1.061 x 1.102) = 68.42 kN/m^2

For a 45-unit HB vehicle;

Wheel load = 45 x (10/4) = 112.5kN. Contact patch area to produce an effective pressure of 1.1N/mm^2 = √ (112500/1.1) = 302 × 302 mm.

An axle is dispersed over a total width of C + (n-1) S + H + 2h_{na}

Where *n* is the number of wheels on an axle and *S* is the wheel spacing.

For h_{na} = 100mm the depth to the neutral axis = H + h_{na} = 700mm

Assuming the wheels are spaced at 1m on each axle, the transverse dispersal lines overlap at a depth

= (1000 – 320) mm = 680 mm < 700mm hence the distributed patch load area overlap and four wheels need to be considered. The width over which the axle is dispersed over = 302 + (4-1)1000 + 600 + (2x100) = 4102mm

For an axle spacing of 1.35m, the load dispersal line overlaps at a depth

= (1350 – 320) mm = 1030mm > 700mm hence no need to consider the front and rear axle pairs.

The longitudinal dispersal of axle load = 302 + 600 + (2x100) = 1102mm. Axle load on dispersed area = 112.5/ (4.102 x 1.102) = 24.89kN/m^2

Using the method above, the axle dispersal area for all the culverts at various soil cover depth is obtained and presented in Table 3.8.

Soil cover depth (m)	***30HB Load - Axle load on dispersed area (kN/m²)***					***45HB Load - Axle load on dispersed area (kN/m²)***				
	Span					***Span***				
	2.1	***3***	***4***	***5***	***6***	***2.1***	***3***	***4***	***5***	***6***
1	47.85	46.49	45.83	45.19	43.95	70.10	68.13	67.18	66.25	64.45
2	28.83	28.20	27.89	27.59	27.00	42.47	41.54	41.09	40.65	39.79
3	19.30	18.96	18.79	18.62	18.29	28.53	28.02	27.77	27.53	27.05
4.5	11.94	11.77	11.69	11.61	11.45	17.71	17.46	17.34	17.22	16.98
6	8.12	8.03	7.98	7.93	7.84	12.06	11.92	11.86	11.79	11.65
7	6.51	6.44	6.41	6.38	6.31	9.68	9.58	9.53	9.48	9.39
8	5.34	5.29	5.26	5.24	5.19	7.94	7.87	7.83	7.79	7.72

Table 3.8: BD31/01 30 & 45HB Loading at various soil cover depth

3.6.3 Lateral Earth Pressure on culvert walls

As presented in section 2.3, the earth pressure on culverts side walls is determined from principles of soil mechanics of the backfill or adjacent material. The Rankine earth pressure theory is used in the derivation of the earth pressure for all three design manuals i.e., *equations 13,22 and 23.* For simplicity the back slope is assumed to be level with 30-degree angle of the internal friction. The lateral earth pressure P_a;

$$P_a = K_a \omega \quad \text{and} \quad K_a = \frac{1-Sin\emptyset}{1+Sin\emptyset}$$

Hence K_a = 0.33

Two lateral pressures are determined-

- The pressure due to superimposed and live load, obtained by multiplying the Live Load udl with the coefficient of earth pressure.
- The pressure due to the soil cover, obtained by using the Rankine formula for obtaining Lateral Earth pressure. The pressure due to superimposed and live load is also the lateral pressure at the top (surface) whereas the bottom pressure is the sum of the top lateral pressure and the lateral pressure due to the soil cover. These pressure values are used in the Prokon 2d structural frame analysis of the culverts Lateral pressure values using the TMH7, AASHTO LFRD and BD31/01 manuals are presented in Tables.3.9 to 3.12.

TMH7								
Soil cover depth (m)	***Lateral Earth Pressure due to Na load***			***Lateral Earth Pressure due to Qb (kN/m2)***				
	qa1 (kN/m2)	***qa2 (kN/m2)***	***UDL due to 100kN load (kN/m2)***	*2.1*	*3.0*	*4.0*	*5.0*	*6.0*
0	3.21	0.00	262.61	660.0	872.7	1166.0	1518.0	1943.3
0.6	2.76	6.55	16.41	26.4	34.9	46.6	60.7	77.7
1	2.53	3.60	7.29	11.2	14.8	19.8	25.8	33.1
2	2.08	1.48	2.17	3.2	4.2	5.7	7.4	9.5
3	1.77	0.84	1.03	1.5	2.0	2.6	3.4	4.4
4.5	1.45	0.46	0.48	0.7	0.9	1.2	1.6	2.0
6	1.22	0.29	0.27	0.4	0.5	0.7	0.9	1.2
7	1.11	0.23	0.20	0.9	1.2	1.6	2.0	2.6
8	1.02	0.18	0.16	0.2	0.3	0.4	0.5	0.7

Table 3.9: TMH7 Lateral earth Pressure due to NA and Q_b Load

Soil cover depth (m)	AASHTO - Lateral Earth Pressure due to LL	
	$W_{LLtandem}$(kN/m^2)	$W_{LL+IMtandem}$(kN/m^2)
0.6	1.58	2.37
1.0	10.38	14.88
2.0	4.02	5.11
3.0	2.14	
4.5	1.09	
6.0	0.66	
7.0	0.50	
8.0	0.39	

Table 3.10: AASHTO LRFD Lateral earth Pressure due to LL Load

Soil cover depth (m)	Lateral Earth Pressure due to soil cover depth (kN/m^2)
0.6	3.56
1.0	5.94
2.0	11.88
3.0	17.82
4.5	26.73
6.0	35.64
7.0	41.58
8.0	47.52

Table 3.11: Lateral earth Pressure due to soil cover

BD31/01										
Soil cover depth (m)	Lateral Earth Pressurdue to 30HB Load (kN/m2)					Lateral Earth Pressure due to 45HB Load (kN/m2)				
	Span					Span				
	2.1	3	4	5	6	2.1	3	4	5	6
1	15.79	15.34	15.13	14.91	14.50	23.13	22.48	22.17	21.86	21.27
2	9.51	9.31	9.20	9.10	8.91	14.01	13.71	13.56	13.42	13.13
3	6.37	6.26	6.20	6.15	6.04	9.41	9.25	9.17	9.08	8.93
4.5	3.94	3.89	3.86	3.83	3.78	5.84	5.76	5.72	5.68	5.60
6	2.68	2.65	2.63	2.62	2.59	3.98	3.93	3.91	3.89	3.85
7	2.15	2.13	2.11	2.10	2.08	3.19	3.16	3.15	3.13	3.10
8	1.76	1.74	1.74	1.73	1.71	2.62	2.60	2.58	2.57	2.55

Table 3.12: BD31/01 Lateral earth Pressure due to 30HB and 45HB Load

3.7 Summary

This chapter presents derivation of the dead, live and the lateral earth pressure load using different formulae and methodologies as outlined in TMH7, AASHTO LRFD and BD31/01. All the culverts are assumed to be trenched on an unyielding foundation with a type 1 material. The SDL_{max} is considered under BD31/01 with β=1.5, g_1 for TMH7 and W_E for AASHTO LFRD. The unfactored vertical earth load is calculated for each fill height ranging from 0.6m to 8.0m, for each culvert using MS Excel. The results are presented as Graphs or displayed in Tables.

A similarity exists between TMH7 and BD31/02 live load calculation, the traffic load consists of two components considered in the study: Normal loading (NA/HA) and Abnormal Loading (NB/HB). The pressure from the wheel point load on the road surface is assumed to spread out at approximately 45 degrees (TMH7) and 27 degrees (BD31/01) through the fill depth spreading as a uniformly distributed load, over a perimeter of an area on the culvert. The live load values obtained for TMH7 are generally higher since an additional load consisting of two 100kN NA wheel nominal loads not less than 1m apart are applied anywhere on the top surface of the culvert to cause maximum effect. Whereas BD31/01 considers a single 100kN HA wheel nominal load as a substitute not an addition when it has a more severe effect on the member as opposed to the other HA load components. The influence line theory was used to determine the position of concentrated loads causing adverse effect on the spans for the load derivation.

The live load derivation under AASHTO LFRD is dependent on the soil cover depth and the culvert clear span. The fill depth is categorized into two categories: soil cover depth of less than 0.6m and soil cover depth greater or equal to 0.6m. For a fill cover depth of 0 to 0.6m the effect of the traffic load is more of a concentrated load on the culvert contrary to when the soil cover depth is greater or equal to 0.6m where it then disperses through the fill into a UDL. For single cell culverts, the live load is ignored when the fill height is greater than 2.45m and greater than the culverts' clear span. The analysis of the culverts under the obtained loads is presented in chapter four.

The lateral pressure in all design manuals is derived from principles of soil mechanics of the fill material. The Rankine earth pressure theory is used in this case and the obtained coefficient of lateral earth pressure is the same for TMH7, AASHTO LFRD and BD31/01.

CHAPTER FOUR

ANALYSIS AND DISCUSSION

4.1 Introduction

In chapter three the derivation for the unfactored vertical earth load, live load and the lateral earth pressure was discussed. The load position for the wheel/axle load on the various culvert spans causing the most adverse reaction on the span was obtained using the influence line theorem. A 2d frame analysis of the culverts is carried out in Prokon, the effective span of the top slab is taken from the mid points of the side walls. The lateral pressure on the side walls is assumed to be in equilibrium and the forces acting on the bottom slab are totally ignored. The aim of the analysis is to determine the maximum load forces i.e., maximum bending moments and shear forces for the culverts under varying soil cover depths by loads obtained from TMH7, AASHTO LFRD and BD31/01. The effect of the soil cover depth, the culvert span and the live load on the obtained bending moments and shear forces will also be discussed. Load factors presented in Table 4.1 are used to factor the vertical earth load, the live load and the lateral earth pressure in Prokon for the analysis.

	TMH7		***AASHTO***		***BD31/01***	
	ULS	***SLS***	***ULS***	***SLS***	***ULS***	***SLS***
Dead Load	1.2	1.0	1.25	1.0	1.2	1.0
Vertical Earth Load	1.5	1.1	1.25	1.0	1.2	1.0
Normal Load	1.5	1.0			1.3	1.0
Abnormal Load	1.2	1.0			1.3	1.0
Earth Pressure	1.5	1.1	1.25	1.0	1.2	1.0
Live Load			1.75	1.0		

Table 4.1 Partial load factors Adopted TMH7 (1981), AASHTO LFRD (2014), BD31/02

4.2 Prokon Results Validation

In the absence of actual field data to validate the results obtained from Prokon a study by Ubani et al. (2020) – effects of soil compressibility on the structural response of box culverts using finite element approach was adopted. In the study a box culvert with 2.5m span, 2.0m height, top and bottom slabs of 250mm thick and side walls 300mm thick was subjected to four load cases encountered in practise. The load cases considered were - vertical earth load and traffic uniformly distributed loads, wheel concentrated load, triangular earth pressure on the side walls and uniformly distributed soil surcharge pressure. An action effect (bending moments, shear stresses and axial loads) of the load cases on the culvert was tabulated for various modulus values adopted for the subgrade as a way of varying the soil compressibility.

For the Prokon analysis, all the geometric properties of the culvert were adopted, two load cases were analyzed i.e. vertical earth load and traffic uniformly distributed load and the earth pressure on the side walls since these were the load cases considered in this study (refer to section 3.3 for a description of the load cases considered). Also, this paper focuses on buried box culverts under varying soil cover depth as such any concentrated load depending on the soil cover depth translates to a UDL as such would have a similar impact as load case 1 hence the wheel concentrated load is ignored in the validation process and so was the earth pressure on the side walls.

Ubani et al. used Staad Pro software for the finite element analysis and compared the results obtained with the approximate solution obtained from using equations based on moment distribution coefficients for analysis of rectangular culverts published by Reynolds & Steedman (2005). For the first load case with fully fixed support condition, where the culvert was loaded with a 50kN/m^2 load, the maximum bending moment ($M_{x, max}$) obtained from Staad Pro was 18.917 kNm, the value obtained from using equations by Reynolds & Steedman was 21.147 kNm and the results obtained from the Prokon analysis was 21.890 kNm for the maximum hogging moment and 17.170 kNm for the maximum sagging moment. As previously mentioned, Ahmed & Alarabi (2011) observed that the results obtained in Prokon were in close agreement to those obtained from the equations presented by Reynolds. Figure 4.1 presents the bending moments obtained from Reynolds and Prokon.

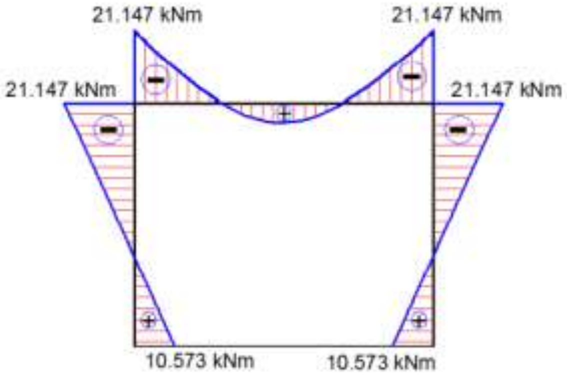


Figure 4.1a: Bending moments according to formula from Reynolds (Ubani et al,2020)

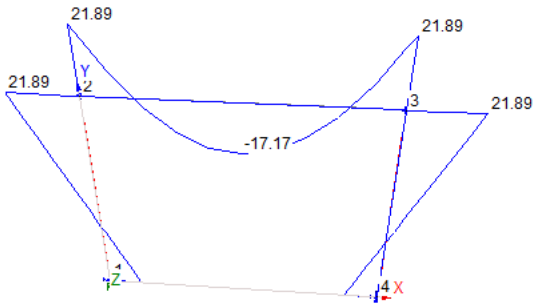


Figure 4.1b: Bending moments from Prokon frame analysis

The Prokon model did not consider the bottom slab and the focus of the analysis was on the reaction of the top slab to the various load cases.

For load case 3 – the effect of the triangular earth pressure on the side walls where an earth pressure of 20kN/m^3 was applied. The maximum bending moment obtained for the top slab for uncompressed soil condition was 0.586 kNm from Staad Pro and 0 .5011 kNm from formula by Reynolds (Ubani et al. 2020). A value of 0.678kNm was obtained from Prokon, this value is conservative since the Prokon frame analysis does not consider the soil condition and the soil-structure interaction among other factors.

Finally, the culvert was analyzed with both load cases to determine the effect that this would have on the load forces on the top slab although this was not done in the study by Ubani et al. It was observed that the hogging moment increased from 20.79kNm to 21.73kNm while the sagging moment decreased from 18.27kNm to 17.33kNm. From these tabulations, the Prokon frame analysis although not specifically designed for culvert design can be used to analyze load forces especially for the top slab.

4.3 Prokon Modelling Analysis

The Frame Analysis module was used for the analysis, the culverts were modelled as plane frames with negligible sway. Nodes defining the frame were used to model the structure in the X-Y plane then the beam elements connecting the nodes were defined and section properties were assigned to the beams. Figure 4.2 shows a 2.1m span frame model analyzed in Prokon showing the X-moments and Y-shear obtained for a soil cover of 2m. Beam elements 1-2 and 3-4 depict the culvert 0.2m thick side walls and 2-3 represents the culverts' 0.2m thick top slab. To attain global stability the frame was restricted against horizontal and vertical movement by assigning various boundary conditions to the nodes; For the bottom nodes – a pinned connection was assigned to both nodes 1 and 4 restricting movement in the X and Y direction only. When analyzing box culverts AASHTO LFRD as previously mentioned recommends a roller and pin joint for the bottom nodes, since the foundation is assumed to be flexible with the soil behaving as a spring. From the Prokon results validation, fixing the top nodes and pinning both the bottom nodes (supports) yielded results in close agreement to those obtained from the equations presented by Reynolds. As such, the culverts were all modelled as having node 2 & 3 fixed and 1 & 4 pinned. The bending moment figures presented are in kNm and the shear forces in kN. The discussion in this paper centers on the X-moments and Y-shear for the beam element 2-3 only i.e., the top slab.

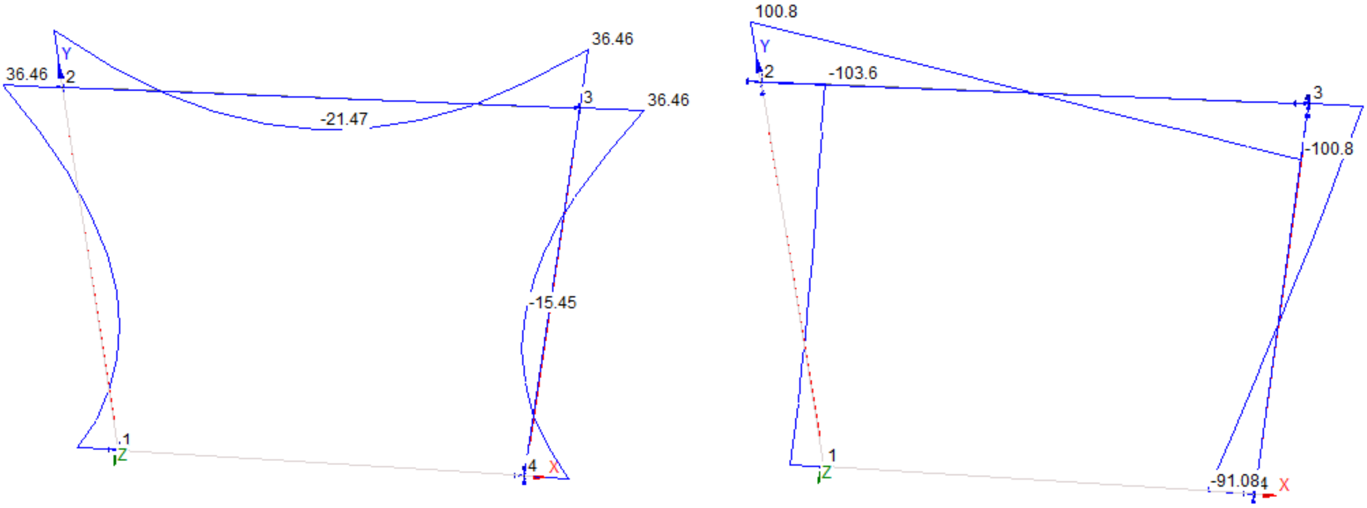


Figure 4.2 TMH7: X-moments and Y-shear for 2.1m span culvert

The dead load, live load and the lateral earth pressure initially tabulated in excel are applied on the beam elements as UDL or concentrated load. The lateral earth pressure on the walls (beam elements 1-2, 3-4) considered in the design is in equilibrium acting along the side wall height only since the program does not model fill heights. A basic linear elastic analysis is then carried out and the analysis results are presented in terms of the deflection, reactions and beam forces. No reinforcement detail is provided after the analysis since the frame was not modelled as a shell. The use of Prokon as a culvert analysis tool is tedious and time consuming, requiring a lot of manual load tabulation and reinforcement detail tabulation too since there are no reinforcement details after the analysis. The deflection, reactions and beam forces obtained are conservative since the program is not designed to consider the soil-structure interaction in buried structures, but the load forces obtained are sufficient to study the response of the culverts' top slab to the applied loads.

4.3.1 Vertical Earth Load

The vertical earth loads for the various spans derived from equations presented in the TMH7, AASHTO LFRD and BD31/01 manuals are presented in Table 3.3. The loads obtained from TMH7 and BD31/01 are constant at a particular soil depth cover for each culvert despite the different span length. The vertical earth load for these two manuals is independent of the culvert span length but influenced by the soil density and the earth fill depth. For instance, the 2.1m span and 6.0m span culverts at 3.0m fill height carry the same vertical earth load of 54kN/m^2 (TMH7) or 81kN/m^2 (BD31/01) despite the different span length. The difference in the values between the obtained load values between TMH7 and BD31/01 is the factor of the cover depth (β) used to obtain the maximum super imposed dead load intensity in BD31/01 which ultimately increased the load. β is not applied when finding the minimum super imposed load intensity in BD31/01 such that, the value obtained from TMH7 is in fact equivalent to the BD31/01 minimum super imposed load intensity.

The load obtained in AASHTO LFRD is the lowest and less than 20% of the load obtained from the other two design manuals. On top of the soil density and earth fill depth, the soil-structure interaction factor for trench installation (F_t) and the culverts outside width are considered when deriving the vertical load. The factor (F_t) is a factor trench width, culvert outside width and the earth fill as such the load for each culvert is different, depending on the outside width and the earth fill height. As such, a wider culvert or an increase in the fill height automatically reduces this factor resulting in a lower load since $F_t = \frac{C_d B_d{}^2}{H B_c}$ refer to chapter two for details of this formula. For instance, at a 3.0m fill height the 2.1m span supports a vertical earth load of 12.3kN/m^2 while the 6.0m span culvert supports a vertical earth load of 16.5kN/m^2 at the same fill height.

The unfactored vertical earth loads obtained from TMH7, AASHTO LFRD and BD31/01 plotted against the soil cover depth for the five culverts are presented in Graph 3.1-3.5. It is apparent that a relationship exists between the soil cover depth and the vertical earth load; the load increases with an increase in the soil cover depth for all vertical earth loads derived from the three manuals. For the vertical earth load obtained from AASHTO, the 3.0m, 4.0 and 5.0m span culverts have similar loads at the same fill heights unlike the 2.1m and 6.0m culverts refer to Table 3.3 for details. A change is also observed in the 6.0m culvert from 6.0m fill depth the vertical earth load remains constant. These changes can be attributed to the role played by factor F_t.

As previously mentioned, the vertical earth load derivation from TMH7 for trenched culverts is concise - a factor of the fill density and the fill height similar to the formula in BD31/01. The only difference between the formulae in these two manuals is the cover depth factor only applied to obtain the maximum super imposed dead load in BD31/01. The vertical load derivation formula in AASHTO LFRD is the most realistic. On top of the fill density and height, the vertical earth load value is a factor of the culvert width, trench width, soil-structure interaction factor and the load coefficient Cd which is a factor of the active pressure and the angle of sliding friction between the backfill and trench sides. Clearly, the vertical earth loads obtained from TMH7 and BD31/01 are unrealistically conservative as compared to those obtained from AASHTO LFRD.

4.3.2 Vertical Earth Load Effect

To study the effect of the vertical load on the culverts' top slab, the longest and shortest culverts are analyzed. The analysis of the 2.1m and 6.0m culvert also expects to present the significance of the culvert span on the load effect. The critical areas considered in the analysis are the centers of the slab to determine the maximum sagging moment and the slab end to determine the maximum hogging moments and positive shear forces. The vertical earth load presented in Table 3.3 is applied to the 2D culvert plane frame, the load forces i.e., Fixed End Moments (FEM), Mid Span Moment (MSM) and Shear Force (SF) obtained from the Prokon analysis are plotted against the soil cover depth. Live load forces for the spans are equally plotted against the soil cover depth. The live load effect and the comparison between the effects of the live and dead load are discussed in the preceding section. In Graphs 4.1- 4.6 the maximum vertical earth load forces for the two spans are presented.

An increasing non-linear relationship exists between the soil cover depth and the obtained FEM, MSM and SF. An increase in the soil cover depth results to an increase in these three forces for the 2.1m span for all three loads unlike the 6.0m span. For this span the forces increase constantly as expected for the BD31/01 contrary to the effect observed for TMH7 and AASHTO LFRD load cases. There is a sudden decrease in the load forces past the 7.0m fill height for TMH7, it is unclear at this point whether this is due to the span length since this is not observed in the shorter span. Conversely, the load forces due to the AASHTO LFRD load for the 6.0m span increase with increasing soil cover depth, but rather than reducing - the load forces become constant from the 6m fill depth.

The load forces are higher on the longer span as compared to the shorter span even though the load is the same at each fill height, in both cases the maximum hogging moments are higher than the maximum sagging moments for all fill heights for both spans except for fill heights of 0.6m to 1.0m for the 6.0m span with load from TMH7. But clearly an increase in the span length results in a remarkable increment of the FEM, MSM and SF in the top slab, the FEM for the two spans are presented in Graph 4.1-4.6. From the results obtained, the soil cover depth and the culvert span length are an influencing factor to the vertical earth load forces; an increase in either increases the forces non-linearly to a certain depth.

4.3.3 Live Load Effect

Equally the live load was applied separately on the two spans as outlined in TMH7, AASHTO LFRD and BD31/01. For TMH7, the 2-100kN concentrated load for NA loading was observed to be more severe for the soil cover depth of 0.6m and 1.0m, as such q_{a1} and q_{a2} loading were only applied for soil cover depths from 2.0m to 8.0m and the 2-100kN loads for the 0.6m and 1.0m soil depth. AASHTO LFRD recommends that live load should not be applied to single box culverts with a fill height ≥ 2.45m and greater than the culverts' clear span during the design. As a result, the live load for the 2.1m span culvert (clear span = 2.3m) was only applied to 2.0m fill height and for the 6.0m span culvert (clear span = 6.35m) up to 6.0m.

Contrary to the effect of the vertical earth load, the effect of the live load diminishes with respect to the soil cover depth i.e., the greater the soil cover depth, the lesser the live load impact. From the graphs, a significant decrease on the impact of the live load on the 2.1m span beyond the 2.0m soil cover depth is observed for TMH7. The load forces are constant from a soil cover depth of 7.0m this is only observed for this span and under TMH7 load only.

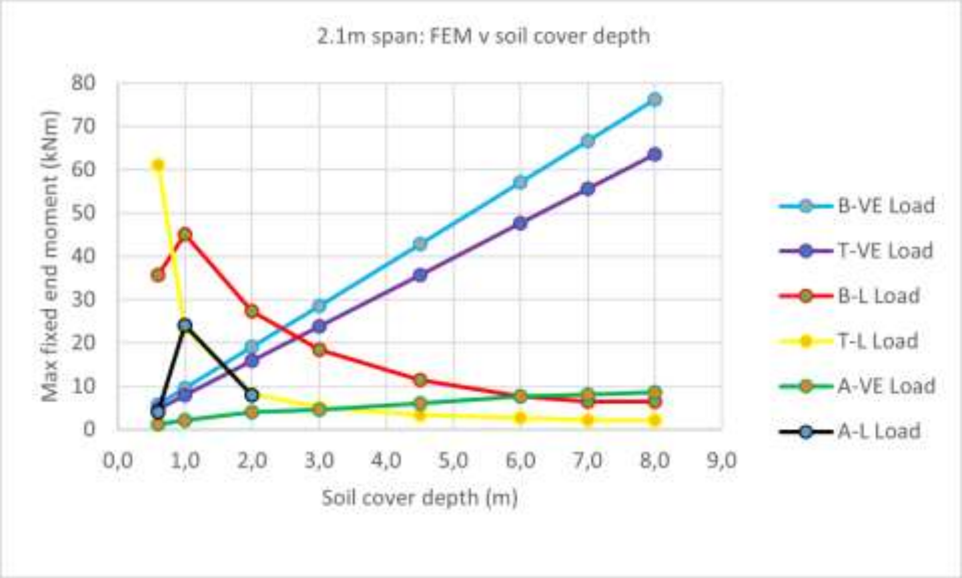
Clearly the live load is more critical for culverts with a shallow soil cover (less than 1.0m fill depth in our case) - decreasing with an increase in the soil cover depth.

4.3.4 Vertical Earth Load Effect v Live Load Effect

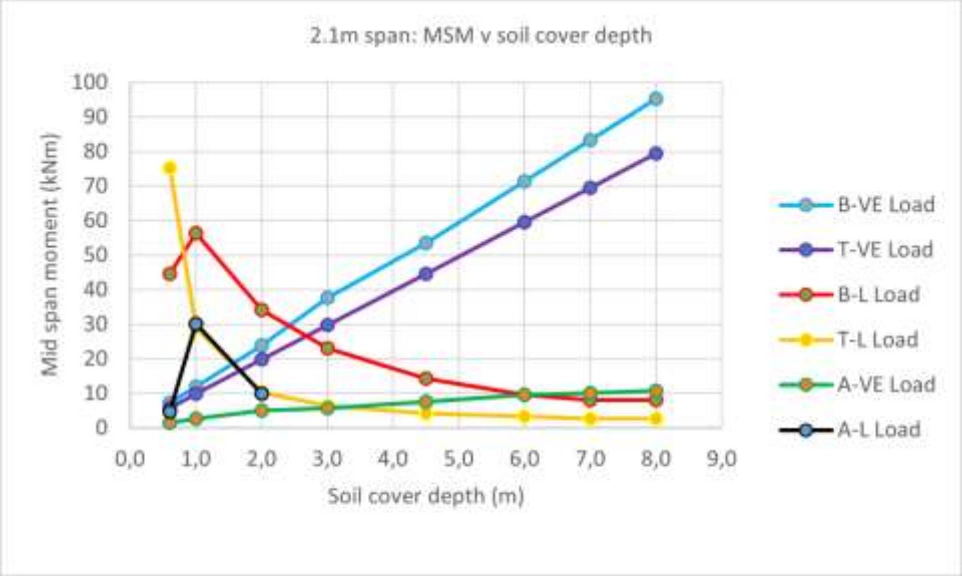
From the forces observed, the FEM are generally higher than the MSM for both load cases which might be influenced by the boundary condition (nodes 2 and 3 in Figure 4.1). Culverts are commonly designed as rigid structures, but their true behavior lies between fixed and pinned connection Orton et al. (2013). The moments and shear forces obtained for the 6.0m span are extremely high as compared to those obtained for the 2.1m span signifying that the culvert span influences the load forces obtained. In a study to find the effect of haunch on the stresses of a box culvert, Hussien (2020) found that; when the thickness of the culvert was increased by 12.5% of the original culvert thickness, the stresses both in the vertical and horizontal direction decreased by a certain percentage. As such, the effective span was kept constant while the thickness of the top slab and side walls were varied to observe the effect this would have on the bending moment and shear forces. It was observed that contrary to the study, the two factors did not influence the load forces in anyway. The culvert height was then kept constant while reducing and increasing the effective span, this was observed to have a significant influence on the obtained load forces. Thus, the study established that the culverts' length (L) and height (H) ratio has a direct relationship with the load forces.

In conclusion, the effective span influences the load forces under two conditions: a high L/H ratio signifying a longer culvert span and a general increase in the span length despite having a low L/H ratio. All the culverts considered in this study are square culverts so the L/H ratio for all the culverts = 1.0.

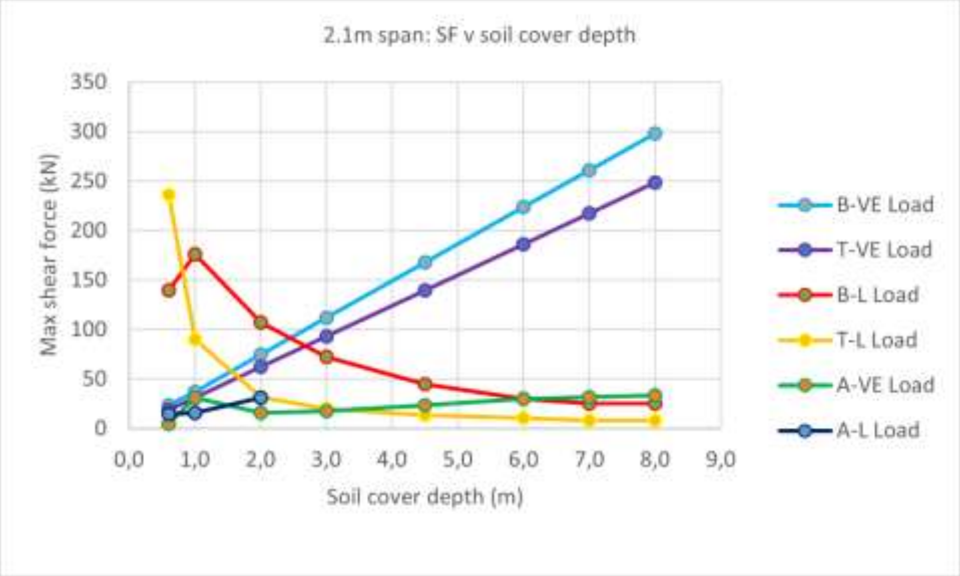
4.3.4.1 Vertical Earth and Live Load forces for 2.1m span



Graph 4.1: 2.1m span FEM - Vertical Earth (VE), Live (L) Load v soil cover depth

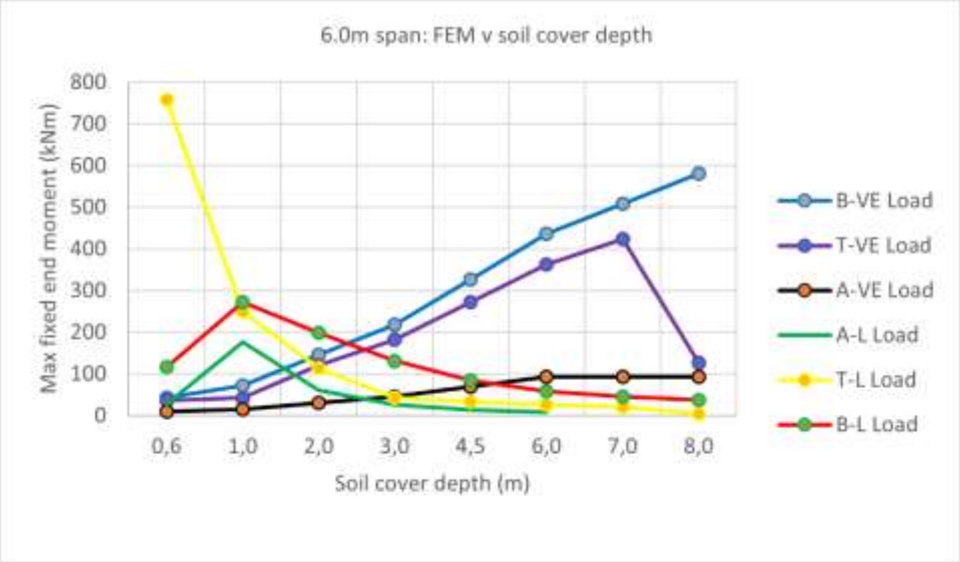


Graph 4.2: 2.1m span MSM - Vertical Earth (VE), Live (L) Load v soil cover depth

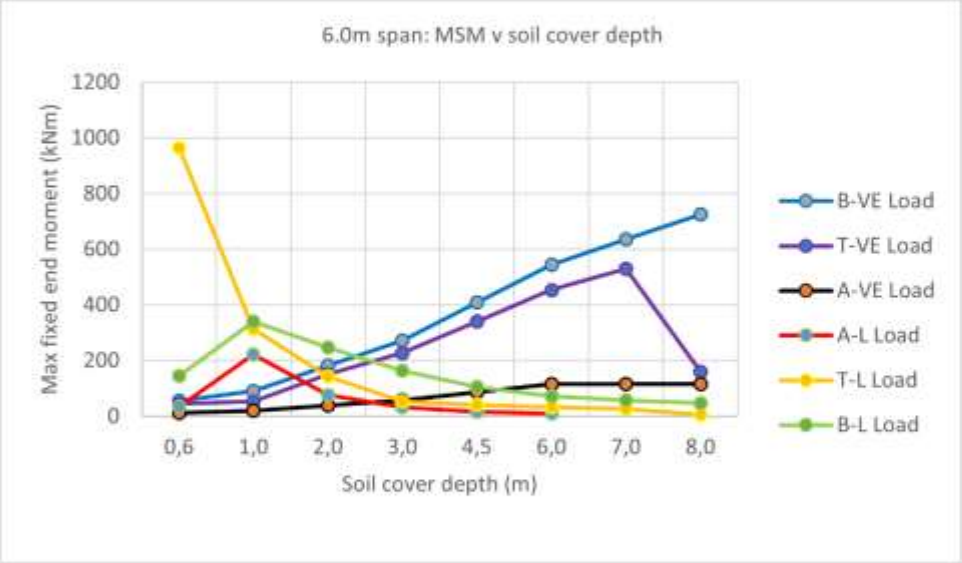


Graph 4.3: 2.1m span SF - Vertical Earth (VE), Live (L) Load v soil cover depth

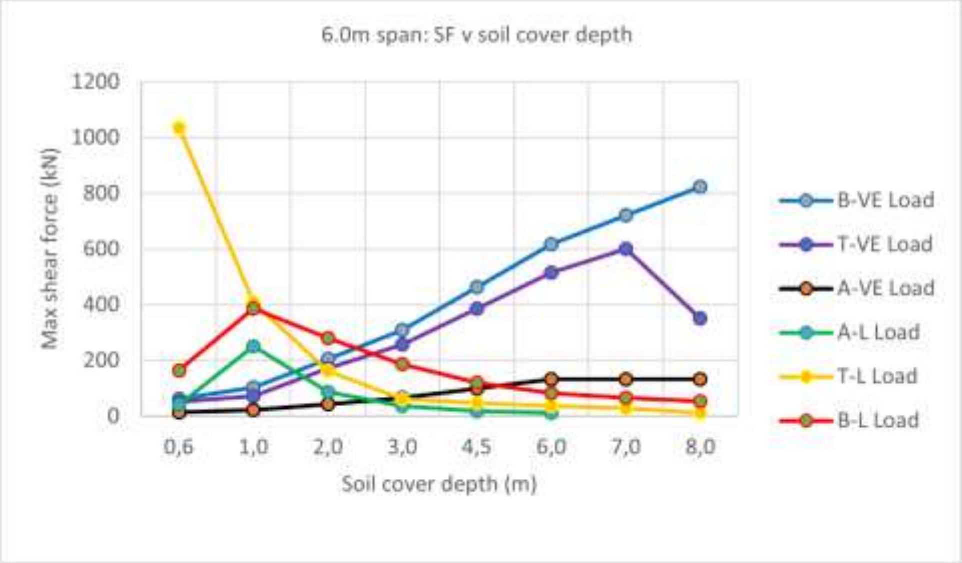
4.3.4.2 Vertical Earth and Live Load forces for 6.0m span



Graph 4.4: 6.0m span FEM - Vertical Earth (VE), Live (L) Load v soil cover depth



Graph 4.5: 6.0m span MSM - Vertical Earth (VE), Live (L) Load v soil cover depth

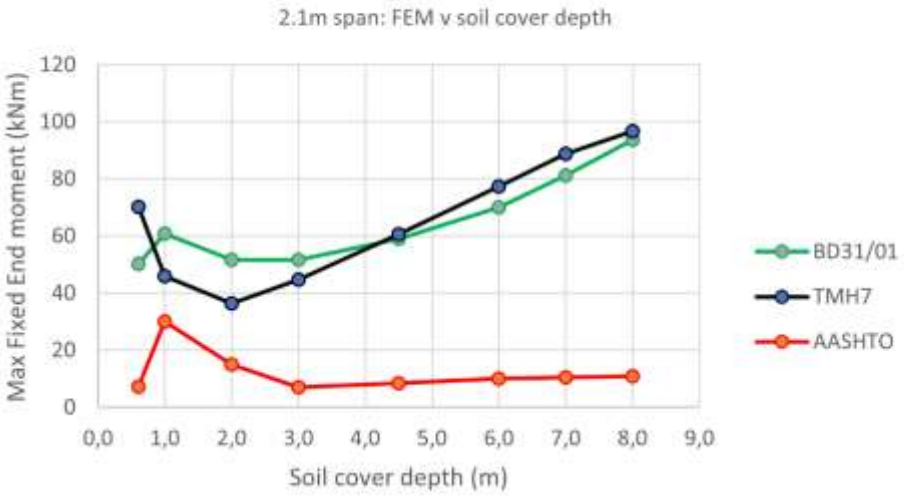


Graph 4.6: 6.0m span SF - Vertical Earth (VE), Live (L) Load v soil cover depth

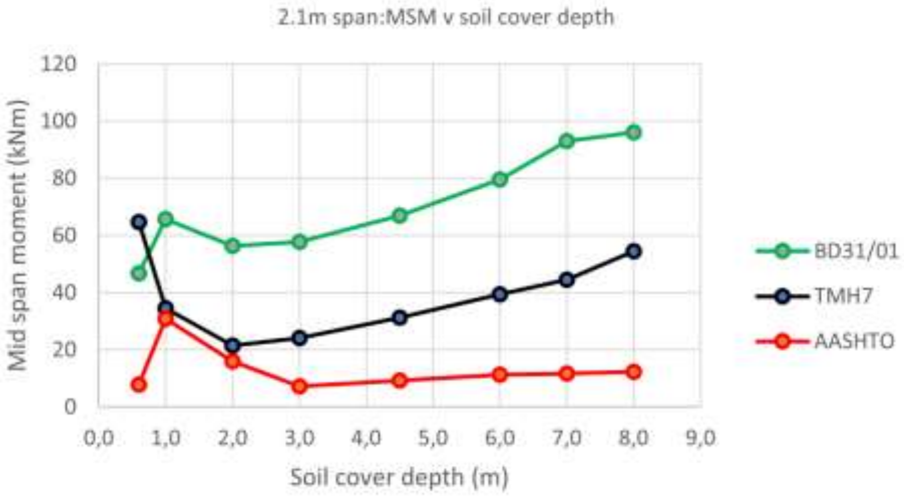
4.3.5 Results and Discussion - Combined Load Analysis

This section presents the results for the discrete analysis for all the culverts by applying all the load cases i.e., vertical earth load, vehicular live load and lateral earth pressure obtained from the three design manuals. The unfactored load obtained from the three manuals is presented in Table 3.3-3.5, the partial load factors presented in Table 4.1 are applied in Prokon for the analysis.

4.3.5.1 : 2.1m span Analysis Results

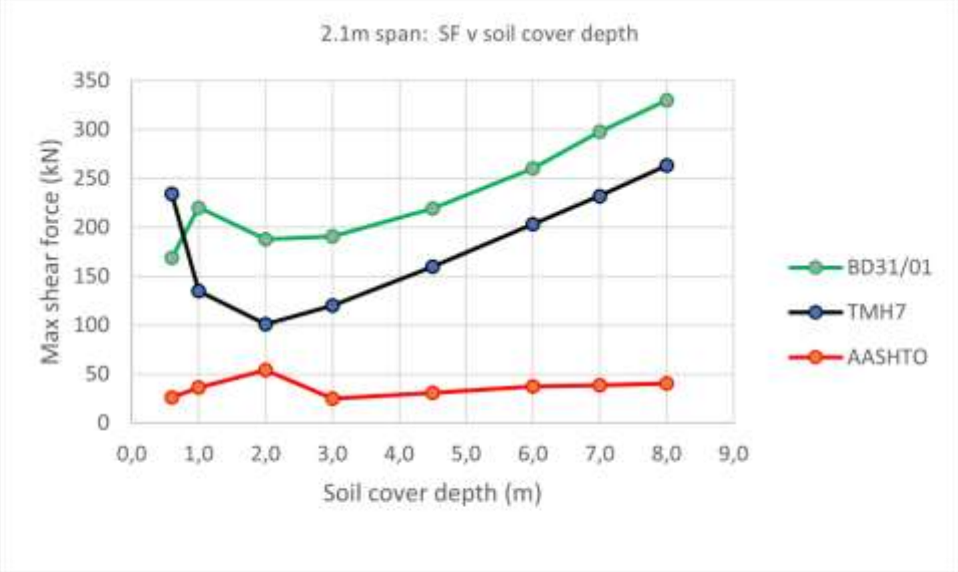


Graph 4.7: 2.1m span FEM v soil cover depth



Graph 4.8: 2.1m span MSM v soil cover depth

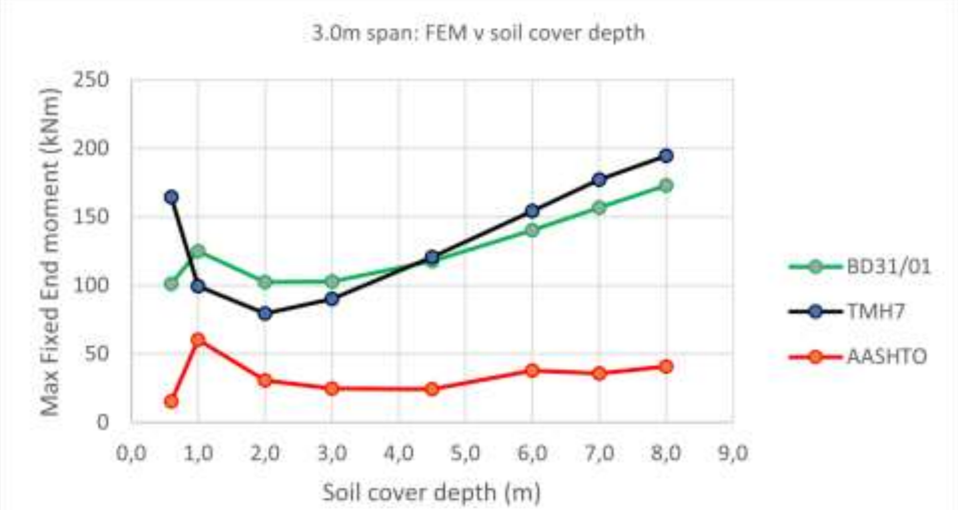
For this span, the maximum hogging moment on the top slab is located at the edge of the slab, the maximum sagging moments are at mid-span and the critical shear force is found at the supports for all load cases from all three design manuals. An interesting phenomenon for TMH7 and BD31/01, is the sudden decrease in the FEM, MSM and SF at the 2.0m fill height - this is the fill height at which the live load reduces tremendously causing the overall load to decrease hence the decrease in the load force values. This is then followed by a constant increase in the load forces (Graph 4.5-4.7).



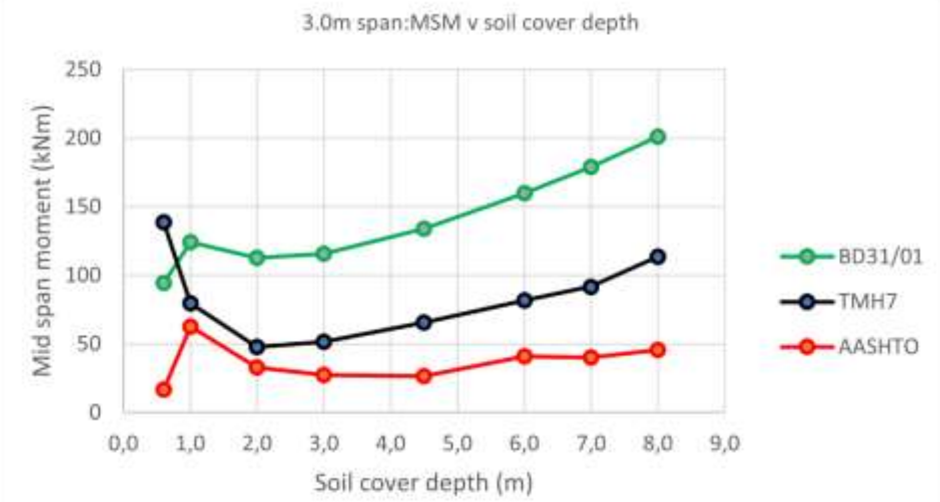
Graph 4.9: 2.1m span SF v soil cover depth

TMH7 and BD31/01 load forces are almost parallel to each other, increasing with an increase in the fill height beyond 2.0m unlike those obtained for the AASHTO LFDR analysis although a reduction is equally observed after the 2.0m fill height. The variance in the load force values obtained from the three manuals is noteworthy. BD31/01 is the most conservative load design methodology resulting in very high load force values while AASHTO is more specific resulting in lower load forces hence an economic design. THM7 lies in between the two.

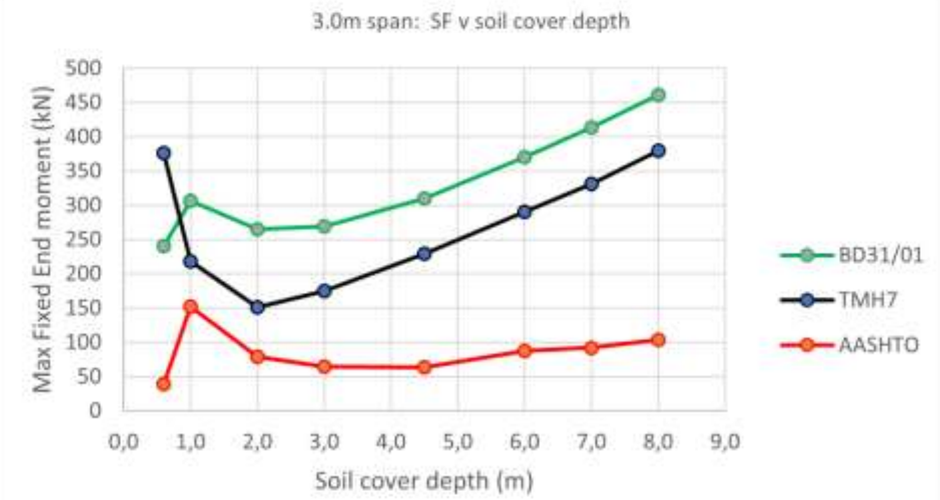
4.3.5.2 : 3.0m span Analysis Results



Graph 4.10: 3.0m span FEM v soil cover depth



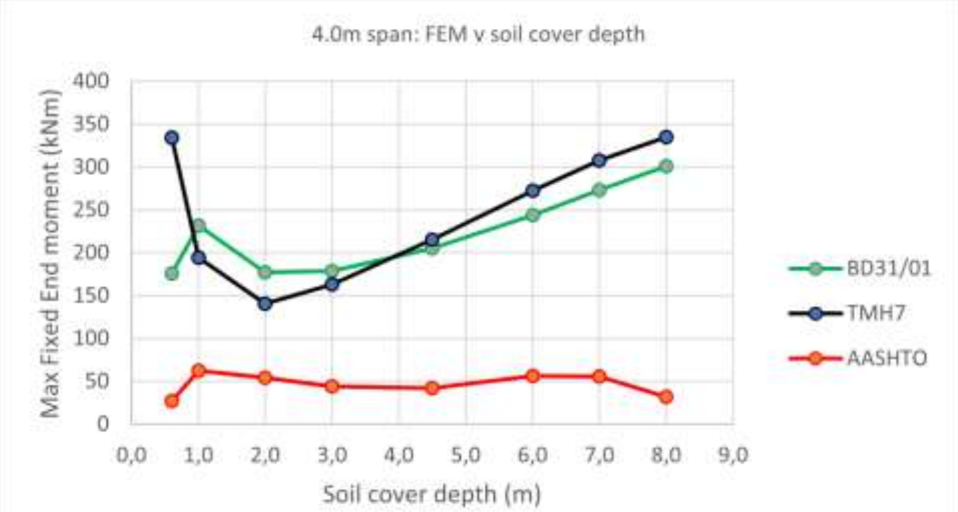
Graph 4.11: 3.0m span MSM v soil cover depth



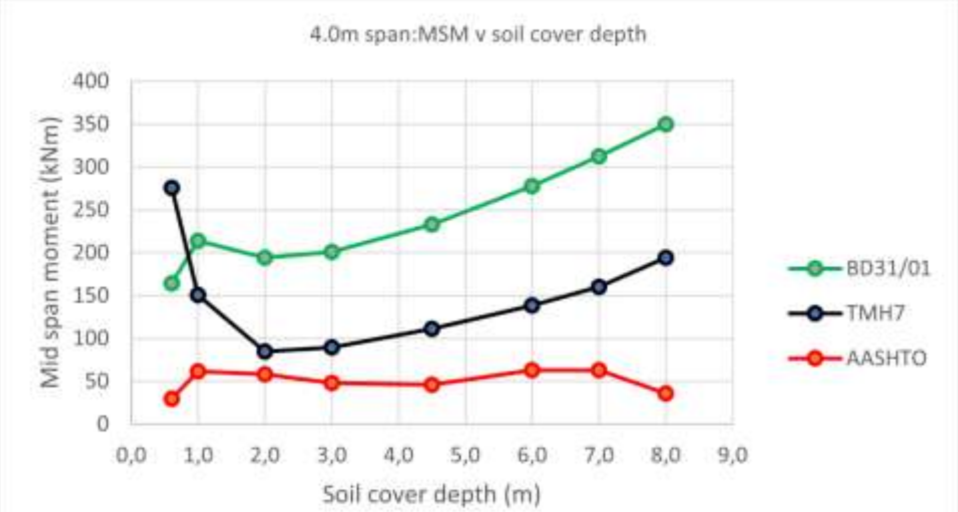
Graph 4.12: 3.0m span SF v soil cover depth

Although the culvert span increases from 2.1m to 3.0m, the L/H ratio remains the same. Similarly, the sudden decrease in the load forces value is observed at a fill height of 2.0m. As previously mentioned, the load forces below the 2.0m fill height are governed by the live load; TMH7 has the highest live load value for 0.6m fill height. The FEM, MSM and SF non- linearly increase after this fill height. The values obtained for the load forces are obviously higher than those previously obtained for the 2.1m span. It is quite clear that a longer span will automatically increase the internal load forces within the top slab irrespective of the culvert height.

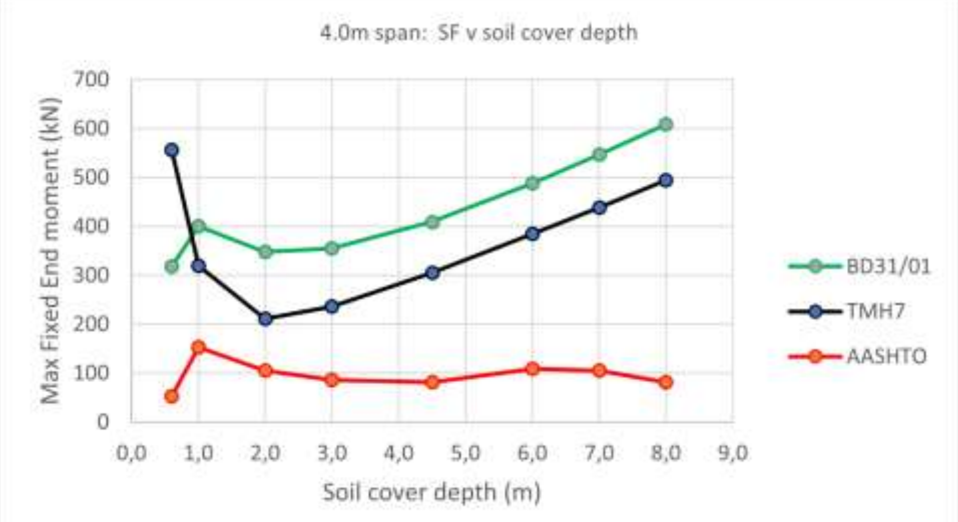
4.3.5.3 : 4.0m span Analysis Results



Graph 4.13: 4.0m span FEM v soil cover depth



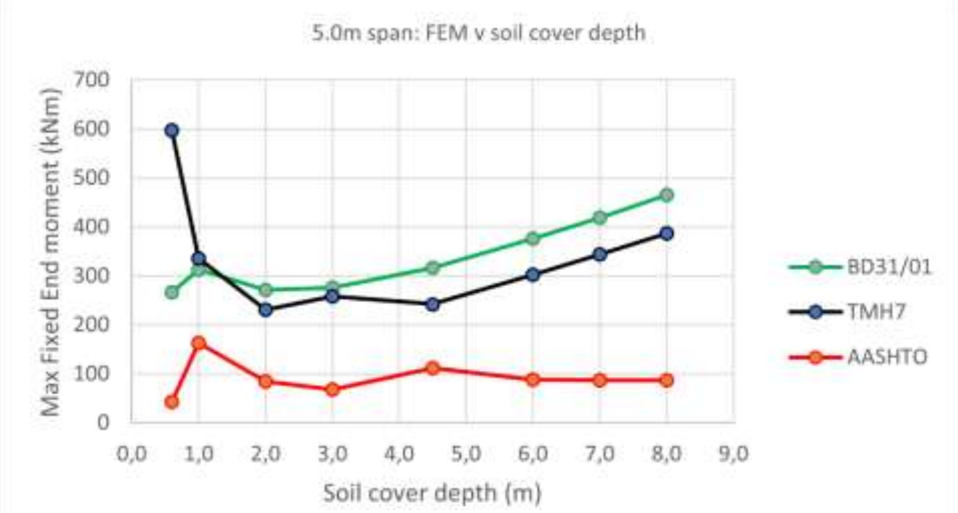
Graph 4.14: 4.0m span MSM v soil cover depth



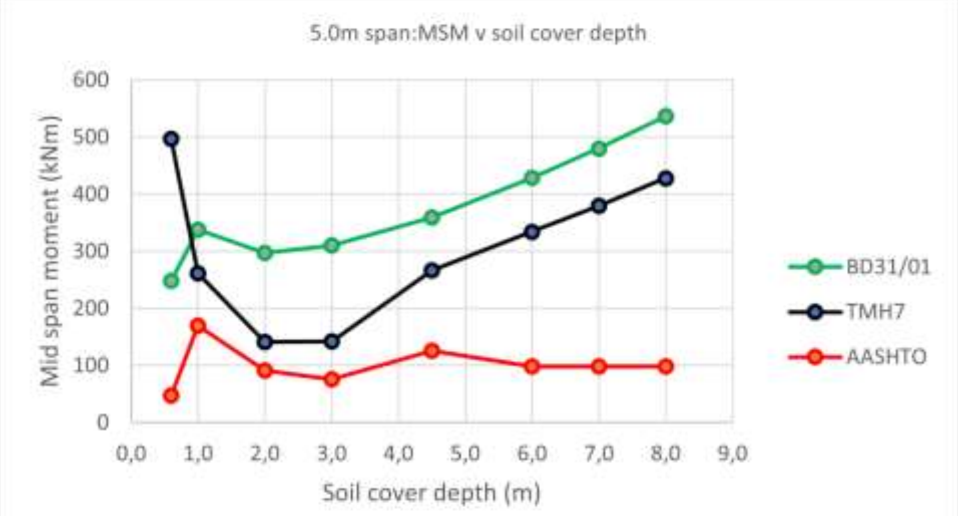
Graph 4.15: 4.0m span SF v soil cover depth

Equally L/H = 1 for the 4m span culvert but due to the increase in span length, the FEM, MSM and SF values obtained from the analysis are greater than those obtained for the 3.0m span. The line trends for all the graphs remain the same, a non-linear increasing relationship exists between the load forces, span length and the fill height after the 2.0m fill height.

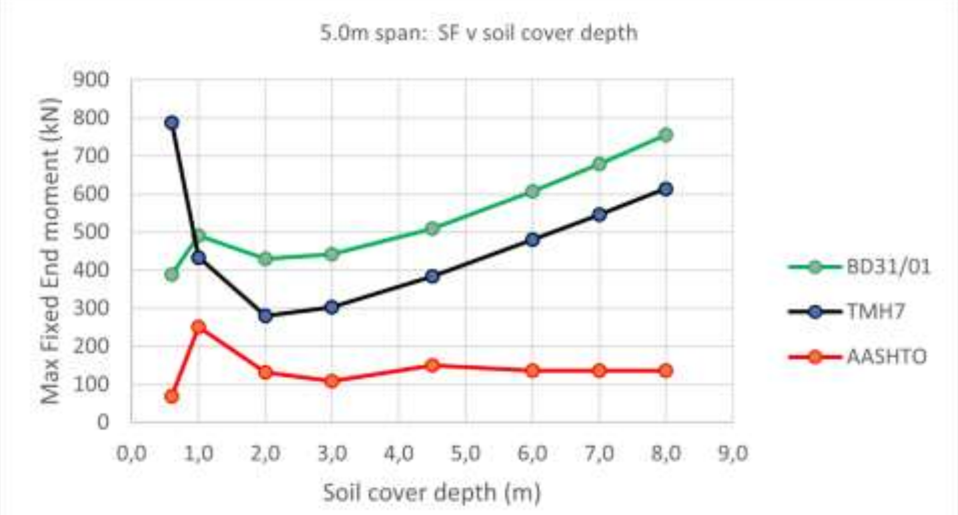
4.3.5.4 : 5.0m span Analysis Results



Graph 4.16: 5.0m span FEM v soil cover depth



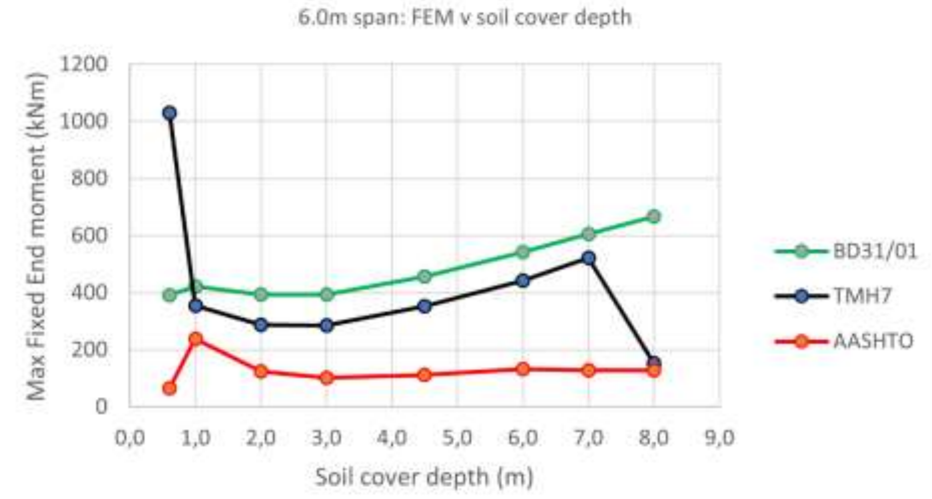
Graph 4.17: 5.0m span MSM v soil cover depth



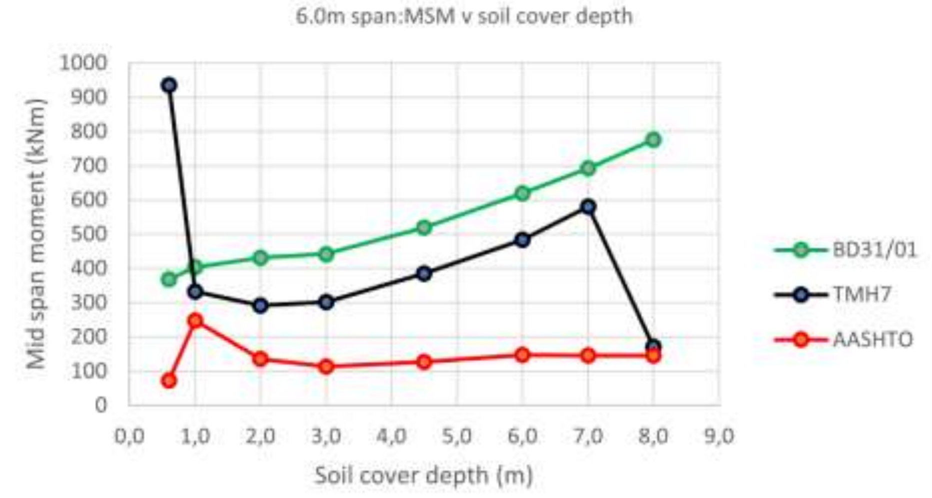
Graph 4.18: 5.0m span SF v soil cover depth

So far, the FEM, MSM and the SF trend remains the same for all the analyzed spans, an increase in the span length automatically increases the load factors. All the culverts analyzed – 2.1m, 3.0m, 4.0m and 5.0m have L/H ratio = 1.0. Although this ratio is the same for all the culverts, the FEM, MSM and SF values obtained for each span at the same fill height are different owing to the varying span lengths.

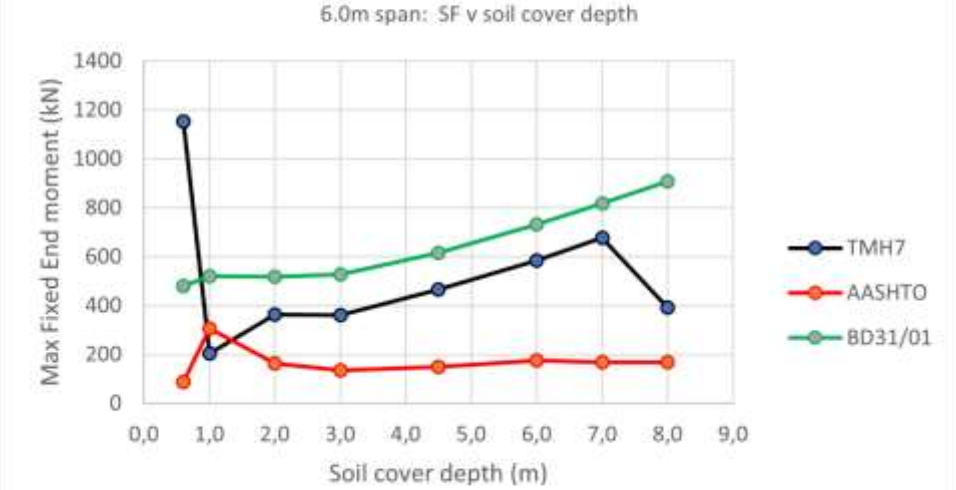
4.3.5.5 : 6.0m span Analysis Results



Graph 4.19: 6.0m span FEM v soil cover depth



Graph 4.20: 6.0m span MSM v soil cover depth



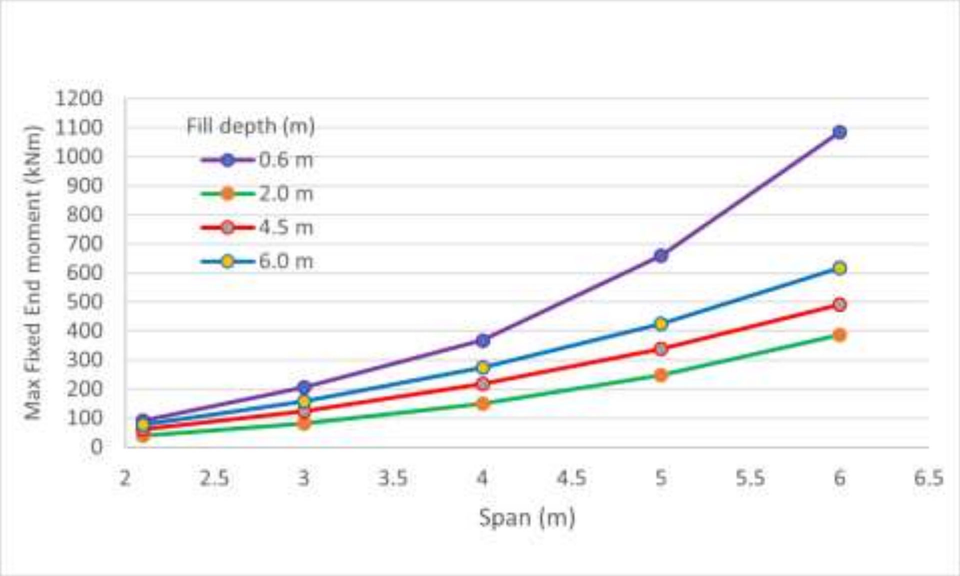
Graph 4.21: 6.0m span SF v soil cover depth

The FEM, MSM and SF values obtained for this span are extremely high for TMH7 and BD31/01. Clearly, when using these two design manuals multicell culverts with shorter span lengths should be considered as opposed to single cell culvert with a much longer span. The trend for the load forces for BD31/01 remains the same as for the previous spans; beyond the 2.0m fill height, a non-linear relationship exists between the FEM, MSM and SF obtained and the fill depth; the load forces increasing with an increase in the fill depth. This relationship exists for TMH7 load forces up to the 7.0m fill height after which a decrease is observed for the FEM, MSM and SF despite an increase in the fill height. Similarly, a change is observed in AASHTO LFRD load forces, from the 6.0m fill height the FEM, MSM and SF values remain constant despite the increase in fill depth, this might be due to the absence of the live load effect. The live load was only applied to a fill depth of 6.0m as previously mentioned in section 4.14.

Despite the varying response observed beyond the 7.0m fill height, the load forces obtained from BD31/01 analysis remain conservative as compared to those of TMH7 and AASHTO.

4.3.6 Effect of culvert geometry

The effect of culvert geometry especially the span length has been mentioned a number of times. Graph 4.22 shows the variation of the maximum hogging moment on the culverts at different fill depths i.e., 0.6m, 2.0m, 4.5m and 6.0m. The load forces clearly increased with an increase in the fill depth along the span. Secondly, at every fill depth, the longer span has a higher force load value.



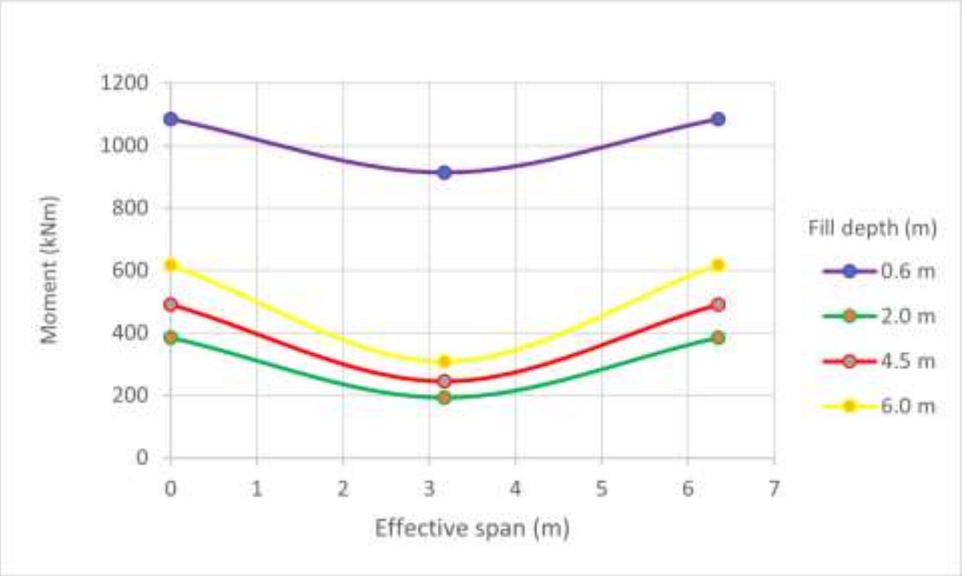
Graph 4.22: FEM v span @various fill depth

This effect of the span variation is evident for all the analysis carried out for TMH7, AASHTO LFRD and BD31/01.

Graph 4.23 shows the distribution of the bending moment along the 6.0m span culverts top slab at different fill heights i.e. 0.6m, 2.0m, 4.5m and 6.0m. The bending moment clearly increased with an increase in the fill depth, the hogging moments in all four cases were higher than the mid span moments.

It can also be observed that moments are highest at a low fill depth – 0.6m, at this depth the live load is the most critical load. As the fill depth increases, a point is reached (2.0m) where the live load is less significant and slowly the dead load becomes more significant. Beyond this point we have an increasing vertical earth load dominating the load component on the culvert.

Another parameter affecting the load forces on the top slab is the effect of the change in the culvert width (B_c) to the fill height *(H)* (Abuhajar,2017). An increase in this ratio increases the bending moment values. The 4.5m fill height was considered to verify the influence. From the 2.1m, 3.0m, 4.0m, 5.0m and 6.0m span culverts, we have B_c/H ratios of 0.5, 0.7, 0.9, 1.1 and 1.3. From the analysis this is verified to be correct.



Graph 4.23: Bending moment for 6.0mspan @various fill depth

4.3.7 Summary

Load obtained from TMH7, AASHTO LFRD and BD31/01 was applied in the analysis of five single cell box culverts with spans ranging from 2.1m to 6.0m. Although the culvert spans are different, the L/H ratio =1.0 for all the culverts. The culverts' slab and wall thicknesses are different for each culvert, ranging from 0.2m to 0.35m.

The Frame Analysis module was used for the analysis, the culverts were modelled as plane frames structures with negligible sway. To study the effect of the vertical load on the culverts' top slab and the effect of the span length on the load forces, the longest and shortest culverts were analyzed (2.1m and 6.0m span culverts). The frames were analyzed, and the load forces obtained i.e. maximum hogging and sagging moments and the shear force for both spans at defined fill heights were recorded. The FEM, MSM and SF obtained from the analysis were observed to be higher on the longer span as compared to the shorter span even though the vertical earth load at a defined fill height was the same. In both spans FEM was higher than the MSM for all fill heights for both spans except for fill heights of 0.6m to 1.0m for the longer span. Clearly an increase in the span length resulted in increase of the obtained load forces for the top slab. Equally the live load was applied separately on the two spans as outlined in TMH7, AASHTO LFRD and BD31/01. Contrary to the effect of the vertical earth load, the effect of the live load diminished with an increasing soil depth. From the analysis it was clear that the obtained load forces were influenced by the soil cover depth, the culvert span length and the load type; an increase in either the fill depth or the span length increased the forces non-linearly to a certain depth. The live load is significant for culverts with a shallow soil cover (less than 1.0m fill depth) but diminishes with an increase in the soil cover depth unlike the vertical earth load which increases with an increase in the fill depth.

To study the effect of the combined loads, a discrete analysis for all the culverts was carried out by applying all the load cases i.e., dead load, vehicular live load and lateral earth pressure obtained from the three design manuals. The FEM, MSM and SF obtained were plotted against the soil cover depth to study the relationship between the load forces and the soil cover depth. Although the trend/response of the culverts remained the same for all loads obtained from the three manuals, the values were different since the formulae for the various loads were all different.

CHAPTER FIVE

CONCLUSION, RECOMMENDATION AND FURTHER RESEARCH

5.1 Conclusion

The main objective of the study was to recommend the most effective methodology to determine the vertical earth load acting on box culverts specific and appropriate for South Africa and to determine the need for updating TMH7. The formulae for estimating the vertical earth load in AASHTO LFRD and BD31/01 were equally applied and the load obtained was used in the Prokon analysis to review, the effect of the vertical earth load on concrete box culverts at varying soil depth, the relationship between the culvert span and the soil cover depth and the relationship between the vehicular live load and the soil cover depth.

Several challenges were faced during the study, no actual field data from existing reinforced concrete culverts was available for the study, the research depended on the information provided in TMH7, AASHTO LFRD and BD31/01 design manuals and past research paper on box culverts as the basis for the study. The absence of actual field data meant there was no probable basis especially since some results obtained contradicted some previous research finding.

Secondly, the Prokon analysis did not consider the soil-structure interaction as such the results obtained from the analysis are conservative. Thirdly, due to time constraint, the equation for estimating the vertical earth load for trenched culverts was the only one considered for the study, the research does not discuss the untrenched culverts.

Based on this study, the following conclusions are made:

1. The formula for the culvert in trench on unyielding foundation with no projection presented in TMH7 overestimates the vertical earth load. The equation concisely estimated the load as equivalent to ρh ignoring the soil – structure interaction, effect of the overall trench width or the culvert width. The equation for estimating the earth load for AASHTO LFRD is a factor of the culverts outside width and the soil-structure interaction factor for trench installation on top of ρh. The soil-structure interaction factor reduces the vertical earth, making AASHTO LFRD a more economic design specification.

2. For TMH7, the NA load on culverts consists of two uniformly distributed pressures q_{a1} and q_{a2} and an additional 2-100kN wheel nominal loads which yields very high load values. On the other hand,

the HA load on culverts (BD31/01) consists of an HA UDL/KEL or HB30 load or these two loads can be replaced by a single 100kN HA wheel nominal load when it has a more severe effect on the member under consideration than the other two cases. The live load values obtained for TMH7 are generally higher than those obtained from the other two manuals due to the additional 2-100kN wheel. For the live load design, the, TMH7 is the least economic among the three design manuals.

3. The soil cover depth is a crucial factor in the design of culverts; an increase in the soil cover depth increases the vertical earth load which increases the resultant load forces. Conversely, an increase in the soil cover diminishes the effect of the live load; the live load is significant for culverts with shallow soil cover depth. From the analysis, the FEM, MSM and SF significantly reduced at 2.0m fill for all culverts, this can be taken as the fill depth at which the live load effect diminishes greatly, and the dead load becomes more significant- dominating the load component.

4. The longer the culvert span the higher the load forces on the top slab and vice versa. The FEM, MSM and SF for culverts with longer spans were observed to be higher than those for shorter span culverts at the same soil cover depth. At shallow fill height, this effect is from the live load acting more as a concentrated load than a UDL but as the fill height increases, it becomes the influence of the dead load.

5. FEM are the most crucial moments for the top slab of single cell box culverts. From the analysis, it was observed that the maximum hogging moments were higher than the maximum sagging moments for all spans at any fill heights.

6. Higher load forces were observed for higher culvert width to fill height ratio; at 4.5m fill height the B_c / H ratios for the 5.0m and 6.0m spans are 1.1 and 1.3. From the analysis, the FEM, MSM and SF were higher for the 6.0m span at this fill height.

5.2 Recommendation and further research

Based on this study, the following recommendations are made:

1. Further research to be done on the formula for trenched culverts on unyielding foundation with no projection presented in TMH7. This should be accompanied with field data obtained from existing reinforced concrete box culverts with varying fill depth should be identified for testing. This is also recommended for the formulae for untrenched culverts.

2. The application of the Normal Load (NA) load on rigid culverts in TMH7 (section 2.6.6.2) needs to be reviewed and clarified; currently the NA load consists of two uniformly distributed pressures q_{a1} and q_{a2} and an additional 2-100kN wheel nominal loads. Which is different from the NA load for bridge design (section 2.6.3.1), the structure is designed to resist the most severe effect of Q_a and a single axle load of $144/\sqrt{n}$ or two nominal 100kN wheel loads. There seems to be a discrepancy between the two cases - for the culvert design all three loads are considered while for the bridge design considers the two UDL only or the 2-100kN wheel load when it has a more adverse effect.

3. From the analysis, a decrease was observed on all the values for the load forces i.e., the bending moments and shear forces for all culverts at 2.0m fill height likely due to the diminishing effect of the live load. The point at which the live load becomes irrelevant in a design needs to be investigated and documented for easier design options. For instance, AASHTO LFRD recommends that live load should not be applied on single box culverts when the fill height is greater than 2.45m and greater than the culvert span.

4. Increase research on reinforced concrete culverts in South Africa under roadways and railways. Few research papers are available by local researchers on reinforced concrete box culverts despite being widely used in the country.

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