DESIGN BENDING MOMENT IN CONCRETE BOX STRUCTURES

A COMPARATIVE ANALYSIS BETWEEN SHELL AND SOLID ELEMENT MODELS

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Dissertation submitted in partial fulfilment of the requirements for the degree Master of Engineering in Structural Engineering Designs

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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A.A.D.I. Rasikamal Date: 29th of March 2016

The above candidate has carried out research for the Masters Dissertation under my supervision.

Dr. K.Baskaran Date: 29th of March 2016

ABSTRACT

Concrete box structures are mainly used in railway and highway projects as culverts or frame bridges. Structural engineers prefer to do finite element method (FEM) analysis using shell or frame element models to obtain bending moment diagram (BMD) for design. Structures are modelled center to center supports in shell element models. BMD of general shell element models are continuous throughout the center to center spans and maximum support moment occurs at center of supports. ACI design practice recommends selecting bending moment at face of the support as design value, but BS design practice is different and obtains bending moment value at center of the support for designs. Some literature suggests tedious bending moment correction according to the stiffness of the members of the joint.

In general shell element modeling, inside rigidity of supports is not considered. However general shell element models can be modified at support region to represent the rigidity of the support area.

Previously tested concrete box structure was modelled using general shell, modified shell and solid elements. Results of solid element model are much closer to experimental results at supports and spans than other models. This result validated that solid element of box culvert can be used as a base for comparison of general and modified shell models.

In this study, BMD of general shell, modified shell and solid element models relevant to concrete box structures were compared to load combinations relevant to Sri Lankan Railways. The results show that BMD of solid and modified shell elements are much more similar than the general shell models. Support design bending moment can be obtained from modified shell models with reliability without confusion of center or face value to select for the design as for the general shell element models.

Keywords: Bending moment diagram, Modified shell model, Solid elements, concrete box culverts, maximum support moment.

ACKNOWLEDGEMENT

There are many individuals who deserve acknowledgement for their contribution towards successful completion of this research.

First, I would like to express my gratitude to my supervisor, Dr. K.Baskaran his valuable advice, guidance and assistance throughout the entire period of study. I am much grateful for sharing his vast knowledge and expertise on the field of structural analysis.

Secondly, my sincere acknowledgement is towards my employer, Central Engineering Consultancy Bureau for granting me the sponsorship for following the course and other assistances provided for my research works.

I am much grateful to the Head of the Department of Civil Engineering, the Course Coordinator of Master of Structural Engineering and the staff of the Department of Civil Engineering for their valuable guidance and corporation.

My very special thanks go to my dear wife Suseema, mother in law Gnawathee and colleague Nalaka for their continuous encouragement, assistance and patience during the entire period. My research would never be successful without their tremendous support and patience of our loving daughter Isumi.

Lastly, there are many friends, relations and colleagues who have not been personally mentioned here that I am much indebted to their contribution at various stages of the research to make it successful.

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LIST OF ABBREVIATIONS

Abbreviation	Description
ACI	American concrete institute
BMD	Bending moment diagram
BME	Bending moment envelop
BS	British Standard
FEM	Finite element method
RC	Reinforced Concrete
SLS	Service limit state
ULS	Ultimate limit state

LIST OF APPENDICES

Chapter 01

INTRODUCTION

1.1 General

All over the world concrete box culverts are used for infrastructure development in rail and road development. With the development of finite element software, civil engineers prefer to design civil structures with finite element method model analysis results. Analysis model is simplified version of the real structure which has to be built in future. As in building structures or bridges, box culverts are also analyzed using finite element method with frame elements or shell elements. Due to centerline modeling and representing three dimensional structures with two dimensional or one dimensional element make assumption that members are prismatic with constant moment of inertia between centerlines but it is not correct, because member is prismatic until support face only. Members are connected not only at center of the support, but also face of the support in solid element models. For general civil structural analysis it is difficult to use solid element analysis.

1.2 Need for Research

Most structural analysis method used in manual calculation or computer based finite element method of analysis, structures are represented by centerline elements. In calculation stiffness effects are represented. With this representation, continuous smooth bending moment diagram can be drawn to each element from start to end of element between center to center of element jointed length. In FEM analysis using frame or shell elements and structural frame analysis, it is assumed that members are prismatic with constant moment of inertia between centerlines, but it is not correct, because member is prismatic until support face only, but from that point to support centerline it has greatly increased the depth with very high moment of inertia. With this error BMD of general shell element models are continuous throughout the center to center spans and maximum support moment occurs at center of supports. Hence designers are confused in selecting design bending moments. Some engineers select design bending moment as joint midpoint value and some select at face of the member joints. Some literature suggests tedious bending moment correction according to the stiffness of the members of the joint.

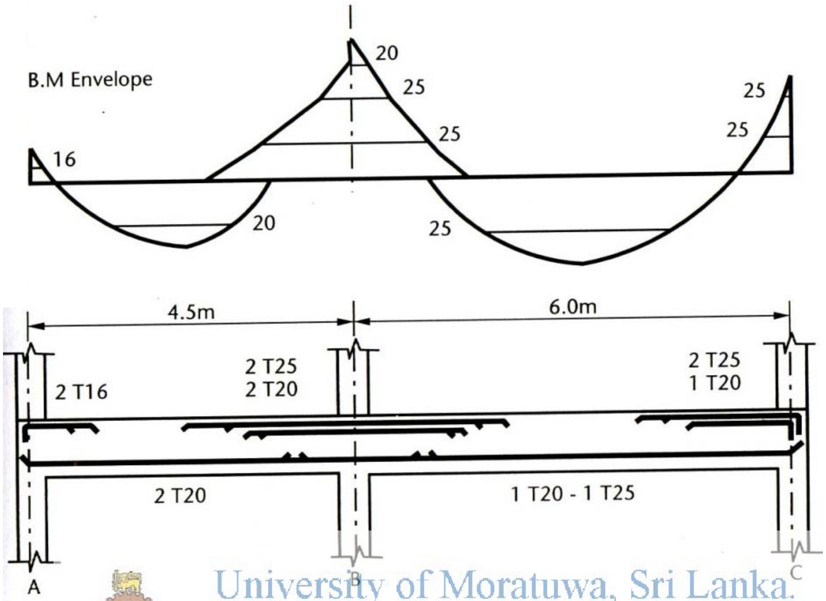


Figure 1.1: Bending moment diagram representation to BS [10]

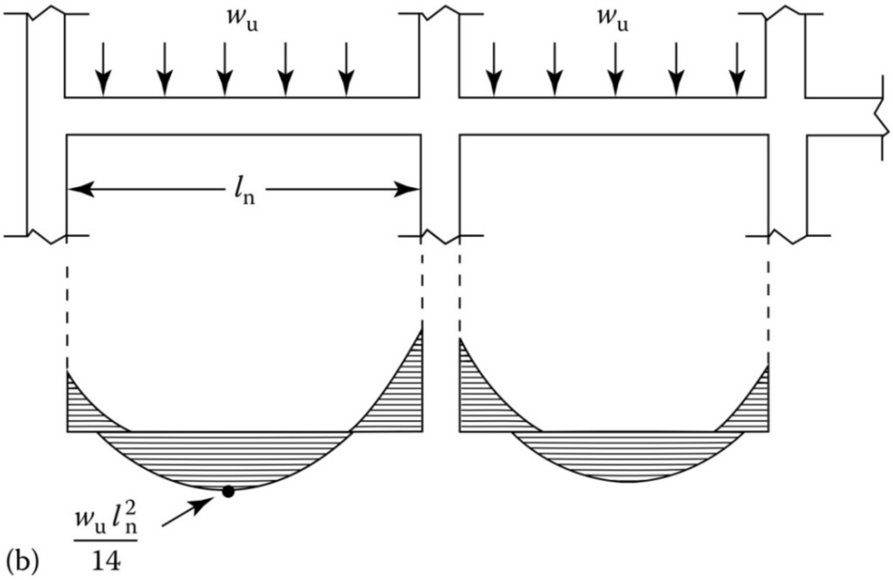


Figure 1.2: Bending moment diagram representation to ACI [8]

In building design, British Standard code of practice guides to select joint center bending moment value as in figure 1.1. On the other hand, American concrete institution code of practice guides to select bending moment value at face of the support as in figure 1.2. Generally bending moment value at center is higher than that at the face of the support. Hence designers of contractor's party prefer to select face value as cost reduction method, but consultant's engineers prefer to select center value as safe conservative method.

There is a need to understand the behavior of bending moment diagram of real structure and deviation of design values obtain from shell element or frame element finite element modeling over the real behavior.

1.3 Finite element modeling of structures

1.3.1 Shell and frame element modeling

In this type of finite element modeling, members of structures are represented by two dimensional area elements or one dimensional frame elements and they are connected at center point of joints. Bending moment values are usually obtained from this method of modeling in civil structural design. In this modeling type, a member joint represent from a point object (node) and deflection shape looks like in figure 1.3 and some deviation from real structure can be observed.

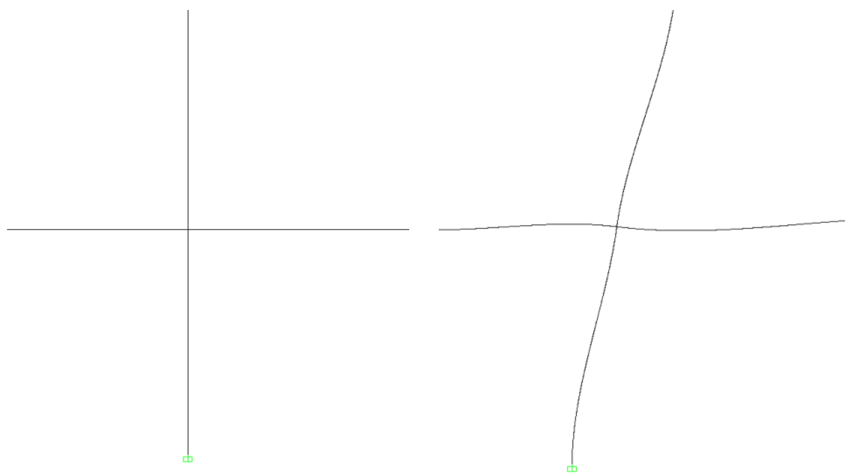


Figure 1.3: Deflection shape at member joint in frame or shell element models

1.3.2 Solid element modeling

In this type, members are modeled using solid elements and it has very similar three dimensional representations, but only with inside element mesh. Member joints are represented with several solid elements with number of nodes and deflection of members at joint look like as in figure 1.4. The elements within the corner cannot move independently as shown in figure 1.5(a), but figure 1.5(b) shows deformation of shell of frame element models which neglect the corner rigidity.

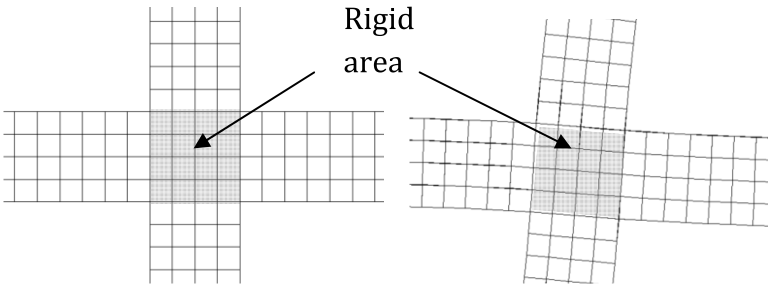


Figure 1.4: Deflection shape at a member joint in solid element models

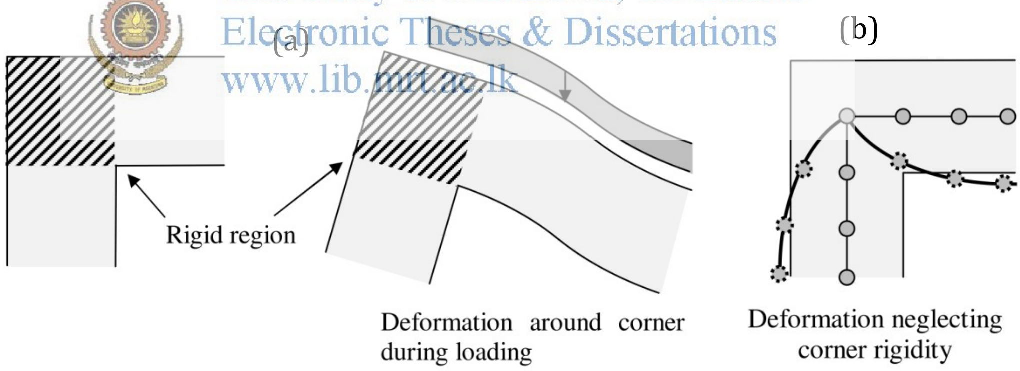


Figure 1.5: Response of a frame corner during loading [5]

Although, structural modeling using solid elements and obtaining bending moment is difficult than shell element modeling, it represents joint much more related to real structure and achieves deflection shape very much similar to the real structure. Since deflection shape and bending moment diagram relate to each other, it indicates that accuracy of bending moment obtained from solid modeling is higher than shell or frame element modeling.

1.4 Objectives of the Research Study

The objective of this research was to investigate the level of accuracy of design bending moment obtaining from shell element finite element models of concrete box structures.

1.5 Methodology

To obtain level of accuracy of shell element finite element models with respect to design bending moments, concrete box structures were modeled with shell elements and solid elements.

To achieve the above goal, following Methodology was adopted:

- A literature review on previous research work was carried out in the area of study including behavior of the concrete member joints, bending moments, crack patterns and finite element method of analysis;
- Studied software packages for analysis of shell and solid elements;
- Modeled concrete box structures using shell and solid elements separately;
- Prepared spread sheets to obtain bending moments from stresses given in solid element models;
- Tabulated results for load cases and design combinations and evaluated the percentage of deviation of bending moments. Drew bending moment diagrams for each member;
- Compared results and prepared instruction to select design bending moment for critical section in finite element models.

1.6 Outline of the Dissertation

The second chapter of this dissertation deals with the literature review, which includes the study and research on concrete member joints, standard guidance and suggestions given for finite element modeling by various authors.

The third chapter provides details of various models considered and their loadings. It also describes the method adapted for solid model to obtain bending moments and improvements done to obtain accurate bending moment value at critical section in all models.

The fourth chapter provides graphical representation of bending moment variation.

In chapter five, results were compared members vise separately for each box structure type.

In chapter six, experimental results of previously tested box culvert compared with results obtained from FEM analysis models.

The dissertation concludes with Chapter 7, indicating the conclusions of the study and giving suggestions for obtaining design bending moments from finite element models for future design of concrete structures.

Chapter 02

LITERATURE REVIEW

2.1 Introduction

The literature review was carried out to gather information from previous research studies in this area of study and guidelines for finite element analysis regarding concrete structures. This chapter summarizes the important and most relevant information gathered from the literature for this research study.

2.2 Finite element method of concrete box structures

To obtain bending moment diagram of concrete box structures frame element and shell element modeling and linear analysis is widely used.

Generally linear elastic analysis is considered as good design approach, because linear elastic analysis will require small amount of plastic rotation. If skew angles are not present in box structure, it can be modeled with frame elements. The same structure modeling with frame or shell elements, little variation can be seen in figure 2.1. Because, 1m wide beams are used in frame analysis in which no transversal redistribution of force can take place. In shell models, more stiff regions tend to attract forces from adjacent regions and it creates variation in bending moments [1, 5].

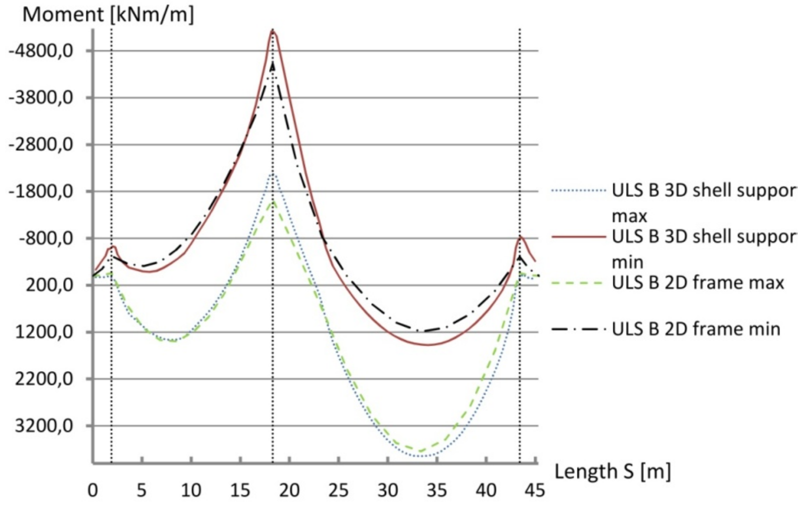


Figure 2.1: BMD shell and frame analysis [1]

2.3 Variation in bending moment diagrams in finite element method analysis model

According to element type, mesh density, support width, support stiffness, considerable variation can be shown in bending moment diagrams of figure 2.2. Support moment increases with the increase of mesh density. Since solid elements have more tangible material thickness, support moment obtained from solid models are smaller than shell element models. Although shell elements give acceptable accuracy in bending moment values with faster calculation, solid elements give better response in bending than shell elements. FEM model support moments are about 12-25% larger than the traditional methods such as yield line theory and strip method. It can be seen that support moment increases with mesh density increases, but span moments less sensitive with mesh density increases as shown in figure 2.2(a). In figure 2.2(b) shows BMD of slabs for shell and solid element models and BMD for various column thicknesses are shown in figure 2.2(c). Number of nodes used to apply column stiffness is changed and BMD are given in figure 2.2(d). According to all BMD in figure 2.2, it can be seen that significant support moment variation can be identified and negligible variation can be seen in span moments [6].

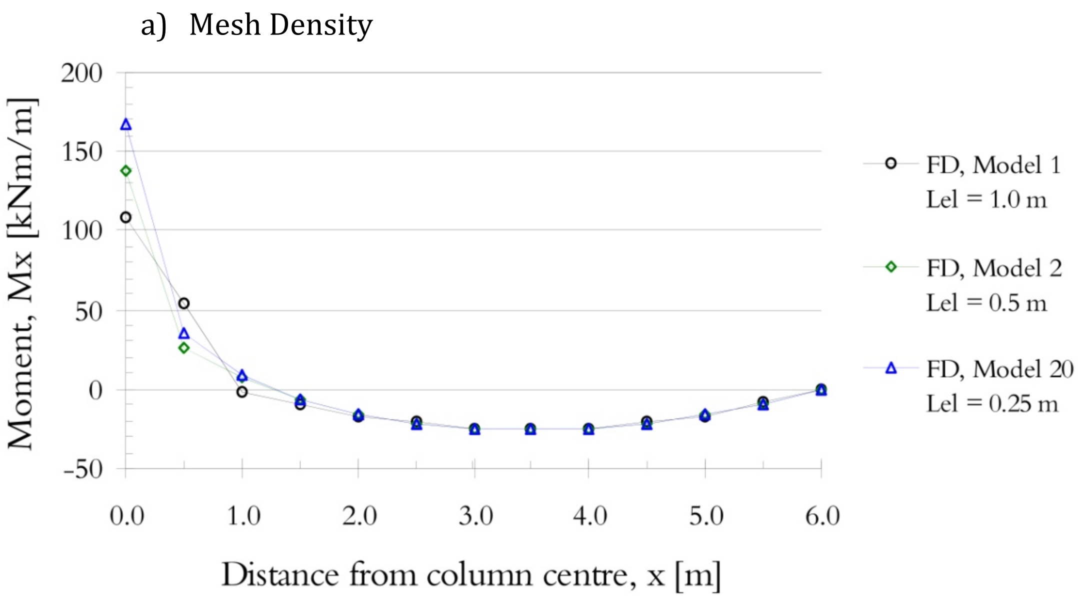


Figure 2.2 (a): BMD Variation in FEM [6]

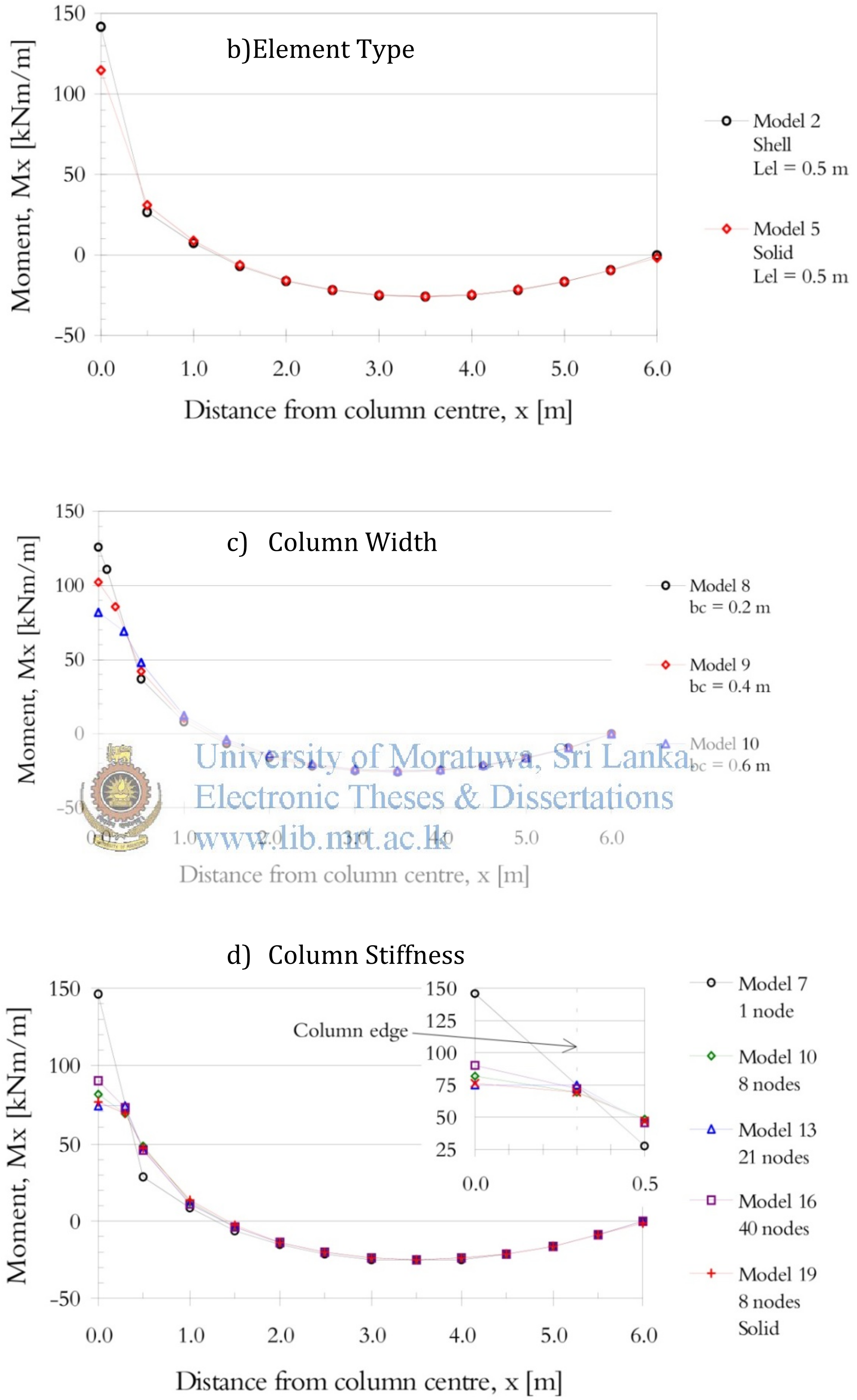


Figure 2.2: BMD Variation in FEM [6]

2.4 Problems associated in centerline modeling

2.4.1 Corner effects

The effects of frame corner region is generally not taken into account in FEM shell or frame element modeling as shown in figure 2.3. It is advisable to model corners with infinite stiff truss element or by coupling of joint faces nodes, because it creates corner region rigidity and deformation pattern according to real structure. Since deformation and bending moment relate to each other, it creates more accurate BMD [2].

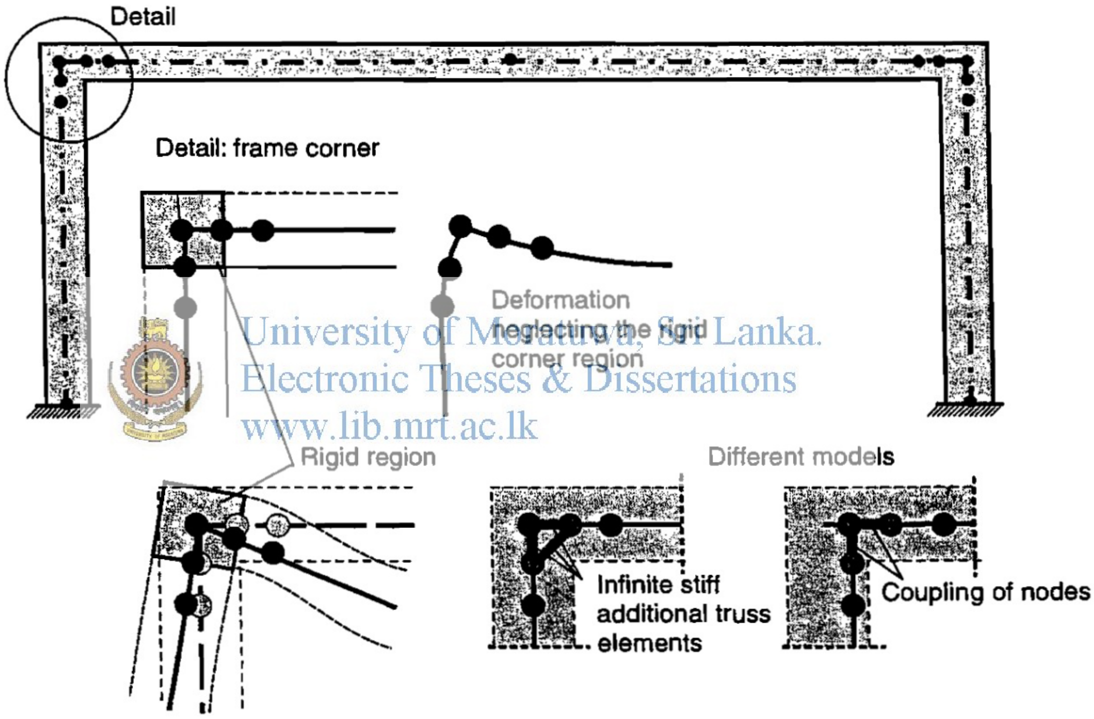


Figure 2.3: Corner region effects in FEM [2]

2.4.2 Load reduction

In shell or frame element centerline modeling, corner region outside the centerline is not modeled. Since loading at that region is neglected in general shell and frame element modeling. This error can be reduced by applying a force and moment same as excluded amount or model with dummy elements just to apply loads as shown in figure 2.4 [5].

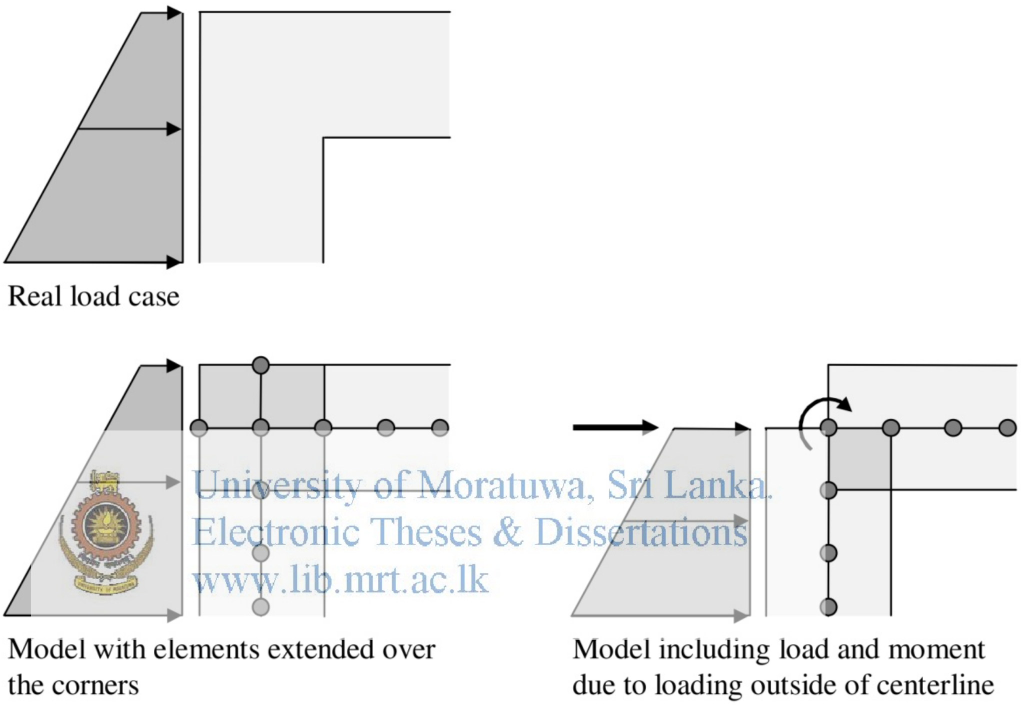


Figure 2.4: Various models for accounting loading outside of centerlines [5]

2.5 Selecting design bending moment at supports

Different methods are discussed to obtain critical bending moment at support in BMD of frame or shell element of FEM models and manual frame analysis.

2.5.1 BS, Euro code method

British Standard design practice obtains BMD continuously center to center spans neglecting support width as shown in figure 1.1 and figure 2.5. Support center bending moment is selected as design moment at supports [16].

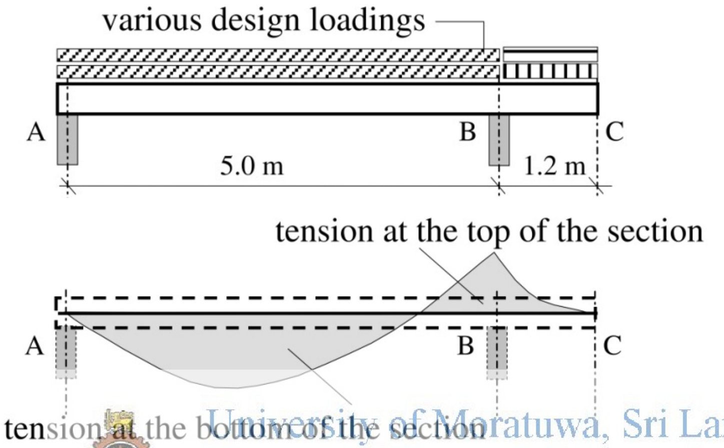


Figure 2.5: Bending moment diagram representation to BS [16]

2.5.2 ACI method

ACI design practice is different to BS, because it recommends selecting bending moment at face of the support as design value and it is lesser than center of the support bending moment as shown in figure 2.6 [8].

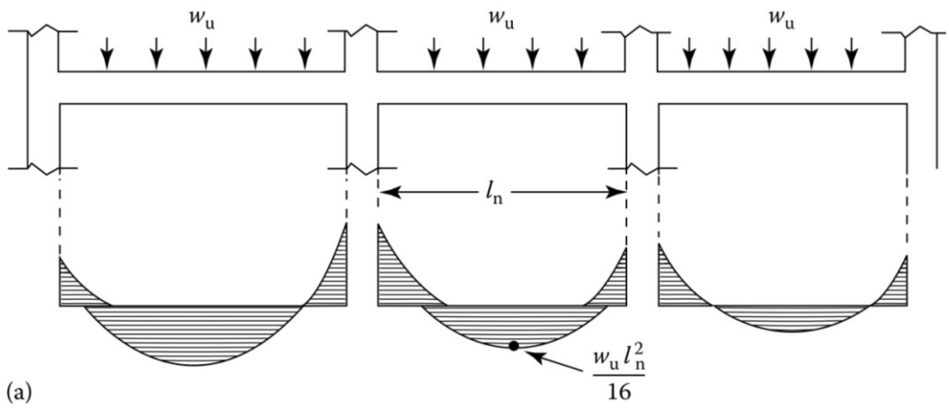


Figure 2.6: Bending moment diagram representation to ACI [8]

2.5.3 Correction for BMD

In frame analysis, it is assumed that members are prismatic with constant moment of inertia between centerlines, but it is not correct, because beam is prismatic until support face only, but from that point to column centerline it has greatly increased the depth with very high moment of inertia. Therefore bending moment at face of the support is increased and same amount is deducted from span bending moment value as a correction for BMD [7]. This method is shown in figure 2.7.

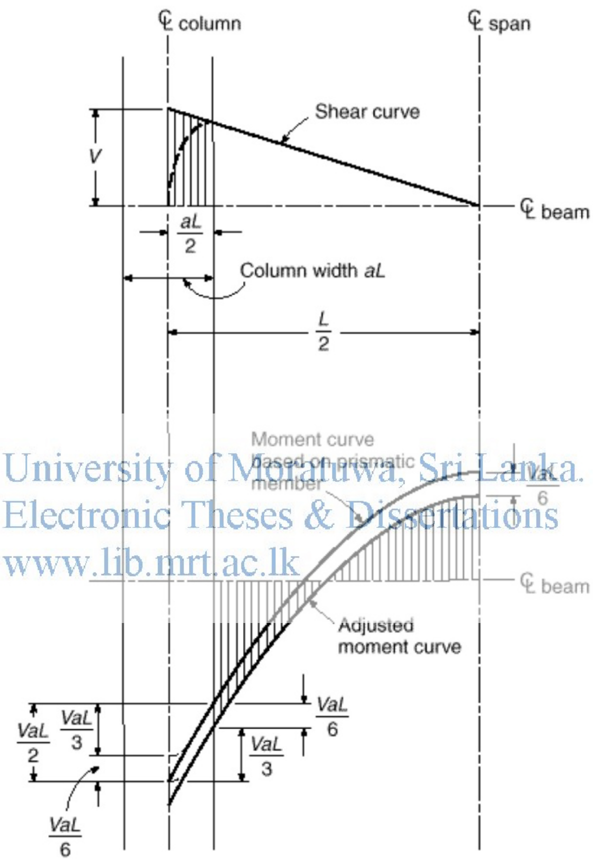


Figure 2.7: BMD correction [7]

The slope of BMD for beams is steep in region of support and there is a substantial difference between support centerline moment and the moment at support face. Therefore an unnecessary large section would be result, if centerline moment is used for design. Then it is reasonable to reduce centerline support moment to account for the width of support. In case of columns, the moment gradient is not very steep and there is not much difference between centerline moment and moment at face of the beam and this correction can be neglected [7].

2.5.4 Support moment from FEM

It is recommended to model the supports in lines or discrete points, mesh needs to be sufficiently dense. Then the bending moment at face of the support as shown in figure 2.8, can be used as design value without influence of the singularities that may occur at support nodes [3].

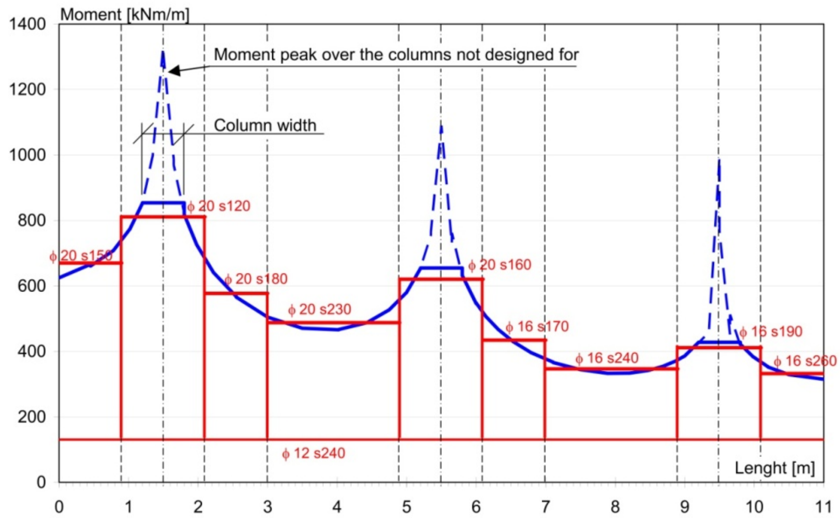


Figure 2.8 : Design moment in FEM models [11]

2.6 Corner rigidity at supports

According to experimental investigation, cracks formation along the face of the wall and slab joint at elastic stage is shown in figure 2.9. This experimental result indicates that the member supporting area is very rigid compare to member spanning area [4].

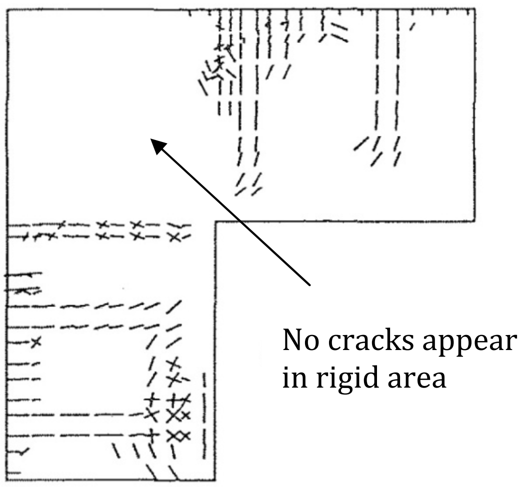


Figure 2.9: Cracks at supports [4]

2.7 Bending moment values from experiments

Double cell box culvert was tested in university of Tennessee. Details of the box culvert and placement of strain gauges are shown in appendix A. In this experiment strains of reinforcement were measured at middle of the spans and faces of the support in the top slab and an outside wall for various heights of soil fill. Bending moments are calculated from those strains. These results are shown in figure 2.10. In this figure, moment A4 indicates face moment of edge support, moment A5 indicates support moment at middle of each span and moment A6 shows face moment at middle support in top slab [18].

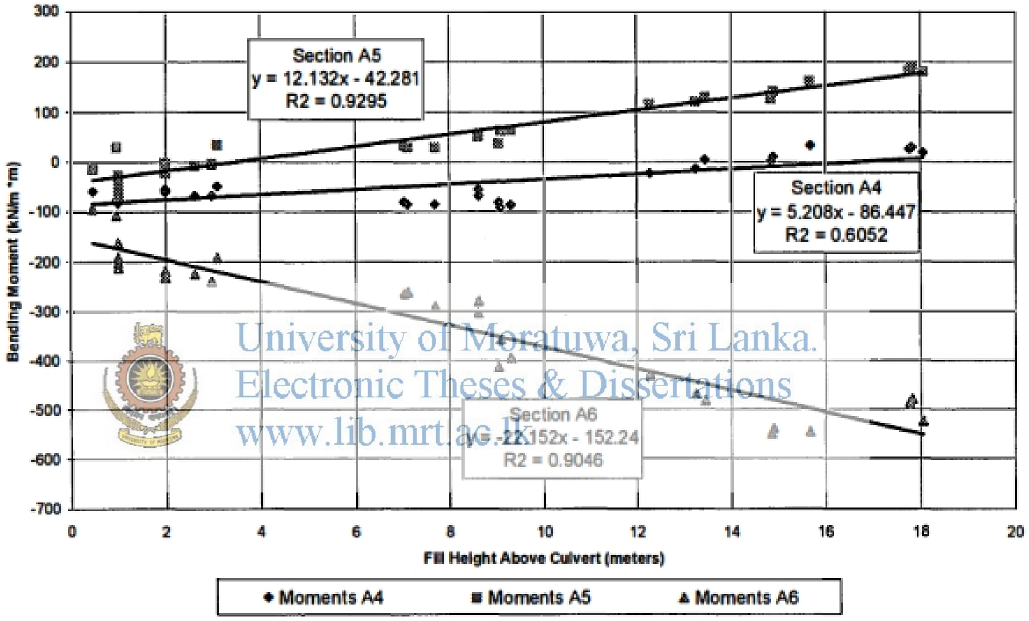


Figure 2.10: Bending moments vs. Fill height in top slab [18]

This literature review indicates that simplification used in analysis in manual or frame and shell FEM models creates continuous bending moment curve in between center to center supports and maximum bending moment occur at center of supports. In structural analysis, it is assumed that members are prismatic with constant moment of inertia between centerlines and support rigidity is not taken into models. To mitigate this error, solid element models and modified shell element models were used and comparison of those models related to design of concrete box structures were discussed in next chapters.

Chapter 03

MODELS OF FINITE ELEMENT METHOD OF ANALYSIS

3.1 Introduction

In this research study, main objective is comparing BMD of shell element model vs. solid element model. For comparison three main type of concrete box structures which are recently constructed in Matara-Beliatta railway project have been selected for computer modeling. This chapter represents the details of those models and chapter 06 provides modeling details for tested culvert in University of Tennessee.

3.2 FEM models

Three major types of concrete box culverts selected for modeling are as follows;

1) Single cell
2) Double cell
3) Story cell

Details of above selected box culvert structures are shown in appendix A and geometric details which are important to model are given in table 3.1.

Table 3.1: Details of main box structures

Box structure	Width (m)	Height (m)	Skew angle ^{0}	Fill height (m)	Slab thickness (mm)		
					Top	Bottom	Wall
Single cell	8.4	6.3	15	1.0	700	800	700
Double cell	33.6	8.7	42	2.1	1300	1400	1200
Story cell	12.0	15.4	30	2.7	900	1000	1000

Box structures mentioned in table 3.1 were modeled using shell element and solid element FEM. To understand the variation in BMD, several models were considered by changing geometry, stiffness, loading etc as shown in table 3.2. For each box culvert type, 16 variations were considered as given in appendix D. Each variation is modeled with three computer models;

1) General shell element FEM model
2) Modified shell element FEM model
3) Solid element FEM model

For above all 144 variations (3x16x3), 144 FEM computer models were prepared using SAP2000 software. Then for each member, BMD were drawn using EXCEL software.

Table 3.2: Variables considered in modeling

Variables	**Single Cell**			**Double Cell**			**Story Cell**		
Mesh density	4	6	8	4	6	8	4	6	8
Skew angle (degrees)	0	15	30	0	30	42	0	30	45
Soil fill height (m)	0	1	6	0	2.1	6	0	2.7	6
Wall thickness (m)	0.35	0.7	1.05	0.6	1.2	1.8	0.5	1.0	1.5
Span Length (m)	6.3	8.4	12.6	25.0	33.6	47.4	10.0	12.0	14.0
Transverse width (m)	4.65	9.3	14.0	7.4	22.2	14.8	11.6	5.8	17.4
Vertical Soil springs (MN/m^2)	7.5	15	22.5	7.5	15	22.5	7.5	15	22.5
Maximum Haunch Thickness (mm)	0	400	-	0	700	-	0	500	-

3.2.1 General shell element FEM model

This is the typical finite element modeling use in current design practice especially when skew angle is present. If skew angle is zero, the model can be simplified and it can be modeled with 1m width frame elements. In this research 48 shell models were prepared using 4 node thin shell elements in SAP2000 as shown in figure 3.1.

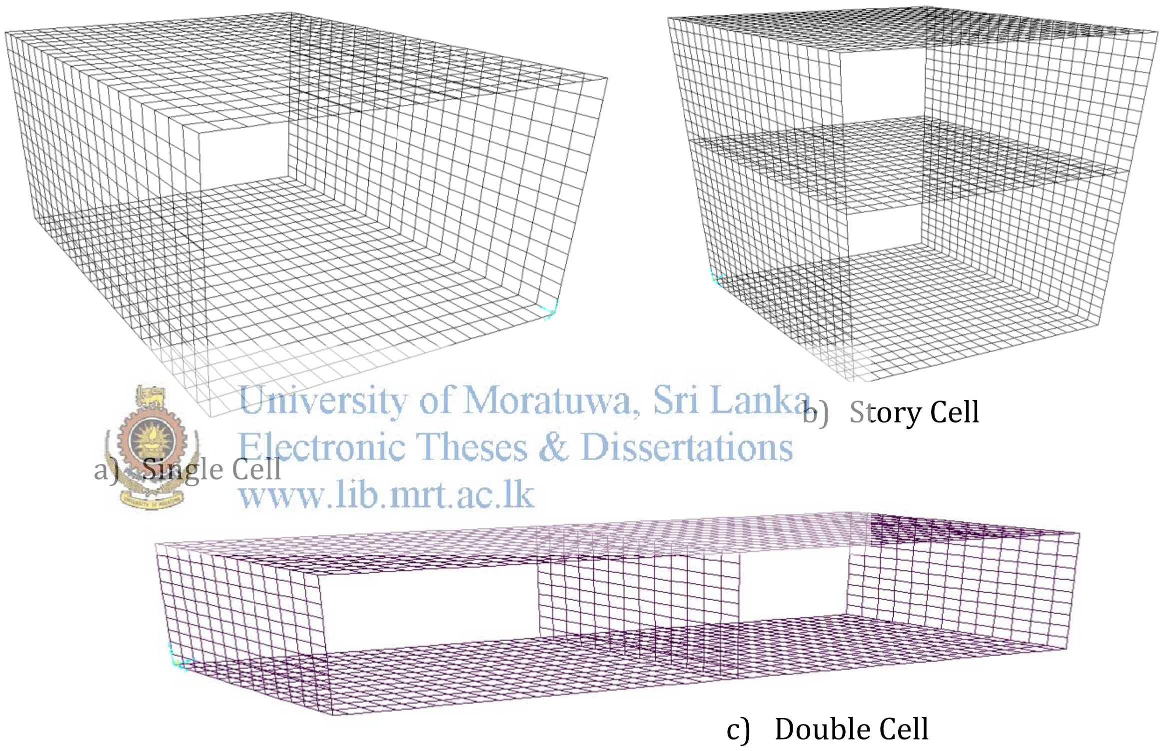
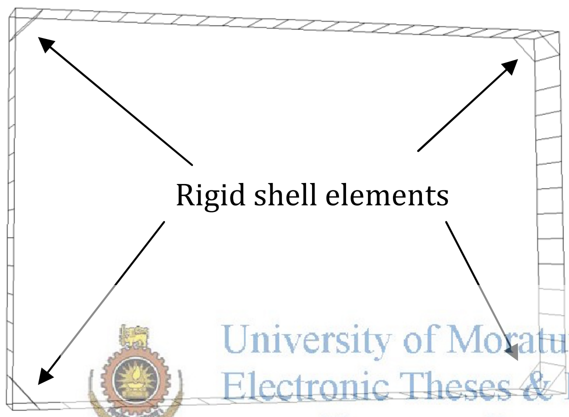
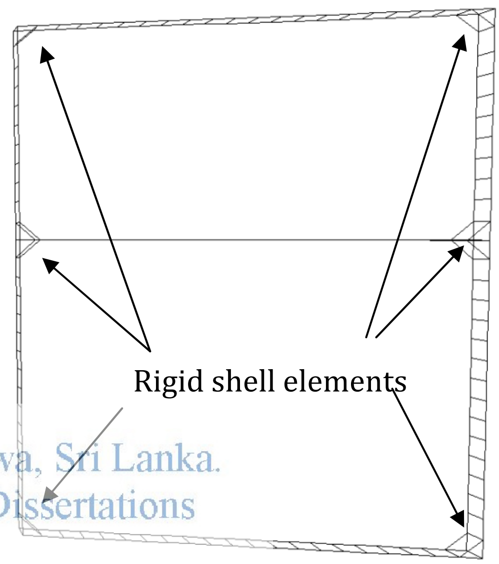


Figure 3.1: Shell element models of box structures

3.2.2 Modified shell element FEM model

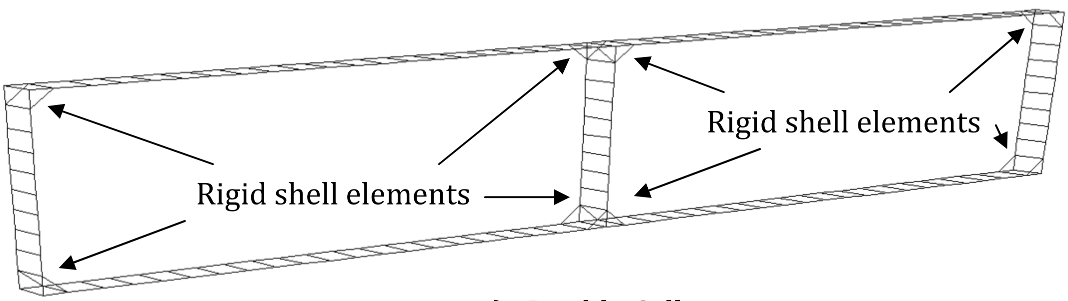
In this modeling method shell elements used to model structure, but joints or corners of elements are modeled with infinitely rigid shell elements to create corner region rigidity. In this research 48 number of corner modified shell element models were used. Figure 3.2 indicates the locations of rigid shell elements and for clarity diagrams shows only one shell in transverse direction. This model is same as general shell model shown in figure 3.1, but it includes the rigid shell element containing joins throughout the model.





b) Single Cell

b) Story Cell

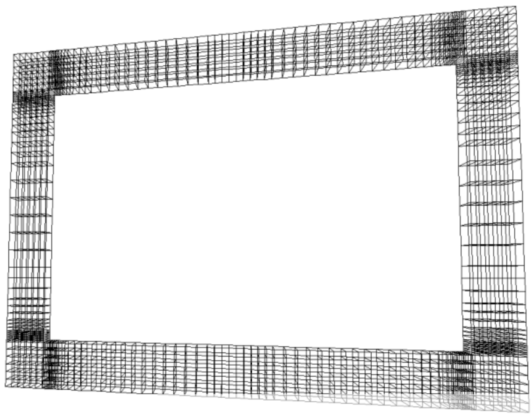


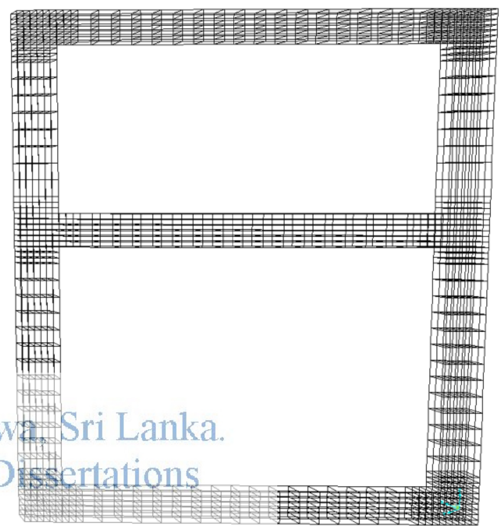
c) Double Cell

Figure 3.2: Shell element –joint modified models of box structures

3.2.3 Solid element model

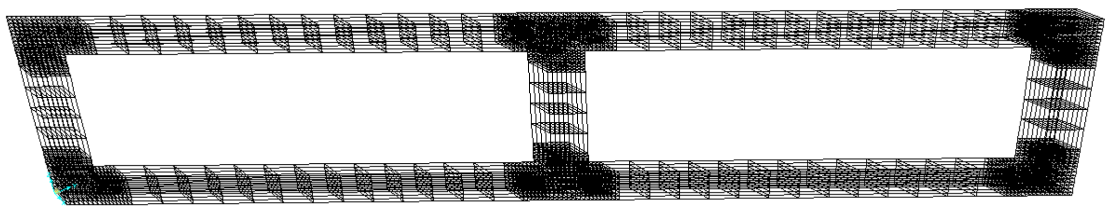
Eight node solid finite elements are used in this type modeling in SAP2000 software. For the comparison of shell models, same 48 models were created using solid elements. Figure 3.3 shows three solid element models and for clarity diagrams shows only one solid element in transverse direction





a) Single Cell

b) Story Cell



c) Double Cell

Figure 3.3: Solid elements models of box structures

3.3Model modification at critical section

3.3.1 General shell element FEM model

Although typical FEM shell element meshing was done in model, each corner shell elements were meshed exact at face of the joint to obtain Bending moment value at face of members as shown in figure 3.4(a).

3.3.2 Modified shell element FEM model

Here, each corner shell elements were meshed exact at face of the joint and those joints are connected from rigid shell elements as shown in figure 3.4(b).

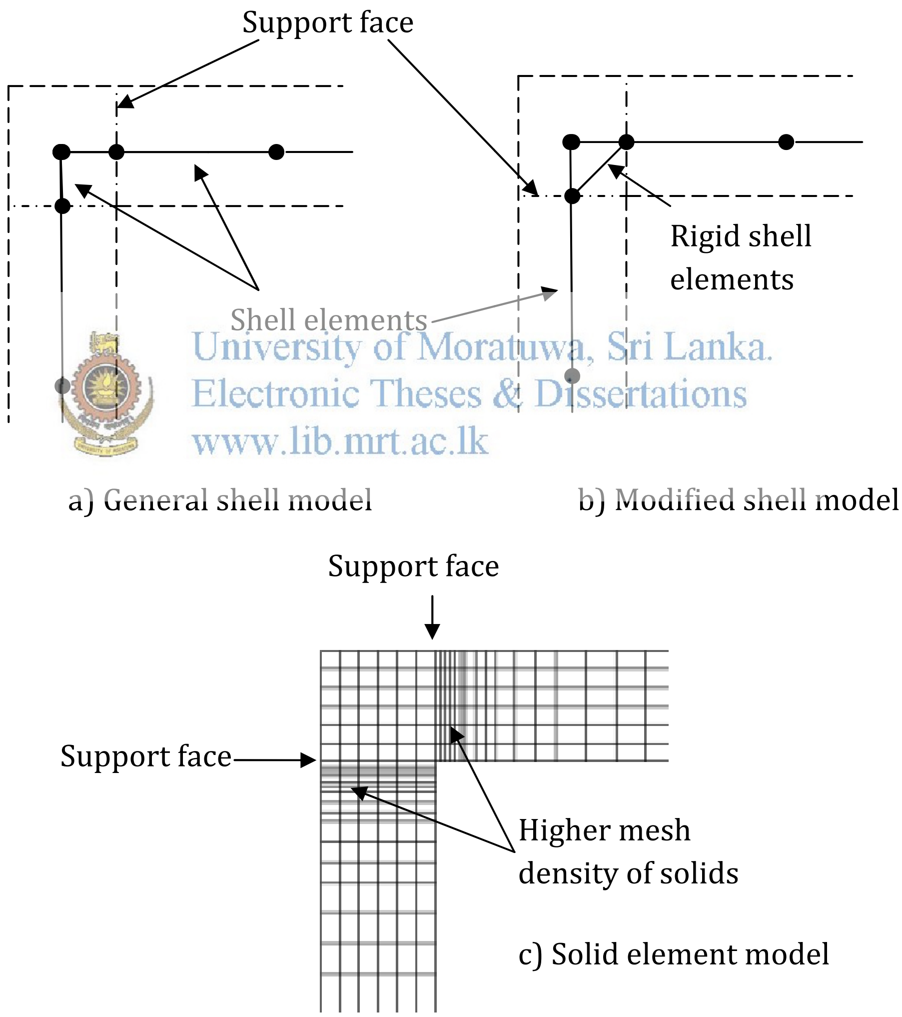


Figure 3.4: Model modification at critical section

3.3.3Solid element model

It was noted that solid element model at critical section at joints, bending moment values converges to maximum value. Therefore mesh densities were increased at critical section as shown in figure 3.4(c) and 3.5 to obtain sufficient accurate value at critical section. The aspect ratio of all elements is maintained below ten.

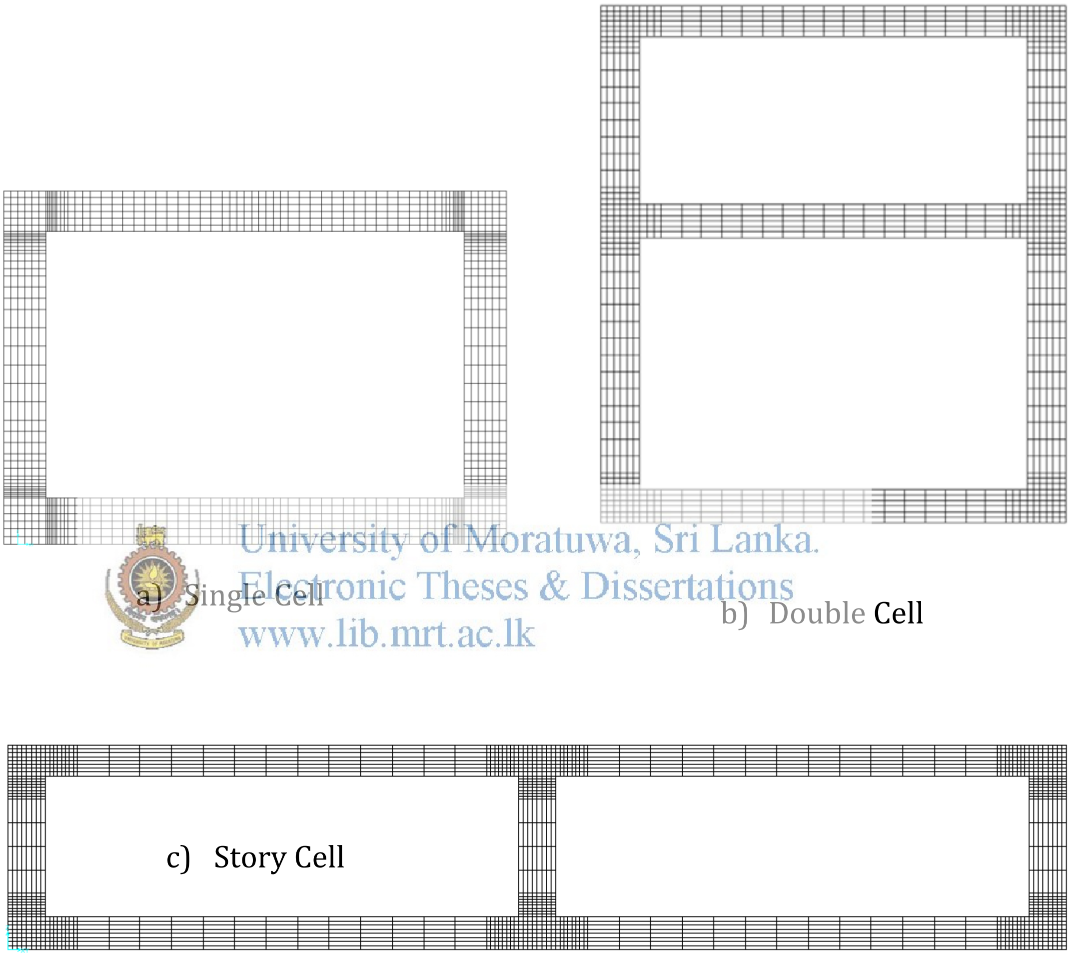


Figure 3.5: Mesh density increase at joints in solid elements

3.4 Loads and load combinations

These box structures were designed for railway loadings according to BS 5400 part 2 [13]. Loads were calculated following the guidance given in BD 3101 [14] and dynamic factor modification according to UIC 776 [15] were used in load calculations. Railway live loads were modified according to Sri Lanka railway department guidelines. The load calculation methodology is summarized in appendix B and it also represents load calculation for three main box structural types.

Typical load combinations given in BS 5400 & BD 3101 were considered and critical load combinations were identified. Those ULS & SLS critical design combinations which were used in models are summarized in appendix B.

3.5 BMD from solid FEM model

In SAP 2000 FEM analysis software, for shell or frame element models, the software itself provides bending moment value at any member locations. But for solid element model the software only provides stresses of each element. Therefore each member location, bending moment value should be calculated using integral of stresses. Based on $M=\int \sigma A dx$ for each plane of the member location relevant bending moment should be found out. This integration can be simplified according to mesh sizes. Appendix C shows derivation formulas for various mesh densities to obtain bending moment values from stresses. In this research 2, 4, 6 and 8 number of solid elements were used to present each location of the members in various models. Nodes in solid element models are renamed by including suffix to identify member and its location. Then numbering is done as a pattern relevant to joint coordinates. This node renaming is important, because stress results of those nodes were used for bending moment value calculations.

It was noted that bending moment values are convergent to a maximum value at faces of joint of the members. At those locations higher mesh densities were used and extrapolation of bending moment value near the face of joint was used to get bending moment value at the face.

Chapter 04

BENDING MOMENTS OF BOX STRUCTURES

4.1 General

In SAP2000 software, graphical representation of bending moment as contours in shell element can be obtained. This representation of each model cannot be used for proper comparison. Hence software bending moment values of each node of the cross sections A-A, B-B and C-C as shown in figure 4.1 were obtained and exported to excel as load cases and combinations. Then BMD was drawn for each model using results exported to excel.

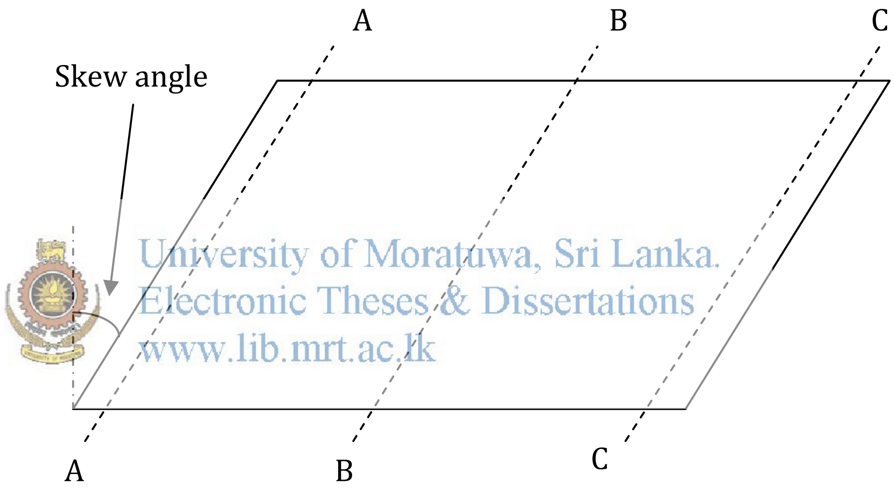


Figure4.1: Plan of box structure-location of BMD

In solid element models, the software does not provide direct results of bending moment of members. Hence SAP2000 solid model stresses of each node of cross sections A-A, B-B and C-C as shown in figure 4.1 were exported to excel according to load cases and their combinations. Bending moment values for the each cross section were calculated in excel from using above stresses. Then BMD was drawn for each member. BMD of general shell element, modified shell and solid element models were drawn for comparison in same graph.

To obtain proper understanding of variation of BMD, for all members (slabs and walls) of box structures, BME are drawn for each load cases and combinations. As a sample, ULS bending moment envelopes are presented for top slab of the main three box structures in figure 4.2 to 4.4. Those figures also indicate the locations where critical bending moment values occur relevant to BME of general shell model. Appendix G provides all other important bending moment envelops.

Each member BME of general shell, modified shell and solid element models indicate that there is completely different variation of each curve at the support area. But in between supports varies with similar pattern. It indicates that in design point of view they may not change in reinforcement curtail points from designing according to each model, but critical maximum and minimum bending moment values shall be selected with a proper understanding of each model.

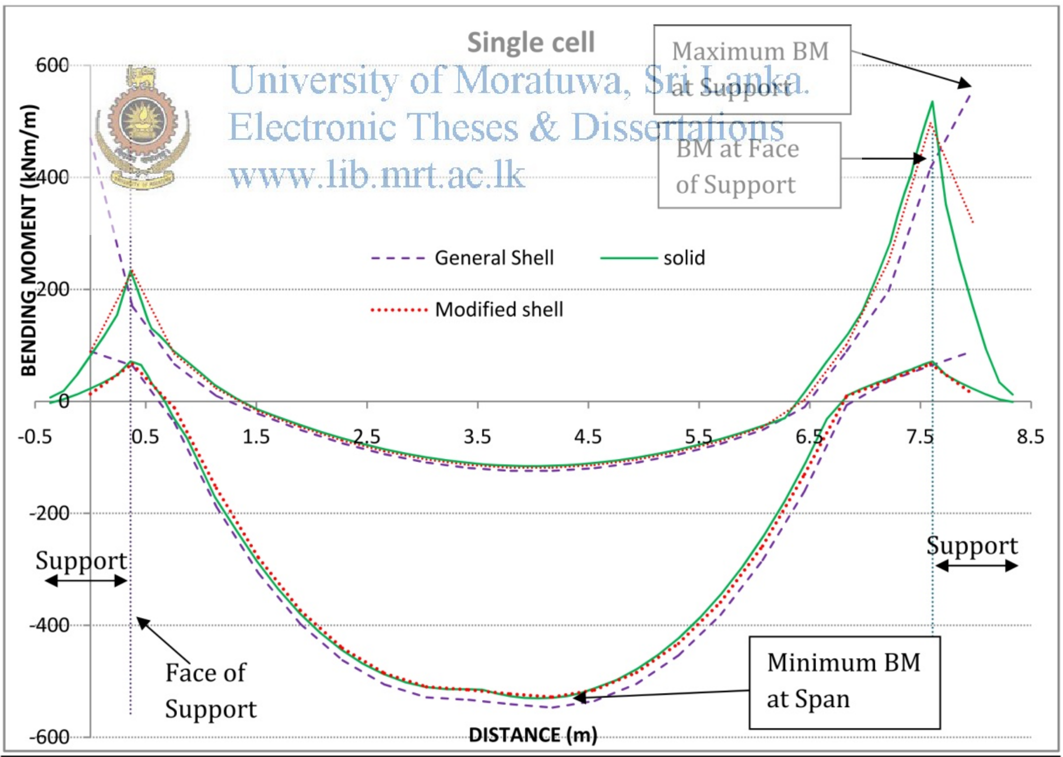


Figure 4.2 : BME of top slab in single cell

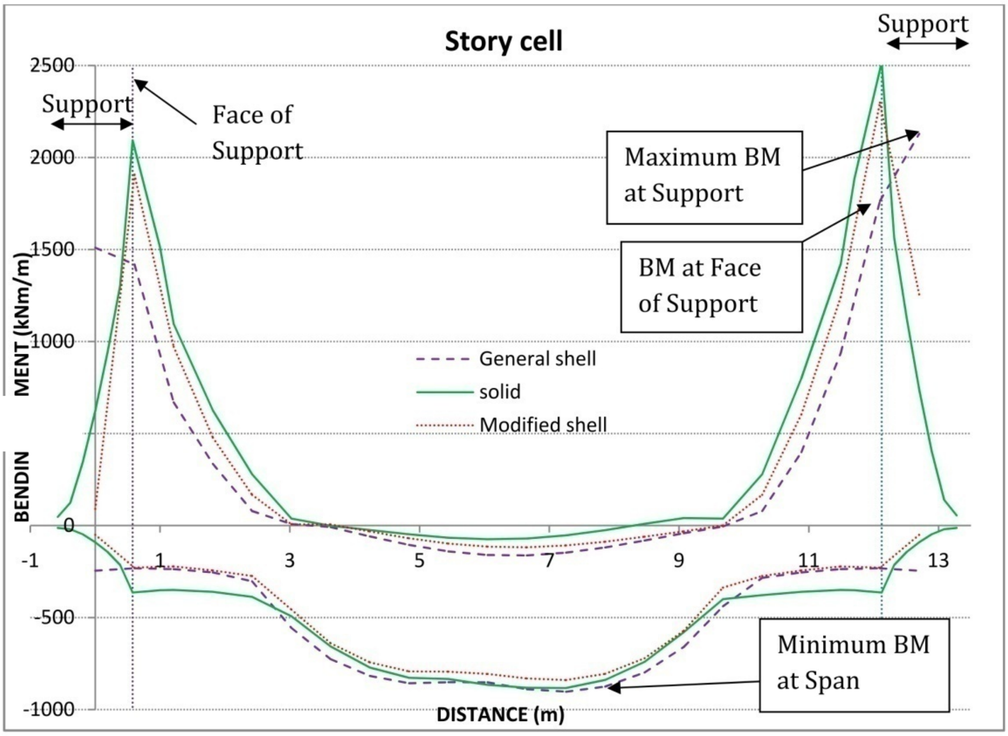


Figure 4.3 : BME of top slab in story cell

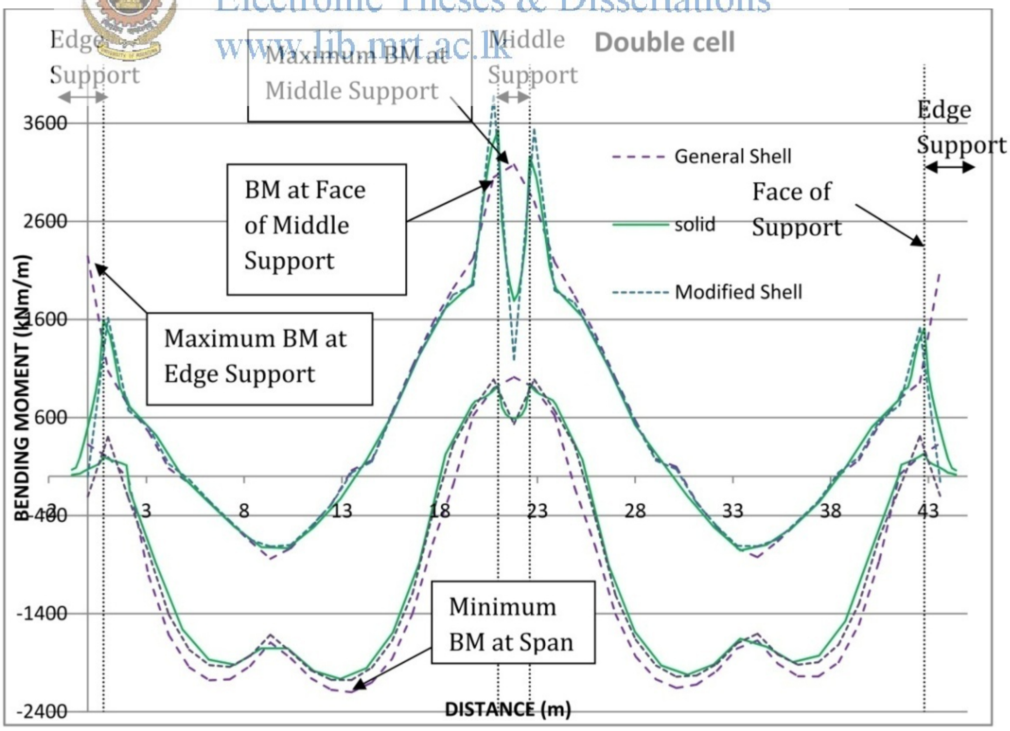


Figure 4.4 : BME of top slab in double cell

Chapter 05

USE OF BENDING MOMENT VALUES FOR DESIGN

5.1 Critical value obtaining method

After BME was drawn as in Chapter 4, it can be identified critical locations to obtain bending moment values for design. Critical locations and methodology to identify critical value can be obtained from going through ULS & SLS bending moment envelops.

For general shell, modified shell and solid element models maximum moment at each span was tabulated. In general shell model maximum support moment and maximum bending moment value at faces of the support were recorded. In solid and modified shell element model bending moment drastically reduces between faces of the support and maximum value at support was tabulated. Although it is the maximum, actually it presents at the face of the support. Those critical Bending moment values are shown in appendix E in tabular format. Appendix F presents total reaction force of each model relevant to all load cases.

Then each span and support moment values from general shell model and modified shell model were compared with relevant solid element model values. Considering results of solid as the reference values, bending moment percentages are calculated as shown in following equation;

$$\text{Bending moment percentage} = \frac{\text{Moment in shell model}}{\text{Moment in solid model}} \times 100\%$$

5.2 Design bending moment value in comparison with solid model

5.2.1 Single cell

Table 5.1 to table 5.3 indicate that for all members face values of general shell models are always under estimated, but support maximum values are always over estimated. Span moment values are always in safe side.

Modified shell models show the results within reasonable accuracy with solid element models.

Table 5.1: Top slab bending moment percentage-single cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	103	125	77	103	104	78	100	93	100	93
2-Mesh2	104	128	82	104	107	82	100	94	100	94
3-Mesh3	103	129	80	103	106	81	100	95	100	94
4-Angle0	103	123	83	103	122	83	99	89	99	89
5-Angle30	102	112	68	102	96	69	98	91	98	90
6-Fill0	103	124	80	103	104	80	100	92	100	92
7-Fill6	103	128	77	103	109	78	100	95	100	95
8-Wall0.5	105	102	71	118	100	78	103	85	116	93
9-Wall1.5	108	143	79	108	112	79	101	92	101	92
10-B0.75	104	130	75	103	106	76	99	87	99	87
11-B1.5	98	110	81	98	97	81	95	92	95	92
12-L0.5	104	127	77	104	104	78	101	97	101	96
13-L1.5	103	126	83	103	107	84	99	91	99	91
14-Haunch	110	123	85	110	107	86	108	96	107	96
15-Spring0.5	103	125	80	103	105	80	100	93	99	93
16-Spring1.5	104	125	80	103	105	80	100	93	100	93

Table 5.2: Bottom slab bending moment percentage-single cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	108	128	89	107	113	89	105	93	104	92
2-Mesh2	109	133	94	108	114	93	105	95	104	94
3-Mesh3	108	132	93	107	113	92	105	95	104	93
4-Angle0	107	129	86	107	126	86	104	94	104	94
5-Angle30	107	122	90	106	92	89	103	88	102	86
6-Fill0	108	129	91	107	111	90	104	93	104	92
7-Fill6	107	124	87	107	120	86	104	94	104	92
8-Wall0.5	107	94	75	121	101	82	106	78	119	85
9-Wall1.5	115	164	96	114	124	95	108	102	107	99
10-B0.75	109	118	86	108	113	86	104	88	104	88
11-B1.5	106	133	87	106	103	88	105	102	104	102
12-L0.5	109	129	95	108	108	94	106	96	105	94
13-L1.5	108	129	90	107	118	89	104	94	104	93
14-Haunch	108	132	93	107	116	92	104	96	104	95
15-Spring0.5	107	126	90	107	111	90	104	93	103	92
16-Spring1.5	109	130	91	108	115	90	106	94	105	93

Table 5.3: Walls bending moment percentage-single cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	98	104	92	98	105	91	104	99	104	99
2-Mesh2	97	104	94	97	105	94	103	99	103	99
3-Mesh3	98	104	92	98	105	91	105	99	105	98
4-Angle0	98	112	94	99	112	94	105	100	105	99
5-Angle30	109	102	93	117	111	101	117	98	125	106
6-Fill0	97	104	94	98	105	94	104	99	104	99
7-Fill6	96	109	92	97	110	91	104	101	104	101
8-Wall0.5	88	107	88	95	118	96	108	93	111	101
9-Wall1.5	100	110	101	100	107	99	107	109	106	106
10-B0.75	93	112	92	95	112	91	105	97	105	96
11-B1.5	94	98	91	94	99	91	98	96	98	95
12-L0.5	97	106	93	97	106	93	104	98	104	97
13-L1.5	98	104	94	98	104	94	104	99	104	99
14-Haunch	95	110	97	96	112	97	102	101	102	101
15-Spring0.5	97	104	94	97	105	94	103	99	103	99
16-Spring1.5	99	105	94	99	105	94	106	99	106	99

5.2.2 Double cell

Design bending moment variation in double cell box structures are illustrated in Table 5.4 to 5.7 according to the member type. In slabs span moment values shows that all general shell and modified shell models provide safe and accurate results. Support moments of slabs in modified shell element model give very near values according to solid models.

Top slab support moments at face are highly under estimated and Bottom slab it is little under estimate in general shell models. Edge support moment in general shell model is little over conservative, but mid support is reasonable. Bending moment values in walls are very much similar for all three models.

Table 5.4: Top slab bending moment percentage-double cell

Model No /Variable	General shell model										Modified shell model					
	SLS					ULS					SLS			ULS		
	Min	Max Edge	face edge	Max mid	face mid	Min	Max Edge	face edge	Max mid	face mid	Min	Max Edge	Max mid	Min	Max Edge	Max mid
1-Real	107	141	65	90	87	107	141	67	90	86	100	99	110	100	101	110
2-Mesh2	104	131	78	99	99	104	130	80	99	99	98	103	104	98	101	104
3-Mesh3	103	119	61	90	90	103	118	63	90	90	97	103	98	97	101	97
4-Angle0	107	134	71	124	103	107	134	73	123	103	103	87	109	103	87	108
5-Angle30	106	140	72	105	99	106	139	74	105	99	102	115	108	101	111	108
6-Fill0	107	151	55	97	75	107	151	54	97	75	101	100	113	100	100	113
7-Fill6	106	141	67	93	88	106	139	69	92	88	100	103	112	100	104	111
8-Wall0.5	99	117	31	95	94	99	117	36	95	94	95	110	83	95	110	83
9-Wall1.5	117	147	58	93	76	117	148	60	93	76	108	100	112	108	101	112
10-B0.75	108	148	38	99	83	108	156	48	99	83	101	122	105	101	122	105
11-B1.5	109	119	85	102	102	109	119	86	103	103	104	114	125	104	115	125
12-L0.5	108	128	60	103	81	108	130	59	103	81	101	105	122	101	107	122
13-L1.5	108	126	77	93	93	108	125	79	93	93	103	115	105	103	112	105
14-Haunch	114	113	49	87	79	114	114	50	87	79	109	84	94	109	83	94
15-Spring0.5	106	141	65	92	89	106	140	68	92	89	101	98	112	101	99	112
16-Spring1.5	107	141	66	92	89	107	140	67	93	89	101	101	113	101	102	113

Table 5.5: Bottom slab bending moment percentage-double cell

Model No /Variable	General shell model										Modified shell model					
	SLS					ULS					SLS			ULS		
	Min	Max Edge	face edge	Max mid	face mid	Min	Max Edge	face edge	Max mid	face mid	Min	Max Edge	Max mid	Min	Max Edge	Max mid
1-Real	113	140	103	111	92	114	134	101	110	91	107	109	99	108	106	100
2-Mesh2	111	145	106	118	98	112	138	104	119	98	105	102	100	106	100	101
3-Mesh3	110	124	102	108	97	111	119	101	108	97	105	100	91	106	92	92
4-Angle0	112	161	99	126	103	112	158	99	125	103	108	108	109	108	108	109
5-Angle45	110	128	99	117	101	110	121	98	117	101	106	107	98	107	105	100
6-Fill0	115	166	99	121	93	115	158	98	120	92	109	111	107	109	108	108
7-Fill6	92	114	80	101	84	90	109	79	100	83	87	88	91	87	84	91
8-Wall0.5	108	123	54	101	92	108	121	63	102	92	103	122	85	102	121	85
9-Wall1.5	119	189	98	118	84	120	186	99	117	82	113	127	105	113	125	105
10-B0.75	109	104	98	116	95	109	101	97	117	95	102	100	88	103	97	88
11-B1.5	117	168	93	115	102	116	167	96	116	102	113	117	104	113	116	105
12-L0.5	113	168	106	131	101	113	158	104	129	99	109	134	125	109	126	125
13-L1.5	110	113	99	113	98	111	111	98	113	98	106	113	94	106	110	95
14-Haunch	111	132	102	119	99	112	126	101	118	98	106	109	108	106	106	109
15-Spring0.5	108	135	101	115	94	109	129	99	114	92	104	105	105	104	102	105
16-Spring1.5	116	145	102	118	99	116	139	101	118	98	111	113	103	111	110	104

Table 5.6: Edge Walls bending moment percentage-double cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	99	100	98	99	101	98	104	104	104	104
2-Mesh2	98	99	97	99	99	97	105	103	105	103
3-Mesh3	99	98	97	99	99	97	105	103	105	103
4-Angle0	99	124	105	100	124	103	106	113	106	111
5-Angle30	99	117	101	99	117	99	105	105	106	102
6-Fill0	98	99	98	99	99	98	104	106	104	104
7-Fill6	101	104	99	101	106	98	106	105	107	105
8-Wall0.5	79	118	85	81	119	83	85	89	87	88
9-Wall1.5	106	117	117	107	116	116	111	129	112	129
10-B0.75	94	112	97	95	113	95	101	98	101	95
11-B1.5	114	108	102	113	108	102	125	108	123	108
12-L0.5	96	106	100	96	106	100	100	106	101	106
13-L1.5	99	113	102	100	113	100	104	104	104	101
14-Haunch	95	94	94	96	96	93	101	97	101	95
15-Spring0.5	97	99	99	98	98	97	102	105	102	102
16-Spring1.5	101	100	98	102	100	98	107	104	108	104

5.2.3 Story Cell

The bending moment values of all the members in modified shell element models give similar values as in solid element models. General shell models always shows under estimated values for support moments at face. It shows that maximum moment values at support are more reasonable to use as design moment. The results of story cell models are shown in table 5.7 to table 5.9.

Table 5.7: Top slab bending moment percentage-story cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	107	100	73	107	88	73	99	96	100	95
2-Mesh2	105	93	72	106	89	71	98	91	98	90
3-Mesh3	105	90	72	105	87	72	97	88	98	88
4-Angle0	108	127	91	108	127	91	100	98	100	98
5-Angle45	107	84	54	108	66	54	99	98	99	97
6-Fill0	106	101	74	106	89	74	99	96	98	95
7-Fill6	107	99	72	106	88	72	99	96	99	95
8-Wall0.5	104	82	44	104	69	46	99	73	98	74
9-Wall1.5	113	108	87	113	97	87	105	109	106	108
10-B0.75	100	95	67	99	83	67	93	87	93	87
11-B1.5	106	102	77	106	90	77	100	100	100	99
12-L0.5	111	116	65	110	94	64	102	103	102	102
13-L1.5	105	98	81	104	90	81	97	93	97	93
14-Haunch	113	99	80	110	93	80	107	101	105	100
15-Spring0.5	107	99	73	107	88	73	99	95	99	95
16-Spring1.5	107	100	73	107	89	73	99	96	99	95

Table 5.8: Bottom slab bending moment percentage-story cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	115	95	93	114	93	92	109	90	109	88
2-Mesh2	114	92	92	113	91	91	108	86	108	84
3-Mesh3	113	92	92	113	91	91	108	84	107	83
4-Angle0	118	132	96	117	128	96	112	104	111	103
5-Angle45	110	93	91	107	91	90	107	84	105	83
6-Fill0	115	94	94	115	93	93	110	90	109	89
7-Fill6	113	95	92	113	93	90	108	88	107	87
8-Wall0.5	109	88	73	108	87	74	104	71	104	71
9-Wall1.5	123	120	97	121	94	94	116	100	115	94
10-B0.75	112	92	89	111	90	88	105	85	104	83
11-B1.5	115	95	95	114	94	94	110	92	110	91
12-L0.5	116	96	96	116	94	94	111	91	111	89
13-L1.5	115	99	92	114	97	91	108	91	108	89
14-Haunch	122	115	104	119	114	104	117	102	114	101
15-Spring0.5	113	93	93	113	92	92	107	89	107	87
16-Spring1.5	116	96	93	116	94	92	111	90	110	88

Table 5.9: Walls bending moment percentage- story cell

Model No /Variable	General shell model						Modified shell model			
	SLS			ULS			SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max
1-Real	97	122	98	98	120	95	109	100	110	97
2-Mesh2	98	122	98	98	120	95	110	101	111	97
3-Mesh3	98	122	98	98	120	95	110	101	111	97
4-Angle0	103	127	100	104	129	99	110	107	110	106
5-Angle45	95	123	99	93	124	98	104	97	102	96
6-Fill0	98	126	102	99	127	101	110	104	111	103
7-Fill6	93	108	86	92	111	85	106	89	104	90
8-Wall0.5	98	119	88	104	120	88	99	98	99	97
9-Wall1.5	98	127	104	99	124	99	113	109	114	104
10-B0.75	90	118	91	97	118	88	103	94	99	93
11-B1.5	100	110	90	100	109	88	112	92	112	90
12-L0.5	95	120	94	96	120	91	112	96	113	93
13-L1.5	100	123	96	100	123	94	112	99	112	97
14-Haunch	107	139	112	105	141	111	115	116	112	115
15-Spring0.5	96	123	99	96	121	96	107	102	107	98
16-Spring1.5	98	121	97	99	120	94	111	99	111	97

5.3 Summary of bending moment variation

Above all results of box structures are summarized in table 5.10. It indicates bending moment variation percentage relevant to general and modified shell models.

5.3.1 Span moments

Span moments of modified shell models are within 85% to 125% of solid model values. For general shell model it is 79% to 123%. It indicate that some cases bending moment value is 21% below in general shell models and only 15% below the modified shell models.

5.3.2 Support moments

Support moments of modified shell models are within 71% and 134% of solid model values. But support moment at center is varied 66% to 189% and at face it is varied between 31% and 117%.

Table 5.10: Summary of bending moment percentage

Concrete Box		General Shell			Modified Shell	
Cell	Member	Span	Support		Span	Support
			Center	face		
single	top slab	98-118	96-143	68-86	95-116	85-97
	Bottom slab	106-121	92-164	75-96	102-119	78-102
	walls	88-117	98-118	88-101	98-125	93-109
Double	top slab	99-117	87-156	31-103	95-109	83-125
	Bottom slab	90-120	100-189	54-106	87-113	84-134
	outer walls	79-114	94-124	83-117	85-125	88-129
Story	top slab	99-113	66-127	44-91	93-107	73-109
	Bottom slab	107-123	87-132	73-104	104-117	71-104
	walls	90-107	108-141	85-112	99-115	89-116
		79-123	**66-189**	**31-117**	**85-125**	**71-134**

Chapter 06

FEM analysis and experimental results

6.1 General

Tested culvert of University of Tennessee [18] which is shown in appendix A was modelled using general shell, modified shell and solid element models in SAP2000 software. Then soil pressure for 3,8,12 and 18m were applied into finite element models. Those pressure values were obtained from the experimental results. Bending moments obtained from FEM analysis at span and support are represented in figure 6.1 and figure 6.2 respectively. In those figures it is represented experimental results obtained from figure 2.10. Those graphs show bending moments obtained from frame analysis as theoretical values.

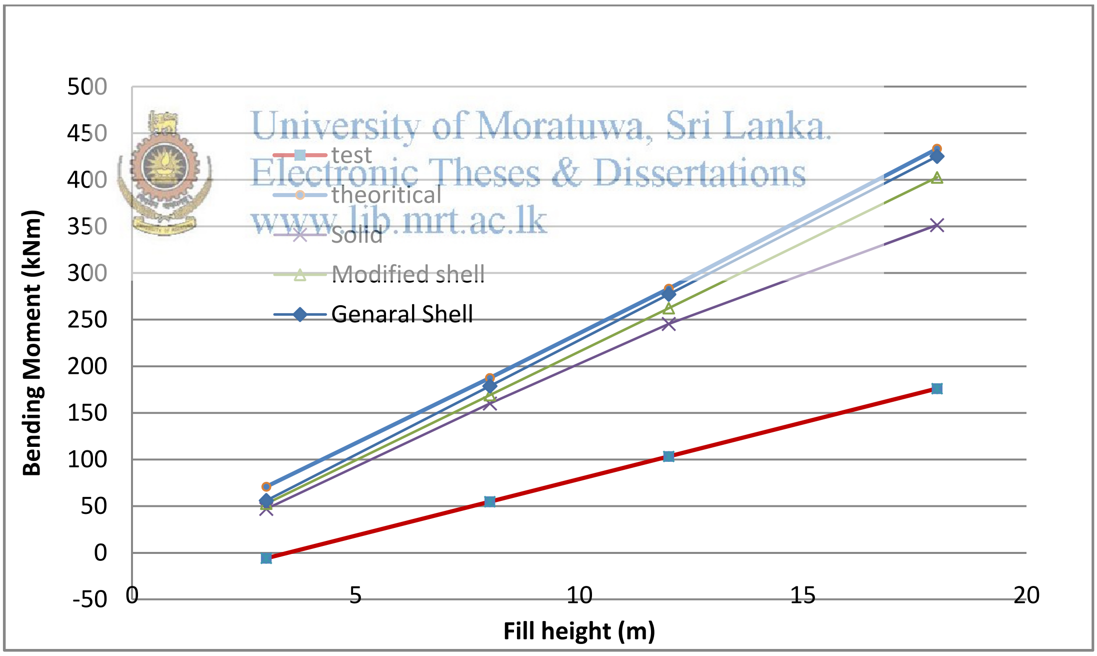


Figure 6.1: Span bending moment variation

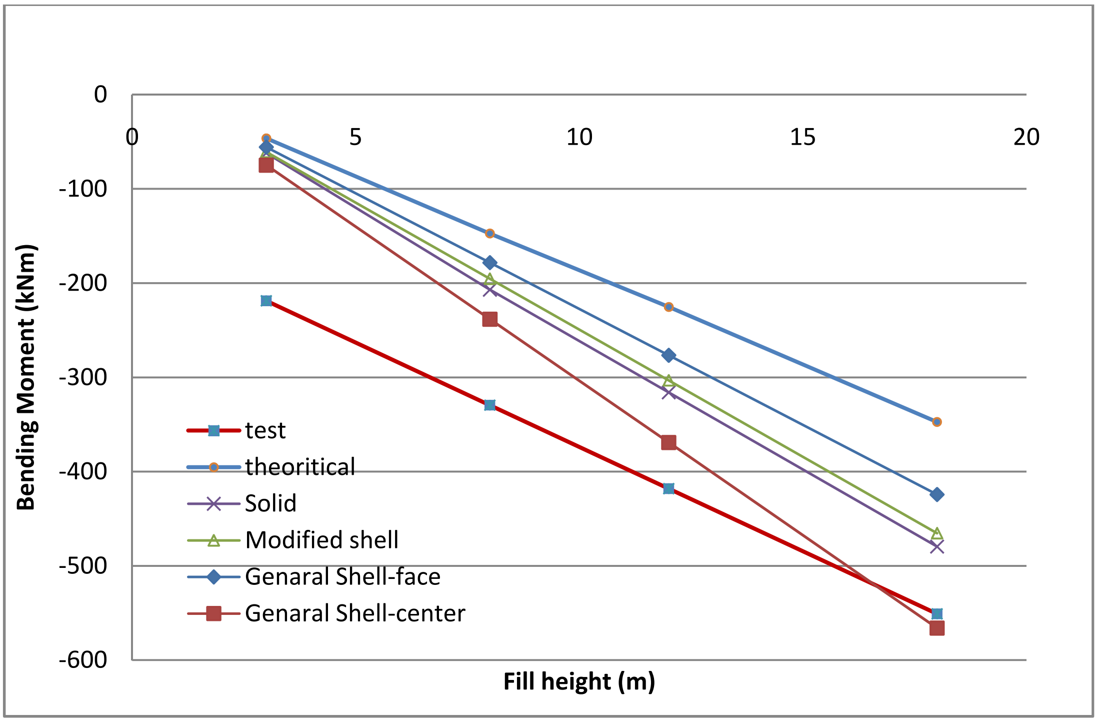


Figure 6.2: Support bending moment variation

6.2 Comparison

Figure 6.1 shows maximum bending moment at span of top slab. FEM model results are within experimental and theoretical values. Bending moment values are varied toward test results first solid, then modified shell and next general shell model values. In experiment span moments are calculated from strain gauges which are located at center of the span, but not at the place where maximum bending moment occur. Therefore some reduction of bending moment in test values can be expected at span. Precast concrete panel was used at the bottom of the top slab in the test culvert and bottom reinforcement provide on top of it. Therefore full thickness is not effectively use for moment carrying at the span. As a result it can be expected that some amount of the span moment to be distributed towards the supports. It is indicated in results, because span moments from experiments are lesser than theoretical and support moments are higher than the theoretical values.

Figure 6.2 shows bending moment variation at middle support of top slab. All variations other than the support moment at center of general shell model behave in similar slope, but support moment at center of general shell model varied maintaining high slope and cut the test result line. It shows that those locations, support moment at center of general shell model are much conservative.

Based on above comparison, it shows that results of solid element models are much closer to experimental results. Then modified shell results come closer but behind solid element model results. Above results validate that solid element models of box culverts can be used as a base for comparison of general shell and modified shell models.

Chapter 07

CONCLUSIONS AND RECOMMENDATIONS

7.1 Concrete Box Structures

It is shown that results of solid element models are much closer to experimental results which obtained from previously tested box culvert. This result validate that solid element models of box culverts can be used as a base for comparison of general shell and modified shell models.

In this research, it is found that span moment variation is 79-123% in general shell models and it is 85-125% for modified shell models with reference to solid element models. Support bending moment of modified shell models varies 71-134%. But in general shell models, support center value varies 61-189% and face value varies 31-117%. According to above results, it can be seen that by modifying shell models, bending moment values in both span and support are improved towards solid element model values.

General shell model, modified shell model and solid model indicate similar bending moment curves especially at member spans, but considerable variation is found at member supports.

At the face of the support, bending moment value obtained from general shell models are under estimating compare to other models in many cases. Therefore, in general shell models, as the support design moment, it should be selected the maximum value which is at the center line of the support. These centerline values are little higher than the value at the face of the supports and it is slightly conservative.

Reinforced concrete design guide lines such as BS 8110 [17] generally allow 30% reduction of support moment redistribution. Results of some cases indicate that face bending moment values of general shell models are below that 30% reduction. Therefore bending moments values at face of the support cannot be justified as design value.

According to results, it is indicated that all models provided similar bending moment curves with little variation at spans and higher variation at supports.

Modified shell element models give results with little variation than the general model compare to the solid models. Support design bending moment can be obtained from modified shell models with reliability without confusion of center or face value to select for the design as for the general shell element models. Therefore box structures to be analyzed according to modified shell element models to obtain bending moment values for more economical and reliable designs.

In this research, only simple equations are used for calculating bending moments from stresses of solid element models. Using the same method in any other structure, the bending moment values can be calculated easily from solid models with sufficient accuracy.

7.2 Suggestions for Future Works

In this research only box type concrete structures are selected for modeling. Bending moment critical values of any other shell or frame element models can be verified with solid element models. Critical bending moments obtained from FEM analytical models to be verified with more experimental results which use only reinforced concrete but without using precast panels in the future.

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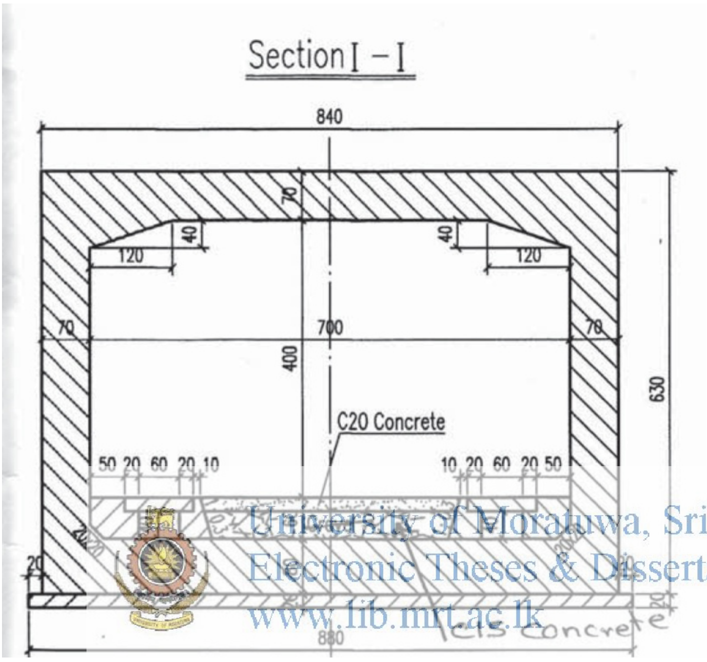
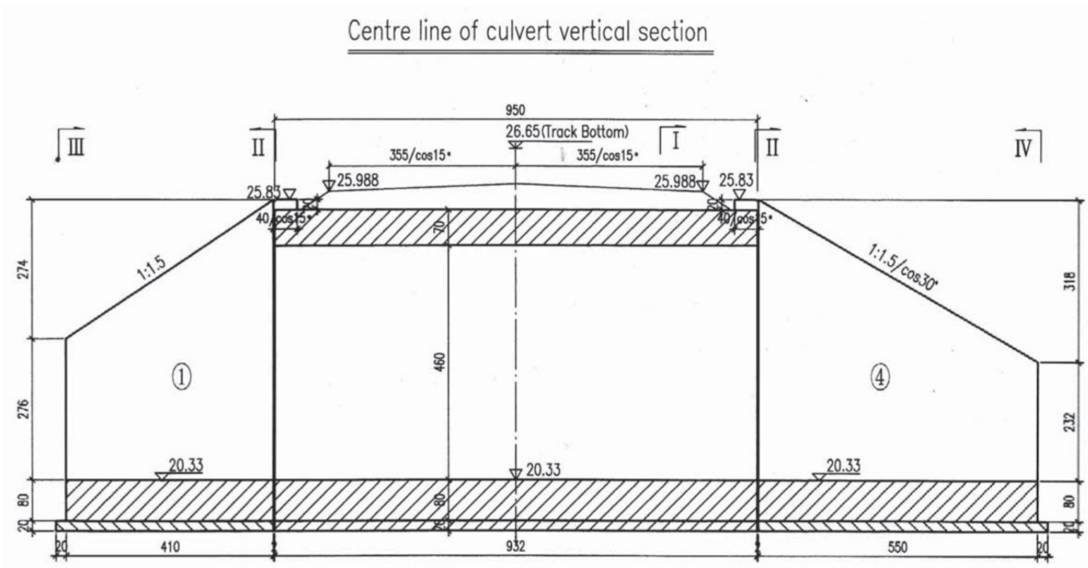
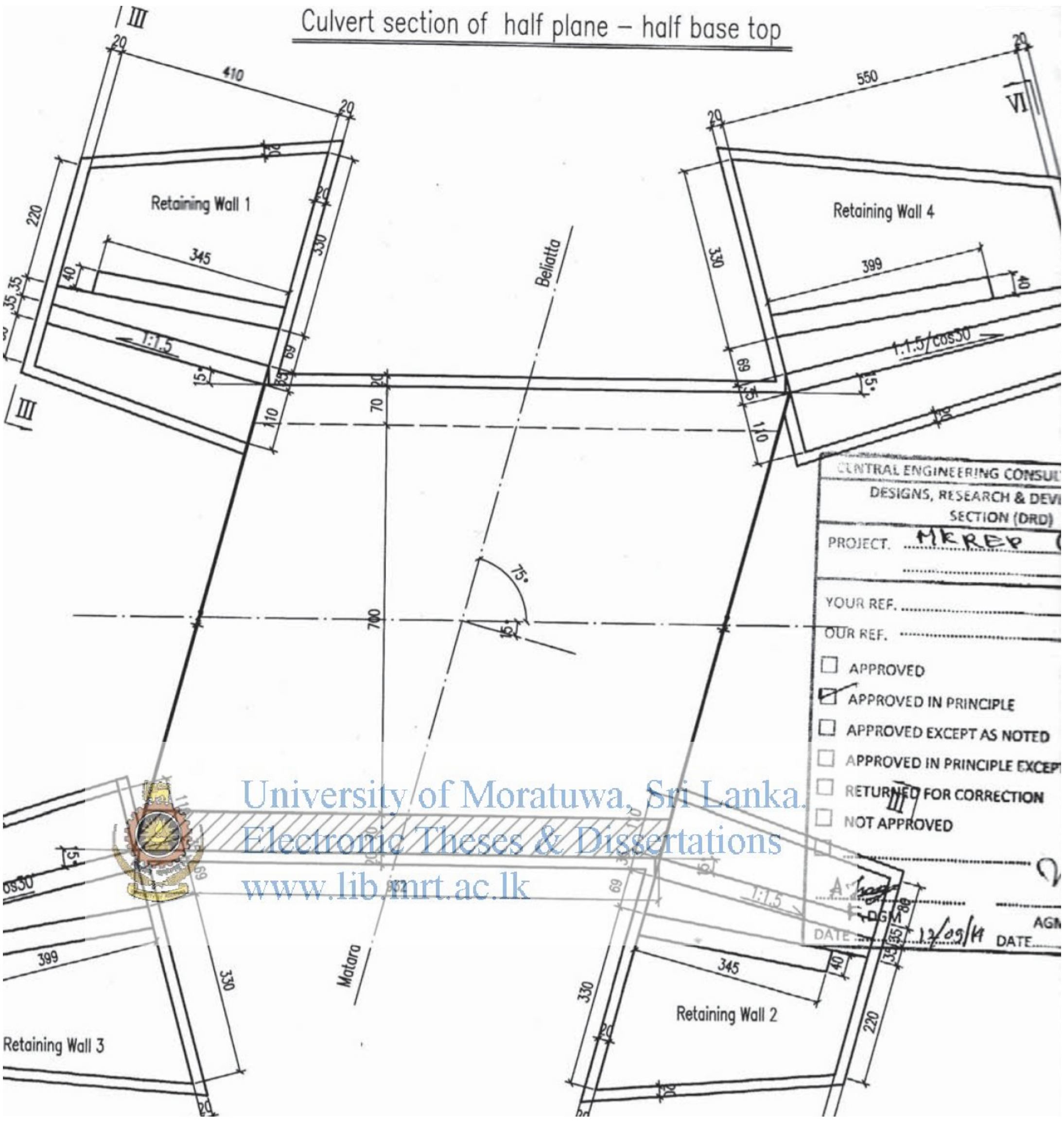
Appendix A: General arrangement of concrete box structures

Drawings used in Matara-Beliatta Railway project in Sri Lanka are shown in this appendix A.1 to A.3. In A.4 shows the culvert details related to experiment done in the University of Tennessee [18].

A.1 Single cell

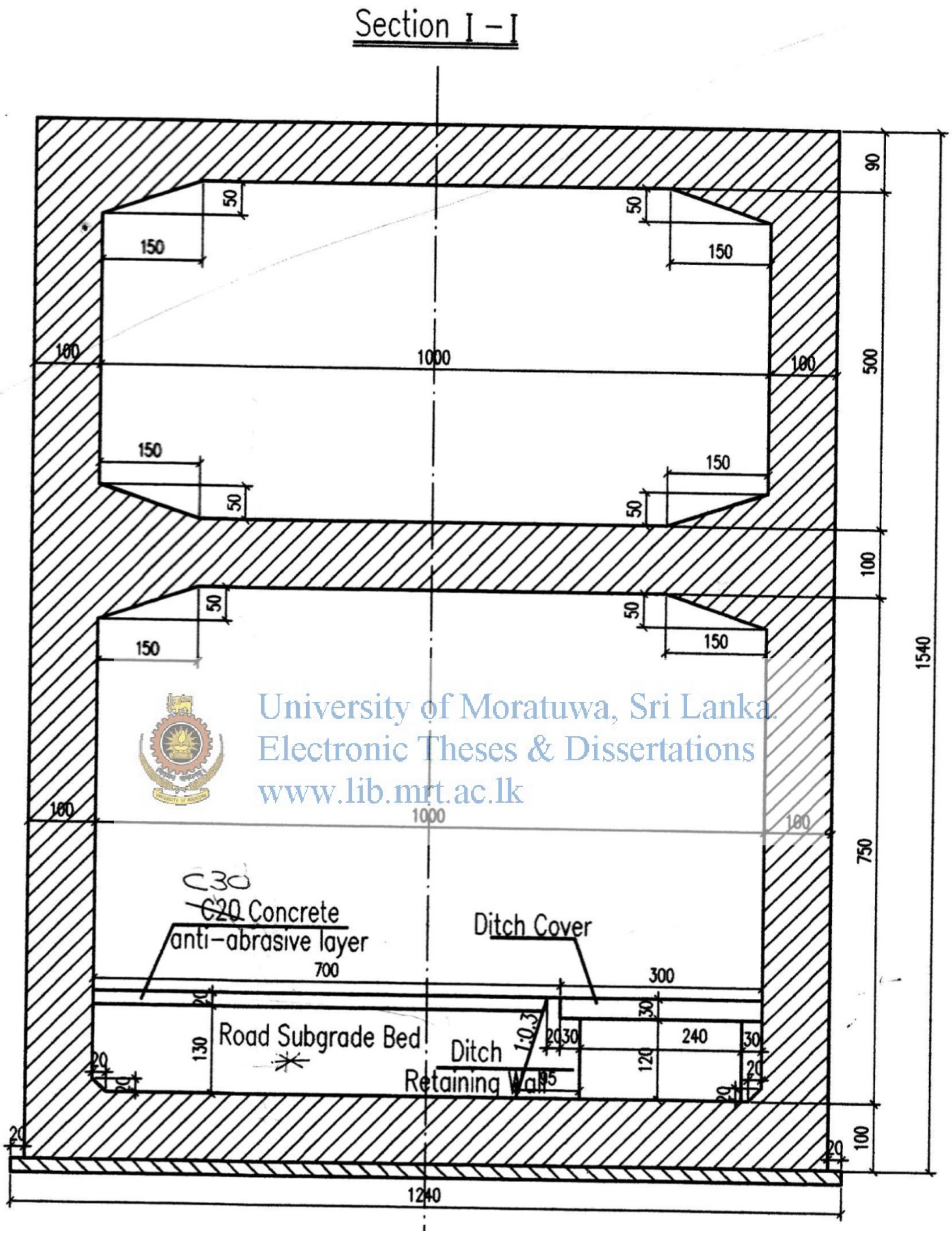




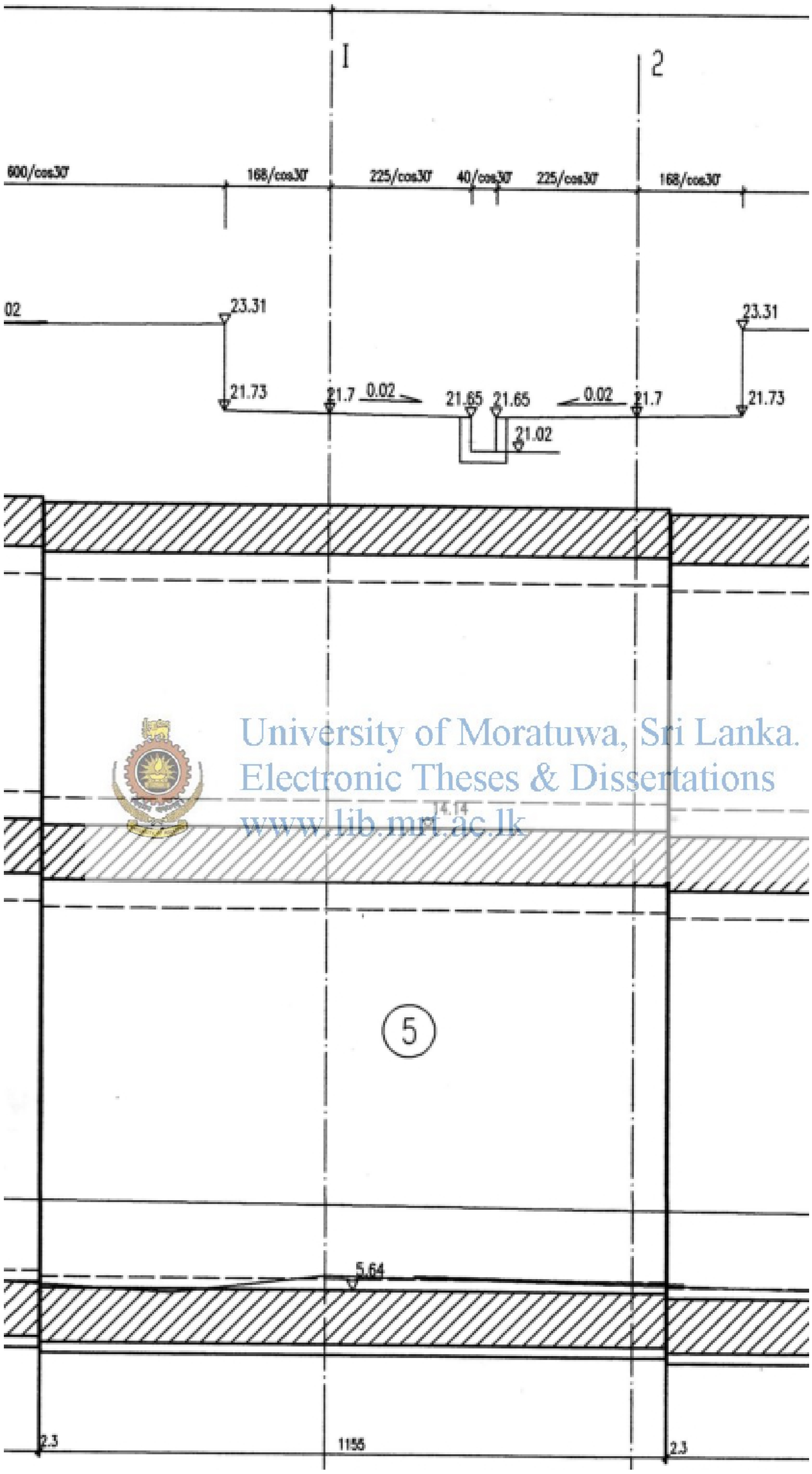


Culvert section of half plane – half base top
Retaining Wall 1
Retaining Wall 4
Retaining Wall 2
Retaining Wall 3
Beliatta
Matara
CENTRAL ENGINEERING CONSUL
DESIGNS, RESEARCH & DEVE
SECTION (DRD)
PROJECT. MEREP
YOUR REF.
OUR REF.
APPROVED
APPROVED IN PRINCIPLE
APPROVED EXCEPT AS NOTED
APPROVED IN PRINCIPLE EXCEPT
RETURNED FOR CORRECTION
NOT APPROVED
DGM
AGM
DATE 12/09/14 DATE

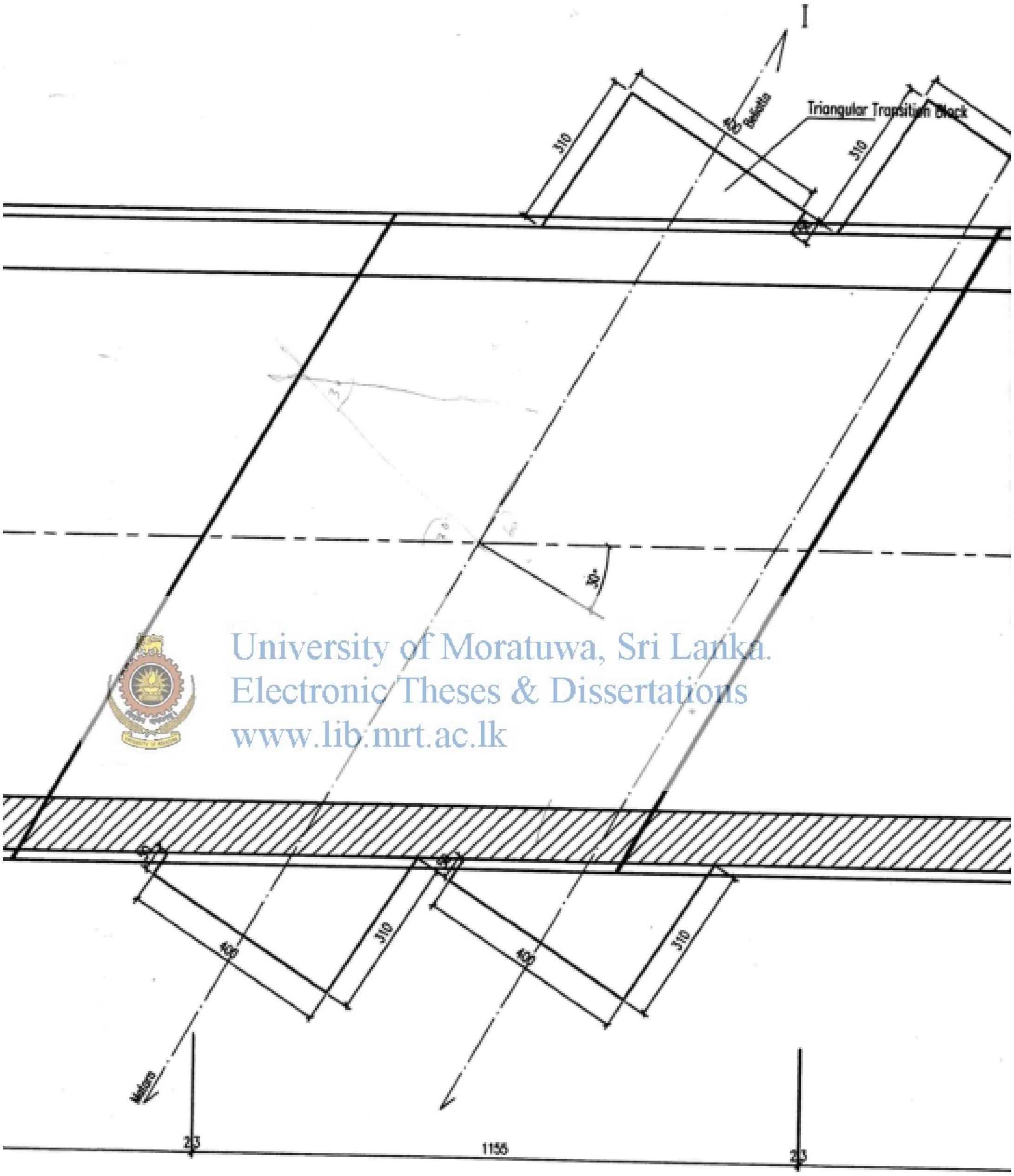
A.2 Story cell



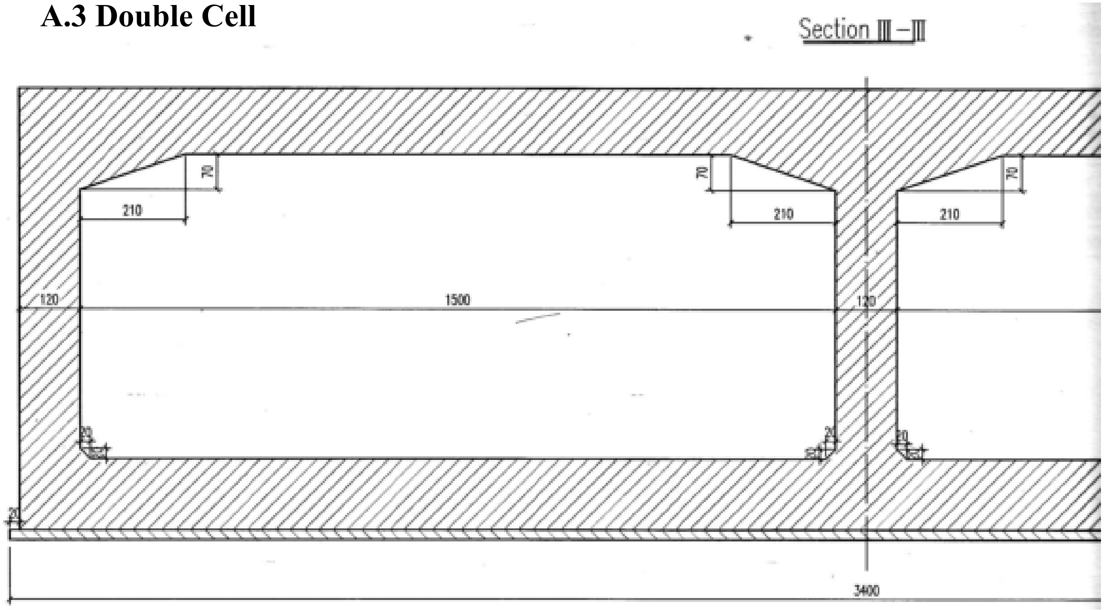
Centre line of culvert vertical section

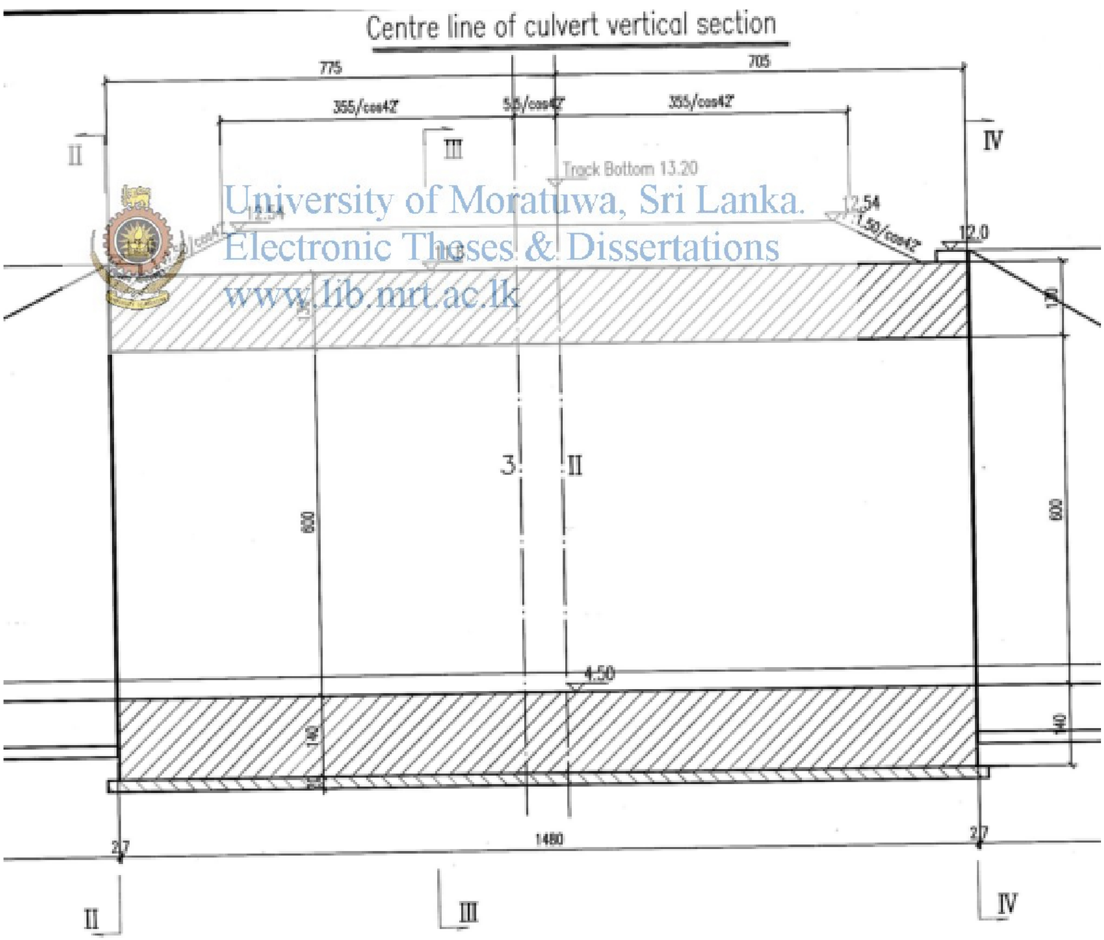


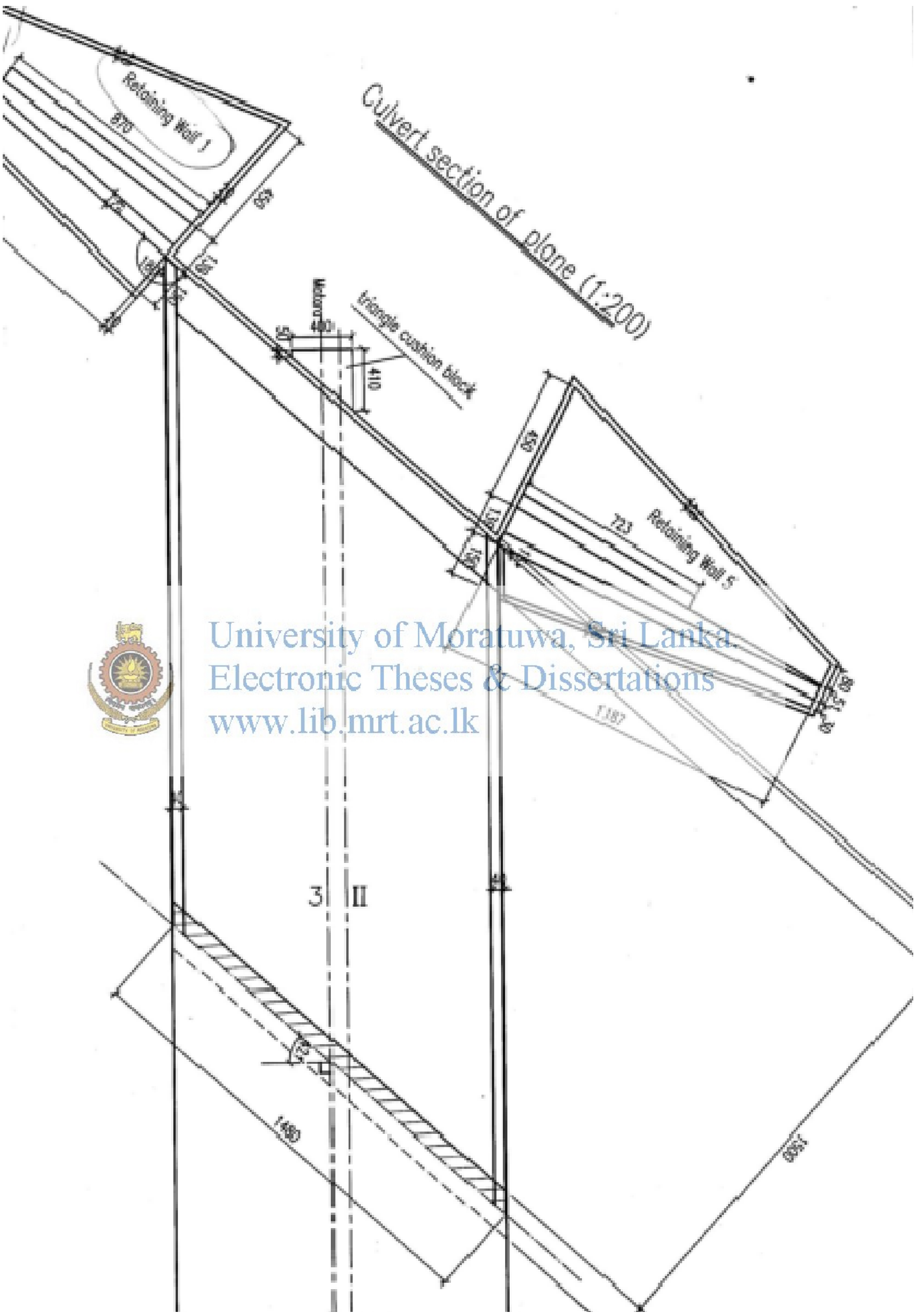
Half Plan–Half Foundation Top



A.3 Double Cell






Culvert section of plane (1:200)
Retaining Wall 1
870
Retaining Wall 5
723
triangle cushion block
410
3
II
1480
1390

A.4 Test culvert details [18]

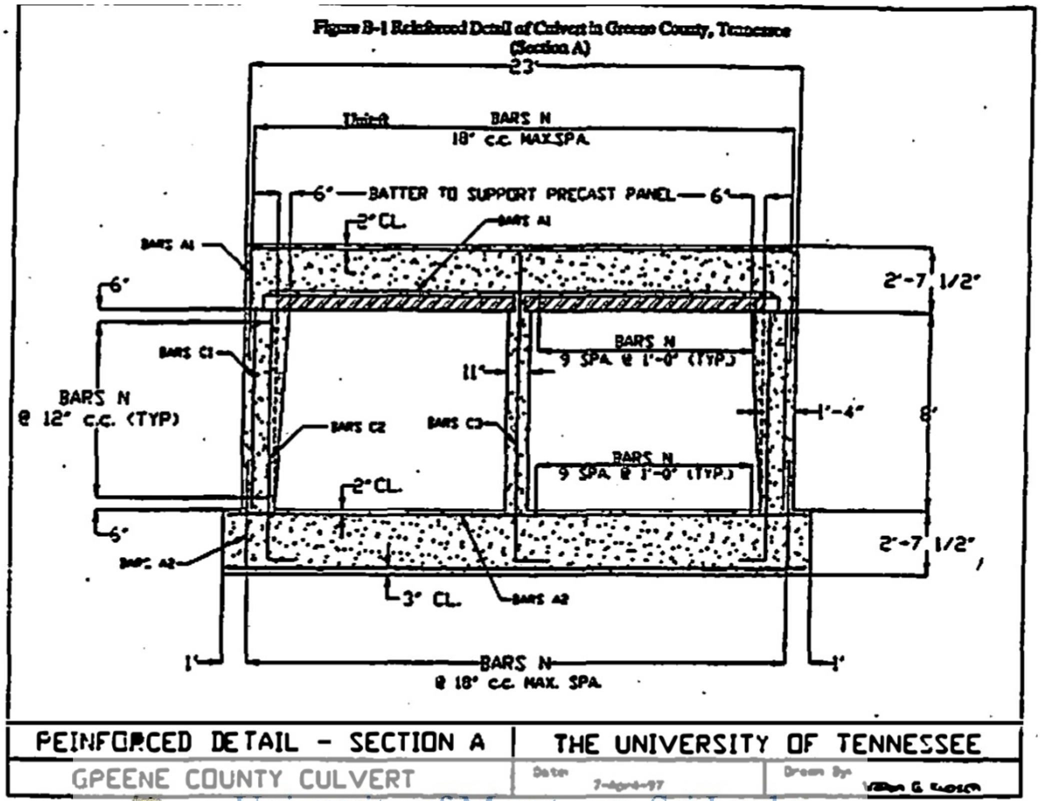


Figure B-1 Reinforced Detail of Culvert in Greene County, Tennessee (Section A)

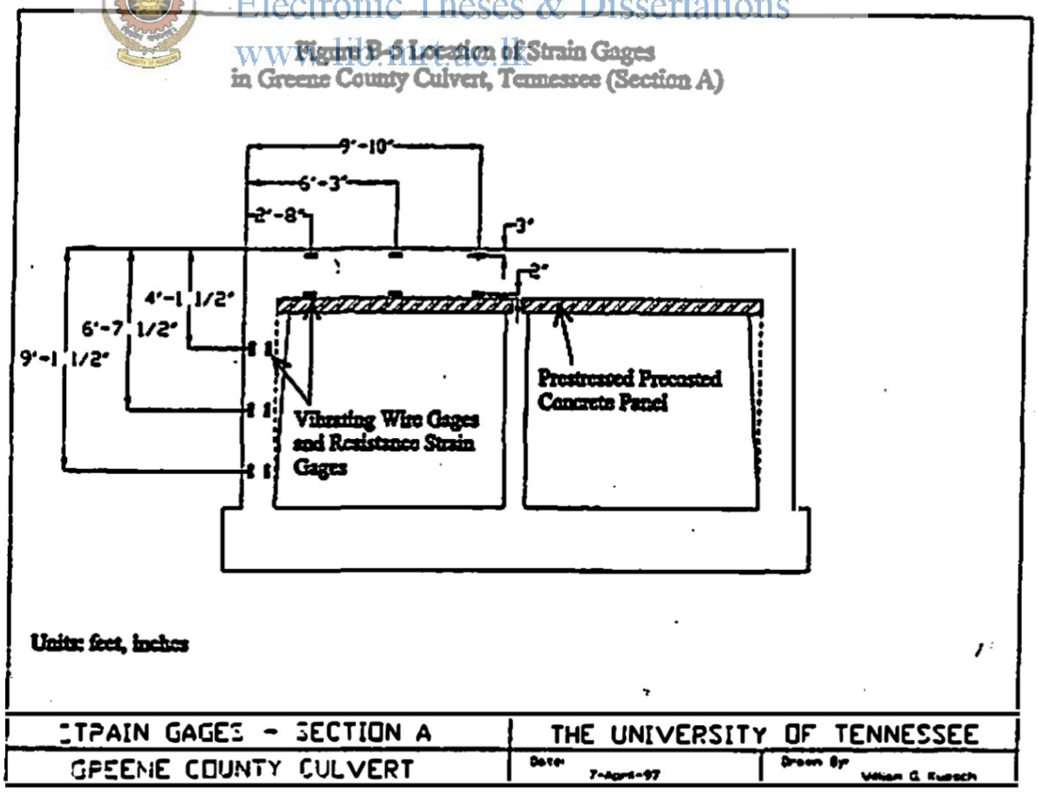
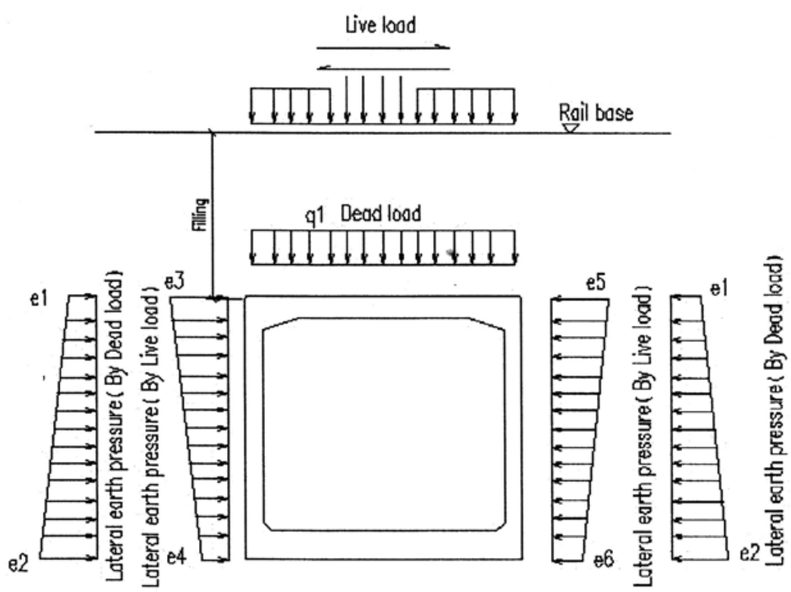


Figure B-5 Location of Strain Gages in Greene County Culvert, Tennessee (Section A)

Appendix B: Loads

B.1 load cases

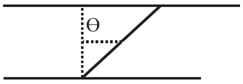


Load cases	Notation
Self weight	SW
Super Dead loads-Ballast	SIDL-S
Super Dead loads-Soil fill	SIDL-F
Live load -all spans	LL
Live load -alternate spans	LL1
Earth Pressure-Active	ERTKA
Earth Pressure-At rest	ERTK0
Live surcharge	LLSK0A
Traction or Braking	BREKAA

B.2 Load combinations

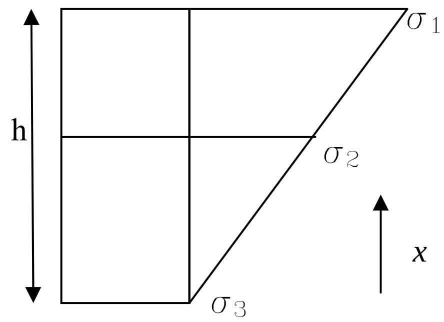
Load cases	SLS1	SLS2	SLS3	SLS4	ULS1	ULS2	ULS3	ULS4
SW	1	1	1	1	1.15	1.15	1	1.15
SIDL-S	1.2	1.2	1	1.2	1.75	1.75	1	1.75
SIDL-F	1	1	1	1	1.2	1.2	1	1.2
LL	1.1	1.1	0	0	1.4	1.4	0	0
LL1	0	0	0	1.1	0	0	0	1.4
ERTKA	1	0	0	1	1	0	0	1
ERTK0	0	1	1	0	0	1.5	1.5	0
LLSK0A	1	1	0	1	1.5	1.5	0	1.5
BREKAA	1	1	0	1	1.4	1.4	0	1.4

B.3 Load calculation sheet

Reference	Calculation					Outputs
	density- Concrete	$\gamma_{concrete}$	=	25	kN/m^3	
	density- soil	γ_{soil}	=	18	kN/m^3	
	density- Ballast	γ_{ball}	=	20	kN/m^3	
	track angle		=	15	deg	
			=	0.26	rad	
	box culvert dimensions	h	=	4.6	m	
		b	=	7	m	
		t_t	=	700	mm	
		t_b	=	800	mm	
		t_w	=	700	mm	
	fill+ballast	h_f	=	1	m	
	Ballast thickness	h_b	=	0.7	m	
BD3101 cl 3.1.2		β	=	1.15		
		q_1	=	18.10	kN/m^2	
		q_2	=	6.21	kN/m^2	
	internal friction angle	φ	=	35	deg	
			=	0.61	rad	
		K_0	=	0.43		
		e_1	=	10.37	kN/m^2	
		e_2	=	57.19	kN/m^2	
BD3101 cl3.2.7		L_L	=	8.70	m	
bs5400-2-2006 tb18		Kt	=	0.95		
	nominal traction force		=	340.71	kN	
bs5400-2-2006 cl 8.2.10		Ft	=	323.88	kN	
	2/3 and sl loads		=	190.01	kN	
	Distributed force per m		=	56.78	kN/m	
	Dynamic factor Ru loading		=	1.52		
uic776 cl2.4.2.4	culvert top	φu	=	1.52		
cl 5.8.2	culvert bottom	φu	=	0.91		
bs5400-2-2006						
	loaded length (sleeper size)	B	=	3.00	m	
		Qli	=	48.16		
		e_3	=	12.35		
		e_4	=	5.03		
		KA/K0	=	0.635		

Appendix C: Bending moment Derivation from stresses

C.1 Mesh density 2

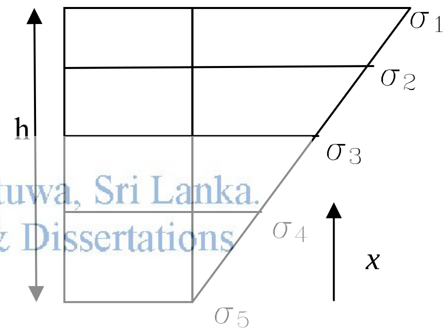


$$M = \int \sigma A \, dx$$

$$M = \sigma_2 \frac{h}{2}\frac{h}{2}\frac{1}{2} - \sigma_3 \frac{h}{2}\frac{h}{2}\frac{1}{2} + \frac{(\sigma_1 - \sigma_2)}{2}\frac{h}{2}\frac{h}{2}\frac{2}{3} - \frac{(\sigma_2 - \sigma_3)}{2}\frac{h}{2}\frac{h}{2}\frac{1}{3}$$

$$M = \frac{h^2}{12}(\sigma_1 - \sigma_3)$$

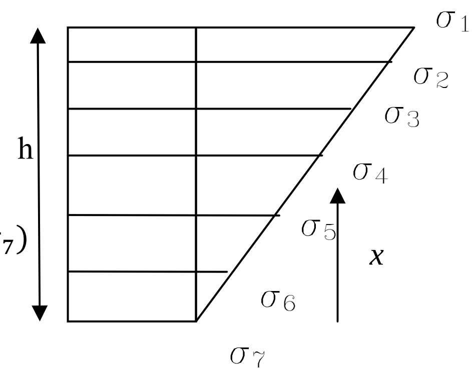
C.2 Mesh density 4



$$M = \int \sigma A \, dx$$

$$M = \frac{h^2}{96}(5\sigma_1 + 6\sigma_2 - 6\sigma_4 - 5\sigma_5)$$

C.3 Mesh density 6



$$M = \int \sigma A \, dx$$

$$M = \frac{h^2}{108}(4\sigma_1 + 6\sigma_2 + 3\sigma_3 - 3\sigma_5 - 6\sigma_6 - 4\sigma_7)$$

C.4 Mesh density 8

Similarly,

$$M = \frac{h^2}{384}(11\sigma_1 + 18\sigma_2 + 12\sigma_3 + 6\sigma_4 - 6\sigma_6 - 12\sigma_7 - 18\sigma_8 - 11\sigma_9)$$

Appendix D: Computer models and variables

Table D.1: Single Cell model variables

Model No /Variable	Mesh density	Skew angle (degrees)	Soil fill height (m)	Wall thickness (m)	Span Length (m)	Transverse width (m)	Haunch Thickness (mm)	Vertical Soil springs (MN/m^2)
1-Real	4	42	1	0.7	8.4	9.3	0	15
2-Mesh2	6	42	1	0.7	8.4	9.3	0	15
3-Mesh3	8	42	1	0.7	8.4	9.3	0	15
4-Angle0	1	0	1	0.7	8.4	9.3	0	15
5-Angle30	1	30	1	0.7	8.4	9.3	0	15
6-Fill0	1	42	0	0.7	8.4	9.3	0	15
7-Fill6	1	42	6	0.7	8.4	9.3	0	15
8-Wall0.5	1	42	1	0.35	8.4	9.3	0	15
9-Wall1.5	1	42	1	1.05	8.4	9.3	0	15
10-B0.75	1	42	1	0.7	6.3	9.3	0	15
11-B1.5	1	42	1	0.7	12.6	9.3	0	15
12-L0.5	1	42	1	0.7	8.4	4.65	0	15
13-L1.5	1	42	1	0.7	8.4	14	0	15
14-Haunch	1	42	1	0.7	8.4	9.3	400	15
15-Spring0.5	1	42	1	0.7	8.4	9.3	0	7.5
16-Spring1.5	1	42	1	0.7	8.4	9.3	0	22.5

Table D.2: Double Cell model variables

Model No /Variable	Mesh density	Skew angle (degrees)	Soil fill height (m)	Wall thickness (m)	Span Length (m)	Transverse width (m)	Haunch Thickness (mm)	Vertical Soil springs (MN/m^2)
1-Real	4	15	2.1	1.2	33.6	14.8	0	15
2-Mesh2	6	15	2.1	1.2	33.6	14.8	0	15
3-Mesh3	8	15	2.1	1.2	33.6	14.8	0	15
4-Angle0	1	0	2.1	1.2	33.6	14.8	0	15
5-Angle30	1	30	2.1	1.2	33.6	14.8	0	15
6-Fill0	1	15	0	1.2	33.6	14.8	0	15
7-Fill6	1	15	6	1.2	33.6	14.8	0	15
8-Wall0.5	1	15	2.1	0.35	33.6	14.8	0	15
9-Wall1.5	1	15	2.1	1.05	33.6	14.8	0	15
10-B0.75	1	15	2.1	1.2	25	14.8	0	15
11-B1.5	1	15	2.1	1.2	47.4	14.8	0	15
12-L0.5	1	15	2.1	1.2	33.6	4.65	0	15
13-L1.5	1	15	2.1	1.2	33.6	14	0	15
14-Haunch	1	15	2.1	1.2	33.6	14.8	700	15
15-Spring0.5	1	15	2.1	1.2	33.6	14.8	0	7.5
16-Spring1.5	1	15	2.1	1.2	33.6	14.8	0	22.5

Table D.3: Story Cell model variables

Model No /Variable	Mesh density	Skew angle (degrees)	Soil fill height (m)	Wall thickness (m)	Span Length (m)	Transverse width (m)	Haunch Thickness (mm)	Vertical Soil springs (MN/m^2)
1-Real	4	30	2.7	1	12	11.6	0	15
2-Mesh2	6	30	2.7	1	12	11.6	0	15
3-Mesh3	8	30	2.7	1	12	11.6	0	15
4-Angle0	1	0	2.7	1	12	11.6	0	15
5-Angle30	1	45	2.7	1	12	11.6	0	15
6-Fill0	1	30	0	1	12	11.6	0	15
7-Fill6	1	30	6	1	12	11.6	0	15
8-Wall0.5	1	30	2.7	0.5	12	11.6	0	15
9-Wall1.5	1	30	2.7	1.5	12	11.6	0	15
10-B0.75	1	30	2.7	1	10	11.6	0	15
11-B1.5	1	30	2.7	1	14	11.6	0	15
12-L0.5	1	30	2.7	1	12	5.8	0	15
13-L1.5	1	30	2.7	1	12	17.4	0	15
14-Haunch	1	30	2.7	1	12	11.6	500	15
15-Spring0.5	1	30	2.7	1	12	11.6	0	7.5
16-Spring1.5	1	30	2.7	1	12	11.6	0	22.5

Appendix E: Bending moments in critical sections

E.1 Single cell

Table E.1: Top slab bending moment (kNm)

Model No /Variable	General shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	-543	433	303	-697	528	416	-526	316	-676	431	-503	339	-650	468
2-Mesh2	-543	438	309	-697	519	423	-525	314	-676	428	-500	330	-647	456
3-Mesh3	-543	437	306	-697	518	420	-525	313	-676	426	-502	330	-650	457
4-Angle0	-548	416	275	-705	554	377	-532	303	-684	412	-511	321	-660	440
5-Angle45	-512	440	324	-655	462	442	-491	318	-629	432	-477	360	-615	500
6-Fill0	-546	446	313	-704	532	429	-529	321	-683	438	-508	346	-659	478
7-Fill6	-865	587	412	-1072	778	559	-837	443	-1039	597	-804	473	-1000	647
8-Wall0.5	-648	234	185	-842	340	277	-640	194	-833	288	-604	249	-698	337
9-Wall1.5	-449	647	381	-571	653	503	-422	400	-537	524	-391	394	-500	527
10-B0.75	-348	284	208	-453	389	296	-333	213	-433	301	-319	241	-418	344
11-B1.5	-807	790	517	-1036	805	689	-793	607	-1018	794	-758	594	-977	781
12-L0.5	-550	431	318	-707	502	436	-534	321	-687	437	-505	335	-653	464
13-L1.5	-535	428	297	-687	539	407	-516	310	-663	423	-496	332	-641	457
14-Haunch	-555	429	301	-711	520	411	-536	312	-688	424	-514	325	-663	447
15-Spring0.5	-562	441	317	-722	538	433	-544	325	-699	443	-525	350	-678	482
16-Spring1.5	-508	413	289	-653	507	398	-493	298	-635	409	-465	318	-602	442

Table E.2: Bottom slab bending moment (kNm)-single cell

Model No /Variable	General shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	-543	433	303	-697	528	416	-526	316	-676	431	-503	339	-650	468
2-Mesh2	-543	438	309	-697	519	423	-525	314	-676	428	-500	330	-647	456
3-Mesh3	-543	437	306	-697	518	420	-525	313	-676	426	-502	330	-650	457
4-Angle0	-548	416	275	-705	554	377	-532	303	-684	412	-511	321	-660	440
5-Angle45	-512	440	324	-655	462	442	-491	318	-629	432	-477	360	-615	500
6-Fill0	-546	446	313	-704	532	429	-529	321	-683	438	-508	346	-659	478
7-Fill6	-865	587	412	-1072	778	559	-837	443	-1039	597	-804	473	-1000	647
8-Wall0.5	-648	234	185	-842	340	277	-640	194	-833	288	-604	249	-698	337
9-Wall1.5	-449	647	381	-571	653	503	-422	400	-537	524	-391	394	-500	527
10-B0.75	-348	284	208	-453	389	296	-333	213	-433	301	-319	241	-418	344
11-B1.5	-807	790	517	-1036	805	689	-793	607	-1018	794	-758	594	-977	781
12-L0.5	-550	431	318	-707	502	436	-534	321	-687	437	-505	335	-653	464
13-L1.5	-535	428	297	-687	539	407	-516	310	-663	423	-496	332	-641	457
14-Haunch	-555	429	301	-711	520	411	-536	312	-688	424	-514	325	-663	447
15-Spring0.5	-562	441	317	-722	538	433	-544	325	-699	443	-525	350	-678	482
16-Spring1.5	-508	413	289	-653	507	398	-493	298	-635	409	-465	318	-602	442

Table E.3: Walls bending moment (kNm)-single cell

Model No /Variable	General shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	239	494	434	319	666	578	255	470	339	626	245	473	325	634
2-Mesh2	240	495	446	320	667	595	256	470	340	627	248	474	329	635
3-Mesh3	240	495	435	320	667	580	256	470	340	627	245	476	325	637
4-Angle0	229	451	379	305	600	503	243	401	323	529	233	402	309	534
5-Angle45	251	539	493	333	730	660	268	522	355	698	229	531	284	656
6-Fill0	242	504	454	322	681	609	258	480	342	642	248	484	330	650
7-Fill6	364	760	646	476	983	816	392	709	510	899	378	700	492	893
8-Wall0.5	32	279	230	49	391	319	39	241	58	335	36	260	52	332
9-Wall1.5	403	651	599	528	838	775	430	643	562	830	403	592	528	784
10-B0.75	91	321	263	128	439	358	102	278	142	378	98	287	136	392
11-B1.5	649	1097	1012	846	1448	1327	678	1066	883	1398	689	1115	898	1465
12-L0.5	236	518	456	315	697	607	253	478	337	637	243	489	323	655
13-L1.5	236	470	428	315	634	571	252	451	334	600	241	453	320	607
14-Haunch	242	531	466	320	717	624	259	486	341	650	254	482	335	641
15-Spring0.5	243	495	445	324	667	594	259	471	344	628	251	474	333	636
16-Spring1.5	231	493	443	309	664	590	247	468	329	624	233	471	310	630

E.2 Double cell

Table E.4a: Top slab bending moment (kNm)-double cell

Model No /Variable	General shell model									
	SLS					ULS				
	Min	Max edge	face edge	Max mid	Face mid	Min	Max edge	face edge	Max mid	Face mid
1-Real	-1746	1737	807	2527	2433	-2201	2243	1074	3179	3050
2-Mesh2	-1734	1561	934	2664	2664	-2186	2006	1234	3338	3338
3-Mesh3	-1731	1432	738	2424	2424	-2183	1841	987	3037	3037
4-Angle0	-1634	1184	625	3173	2648	-2059	1502	817	3979	3337
5-Angle45	-1673	1385	712	2752	2576	-2108	1800	954	3459	3235
6-Fill0	-1559	1648	597	2397	1867	-1995	2136	767	3062	2383
7-Fill6	-2949	2978	1412	4217	3985	-3629	3766	1853	5178	4910
8-Wall0.5	-2254	1656	440	3457	3421	-2852	2102	640	4356	4312
9-Wall1.5	-1476	2008	790	1961	1615	-1860	2544	1035	2465	2016
10-B0.75	-946	744	189	1407	1190	-1197	1019	310	1767	1482
11-B1.5	-3708	4638	3324	5797	5797	-4660	5856	4212	7282	7282
12-L0.5	-2100	2507	1165	3498	2775	-2644	3214	1468	4403	3487
13-L1.5	-1592	1094	668	2060	2060	-2005	1427	898	2583	2583
14-Haunch	-1561	1762	773	3681	3321	-1968	2302	998	4621	4158
15-Spring0.5	-1749	1717	798	2586	2516	-2207	2236	1075	3250	3146
16-Spring1.5	-1742	1742	814	2488	2384	-2196	2236	1075	3131	2993

Table E.4b: Top slab bending moment (kNm)-double cell

Model No /Variable	Modified shell model						Solid model					
	SLS			ULS			SLS			ULS		
	Min	Max edge	Max mid	Min	Max edge	Max mid	Min	Max edge	Max mid	Min	Max edge	Max mid
1-Real	-1646	1226	3091	-2076	1615	3877	-1639	1233	2811	-2066	1595	3530
2-Mesh2	-1634	1225	2789	-2061	1558	3496	-1670	1193	2686	-2105	1544	3372
3-Mesh3	-1632	1232	2628	-2058	1568	3292	-1676	1201	2692	-2113	1558	3380
4-Angle0	-1573	766	2780	-1982	975	3503	-1526	886	2559	-1925	1123	3230
5-Angle45	-1606	1135	2829	-2023	1440	3552	-1582	990	2611	-1994	1292	3283
6-Fill0	-1468	1096	2807	-1879	1416	3582	-1461	1095	2478	-1870	1417	3170
7-Fill6	-2783	2177	5068	-3427	2809	6248	-2771	2119	4541	-3410	2704	5608
8-Wall0.5	-2161	1553	2997	-2734	1974	3791	-2270	1414	3630	-2871	1798	4577
9-Wall1.5	-1365	1360	2363	-1720	1741	2952	-1258	1364	2114	-1586	1717	2647
10-B0.75	-887	617	1497	-1122	794	1865	-875	504	1426	-1107	651	1781
11-B1.5	-3537	4477	7051	-4445	5662	8857	-3407	3911	5661	-4280	4912	7075
12-L0.5	-1964	2050	4146	-2475	2645	5202	-1936	1953	3407	-2440	2479	4279
13-L1.5	-1506	1000	2336	-1897	1270	2927	-1468	868	2218	-1850	1138	2783
14-Haunch	-1494	1319	3957	-1883	1673	4956	-1365	1562	4210	-1722	2013	5287
15-Spring0.5	-1656	1194	3177	-2089	1571	3976	-1648	1220	2824	-2079	1592	3538
16-Spring1.5	-1642	1253	3041	-2070	1635	3820	-1631	1239	2690	-2056	1597	3381

Table E.5a: Bottom slab bending moment (kNm)-double cell

Model No /Variable	General shell model									
	SLS					ULS				
	Min	Max edge	face edge	Max mid	Face mid	Min	Max edge	face edge	Max mid	Face mid
1-Real	-1553	1464	1072	2301	1906	-1940	1857	1405	2876	2368
2-Mesh2	-1553	1464	1072	2301	1906	-1940	1857	1405	2876	2368
3-Mesh3	-1546	1263	1040	2102	1902	-1931	1601	1360	2625	2364
4-Angle0	-1666	1483	913	2986	2434	-2085	1881	1176	3727	3059
5-Angle45	-1582	1358	1053	2517	2171	-1978	1700	1377	3149	2707
6-Fill0	-1421	1493	894	2176	1668	-1799	1902	1179	2759	2105
7-Fill6	-2077	1960	1376	3266	2723	-2531	2479	1789	3996	3335
8-Wall0.5	-1714	1073	470	2495	2274	-2157	1332	691	3136	2850
9-Wall1.5	-1464	2150	1118	2020	1437	-1815	2685	1428	2512	1774
10-B0.75	-1102	815	768	1347	1109	-1367	1079	1030	1695	1378
11-B1.5	-1637	2465	1372	3354	2956	-2052	3105	1778	4189	3683
12-L0.5	-1751	1968	1247	3080	2373	-2183	2469	1631	3853	2937
13-L1.5	-1364	1060	924	1888	1633	-1692	1372	1210	2357	2033
14-Haunch	-1570	1389	1076	2391	1992	-1957	1756	1406	2982	2471
15-Spring0.5	-1808	1644	1232	2514	2063	-2249	2075	1603	3147	2562
16-Spring1.5	-1364	1341	943	2127	1780	-1707	1707	1244	2656	2213

Table E.5b: Bottom slab bending moment (kNm)-double cell

Model No /Variable	Modified shell model						Solid model					
	SLS			ULS			SLS			ULS		
	Min	Max edge	Max mid	Min	Max edge	Max mid	Min	Max edge	Max mid	Min	Max edge	Max mid
1-Real	-1476	1139	2062	-1842	1478	2611	-1378	1044	2073	-1706	1389	2608
2-Mesh2	-1469	1034	1941	-1833	1343	2453	-1398	1011	1949	-1731	1346	2426
3-Mesh3	-1468	1016	1767	-1832	1247	2236	-1402	1015	1952	-1735	1351	2430
4-Angle0	-1612	996	2569	-2018	1279	3230	-1489	919	2360	-1869	1190	2973
5-Angle45	-1529	1139	2112	-1909	1479	2672	-1440	1061	2148	-1791	1403	2684
6-Fill0	-1349	1000	1931	-1707	1301	2481	-1239	902	1798	-1560	1203	2299
7-Fill6	-1979	1507	2951	-2447	1907	3651	-2263	1722	3233	-2800	2277	4002
8-Wall0.5	-1631	1067	2093	-2050	1322	2624	-1588	874	2465	-2003	1096	3089
9-Wall1.5	-1384	1443	1798	-1715	1804	2266	-1228	1140	1716	-1512	1447	2154
10-B0.75	-1034	781	1027	-1283	1036	1274	-1011	783	1166	-1250	1066	1450
11-B1.5	-1584	1717	3024	-1985	2157	3805	-1403	1469	2906	-1764	1861	3614
12-L0.5	-1686	1568	2946	-2102	1972	3724	-1551	1172	2355	-1931	1566	2976
13-L1.5	-1310	1057	1567	-1625	1367	1980	-1237	937	1669	-1531	1238	2081
14-Haunch	-1496	1140	2180	-1861	1476	2753	-1416	1050	2010	-1752	1392	2530
15-Spring0.5	-1737	1275	2295	-2155	1651	2916	-1668	1218	2193	-2067	1612	2772
16-Spring1.5	-1303	1040	1856	-1630	1353	2347	-1172	922	1804	-1472	1232	2247

Table E.6: Edge Walls bending moment (kNm)-double cell

Model No /Variable	General shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	1372	1674	1646	1740	2140	2085	1450	1749	1836	2215	1391	1679	1757	2130
2-Mesh2	1372	1674	1646	1740	2140	2085	1463	1755	1852	2222	1394	1698	1762	2153
3-Mesh3	1382	1676	1659	1753	2141	2101	1465	1756	1854	2224	1395	1703	1763	2159
4-Angle0	956	1499	1274	1228	1900	1582	1019	1372	1306	1701	962	1212	1233	1529
5-Angle30	1143	1684	1461	1455	2172	1833	1219	1515	1550	1898	1156	1445	1467	1854
6-Fill0	1240	1514	1488	1586	1960	1926	1308	1614	1672	2046	1260	1525	1610	1974
7-Fill6	2236	2940	2783	2780	3684	3411	2357	2968	2931	3647	2223	2820	2743	3463
8-Wall0.5	263	783	563	352	1086	761	284	594	377	801	332	665	434	913
9-Wall1.5	2421	2796	2796	3059	3467	3467	2540	3096	3214	3833	2284	2391	2870	2981
10-B0.75	584	1257	1096	761	1652	1395	629	1103	817	1398	624	1127	805	1467
11-B1.5	2376	4657	4392	2963	5864	5535	2590	4640	3226	5847	2080	4303	2629	5426
12-L0.5	1442	2084	1969	1822	2640	2499	1509	2089	1911	2649	1509	1964	1900	2493
13-L1.5	1224	1769	1589	1561	2283	2004	1282	1619	1626	2037	1233	1561	1568	2013
14-Haunch	1332	1661	1645	1688	2150	2074	1409	1704	1782	2113	1396	1757	1757	2235
15-Spring0.5	1476	1815	1815	1878	2298	2289	1546	1932	1965	2399	1522	1835	1924	2352
16-Spring1.5	1288	1711	1673	1634	2163	2118	1363	1777	1728	2249	1278	1708	1606	2164

Table E.7: Middle Wall bending moment (kNm)-double cell

Model No /Variable	General shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	-1596	1084	-1463	-2063	1312	-1885	-1609	1160	-2070	1413	-1335	867	-1728	1049
2-Mesh2	-1596	1084	-1463	-2063	1312	-1885	-1640	1188	-2111	1447	-1358	891	-1757	1083
3-Mesh3	-1593	1083	-1487	-2059	1311	-1914	-1645	1192	-2117	1453	-1364	896	-1764	1089
4-Angle0	-520	262	-447	-695	373	-594	-481	229	-639	327	-473	219	-630	313
5-Angle30	-1251	658	-1150	-1628	767	-1491	-1276	742	-1652	887	-1054	532	-1372	637
6-Fill0	-1623	864	-1461	-2122	1650	-1903	-1614	947	-2100	1163	-1386	697	-1811	858
7-Fill6	-2277	2056	-2106	-2878	2489	-2653	-2337	2125	-2942	2589	-1859	1665	-2355	2001
8-Wall0.5	-535	251	-478	-704	306	-627	-566	283	-742	312	-542	250	-713	324
9-Wall1.5	-2217	1671	-2080	-2847	2039	-2662	-2320	1851	-2960	2271	-1756	1308	-2261	1608
10-B0.75	-902	534	-824	-1190	610	-1081	-918	567	-1202	642	-735	407	-975	470
11-B1.5	-3546	2838	-3197	-4516	3520	-4066	-3487	2865	-4434	3559	-2585	2431	-3300	3017
12-L0.5	-1968	1451	-1636	-2552	1763	-2116	-1835	1351	-2380	1642	-1577	1091	-2053	1322
13-L1.5	-1329	816	-1236	-1718	979	-1592	-1380	940	-1773	1141	-1137	679	-1471	826
14-Haunch	-1532	961	-1389	-1992	1151	-1800	-1512	1005	-1960	1212	-1398	876	-1814	1056
15-Spring0.5	-1638	1112	-1508	-2121	1338	-1946	-1657	1193	-2137	1446	-1366	886	-1772	1074
16-Spring1.5	-1581	1077	-1443	-2040	1308	-1856	-1587	1149	-2040	1403	-1324	862	-1710	1048

E.3 Story Cell

Table E.8: Top slab bending moment (kNm)-story cell

Model No /Variable	General Shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	107	100	73	107	88	73	99	96	100	95	99	96	100	95
2-Mesh2	-732	1734	1331	-935	2261	1809	-680	1686	-868	2284	-695	1857	-886	2535
3-Mesh3	-732	1679	1344	-934	2205	1828	-679	1650	-867	2236	-697	1867	-889	2548
4-Angle0	-790	1121	799	-999	1432	1024	-735	861	-931	1101	-734	880	-928	1128
5-Angle45	-658	1983	1276	-864	2164	1772	-605	2302	-796	3149	-613	2356	-803	3257
6-Fill0	-578	1497	1102	-757	1820	1516	-540	1429	-704	1959	-547	1486	-716	2052
7-Fill6	-1144	2625	1912	-1425	3122	2563	-1067	2523	-1328	3368	-1074	2641	-1338	3554
8-Wall0.5	-1111	1456	776	-1427	1672	1111	-1055	1287	-1351	1792	-1070	1768	-1372	2435
9-Wall1.5	-644	1755	1421	-821	2135	1905	-599	1770	-764	2367	-568	1625	-724	2201
10-B0.75	-527	1307	927	-679	1601	1286	-489	1205	-635	1661	-525	1383	-684	1917
11-B1.5	-1003	2387	1803	-1279	2851	2413	-941	2341	-1200	3128	-942	2344	-1202	3152
12-L0.5	-786	2036	1141	-1005	2225	1530	-726	1803	-929	2425	-709	1754	-910	2377
13-L1.5	-754	1597	1324	-963	1989	1794	-701	1528	-896	2061	-719	1635	-923	2221
14-Haunch	-622	2148	1751	-791	2758	2387	-591	2192	-753	2979	-551	2180	-718	2974
15-Spring0.5	-732	1834	1359	-935	2229	1850	-680	1775	-869	2406	-687	1860	-875	2542
16-Spring1.5	-738	1784	1305	-942	2146	1773	-686	1708	-876	2313	-690	1776	-881	2422

Table E.9: Bottom slab bending moment (kNm)-story cell

Model No /Variable	General Shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	-1381	1706	1680	-1713	2331	2305	-1315	1615	-1630	2208	-1204	1804	-1499	2513
2-Mesh2	-1378	1680	1680	-1709	2306	2306	-1310	1554	-1625	2125	-1214	1817	-1511	2529
3-Mesh3	-1377	1679	1679	-1708	2305	2305	-1309	1528	-1624	2090	-1217	1817	-1515	2529
4-Angle0	-1352	1818	1327	-1685	2342	1756	-1281	1432	-1599	1883	-1144	1379	-1435	1827
5-Angle45	-1420	1766	1737	-1783	2472	2428	-1383	1608	-1760	2243	-1289	1907	-1670	2709
6-Fill0	-1243	1462	1462	-1573	2008	2008	-1184	1401	-1490	1916	-1077	1550	-1370	2162
7-Fill6	-1770	2287	2209	-2162	3124	3025	-1682	2132	-2054	2909	-1564	2410	-1912	3349
8-Wall0.5	-1571	1498	1241	-1984	2158	1821	-1507	1221	-1903	1766	-1446	1708	-1838	2476
9-Wall1.5	-1338	1936	1569	-1642	2076	2076	-1271	1618	-1563	2076	-1091	1617	-1359	2201
10-B0.75	-1112	1464	1411	-1389	2020	1965	-1043	1345	-1300	1867	-990	1586	-1248	2236
11-B1.5	-1559	1929	1929	-1933	2622	2622	-1501	1866	-1860	2526	-1361	2022	-1692	2791
12-L0.5	-1464	1814	1814	-1817	2490	2490	-1399	1714	-1733	2344	-1257	1885	-1562	2636
13-L1.5	-1313	1688	1560	-1630	2289	2134	-1237	1546	-1536	2107	-1143	1700	-1426	2357
14-Haunch	-1349	2317	2110	-1670	3163	2889	-1291	2055	-1598	2801	-1106	2019	-1402	2783
15-Spring0.5	-1501	1737	1737	-1856	2376	2376	-1422	1661	-1758	2263	-1326	1866	-1646	2590
16-Spring1.5	-1277	1680	1630	-1588	2301	2243	-1221	1575	-1518	2158	-1101	1751	-1374	2446

Table E.10: Middle slab bending moment (kNm)-story cell

Model No /Variable	General Shell model						Modified shell model				Modified shell model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	-684	1478	1352	-1034	2129	1959	-642	1813	-971	2623	-823	1841	-1248	2668
2-Mesh2	-684	1501	1352	-1034	2160	1959	-639	1754	-963	2539	-825	1865	-1250	2704
3-Mesh3	-683	1462	1365	-1034	2105	1979	-639	1713	-964	2481	-824	1873	-1250	2714
4-Angle0	-190	574	487	-272	791	686	-181	511	-264	718	-179	531	-266	745
5-Angle45	-913	1397	1397	-1379	2037	2037	-846	2186	-1275	3171	-1067	2390	-1616	3472
6-Fill0	-575	1365	1242	-864	1953	1789	-549	1659	-818	2386	-659	1661	-999	2392
7-Fill6	-971	1814	1673	-1467	2638	2445	-920	2252	-1389	3286	-1199	2333	-1815	3411
8-Wall0.5	-710	1674	1404	-1071	2437	2062	-522	1938	-788	2832	-828	2130	-1254	3094
9-Wall1.5	-448	1141	1102	-688	1620	1575	-453	1472	-688	2103	-609	1397	-931	2012
10-B0.75	-644	1323	1196	-960	1926	1752	-599	1594	-888	2332	-791	1674	-1189	2448
11-B1.5	-685	1608	1479	-1055	2288	2118	-654	1984	-1004	2837	-812	1967	-1251	2822
12-L0.5	-833	1471	1031	-1254	2028	1486	-723	1746	-1092	2509	-1009	1710	-1525	2469
13-L1.5	-578	1326	1312	-867	1907	1896	-557	1594	-832	2309	-640	1609	-975	2327
14-Haunch	-1036	1997	1822	-1563	2880	2643	-949	2321	-1424	3357	-1338	2823	-2025	4097
15-Spring0.5	-721	1522	1392	-1087	2191	2017	-675	1864	-1016	2697	-875	1908	-1322	2765
16-Spring1.5	-651	1441	1317	-989	2075	1909	-614	1768	-931	2558	-779	1784	-1185	2585

Table E.11: Walls bending moment (kNm)- story cell

Model No /Variable	General Shell model						Modified shell model				Solid model			
	SLS			ULS			SLS		ULS		SLS		ULS	
	Min	Max	face	Min	Max	face	Min	Max	Min	Max	Min	Max	Min	Max
1-Real	-740	2217	1780	-936	2930	2310	-834	1823	-1054	2356	-762	1816	-958	2435
2-Mesh2	-741	2221	1784	-938	2936	2315	-837	1831	-1058	2365	-760	1819	-955	2438
3-Mesh3	-741	2222	1785	-938	2937	2316	-838	1832	-1059	2367	-759	1819	-953	2438
4-Angle0	-365	1868	1465	-567	2407	1843	-392	1570	-599	1972	-355	1465	-545	1864
5-Angle45	-891	2730	2196	-1122	3678	2917	-974	2153	-1229	2840	-940	2213	-1201	2967
6-Fill0	-687	1990	1605	-888	2648	2099	-771	1642	-996	2140	-700	1574	-901	2087
7-Fill6	-931	2843	2271	-1146	3848	2942	-1055	2344	-1298	3118	-999	2637	-1250	3466
8-Wall0.5	-421	1663	1229	-632	2381	1745	-426	1367	-605	1938	-428	1397	-610	1990
9-Wall1.5	-815	2665	2178	-1036	3401	2722	-943	2277	-1193	2867	-834	2090	-1046	2745
10-B0.75	-499	1830	1410	-723	2507	1860	-566	1463	-738	1968	-552	1550	-744	2116
11-B1.5	-998	2617	2145	-1252	3428	2762	-1122	2201	-1407	2822	-1003	2380	-1252	3153
12-L0.5	-685	2299	1792	-875	3059	2333	-806	1831	-1023	2367	-721	1911	-907	2550
13-L1.5	-682	2205	1720	-867	2966	2271	-765	1781	-971	2348	-685	1797	-865	2411
14-Haunch	-918	2454	1965	-1155	3315	2610	-987	2046	-1235	2719	-860	1759	-1102	2359
15-Spring0.5	-772	2284	1840	-972	3012	2382	-867	1879	-1093	2423	-807	1850	-1017	2483
16-Spring1.5	-713	2158	1728	-904	2873	2247	-805	1774	-1021	2319	-728	1786	-916	2394

Appendix F: Support Reactions

F.1 Single cell

Table F.1: Total soil support reactions –single cell (kN)

Model No /Variable	Load case													
	General or Modified shell model							Solid model						
	BRKEA	ERTK0	LL	LLSK0A	SIDL-f	SIDL-S	SW	BRKEA	ERTK0	LL	LLSK0A	SIDL-f	SIDL-S	SW
1-Real	452	328	3452	-430	444	1296	4162	510	445	3765	-525	484	1414	4172
2-Mesh2	452	329	3452	-430	444	1296	4162	510	443	3765	-522	484	1414	4172
3-Mesh3	452	328	3452	-431	444	1296	4162	510	446	3765	-525	484	1414	4172
4-Angle0	473	3	3480	-430	444	1296	4162	516	3	3797	-522	484	1414	4172
5-Angle45	388	678	3344	-430	444	1296	4162	493	929	3648	-522	484	1414	4172
6-Fill0	526	302	3838	-462	0	1296	4162	591	413	4187	-564	0	1414	4172
7-Fill6	36	814	831	-206	8894	1296	4162	45	1107	906	-240	9702	1414	4172
8-Wall0.5	452	328	3452	-430	444	1296	3343	510	443	3608	-525	464	1355	3352
9-Wall1.5	452	328	3452	-430	444	1296	4980	510	446	3922	-525	505	1473	4993
10-B0.75	378	295	2724	-430	323	943	3473	440	415	3064	-525	363	1060	3482
11-B1.5	617	328	4792	-430	686	2003	5539	678	397	5215	-525	747	2180	5668
12-L0.5	226	152	1726	-215	222	648	2081	255	171	1883	-263	242	707	2086
13-L1.5	677	424	5177	-645	666	1944	6242	765	587	5648	-788	727	2121	6259
14-Haunch	452	328	3452	-430	444	1296	4321	510	444	3765	-525	484	1414	4285
15-Spring0.5	452	328	3452	-430	444	1296	4162	510	445	3765	-525	484	1414	4172
16-Spring1.5	452	328	3452	-430	444	1296	4162	510	445	3765	-525	484	1414	4172

F.2 Double cell

Table F.2: Total soil support reactions –double cell (kN)

Model No	Load case															
	General or Modified shell model								Solid model							
	BRKEA	ERTKO	LL	LL1	LLSKOA	SIDL-f	SIDL-S	SW	BRKEA	ERTKO	LL	LL1	LLSKOA	SIDL-f	SIDL-S	SW
1	1012	3831	11077	5538	-758	13906	8679	39628	1014	4538	11487	5949	-897	14421	9001	39065
2	1012	3831	11077	5538	-758	13906	8679	39628	1014	4542	11487	5949	-897	14421	9001	39065
3	1012	3832	11077	5538	-758	13906	8679	39628	1014	4543	11487	5949	-897	14421	9001	39065
4	1347	101	11748	5874	-758	13906	8679	39628	1346	145	12183	6309	-897	14421	9001	39065
5	1175	2352	11413	5706	-758	13906	8679	39628	1171	2777	11835	6129	-897	14421	9001	39065
6	1611	2945	18126	9063	-1028	0	8679	39653	1609	3494	18797	9734	-1218	0	9001	39065
7	422	6719	2877	1439	-431	59556	8679	39628	420	7957	2984	1545	-511	61762	9001	39065
8	1012	3819	11077	5538	-758	13906	8679	35047	1014	4514	11487	5846	-897	14421	9001	35309
9	1012	3829	11077	5538	-758	13906	8679	44261	1014	4545	11487	6051	-897	14421	9001	42821
10	1000	3751	8630	4315	-758	10215	6376	31577	1000	4449	9065	4750	-897	10730	6697	30989
11	1026	3840	14906	7453	-758	19829	12376	52612	1024	4550	14626	7360	-897	19829	12376	50897
12	506	1913	5538	2769	-379	6953	4340	19827	507	2255	5744	2974	-449	7211	4500	19532
13	1518	5598	16615	8308	-1137	20859	13019	59480	1522	6648	17231	8923	-1346	21632	13501	58597
14	1012	3825	11077	5538	-758	13906	8679	41156	1401	4537	11487	5949	-897	14421	9001	40039
15	1012	3818	11077	5538	-758	13906	8679	39653	1014	4522	11487	5949	-897	14421	9001	39065
16	1012	3833	11077	5538	-758	13906	8679	39653	1014	4552	11487	5949	-897	14421	9001	39065

F.3 Story Cell

Table F.3: Total soil support reactions –story cell (kN)

Model No /Variable	Load case											
	General or Modified shell model						Solid model					
	BRKEA	ERTK0	LL	LLSK0A	SIDL-f	SW	BRKEA	ERTK0	LL	LLSK0A	SIDL-f	SW
1-Real	415	5785	3659	-1139	5260	16504	450	6204	3895	-1254	5738	16231
2-Mesh2	415	5796	3659	-1139	5260	16504	450	6211	3895	-1254	5738	16231
3-Mesh3	415	5798	3659	-1139	5260	16504	449	6213	3895	-1254	5738	16231
4-Angle0	417	25	3723	-1139	5260	16503	455	35	4061	-1219	5738	16231
5-Angle45	408	9305	3456	-1139	5260	16504	441	10059	3687	-1254	5738	16231
6-Fill0	644	4573	5400	-1364	0	16504	685	4906	5766	-1521	0	16231
7-Fill6	171	8200	1715	-868	15780	16504	198	8793	1816	-941	17214	16231
8-Wall0.5	415	5778	3659	-1139	5260	12581	450	6184	3732	-1254	5499	12445
9-Wall1.5	415	5786	3659	-1139	5260	20425	450	6216	4057	-1254	5977	20018
10-B0.75	345	5599	3170	-1139	4304	14930	380	6109	3476	-1254	4861	14788
11-B1.5	484	5825	4129	-1139	6216	18077	517	6207	4366	-1254	6694	17805
12-L0.5	207	2797	1830	-570	2630	8252	225	2964	1947	-627	2869	8116
13-L1.5	622	7864	5489	-1709	7890	24754	674	8651	5842	-1882	8607	24347
14-Haunch	415	5786	3659	-1139	5260	17784	581	6190	3895	-1254	5738	17097
15-Spring0.5	415	5783	3659	-1139	5260	16504	450	6202	3895	-1254	5738	16231
16-Spring1.5	415	5787	3659	-1139	5260	16504	450	6206	3895	-1254	5738	16231

F.4 Shell model Reactions variation vs. solid model

Table F.3: Total soil support reactions variation – (%)

Model No /Variable	Load case																				
	Single cell							Story cell							Double cell						
	BRKEA	ERTKO	LL	LLSKOA	SIDL-f	SIDL-S	SW	BRKEA	ERTKO	LL	LLSKOA	SIDL-f	SW	BRKEA	ERTKO	LL	LL1	LLSKOA	SIDL-f	SIDL-S	SW
1-Real	89	74	92	82	92	92	100	92	93	94	91	92	102	100	84	96	93	84	96	96	101
2-Mesh2	89	74	92	82	92	92	100	92	93	94	91	92	102	100	84	96	93	85	96	96	101
3-Mesh3	89	74	92	82	92	92	100	92	93	94	91	92	102	100	84	96	93	85	96	96	101
4-Angle0	92	93	92	82	92	92	100	92	73	92	93	92	102	100	70	96	93	84	96	96	101
5-Angle45	79	73	92	82	92	92	100	92	92	94	91	92	102	100	85	96	93	84	96	96	101
6-Fill0	89	73	92	82	-	92	100	94	93	94	90	-	102	100	84	96	93	84	0	96	102
7-Fill6	81	74	92	86	92	92	100	86	93	94	92	92	102	100	84	96	93	84	96	96	101
8-Wall0.5	89	74	96	82	96	96	100	92	93	98	91	96	101	100	85	96	95	84	96	96	99
9-Wall1.5	89	74	88	82	88	88	100	92	93	90	91	88	102	100	84	96	92	84	96	96	103
10-B0.75	86	71	89	82	89	89	100	91	92	91	91	89	101	100	84	95	91	84	95	95	102
11-B1.5	91	83	92	82	92	92	98	94	94	95	91	93	102	100	84	102	101	84	100	100	103
12-L0.5	89	89	92	82	92	92	100	92	94	94	91	92	102	100	85	96	93	84	96	96	102
13-L1.5	89	72	92	82	92	92	100	92	91	94	91	92	102	100	84	96	93	84	96	96	102
14-Haunch	89	74	92	82	92	92	101	71	93	94	91	92	104	72	84	96	93	84	96	96	103
15-Spring0.5	89	74	92	82	92	92	100	92	93	94	91	92	102	100	84	96	93	84	96	96	102
16-Spring1.5	89	74	92	82	92	92	100	92	93	94	91	92	102	100	84	96	93	84	96	96	102

Appendix G: ULS Bending moment envelops

G.1 Skew angle 30^0 models

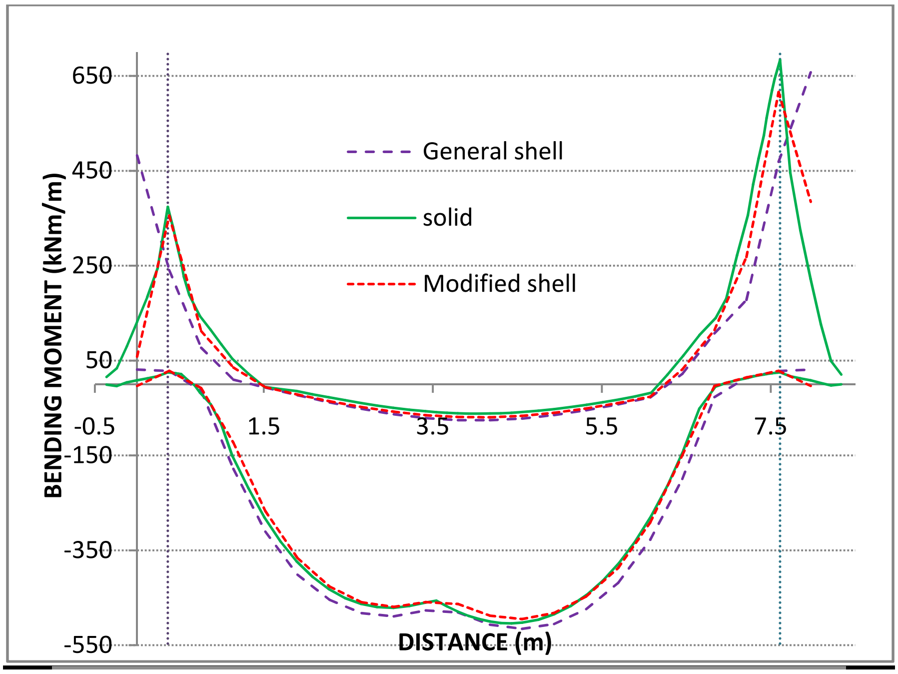


Figure F.1: BME of Top slab-Single cell (model no: 5)

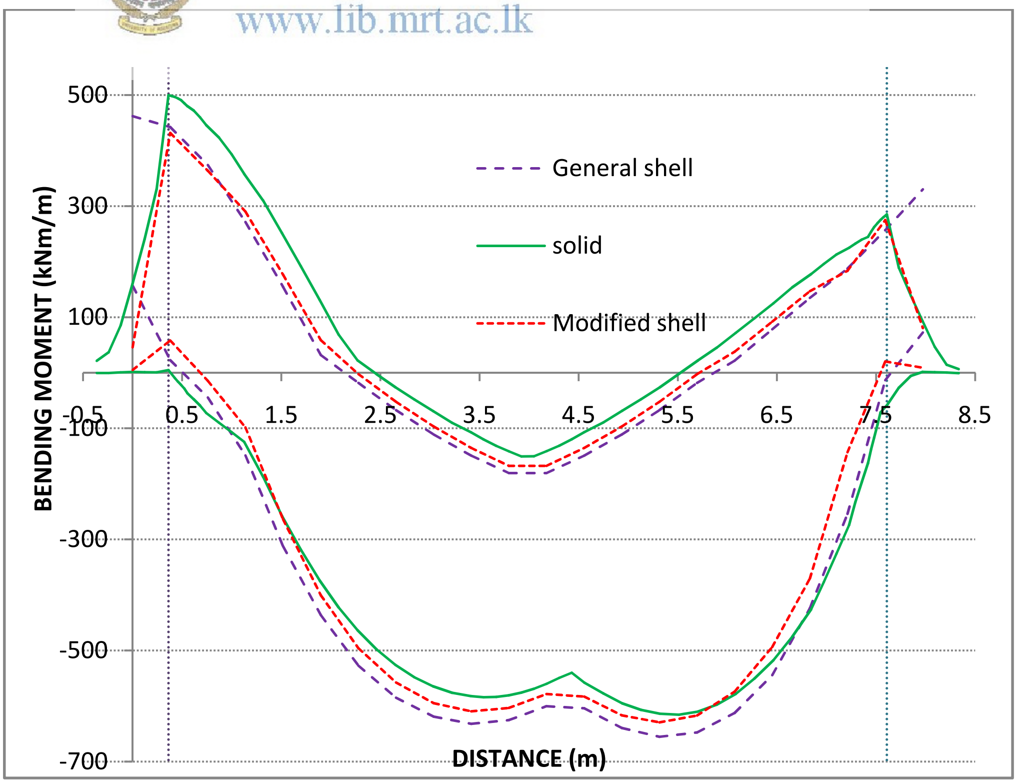


Figure F.2: BME of Bottom slab-Single cell (model no: 5)

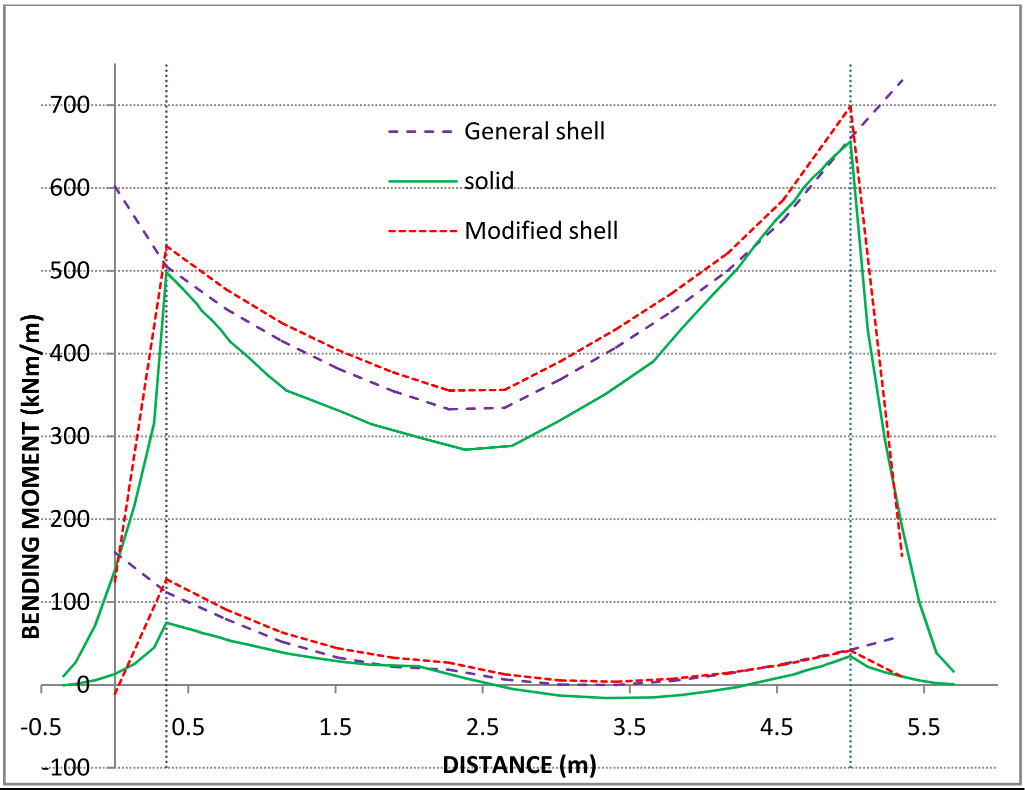


Figure F.3: BME of Walls-Single cell (model no: 5)

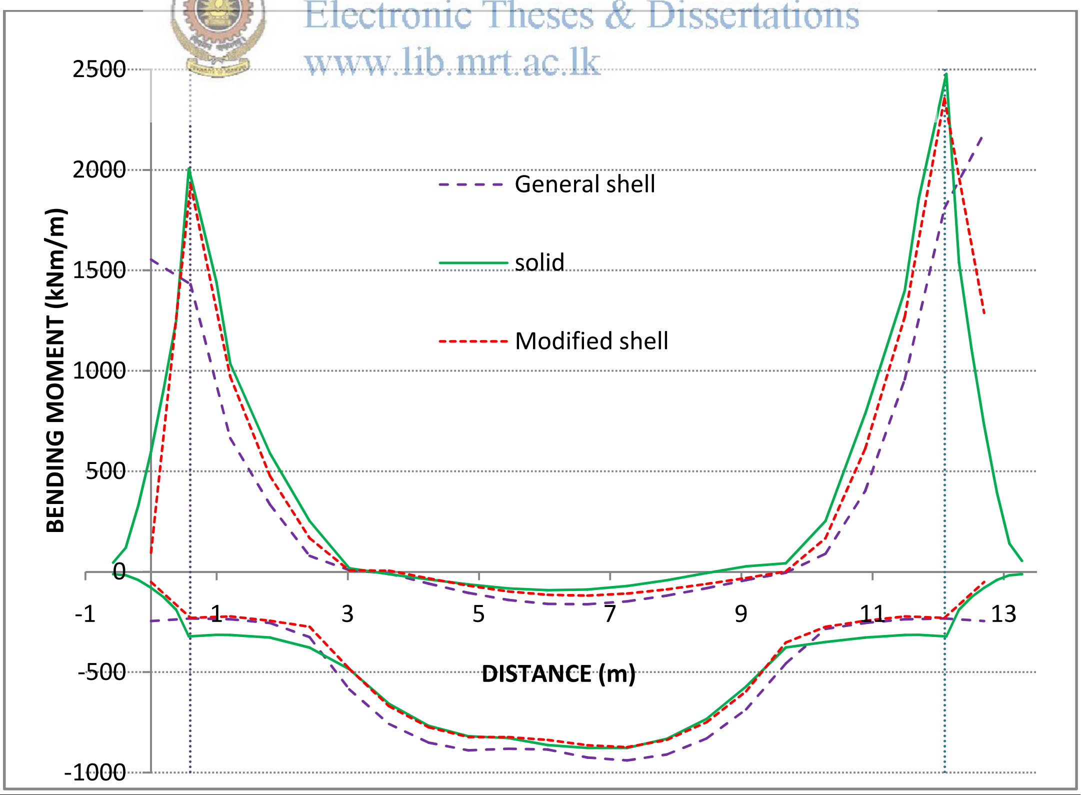


Figure F.4: BME of Top slab-Story cell (model no: 1)

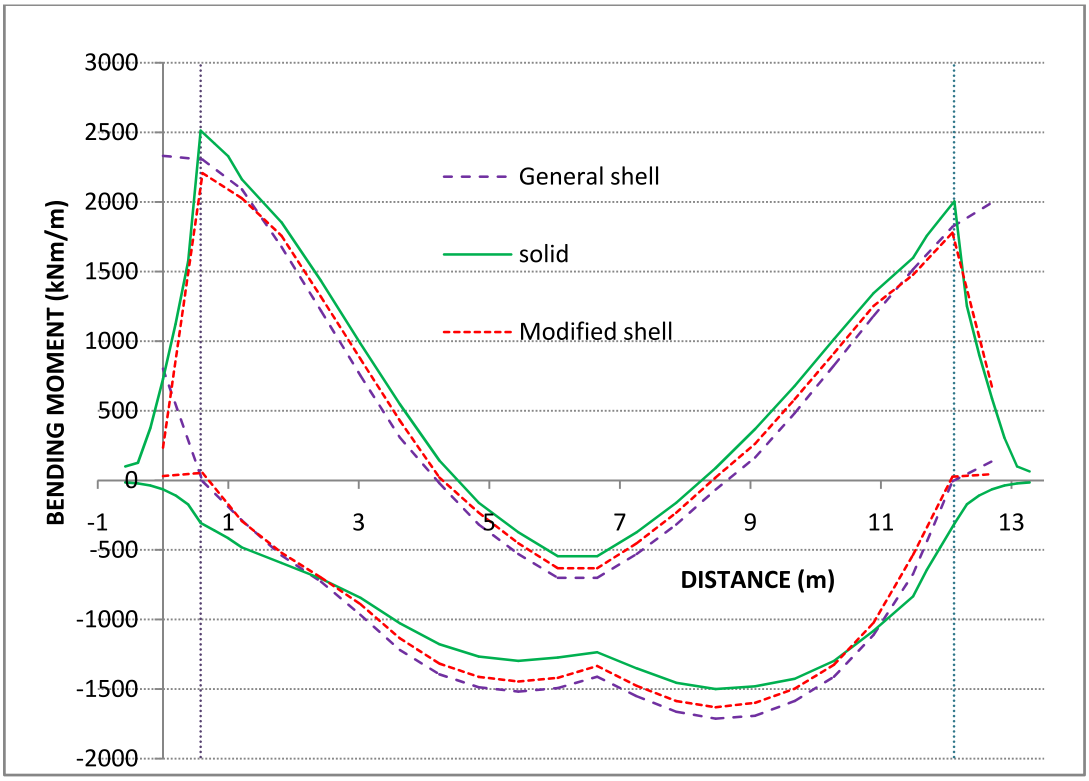


Figure F.5: BME of Bottom slab-Story cell (model no: 1)

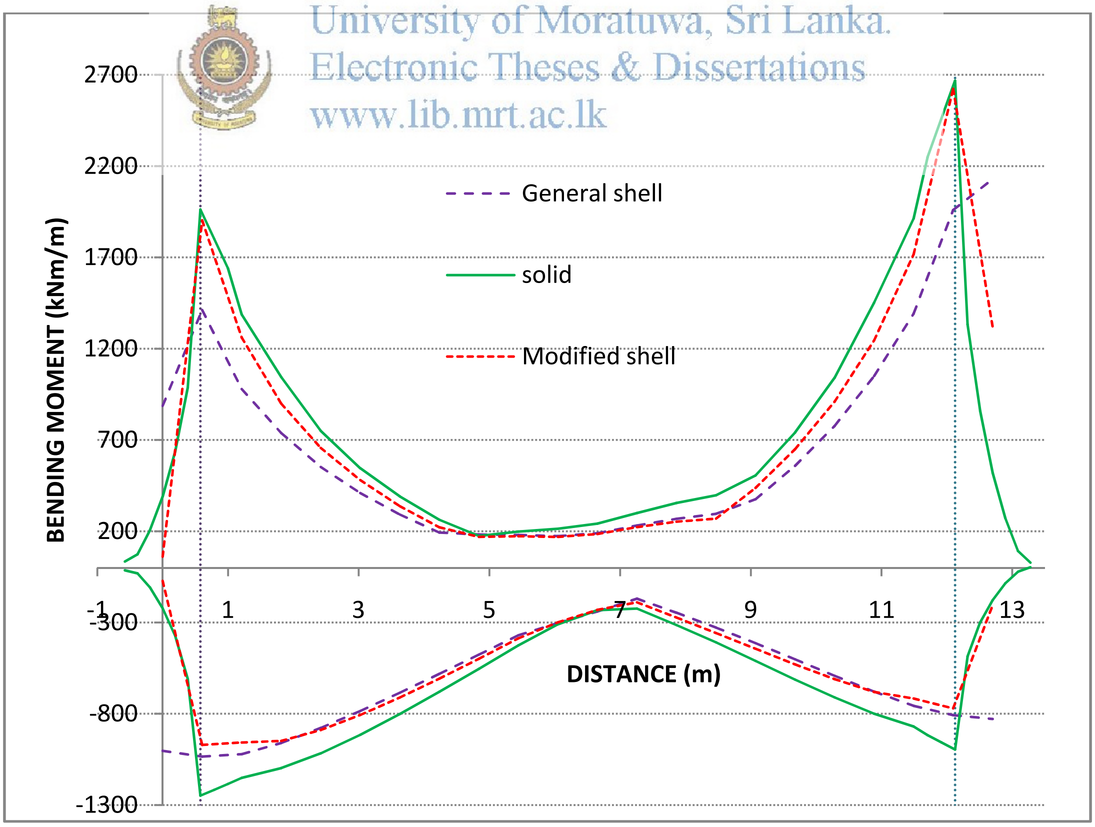


Figure F.6: BME of Middle slab-Story cell (model no: 1)

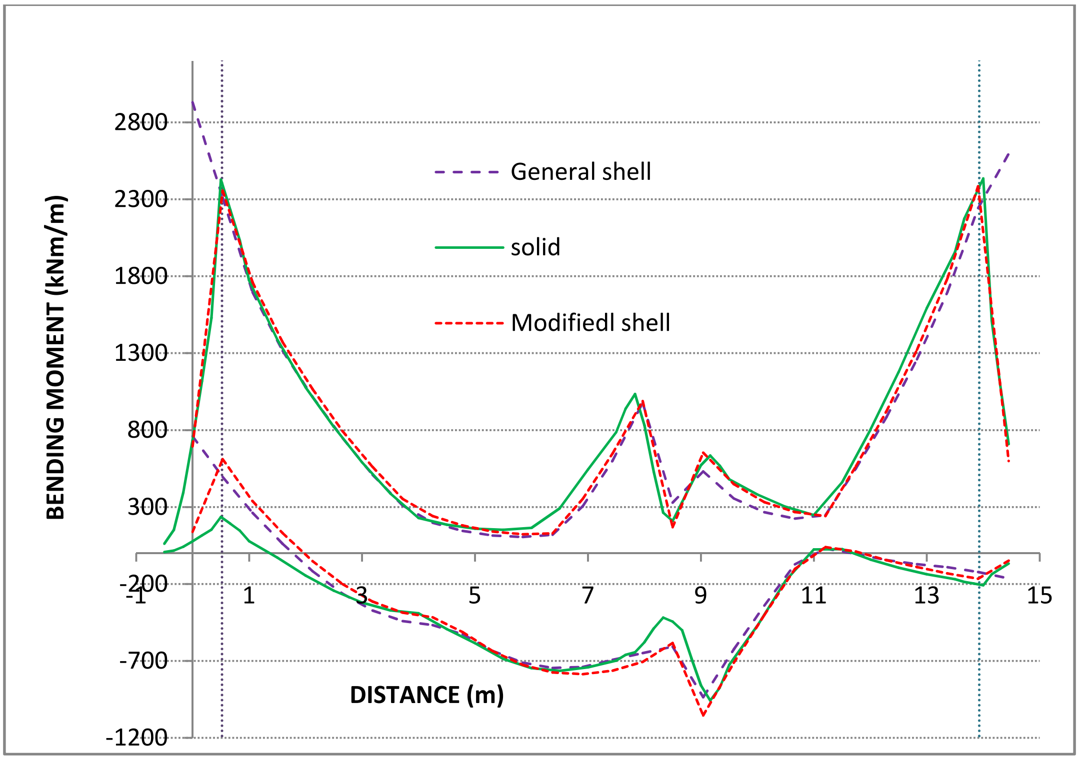


Figure F.7: BME of Walls-Story cell (model no: 1)

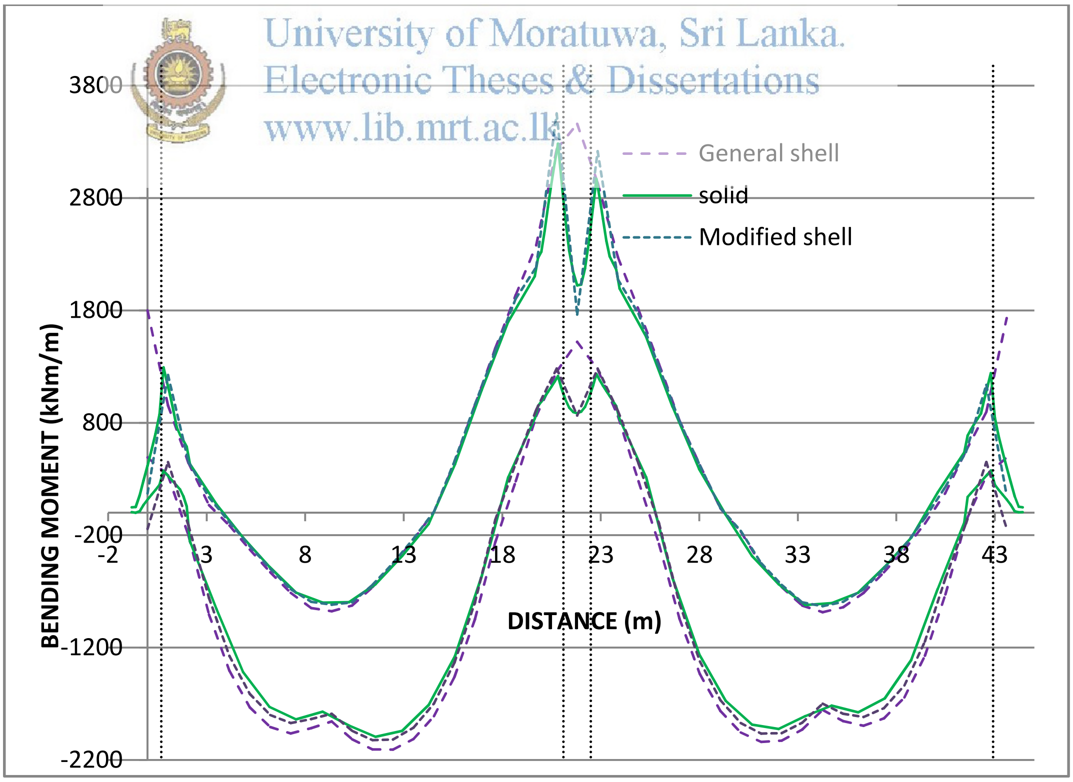


Figure F.8: BME of Top slab-Double cell (model no: 5)

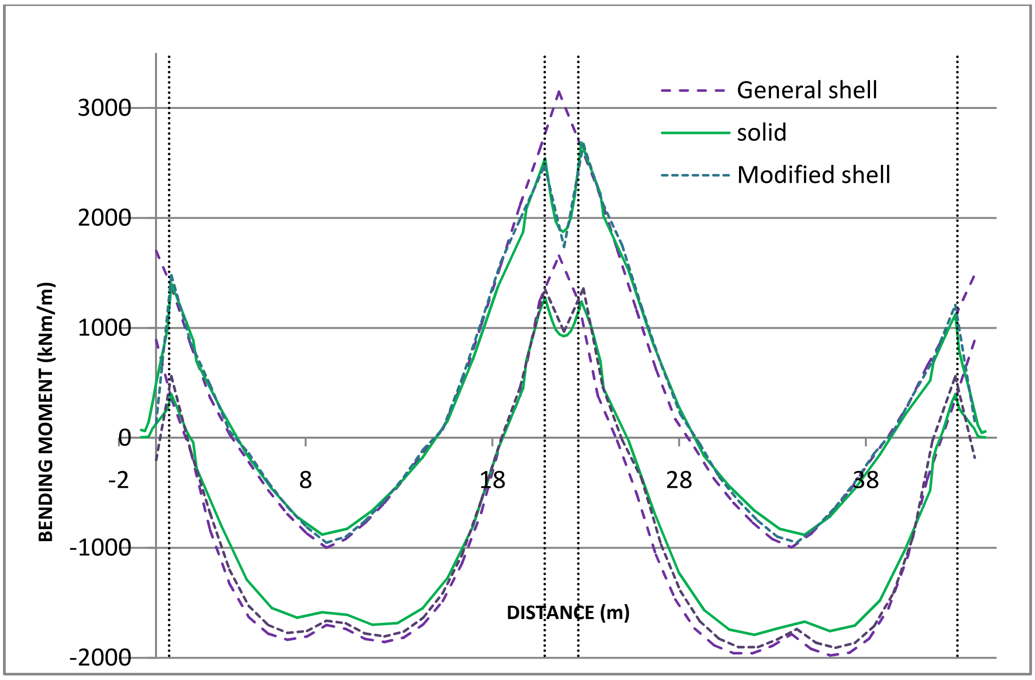


Figure F.9: BME of Bottom slab-Double cell (model no: 5)

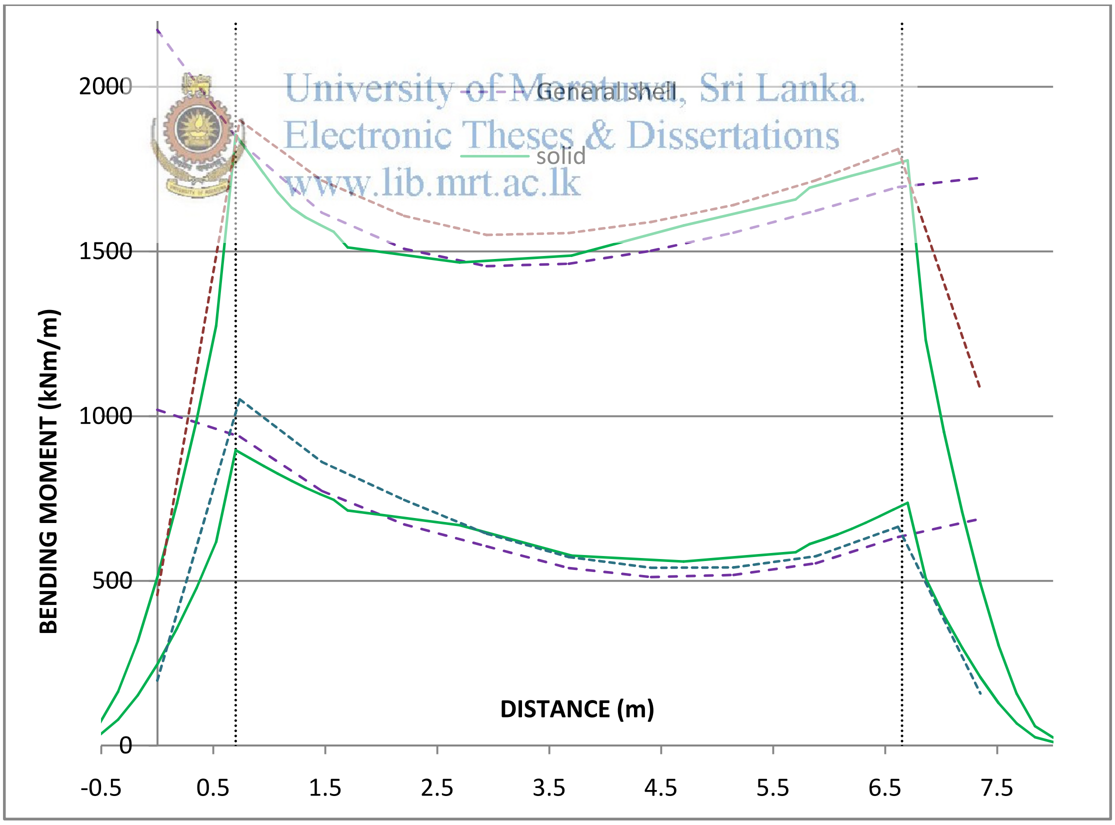


Figure F.10: BME of Outside walls-Double cell (model no: 5)

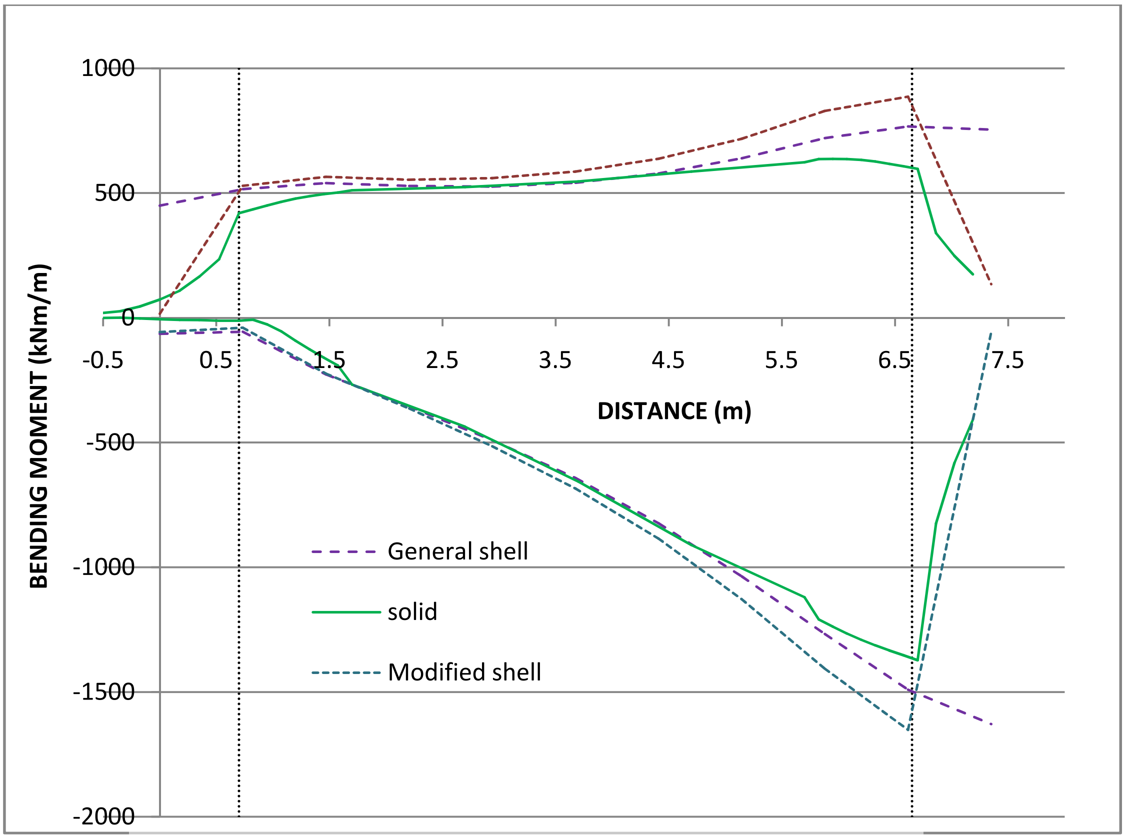
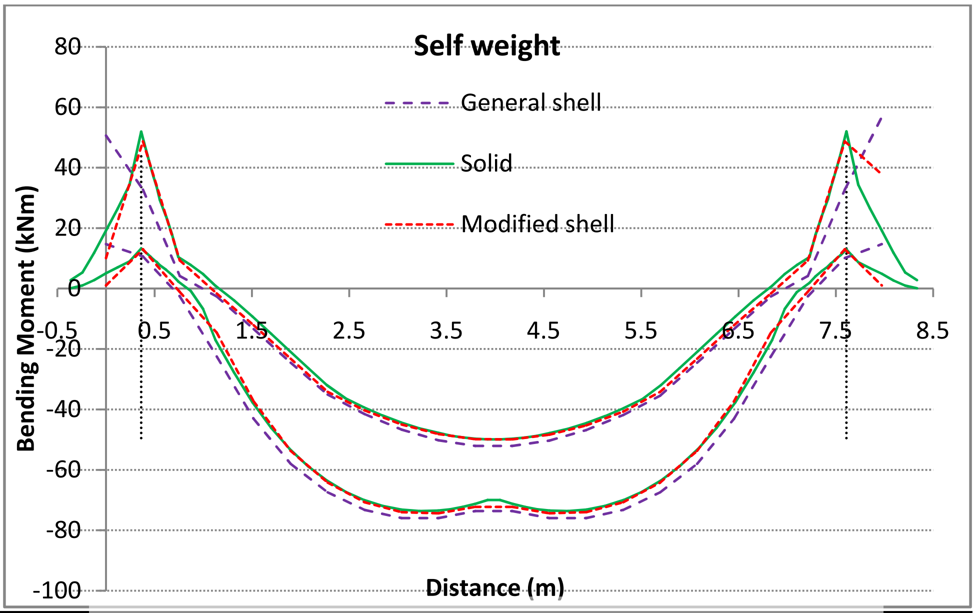


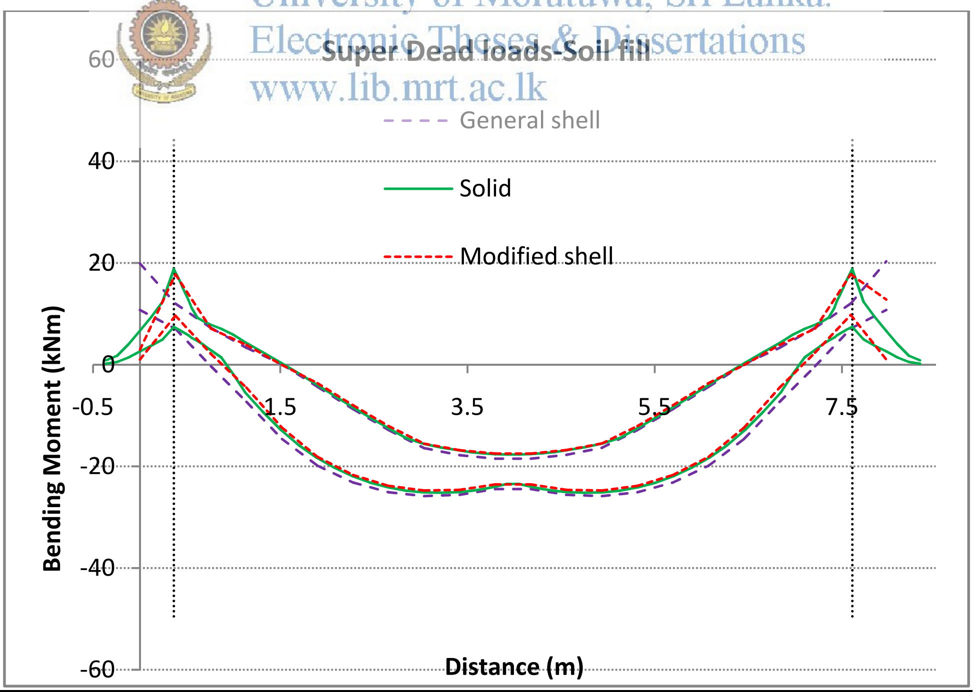
Figure F.11: BME of Inside walls-Double cell (model no: 5)

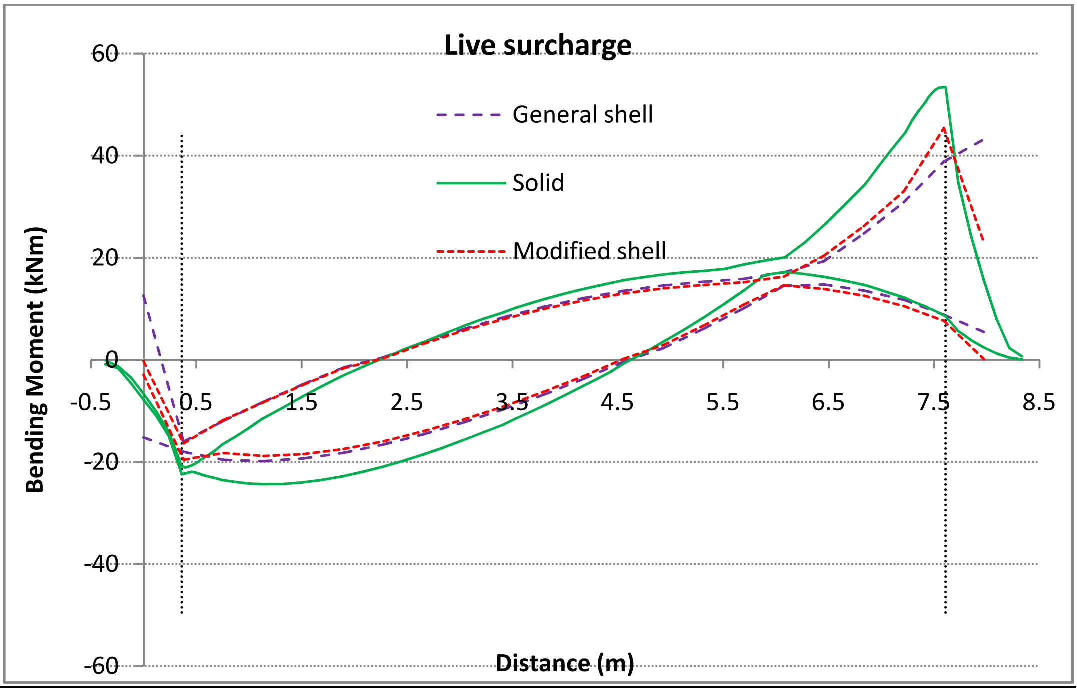
Appendix H: Bending moment envelops for Load cases

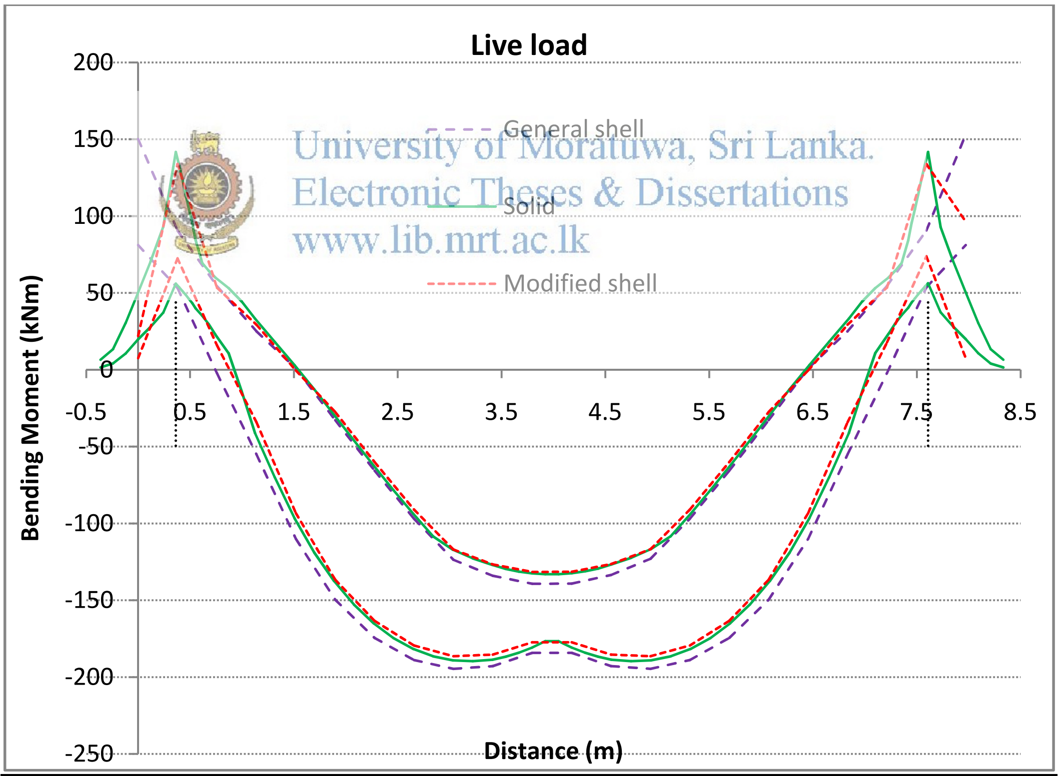
H.1 Skew angle 30^0 models

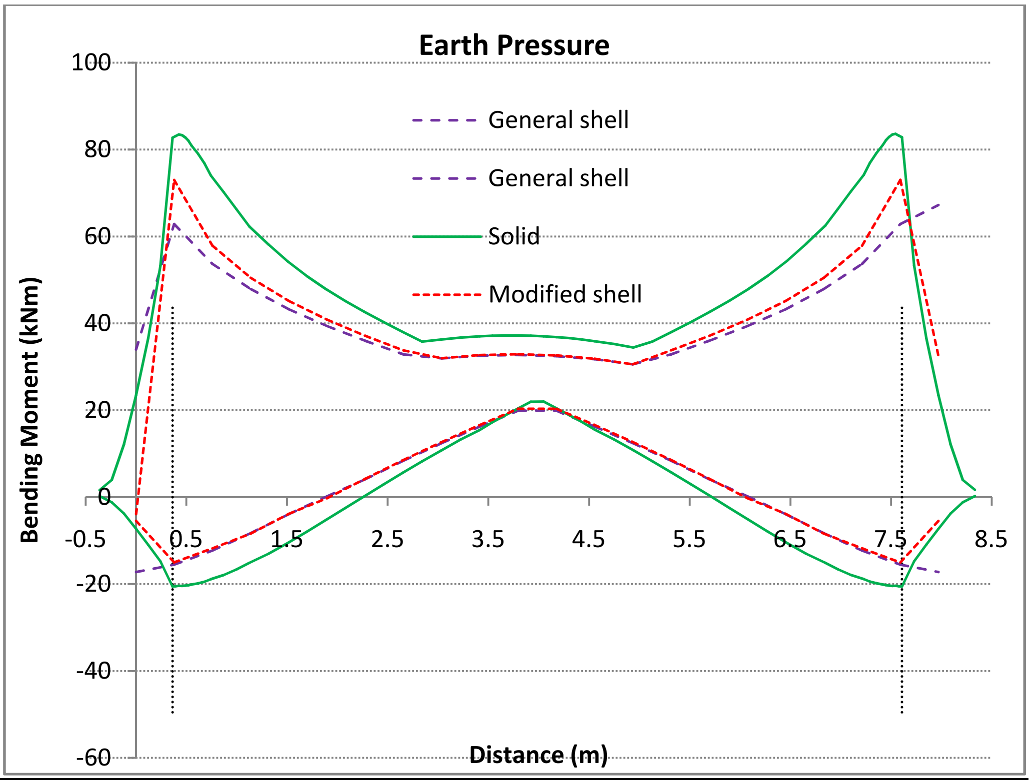
H.1.1 BME of Top slab-Single cell (model no: 5)

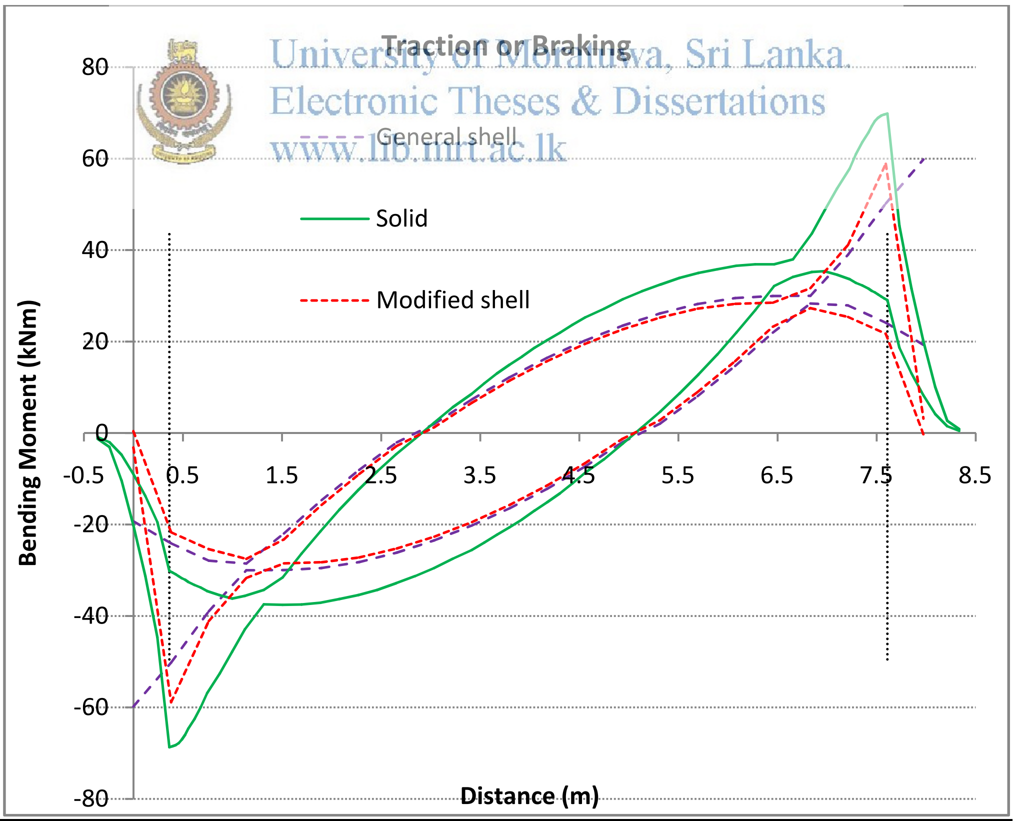




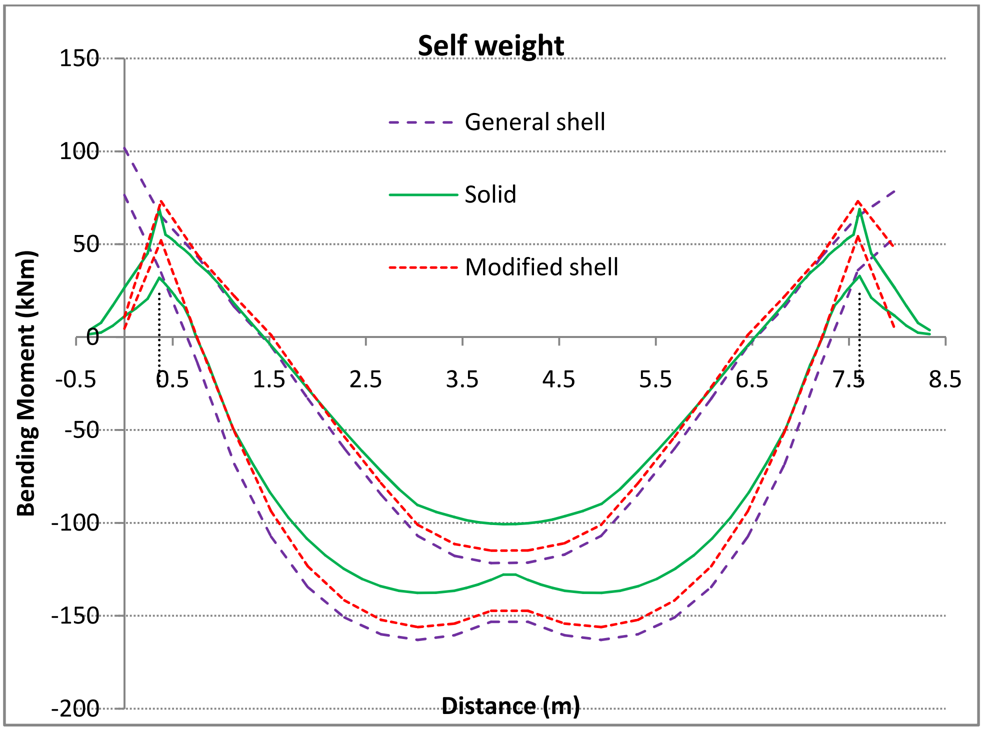

Live surcharge
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
60
40
20
0
-20
-40
-60
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5

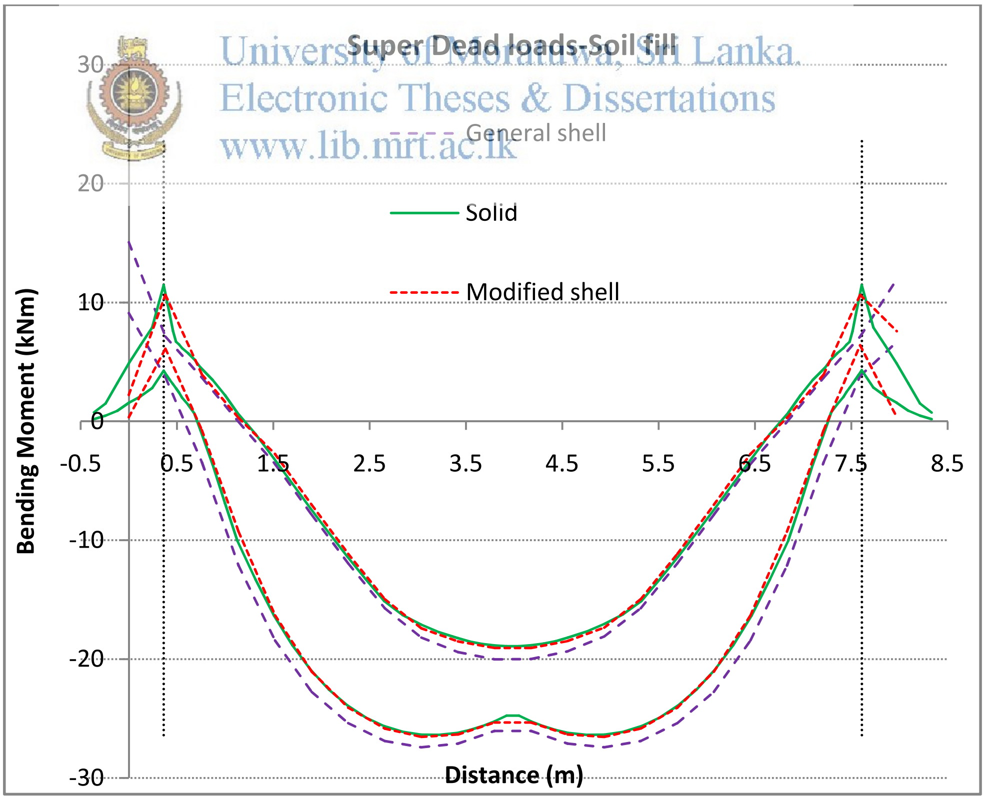

Live load
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
200
150
100
50
0
-50
-100
-150
-200
-250
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5

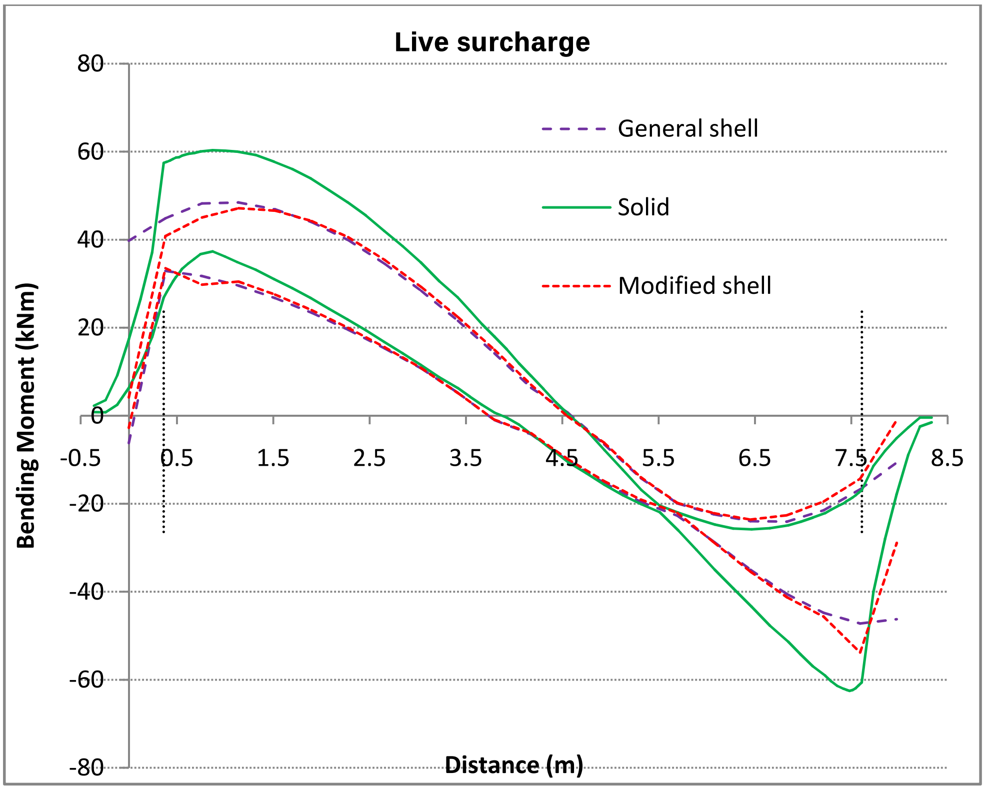

Earth Pressure
General shell
General shell
Solid
Modified shell
100
80
60
40
20
0
-20
-40
-60
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
Bending Moment (kNm)
Distance (m)

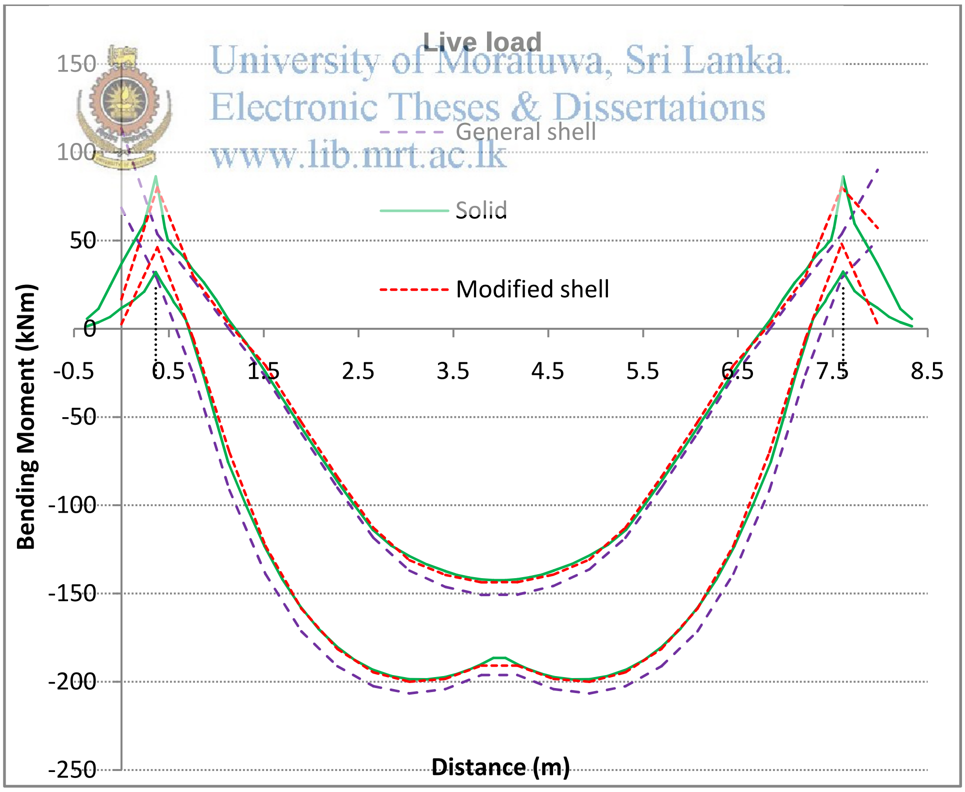

Traction or Braking
General shell
Solid
Modified shell
80
60
40
20
0
-20
-40
-60
-80
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
Bending Moment (kNm)
Distance (m)

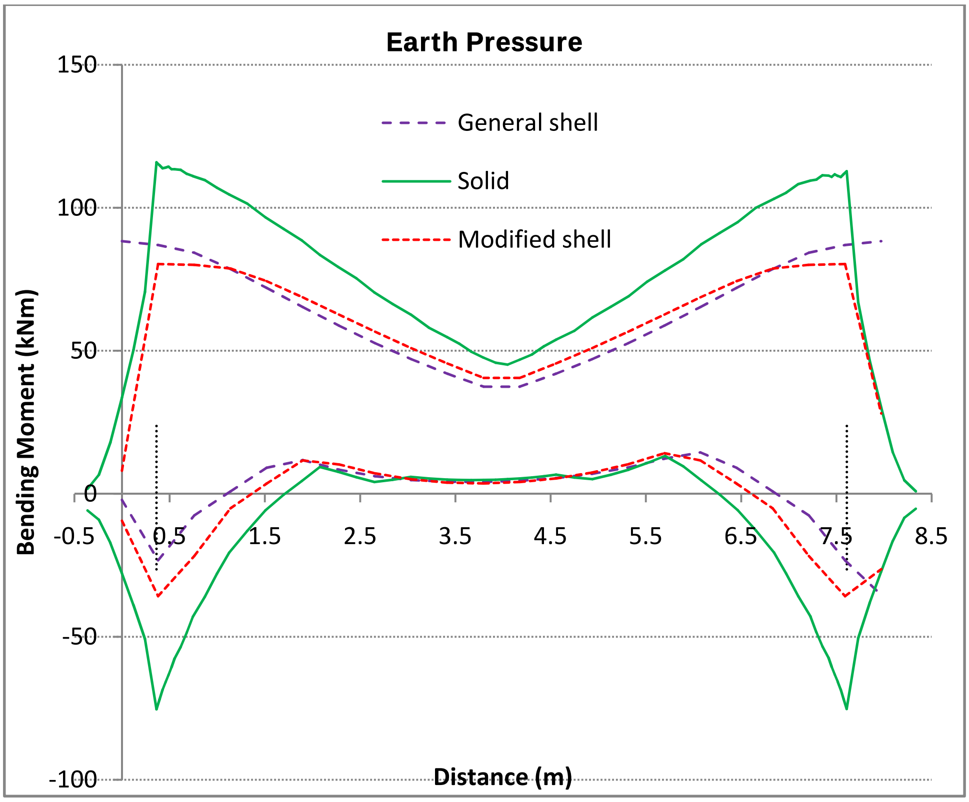
H.1.2: BMD of Bottom slab-Single cell (model no: 5)

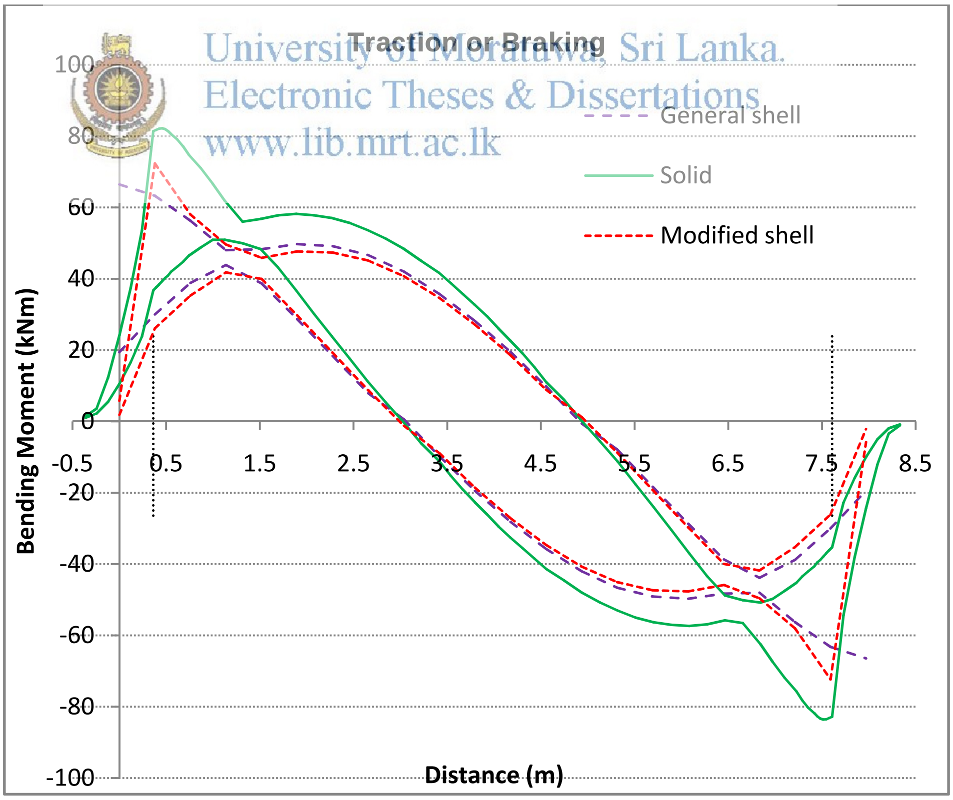




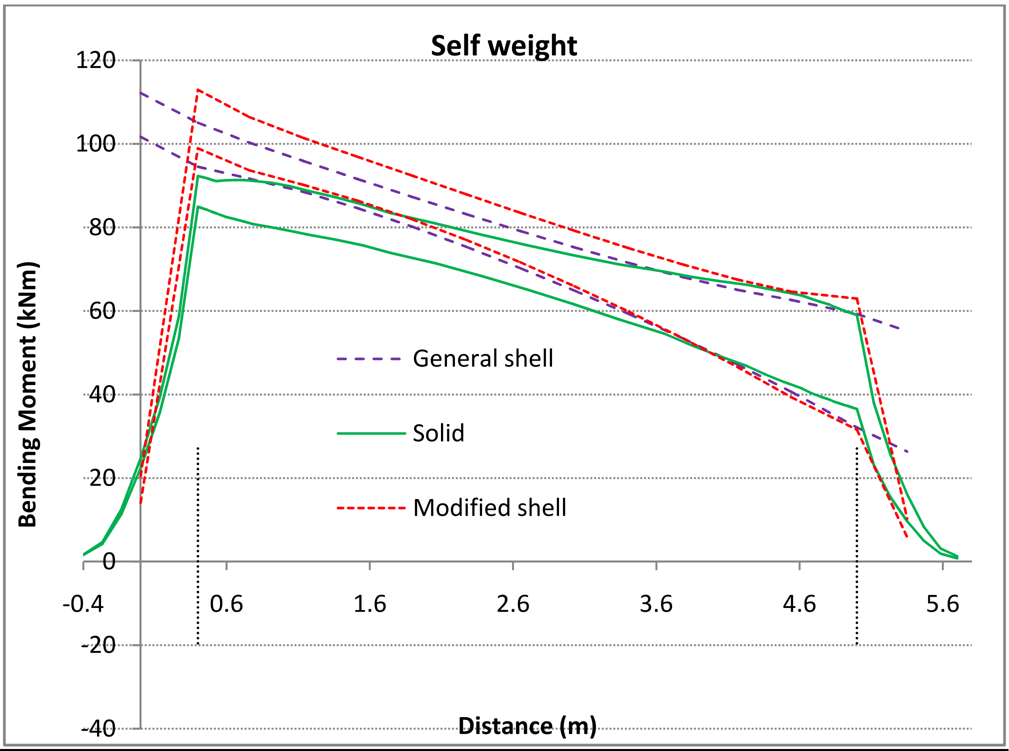

Live surcharge
80
60
40
20
0
-20
-40
-60
-80
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)

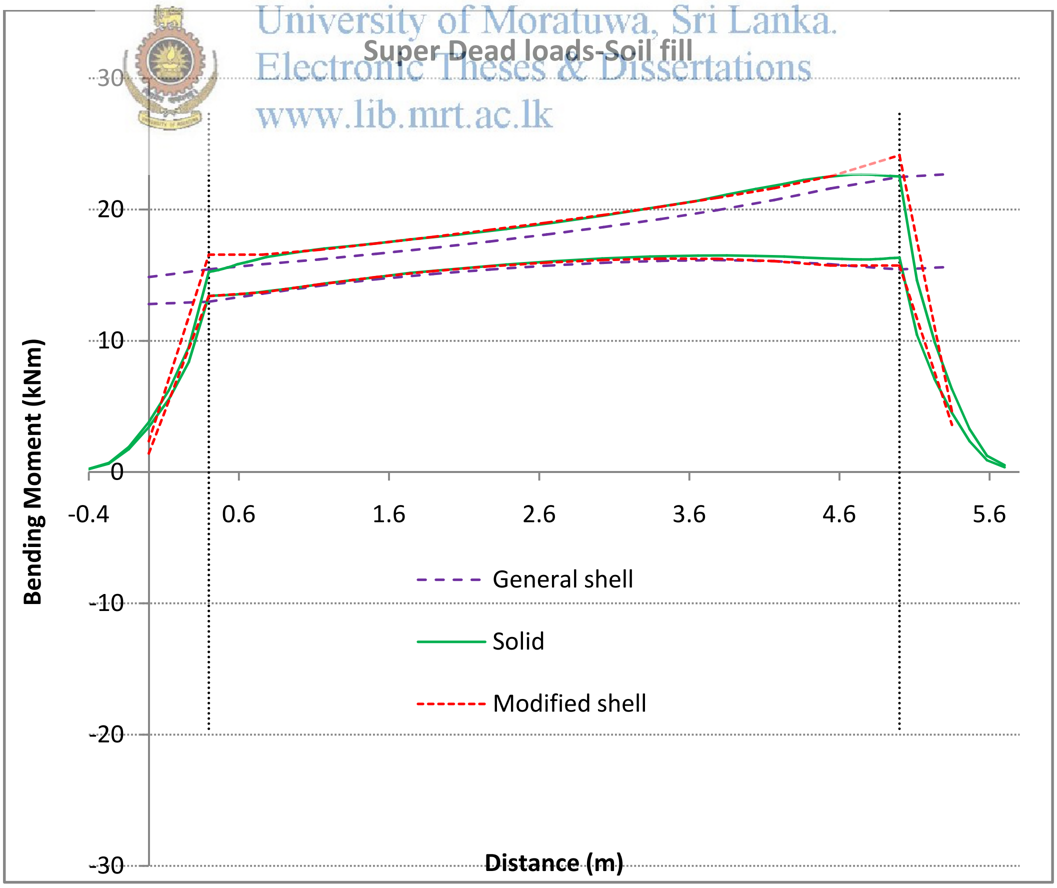

Live load
150
100
50
0
-50
-100
-150
-200
-250
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)

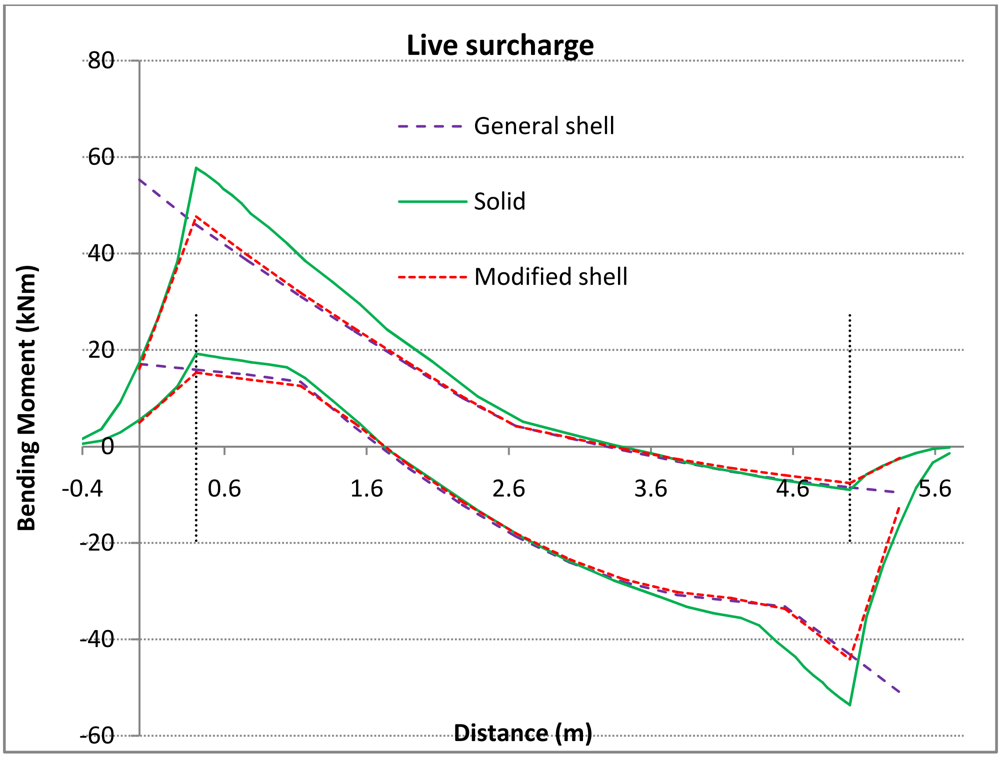

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
150
100
50
0
-50
-100
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
Distance (m)

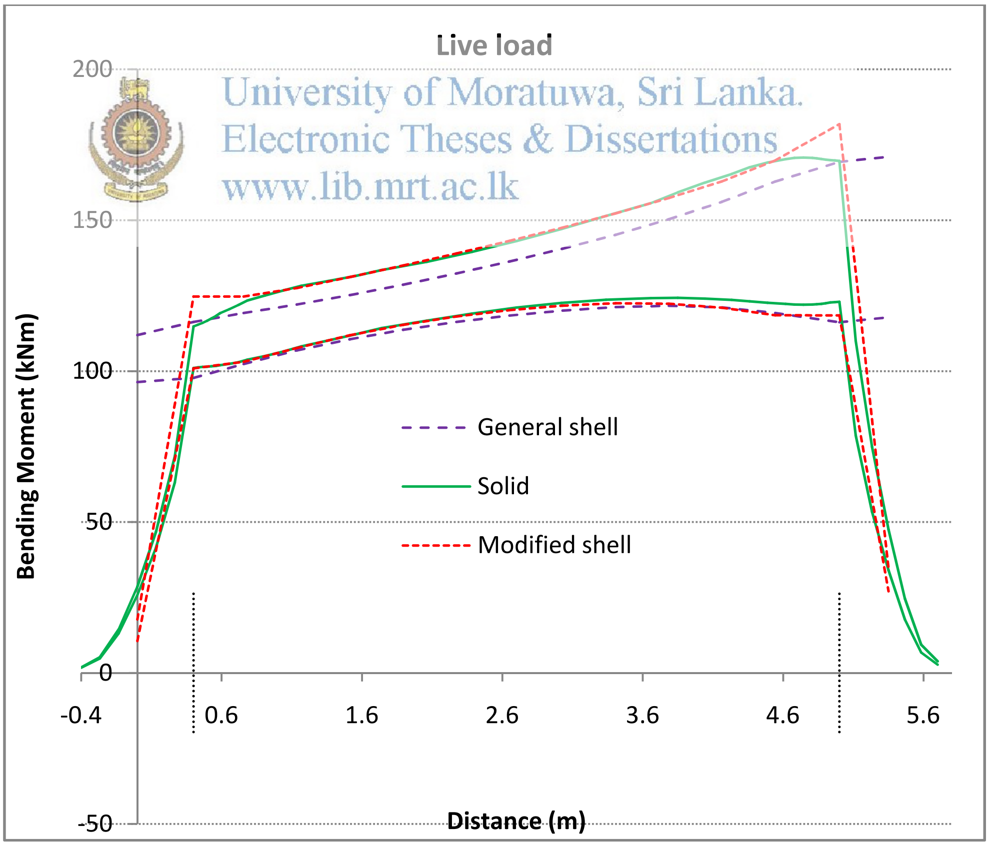

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
Distance (m)

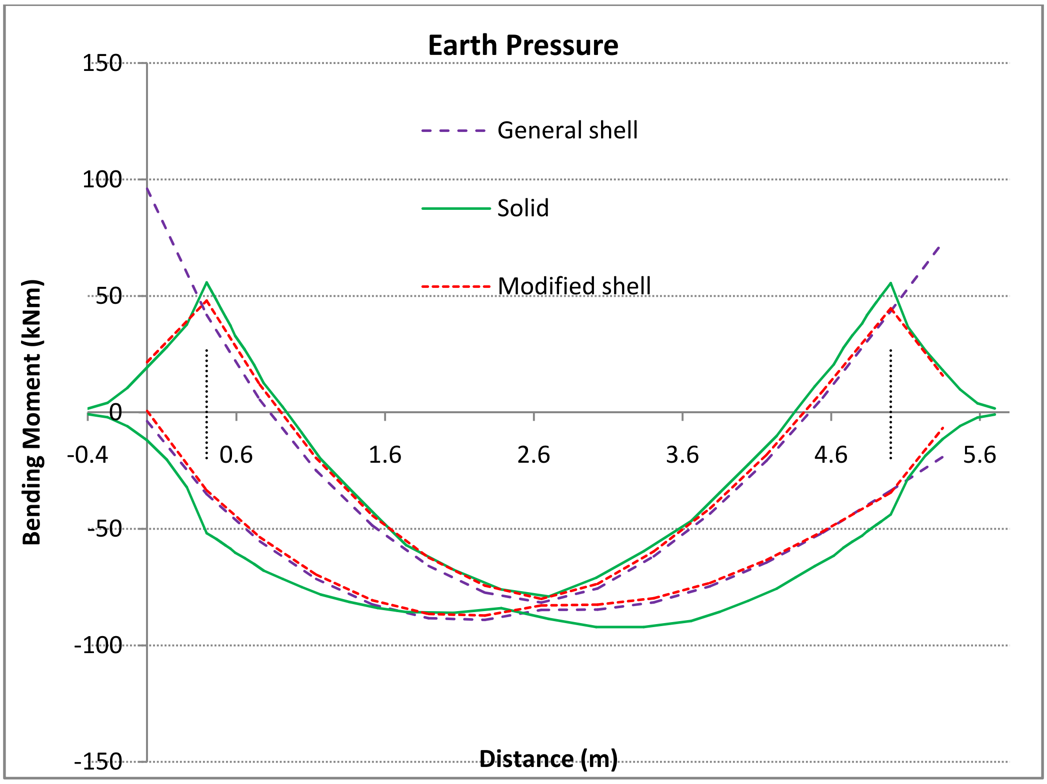
H.1.3: BMD of Walls-Single cell (model no: 5)

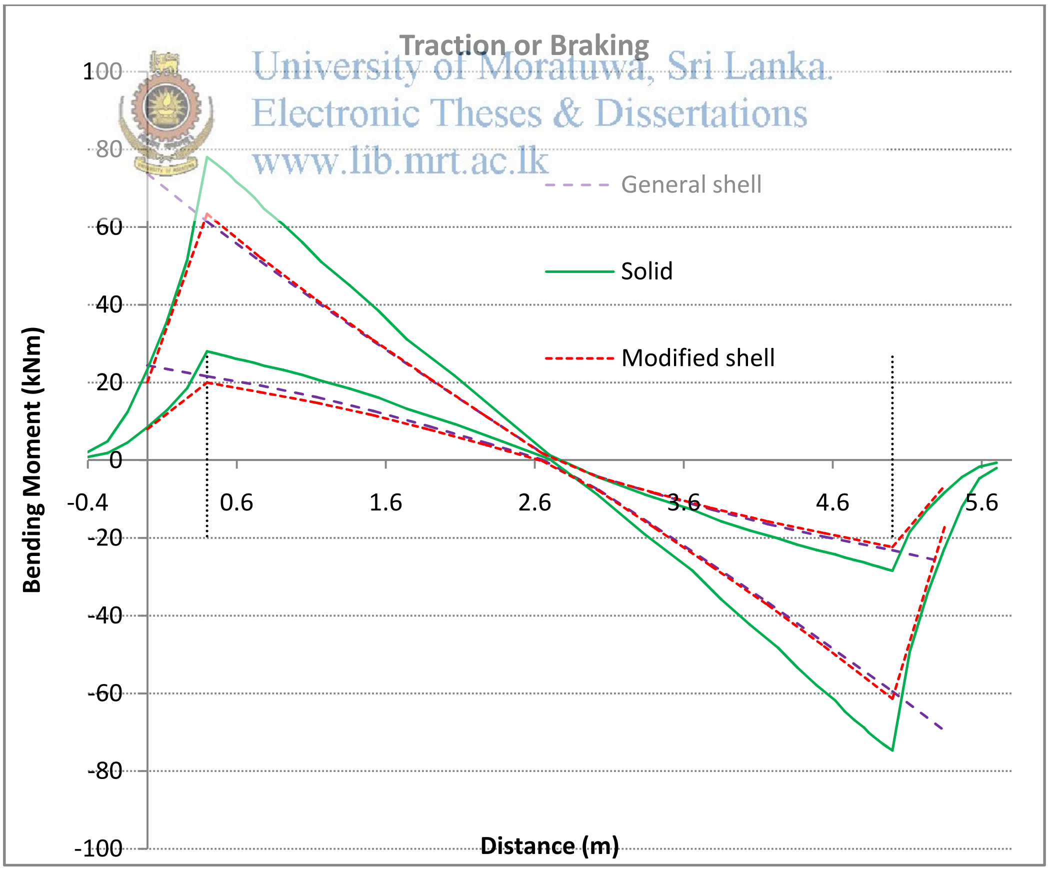




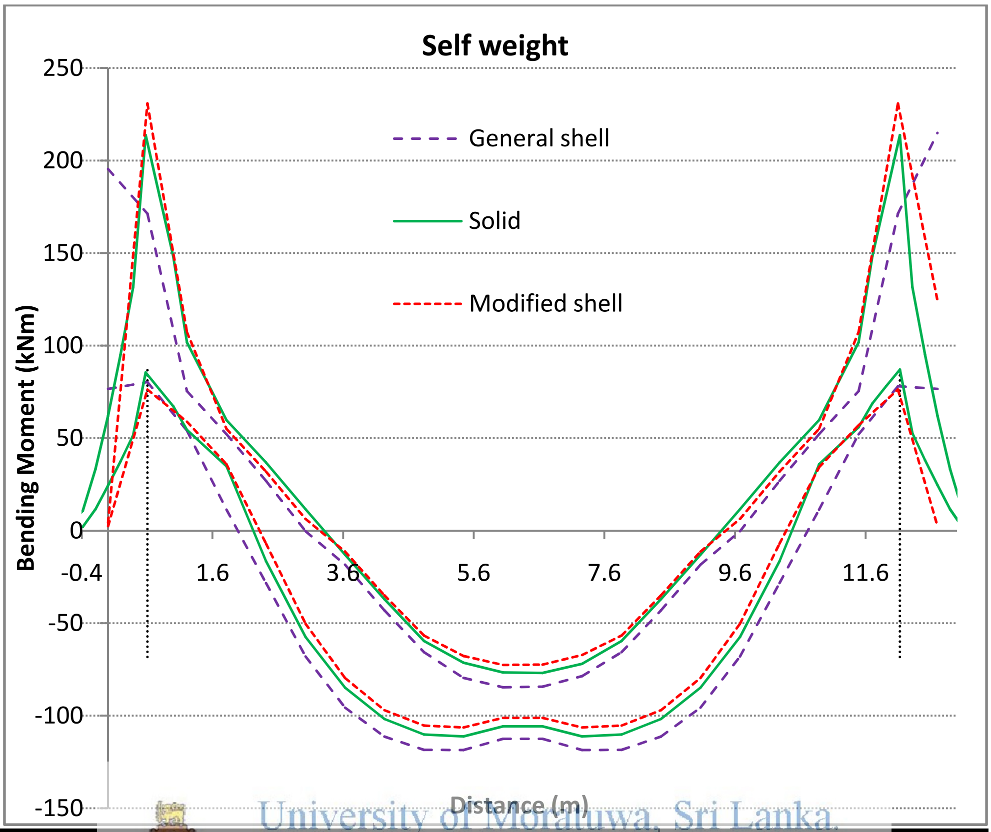

Live surcharge
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
80
60
40
20
0
-20
-40
-60
-0.4
0.6
1.6
2.6
3.6
4.6
5.6

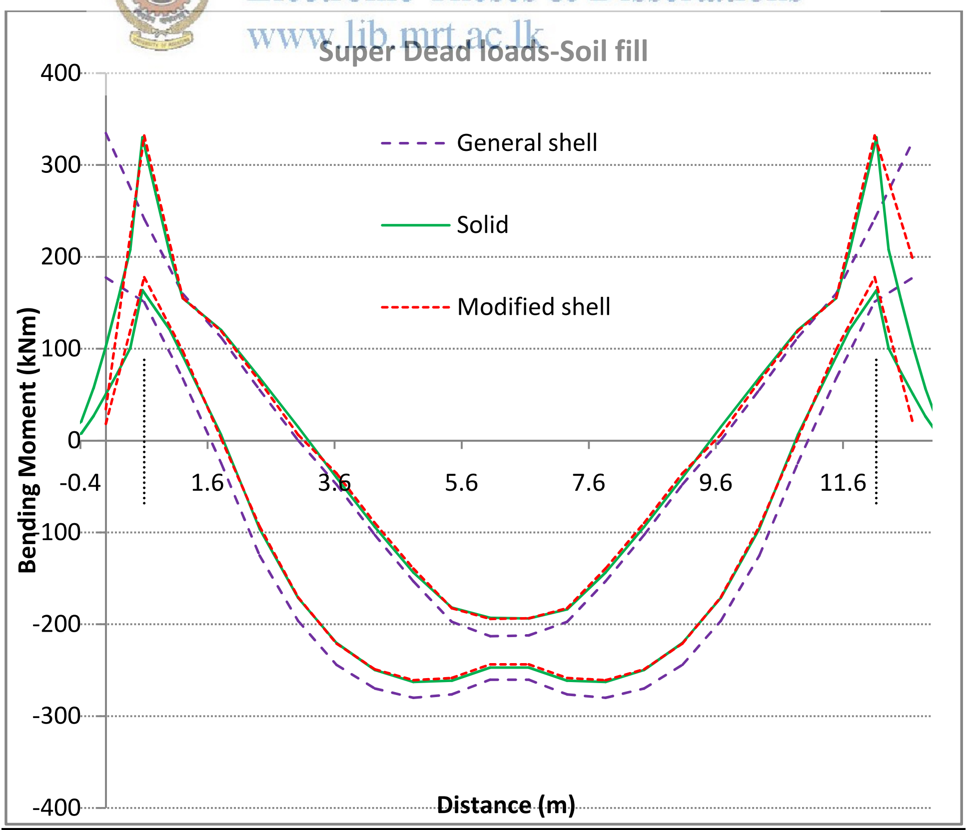

Live load
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
200
150
100
50
0
-50
-0.4
0.6
1.6
2.6
3.6
4.6
5.6

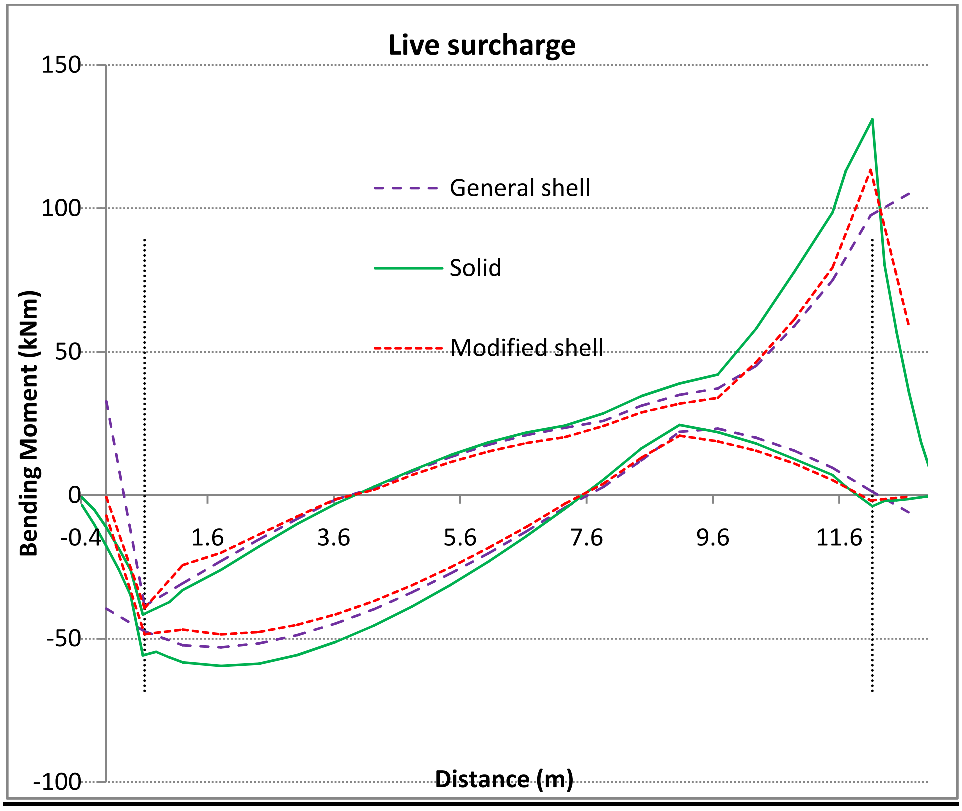

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
150
100
50
0
-50
-100
-150
-0.4
0.6
1.6
2.6
3.6
4.6
5.6

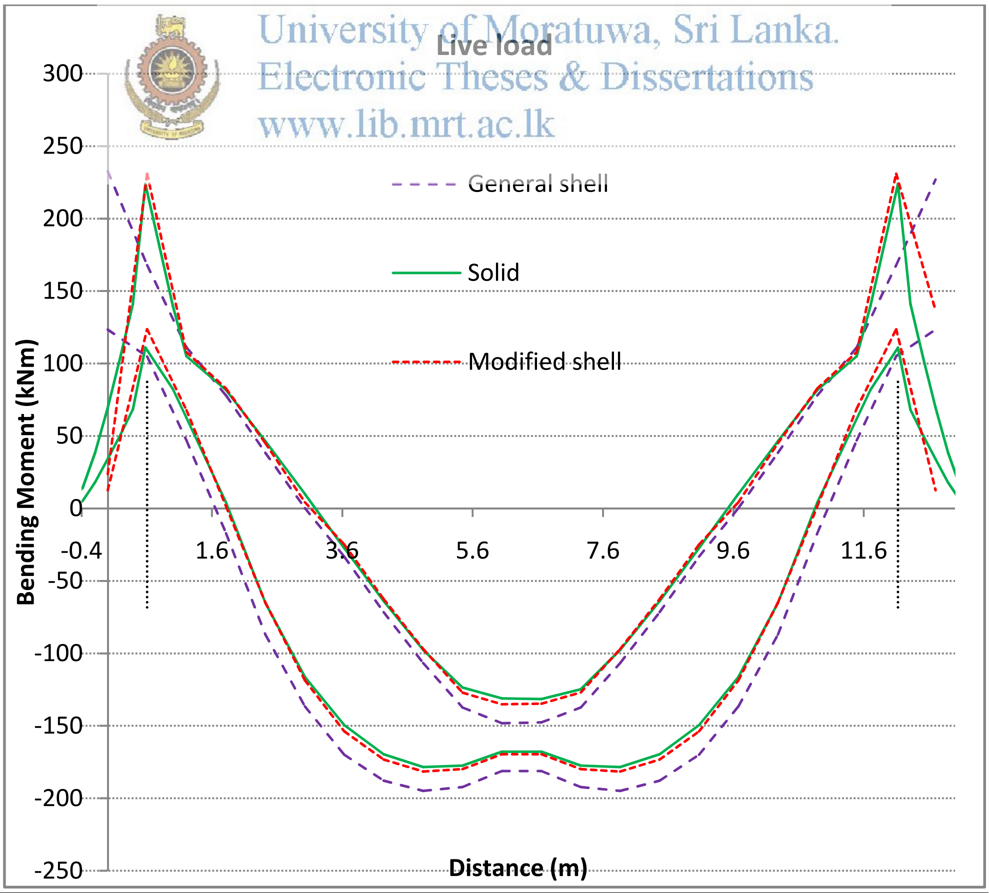

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-0.4
0.6
1.6
2.6
3.6
4.6
5.6

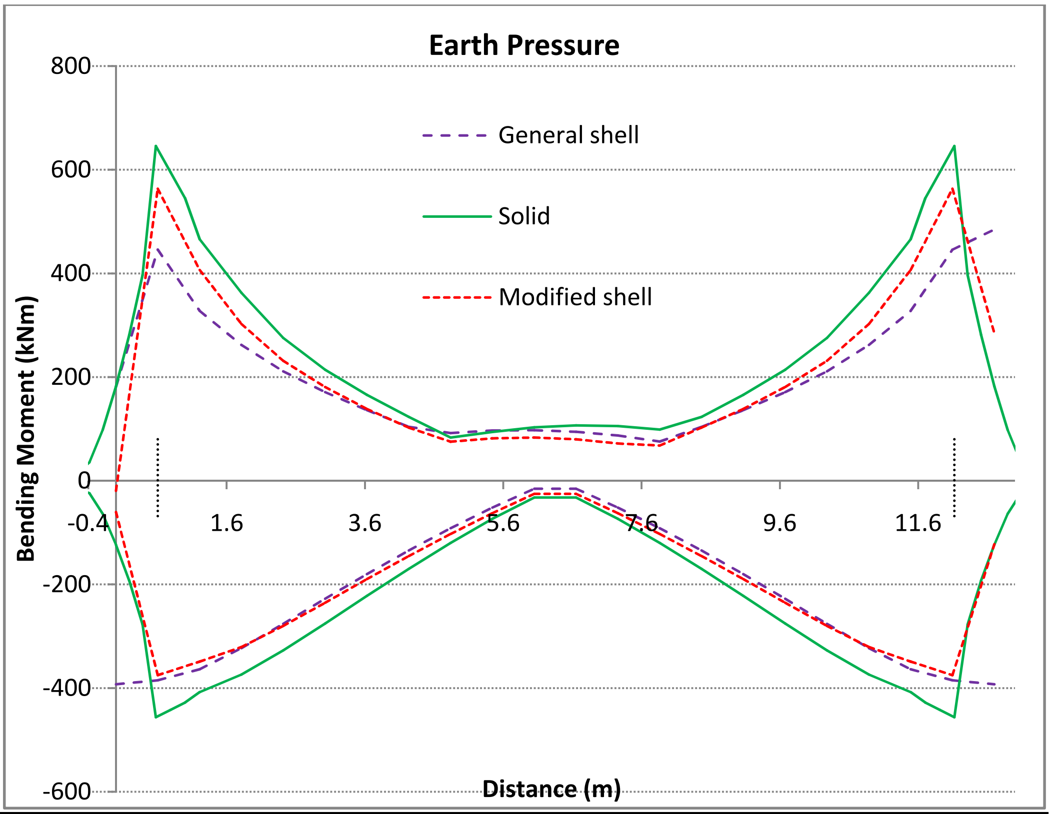
H.1.4: BMD of Top slab-Story cell (model no: 1)

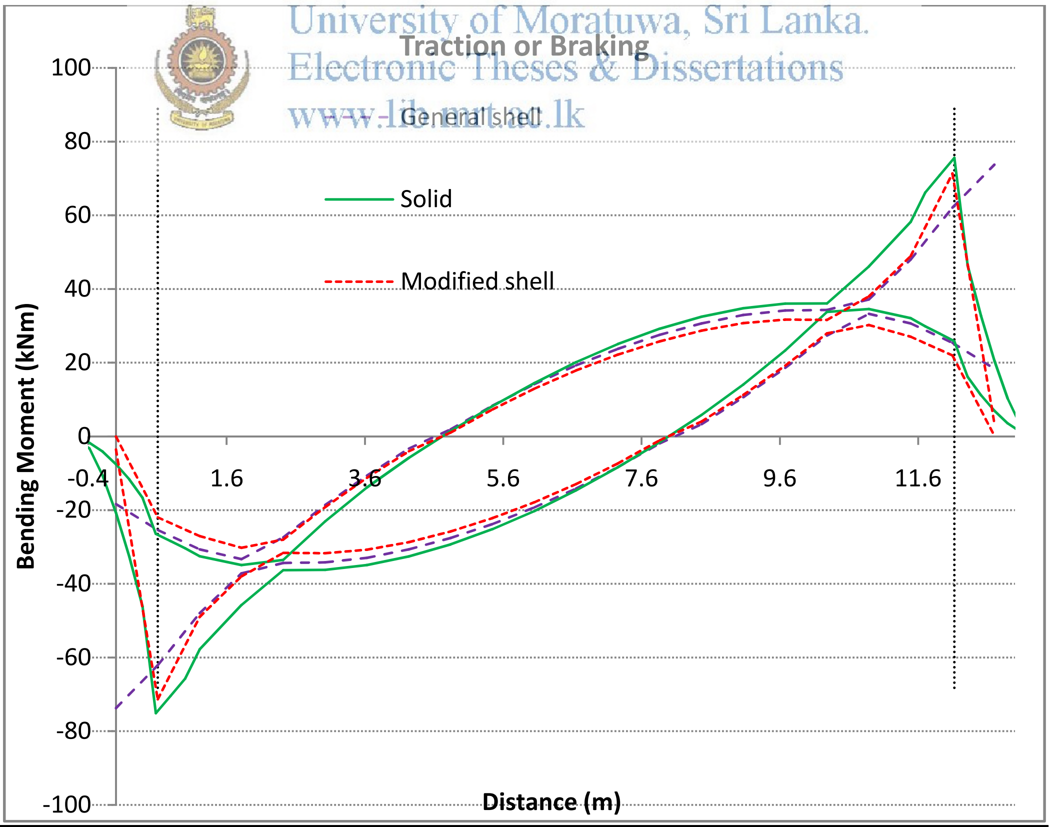




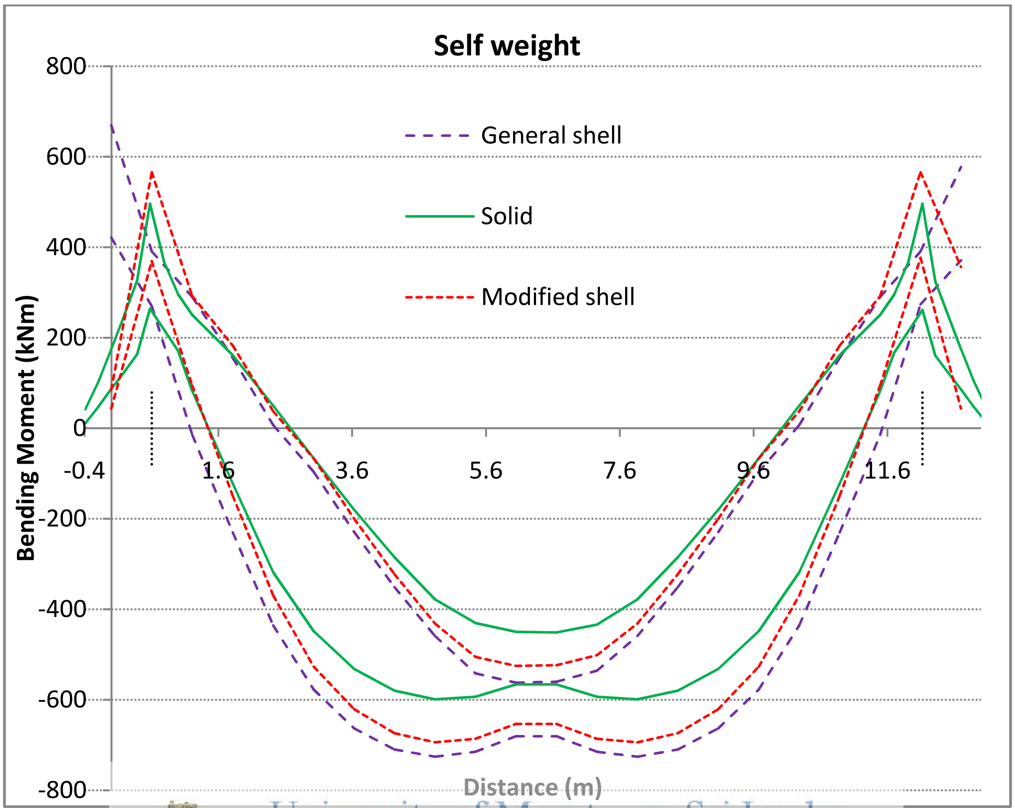

Live surcharge
150
100
50
0
-50
-100
Bending Moment (kNm)
-0.4
1.6
3.6
5.6
7.6
9.6
11.6
General shell
Solid
Modified shell
Distance (m)

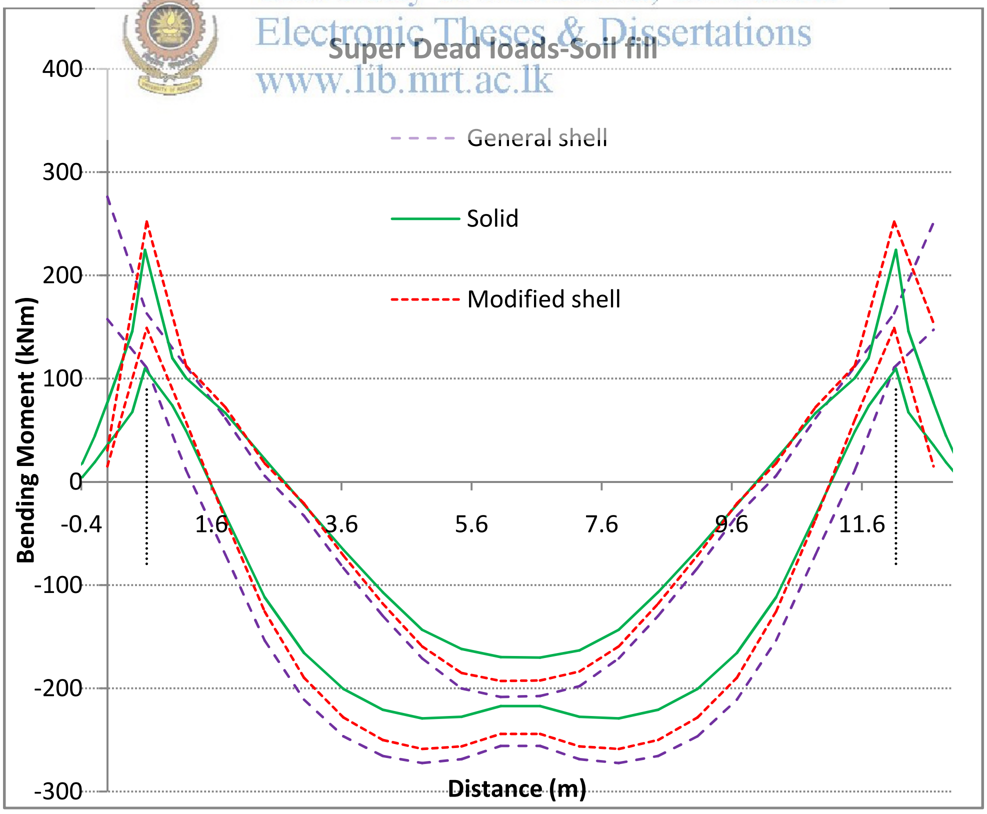

Live load
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
Bending Moment (kNm)
-0.4
1.6
3.6
5.6
7.6
9.6
11.6
General shell
Solid
Modified shell
Distance (m)

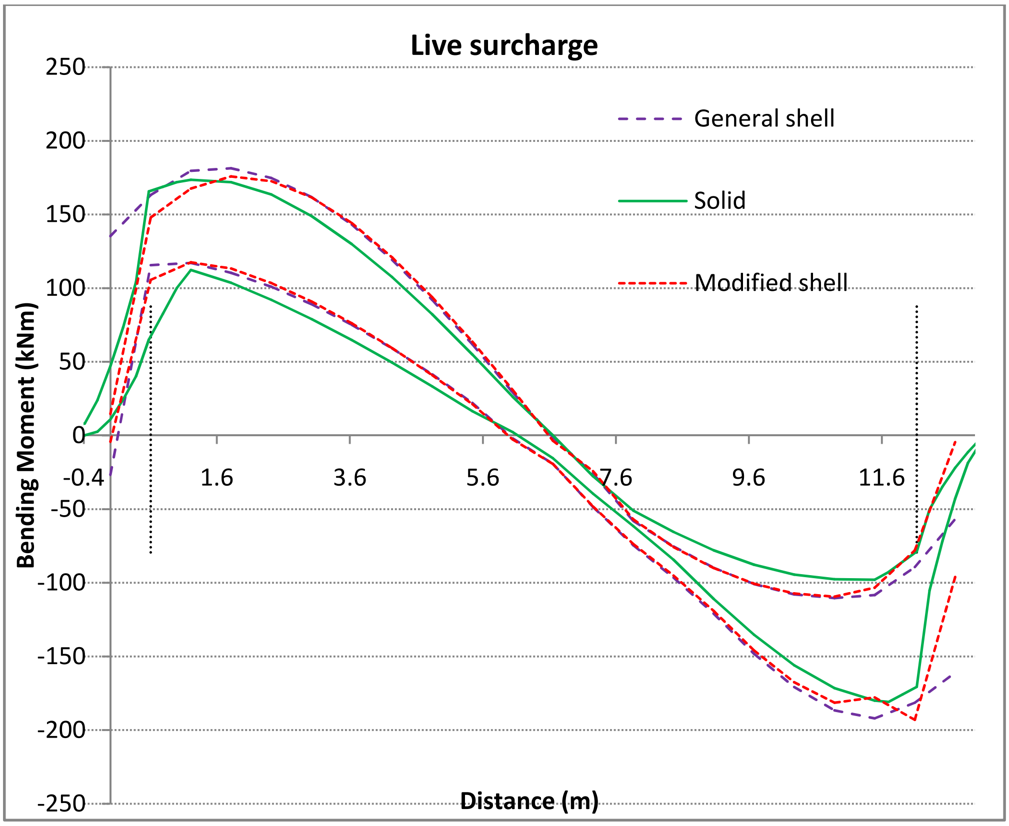

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
800
600
400
200
0
-200
-400
-600
-0.4
1.6
3.6
5.6
7.6
9.6
11.6

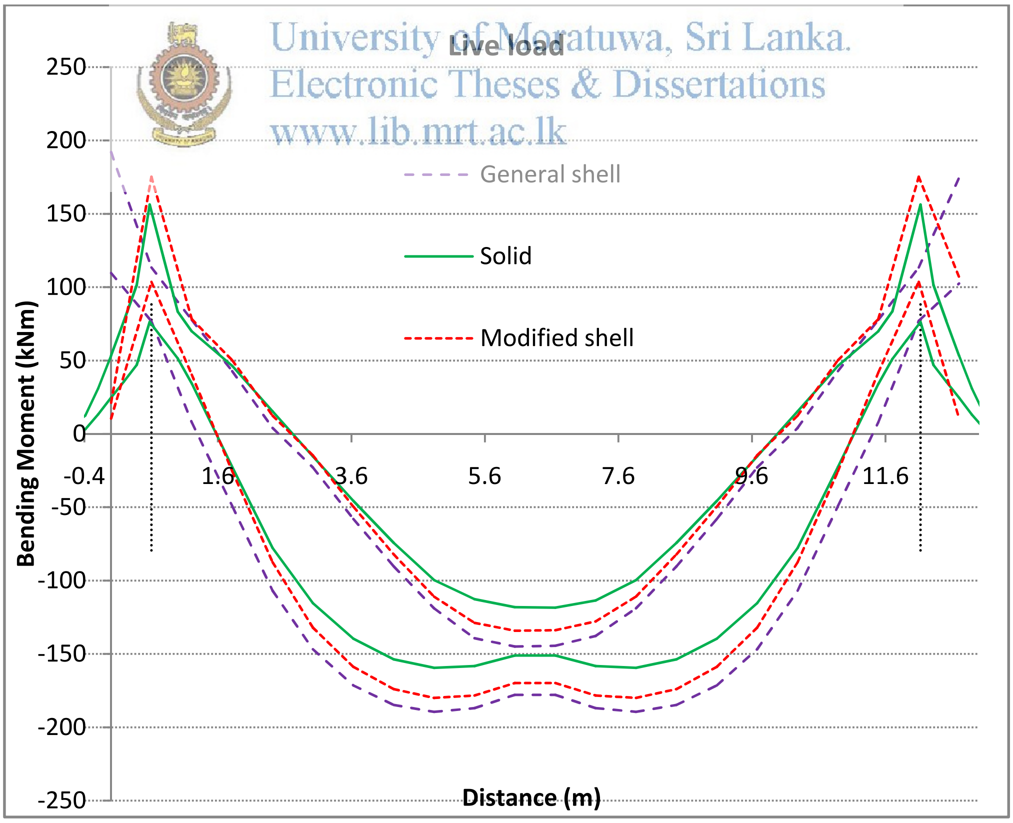

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-0.4
1.6
3.6
5.6
7.6
9.6
11.6

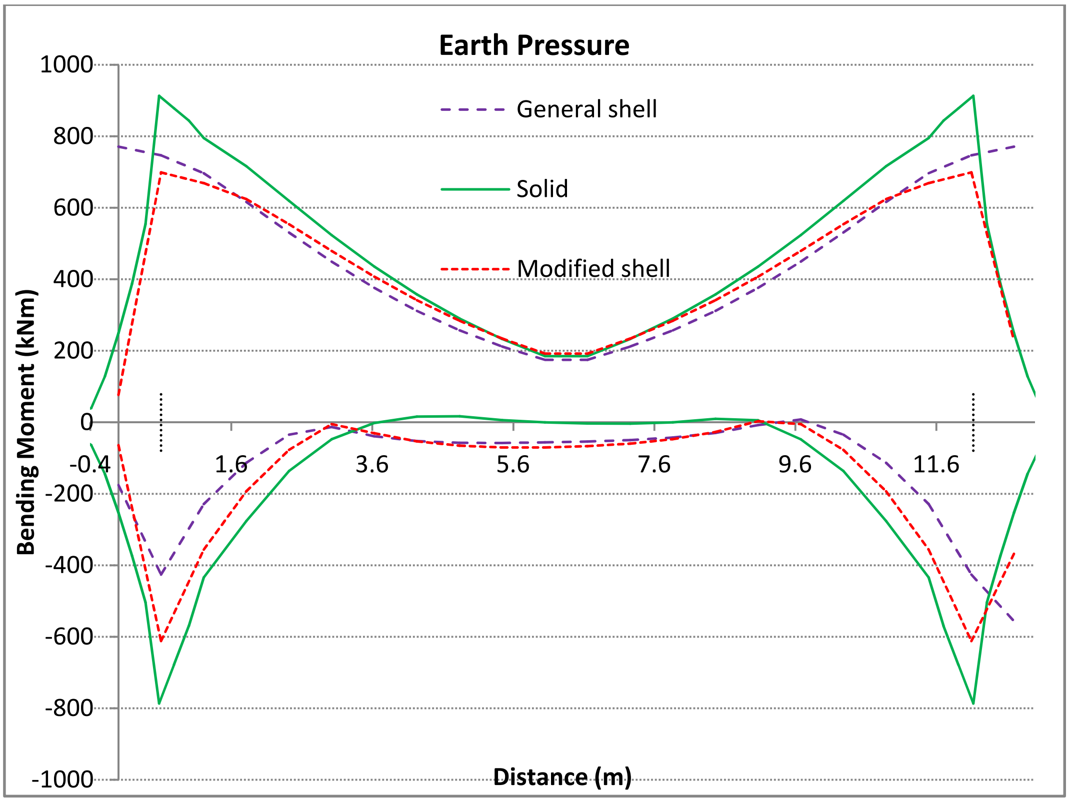
H.1.5: BMD of Bottom slab-Story cell (model no: 1)

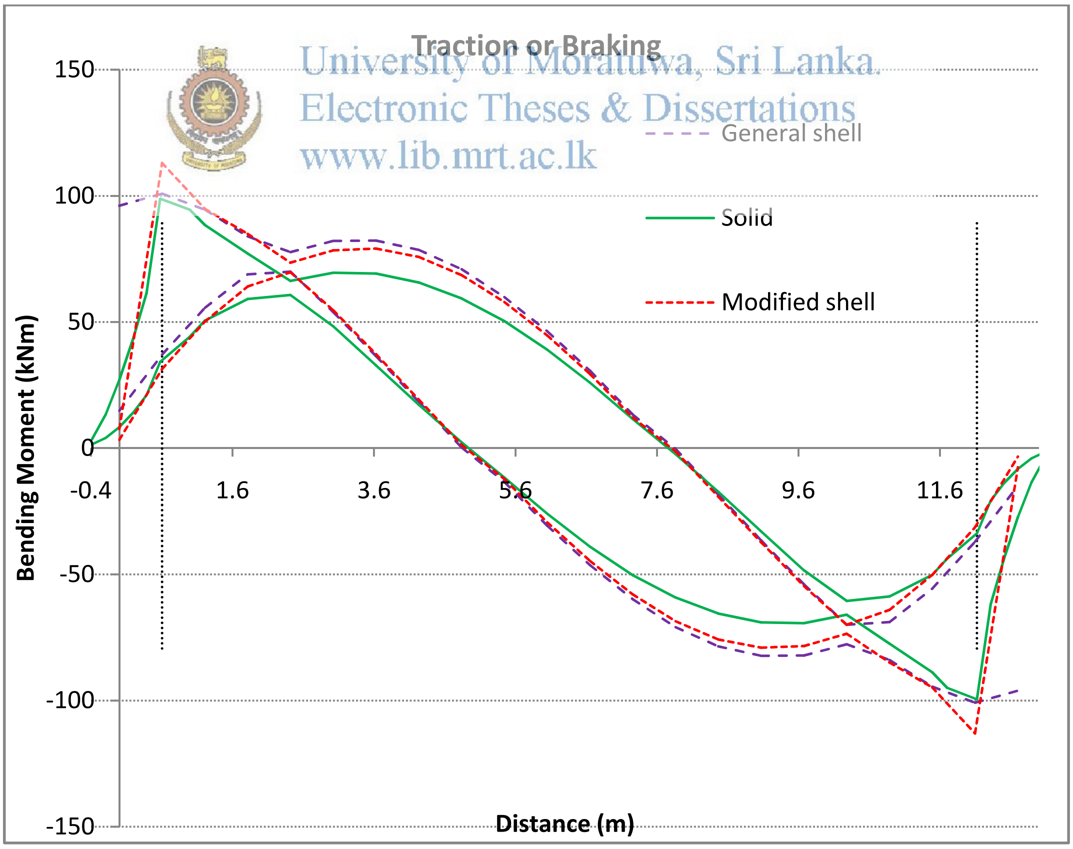




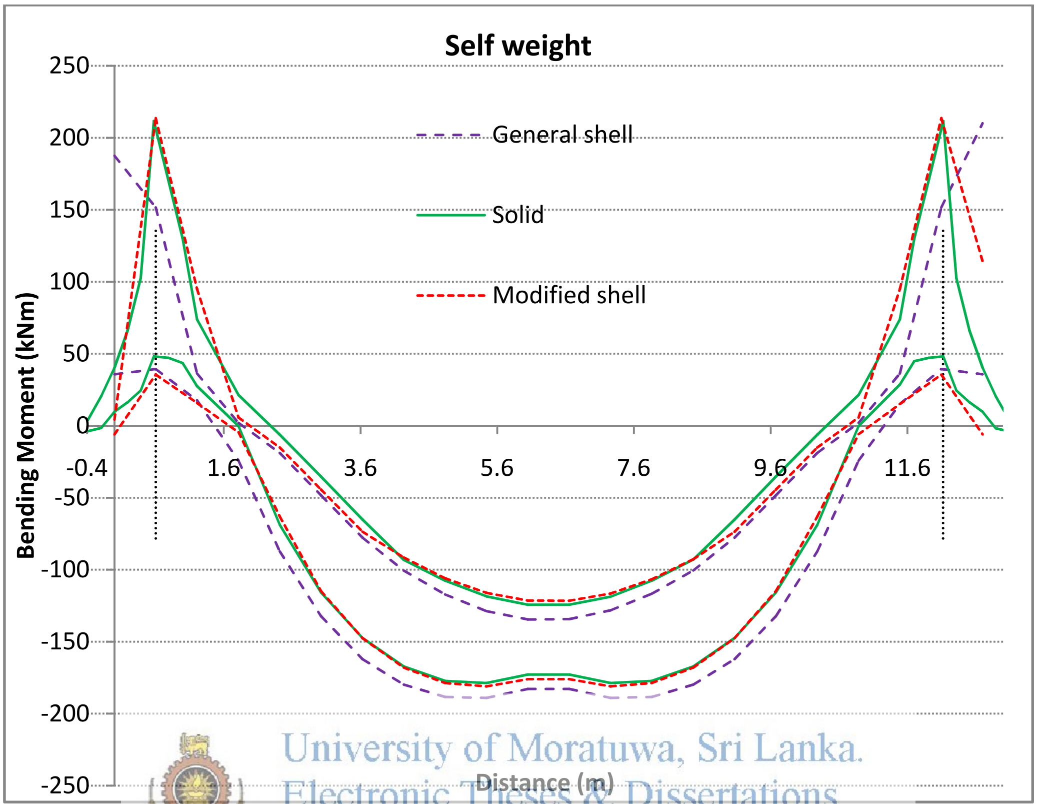

Live surcharge
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-0.4
1.6
3.6
5.6
7.6
9.6
11.6

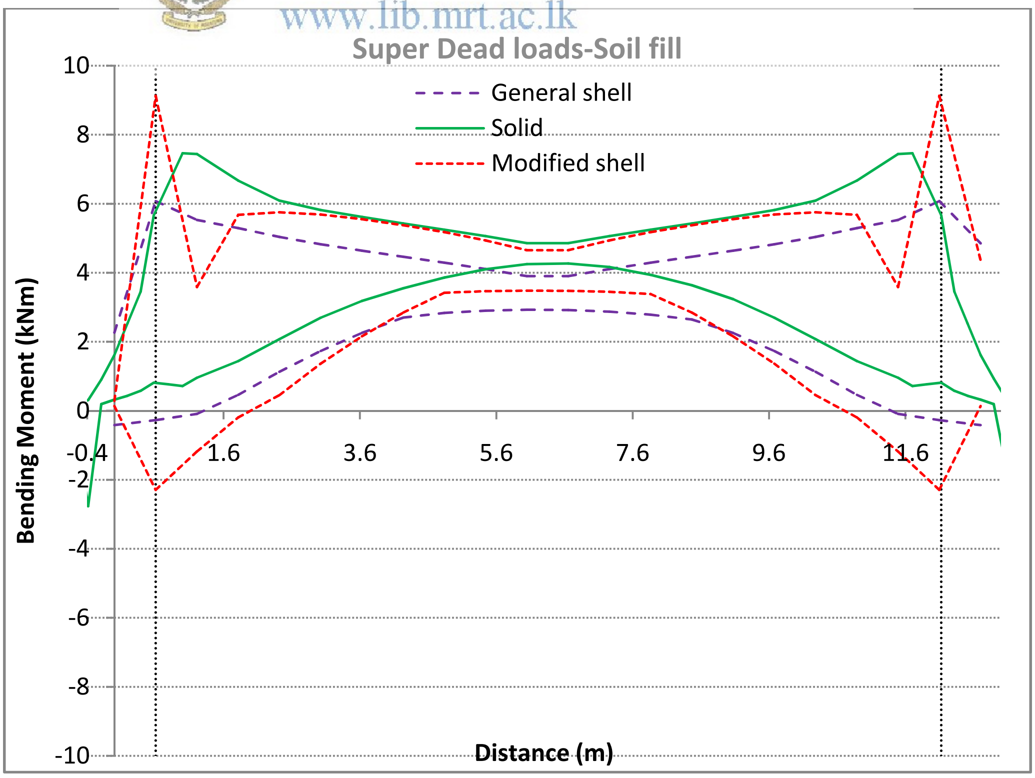

Live load
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-0.4
1.6
3.6
5.6
7.6
9.6
11.6

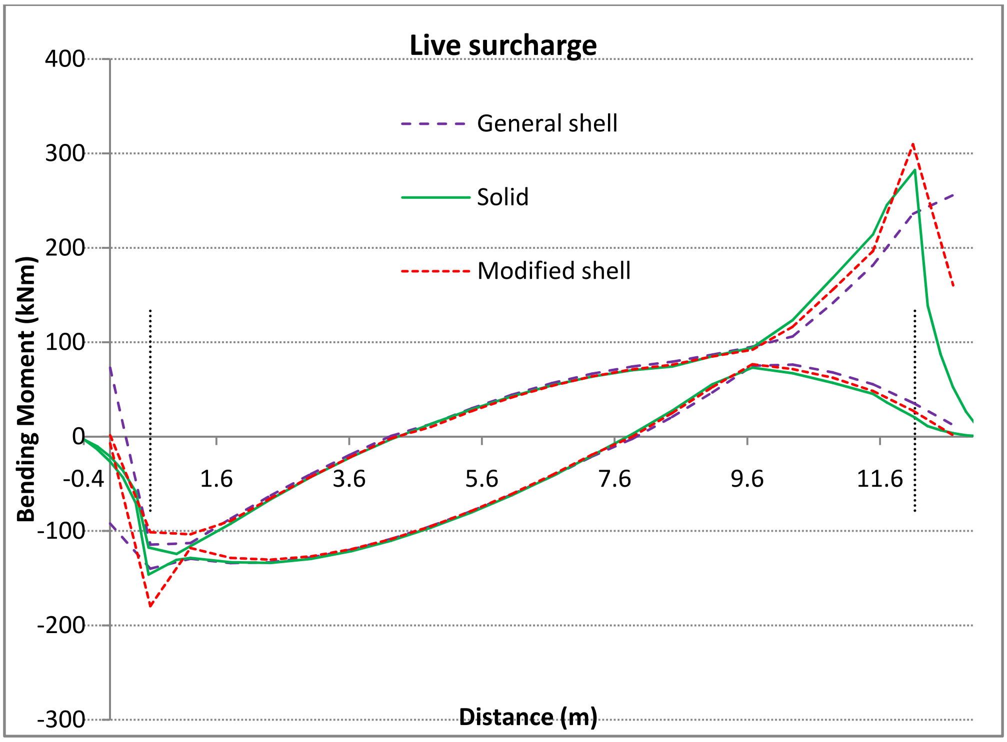

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-0.4
1.6
3.6
5.6
7.6
9.6
11.6

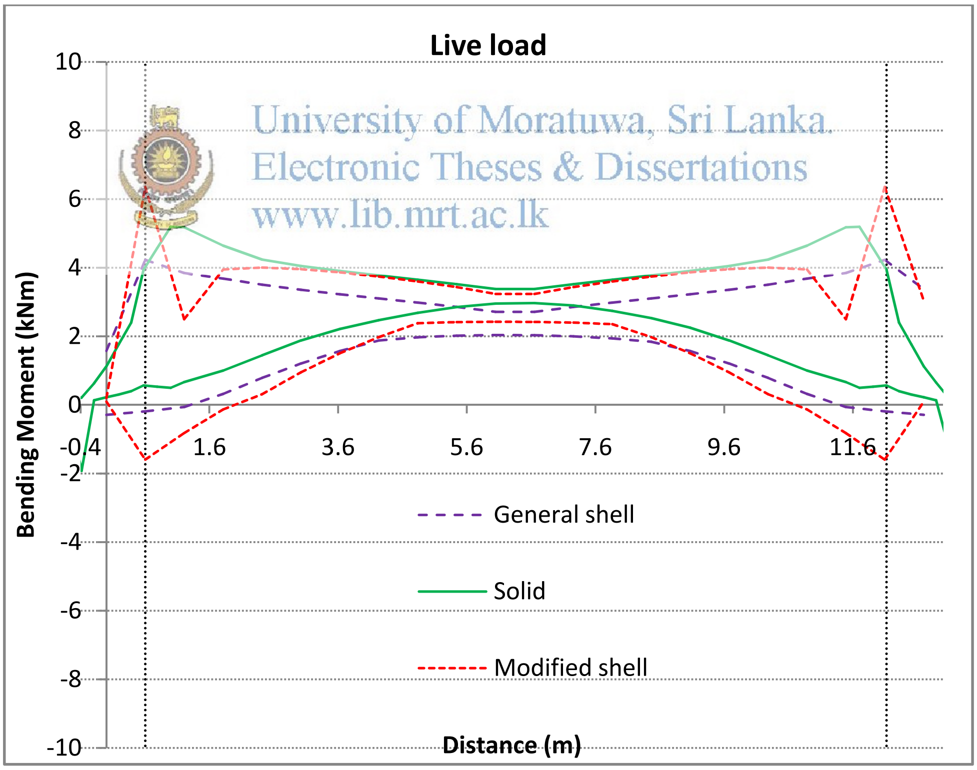

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
150
100
50
0
-50
-100
-150
-0.4
1.6
3.6
5.6
7.6
9.6
11.6

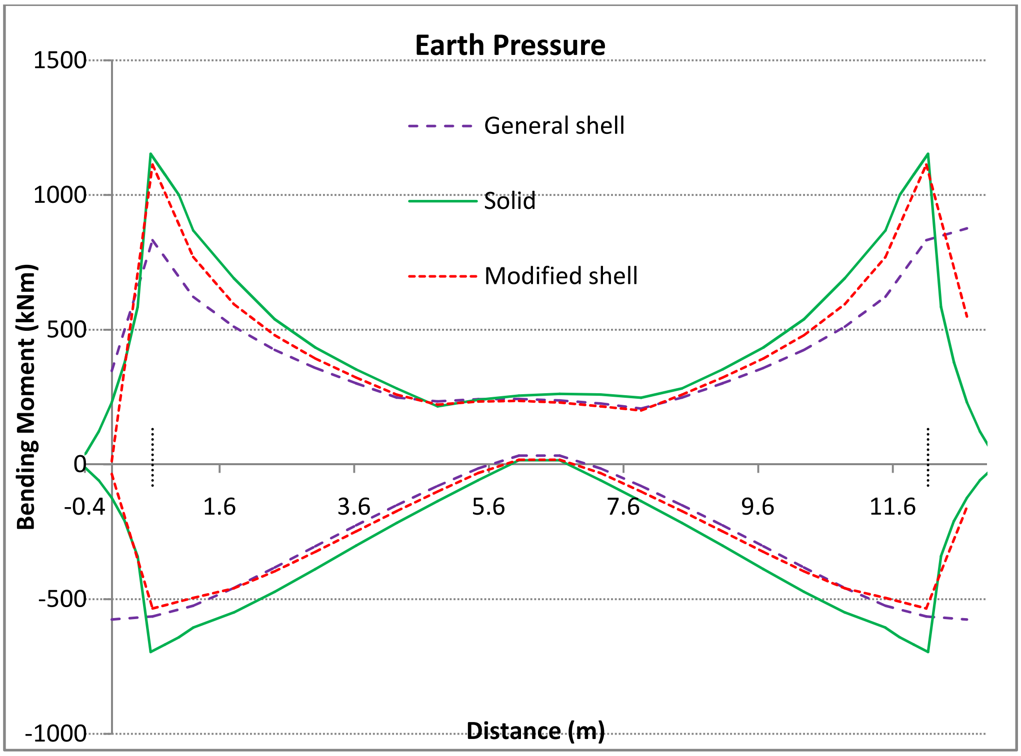
H.1.6: BMD of Middle slab-Story cell (model no: 1)

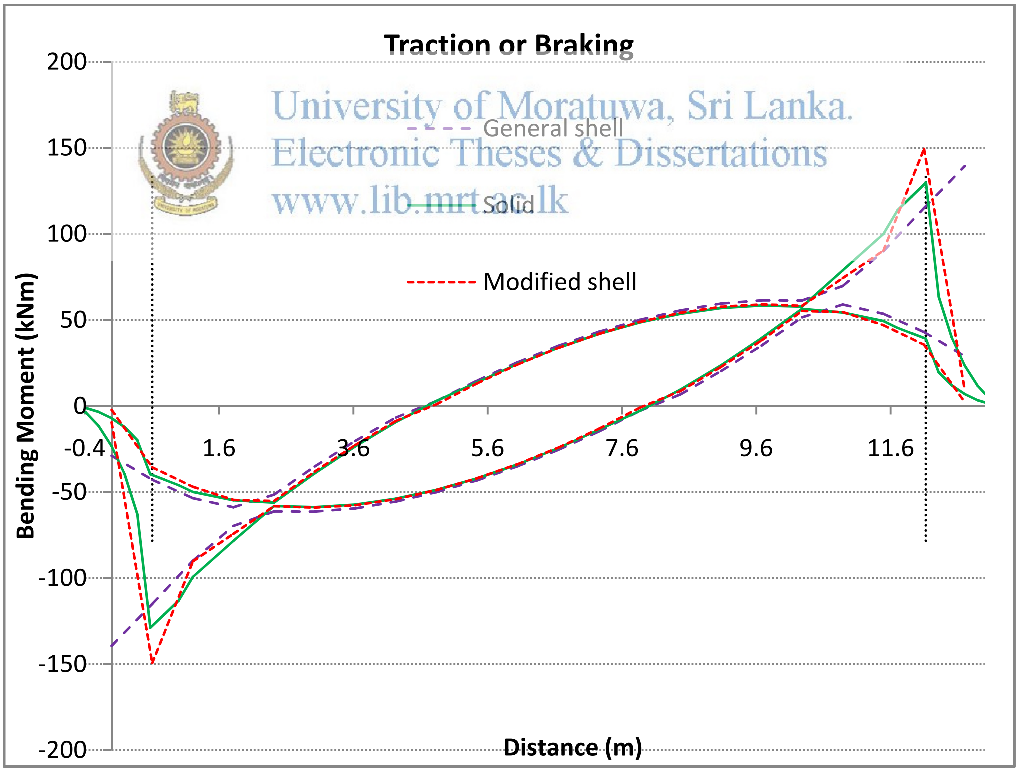




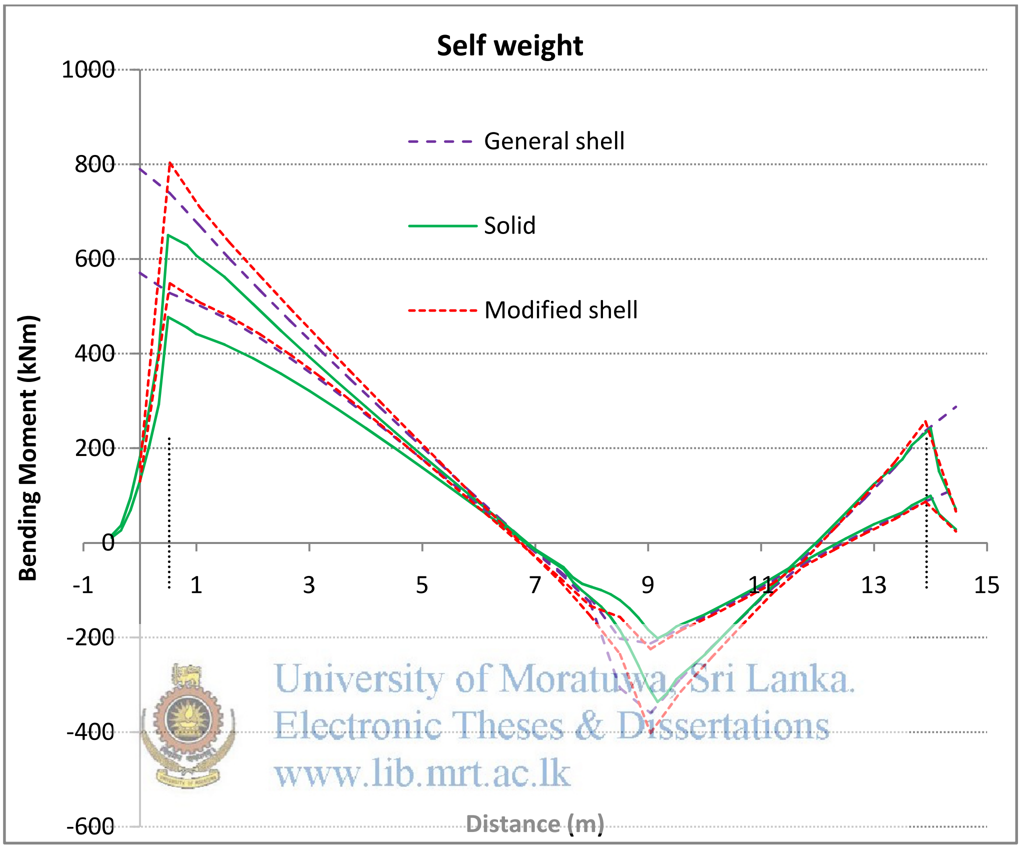

Live surcharge
General shell
Solid
Modified shell
400
300
200
100
0
-100
-200
-300
-0.4
1.6
3.6
5.6
7.6
9.6
11.6
Bending Moment (kNm)
Distance (m)

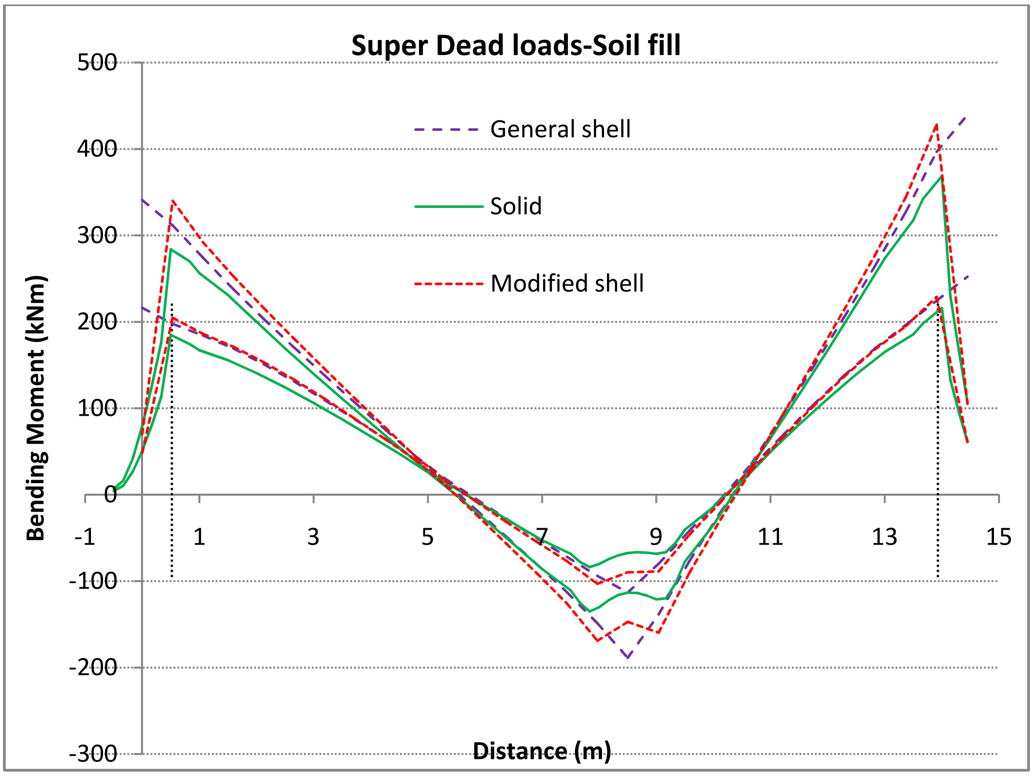

Live load
General shell
Solid
Modified shell
10
8
6
4
2
0
-2
-4
-6
-8
-10
-0.4
1.6
3.6
5.6
7.6
9.6
11.6
Bending Moment (kNm)
Distance (m)

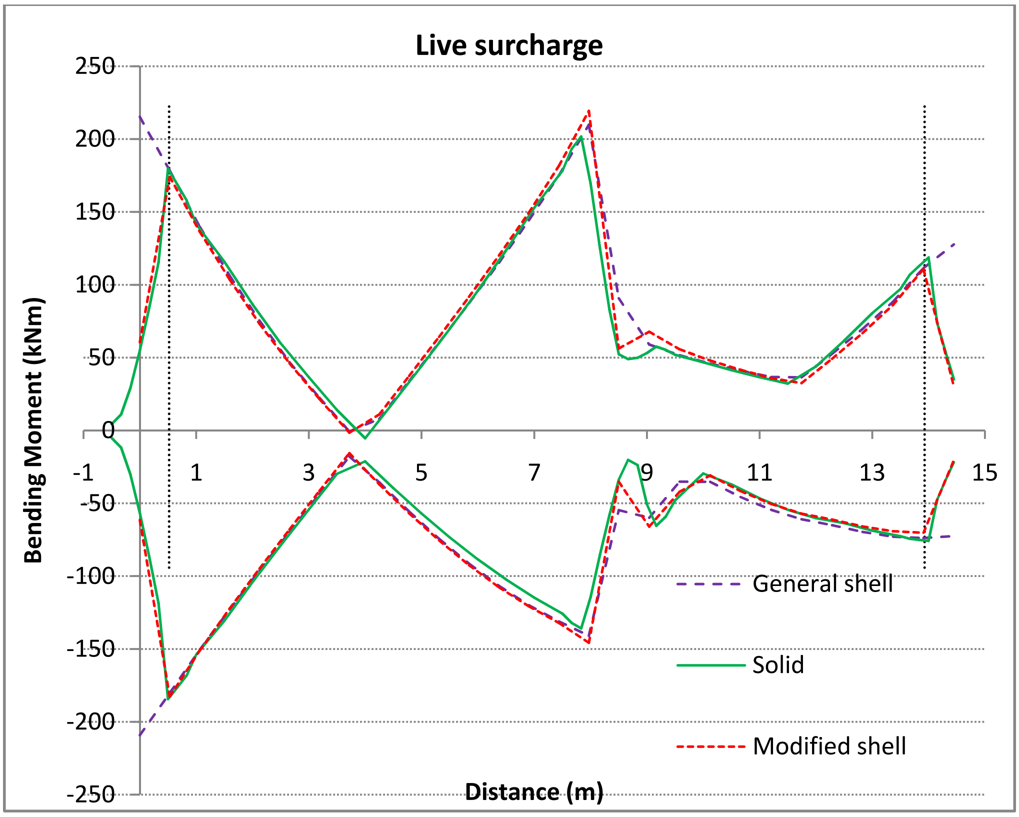

Earth Pressure
1500
1000
500
0
-500
-1000
General shell
Solid
Modified shell
Bending Moment (kNm)
-0.4
1.6
3.6
5.6
7.6
9.6
11.6
Distance (m)

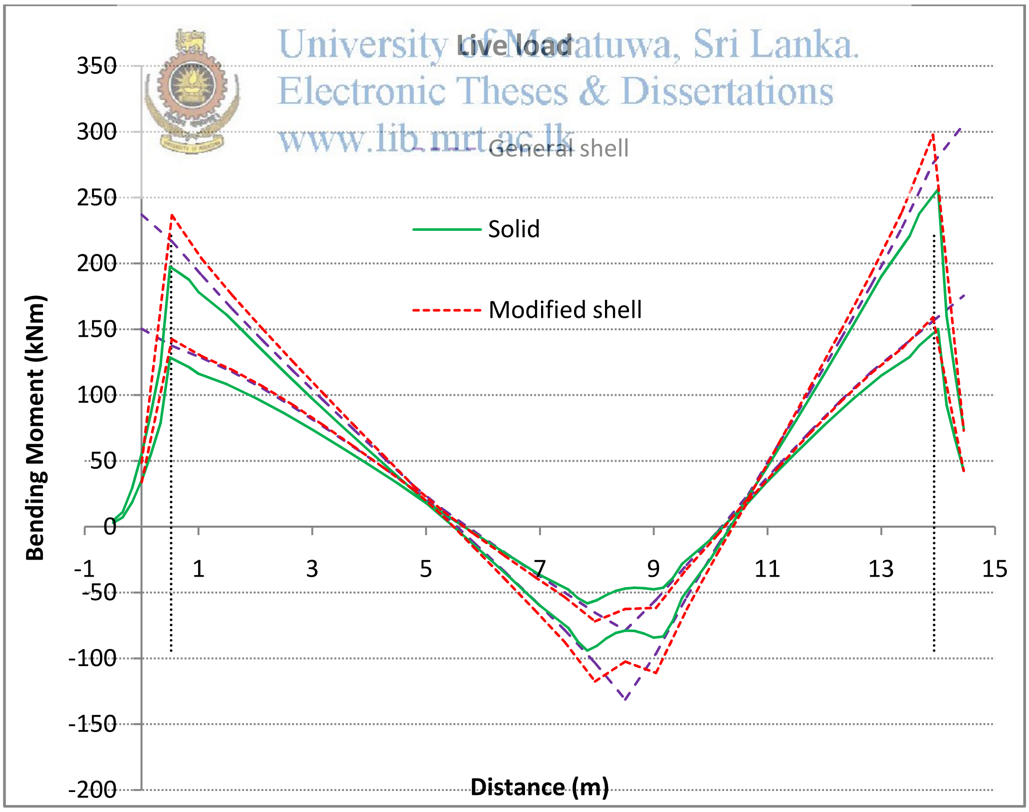

Traction or Braking
200
150
100
50
0
-50
-100
-150
-200
General shell
Solid
Modified shell
Bending Moment (kNm)
-0.4
1.6
3.6
5.6
7.6
9.6
11.6
Distance (m)

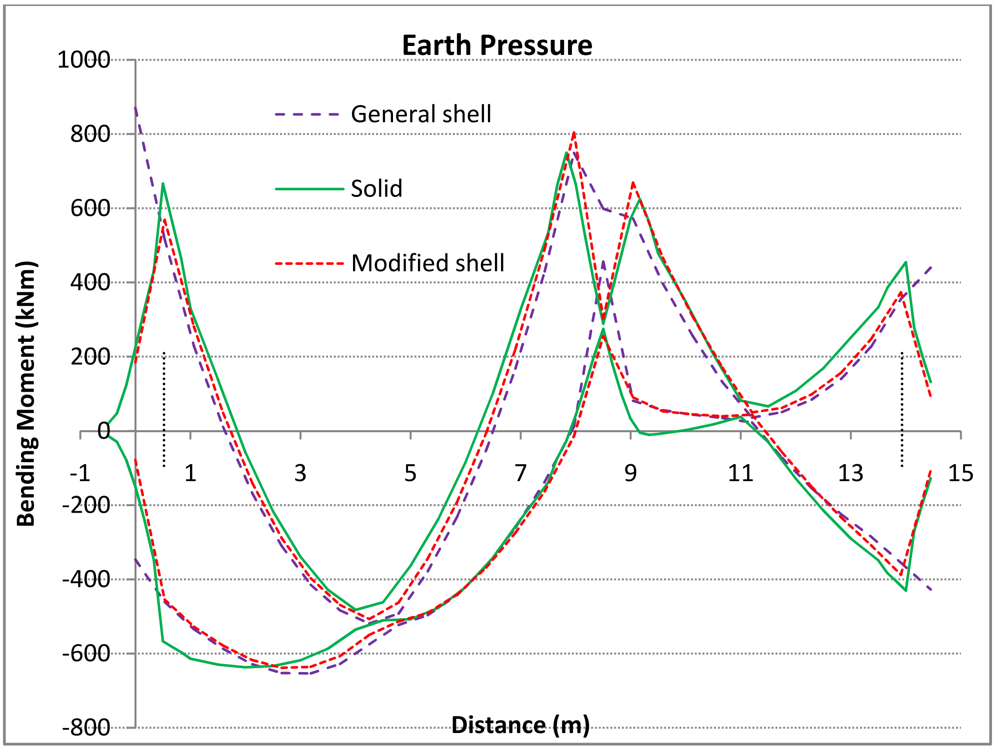
H.1.7: BMD of Walls-Story cell (model no: 1)

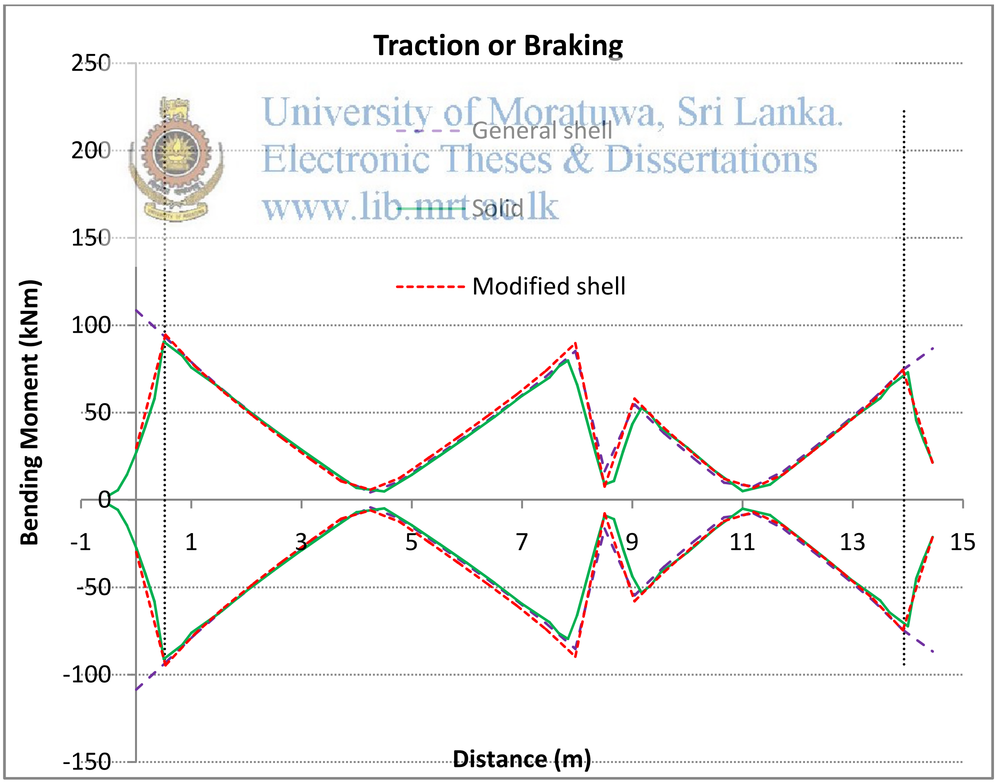




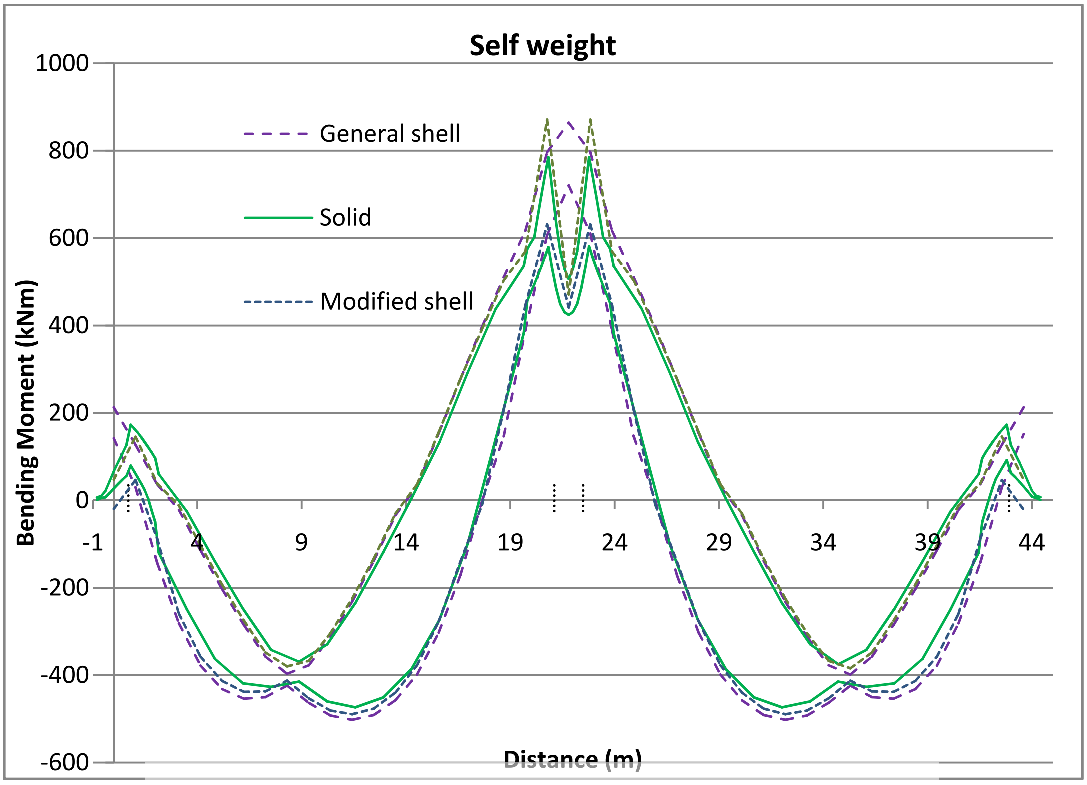

Live surcharge
250
200
150
100
50
0
-50
-100
-150
-200
-250
-1
1
3
5
7
9
11
13
15
Bending Moment (kNm)
Distance (m)
General shell
Solid
Modified shell

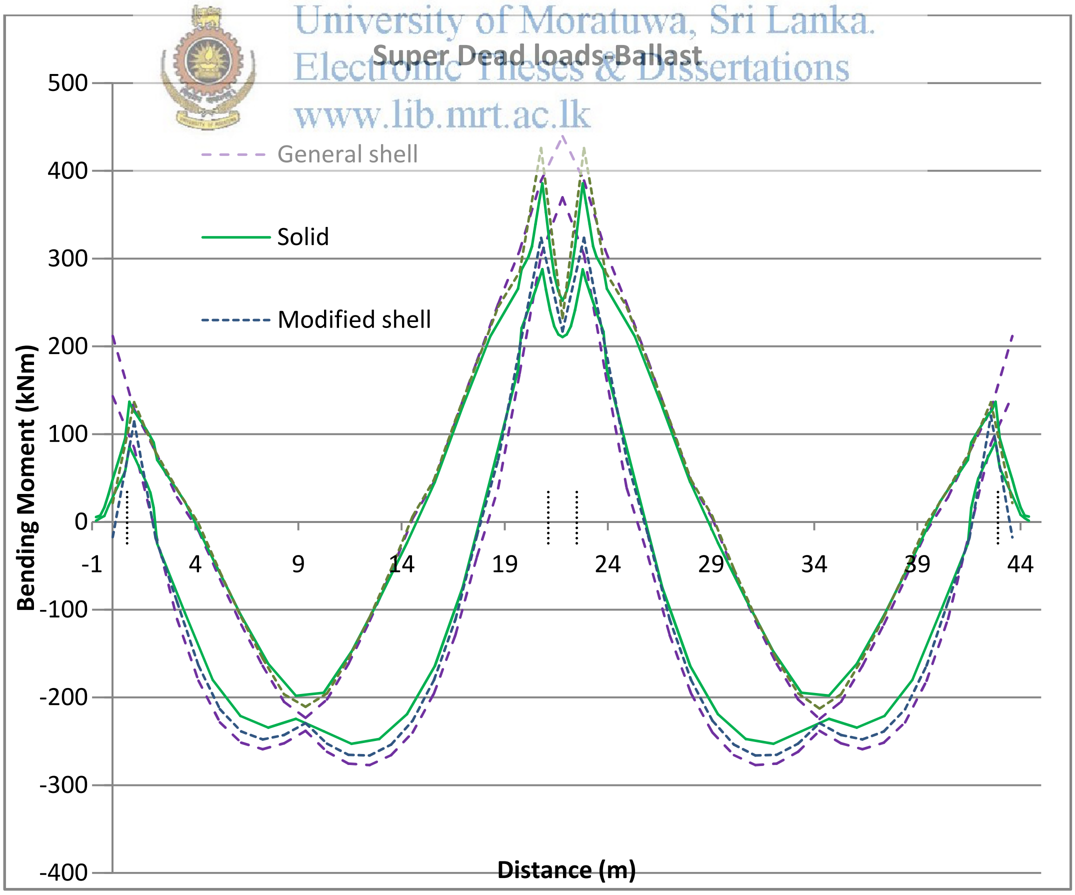

Live load
350
300
250
200
150
100
50
0
-50
-100
-150
-200
-1
1
3
5
7
9
11
13
15
Bending Moment (kNm)
Distance (m)
General shell
Solid
Modified shell

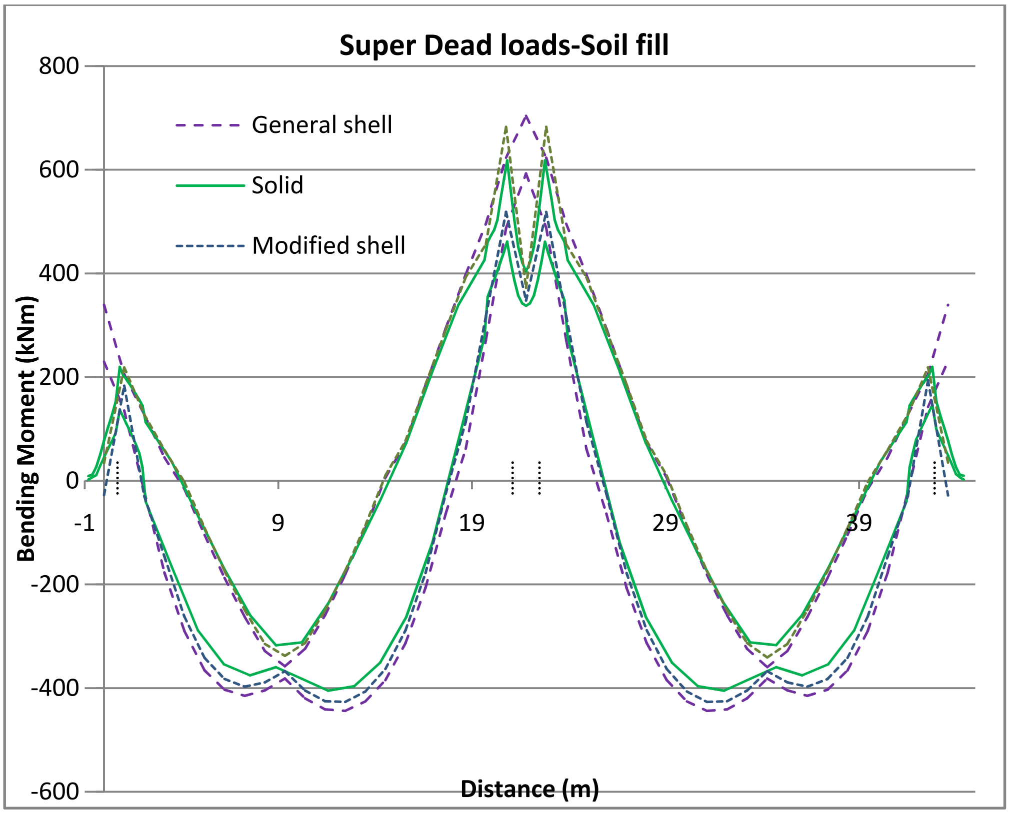

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
1000
800
600
400
200
0
-200
-400
-600
-800
-1
1
3
5
7
9
11
13
15

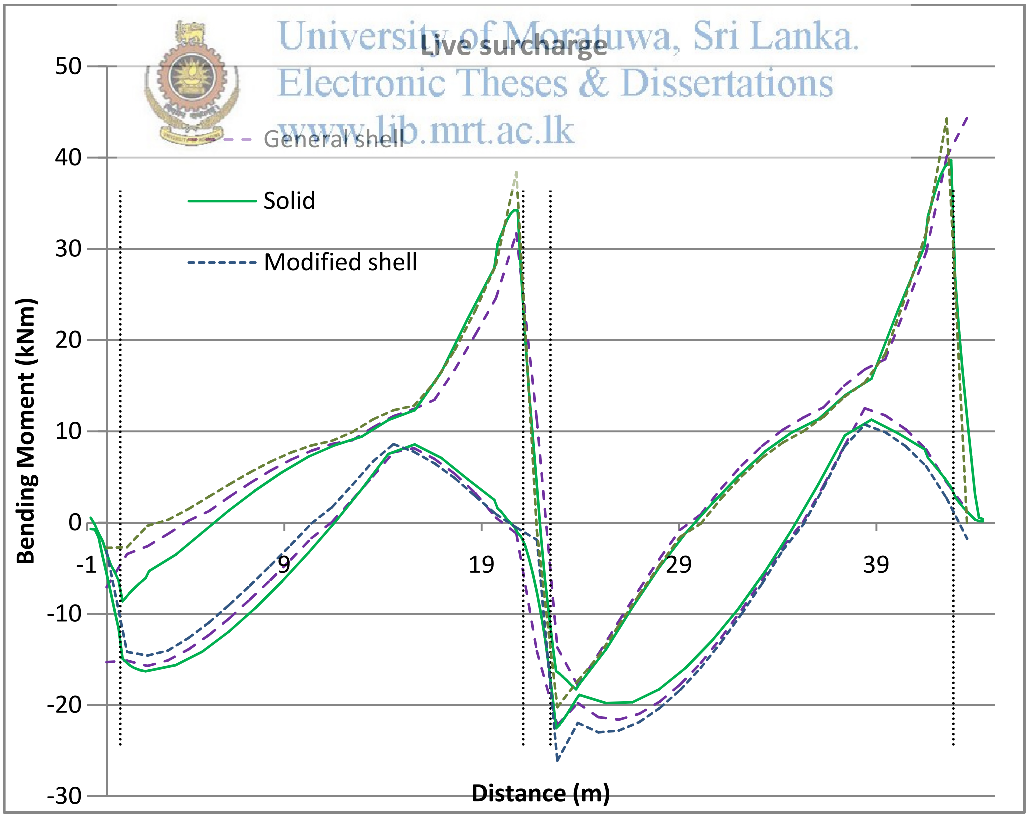

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
250
200
150
100
50
0
-50
-100
-150
-1
1
3
5
7
9
11
13
15

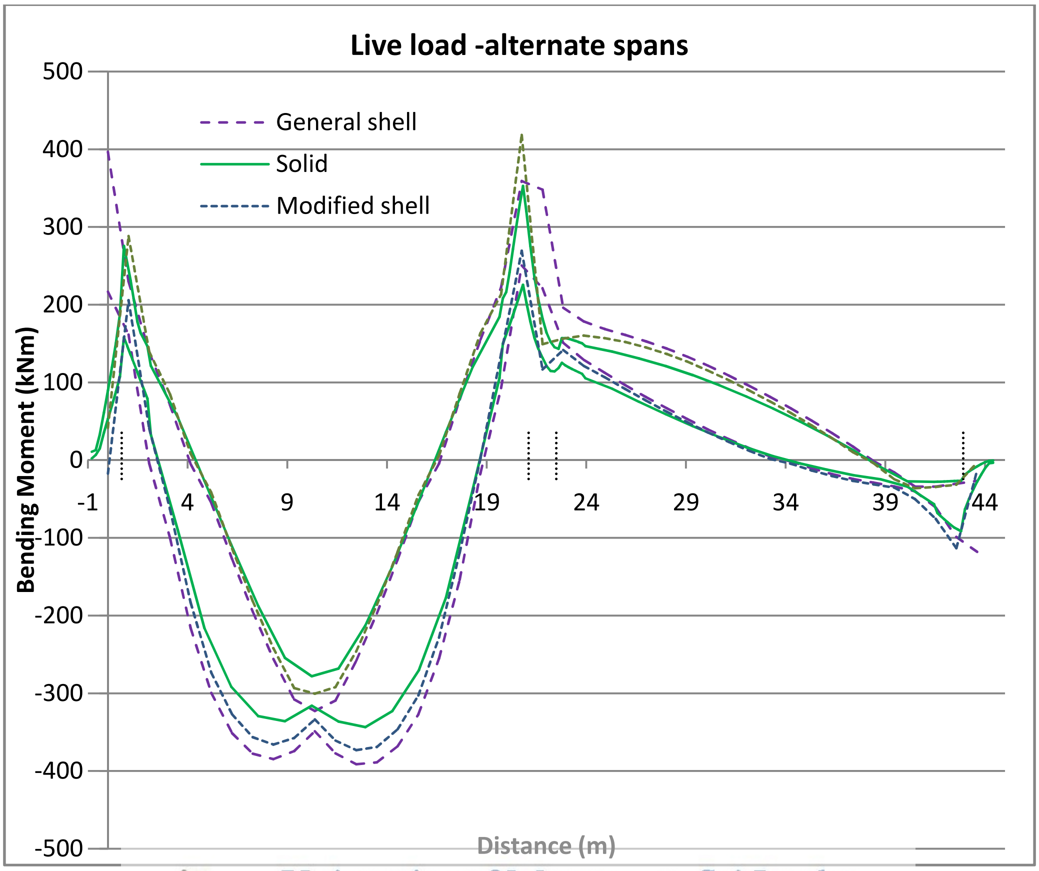
H.1.8: BMD of Top slab-Double cell (model no: 5)

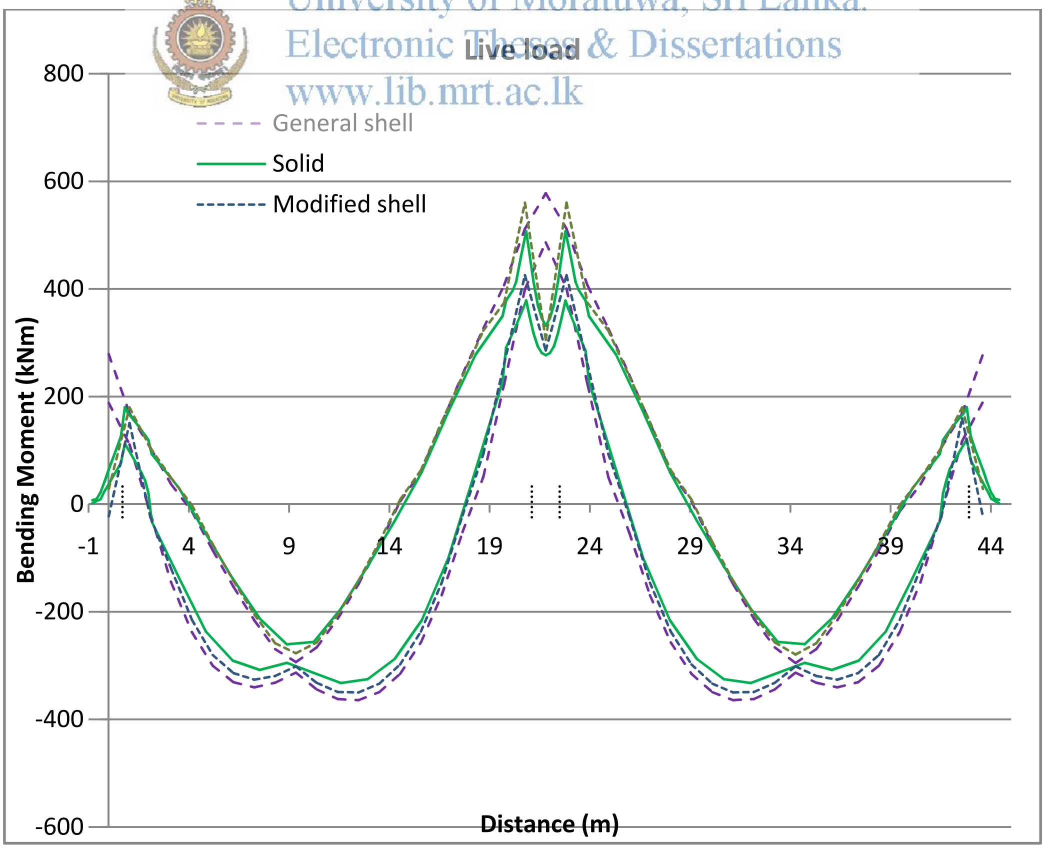


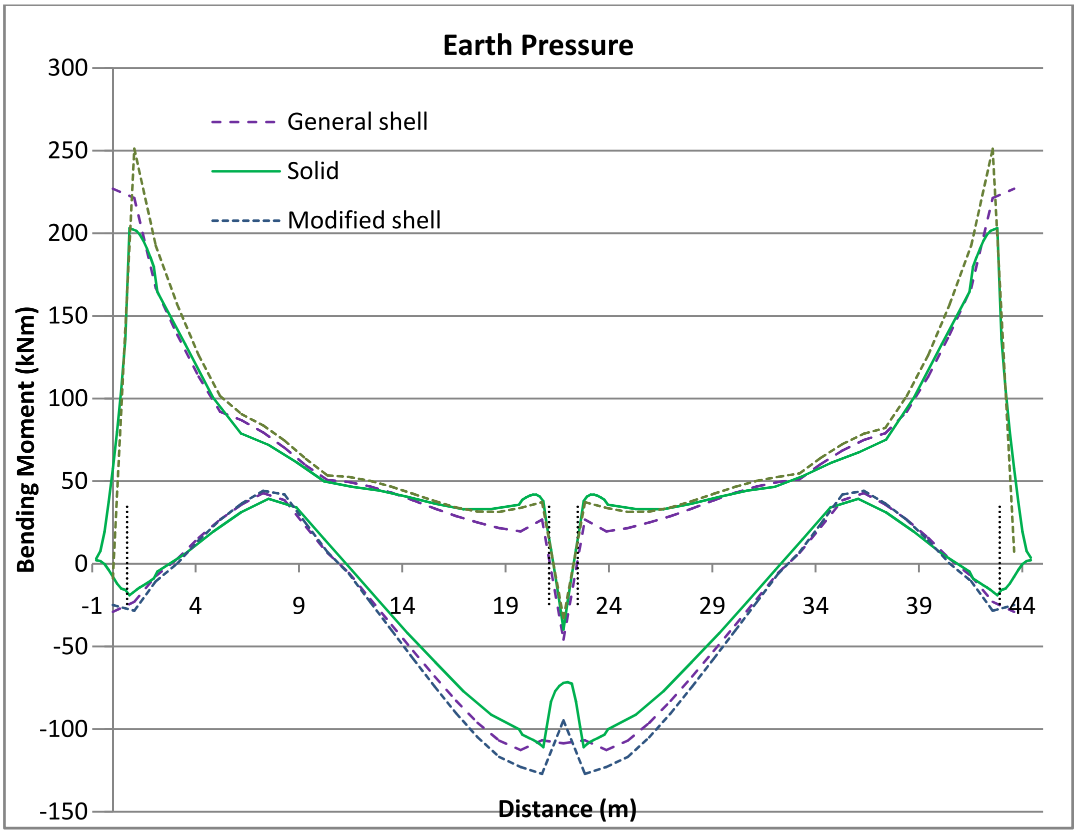


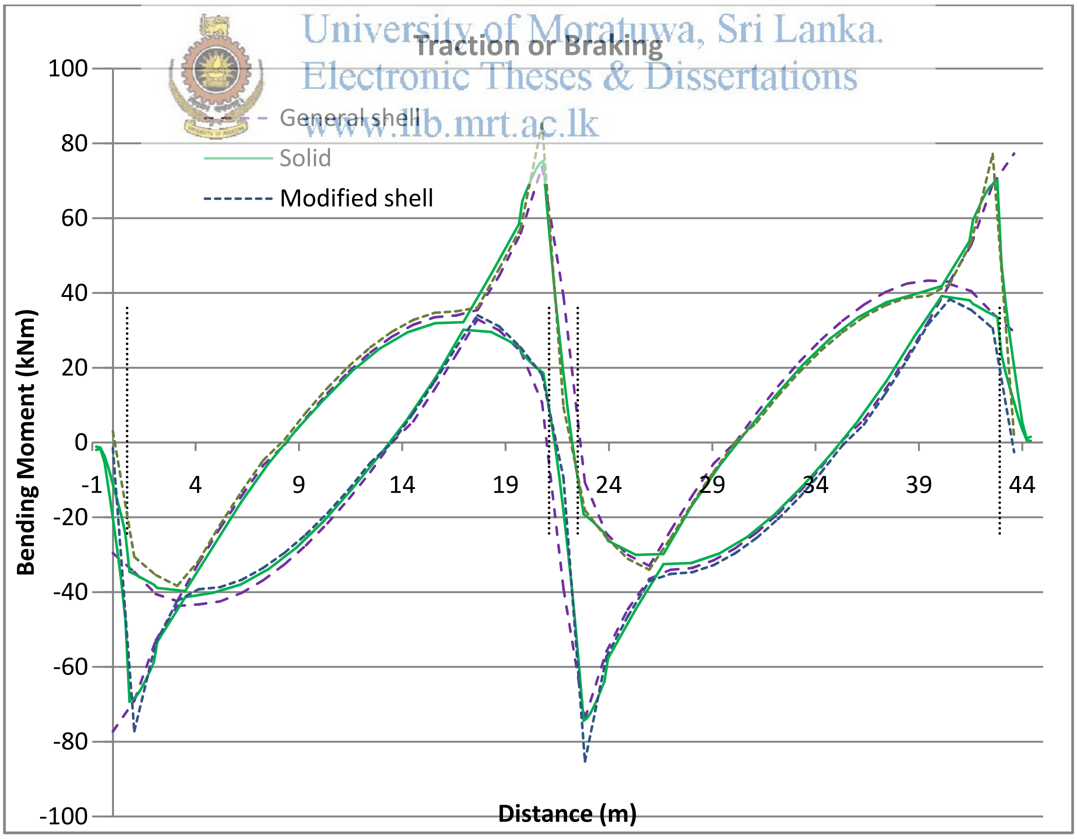

Super Dead loads-Soil fill
800
600
400
200
0
-200
-400
-600
-1
9
19
29
39
Bending Moment (kNm)
Distance (m)
General shell
Solid
Modified shell


Live surcharge
50
40
30
20
10
0
-10
-20
-30
-1
9
19
29
39
Bending Moment (kNm)
Distance (m)
General shell
Solid
Modified shell

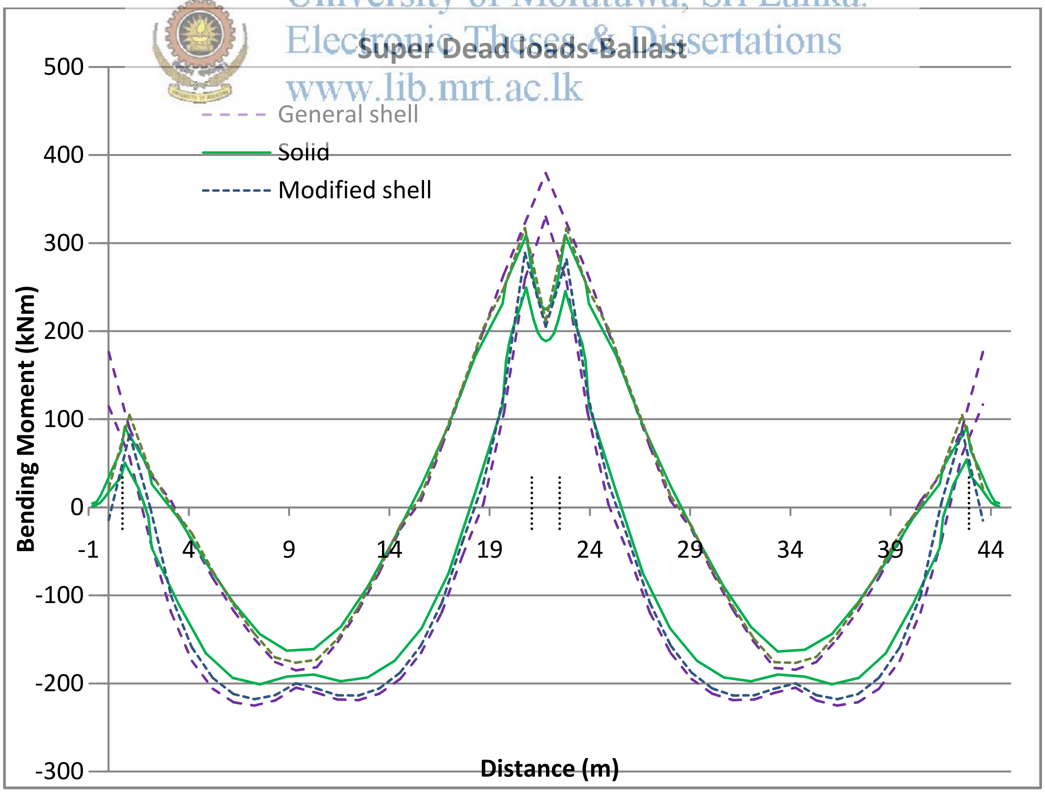

Live load -alternate spans
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
500
400
300
200
100
0
-100
-200
-300
-400
-500
-1
4
9
14
19
24
29
34
39
44

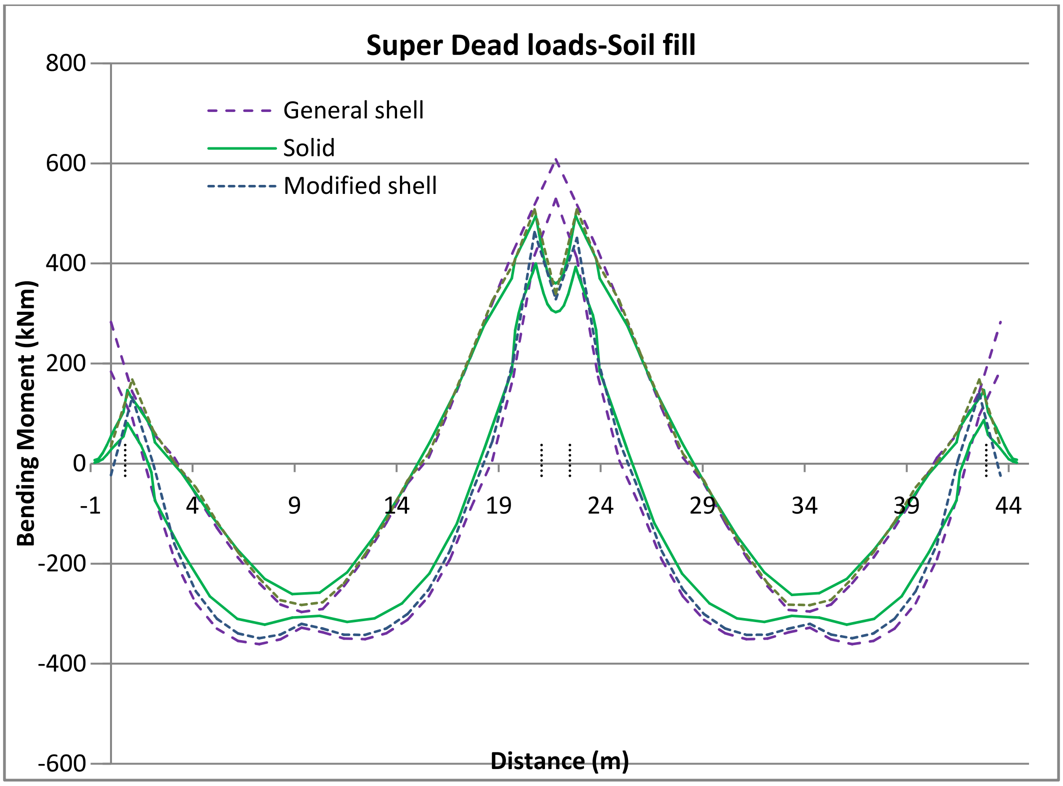

Live load
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
800
600
400
200
0
-200
-400
-600
-1
4
9
14
19
24
29
34
39
44

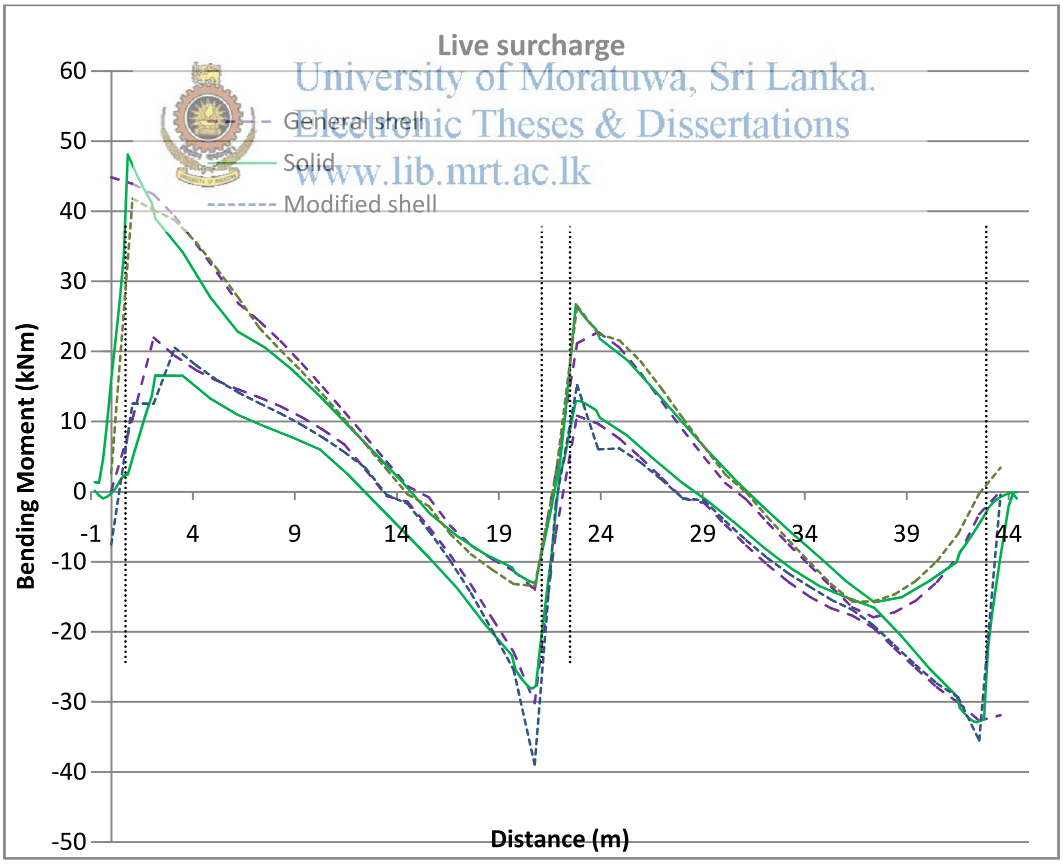

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
300
250
200
150
100
50
0
-50
-100
-150
-1
4
9
14
19
24
29
34
39
44

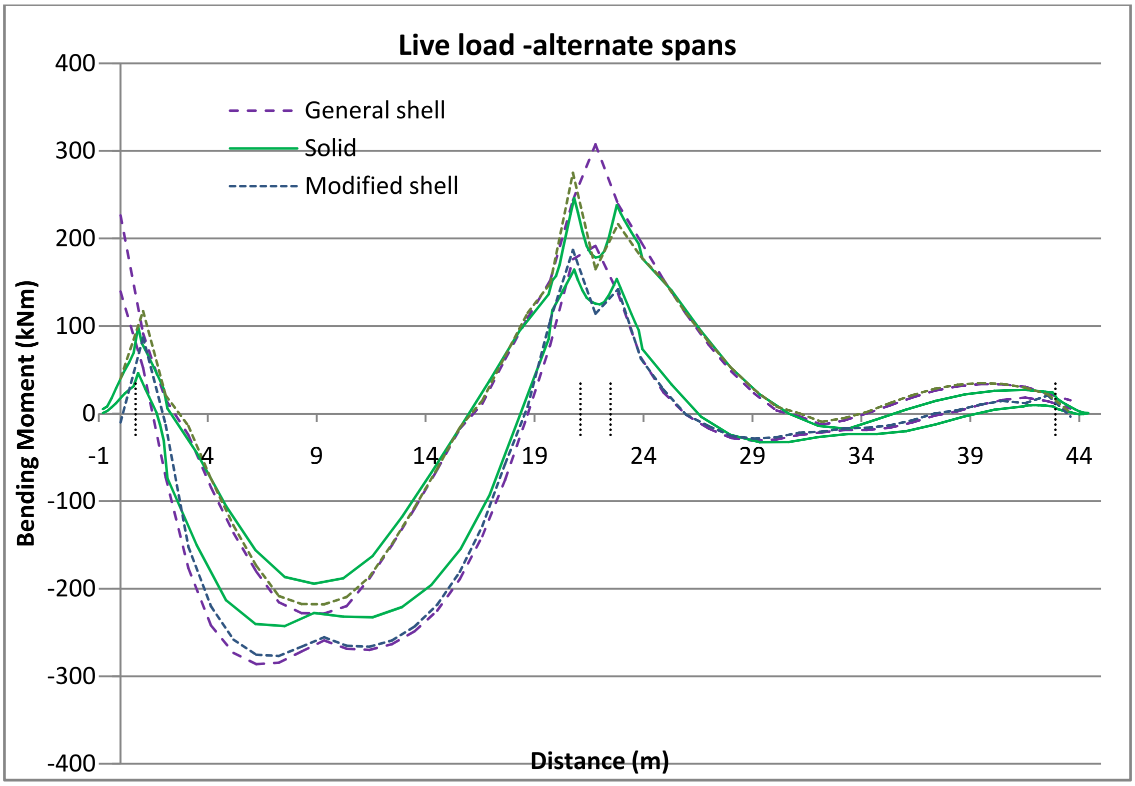

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-1
4
9
14
19
24
29
34
39
44

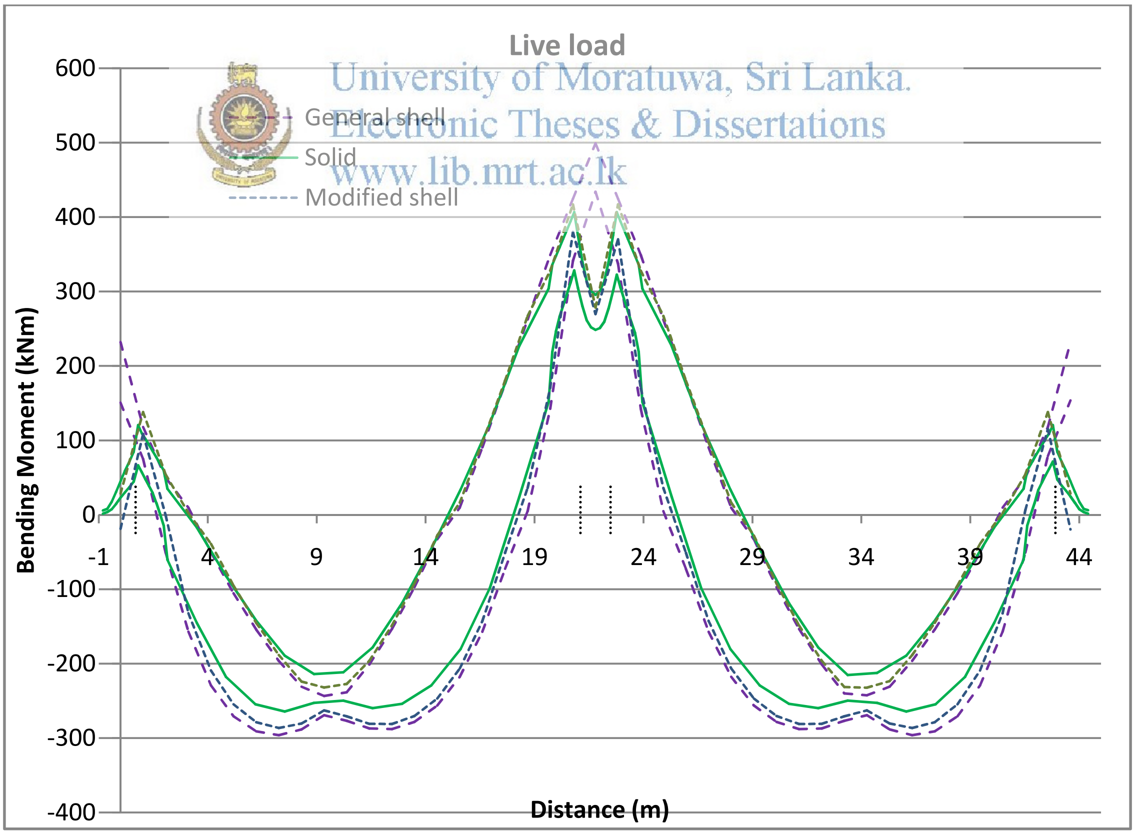
H.1.9: BMD of Bottom slab-Double cell (model no: 5)

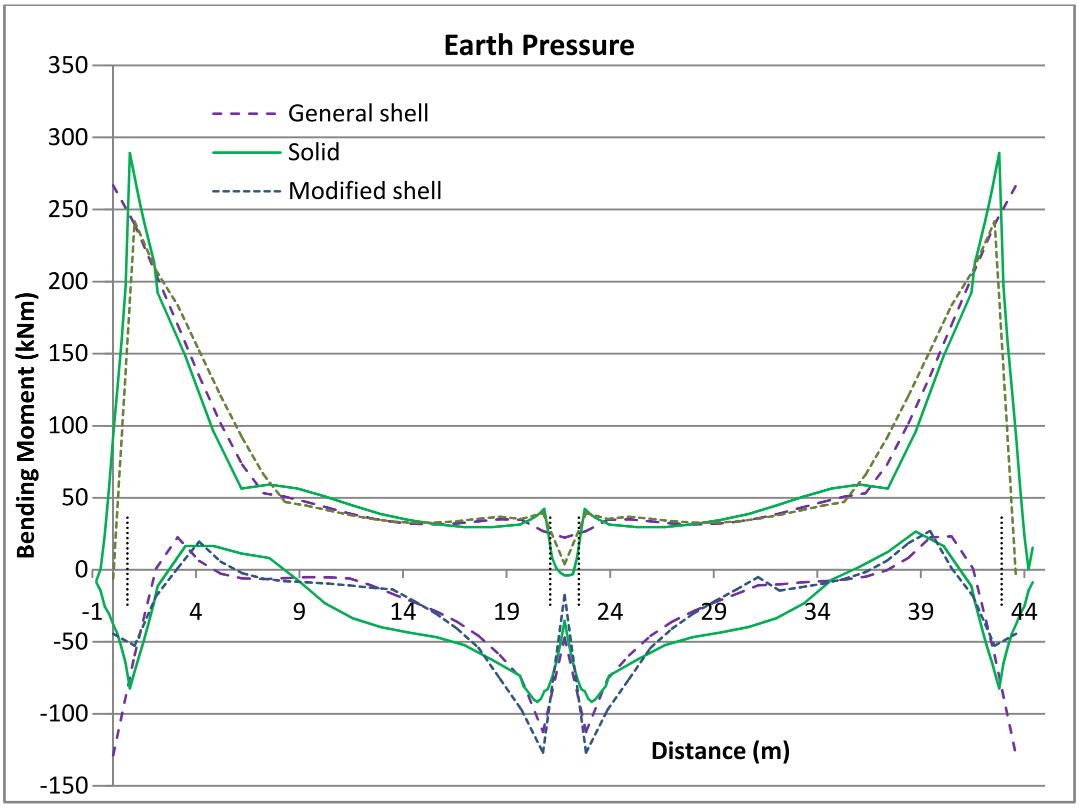


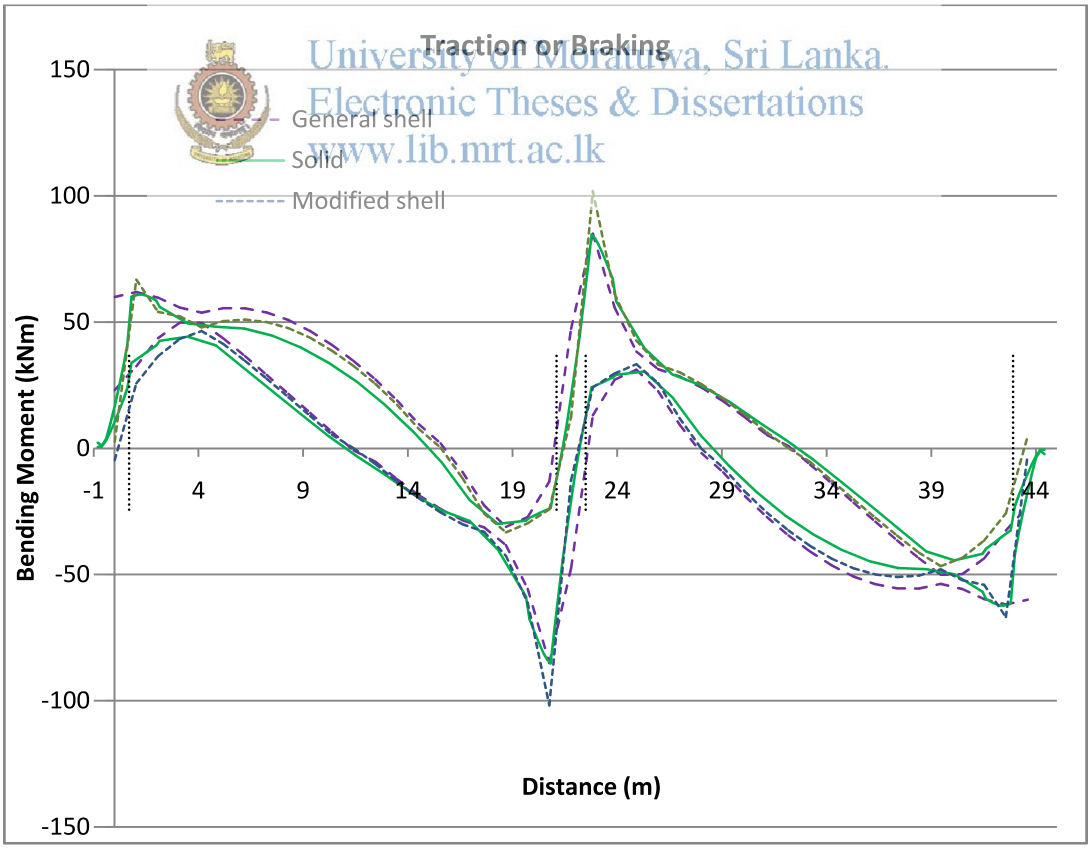

Super Dead loads-Soil fill
800
600
400
200
0
-200
-400
-600
-1
4
9
14
19
24
29
34
39
44
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)


Live surcharge
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-1
4
9
14
19
24
29
34
39
44
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)

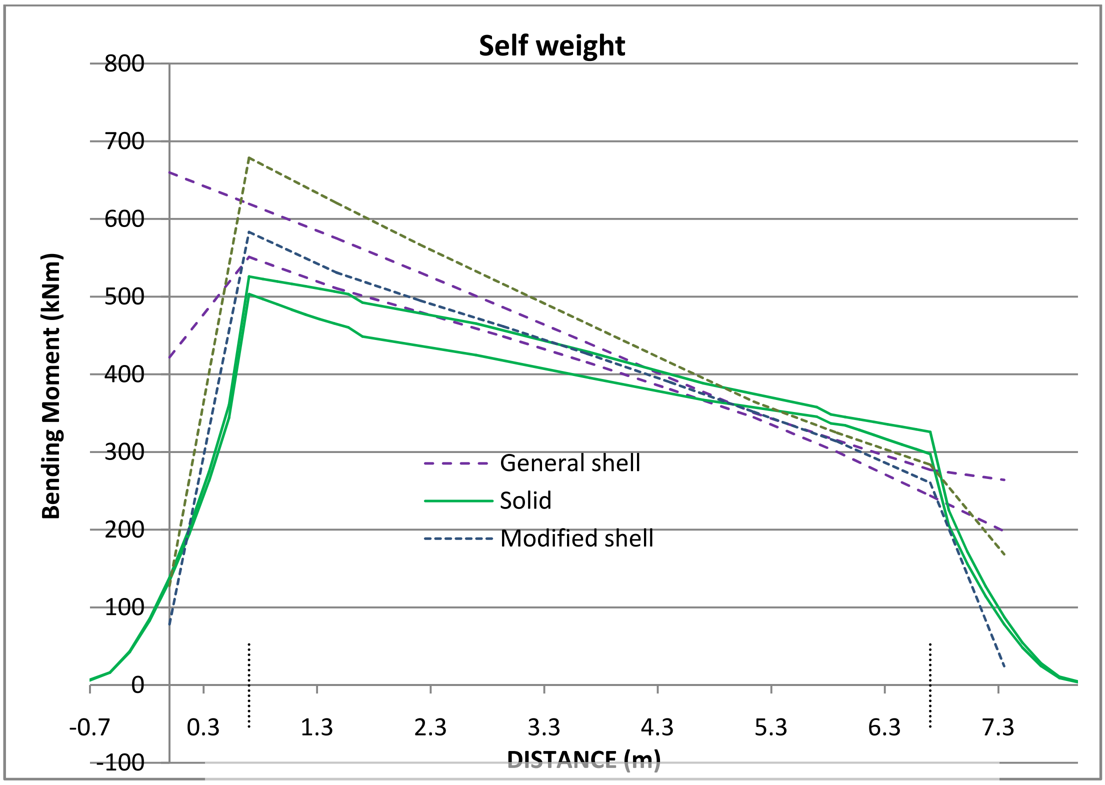

Live load -alternate spans
General shell
Solid
Modified shell
Bending Moment (kNm)
400
300
200
100
0
-100
-200
-300
-400
-1
4
9
14
19
24
29
34
39
44
Distance (m)

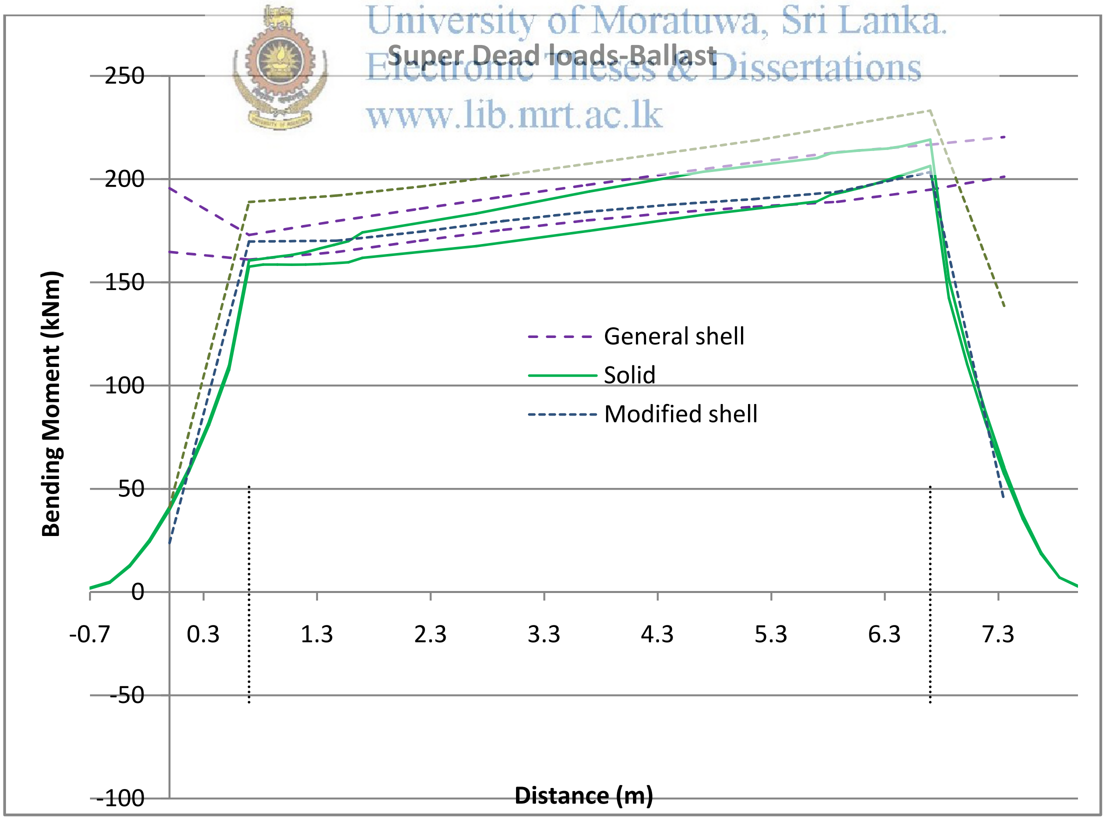

Live load
General shell
Solid
Modified shell
Bending Moment (kNm)
600
500
400
300
200
100
0
-100
-200
-300
-400
-1
4
9
14
19
24
29
34
39
44
Distance (m)

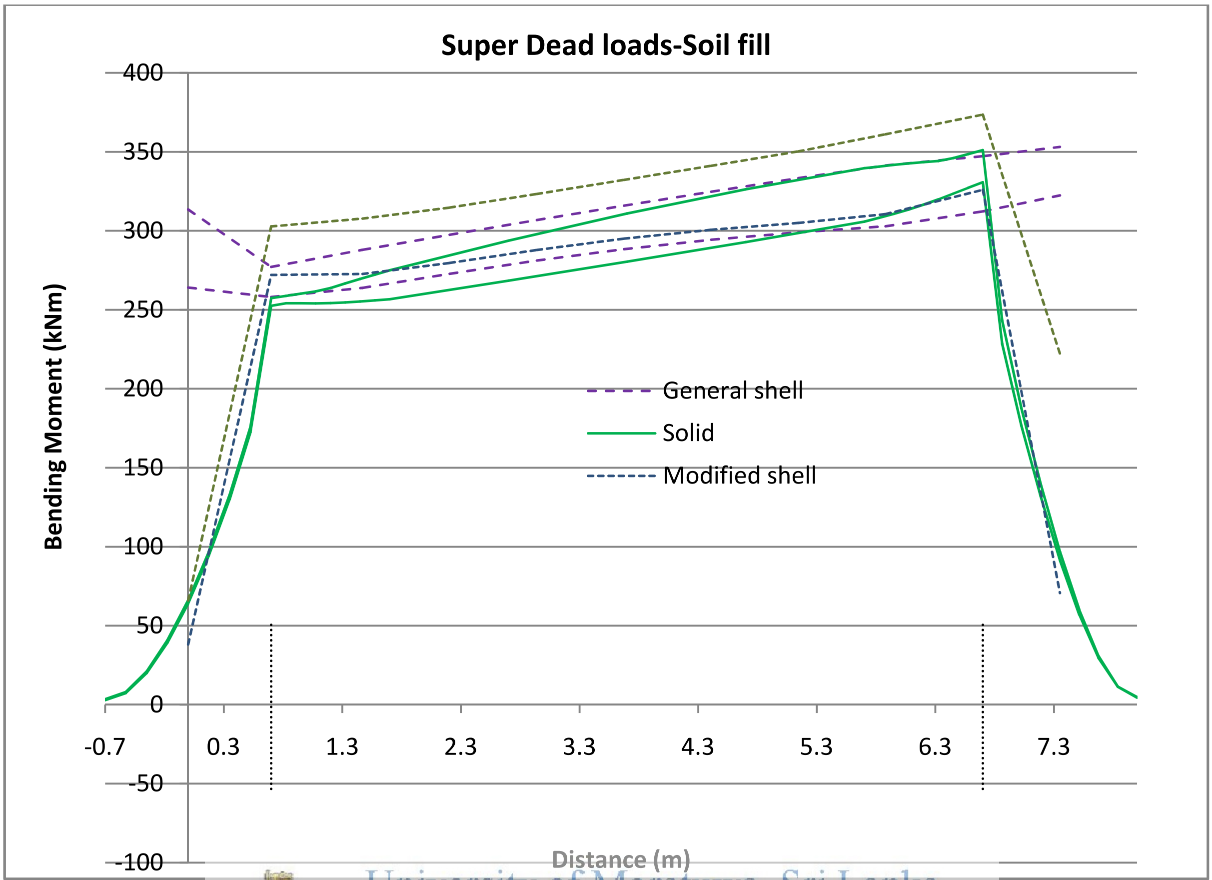

Earth Pressure
350
300
250
200
150
100
50
0
-50
-100
-150
Bending Moment (kNm)
General shell
Solid
Modified shell
-1
4
9
14
19
24
29
34
39
44
Distance (m)

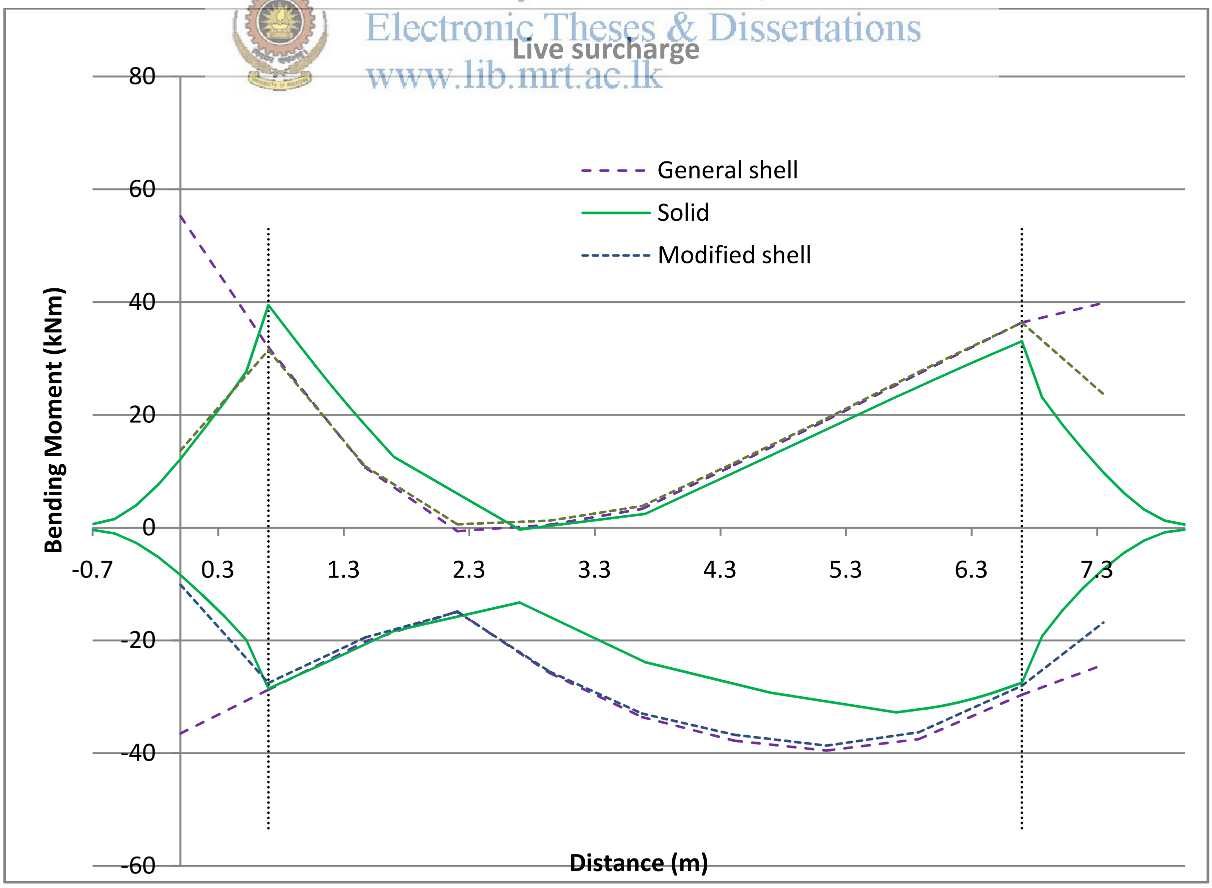

Traction or Braking
150
100
50
0
-50
-100
-150
Bending Moment (kNm)
General shell
Solid
Modified shell
-1
4
9
14
19
24
29
34
39
44
Distance (m)

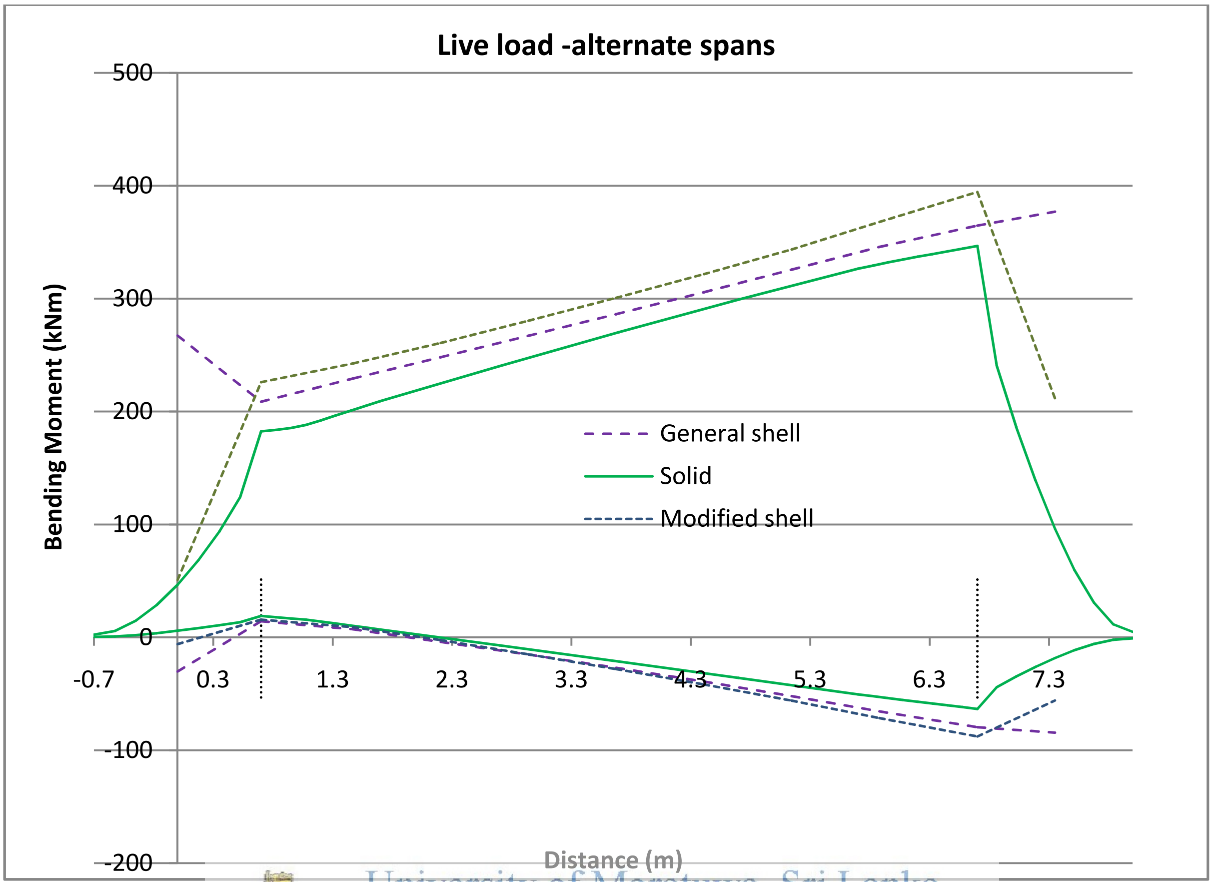
H.1.10: BME of Outside walls-Double cell (model no: 5)

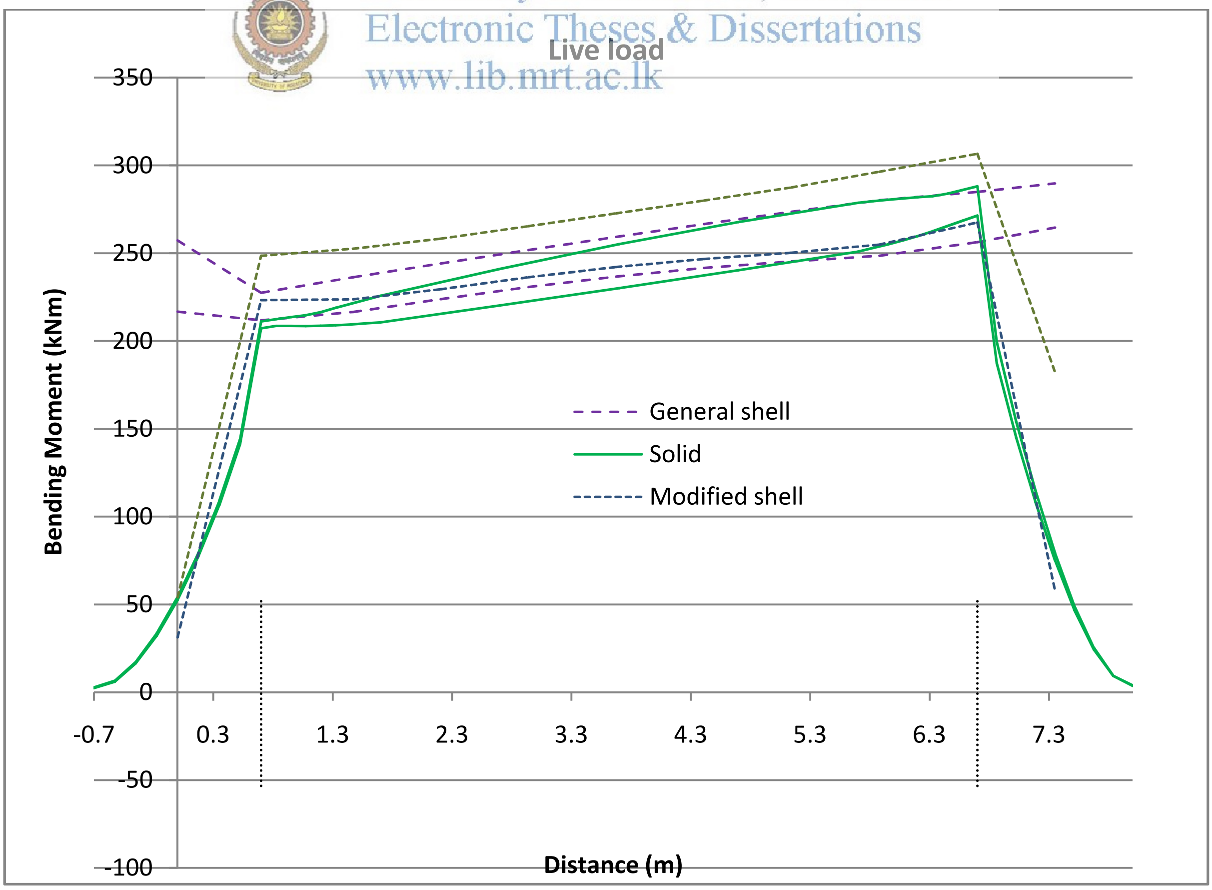


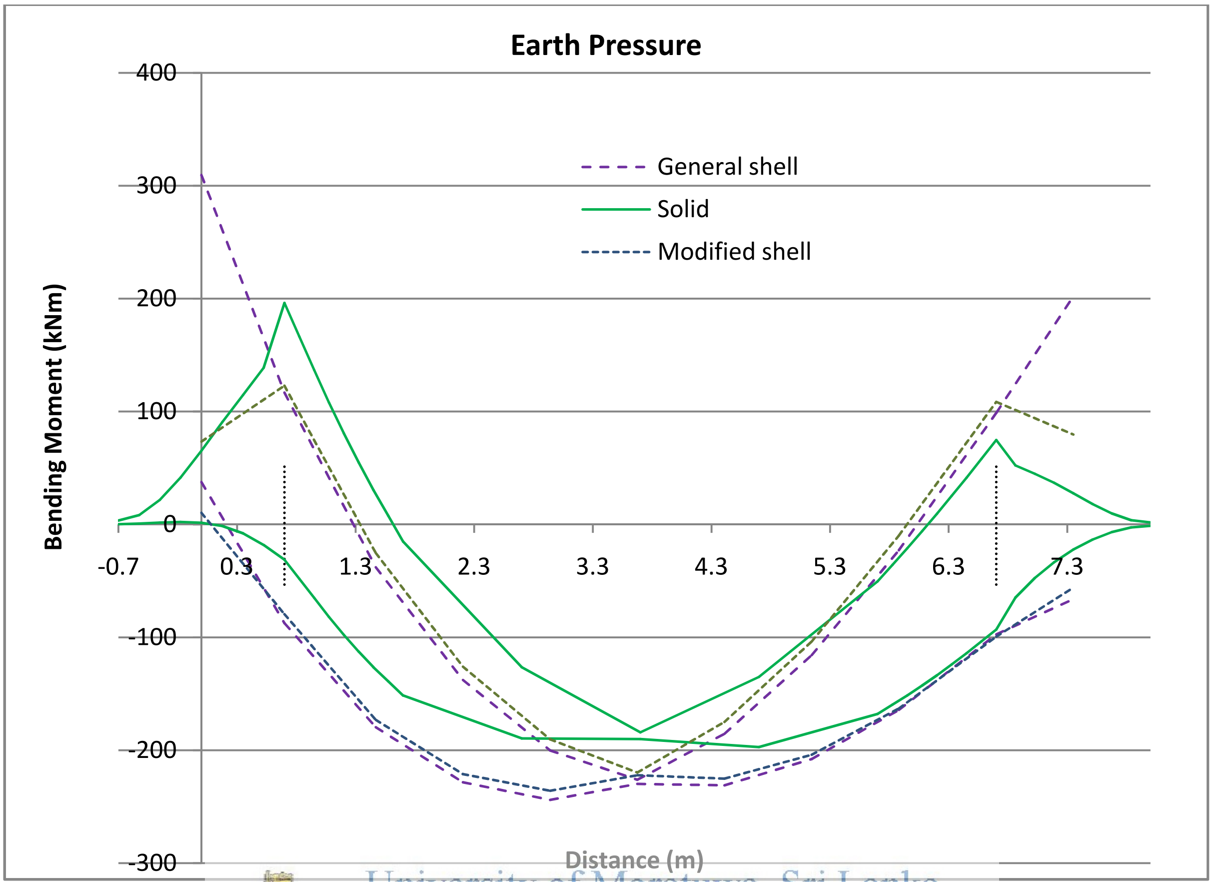


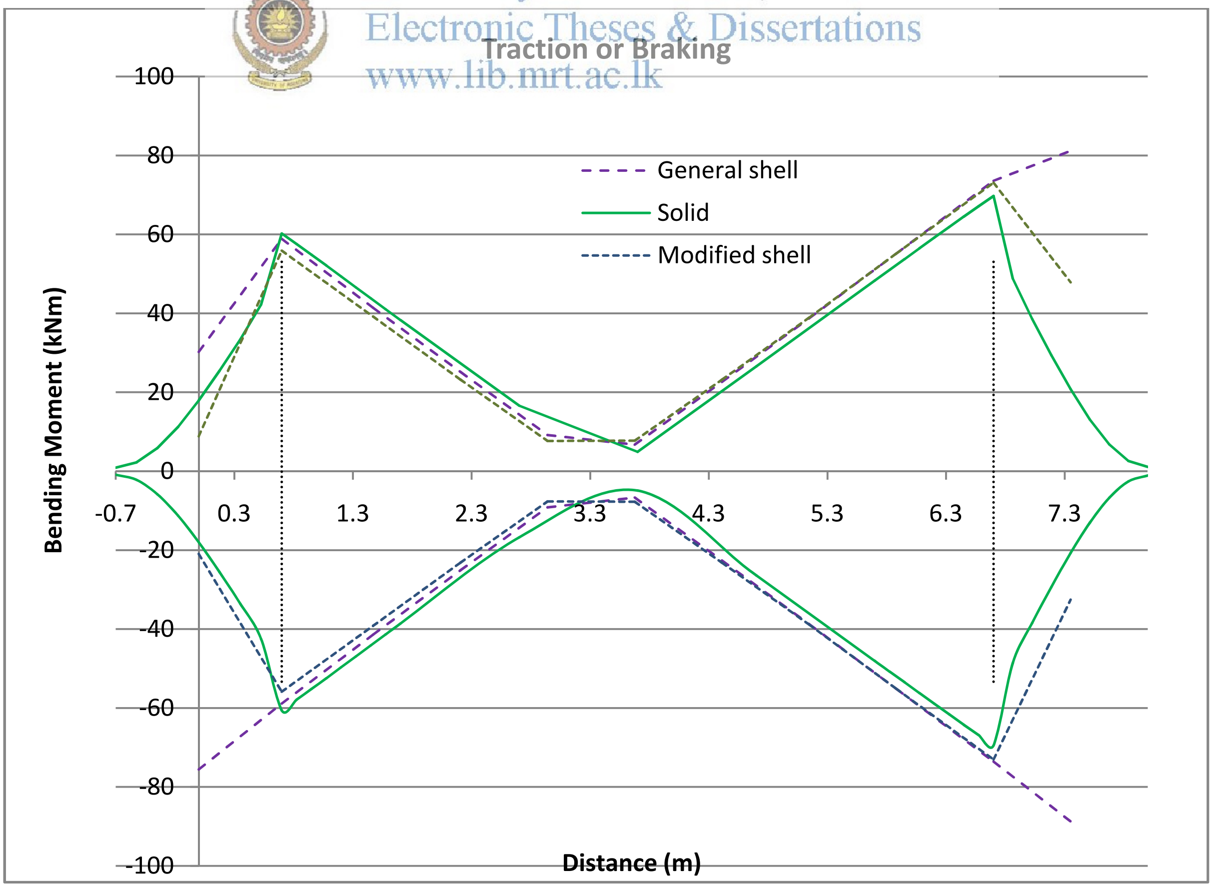

Super Dead loads-Soil fill
Bending Moment (kNm)
400
350
300
250
200
150
100
50
0
-50
-100
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3
General shell
Solid
Modified shell
Distance (m)


Live surcharge
Bending Moment (kNm)
80
60
40
20
0
-20
-40
-60
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3
General shell
Solid
Modified shell
Distance (m)

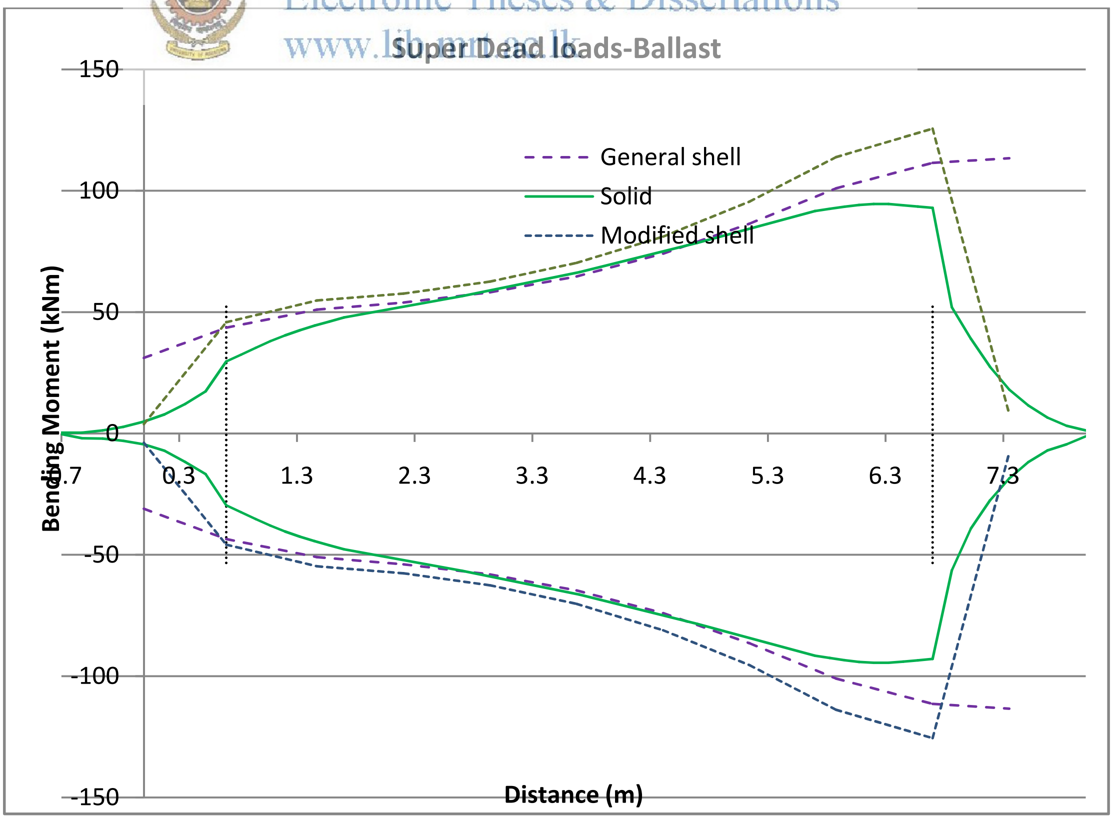

Live load -alternate spans
Bending Moment (kNm)
500
400
300
200
100
0
-100
-200
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3
General shell
Solid
Modified shell
Distance (m)

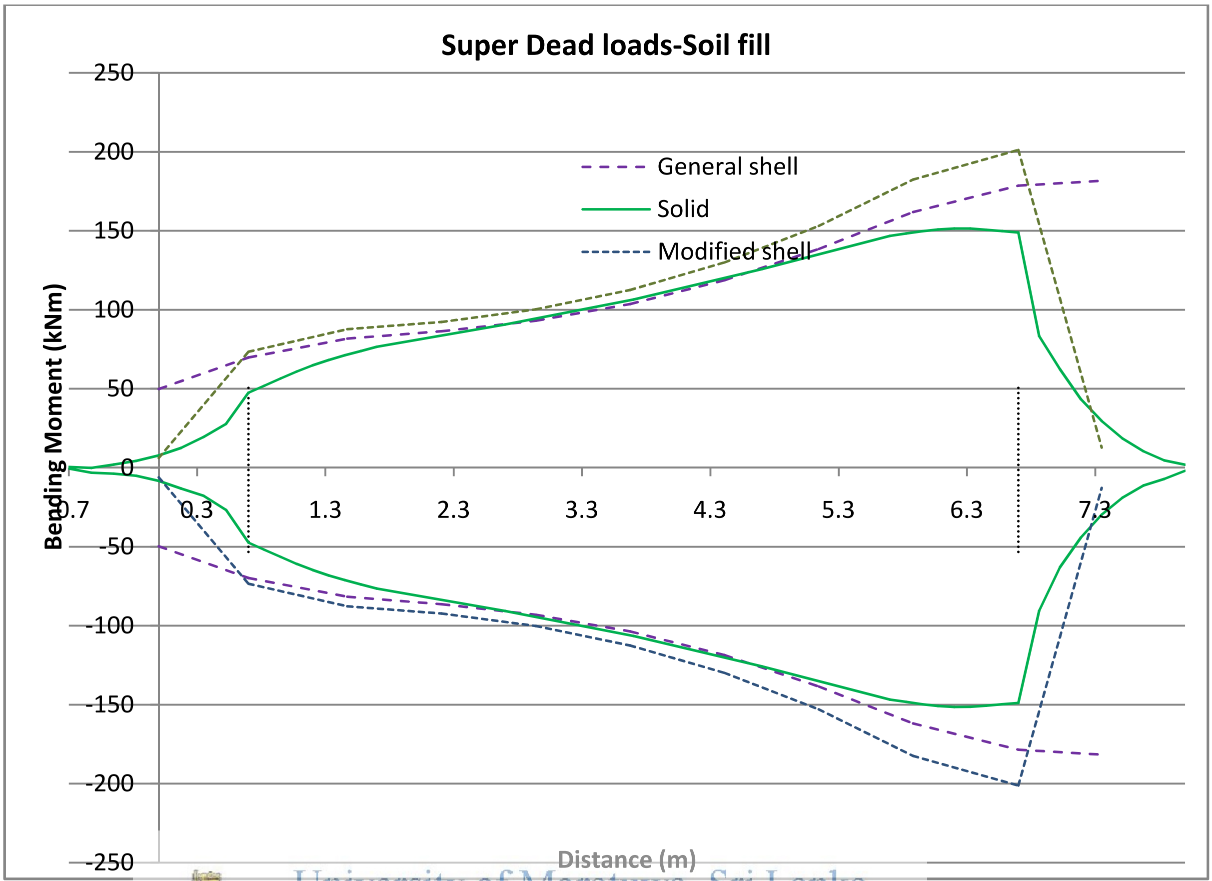

Live load
Bending Moment (kNm)
350
300
250
200
150
100
50
0
-50
-100
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3
General shell
Solid
Modified shell
Distance (m)

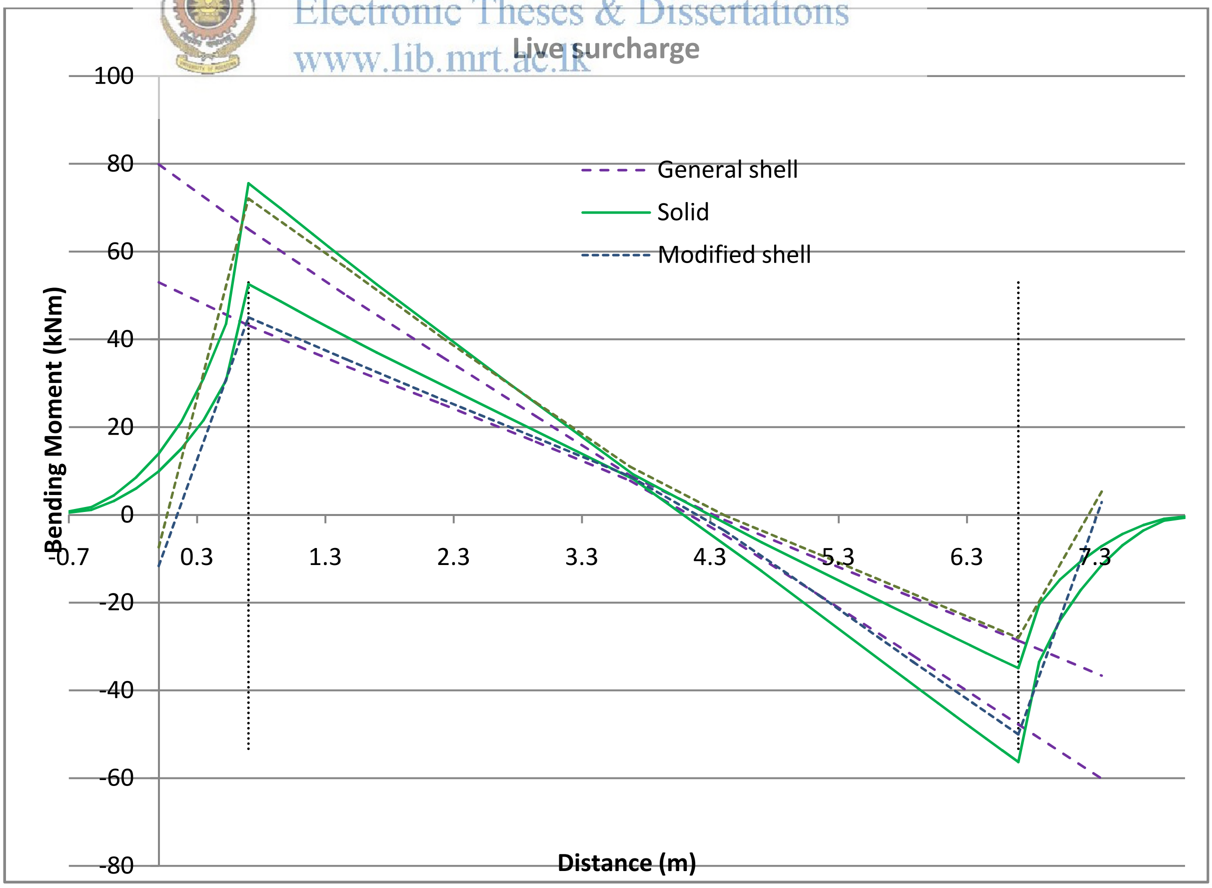

Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
400
300
200
100
0
-100
-200
-300
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3

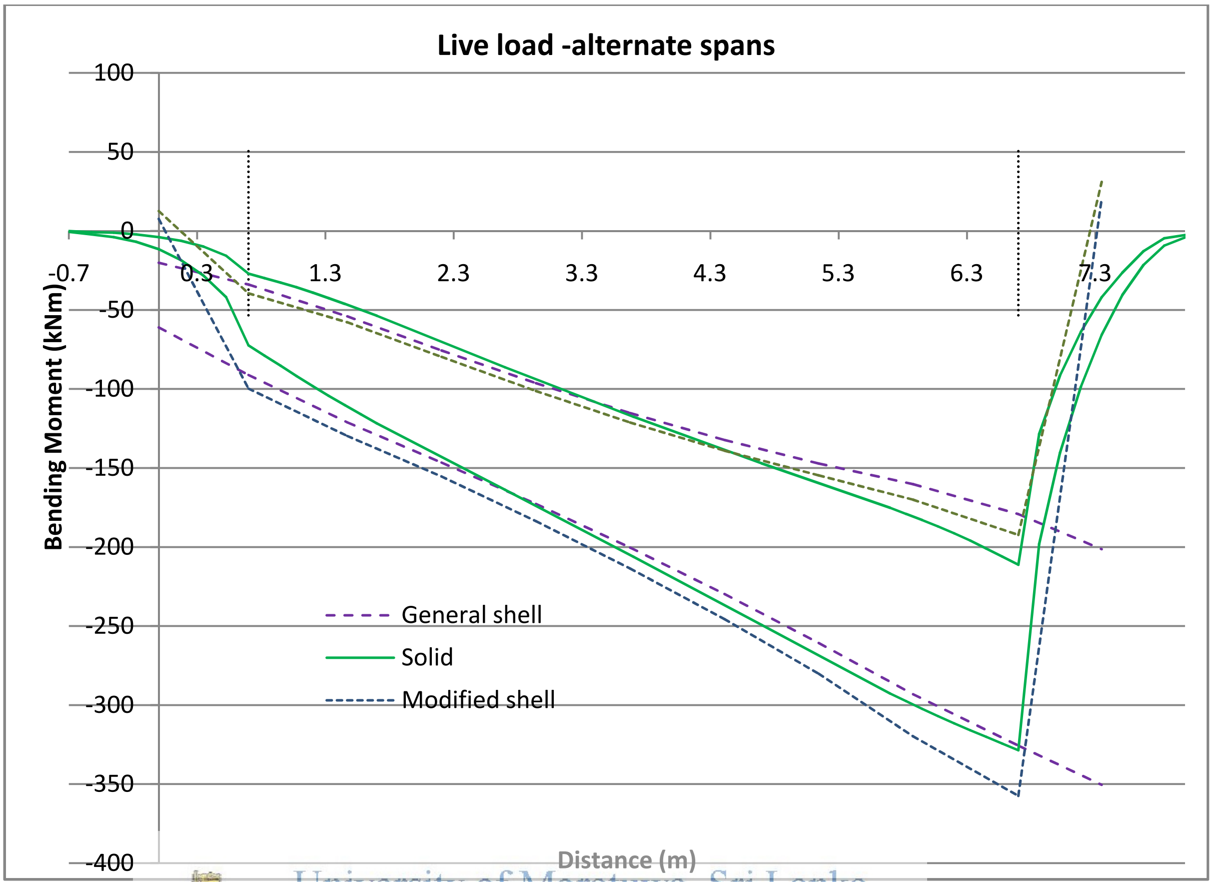

Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3

H.1.11: BME of Inside walls-Double cell (model no: 5)

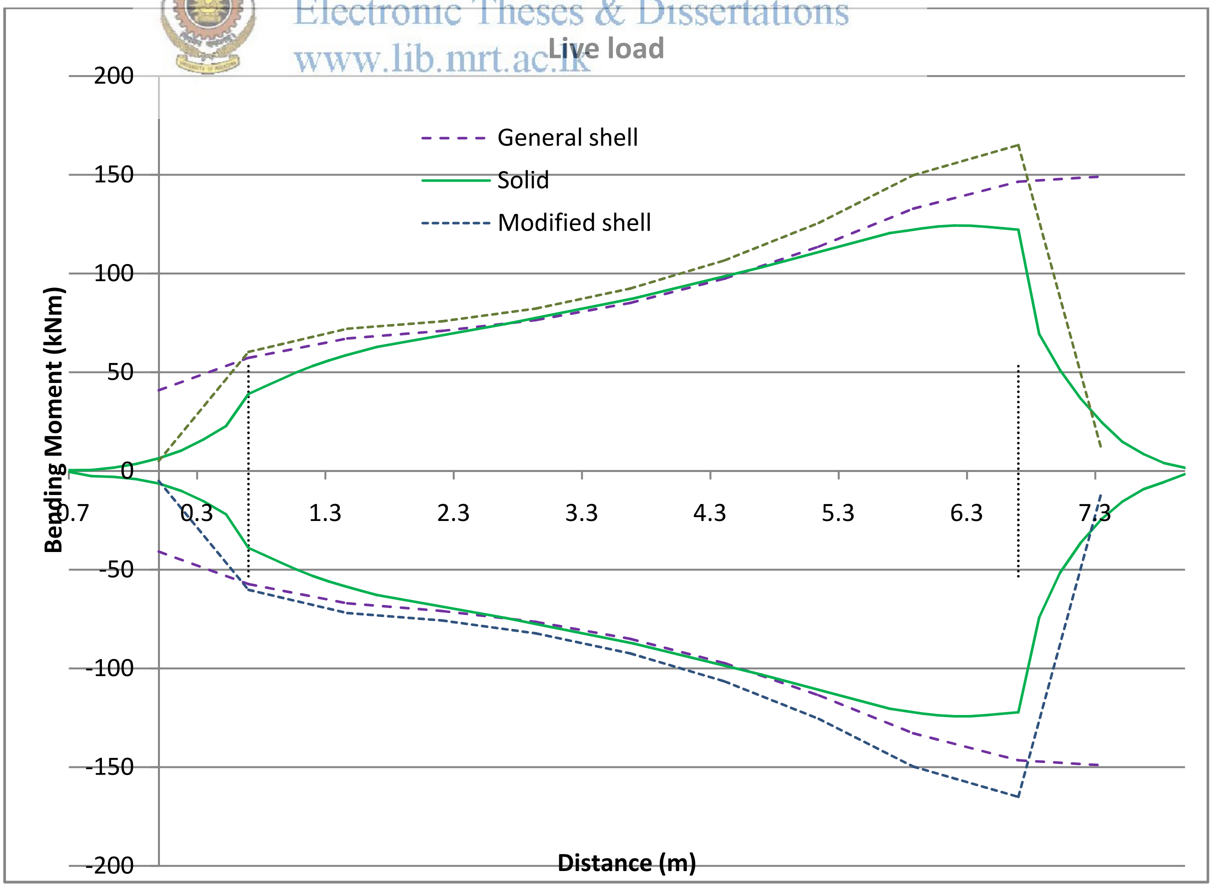



Super Dead loads-Soil fill
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3

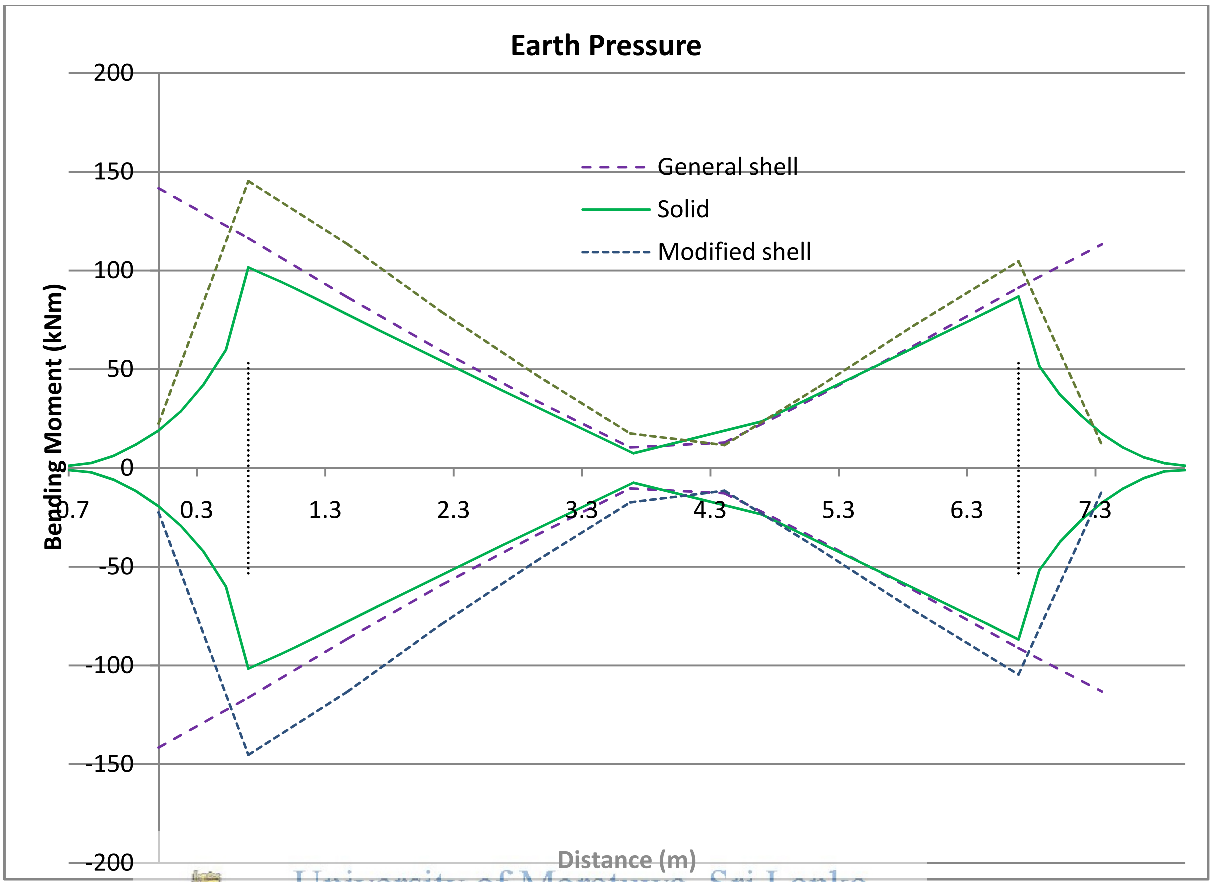

Live surcharge
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
100
80
60
40
20
0
-20
-40
-60
-80
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3

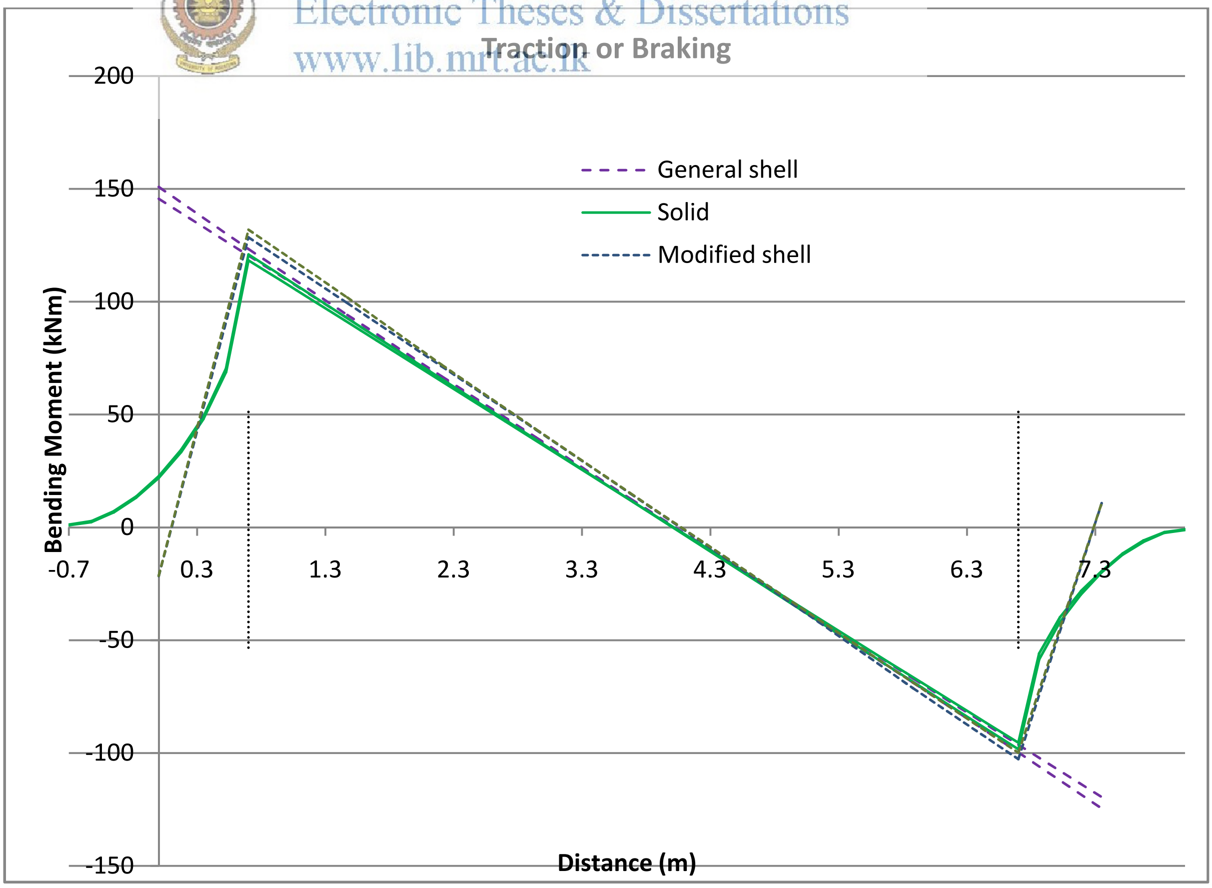


Live load -alternate spans
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3
Bending Moment (kNm)
General shell
Solid
Modified shell
Distance (m)



Live load
200
150
100
50
0
-50
-100
-150
-200
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3
Bending Moment (kNm)
General shell
Solid
Modified shell
Distance (m)


Earth Pressure
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
200
150
100
50
0
-50
-100
-150
-200
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3


Traction or Braking
General shell
Solid
Modified shell
Bending Moment (kNm)
Distance (m)
200
150
100
50
0
-50
-100
-150
-0.7
0.3
1.3
2.3
3.3
4.3
5.3
6.3
7.3