THE ANALYSIS OF CONNECTED BACK TO BACK MECHANICALLY STABILISED EARTH WALLS

by

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ABSTRACT

Back to back mechanically stabilised earth walls (MSEW's) are designed independently as there is a lack of design guidance in the British Standard - Code of practice for strengthened/reinforced soils and other fills (BS8006-1:2010) for their analysis and design. Designers are sometimes tempted to have continuous reinforcement from each face of the back to back MSEW's to save time and money especially when narrow back to back MSEW's cause an overlap of reinforcement from each wall face. Unfortunately, the design guidance available is few and far between with vague recommendations presented by various authors and organisations. This dissertation focuses mainly on the forces generated in the reinforcement of the MSEW's. A case study of an existing back to back MSEW with continuous reinforcement between the walls was first carried out using BS8006-1:2010 and finite element methods (FEM). The FEM analysis was carried out using the finite element modelling software package Plaxis 2D. Thereafter, a study using FEM was carried out to investigate the effects on the forces generated in the reinforcements for various types of geometries. The different geometries varied by having back to back MSEW's with independent reinforcement, continuous reinforcement, and overlapping reinforcement. The forces generated in each configuration was then compared to forces that would have been calculated had the MSEW's been designed using BS8006-1:2010. Conclusions and recommendations are then provided which would assist a designer wanting to have continuous reinforcement in a back to back MSEW.

ACKNOWLEDGMENTS

Firstly, I want to thank God (Krishna). Please chant Hare Krishna Hare Krishna Krishna Krishna Hare Hare / Hare Rama Hare Rama Rama Rama Hare Hare and be happy.

I would like to thank my supervisors, Dario and Georgios for assisting me with this dissertation.

I thank my parents, friends and family for the constant encouragement.

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LIST OF ABBREVIATIONS

BS8006-1:2010	British Standard - Code of practice for strengthened/reinforced soils and other fills
FEM	Finite element method
H	Mechanical height of MSEW
L	Length of reinforcement in MSEW
MSEW	Mechanically stabilised earth wall
N/A	Not applicable
RSS	Reinforced soil slopes
SLS	Serviceability limit state
ULS	Ultimate limit state

CHAPTER 1 : INTRODUCTION

This chapter introduces the purpose of this study and elaborates on the background, scope, and objectives of this study.

1.1 Framework

The growth of and expansion of the human population has rapidly caused urbanization with space for development always a concern. Structures are being built to maximize on the available space in most major cities around the globe. Mechanically stabilised earth walls (MSEW's) are used to construct retaining walls, ramps, and abutments. An MSEW comprises of layers of reinforcement placed within a soil mass which carry the loads imposed on the soil mass (The Canadian Geotechnical Society, 2006). The requirement of space and costs of construction are pushing designers towards narrower MSEW's. Narrower back to back MSEW's address the following concerns of the modern-day designer:

- They use up less space
- Require less earthworks and fill material
- Aesthetically pleasing when compared to bulk fill embankments

Mechanically stabilised earth walls seem to solve the designer's dilemma but the design approach of the narrower connected back to back MSEW's are not clearly defined and the designer has to resort to conservative approaches which are less economical.

1.2 Problem Statement

Mechanically stabilised earth walls that are currently designed to BS8006-1:2010 do not have any specific design guidance or separate analyses for back to back MSEW's. Back to back MSEW's are therefore designed as independent MSEW's and analysed separately. Some back to back MSEW's are narrow enough to cause the reinforcement from each MSEW to meet in the middle or overlap. Being able to have continuous reinforcement between a back to back MSEW could potentially then save time and money. Less reinforcement would be required for back to back MSEW's that required overlapping reinforcement and construction time could be improved by having continuous reinforcement.

The U. S. Department of Transportation Federal Highway Administration have a publication (Berg, et al., 2009) which vaguely provides some guidance into designing back to back MSEW's with continuous reinforcement while The Hong Kong government, (Jones, 2002), mentions that back to back MSEW's with continuous reinforcement fall out of the scope of reinforced soil structures. However, (Berg, et al., 2009) does mention that finite element methods (FEM) may be employed to analyse back to back MSEW's with continuous reinforcement.

1.3 Scope and Objective of Dissertation

The vagueness of design guidelines and standards for back to back MSEW's with continuous reinforcement between the walls has prompted this research in order to investigate the effects on the MSEW behaviour when the reinforcement is continuous between a back to back MSEW. The main focus of the study is to compare the forces generated in the reinforcement since the design guidelines that do provide some guidance (although vague) such as (Berg, et al., 2009) mention that having continuous reinforcement will increase the forces in the reinforcement. Other parts that will be also looked at is the maximum horizontal displacement of the facing panels of the MSEW and the vertical settlement near the surface of the MSEW. The objective of the investigation is to determine whether having continuous reinforcement between back to back MSEW's is actually viable or not and to provide some design guidance for back to back MSEW's with continuous reinforcement.

The investigation will be carried out using an existing constructed back to back MSEW with continuous reinforcement whereby the MSEW's will be designed using BS8006-1:2010 and then checked using FEM. The study will then be expanded on by using various types of geometries to mainly investigate the effects on the forces generated in the reinforcements for continuous reinforcement, overlapping reinforcement, and independent reinforcement.

1.4 Dissertation Organisation

The first chapter provides the framework, problem statement, objectives and organisation of this dissertation. The second chapter is a literature review which covers topics associated with reinforced soil structures, geosynthetics and FEM. The third chapter details the methodology that will be used in this study for designing MSEW's using analytical methods and FEM methods. The fourth chapter contains the analysis and results of the case study investigated along with the results of the various configurations being investigated. The fifth chapter presents the discussion and conclusion of the research carried out.

CHAPTER 2 : LITERATURE REVIEW

This chapter covers the review of literature associated with this dissertation.

2.1 Geosynthetics

“Geosynthetics is a general term for all synthetic materials used with soil, rock and/or any other civil-engineering related material as an integral part of a man-made project, structure or system.” (Shukla, 2012).

There are a number of geosynthetic products (mostly polymeric) available on the market and they can be grouped into categories based on their method of manufacture which are summarised as follows (Bathurst, 2018) and (Shukla, 2012):

a) Geotextiles

These are permeable textile products manufactured in the form of flexible sheets. There are various types of geotextiles given below as follows:

- Woven geotextiles (has a regular textile structure made from yarns of one or several fibres)
- Non-woven geotextiles (produced by bonding fibres in a loose web placed in an ordered direction or randomly)
- Knitted geotextiles (made by interloping one or more yarns together)
- Stitch-bonded geotextiles (made by stitching fibres and/or yarns together)

Figure 2-1 below shows a picture of various types of geotextiles.

Figure 2-1: Picture of various geotextiles (Wikimedia Commons, 2014)

b) Geogrid

A planar mesh is formed by intersecting elements to form the grid. The elements are joined by bonding, extruding, or interlacing the elements. Depending on the type of join used in creating the geogrid, the geogrid is said to be bonded, extruded, or woven. Figure 2-2 below shows a picture of various types of geogrids.

Figure 2-2: Picture of various geogrids (Wikimedia Commons, 2014)

c) Geonets

They comprise of a network of elements joined in a variety of angles to form the grid pattern. These are similar to geogrids and vary more in their use than their method of manufacture. Figure 2-3 below shows a picture of a geonet.

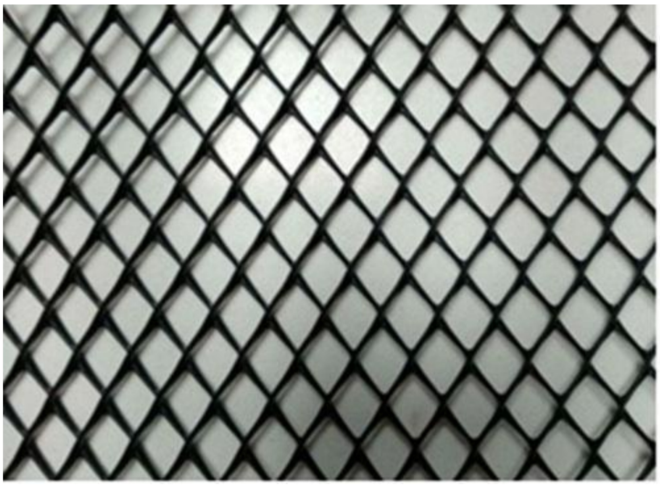

Figure 2-3: Picture of a geonet (Indiamart, 2018)

d) Geocomposites

When two or more geosynthetics are combined to form a composite, they are called a geocomposite. The combination of two or more geosynthetics to form the geocomposite are carried out because they work better being applied together than separately to perform their different functions. Figure 2-4 below shows a picture of various types of geocomposites.

Figure 2-4: Picture of various geocomposites (Wikimedia Commons, 2014)

e) Geofoam

This is a light weight high void ratio material used for fill, insulation, and drainage. Figure 2-5 below shows a picture of geofoam on a construction site.

Figure 2-5: Picture of geofoam (Wikimedia Commons, 2018)

f) Geomembrane

This geosynthetic comprises of a membrane that is continuous and assists in the control of fluid flow. Figure 2-6 below shows a geomembrane being laid on site.

Figure 2-6: Picture of geomembrane (Alibaba, 2018)

Geosynthetics are used in various applications and the type of geosynthetic used is controlled by the function they need to fulfil in their application. The geosynthetics main function may be broken down and summarized as follows (The Canadian Geotechnical Society, 2006):

i. Separation

A geosynthetic may be used to separate two layers of material that have different particle size distributions (see Figure 2-7 below). An example of this may be when competent material is placed over a weaker material during the construction of a road. The geosynthetic will separate the two layers of material so that the weaker material does not mix into and compromise the integrity of the competent layer.

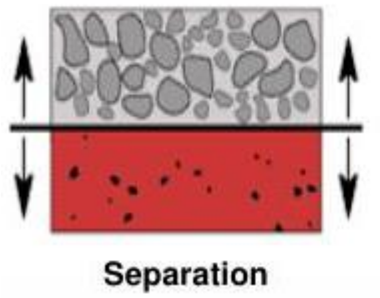

Figure 2-7: Geosynthetic used to separate two layers (Maccaferri Industrial Group, 2018)

ii. Filtration

The function of the geosynthetic is to allow the movement of fluid through the geosynthetic while preventing the material through which the fluid is flowing to pass through (see Figure 2-8 below). An example of this function could be given as a geosynthetic at the end of a drainage pipe allowing the water to exit while preventing the soil material from passing through.

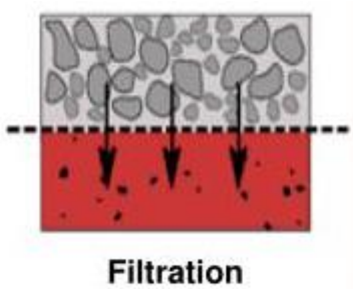

Figure 2-8: Geosynthetic used to allow movement of fluid between two layers (Maccaferri Industrial Group, 2018)

iii. Drainage

The geosynthetic functions as the permeable media through which fluids can flow (see Figure 2-9 below). An example of this can be when wick drains are placed in clays to allow the faster migration of water out of the clays decreasing the consolidation time.

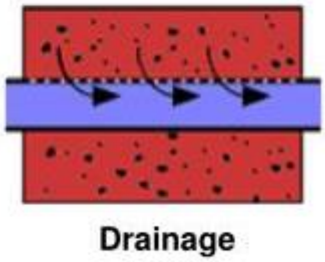

Figure 2-9: Geosynthetic used as permeable media for fluid flow (Maccaferri Industrial Group, 2018)

iv. Reinforcement

The geosynthetic material is placed within other materials like soil to increase the strength and deformation characteristics of the material similar to how steel is placed within concrete to increase the tensile strength of the concrete (see Figure 2-10 below). Examples of how geosynthetics are used as reinforcement are when they are used to construct embankments over soft soils, used to bridge over voids that may develop, and when they are used in the construction of reinforced soil walls.

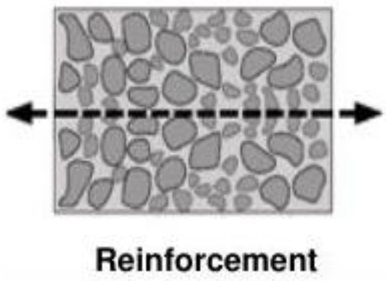

Figure 2-10: Geosynthetic placed in material to act as reinforcement (Maccaferri Industrial Group, 2018)

v. Fluid/Gas (barrier containment)

The geosynthetic functions as an impermeable layer preventing fluids or gases from passing through (see Figure 2-11 below). An example of this function could be when liners are placed in landfill sites to prevent contaminants from entering the in situ material.

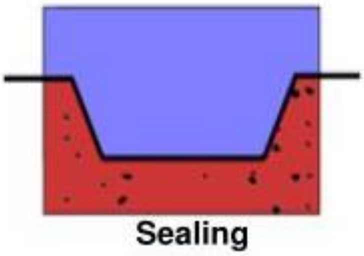

Figure 2-11: Geosynthetic used to prevent gas or liquid from entering a layer (Maccaferri Industrial Group, 2018)

vi. Erosion control

The geosynthetic is used to reduce the erosion of material by acts of rainfall impact and surface water run-off (see Figure 2-12 below). An example of this function can be when geosynthetics are placed over newly constructed slopes to prevent the erosion of the soil material by the action of wind and water while allowing the growth of natural vegetation which will eventually serve as the primary erosion control mechanism.

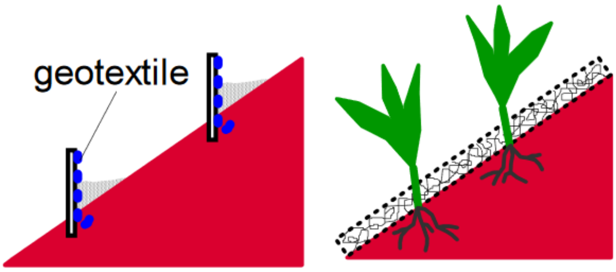

Figure 2-12: Geosynthetics used to control erosion (Bathurst , 2018)

2.2 Earth retaining structures

In civil engineering projects the change of elevation between two points sometimes creates the need to allow for a transition between the two elevations. When space is available, this transition is accomplished using slopes but when space is limited, retaining structures are used to create the required support and space. Earth retaining structures can be used to create straighter paths for road construction, retain soil/rock and are also used in a variety of projects such as (Coduto, 2001):

- Railway and highway construction
- Bridge abutments
- Quay walls
- Creating level construction surfaces

- Stabilizing potentially unstable slopes
- Flood mitigation projects

Earth reinforcement has been an ongoing practice with a known existence dating back to 4000-5000 B.C (Ziegler, 2017). Inclusions acting as reinforcement has been used since prehistoric times with straw being used in adobe bricks which dates back to the earliest human history (Berg, et al., 2009). The earliest structures which incorporated earth reinforcement that are still present are the Aqar Quf (Figure 2-13 below) in Mesopotamia near Bagdad and the Great Wall of China. The Agar Quf is about 3500 years old and was erected by the Sumerians under King Kurigalzu using clay bricks and woven reed mats acting as reinforcement (Ziegler, 2017). The Great Wall of China constructed circa 200 B.C. has portions of it that has soil reinforcement comprising gravel and clay with tamarisk branches acting as reinforcement (Jones, 1985).

Figure 2-13: Agar Quf in Bagdad constructed using soil reinforcing techniques dating back 3500 years (Knapp, 2014)

The Romans and Gauls used reinforcing techniques to construct fortifications while Colonel Pasley in 1822 used brushwood to reinforce fill reducing the lateral earth pressures from the fill. Soil reinforcement was used in various other applications such as dam construction, river control measures, and reinforcement of weak soils. Henri Vidal in the 1960's used steel strips laid horizontally in fill material to act as reinforcement. The weight of the fill on the steel strips and the roughness of the strips created the frictional component of the reinforcing element. Through technological advances, synthetic materials are now also being used in soil reinforcement (Jones, 2002).

Earth retaining structures can be broken up into two broad categories depending on the method the structure fulfils the required function namely, externally stabilised systems and internally stabilised systems. Figure 2-14 below provides some insight into the various categories and into which families they belong (Coduto, 2001):

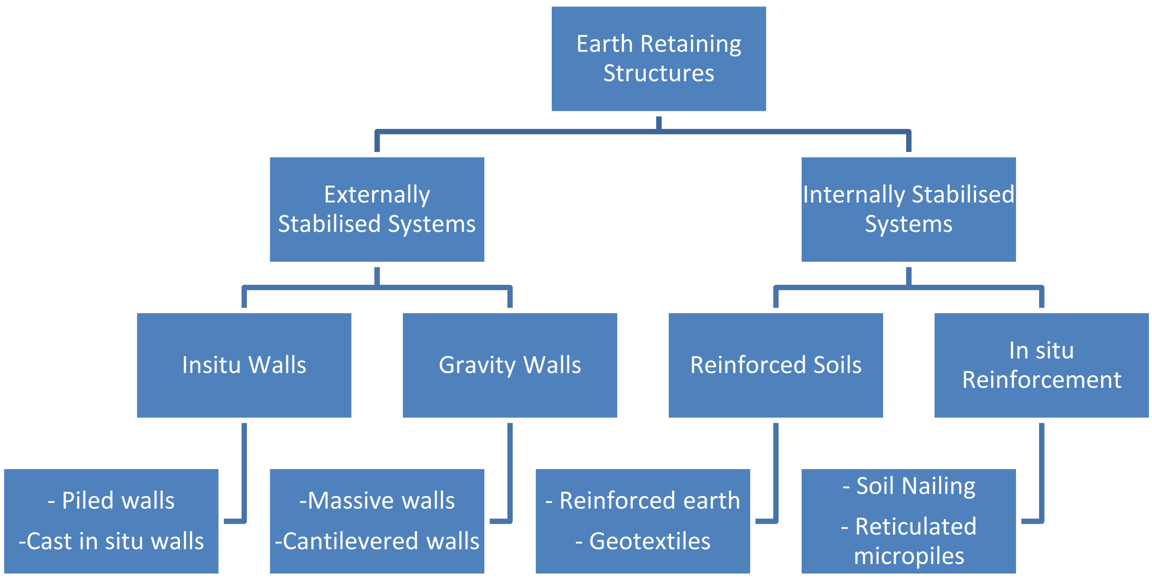

Figure 2-14: The classification of earth retaining structures (Coduto, 2001)

a) Hybrid systems

In some cases, systems employing facets of both systems are utilised creating a hybrid system such as a gabion wall tied back with geosynthetics. Figure 2-15 below gives examples of hybrid systems.

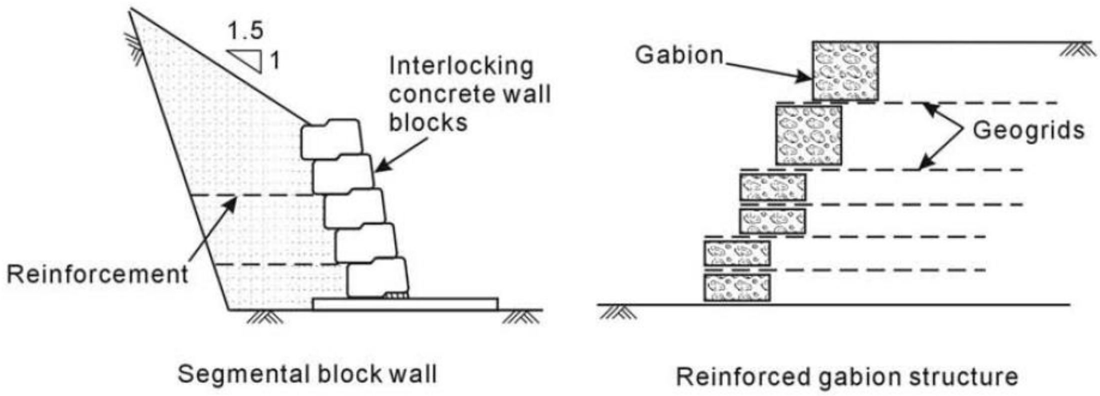

Figure 2-15: Hybrid systems

b) Externally stabilised systems

i. In situ Walls

These types of walls gain their retaining capabilities in the members flexural strength rather than their weight when compared to gravity type walls. Some examples of these types of walls are sheet piled walls, soldier piled walls, secant piled walls, and slurry walls. These wall types can be braced, anchored, and tied back to aid in their restraining abilities (Coduto, 2001).

ii. Gravity Walls

These types of walls gain their retaining capabilities by utilising the weight of the wall and the backfill used during construction. The use of only massive walls is labour intensive and require a fair amount of material for construction therefore they are generally avoided. The use of gravity walls such as cantilevered walls and crib walls utilises the weight of the wall and the backfill to provide the required restraint (Coduto, 2001).

Figure 2-16 below shows examples of externally stabilised systems.

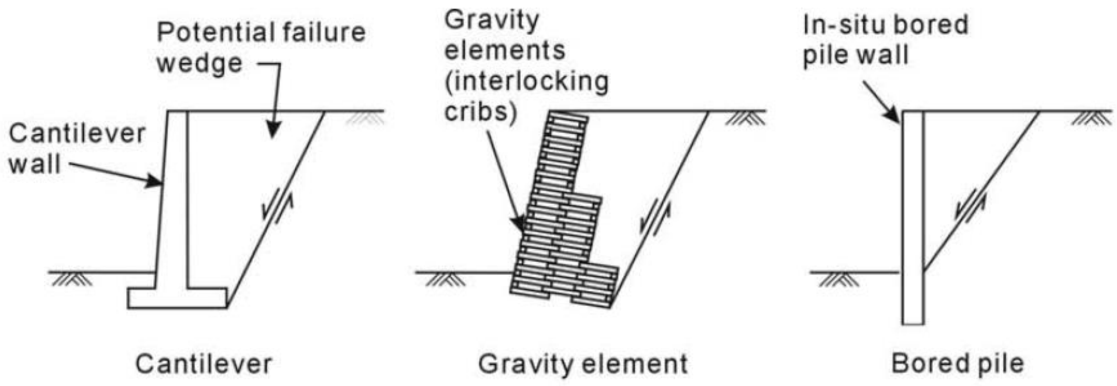

Figure 2-16: Externally stabilised systems (Jones, 2002)

c) Internally stabilised systems

i. In situ Reinforcement Type Walls

These walls have reinforcement such as soil nails or reticulated micropiles which are inserted into the soil body. These tensile members which are added into the soil body increases the shear strength of the body allowing the soil mass to be held up at various angles (Coduto, 2001).

ii. Reinforced Soils Structures

Reinforced soil structures are covered in detail in section 2.2.1 since the topic of study deals with this wall type.

Figure 2-17 below gives examples of internally stabilised systems

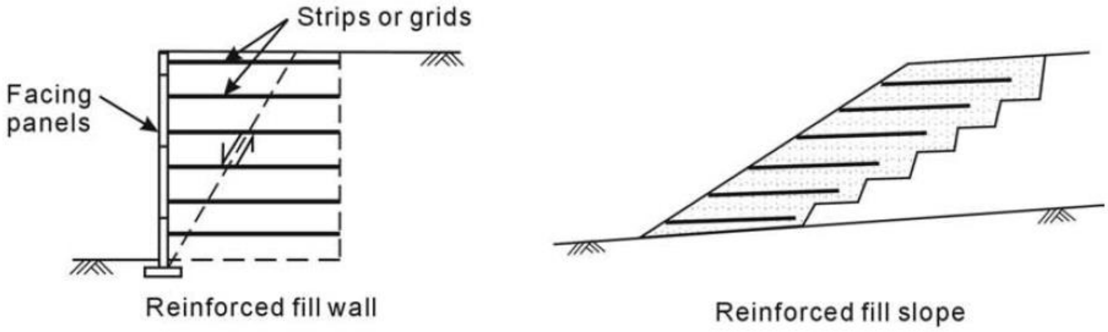

Figure 2-17: Internally stabilised system (Jones, 2002)

2.2.1 Reinforced soil structures

Reinforced soil structures comprise of layers of reinforcement (geosynthetics or steel materials) placed within a soil mass creating a reinforced zone. This reinforced zone behaves like a gravity wall and carries the loads imposed on it which can comprise of external surcharge loads and earth forces acting behind the reinforced zone (The Canadian Geotechnical Society, 2006). These types of structures differ from structures with in situ reinforced walls in that these structures have reinforcement placed within the soil body during fill placement compared to the in situ reinforced walls which have the reinforcement inserted into the soil mass (Coduto, 2001). In the same way that steel reinforcement is placed within concrete to increase the tensile strength of the concrete, soil reinforcement is placed within a soil mass to increase the tensile carrying capacity of the soil (Bowels, 1997). There are various types of reinforced soil structures available which are summarised as follows (Jones, 2002):

a) Elemental systems

Uses discrete concrete facing elements which allows settlement in the fill mass to be taken up by the panels closing shown in Figure 2-18 below.

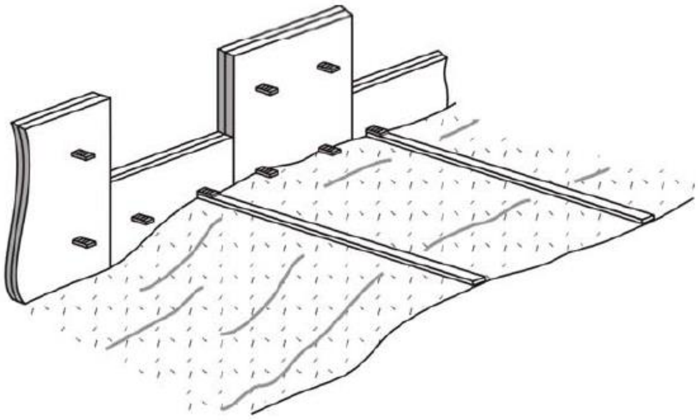

Figure 2-18: Elemental system showing concrete facing with strip reinforcement (Jones, 2002)

b) Full Height system

The facing element is the full height of retention with differential settlements in the fill being taken up by the reinforcing members ability to slide along the facing element which is shown in Figure 2-19 below.

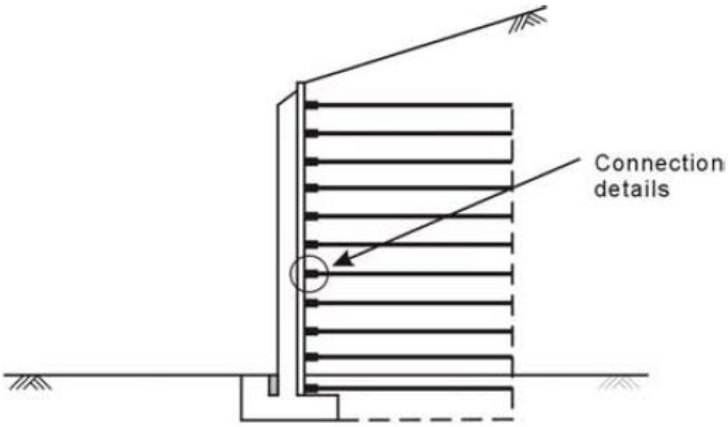

Figure 2-19: Full height system (Jones, 2002)

c) Wrap-around system

Reinforcing elements form the wrap around front face of the system. Differential settlements within the fill is taken up by the closing of the wrap around sections. An example of a wrap around system is shown in Figure 2-20 below.

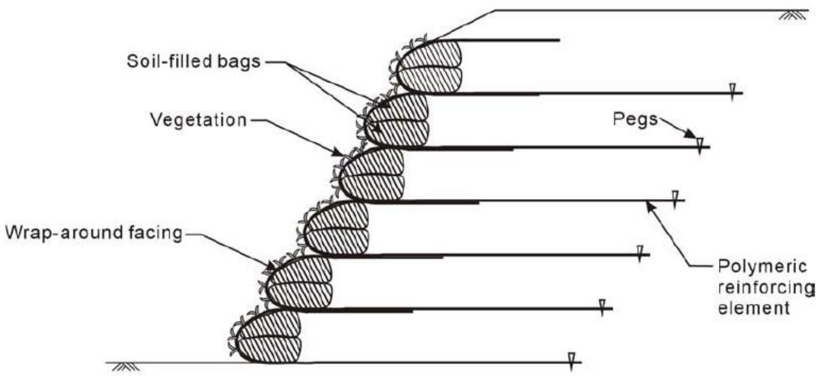

Figure 2-20: Wrap-around system (Jones, 2002)

d) Segmental block system

This system is a conventional block wall with a reinforced soil fill section. This system does not deal too well with differential settlements due to the rigid nature of the blocks therefore the system must be constructed with good backfill and proper compaction. An example of a segmental block wall is shown in Figure 2-21 below.

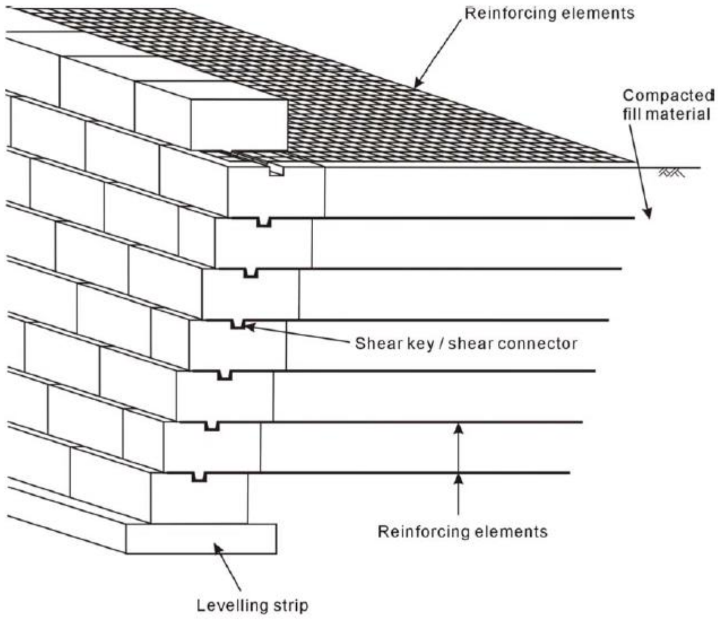

Figure 2-21: Segmental block wall with reinforcing elements

e) Anchored earth system

This system comprises anchors being used as the reinforcing elements for the elemental, full height, or wrap around systems. Anchors can sometimes be more efficient when compared to conventional reinforcing materials. An example of a plate anchor is shown in Figure 2-22 below.

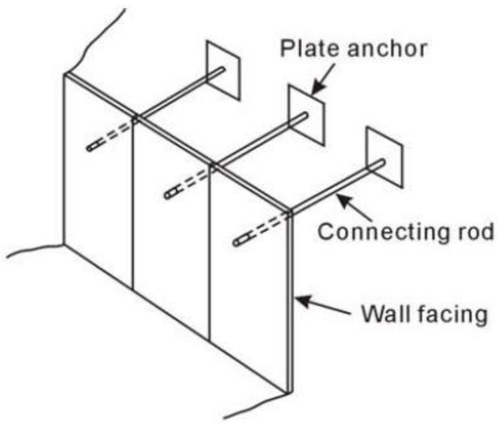

Figure 2-22: Plate anchor (Jones, 2002)

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2.2.2 Mechanically stabilised earth walls

The design of reinforced soil structures is split into two categories namely reinforced soil slopes (RSS) and reinforced soil walls (MSEW's). The defining characteristic differentiating between the two types of design approaches are separated by the angle from the vertical that the structure is inclined. If the batter of the structure falls within 20 degrees from the vertical, the structure is designed as a wall (BS8006-1:2010, 2010). Mechanically stabilised earth walls contain reinforcements that are predominantly horizontal and increase the tensile strength, deformation capability, and shear capacity of the compacted fill that they are placed in (Jones, 2002). Although the concept of using reinforcement elements within a soil mass has been used in ancient civilisations, the French architect named Henry Vidal was the first person to patent (in 1960) the MSEW system comprising of facing elements and steel strip reinforcement creating Reinforced Earth® (Bowels, 1997). Mechanically stabilised earth walls can be used for a variety of applications summarised as follows:

- Bridge abutments
- Bridge wing walls
- Retaining walls and ramps

The various forms of MSEW's that are used as abutments and walls are shown in Figure 2-23 below:

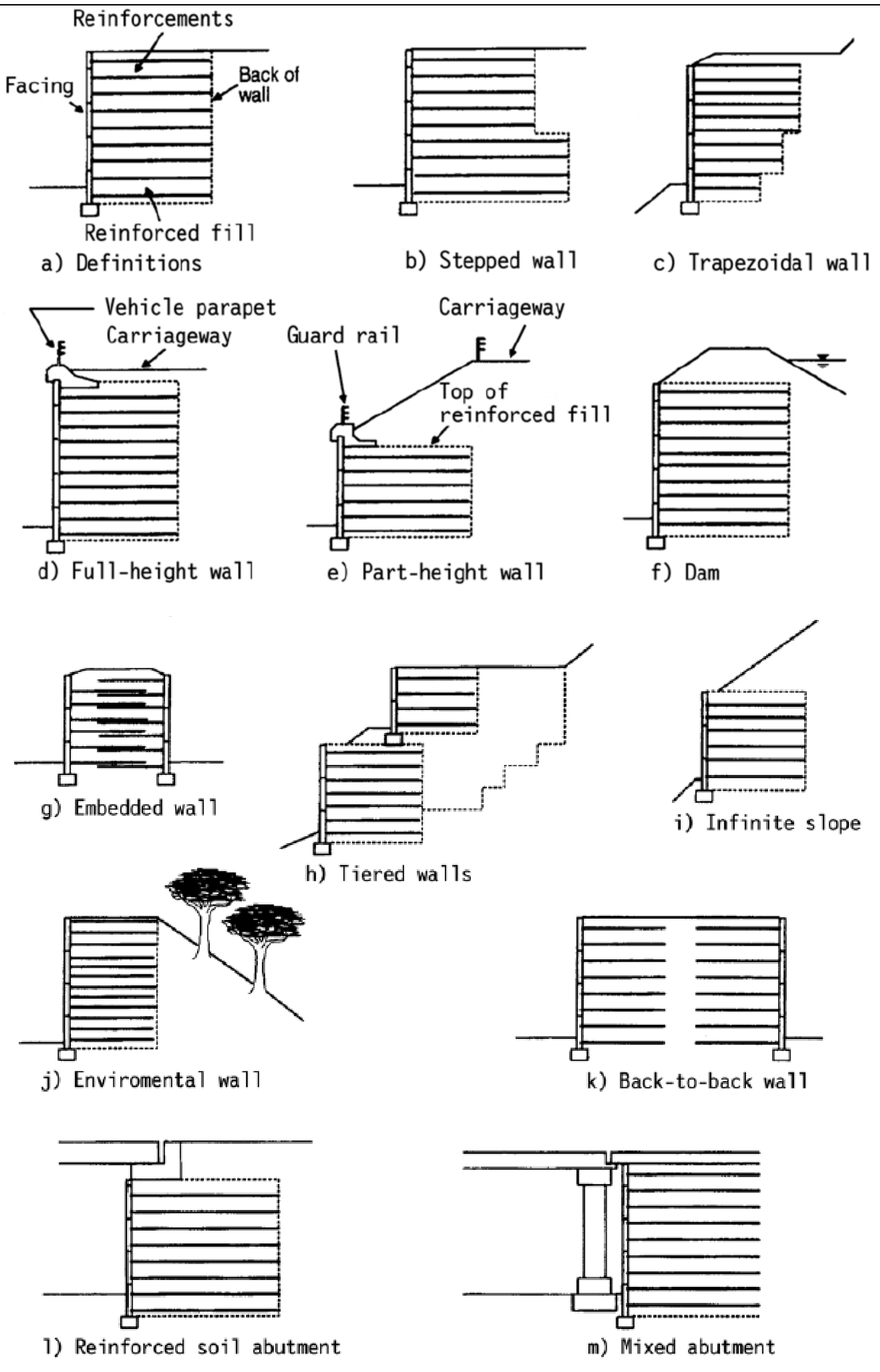


Figure 2-23: Various types of walls and abutments (SANS207, 2006)

There are technical and economic advantages of using MSEW's over conventional methods such as reinforced concrete retaining walls. There is a 20-50% saving in the capital cost when using reinforced soils compared to traditional methods (Jones, 2002). The technical benefits of using

MSEW's over conventional methods lie in their ease of construction, their ability to handle differential settlements and their ability to be constructed over difficult terrain such as weak foundation soils and confined spaces. Conventional reinforced concrete retaining structures on poor foundation soils would generally require some form of ground improvement or piling which ultimately increases the total project cost. Mechanically stabilised earth walls constructed over poor foundation material have shown to have a cost saving of greater than 50 percent when compared to conventional reinforced concrete retaining structures (Berg, et al., 2009). Another economical advantage is that MSEW's due to their flexibility have been used to allow tall structures to be built on sloping ground instead of rigid concrete retaining walls that impose high bearing stresses at the toe which sometimes forces the designer to support the wall using piles (Jones, 2002).

There are a number of design codes, standards and guidelines available to assist in designing MSEW's. Some of the references used in the design of MSEW's are listed as follows:

- Guide to Reinforced Fill Structure and Slope Design (Hong Kong)
- BS 8006-1: 2010 – Code of Practice for Strengthened/Reinforced Soils and Other Fills (United Kingdom)
- Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes – Volume I (United States of America).

2.2.3 Back to back mechanically stabilised earth walls

Back to Back MSEW's are predominately used for highway ramps and embankments approaching bridges (Berg, et al., 2009), (Han & Leshchinsky, 2009). Although these walls are used on many projects, there still seems to be a lack of design guidance for the analysis of these walls. The (BS8006-1:2010, 2010) - Code of practice for strengthened/reinforced soils and other fills does not contain any design guidance for back to back MSEW's. However, the National Highway Institute Federal Highway Administration U.S. Department of Transportation (Berg, et al., 2009) and The Government of the Hong Kong Special Administrative Region (Jones, 2002) have produced publications which have small sections that provide some design guidance.

In the calculation of the lateral pressures affecting external stability, both publications categorise back to back MSEW's into two cases which are dependent on the distance between the opposing MSEW's. Case one is shown in Figure 2-24 below with a discussion on both cases also provided.

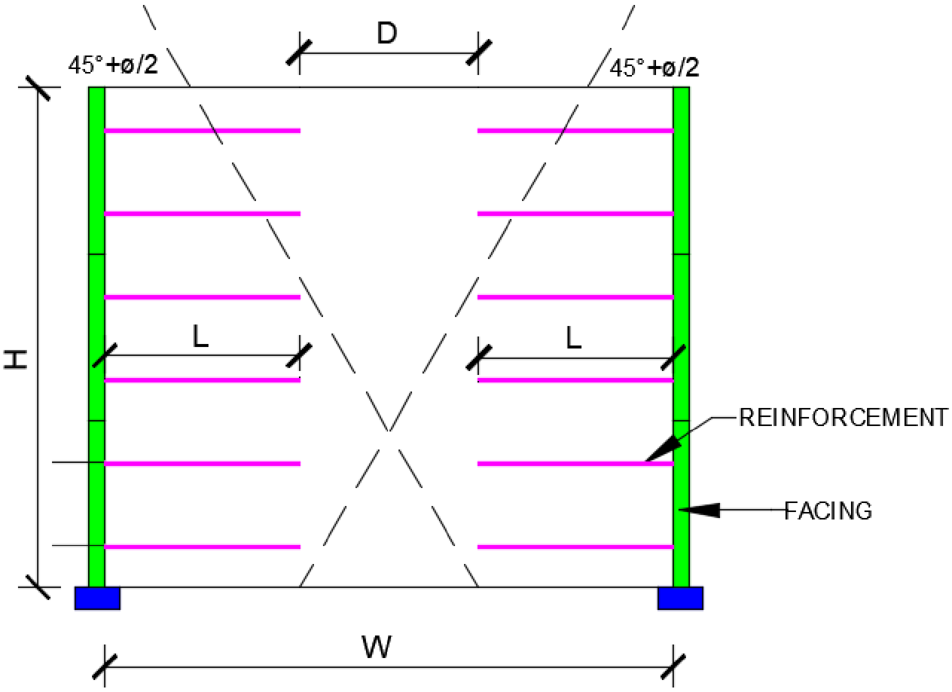


Figure 2-24: Back to back MSEW case 1

a) Case 1

The back to back MSEW's base width (W) is large enough that there is no overlapping of reinforcement and the MSEW's may therefore act somewhat independently. If $D > H\tan(45° - \emptyset/2)$, full active pressure onto the reinforced zone is mobilised and the MSEW's may be designed as a single independent MSEW (where $\emptyset$ is the backfill soil friction angle, H is the height of the MSEW and L is the length of the reinforcement). If $D < H\tan(45° - \emptyset/2)$ then there is a reduced active pressure mobilised onto the reinforced zone (Berg, et al., 2009). (Jones, 2002) suggests that when $D < H\tan(45° - \emptyset/2)$, the active pressure onto the reinforced zone is reduced but this reduction should be ignored in order to simplify the calculation process. (Berg, et al., 2009) suggests that when the active earth pressure on the reinforced zone is reduced, the active earth pressure may be calculated by linear interpolation from the full active case to zero but this recommendation has not been justified (Han & Leshchinsky, 2009).

b) Case 2

Case two is when the wall reinforcements of the back to back MSEW overlap creating a situation whereby the two MSEW's act as in integral unit. (Berg, et al., 2009) suggests that when the reinforcement overlap is greater than 0.3H, no active earth pressure from the backfill needs to be considered for external stability calculations while (Jones, 1985) states that no active pressure needs to be considered.

Although some guidance has been given to calculating the external stability of back to back MSEW's, there is no mention of how these types of MSEW's affect the calculation of the internal stability of the MSEW. Since the calculations involved in the internal stability of the MSEW take into account the earth pressures induced, surely when a reduced earth pressure is recommended (in the external stability calculation) the internal stability should also be affected in some way. None of the codes or guidelines gives any information on the aspect of internal stability calculations for back to back MSEW's.

(Berg, et al., 2009) mention that some designers may decide to use single layers of reinforcement that are connected to both wall facings creating a connected back to back MSEW. This creates an at rest condition (K_o) for the entire wall and increases the tension in the reinforcement when compared to unconnected back to back MSEW's. Very few instrumented structures have been constructed in order to confirm the stresses induced therefore (Berg, et al., 2009) maintains that the reinforcement tension in connected back to back MSEW's should be designed using at rest conditions (K_o) unless numerical modelling and instrumentation is used to confirm the use of lower stresses. (Jones, 2002) indicates that connected back to back MSEW's result in a tied structure with higher reinforcement tensions but states that this type of structure is not strictly reinforced fill and no further guidance on the design of connected back to back MSEW's was given in the reference.

Other factors that may affect the design/construction of connected back to back MSEW's include the following:

- Increase of tension in the reinforcement
- Increase of lateral stresses on the connection elements
- Facing elements to be designed for increased stresses
- Compaction may induce increased stresses at the connections
- Maintaining wall alignment especially when the walls are not in a tangent section

An Instrumented large scale MSEW has been constructed in the past (Won & Kim, 2006) to investigate the local deformation of various types of geosynthetics but no investigation was conducted to investigate the effect of the distance between MSEW's (Han & Leshchinsky, 2009). It is clear from this literature review that there is a limited amount of information available from reliable sources to design back to back MSEW's and when there is some guidance, the guidance is conflicting at times and lacks justification for recommendations given. Recommendations for the design of back to back MSEW's with continuous/connected reinforcement between the MSEW's is far less and lacking as seen in this literature review.

2.3 Macres system

The specific MSEW system that will be used in this dissertation is the MACRES system. The system is made up of soil reinforcement (geosynthetic) and facing elements (concrete panels) and is marketed by Officine Maccaferri SA. The geosynthetic used are Paraweb strips which are manufactured by encasing high tenacity polyester yarn in a polyethylene sheath (Maccaferri, 2010). Figure 2-25 below shows a schematic of the Macres system in use creating the retaining system required for the construction of a road.

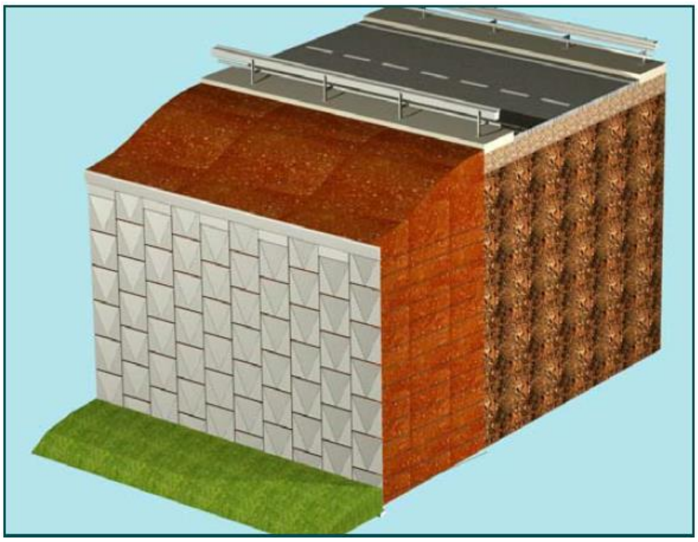


Figure 2-25: Isometric view of Macres System (Maccaferri, 2010)

Figure 2-26 below shows how the Macres system can be used in the construction of a bridge abutment.

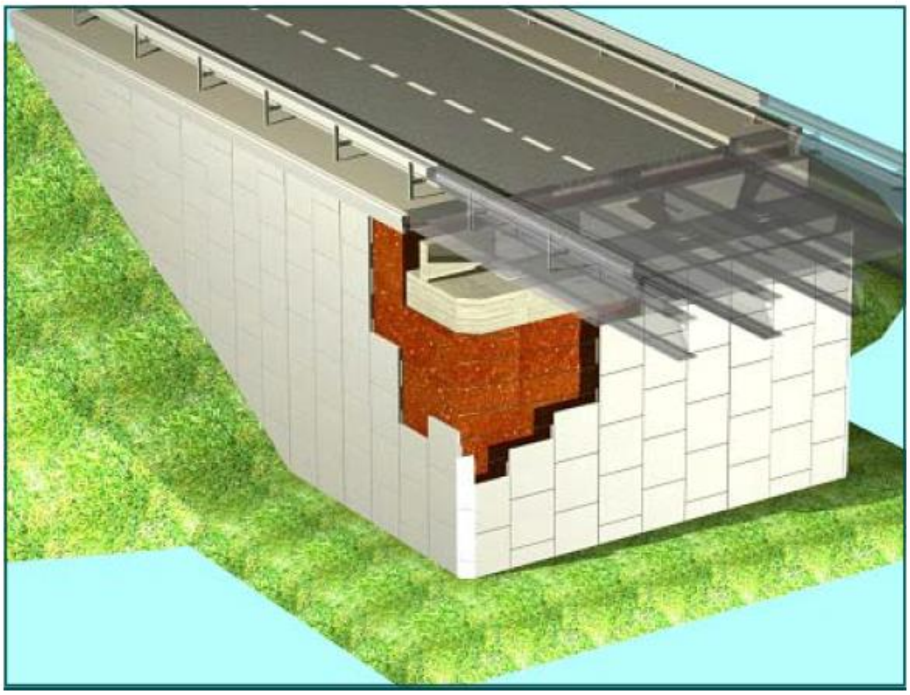


Figure 2-26: Macres system incorporated into a bridge abutment (Maccaferri, 2010)

Figure 2-27 below shows the components of the concrete facing panel used in the Macres system.

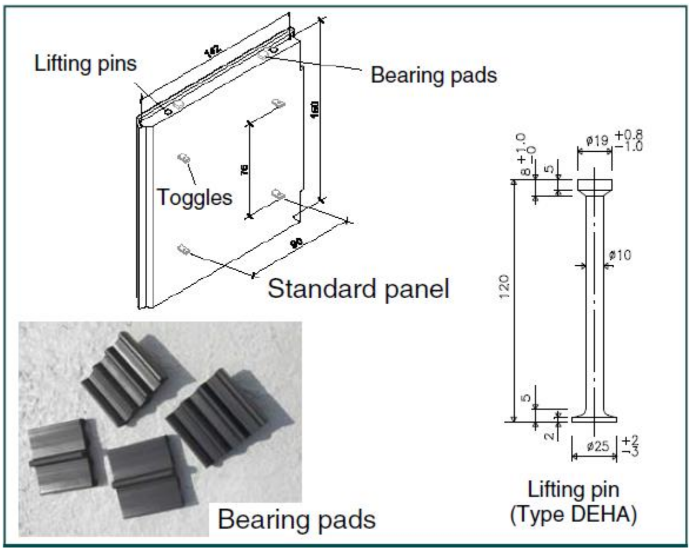


Figure 2-27: Elements of the concrete panel facing (Maccaferri, 2010)

Figure 2-28 below shows the toggle system that is fixed onto the concrete panels which are used as a means to connect the Paraweb strip to the concrete facing panel. In the case study carried out in this dissertation, the toggle connection was replaced with a geosynthetic connection instead.

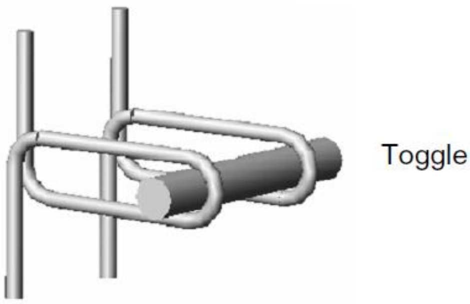


Figure 2-28: Toggle connection (Maccaferri, 2010)

Figure 2-29 below shows the Paraweb product which is used as the geosynthetic reinforcing element of the Macres system. The actual strength of the geosynthetic lies in the polyester strands located within the outer polyethylene coating.

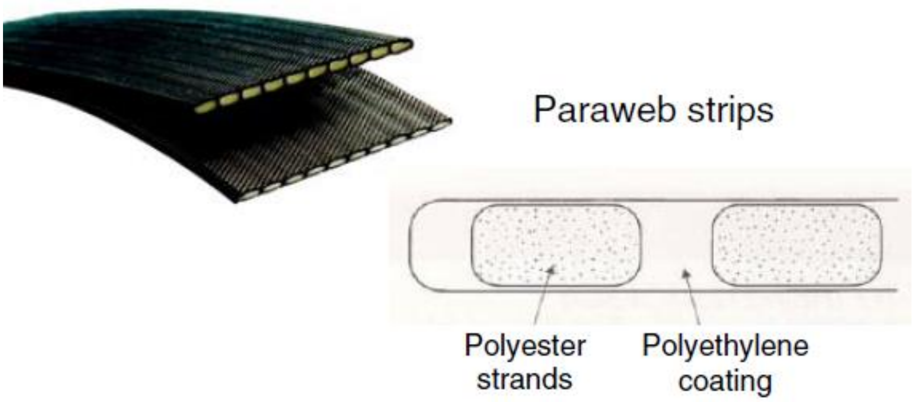


Figure 2-29: Paraweb product (Maccaferri, 2010)

Figure 2-30 below shows the Paraweb product in the manner that they are delivered to site.

Figure 2-30: Paraweb rolls (Maccaferri, 2010)

Figure 2-31 below shows the varieties of concrete front facing panels that can be manufactured. The panels can be produced to suit the aesthetics required for the project

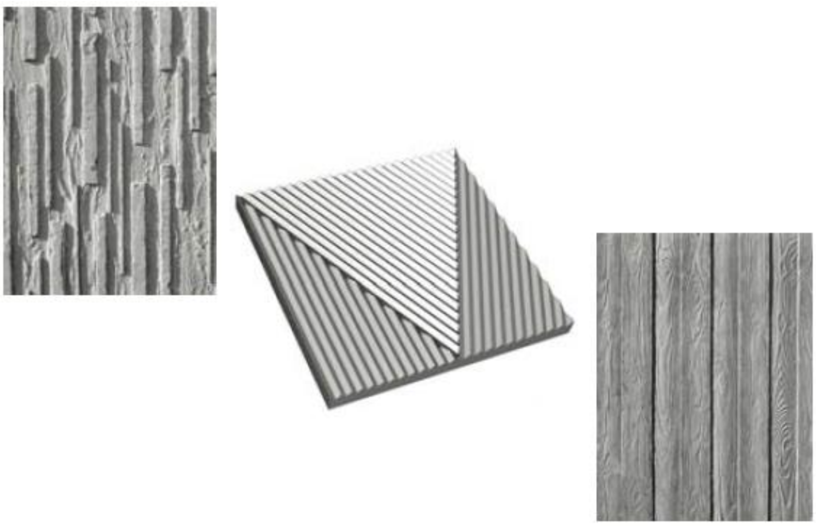


Figure 2-31: Concrete front facing panels (Maccaferri, 2010)

The reinforcement used in the Macres system has been independently tested and certified for use as a reinforcing element for soil retaining walls and bridge abutments by the British Board of Agrément. The precast concrete facing panels are generally manufactured by a third party for the project in accordance with the design requirements of the panel. The certification, technical data sheets and installation manuals of the Macres system are contained in (British Board of Agrément, 2012).

In the design of MSEW's using BS:8006-1:2010 there are two main methods of calculation for the internal stability of the MSEW. These methods are the tie back wedge method and the coherent gravity method. More information regarding these methods are provided in section 3.2.3 with particular information on which method is used when designing the Macres system.

2.4 Numerical methods

Numerical analysis is defined by the online oxford dictionary as follows:

"The branch of mathematics that deals with the development and use of numerical methods for solving problems." (Oxford Dictionary, 2018).

The advent of computers has allowed a user to carry out numerical analysis in a faster more efficient way than previously which has opened up the user into tackling more complex and detailed analysis. In engineering, this has opened up many possibilities to engineers to carry out more complex previously time-consuming exercises in shorter spaces of time. Before the advent of computers, some of the analysis that are performed on computers were practically impossible. There are various forms of numerical methods available to engineers which can be broadly separated into finite difference methods and finite element methods (Reddy, 2015).

2.4.1 Finite difference and finite element methods

The finite difference method uses the truncated Taylor series approximations to approximate derivatives of various orders. The two main problems that may arise when using finite difference methods is as follows:

- Further approximations are required for the boundary data when applying gradient type boundary conditions
- The formulas used in the finite difference method have been mainly developed for rectangular grids which creates problems when trying to use them for irregular domains

There are ways around the problems experienced in the finite difference method but the solution for overcoming the problems are usually very situation specific. Nevertheless, many advances in this method have been made (Reddy, 2015).

A definition of the finite element method is given by (Chandrupatla, et al., 2012) as follows:

"a complex region defining a continuum is discretized into simple geometric shapes called finite elements. The material properties and the governing relationships are considered over these elements and expressed in terms of unknown values at element corners. An assembly process, duly considering the loading and constraints, results in a set of equations. Solution of these equations gives us the approximate behaviour of the continuum." (Chandrupatla, et al., 2012).

The finite element method (FEM) idea arose from the study of the structural behaviour of aircrafts. Hrenikoff presented the frame work method in 1941 while Courant produced a paper in 1943 where he solved torsional problems by interpolating equations separately and Turner et al. made stiffness matrices in 1956. The actual use of the words 'finite elements' was invented by Clough in 1960. The development of the FEM continued with the first book on finite elements being published in 1967 by Zienkiewicz and Cheung. In today's day and age, high speed computers which are readily available have allowed engineers to easily model complex problems ranging from deformation and stress to field analysis. The economic benefit of using FEM are seen when models can be tested and analysed via computer software prior to spending large sums of money on constructing a test model (Chandrupatla, et al., 2012) and (Gupta & Meek, 1996).

Another way of explaining the FEM is the theory that every system is comprised of a number of components and the solution of the system may be represented by the solution of its components with the solution of each component being depicted as unknown parameters and functions of position and time represented in a linear fashion. The components that make up the system can differ from each other in a variety of ways and it has been found that even if there are hardly any variances in the components such as varying types of material and geometry, it is still easier to solve each component separately (Reddy, 2015). The FEM has three basic characteristics summarised as follows:

- Finite elements can be described as a grouping of geometrically basic subdomains that form a domain of a system

- The points that make up the finite element are called nodes. Each node can contain unknown variables which can be approximated using the known equations and parameters that control the system.
- The mathematical relationships between all elements are joined considering balance and continuity between the nodes

An engineer utilising the FEM should study the intricacies surrounding the method so that they have a clearer understanding in the functionality of the method which would allow the user to use more care and discretion when using results obtained from the analysis and it will allow the user to fully exploit the method of analysis. An engineer armed with the knowledge of the FEM will be able to coin new methods of analysis to be used within a finite element package if the engineer feels that the current available models do not satisfy the system being modelled. (Reddy, 2015).

2.4.2 Finite element method in geotechnical engineering

Design in the geotechnical field usually involves using assumptions such as linear elastic behaviour or uniform ground conditions in order to allow the designer to carry out analysis without the aid of numerical methods such as the FEM. Most standard designs, although using these assumptions are still economical and less time consuming to perform when compared to an analysis carried out with the FEM (Lees, 2016) but personal experience in this field has shown that the use of FEM for standard designs can sometimes prove to be more economical. Finite element modelling although able to handle complex geometries using less assumptions, requires careful consideration as they require parameter determination which in itself can be laborious and time consuming and sometimes unavailable (Lees, 2016). Finite element modelling in geotechnical engineering may be considered over conventional methods when the analysis involves the following (Lees, 2016):

- complex ground behaviour or unusual geometry
- complex hydraulic conditions or loading
- soil–structure interaction and internal structural forces in complex structures, and interactions with adjacent structures
- construction techniques that may result in other cases that need to be considered
- The effect of time

- carrying out back analysis of monitored structures in order to analyse new/future trends/effects

Setting up of models and carrying out the analysis can also prove to be time consuming. The designer therefore has to choose when to use finite element methods of analysis over conventional design methods taking into account all of the above mentioned advantages/disadvantages (Lees, 2016).

A constitutive model in finite elements is used to model material behaviour using mathematical formulae which creates equilibrium between the elements. In geotechnical applications the expressions used in the constitutive model may apply to stress and strain behaviour and would allow the user to determine the stress and strain at every node at any particular phase of construction. It is important that the user chooses the appropriate constitutive models when applying FEM since different models are made for a variety of stress strain paths that a particular material may follow. The various models available are also very parameter dependant therefore one needs to have access to enough information in order to properly choose parameters applicable to the model. Before choosing which constitutive model to use, the user should take account of the following (Lees, 2016):

- What is being modelled
- The stress path that the construction will take
- The loading/unloading that may occur during construction
- The availability of enough information from the site investigation report in order to properly determine the required parameters in a model
- The interaction of the models with one another

It is clear that the site investigation plays an important role in the success of a finite element model due to the fact that the parameter determination for the model will need to have been planned and scoped out before, during, and after the geotechnical site investigation. The flow diagram given in Figure 2-32 below gives a path of how parameters can be properly obtained for finite element modelling:

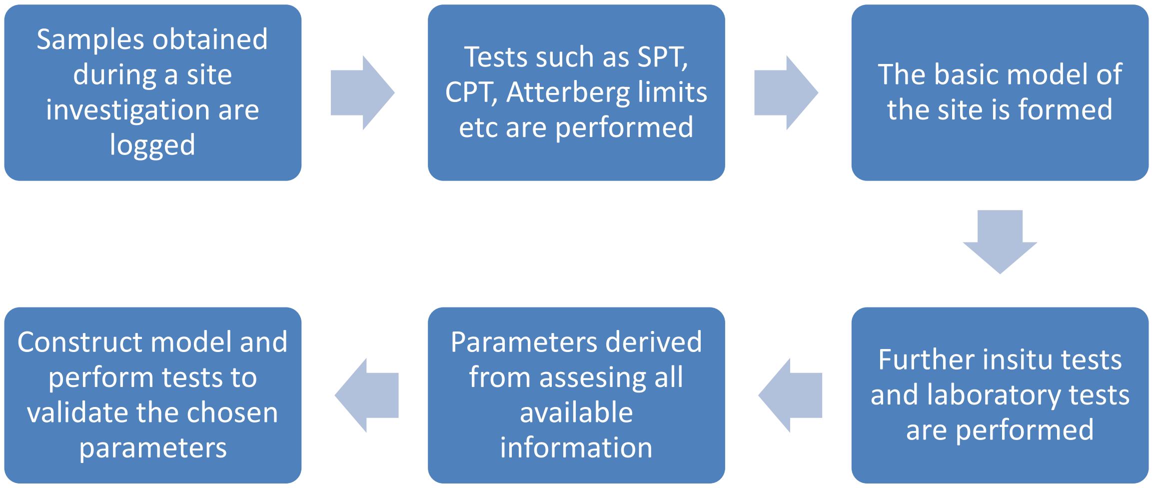


Figure 2-32: Flow diagram of parameter selection (Lees, 2016)

During the site investigation, the geotechnical engineer will break down the ground into various zones that would behave in a similar manner. Laboratory tests are then scheduled to confirm and re-affirm the various zones and properties of the materials. Sometimes, depending on the model requirements, advanced tests on materials obtained during the investigation are carried out which depending on the material can be in situ or at a laboratory. According to the sensitivity of a particular parameter in the model and its importance in the results required extra tests may need to be carried out in order to limit the uncertainty (Lees, 2016).

Groundwater and pore water pressure is usually taken into account when choosing specific constitutive models and can be dry, saturated, or even partially saturated. Complicated parameter determination exists for mainly soils and rock since their characteristics are variable and dependant on many factors. On the other hand, materials used in construction such as steel and concrete are easier to model and they are commonly modelled using a linear elastic relationship (Lee, et al., 2016).

2.4.3 Geosynthetics in finite element modelling

Geosynthetics in the finite element method are usually modelled using membrane elements with interface elements between the membrane element and the soil body. The membrane elements are only able to sustain axial tension loading. The interface element allows for a decrease in parameters values along the boundary of the geosynthetic and the soil body (example, if the user wants to allow some slippage between the geosynthetic and the soil body, this can be achieved through the interface element). The geosynthetic materials bring in a particular problem in that the material is dependent on various other factors such as rate of effects and creep. A geogrid brings in further complexity in modelling since there is a soil body and geogrid interaction created when particles lie in the geogrid spaces which the membrane element is unable to model (Brinkgreve, et al., 2017) and (Lees, 2016).

2.4.4 Mechanically stabilised earth walls in finite element modelling

The modelling of MSEW's using the FEM requires the determination of various parameters in order to construct the model using the different constitutive models available. They can be broadly broken up into the following:

- Facing elements of the MSEW
- Reinforcement used in the MSEW
- The structural backfill and general backfill used in the construction of the MSEW
- The material below and behind the MSEW
- Interface elements required to model the behaviour of one model element with another

In the construction of an MSEW, depending on the materials present and since there would be membrane elements present, it is important that each step of the construction phase is modelled in the same way the MSEW would be constructed. This is because the forces experienced in the elements will change during each phase and the user may find that the highest forces or lowest factors of safety may not always be found at the final construction phase (Lees, 2016).

In normal finite element calculations, the change of geometry of the mesh is not considered in the equilibrium checks. This assumption holds true when the deformation calculated is relatively small which is normal for most types of engineering works. When the finite element method is used in the analysis of MSEW's, it is recommended that an updated mesh analysis be used. When the updated mesh option is selected in Plaxis 2D, the stiffness matrix of the mesh is updated at the start of each load step (Plaxis Bv, 2018).

CHAPTER 3 : METHODOLOGY

3.1 Introduction

This chapter presents the design method of MSEW's using the BS:8006-1:2010 along with a step by step process of how the MSEW is modelled in Plaxis 2D (finite element modelling software package) for this dissertation.

3.2 Design method of MSEW's using BS8006-1:2010

Reinforced soil structures (which includes MSEW's) that are designed to BS:8006-1:2010 follow the same principals as when designing conventional earth retaining structures. The reinforced soil structures are considered as a two-dimensional plane strain model with the design involving checking the external and internal stability of the structure. The external stability of the structure involves looking at the effect of the various loads and forces acting on the structure. The following aspects need to be assessed for the external stability:

- Bearing and/or tilt failure
- Sliding
- Global slip surface stability
- Settlement
- Wall deformation

The internal stability deals with the integrity of the reinforced volume in particular, the reinforcing elements that form part of the reinforced volume. The following aspects need to be assessed for the internal stability:

- Rupture of the reinforcing elements
- Local stability of each layer of reinforcement
- Sliding of the reinforcements on horizontal planes
- Wedge stability

The structure must be designed using both the ultimate limit state (ULS) and the serviceability limit state (SLS). The common practice is to first design for the ULS and then check if this design meets the criteria required for the SLS. The design procedure of reinforced soil walls is given in Figure 3-1 below. This chapter will give a summary of the process shown in Figure 3-1 using BS:8006-1:2010.

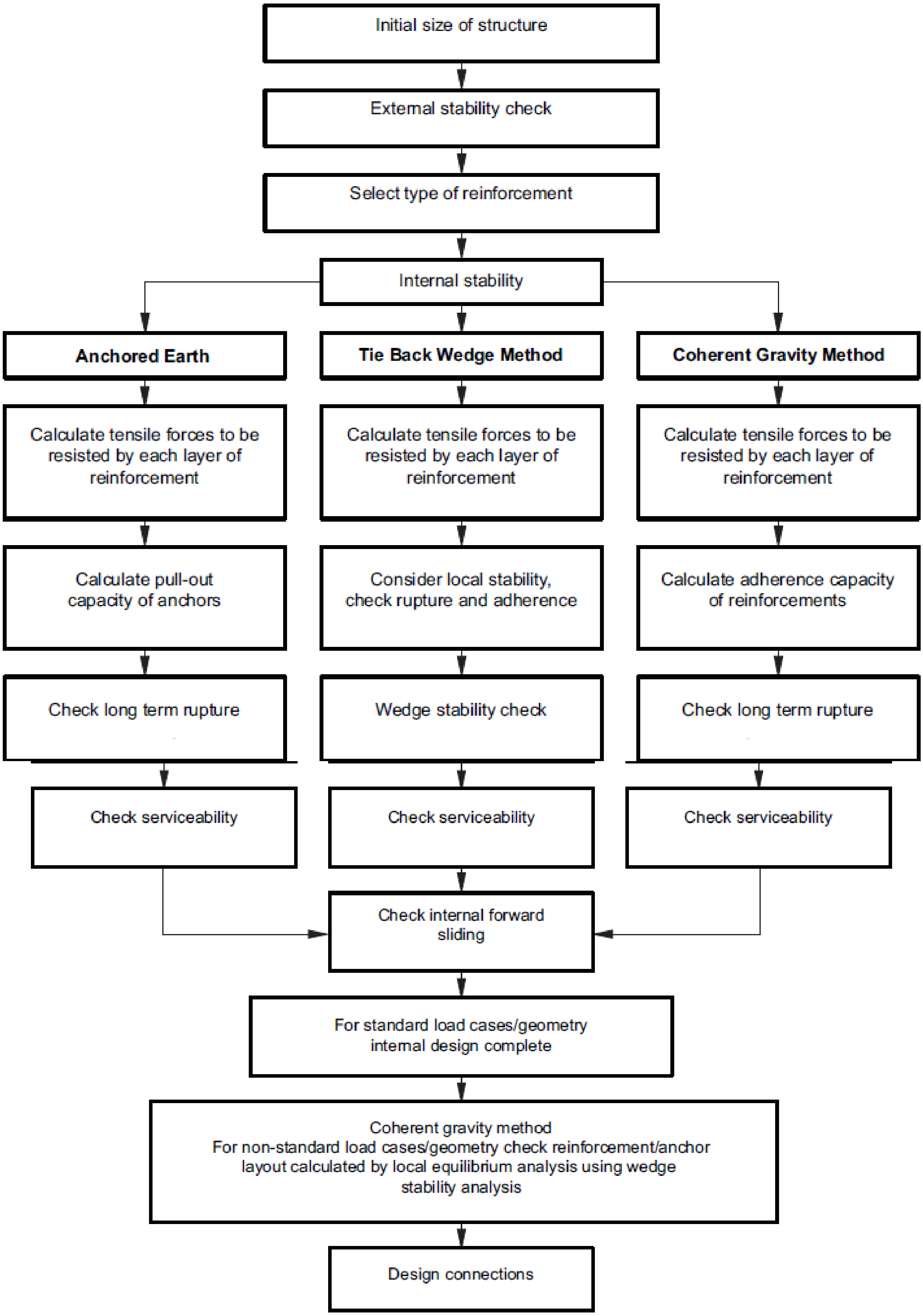


Figure 3-1: Reinforced soil wall design process (BS8006-1:2010, 2010)

3.2.1 Initial size of structure

The initial size of the structure involves determining the mechanical height of the structure, minimum length of reinforcement and the embedment depth. BS:8006-1:2010 provides various tables and figures which assist the designer in choosing the correct parameters based on the structure being designed.

The mechanical height of the structure is calculated by measuring the vertical distance created when one extends a line from the toe of the structure at arc tan 0.3 until the line intersects the top slope ground line which may be inclined.

The minimum embedment of the structure should be greater than or equal to the frost depth in the United Kingdom which is 0.45m. The designer is allowed to choose different minimum embedment depths which can be less than the recommended 0.45m minimum as long as they can justified.

3.2.2 External Stability

When checking the external stability of the structure, all loads imposed must be taken into account. The designer must allow for the short term, long term, and changes in pore water pressure during construction and during the service life of the structure. It is important to note that passive earth pressures exerted on the wall or footing lying below the ground surface should be ignored as a stabilising force. The following external stability checks need to be carried out when designing reinforced soil walls or MSEW's:

- Bearing and tilt failure
- Sliding along the base
- Settlement
- Construction tolerances and serviceability limits
- External slip surfaces

These checks are elaborated upon below:

a) Bearing and tilt failure

The bearing and tilting of a reinforced soil structure is shown in Figure 3-2 below.

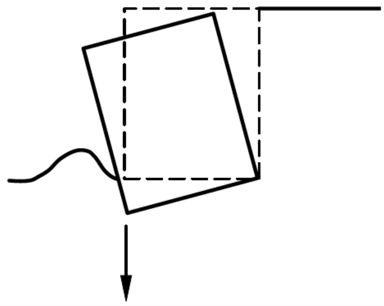


Figure 3-2: Bearing and tilt failure (BS8006-1:2010, 2010)

The bearing pressure that the structure imposes on the foundation material is based on the Meyerhof distribution given by equation (3-1) below:

$$\mathbf{q_r} = \frac{\mathbf{R_v}}{\mathbf{L-2e}}\ [\boldsymbol{kPa}] \qquad (3\text{-}1)$$

q_r [kPa] – The factored bearing pressure that the structure imposes on the foundation material
R_v [kN/m]– Vertical load resultant (load factors for each load case taken from Table 12 and Table 13 of BS 8006-1:2010)
L [m] -Reinforcement length at the base of the structure
E [m] – Eccentricity of R_v taken at the midpoint of L

The design check requires that qr must be less than the ultimate bearing pressure of the foundation material which is shown in equation (3-2) below:

$$\mathbf{q_r} \le \frac{\mathbf{q_{ult}}}{\mathbf{f_{ms}}} + \boldsymbol{\gamma}\mathbf{D_m}\ [\boldsymbol{kPa}] \ (3\text{-}2)$$

q_{ult} [kPa] – Ultimate bearing capacity of the foundation material
f_{ms} – Partial factor for q_{ult} (see Table 11 of BS 8006-1:2010)
γ [kN/m^3] – Density of foundation material
D_m [m] – Embedment depth

b) Sliding along the base

The forward sliding of a reinforced soil structure is shown in Figure 3-3 below:

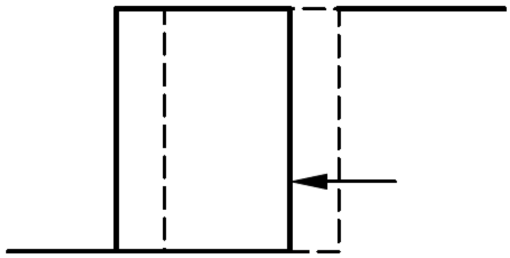


Figure 3-3: Forward sliding (BS8006-1:2010, 2010)

The forward sliding between the reinforced fill and the foundation soil must be checked using the weaker parameters of either material. The sliding must be checked on or between the reinforcement layers at the base of the structure. Equations (3-3), (3-4), (3-5), and (3-6) below provide the checks to be used in the design:

i. Long term stability

<u>Soil to soil contact</u>

$$\mathbf{f_s R_h \leq R_v \frac{\tan \emptyset'_p}{f_{ms}} + \frac{c'}{f_{ms}} L} \qquad (3\text{-}3)$$

<u>Reinforcement on soil contact</u>

$$\mathbf{f_s R_h \leq R_v \frac{a' \tan \emptyset'_p}{f_{ms}} + \frac{a'_{bc} c'}{f_{ms}} L}\ [\boldsymbol{kN}] \qquad (3\text{-}4)$$

ii. Short term stability

<u>Soil to soil contact</u>

$$\mathbf{f_s R_h \leq \frac{C_u}{f_{ms}} L} \qquad (3\text{-}5)$$

<u>Reinforcement on soil contact</u>

$$\mathbf{f_s R_h \leq \frac{a'_{bc} C_u}{f_{ms}} L} \qquad (3\text{-}6)$$

R_h [kN/m] - Horizontal factored disturbing force (load factors for each load case taken from Table 12 and Table 13 of BS 8006-1:2010)

R_v [kN/m] - Vertical factored resultant force (load factors for each load case taken from Table 12 and Table 13 of BS 8006-1:2010)

φ'_p [°]- Peak angle of shearing resistance (effective stress conditions)

c' [kPa] – Soil cohesion (effective stress conditions)

c_u [kPa]– Soil undrained shear strength

L [m] - Effective base width for sliding

f_{ms} - Partial materials factor applied to tan φ'_p, c' and c_u (see Table 11 of BS 8006-1:2010)

f_s - Partial factor against base sliding (varies depending on whether reinforcement is present at the base of the wall, see Table 11 of BS 8006-1:2010)

a' - Interaction coefficient for soil/reinforcement bond angle with tan φ'_p

a'bc - Adhesion coefficient for soil cohesion to soil/reinforcement bond.

c) Settlement

Settlement checks are required for both the external stability and internal stability. The settlement checks required for the external stability applies to the settlement of the foundation soil and differential settlement. There are various to factors to consider when dealing with the settlement of the structure as it can affect the facing elements and general serviceability limits of the structure. General guides are provided in BS:8006-1:2010 with the majority of the choice being left with the designer.

d) Construction tolerances and serviceability limits

In BS:8006-1:2010 there are various requirements regarding the construction tolerances and serviceability limits for reinforced soil structures. The movements that occur during the service life of a structure are predominately due to the creep of the reinforcement under service loads, the settlement of the fill material and the settlement of the foundation material.

e) External slip surfaces

The potential slip surfaces that could be activated must be checked to ensure that they are within the prescribed limits. Surfaces that pass totally outside of the structure (Figure 3-4 below) as well as surfaces that pass partly through the reinforced mass (Figure 3-5 below) must be checked. When the slip surfaces pass partly through the reinforced zones, the reinforcement must be taken into account in the calculations.

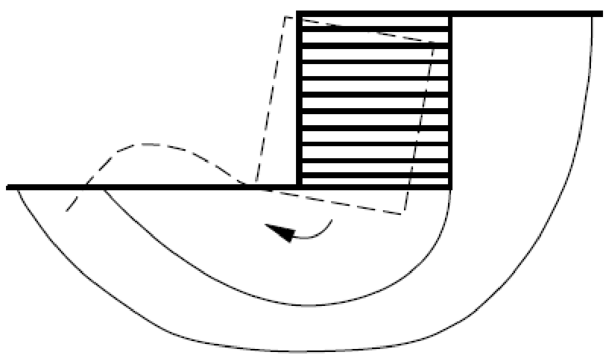


Figure 3-4: Slip surfaces passing totally outside of the structure (BS8006-1:2010, 2010)

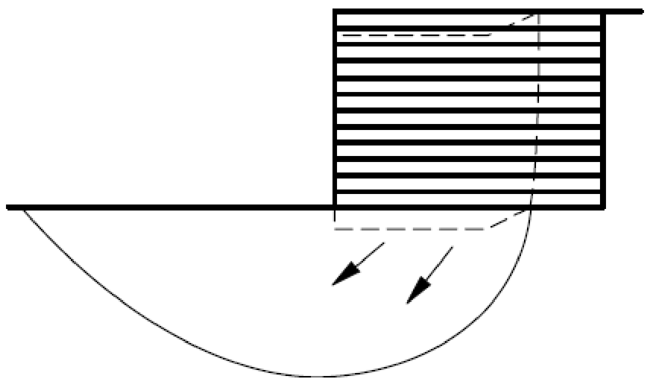


Figure 3-5: Slip surfaces passing partly through the reinforced mass (BS8006-1:2010, 2010)

3.2.3 Internal Stability

The internal stability deals with the stability of the reinforced mass. The stability of the reinforced mass is fulfilled by the reinforcing elements which assist the fill in carrying tensile forces through combinations of friction, adhesion, and bearing. There are two methods of design for the internal stability of a reinforced soil structure, namely the tie back wedge method and the coherent gravity method. The tie back wedge method deals with extensible reinforcements while the coherent gravity method deals with inextensible reinforcement. According to BS:8006-1:2010, the definition of an extensible reinforcement is one that carries the design loads at strains greater than one percent.

3.2.3.1 Tie back wedge method

This method uses design principals from classical and anchored earth walls. The coefficient of earth pressure used in this method is active earth pressure for checking the ULS and the SLS of the structure. Since this dissertation deals with the coherent gravity method only, the tie back wedge method will not be covered.

3.2.3.2 Coherent gravity method

This method is used for inextensible reinforcements and was developed using theory and the results of monitored behaviour of actual walls.

Inextensible reinforcement is generally metallic while extensible reinforcement is generally polymeric owing to the stress/strain relationship of the material. (Berg, et al., 2009). In the design of MSEW's using the Macres system, it has been accepted that although the paraweb strips (reinforcement) are polymeric, the coherent gravity method can be used if the long term reinforcement strain is limited to 1% over the entire design life taking into account the creep of the geosynthetic used.

The following paragraphs summarise the method of calculation required when using the coherent gravity method. Since this dissertation deals with standard load cases, vertical surcharge loading and uniform geometries, only the sections relevant to the calculation of these scenarios will be considered.

The coefficient of earth pressure (internal stability) used in this method is a combination of at rest earth pressures and active earth pressures which are used to check the ULS and the SLS of the structure. The coefficient of earth pressure is taken as K_0 (at rest earth pressure) at the top of the wall and decreases linearly until Ka (active earth pressure) at a depth of 6m below the top of the wall. Figure 3-6 below shows the variation of coefficient of earth pressure with depth for the coherent gravity method. In walls that have sloping backfill, the mechanical height of the wall needs to be considered but this is not covered in this dissertation.

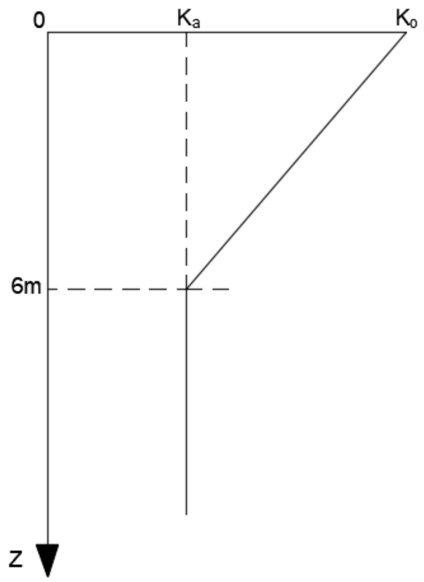
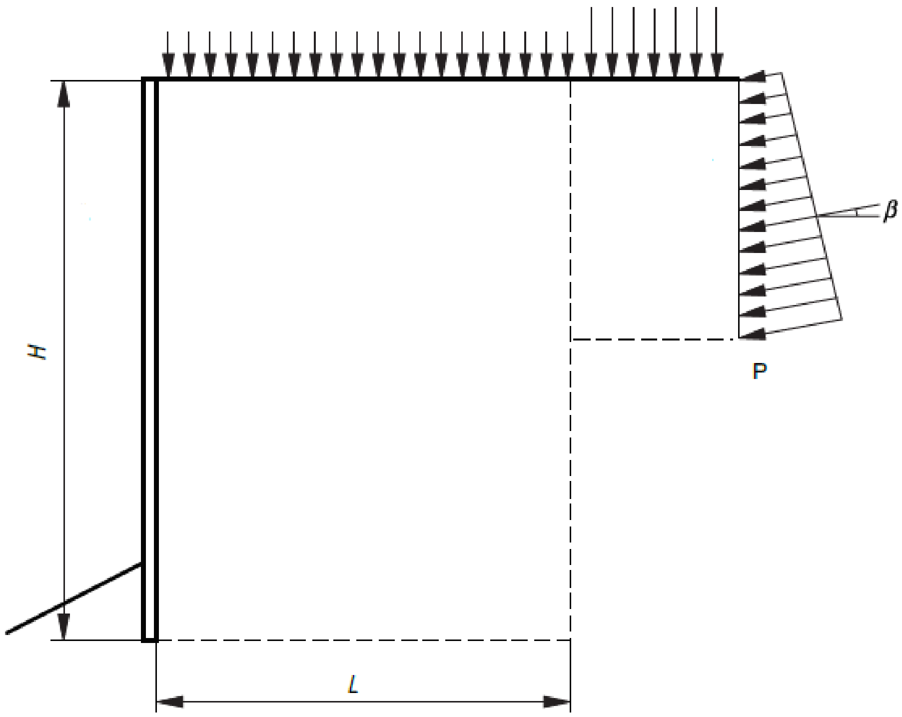


Figure 3-6: Coefficient of earth pressure with depth (Coherent gravity method)

Unlike the tie back wedge method, the coherent gravity method requires that the loads acting behind the reinforced mass be inclined to the horizontal. Figure 3-7 below provides further details on the calculation of this inclination.



$\beta = 0$ for tie back wedge method, $\beta = (1.2 - L/H)\phi'_2$ for coherent gravity method.

Figure 3-7: Inclination of load behind reinforced mass

There are a variety of checks that need to be carried out which fall under the ULS or SLS. The checks required for the ULS are listed below.

- Local stability of each layer of reinforcement
- Lines of maximum tension
- Adherence
- Long term rupture

These checks are elaborated upon below:

a) Local stability of each layer of reinforcement

The tensile force (T) that each layer of reinforcement needs to resist is calculated using equation (3-7) below:

$$\mathbf{T} = \mathbf{T_p} + \mathbf{T_s} + \mathbf{T_f}\ [\boldsymbol{kN/m}] \qquad (3\text{-}7)$$

T_p [kN/m] – This is the tensile force of a layer of reinforcement which is due to the vertical loading caused by the weight of the fill with bending moments and any surcharge.

T_s [kN/m]– This is the tensile force that is caused by a vertical strip load at the top of the wall. The dissertation does not deal with this loading type.

T_f [kN/m]– This is the tensile force imparted onto each reinforcement layer by a horizontal shear force acting on a strip load. The dissertation does not deal with this loading type.

T_p calculated by equation (3-8) below:

$$\mathbf{T_p} = \mathbf{K}\boldsymbol{\sigma_v}\boldsymbol{S_v}\ [\boldsymbol{kN/m}] \qquad (3\text{-}8)$$

K – Coefficient of earth pressure relevant to that layer of reinforcement

σ_v [kPa] – Vertical stress at the layer of reinforcement in question

S_v [m]– The vertical spacing of the reinforcement at that level

The vertical stress at the layer reinforcement (σ_v) is given by equation (3-9) below:

$$\boldsymbol{\sigma_v = \frac{R_v}{L-2e}}\ [\boldsymbol{kPa}] \qquad (3\text{-}9)$$

R_v [kN/m]– Vertical factored load resultant

L [m] - Reinforcement length of layer being calculated

E [m] – Eccentricity of R_v

The calculated pressure should not be taken as less than that due to a fluid with half the unit weight of water in order to avoid an unsafe reduction due to the cohesive effects of fine grained backfill material. It must be noted that when the bending moments due to the surcharge and weight of the fill are being calculated, they must take into account any strip loading that is present. The total tensile force (T) may be reduced if the fill being used is cohesive. The reduction that is applicable is given by equation (3-10) below:

$$\boldsymbol{T_c = 2s_v \frac{c'}{f_{ms}}\sqrt{\sqrt{K}}}\ [\text{kN/m}] \qquad (3\text{-}10)$$

T_c [kN/m]– Tensile force reduction due to cohesion of fill material

K – Coefficient of earth pressure relevant to that layer of reinforcement

c' [kPa]– Cohesion of fill material (effective strength conditions)

f_{ms} – Partial factor for c’

In cohesive fill material the equation (3-11) below applies:

$$\boldsymbol{T_p - T_c \geq 0.5\gamma_w S_v \left(h_j + \frac{f_{fs} w_s}{\gamma}\right)}\ [\boldsymbol{kN/m}] \qquad (3\text{-}11)$$

γ_w [kN/m^3]– Unit weight of water

f_{fs} – Partial factor on surcharge dead loads

w_s [kN/m^2]– Surcharge dead load

γ [kN/m^3]– Density of fill

h_j [m] – Depth of reinforcement layer being calculated

b) Lines of maximum tension

The line of maximum tension is assumed to follow a log spiral but this may be simplified to follow the line given in Figure 3-8 below. The tensile loads should be calculated at the facings, at the maximum tension line for the structure without any superimposed strip loading, and at the maximum tension line for the structure containing superimposed strip loading.

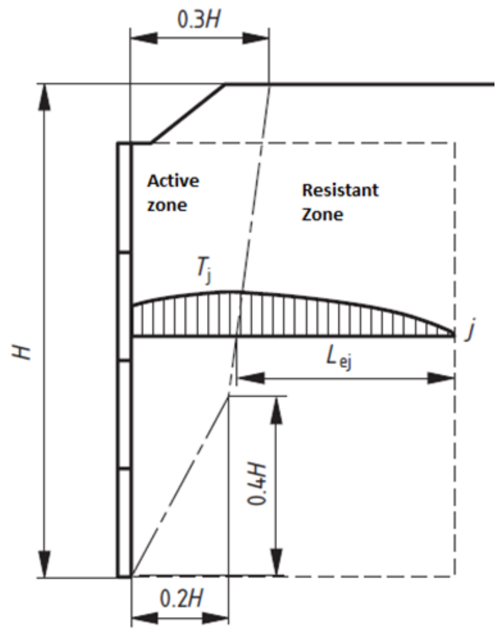


Figure 3-8: Maximum tension line in the coherent gravity method (BS8006-1:2010, 2010)

T_j represents the tensile force distribution in the j^{th} layer of reinforcement. L_{ej} is the length of reinforcement in the resistant zone with the remainder of the reinforcement falling in the active zone. H represents the mechanical height of the wall. Figure 3-8 applies to cases without any strip loading present.

The tensile force in each reinforcement layer calculated in equation (3-7) above is the maximum tensile force present in the reinforcement. Since this dissertation does not deal with any strip loading, the tensile force that occurs at the maximum tension line is given by Tp which is calculated in equation (3-8). If the fill material is cohesive, the tensile force calculated at the face and at the maximum tension line may be reduced by the solution of equation (3-10). The position of the maximum tension force along the layer of reinforcement being calculated can be determined using Figure 3-8 above.

This dissertation does not deal with any strip loading therefore the tensile force from the reinforcement present at the face can be calculated by multiplying the force obtained by (3-8) by 0.85.

c) Adherence

The adherence capacity of each layer of reinforcement may be calculated by equation (3-12) below:

$$\mathbf{T_{adherence}} \leq \frac{\mathbf{2B\mu}}{\mathbf{f_p f_n}} \int_{\mathbf{L-L_{aj}}}^{\mathbf{L}} \mathbf{f_{fs}}\, \boldsymbol{\sigma}_{\mathbf{v}}(\mathbf{x})\mathbf{dx}\ [\boldsymbol{kN}] \qquad (3\text{-}12)$$

f_p – Partial factor for reinforcement pull out resistance

2 – Since there are 2 faces of the reinforcement

B [m] – Width of the reinforcement

L [m] – Length of the reinforcement

L_{aj} [m] – Length of reinforcement at the level being calculated which lies beyond the line of maximum tension

μ – Friction coefficient

σv(*x*) [kPa] – The vertical stress along length x of the reinforcement

f_n – Partial factor for economic ramifications (see Table 9 of BS 8006-1:2010)

f_{fs} – Partial factor (see Table 12 and Table 13 of BS 8006-1:2010)

The friction coefficient μ is calculated in equation (3-13) below as follows:

$$\boldsymbol{\mu} = \frac{\boldsymbol{a'}\,\mathbf{tan}\,\boldsymbol{\emptyset}'_{\mathbf{p}}}{\boldsymbol{f_{ms}}} \qquad (3\text{-}13)$$

Where,

a' – The interaction coefficient between the soil and the reinforcement

f_{ms} – This is the partial factor applied to the friction angle of the soil taken (see Table 11 of BS 8006-1:2010)

d) Long term rupture

Every reinforcing element needs to satisfy the following expression given in equation (3-14) below:

$$\frac{\mathbf{T_D}}{\mathbf{f_n}} \geq \mathbf{T_{max\ tension}}\ [\boldsymbol{kN}] \qquad (3\text{-}14)$$

$T_{max\ tension}$ [kN]– The maximum tensile force calculated in the reinforcement

T_D [kN]– Design strength of the particular reinforcement used (This is calculated separately per type of reinforcing element used. Further details on the calculation of T_D is provided in section 3.2.3.3)

f_n – partial factor for economic ramifications (see Table 9 of BS 8006-1:2010)

e) Serviceability Limit State Check

The post construction movements of the reinforced soil structure need to be considered in order to satisfy the serviceability limit state checks. Settlement of the structure and the deformation of the wall need to be within the prescribed limits provided in BS 8006-1:2010.

The internal settlement of the reinforced soil fill must be checked and guidance on the limits prescribed is given in Table 16 of BS8006-1:2010. The post construction internal creep strain of polymeric reinforcement can influence the SLS of the structure. During the service life of a structure the polymeric reinforcement short term stiffness decreases with time due to internal creep of the reinforcement. The design strength of the reinforcement for the serviceability limit state (T_{cs}) is dependent on the post construction strain limit and applicable reduction factors which are covered in the section 3.2.3.3 below. The BS 8006-1:2010, prescribes the applicable limits on the post construction strains depending on the type of structure being constructed. Bridge abutments and retaining walls with permanent structural loading must limit the post construction internal strain to 0.5% while retaining walls without structural loading must limit the post construction internal strain to 1.0%. Isochronous load strain curves for the end of construction and the design life of the structure along with the required post construction internal strain of the structure are used to determine the serviceability design tensile load of the reinforcement. Figure 3-9 below shows the relationship of these three elements.

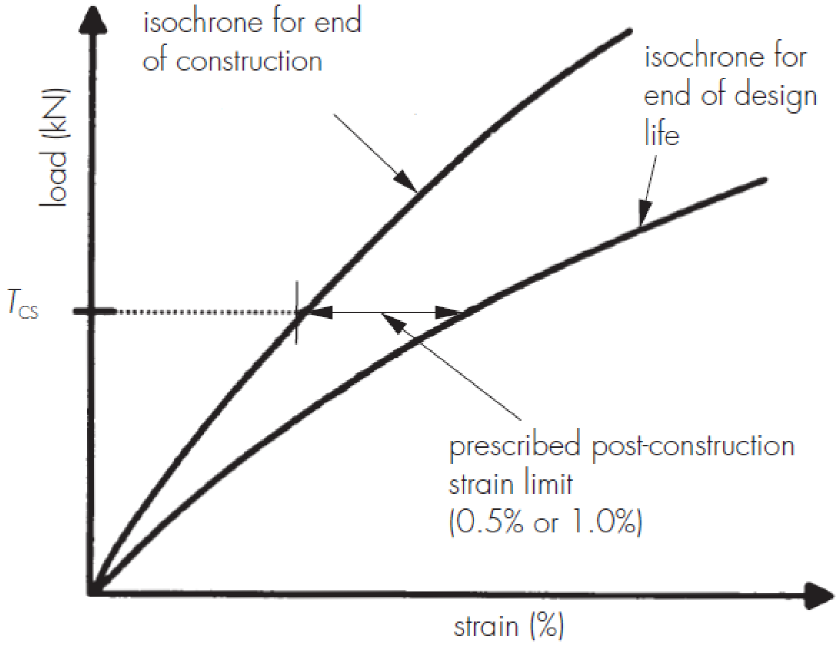


Figure 3-9: Isochronous curves used for calculation of serviceability limit state design load (British Board of Agrément, 2012)

T_{cs} represents the design load to be used for the SLS. Further details regarding this design load is covered in section 3.2.3.3 that follows.

3.2.3.3 Design strength of reinforcement

BS:8006-1:2010 provides recommendations for the calculation of the design strength of reinforcement used in MSEW's. The calculation procedure varies depending on the type of reinforcement used. Only the calculation process that may be used for polymeric reinforcement will be covered as the study deals with this type of reinforcement. The design strength of the reinforcement is required to ensure that the reinforcement does not rupture and the creep of the reinforcement does not exceed the prescribed limits during the design life of the structure. The calculation procedure in order to obtain the design strength is covered below in equations (3-15), (3-16), (3-17), (3-18), and (3-19) for the ULS and the SLS. Some of the factors shown in the steps are specifically for Paraweb straps. Other reinforcement types will have factors specific to that product.

a) Ultimate limit state

$$\mathbf{T_D} = \mathbf{T_{CR}} / (\mathbf{f_n} \times \mathbf{f_m}) \ [\boldsymbol{kN}] \qquad (3\text{-}15)$$

T_D [kN] – Design strength of reinforcement (varies depending on whether it is being used for calculations and checks for the ultimate limit state or serviceability limit state)

T_{char} [kN] – This is the characteristic short term tensile strength of the reinforcement

f_n – Partial factor for ramification of failure (See Table 9 of BS8006-1:2010)

f_m – Material factor of safety (This value is calculated either for the ultimate limit state or the serviceability limit state with each limit state having different factors applicable.)

$$\mathbf{f_m} = \mathbf{RF_{ID}} \times \mathbf{RF_W} \times \mathbf{RF_{CH}} \times \mathbf{f_s} \qquad (3\text{-}16)$$

RF_{ID} – Reduction for material damage (dependant on Paraweb grade and particle size of fill, d50.)

RF_W – Reduction factor for weathering (dependant on time Paraweb is exposed during installation)

RF_{CH} – Reduction factor for chemical/environmental effects (dependant on soil pH level and design temperature)

f_s – Safety factor due to data being extrapolated (this is calculated taking account of creep rupture data and accelerated chemical data)

$$\mathbf{T_{CR}} = \mathbf{T_{char}} / \mathbf{RF_{CRu}} \ [\boldsymbol{kN}] \qquad (3\text{-}17)$$

T_{cr} [kN]- This is the long term tensile creep rupture strength (dependant on the design life and temperature)

RF_{cru} – Creep reduction factor (The ultimate limit state RF_{crs} factors for Paraweb straps at different temperatures are given in Table 3-1 below)

Table 3-1: Creep reduction factors for Paraweb (British Board of Agrément, 2012)

Design Temperature (°C)	Creep reduction factor (RF_{cru})
20	1.38
25	1.40
30	1.43

b) Serviceability limit state

$$\mathbf{T_D = T_{CS}/f_m}\ [\boldsymbol{kN}] \qquad (3\text{-}18)$$

T_{CS} [kN] – This is the maximum allowable tensile load (dependant on the strain required so that the prescribed post construction limits are not exceeded for the serviceability limit state)

$$\mathbf{T_{CS} = T_{char}/RF_{CRs}}\ [\boldsymbol{kN}] \qquad (3\text{-}19)$$

RF_{crs} – Creep reduction factor (The serviceability limit state RF_{crs} factors for Paraweb straps depend on the allowable post construction strain, temperature and design life of the structure)

3.3 Design of MSEW's using the finite element method

This section provides the step by step process that is used to model MSEW's using the finite element method with a specific software package, namely Plaxis 2D. Plaxis 2D is a finite element package for geotechnical engineering that can be used to analyse deformation and stability in two dimensions. Plaxis 2D contains constitutive models within the software package that allows the user to utilise various types of soil and rock along with constitutive models that can be used to model the behaviour of elements used in geotechnical engineering projects like geosynthetics and concrete. The package is able to model the interaction of the soil/rock with the structures being constructed (Plaxis Bv, 2018).

In order to model the MSEW (using the Macres system, see section 2.3) in Plaxis 2D for this dissertation, the following components and behaviour would need to be modelled:

- Concrete levelling pad
- Concrete facing panels
- Geosynthetic reinforcing element
- Foundation material
- Backfill material
- Interaction between the soil and reinforcement

A step by step process that was used for this dissertation for modelling MSEW's in Plaxis 2D is given below. A detailed user manual is supplied with Plaxis 2D therefore the step by step process will be kept brief and to the point.

Step 1: The geometry of the model must be inputted into the program. The geometry must contain all of the relevant structures and soil that will be used to model the MSEW. Plaxis 2D automatically assigns standard boundary conditions which comprise horizontal and vertical fixity at the base and horizontal fixity at the vertical sides. The standard boundary conditions assigned by Plaxis 2D was used for all FEM analysis carried out.

Step 2: The material properties for the foundation and backfill must be inputted and assigned to the relevant soil clusters to which they apply. The soil was modelled using the Mohr Coulomb model. The Mohr Coulomb model is a linear elastic-perfectly plastic model with the linear elastic portion following Hooke's Law while the perfectly plastic portion following the Mohr Coulomb failure criterion. This model is appropriate to use for modelling the foundation material and the backfill material since in the construction of MSEW's the soil does not experience any major unloading with the majority of the construction sequence involving loading of the foundation soil and strain hardening of the soil would not affect the results of the calculations. The following parameters are required for the Mohr Coulomb model:

E' [kPa]: Effective Youngs modulus
c' [kPa]: Cohesion
φ' [°]: Effective angle of internal friction
γ [kN/m^3]: Unit Weight

Step 3: The levelling pad and facing units can now be added to the model. These elements are modelled using the plate element which can be used to model slender structural elements and has a large bending stiffness and a normal stiffness. A plate element will allow the user to check the bending moment and shear forces that occur in the element which is important in checking the suitability of the facing element used. The following parameters are required by the model:

EA [kN/m]: Normal Stiffness
EI [kN/m^2/m]: Bending Stiffness
υ: Poisson's ratio

Step 4: The soil reinforcements are added into the model. Soil reinforcements are modelled using the geogrid element in Plaxis 2D. A geogrid in Plaxis 2D is a slender structure that can only exhibit axial stiffness with no bending stiffness. There are only tensional forces present. There is only one parameter that is required which is the axial stiffness. The axial stiffness of the geosynthetic can be calculated using graphical plots from the geosynthetic manufacturer. The graphical plots used are those of the geosynthetic elongation versus the applied loading in the longitudinal direction. The calculation of the axial stiffness using the plots are given in equation (3-20) below:

$$\mathbf{EA} = \frac{\mathbf{F}}{\mathbf{\Delta L/L}}\ [\boldsymbol{kN/m}] \qquad (3\text{-}20)$$

EA [kN/m]: Axial Stiffness
F [kN]: Axial force per unit width
ΔL [m]: Change in length
L [m]: Length
υ: Poisons ratio

Step 5: The slippage between the reinforcing elements and facing of an MSEW with the backfill soil needs to be allowed for in the finite element model. This is achieved in Plaxis 2D by adding in interface elements between the reinforcing elements, facing panels and the soil. The interface strength properties in Plaxis 2D are linked with a specified material data set and is controlled by the interface strength (R_{inter}). R_{inter} is an elastic-plastic model whereby the elastic (small movements) and plastic (irreversible slippage) behaviour is governed by Coulomb criteria. The interface is in an elastic condition when equation (3-21) applies and in a plastic condition when equation (3-22) applies.

$$|\boldsymbol{\tau}| < -\boldsymbol{\sigma_n} \tan \boldsymbol{\varphi_i} + \boldsymbol{c_i}\ [\boldsymbol{kPa}] \quad (3\text{-}21).$$

$$|\boldsymbol{\tau}| = \boldsymbol{\sigma_n} \tan \boldsymbol{\varphi_i} + \boldsymbol{c_i}\ [\boldsymbol{kPa}] \quad (3\text{-}22).$$

When R_{inter} is 1, that implies that no slippage occurs. Values for R_{inter} below 1 will imply a reduction of the strength properties according to the R_{inter} value chosen. Equation (3-23) and equation (3-24) below show how the interface strength properties are affected when R_{inter} is below 1.

$$c_i = R_{inter} c_{soil}\ [kPa] \qquad (3\text{-}23).$$

$$\tan\varphi_i = R_{inter} \tan\varphi_{soil}\ [°] \qquad (3\text{-}24)$$

τ [kPa]: Shear stress

σ_n [kPa]: effective normal stress

c_i [kPa]: interface cohesion

R_{inter}: interface strength

c_{soil} [kPa]: cohesion of soil associated with the interface

φ [°]: Angle of internal friction of soil associated with the interface

In this dissertation, the interface element will be placed between the geogrid (soil reinforcement) and the backfill and between the facing element and the backfill.

Step 6: If a uniformly distributed load is required to be modelled as part of the MSEW design, this can be done in Plaxis 2D using the line load feature which allows the user to input the uniformly distributed line load in kN/m.

Step 7: After all of the relevant elements are added into the model, the finite element mesh must be generated. Figure 3-10 below shows an example of the MSEW model with finite element mesh along with the elements and soil mentioned in the steps above.

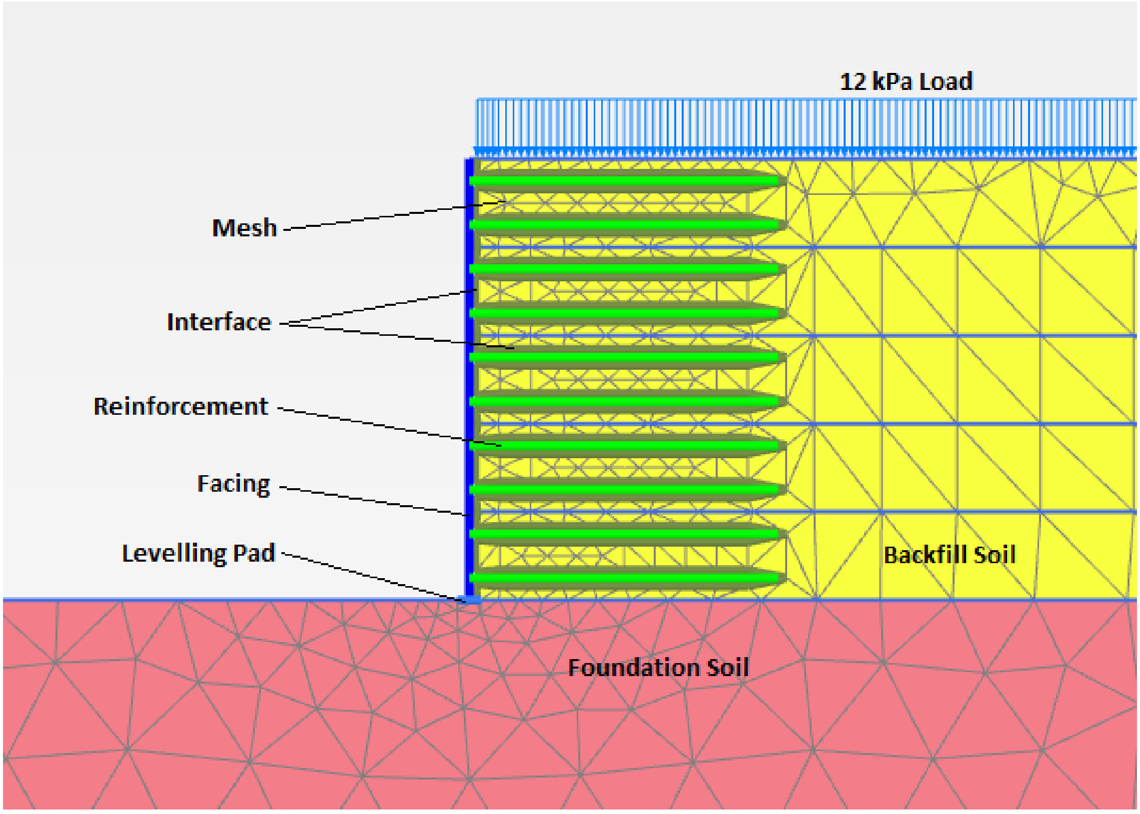


Figure 3-10: Finite element mesh generated

Plaxis 2D has an option for choosing between 6 noded elements or 15 noded elements with the latter providing more detailed results (Brinkgreve, et al., 2017). All FEM models in this dissertation therefore used 15 noded elements with a medium coarse mesh and mesh refinements around structural elements to ensure accurate results are produced especially in the vicinity of the geogrid reinforcement.

Step 8: Before any construction takes place, the initial stresses of the model must be generated as a starting point for the calculation process. Plaxis 2D contains two methods to determine the initial stresses which are the K_0 method and the Gravity loading method. The K_0 method is suitable for use when the surface is horizontal and all the soil layers and the phreatic surface is parallel to the surface. In this study, the K_0 procedure will apply.

Step 9: After the initial stresses have been generated, the MSEW is constructed in a phase by phase manner to simulate the construction steps that would have been followed in a real construction sequence. Each phase of construction is modelled in Plaxis 2D using a plastic calculation analyses which can be used to model elastic-plastic deformation in a phase and does not account for changes of pore water pressure with time. This type of analyses is suitable to model the construction sequence of the MSEW.

When carrying out conventional analyses using finite elements, the mesh generated using the equilibrium conditions is kept the same throughout the calculation. In the modelling of geogrid elements making up an MSEW, the change of the mesh geometry during the load stepping procedure needs to be taken into account. This is required so that the deformations and forces generated in the geogrid can be more accurately determined (Lees, 2016). Therefore, all construction phases used in the modelling of the MSEW's in this dissertation have been carried out with an updated mesh procedure added to the plastic calculation analyses. The updated mesh analysis is automatically performed by Plaxis 2D if selected. The requirement for an updated mesh analysis was discussed earlier in section 2.4.4 as well.

3.4 Summary

Chapter 3 provides details of the process required to design an MSEW using BS8006-1:2010 covering both the external and internal stability (coherent gravity method) requirements. The design process provided is limited to MSEW's with a uniformly distributed load at the surface with horizontal backfill. The design procedure to calculate the design strength of the reinforcement is also given but is limited to Paraweb reinforcement which is the reinforcement used in this dissertation. Chapter 3 also gives a step by step process to model MSEW's using the finite element method and is specific to Plaxis 2D which is the finite element software package used in this dissertation.

CHAPTER 4 : ANALYSIS AND RESULTS

4.1 Introduction

The methodology given in Chapter 3 provides the calculation procedure required by BS8006-1:2010 for the design of MSEW's focusing on the MSEW's covered in this dissertation. Chapter 3 also provided a step by step process to model an MSEW using FEM in Plaxis 2D particularly for this dissertation. The analysis will entail designing the various geometries of MSEW's using BS8006-1:2010 before modelling the geometry using FEM. The results obtained from FEM will be compared to the results obtained from BS8006-1:2010. Some geometry configurations such as the back to back MSEW with continuous reinforcement between each MSEW will be modelled using FEM and compared with each other since these configurations are not explicitly covered in BS8006-1:2010.

4.2 Basis of Analysis

BS8006-1:2010 does not allow reinforcement of back to back MSEW's to be continuous from each wall face but requires that each MSEW be treated independently. The purpose of this dissertation is to investigate if there is a possibility to have the reinforcement continuous from one MSEW face to another in back to back MSEW's. The analysis will firstly look at a case study of an already constructed wall whereby some of the reinforcement of a back to back MSEW is continuous instead of having overlaps which would have been required if the wall was designed using BS8006-1:2010 only. Thereafter, in order to investigate the effects of having continuous reinforcement in back to back MSEW's, various cases will be modelled in order to make comparisons. Further explanations and reasoning for geometry selections will be given in the sections that follow.

4.3 Case Study – Mt Edgecombe Interchange

The upgrade of the existing diamond interchange into a four-level free flow interchange at the Mt Edgecombe Interchange began in April 2013. The project location is shown on Figure 4-1 below. The project is located on National Route 2 section 26 at km 3.6 which is about 30km north of the city of Durban, South Africa.

Figure 4-1: Project Location (SMEC, 2018)

The construction comprised of 9 new road bridges, 1 new pedestrian bridge, 9 MSEW's, and 3 soil nail retaining walls. The project contained the largest incrementally launched viaduct in the southern hemisphere and had three incremental launches being constructed simultaneously with a total length of 1.5km. Figure 4-2 below provides an aerial view of the site during construction. The 9 MSEW's constructed at the interchange comprised of 10,300 square meters of retaining wall which utilised Maccaferri's Macres System (Maccaferri , 2018). The walls ranged in height from 1.5m to 17m and included single sided and back to back MSEW's (South African Institute of Civil Engineering, 2018). More information on the Macres system is contained in section 2.3 of this dissertation.

Figure 4-2: Aerial view of the Mt Edgecombe Interchange under construction in Durban, South Africa (Conchem Construction Chemicals, 2018)

The focus of the dissertation is to investigate the effect of having continuous reinforcement instead of overlapping or independent reinforcement from each face of a back to back MSEW. MSEW's 6-7 of the Mt Edgecombe interchange was the chosen wall to use in this case study since it contained a back to back MSEW wall that had its reinforcement continuous from each wall face and was the tallest MSEW. Figure 4-3 below shows the side view of MSEW 6 and Figure 4-4 below shows the back to back MSEW 6-7 with continuous reinforcement between MSEW 6 and MSEW 7.

Figure 4-3: Side view of MSEW 6 at Mt Edgecombe Interchange (Ramjee, 2017)

Figure 4-4: Reinforcement straps continuous from MSEW 6 face to MSEW 7 face (Ramjee, 2017)

The writer of this dissertation, Amit Ramjee and supervisor Dr Dario Scussel, were part of the design team of the MSEW's at Mt Edgecombe interchange and therefore had on the job experience in the design of the MSEW's and the behaviour of them during and after construction. The design of MSEW 6-7 comprised of using both BS8006-1:2010 and FEM. A cross section of MSEW 6-7 is given below in Figure 4-5 which details the geometry and reinforcement present. MSEW6-7 was not a uniform section since each wall had a different mechanical height with MSEW 6 being the higher of the two. All of the reinforcement of MSEW 7 was connected directly to MSEW 6 while MSEW 6 had some reinforcement that was independent of MSEW 7.

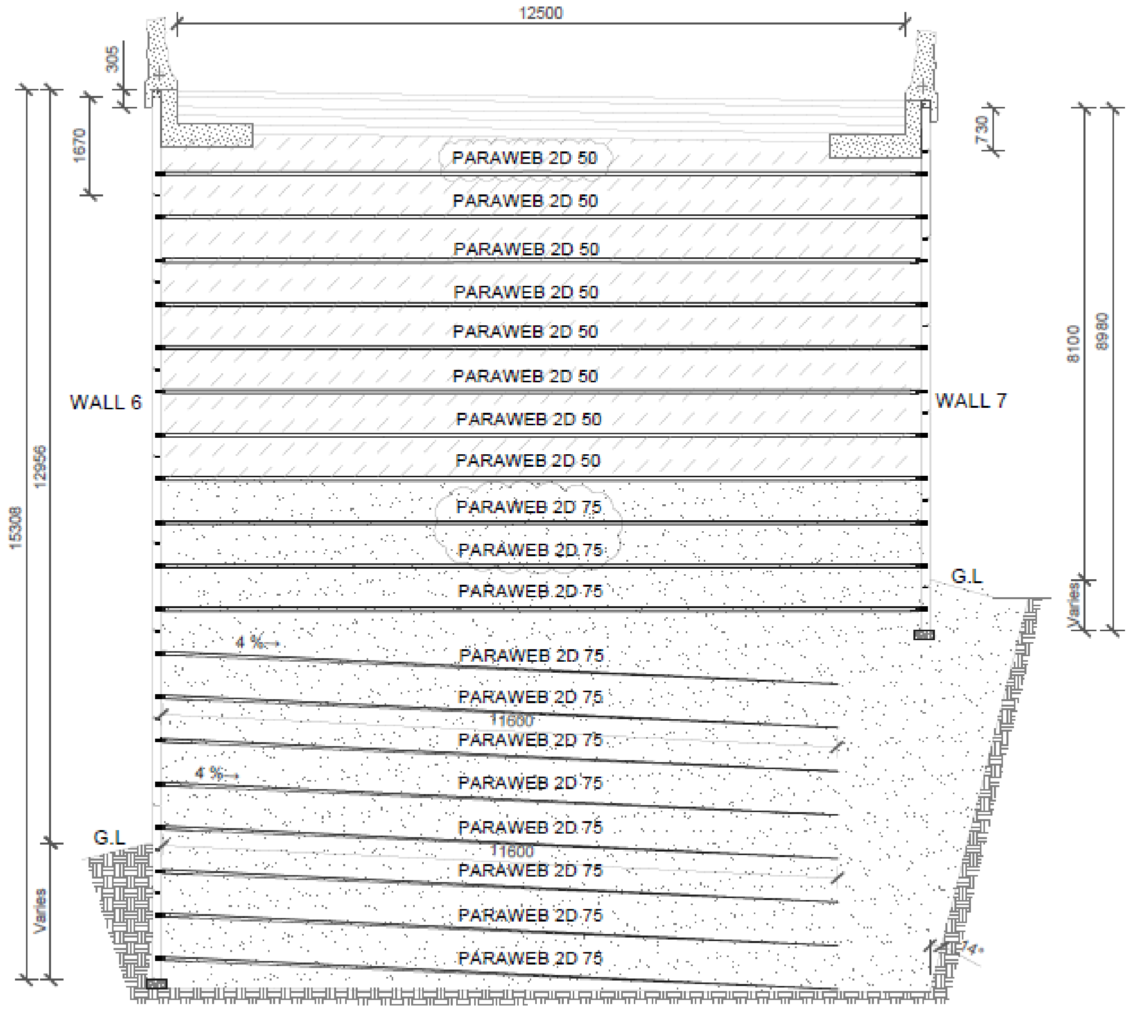


Figure 4-5: Cross Section of MSEW 6-7

When designing according to BS8006-1:2010, MSEW 6 and MSEW 7 would need to be designed as independent one-sided walls with a minimum reinforcement length of 0.7 multiplied by the mechanical height (or a minimum of 3m). The mechanical height of MSEW 6 and MSEW 7 is

15.31m and 8.98m respectively. This means that the minimum reinforcement length of MSEW 6 and MSEW 7 would be 10.72m and 6.29m respectively. The distance between MSEW 6 and MSEW 7 was 13m which meant that there would have been a minimum of 4m of overlap of the reinforcements. The designer of the back to back MSEW 6-7 decided to have continuous reinforcement between each wall instead of providing an overlap of reinforcement from each wall. This meant that the length of reinforcement provided was reduced by more than 23%. In order to design MSEW 6-7 with back to back continuous reinforcement, FEM was used by the designer.

In terms of the serviceability criteria required by BS8006-1:2010, the MSEW's at Mt Edgecombe interchange were found to be satisfactory and were thus signed off and approved for use. Although no instrumentation has been installed for the MSEW's at Mt Edgecombe interchange, it is clear that the back to back MSEW's with continuous reinforcement have behaved in an acceptable manner and shows that there is room for this type of design to be used in future projects.

Since the case study involved successfully implementing the design of a back to back MSEW with continuous reinforcement, further analyses would assist this dissertation in analysing the results of having continuous reinforcement compared to designing the walls independently. This will be achieved by first designing MSEW 6-7 as independent walls using BS8006-1:2010 and thereafter checking the results against an analysis using FEM of the actual constructed MSEW's. Although there are many aspects of a MSEW that can be affected by having continuous reinforcement versus independent reinforcement, this dissertation will mainly focus on the tensile force of the reinforcing element which will be used as the main comparative indicator.

4.3.1 MSEW 6-7 Design

This section contains the analysis and results of MSEW 6-7 which was designed using BS8006-1:2010 and then compared with results obtained from FEM analysis of MSEW 6-7. The FEM software used in all the analyses in this dissertation is Plaxis 2D which has been described section 3.3.

The soil properties used to model (in Plaxis 2D) MSEW 6-7 at chainage 1490 are shown in Table 4-1 below which were obtained from the designer of MSEW 6-7. The relevant properties were then also utilised when designing MSEW 6-7 using BS8006-1:2010.

Table 4-1: Soil Properties for MSEW 6-7

Parameter	Name	Unit	In Situ Soil	Backfill	Layerworks
General					
Material model	Model	-	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb
Type of material behaviour	Type	-	Drained	Drained	Drained
Material Density	γ	kN/m^3	20	21	21.5
Parameters					
Effective internal angle of friction	φ’	°	28	37.1	43.1
Effective cohesion	c’	kPa	5	19.4	25.6
Interface strength	R_{inter}	-	-	0.7	-
Effective stiffness	E’	MPa	50	100	150
Poisson’s ratio	υ	-	0.3	0.3	0.25

Table 4-2 below contains properties used to model (in Plaxis 2D) a 350mm wide and 150mm thick concrete footing used as a foundation levelling pad as specified for MSEW 6-7.

Table 4-2:Parameters for modelling MSEW footing in Plaxis 2D

Parameter	Name	Unit	Value
Material Type	Type	-	Elastic; Isotropic
Normal Stiffness	EA	kN/m	3.00E6
Flexural rigidity	EI	$kN/m^2/m$	5630
Weight	w	kN/m/m	0.45
Poisson’s ratio	υ	-	0.15

Table 4-3 below contains the parameters used to model (in Plaxis 2D) the 140mm thick concrete facing panel of MSEW 6-7.

Table 4-3: Parameters for modelling MSEW facing panel in Plaxis 2D

Parameter	Name	Unit	Value
Material Type	Type	-	Elastic; Isotropic
Normal Stiffness	EA	kN/m	2.80E6
Flexural rigidity	EI	$kN/m^2/m$	4573
Weight	w	kN/m/m	1.89
Poisson's ratio	υ	-	0.15

Various grades of reinforcement were used in MSEW 6-7 with the locations and type of the reinforcements shown in Figure 4-5 above. The properties of the different grades of the reinforcements shown are contained in (British Board of Agrément, 2012). The design strength used for each grade of reinforcement was calculated using the steps given in section 3.2.3.3. Table 4-4 below provides the properties of the reinforcing elements used in the case study analyses using Plaxis 2D.

Table 4-4: Parameters for modelling MSEW 6-7 reinforcement in Plaxis 2D

Parameter	Name	Unit	Paraweb 2D50	Paraweb 2D75	Paraweb 2D50	Paraweb 2D75
Connections per MSEW panel			**2**	**2**	**3**	**3**
Material Type	Type	-	Elastoplastic; Isotropic	Elastoplastic; Isotropic	Elastoplastic; Isotropic	Elastoplastic; Isotropic
Normal Stiffness	EA	kN/m	2793	4190	4190	6283
Maximum Force	N_p	kN/m	80	120	120	180

The triangular mesh generated in Plaxis 2D for MSEW6-7 is shown in Figure 4-6 below along with labels showing the various elements and soil used in the model.

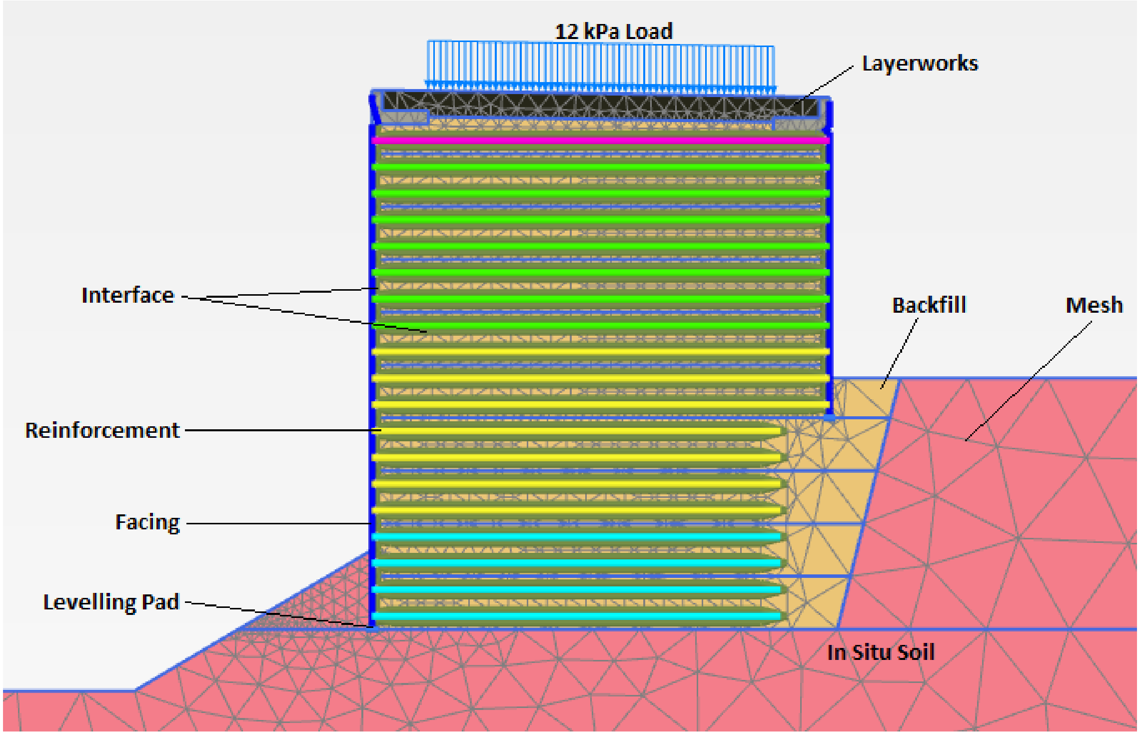


Figure 4-6: MSEW 6-7 Model Showing Mesh Generated in Plaxis 2D

As per the requirements of BS8006-1:2010, MSEW 6-7 were designed as independent walls while the finite element model had the actual wall geometry as shown in Figure 4-5. A uniformly distributed live traffic load of 12 kPa was added to the top of the MSEW6-7 in the Plaxis 2D model and BS8006-1:2010 analysis as well.

The total vertical displacement of MSEW 6-7 for the SLS from Plaxis 2D is shown below in Figure 4-7 below.

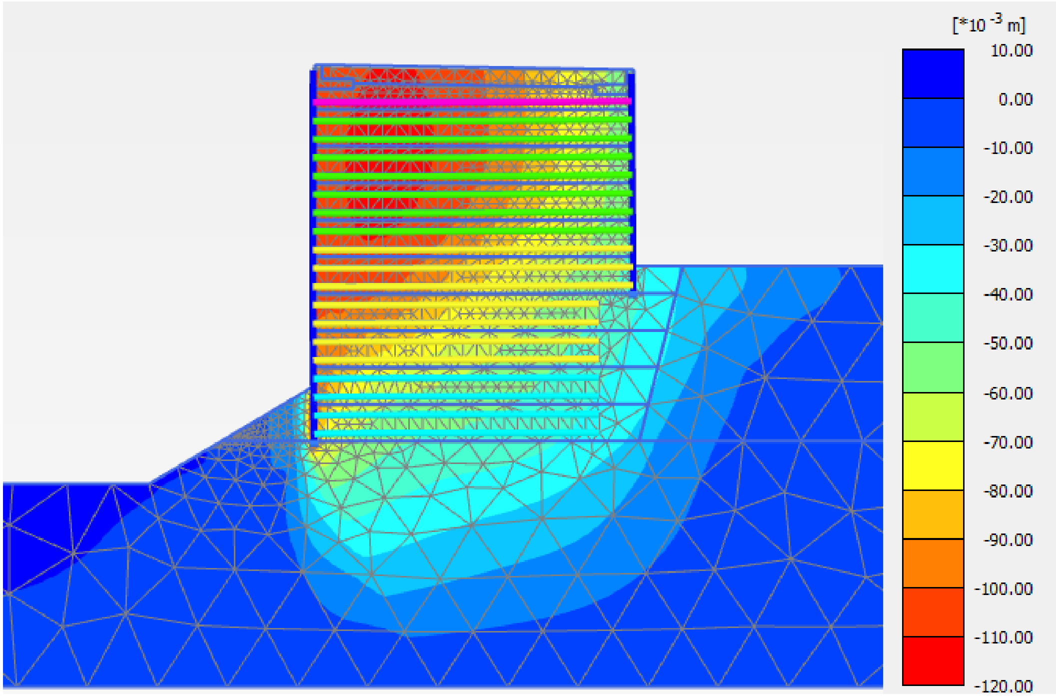


Figure 4-7: Total vertical displacement of FEM model (MSEW 6-7)

The tensile forces obtained in the reinforcement from BS8006-1:2010 and Plaxis 2D at the serviceability limit state (SLS) and the ultimate limit state (ULS) were then compared for MSEW 6 which was the higher MSEW. Table 4-5 below shows the forces generated in the reinforcement for the SLS and the ULS.

Table 4-5: Forces generated in the reinforcements for the ULS and SLS for MSEW6-7

Reinforcement Level (m)	Force (kN/m)			
	SLS		ULS	
	MSEW 6 - BS8006	MSEW 6 - FEM	MSEW 6 - BS8006	MSEW 6 - FEM
13.875	27.32	10.47	1.92	3.23
13.125	16.35	20.84	4.43	7.54
12.375	20.64	23.81	7.60	9.61
11.625	24.24	26.24	10.29	13.73
10.875	27.17	26.40	12.53	14.47
10.125	29.73	31.70	14.43	16.20
9.375	33.81	31.44	17.17	15.63
8.625	38.72	36.29	20.40	14.87
7.875	43.73	49.46	23.71	21.33
7.125	48.91	54.73	27.07	23.40

Reinforcement Level (m)	Force (kN/m)			
	SLS		ULS	
	MSEW 6 - BS8006	MSEW 6 - FEM	MSEW 6 - BS8006	MSEW 6 - FEM
6.375	54.24	58.56	30.56	26.18
5.625	59.71	63.48	34.13	28.66
4.875	65.39	67.56	37.81	33.06
4.125	71.28	70.49	41.65	33.31
3.375	77.39	68.95	45.60	33.30
2.625	83.76	98.24	49.72	45.46
1.875	90.44	88.61	54.04	42.56
1.125	97.40	82.29	58.52	41.71
0.375	103.32	97.59	62.40	53.90

Figure 4-8 below shows the forces generated in the reinforcement in each case for the SLS while Figure 4-9 below shows the forces obtained in the reinforcement in each case for the ULS. The height shown on the y-axis is the height of the reinforcement from the base of MSEW 6.

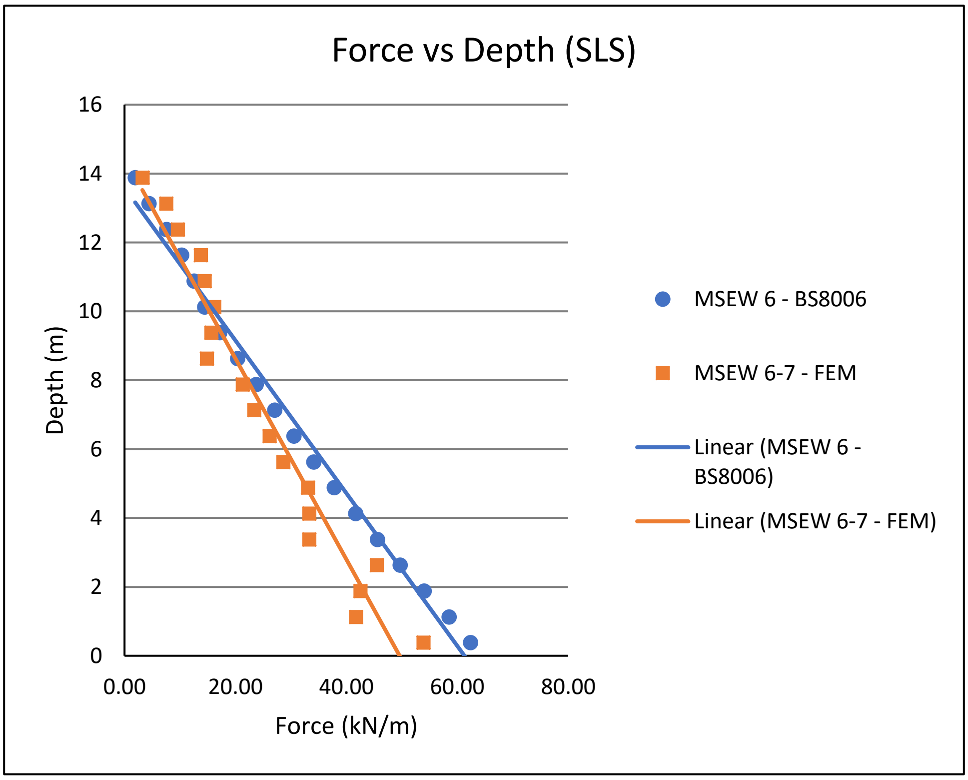


Figure 4-8: Case Study – Reinforcement forces for Serviceability Limit State

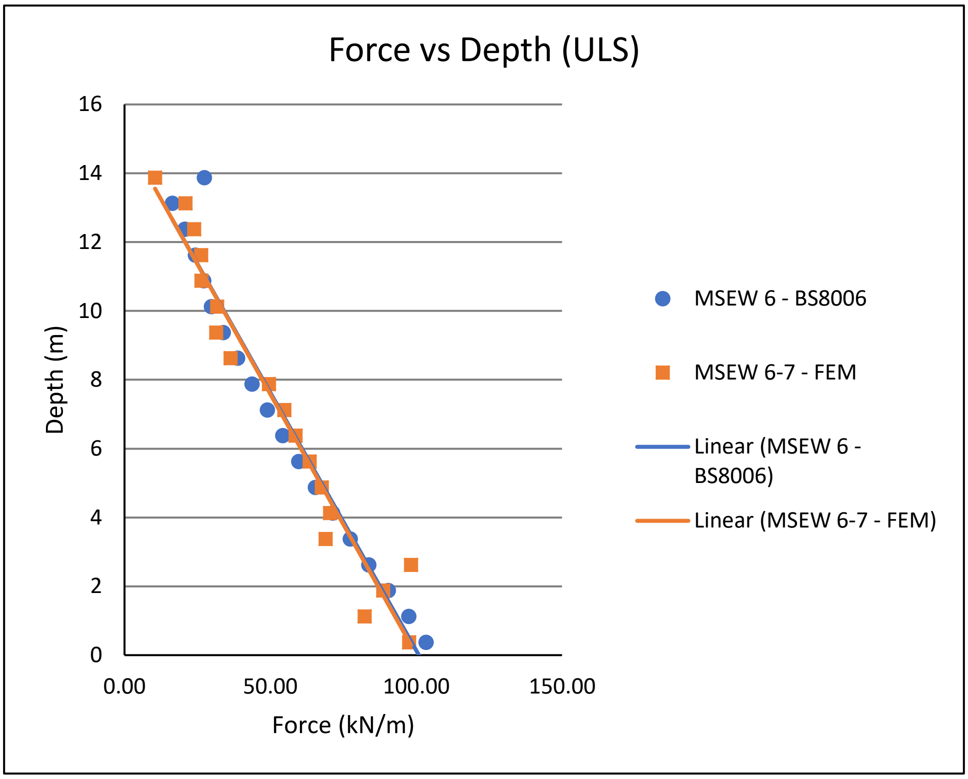


Figure 4-9: Case Study - Reinforcement forces for Ultimate Limit State

Linear trendlines were added to Figure 4-8 and Figure 4-9 as these were the best fit to the data obtained. A comparison of the forces obtained using the BS8006-1:2010 and FEM for MSEW 6 are summarised in the points below:

- It can be seen from Figure 4-8 (forces obtained for the SLS) that FEM produces similar forces in the upper zone before both trendlines separate with the design using BS8006-1:2010 having higher forces. Figure 4-9 (forces obtained for the ULS) shows that the force distribution for both methods produce a similar force distribution.

- The forces obtained in the ULS for both methods of analyses (BS8006-1:2010 and FEM) have shown similar results. This gives confidence in using FEM to further investigate the effects of having continuous reinforcement in back to back MSEW's since these forces (at the ULS) would have been used to choose the required reinforcement. A method to further analyse this is discussed in the next section.

4.4 Comparative Study

It has been shown in section 4.3 that the possibility to have continuous reinforcement instead of independent reinforcement for back to back MSEW's exist. In order to investigate this further, a series of models with varying geometries will be analysed. Four main types of model configurations are detailed below with the notations of the labels summarised as follows:

H - denotes the mechanical height of the MSEW

L - denotes the length of the reinforcement

Type 1: Single Sided MSEW – This MSEW is a single sided wall as shown in Figure 4-10 below.

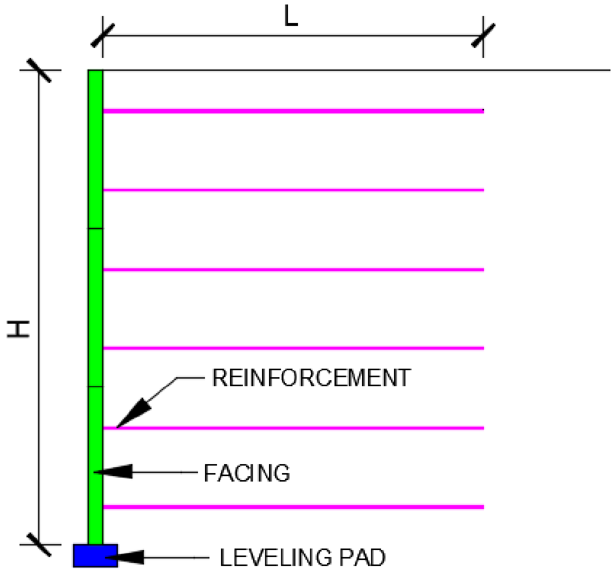


Figure 4-10: Type 1- Single Sided MSEW

Type 2a: A Back to back MSEW is shown in Figure 4-11 below. The reinforcement shown of each MSEW meets at the centre but are independent of each other. The reinforcement meets at the centre but the illustration shows a space in order to indicate that the reinforcement is independent.

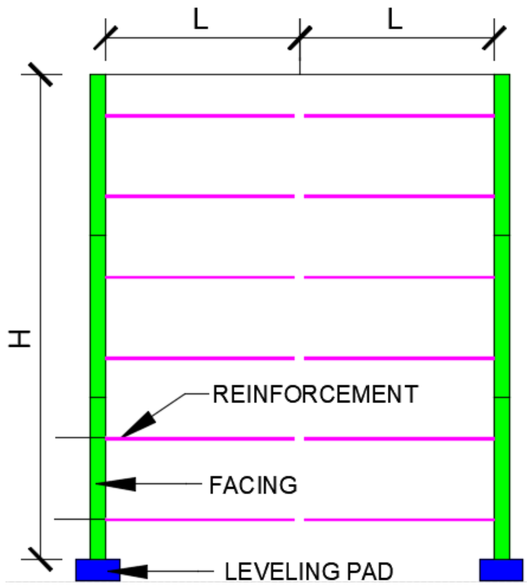


Figure 4-11: Type 2a Back to Back MSEW

Type 2b: A Back to back MSEW is shown in Figure 4-12 below. The reinforcement shown is continuous from one side of the MSEW to the other side.

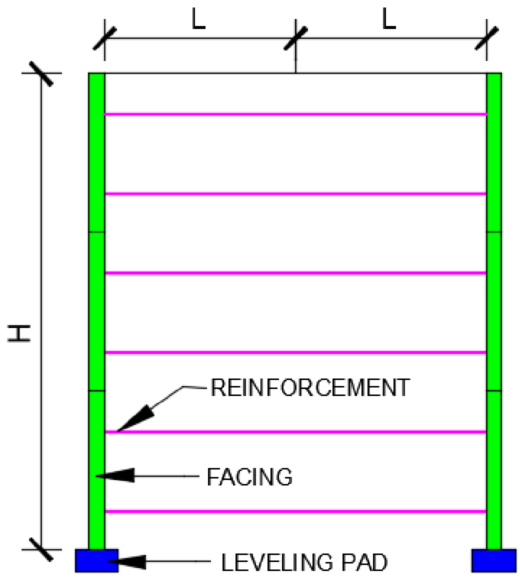


Figure 4-12: Type 2b Back to Back MSEW

Type 3: A back to back MSEW with overlapping reinforcement is shown in Figure 4-13 below.

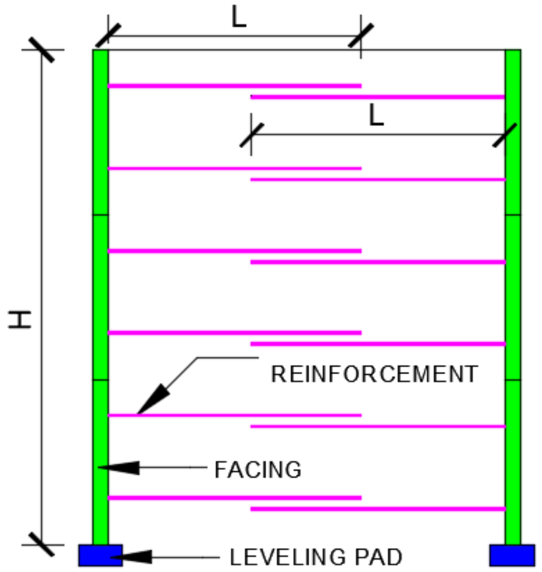


Figure 4-13: Type 3 Back to Back MSEW

Table 4-6 below summarises the various configuration that were investigated. If BS8006 is written after a symbol i.e., X1-BS8006, it that implies that the results are for calculations carried out according to BS8006-1:2010. All other results are generated from FEM.

Table 4-6:Model configurations investigated

Symbol	Wall Type	Wall Height (m)	Reinforcement Length – L (m)	Distance between MSEW faces (m)
X1	Type 1	7.5	0.7H	N/A
X2	Type 2a - Independent		0.7H	1.4H
X3	Type 2b - Continuous		0.7H	1.4H
X4	Type 2b - Continuous		0.5H	1H
X5	Type 3 - Overlap		0.7H	1H
Y1	Type 1	9	0.7H	N/A
Y2	Type 2a - Independent		0.7H	1.4H
Y3	Type 2b - Continuous		0.7H	1.4H
Y4	Type 2b - Continuous		0.5H	1H
Y5	Type 3 - Overlap		0.7H	1H

Symbol	Wall Type	Wall Height (m)	Reinforcement Length – L (m)	Distance between MSEW faces (m)
Z1	Type 1	10.5	0.7H	N/A
Z2	Type 2a - Independent		0.7H	1.4H
Z3	Type 2b - Continuous		0.7H	1.4H
Z4	Type 2b - Continuous		0.5H	1H
Z5	Type 3 - Overlap		0.7H	1H

An explanation into why the geometry of each model shown in Figure 4-10 to Figure 4-13 along with the various configurations shown in Table 4-6 is given below. Configuration X1 to X5 will be explained which would also apply to Y1-5 and Z1-5 since the only difference between X, Y, and Z was the height of the MSEW. The various heights were chosen in order to get sufficient data for comparison.

X1 – This is a single sided MSEW's with a reinforcement length of 0.7 multiplied by H (0.7H). This geometry was chosen to act as a baseline case. A design of this MSEW using BS8006-1:2010 and FEM can be used to directly compare the forces obtained in the reinforcing elements. This comparison can then be used to determine if or by how much the forces obtained differ between the methods of analysis (BS8006-1:2010 versus FEM). This baseline case (designed using BS8006-1:2010) can also be used to compare to the other back to back configurations because if the back to back MSEW was designed solely according to BS8006-1:2010, they would have been designed as single sided walls with independent reinforcement. Since the forces obtained in the ULS are used to choose the reinforcement required, the study will focus on the force results calculated using ULS design only.

X2 and X3 – Both these cases have the same height, reinforcement length (0.7H) and distance between the back to back walls (1.4H) of the MSEW's. The only difference between these two configurations is that X2 has independent reinforcing elements from each wall face while X3 has continuous reinforcement between the walls of the MSEW's. These configurations can be compared to see the differences of the forces in the reinforcing elements for continuous reinforcement versus independent reinforcement.

X4 and X5 - Both these cases have the same height, and distance between the back to back walls (1H) of the MSEW's. The only difference between these two configurations is that X4 has continuous reinforcing elements from each wall face while X5 has overlapping independent reinforcement elements due to the distance between the MSEW faces causing an overlap. The overlap is caused due to the requirement by BS8006-1:2010 specifying that the minimum length of reinforcement shall be 0.7H. These configurations can be compared to see the differences of the forces in the reinforcing elements for continuous reinforcement versus overlapping independent reinforcement. This case can also be used to verify if an overlapping of the reinforcement can be changed to continuous reinforcement instead although not in line with the requirements of BS8006-1:2010.

In order to carry out the investigation, a number of parameters must be chosen. These parameters will be chosen and discussed in the next section.

4.5 Parameters

There are a variety of variables that are used in the design of an MSEW. This dissertation is focused on determining the differences between having reinforcement continuous or independent for back to back MSEW's. The particular result that is being investigated is the force generated in the reinforcing element. After determining the configurations to investigate in the previous section, suitable parameters must now be chosen in order to properly target the area of investigation. The configurations have the following variables:

- Change in height of MSEW's
- Change in reinforcement length
- Varying types of wall types such as singles sided or back to back MSEW's
- Reinforcement for the MSEW's are either independent, continuous, or overlapping

The type of MSEW chosen was the Macres system (see section 2.3) which will be used to get the dimensions and layout to be used. This system was chosen so that the analyses are similar to the case study detailed in section 4.3 above which also used the Macres system. The remainder of the components that were used to model the MSEW's are as follows:

- Facing
- Levelling pad

- Reinforcement
- Structural fill
- Backfill
- Foundation material
- Traffic load (this load was assumed as a uniformly distributed live load of 12kPa acting at the top of the MSEW)

In order to only focus on the forces in the reinforcing elements, it was decided to keep the facing and levelling pad the same in all the analyses. The levelling pad was assumed to comprise of a 200mm thick concrete footing that is 400mm in width. The facing element was the standard panel type used in the Macres system comprising of a 140mm thick concrete panel. The parameters for the facing element and levelling pad to be used in Plaxis 2D are provided in Table 4-7 below.

Table 4-7:Parameters for modelling MSEW footing in Plaxis 2D

			Levelling Pad	**Facing Element**
Parameter	**Name**	**Unit**	**Value**	**Value**
Material Type	Type	-	Elastic; Isotropic	Elastic; Isotropic
Normal Stiffness	EA	kN/m	4.00E6	2.80E6
Flexural rigidity	EI	$kN/m^2/m$	13.33E3	4573
Weight	w	kN/m/m	0.6	1.89
Poisson's ratio	υ	-	0.15	0.15

It was also decided to have the same material parameters for the structural fill, backfill, and foundation material in order to prevent any interferences from these materials on the forces generated in the reinforcement. The structural fill used in the construction of MSEW's usually comprise of good quality cohesionless soil (Berg, et al., 2009). It was therefore chosen to use a well graded sand (SW, according to the unified soil classification system (USCS), (ASTM D2487-17, 2017)). The effective internal angle of friction, effective cohesion, material density, Poisson's ratio (Swiss Standard SN 670 010b, 2014) and Young's modulus (Obrzud & Truty, 2012) for a well graded sand (SW), are given in Table 4-8 below. The interface strength factor (R_{inter}) to allow slippage between the soil reinforcement and the soil was chosen to be 0.7 as recommended for

Paraweb straps used in MSEW's (Macres System), (British Board of Agrément, 2012). The interface strength factor is required for the FEM analyses on Plaxis 2D.

Table 4-8: Soil Properties for MSEW analyses

Parameter	Name	Unit	Structural Fill/ Backfill/ Foundation Material
General			
Material model	Model	-	Mohr Coulomb
Type of material behaviour	Type	-	Drained
Material Density	γ	kN/m^3	21
Parameters			
Effective internal angle of friction	φ'	°	36
Effective cohesion	c'	kPa	0
Interface strength	R_{inter}	-	0.7
Effective stiffness	E'	MPa	80
Poisson's ratio	υ	-	0.3

The reinforcement properties were kept the same throughout the study regardless of the configuration so that the various analyses can be compared directly. By keeping the reinforcement properties the same throughout the study, it also reduces the variables in the study and allows a direct comparison between the various configurations since the only change now between the configurations are the geometry of the model. The reinforcement stiffness properties used in Plaxis 2D for the study for all configurations being investigated is shown in Table 4-9 below.

Table 4-9: Parameters for modelling MSEW reinforcement in Plaxis 2D

Parameter	Name	Unit	Value
Material Type	Type	-	Elastoplastic; Isotropic
Normal Stiffness	EA	kN/m	6000

An example of the Z1 configuration (from Plaxis 2D) is shown below in Figure 4-14. The components making up Z1 are also used in every other configuration investigated.

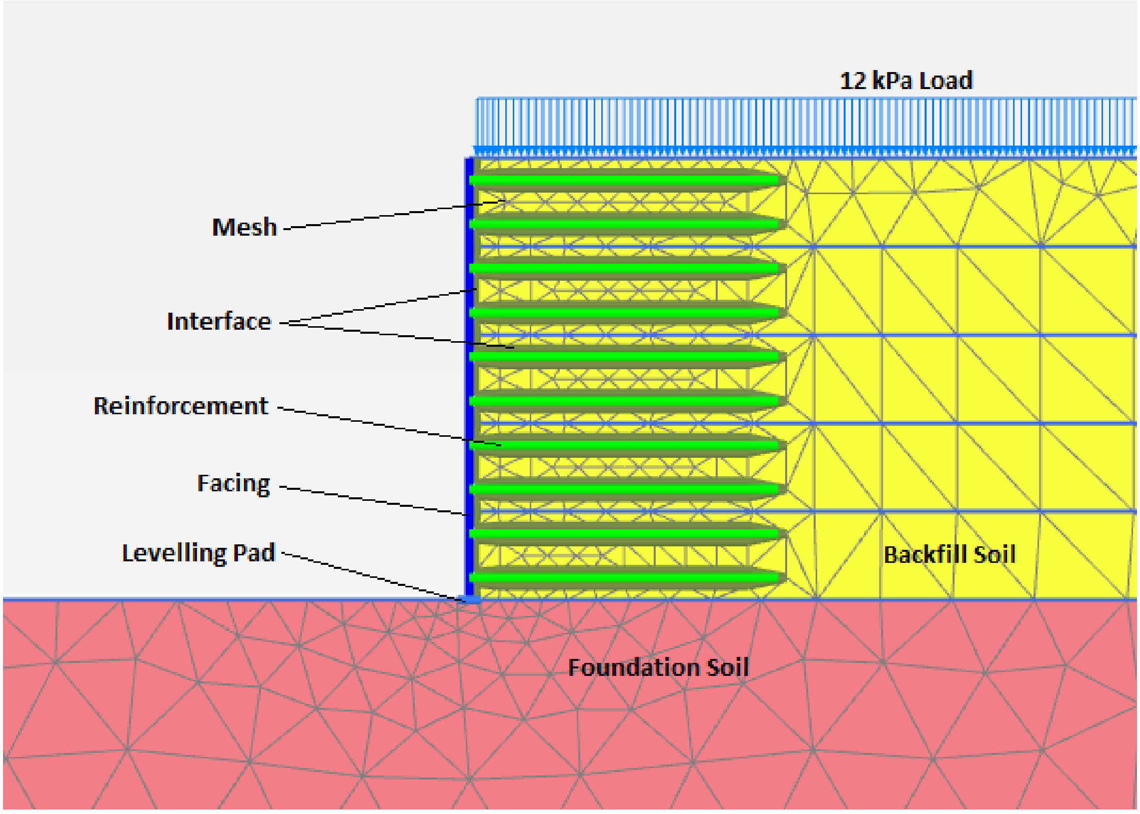


Figure 4-14: Z1 Configuration in Plaxis 2D

4.6 Comparative Analysis

This section presents the analysis and findings of the comparative analyses carried out using the different configurations in section 4.4 above and using the properties shown in section 4.5. In order to compare the difference in forces generated in the reinforcing elements of the MSEW's, different configurations were grouped together as follows:

- Type 1
- Type 2 with distance between the back to back MSEW equal to 1.4H
- Type 2 with distance between the back to back MSEW equal to 1.0H

All results shown are obtained from FEM analysis unless BS8006 is shown after the symbol, example X1 - BS8006 which would imply that the results are obtained using BS8006-1:2010.

4.6.1 Type 1

X1, Y1, and Z1 fall under the Type 1 MSEW. The forces generated in the reinforcement were calculated for the ULS using BS8006-1:2010 and FEM. Table 4-10, Table 4-11, and Table 4-12 below give the forces calculated (at ULS) using BS8006-1:2010 and FEM for X1, Y1, and Z1 respectively. The reinforcement level shown is the height of the reinforcement from the base of the MSEW. The percentage difference between the two methods is also shown which was calculated using equation 4-1 below:

$$\boldsymbol{Difference}\ (\%) = \frac{\boldsymbol{Force\ (FEM) - Force(BS8006)}}{\textbf{Force(FEM)}} \qquad 4\text{-}1$$

Table 4-10: Force difference between X1-BS8006 and X1

Reinforcement Level (m)	Force (kN/m)		Difference (%)
	X1-BS8006	X1	
7.125	9.73	14.51	33
6.375	16.27	15.24	-7
5.625	22.11	23.78	7
4.875	27.07	24.86	-9
4.125	32.00	31.39	-2
3.375	36.61	29.98	-22
2.625	40.69	36.22	-12
1.875	44.21	37.99	-16
1.125	49.17	46.62	-5
0.375	53.84	61.62	13

Table 4-11: Force difference between Y1-BS8006 and Y1

Reinforcement Level (m)	Force (kN/m)		Difference (%)
	Y1-BS8006	Y1	
8.625	9.63	15.17	37
7.875	16.16	17.55	8
7.125	22.00	25.21	13
6.375	27.04	26.33	-3
5.625	31.49	34.22	8
4.875	35.81	33.39	-7
4.125	39.52	38.04	-4
3.375	41.31	43.31	5
2.625	47.04	49.49	5

Reinforcement Level (m)	Force (kN/m)		Difference (%)
	Y1-BS8006	Y1	
1.875	53.39	53.22	0
1.125	60.24	59.24	-2
0.375	66.72	75.13	11

Table 4-12: Force difference between Z1-BS8006 and Z1

Reinforcement Level (m)	Force (kN/m)		Difference (%)
	Z1-BS8006	Z1	
10.125	9.57	15.50	38
9.375	16.05	19.38	17
8.625	21.92	27.79	21
7.875	27.01	30.83	12
7.125	31.31	37.36	16
6.375	35.33	38.80	9
5.625	38.85	43.58	11
4.875	41.73	41.94	0
4.125	45.81	48.00	5
3.375	51.65	53.05	3
2.625	57.81	59.46	3
1.875	64.35	64.57	0
1.125	71.28	70.15	-2
0.375	77.65	90.12	14

It is clear from Table 4-10 to Table 4-12 above, the difference in forces in the reinforcement varies considerably with the biggest variances being experienced in the upper sections. Both methods show that the force in the reinforcement increases with depth. It was therefore decided to plot the forces in the reinforcement versus the height of the reinforcement to see if any relationship could be obtained. Graphs showing forces generated in the reinforcement with depth for X1, Y1, and Z1 are shown below in Figure 4-15, Figure 4-16, and Figure 4-17 respectively. Linear trendlines were added to the data since a linear relationship was apparent.

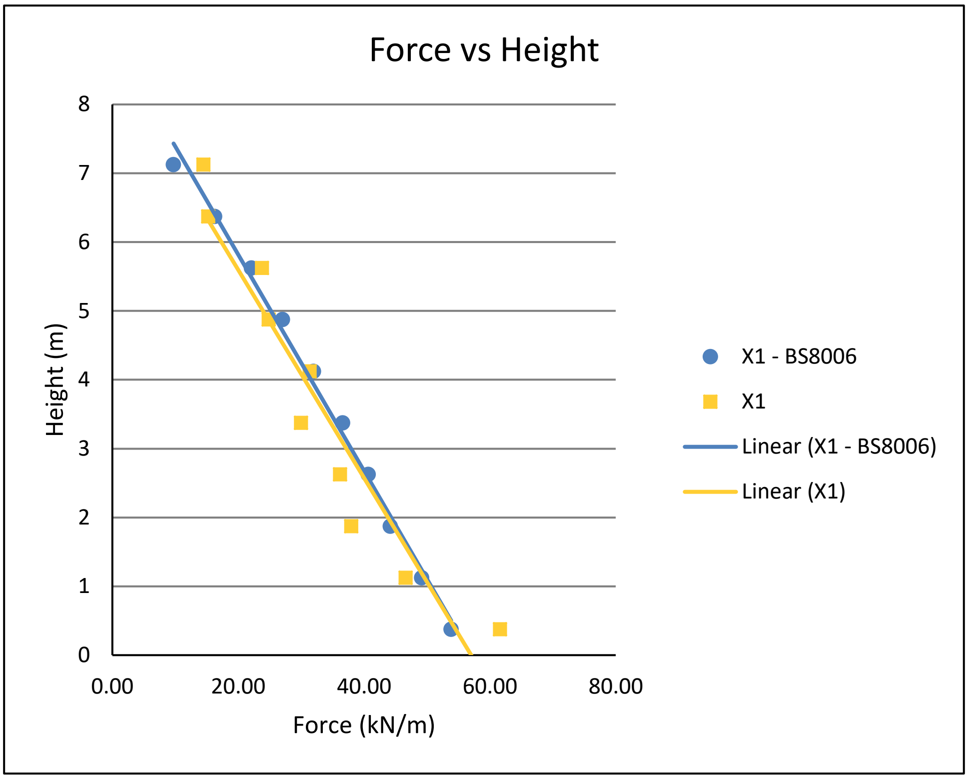


Figure 4-15: Type 1 – X1

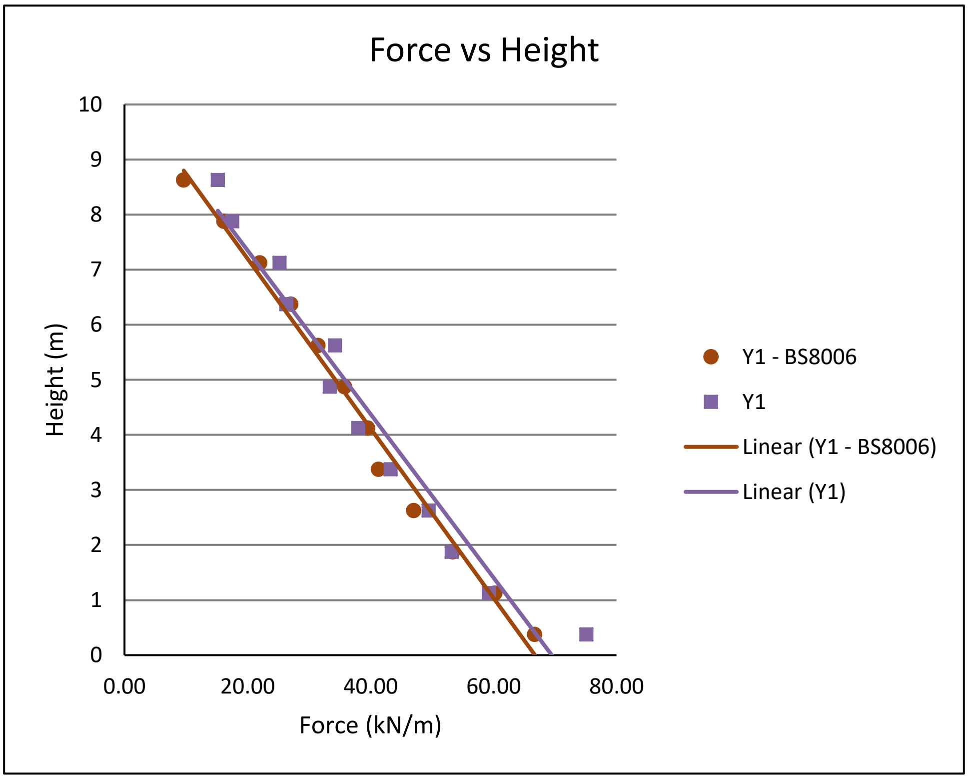


Figure 4-16: Type 1 – Y1

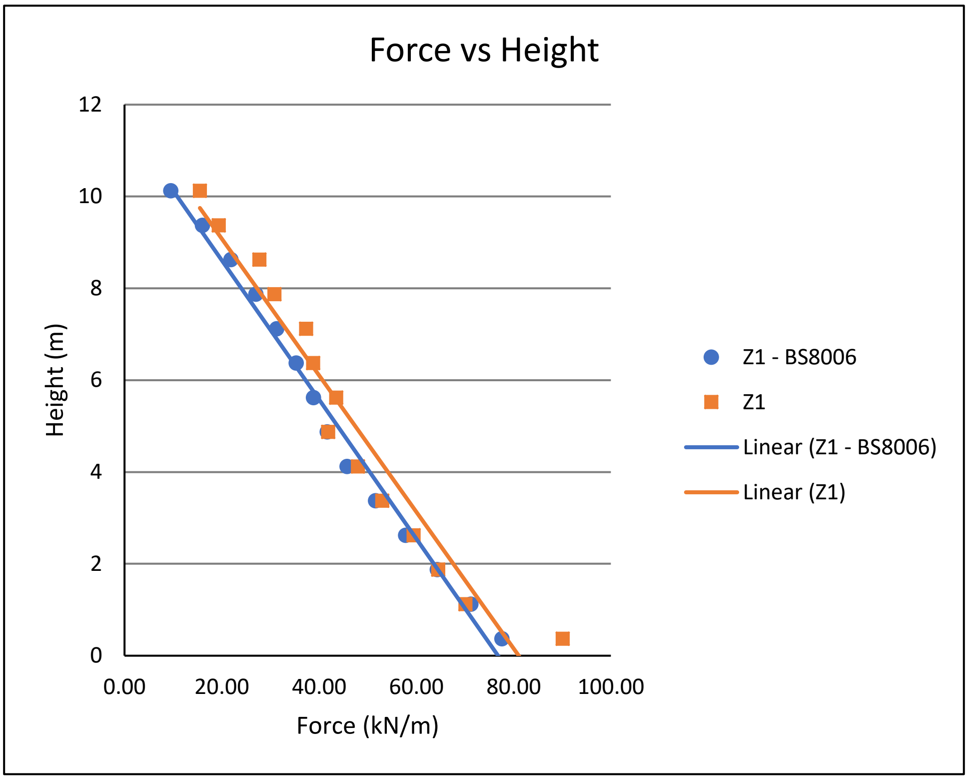


Figure 4-17: Type 1 – Z1

Using the linear trendlines from Figure 4-15 to Figure 4-17 above, it is now seen that BS8006-1:2010 and FEM have a similar trend of forces generated. This provides some confidence in using FEM to compare the various configurations proposed.

The total vertical displacement of the FEM models obtained using Plaxis 2D for the SLS are shown in Figure 4-18, Figure 4-20, and Figure 4-22 below for X1, Y1, and Z1 respectively. Cross sections were taken just below the top of the MSEW's in order to view the vertical settlement that would be experienced in the MSEW's near the surface. These cross sections are shown in Figure 4-19, Figure 4-21, and Figure 4-23 which apply to X1, Y1, and Z1 respectively.

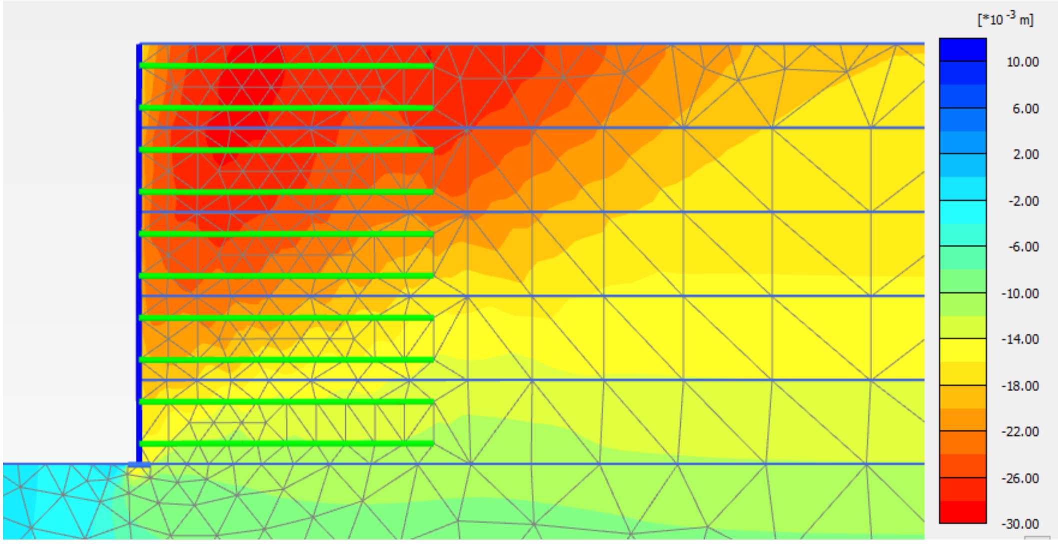


Figure 4-18: X1 Total vertical displacements

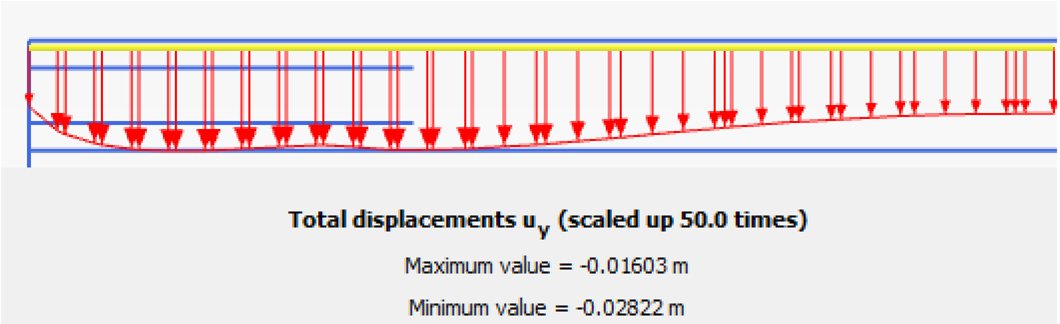


Figure 4-19: X1 Cross section of total vertical displacements near surface of MSEW

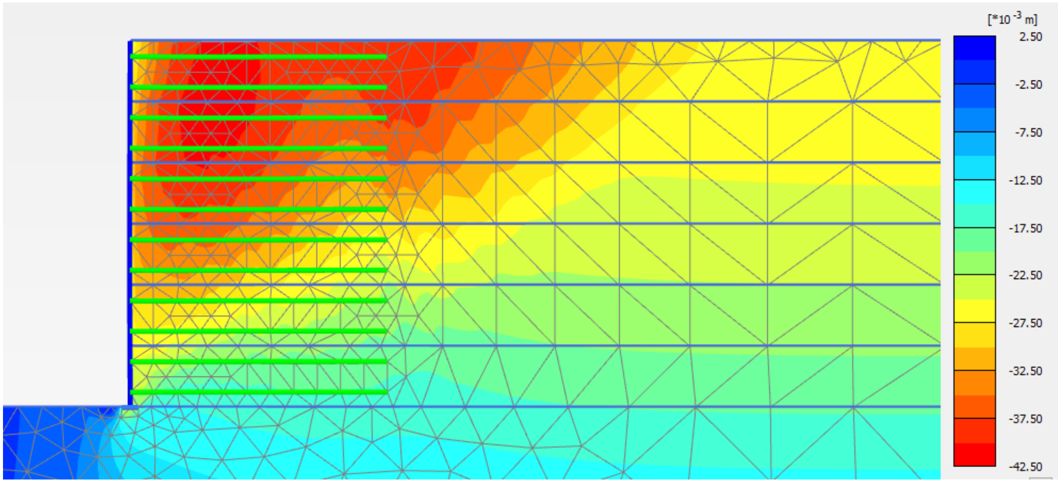


Figure 4-20: Y1 Total vertical displacements

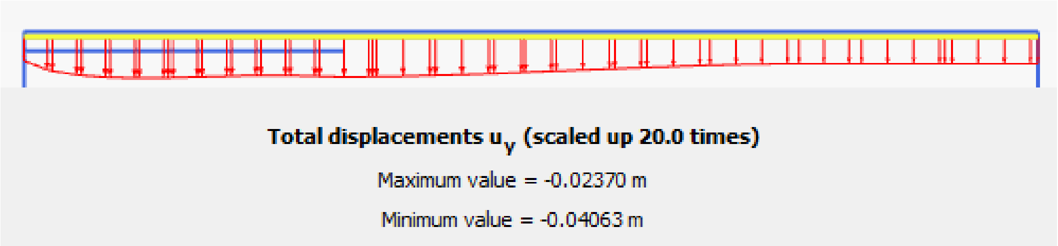


Figure 4-21: Y1 Cross section of total vertical displacements near surface of MSEW

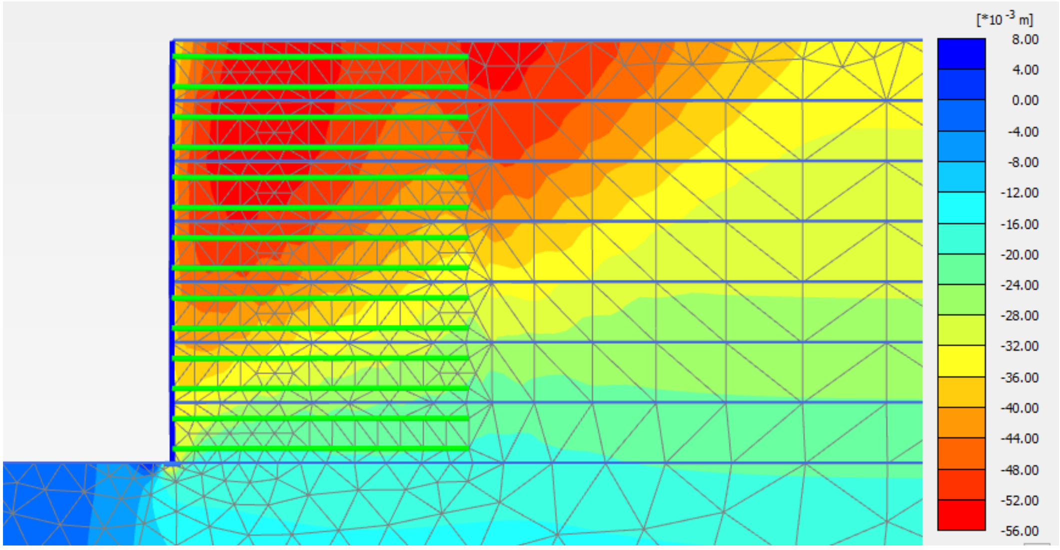


Figure 4-22: Z1 Total vertical displacements

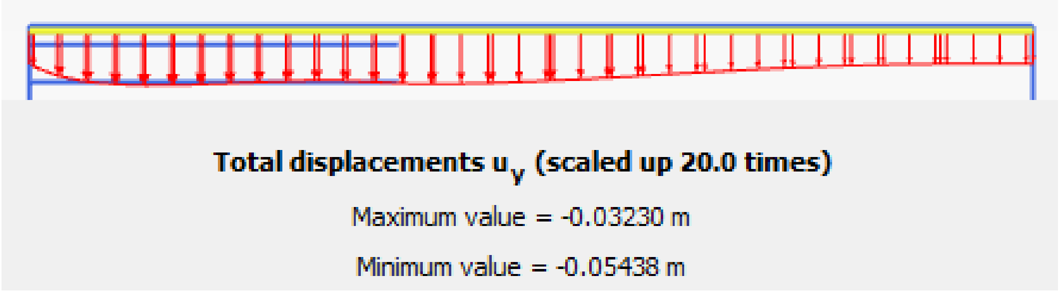


Figure 4-23: Z1 Cross section of total vertical displacements near surface of MSEW

As seen in in Figure 4-18 to Figure 4-23 above, the magnitude of displacement is different for each case since the MSEW's are varying in height but it can be noticed that the vertical displacement and vertical settlement near the surface for each case is similar in shape.

4.6.2 Type 2 with distance between back to back MSEW equal to 1.4H

This section will compare back to back MSEW's that have the distance between the back to back walls equal to 1.4H and have their reinforcement continuous or independent. X2, X3, Y2, Y3, Z2, and Z3 fall into this category and can only be analysed using FEM if they are analysed as a whole. If these MSEW's are designed to BS8006-1:2010 they would have been designed as independent MSEW's with the same geometry. In carrying out any comparisons, it was therefore decided to include the forces that would have been generated in the reinforcement if the MSEW's had been designed to BS8006-1:2010.

Table 4-13, Table 4-14, and Table 4-15 below shows the forces generated in the reinforcements for X1-BS8006/X2/X3, Y1-BS8006/Y2/Y3, and Z1-BS8006/Z2/Z3 at the ULS respectively.

Table 4-13: Force generated in reinforcements for X1-BS8006, X2, and X3

Reinforcement Level (m)	Force (kN/m)		
	X1-BS8006	X2	X3
7.125	9.73	15.29	13.32
6.375	16.27	15.57	14.55
5.625	22.11	20.67	22.29
4.875	27.07	24.04	21.36
4.125	32.00	30.27	27.28
3.375	36.61	31.06	27.45
2.625	40.69	35.29	33.09
1.875	44.21	41.04	35.61
1.125	49.17	42.55	39.11
0.375	53.84	54.51	50.49

Table 4-14: Force generated in reinforcements for Y1-BS8006, Y2, and Y3

Reinforcement Level (m)	Force (kN/m)		
	Y1-BS8006	Y2	Y3
8.625	9.63	15.50	14.20
7.875	16.16	16.28	16.18
7.125	22.00	22.03	22.83
6.375	27.04	24.71	23.98
5.625	31.49	28.74	30.74
4.875	35.81	31.87	29.92
4.125	39.52	36.18	36.46
3.375	41.31	41.05	38.74

Reinforcement Level (m)	Force (kN/m)		
	Y1-BS8006	**Y2**	**Y3**
2.625	47.04	47.65	42.61
1.875	53.39	50.98	43.64
1.125	60.24	53.96	48.96
0.375	66.72	68.60	60.99

Table 4-15: Force generated in reinforcements for Z1-BS8006, Z2, and Z3

Reinforcement Level (m)	Force (kN/m)		
	Z1-BS8006	**Z2**	**Z3**
10.125	9.57	16.53	14.92
9.375	16.05	16.88	17.11
8.625	21.92	23.86	23.96
7.875	27.01	27.42	26.29
7.125	31.31	33.59	32.48
6.375	35.33	34.32	31.84
5.625	38.85	38.94	37.47
4.875	41.73	42.89	40.03
4.125	45.81	46.17	46.07
3.375	51.65	55.55	49.61
2.625	57.81	60.50	53.57
1.875	64.35	62.46	54.22
1.125	71.28	65.07	60.57
0.375	77.65	84.44	79.05

Figure 4-24, Figure 4-25, and Figure 4-26 below contains the comparison carried out for X1-BS8006/X2/X3, Y1-BS8006/Y2/Y3, and Z1-BS8006/Z2/Z3 respectively which shows the forces generated in the reinforcement versus the height of the reinforcement from ground level at the ULS.

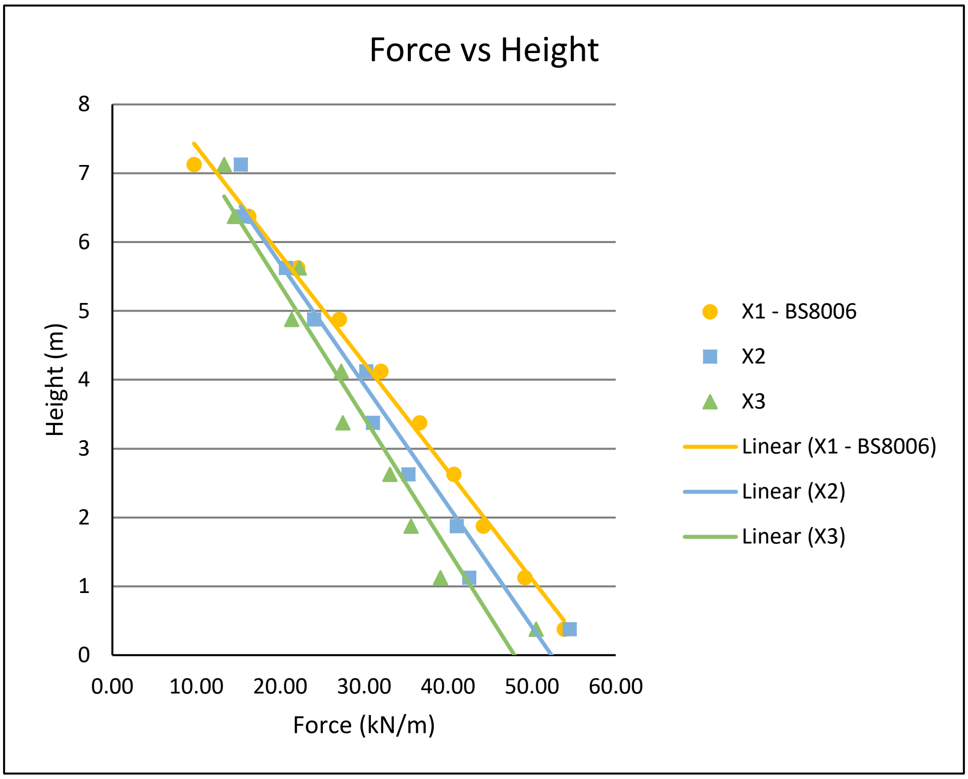


Figure 4-24: X1-BS8006 versus X2 versus X3

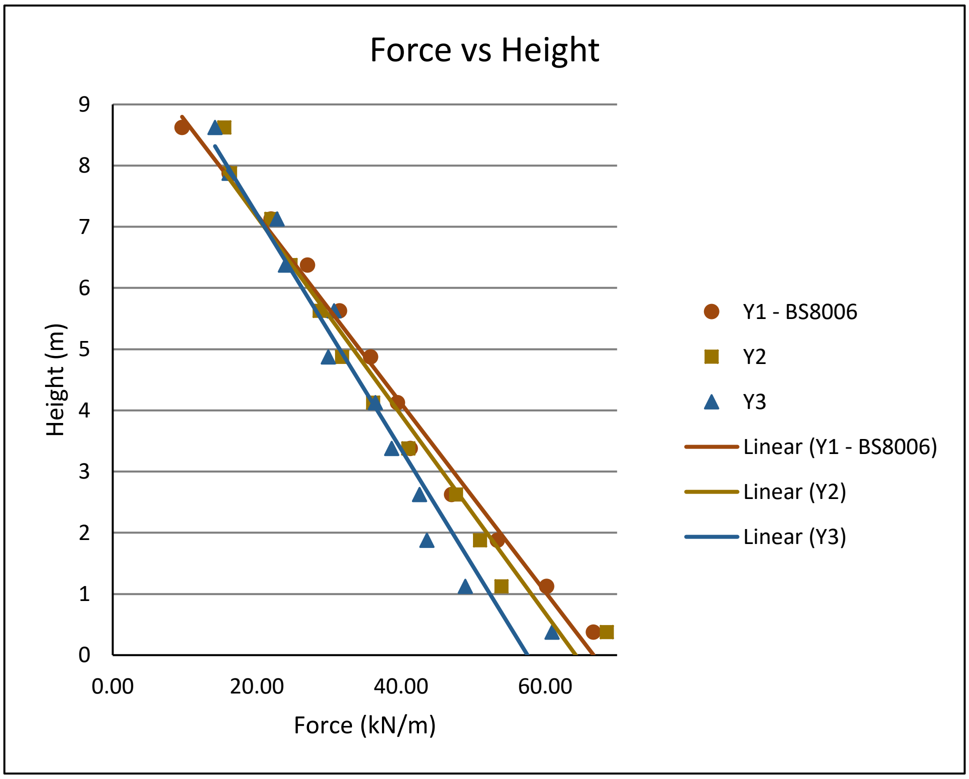


Figure 4-25: Y1-BS8006 versus Y2 versus Y3

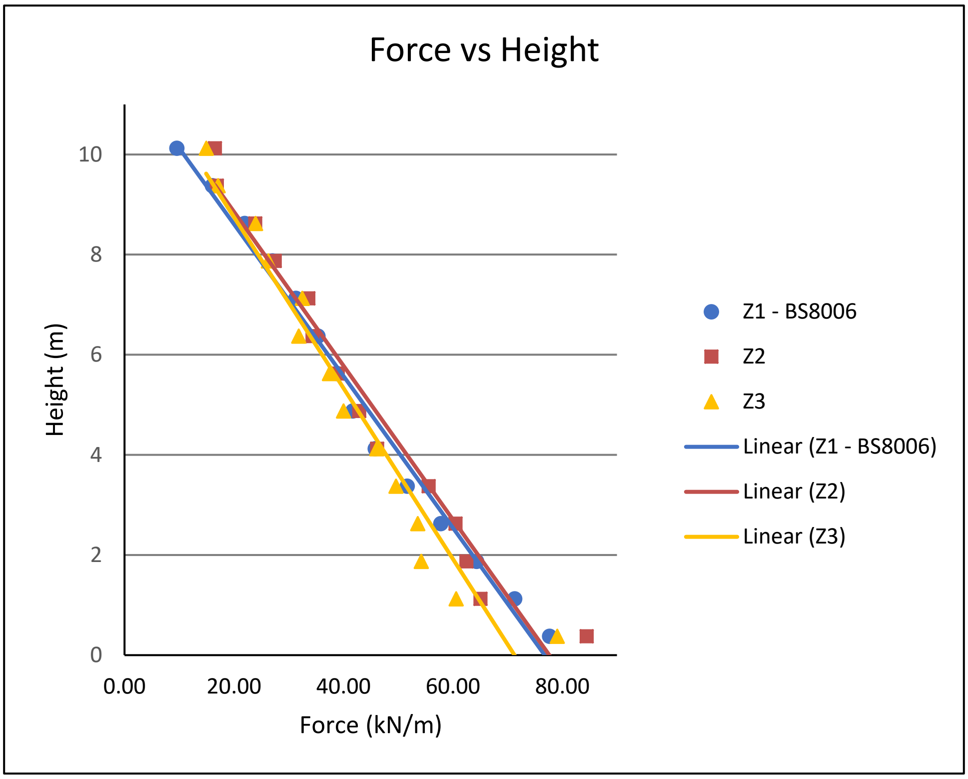


Figure 4-26: Z1-BS8006 versus Z2 versus Z3

The linear trendlines (of the forces calculated) shown in Figure 4-24 to Figure 4-26 above shows that the forces calculated behave as follows:

- X1-BS8006 is larger followed by X2 and then X3
- Y1-BS8006 is generally larger followed closely by Y2 and then Y3
- Z1-BS8006 and Z2 are almost identical while Z3 has lower forces

The force distribution along the length of the reinforcement for X1/X2/X3, Y1/Y2/Y3, and Z1/Z2/Z3 are shown below in Table 4-16, Table 4-17, and Table 4-18 respectively and should only be used to compare the shape of the force distribution along the length of the reinforcement. Figure 4-27 (applies to X1/X2/Y1/Y2/Z1/Z2) and Figure 4-28 (applies to X3/Y3/Z3) shows the side of the MSEW facing, the location of the maximum force in the reinforcement, the reinforcement, and the force distribution. The results of the forces of the right-hand side of MSEW X2/Y2/Z2 are not shown since the results were symmetrical to the left-hand side. X3/Y3/Z3 has two MSEW facings since it had continuous reinforcement between the back to back MSEW.

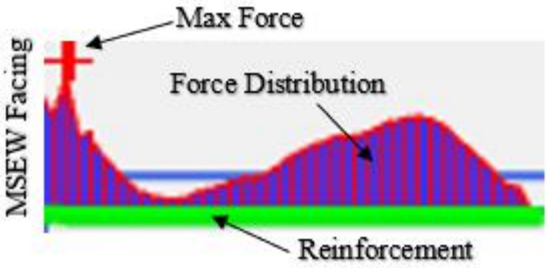


Figure 4-27: Type 1, Type 2a and Type 3 MSEW force distribution

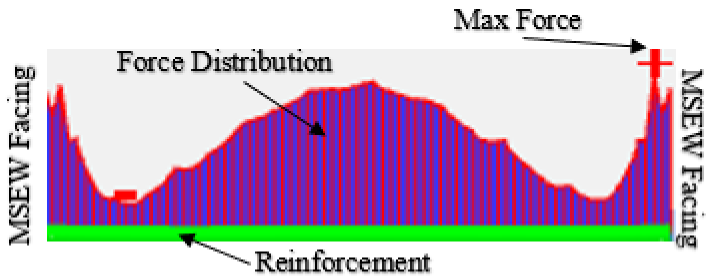
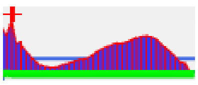
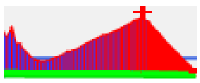
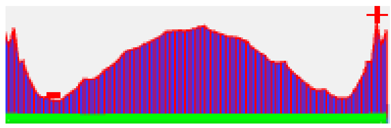
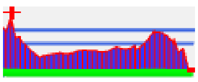
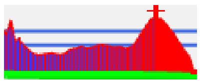
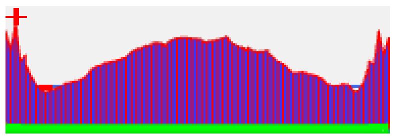
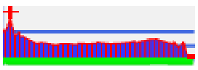
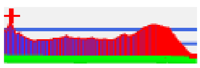
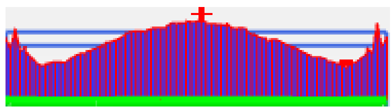
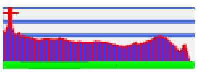
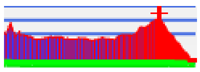
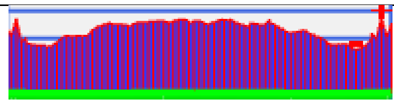
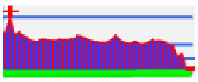
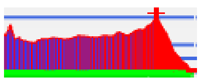
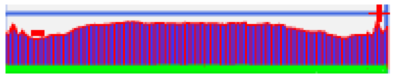


Figure 4-28: Type 2b MSEW force distribution

Table 4-16: Force distribution along reinforcement for X1, X2 and X3

Level (m)	X1	X2	X3
7.125			
6.375			
5.625			
4.875			
4.125			

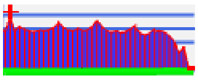
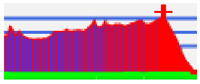
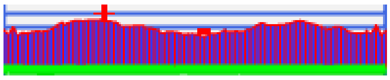
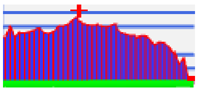
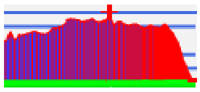
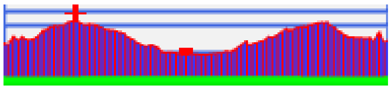
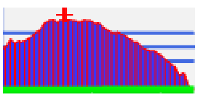
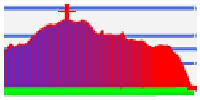
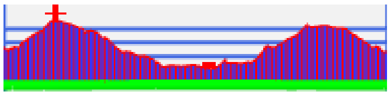
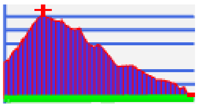
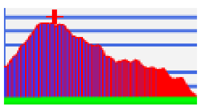
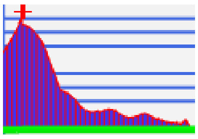
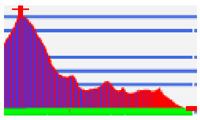
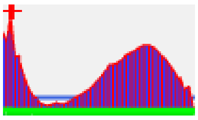
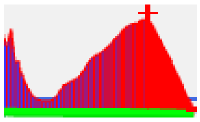
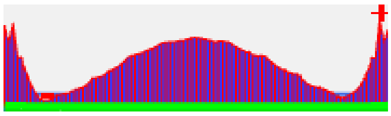
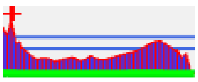
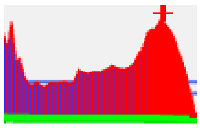
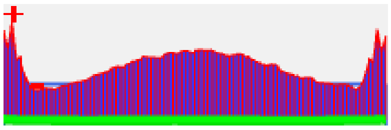
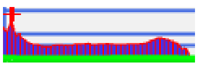
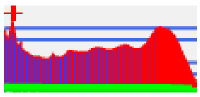
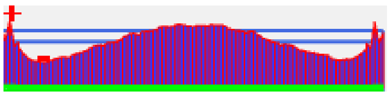
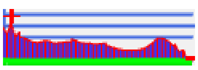
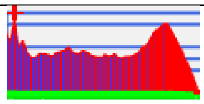
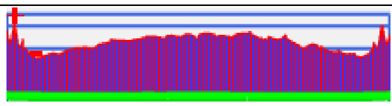
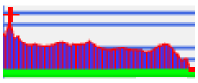
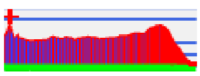
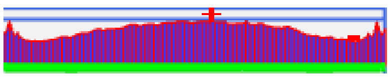
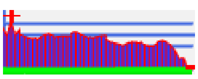
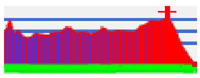
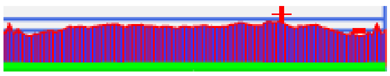
Level (m)	X1	X2	X3
3.375			
2.625			
1.875			
1.125			
0.375			

Table 4-17: Force distribution along reinforcement for Y1, Y2 and Y3

Level (m)	Y1	Y2	Y3
8.625			
7.875			
7.125			
6.375			
5.625			
4.875			

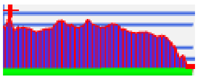
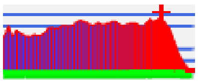
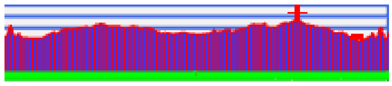
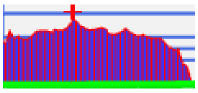
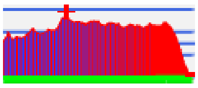
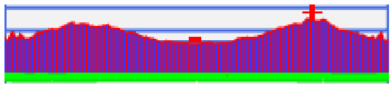
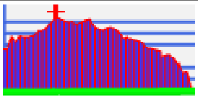
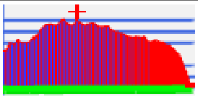
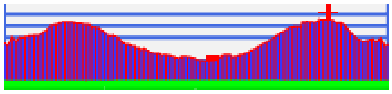
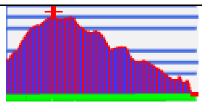
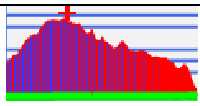
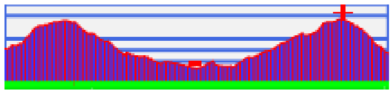
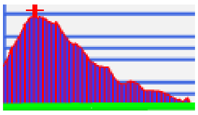
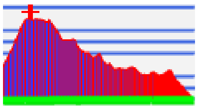
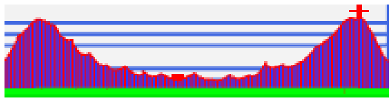
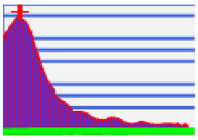
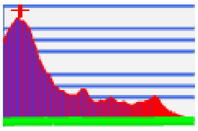
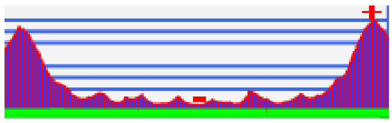
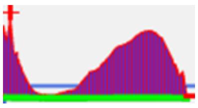
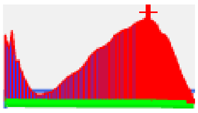
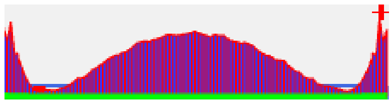
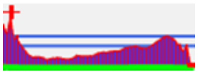
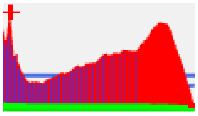
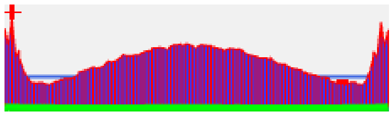
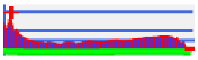
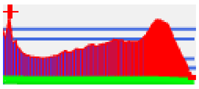
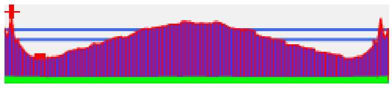
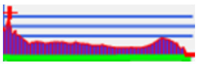
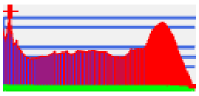
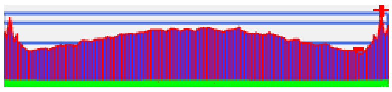
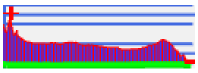
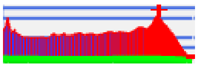
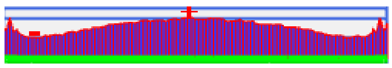
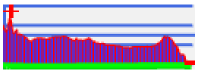
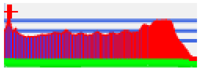
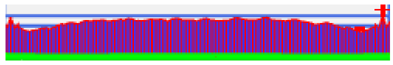
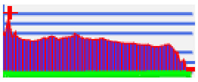
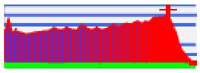
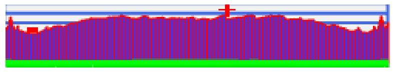
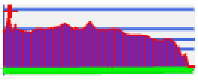
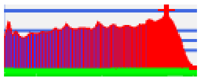
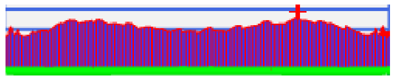
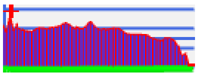
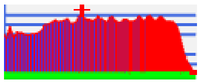
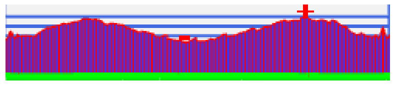
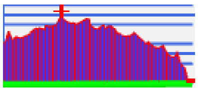
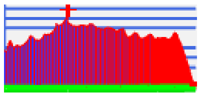
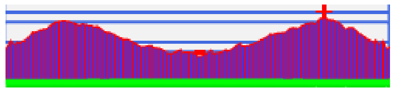
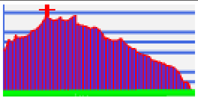
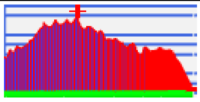
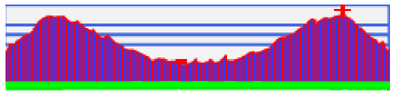
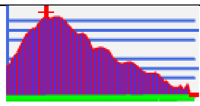
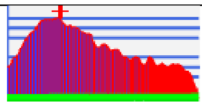
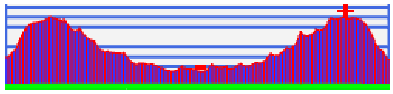
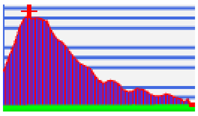
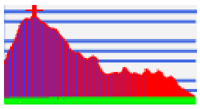
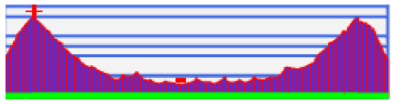
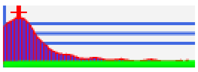
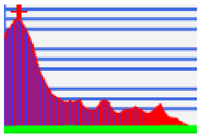
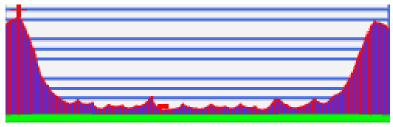
Level (m)	Y1	Y2	Y3
4.125			
3.375			
2.625			
1.875			
1.125			
0.375			

Table 4-18: Force distribution along reinforcement for Z1, Z2 and Z3

Level (m)	Z1	Z2	Z3
10.125			
9.375			
8.625			
7.875			
7.125			

Level (m)	Z1	Z2	Z3
6.375			
5.625			
4.875			
4.125			
3.375			
2.625			
1.875			
1.125			
0.375			

According to Table 4-16, Table 4-17, and Table 4-18 above, it can be seen that the force distribution along the reinforcement follows a similar shape for single sided MSEW's (X1/Y1/Z1) and back to back MSEW's with independent reinforcement (X2/Y2/Z2), however, the location of the maximum force (shown by the + symbol) experienced generally varies in the upper half.

The force distribution along the reinforcement for X3, Y3, and Z3 is different since it is continuous from each face of the back to back MSEW. Due to the continuous reinforcement, the force does not reduce to zero as there are no free ends however, the shape of the force generated along the reinforcement varies as follows:

- The upper half starts off as concave up, then concave down before becoming concave up again
- The lower half starts off as concave down, then concave up before becoming concave down again.

The total vertical displacement of the FEM models obtained using Plaxis 2D for the SLS are shown in Figure 4-29, Figure 4-31, Figure 4-33, Figure 4-35, Figure 4-37, and Figure 4-39, for X2, X3, Y2, Y3, Z2, and Z3 respectively. Cross sections were taken just below the top of the MSEW's in order to view the vertical settlement that would be experienced in the MSEW's near the surface. These cross sections are shown in Figure 4-30, Figure 4-32, Figure 4-34, Figure 4-36, Figure 4-38, and Figure 4-40 which apply to X2, X3, Y2, Y3, Z2, and Z3 respectively.

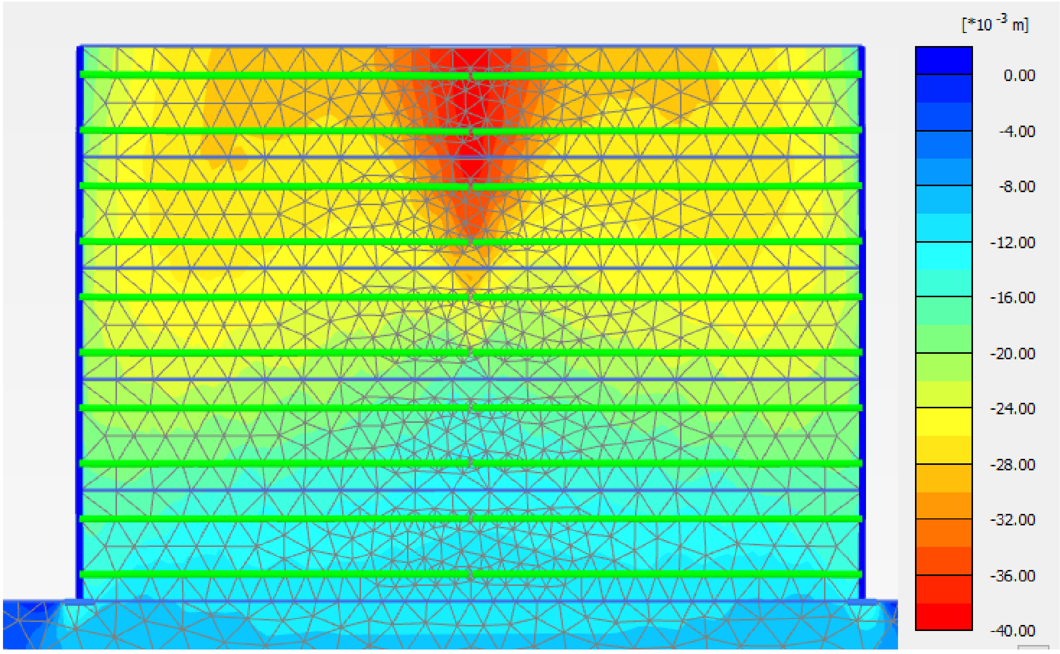


Figure 4-29: X2 Total vertical displacements

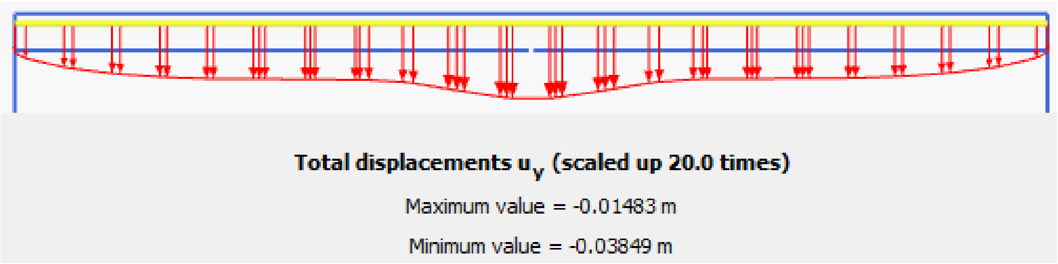


Figure 4-30: X2 Cross section of total vertical displacements near surface of MSEW

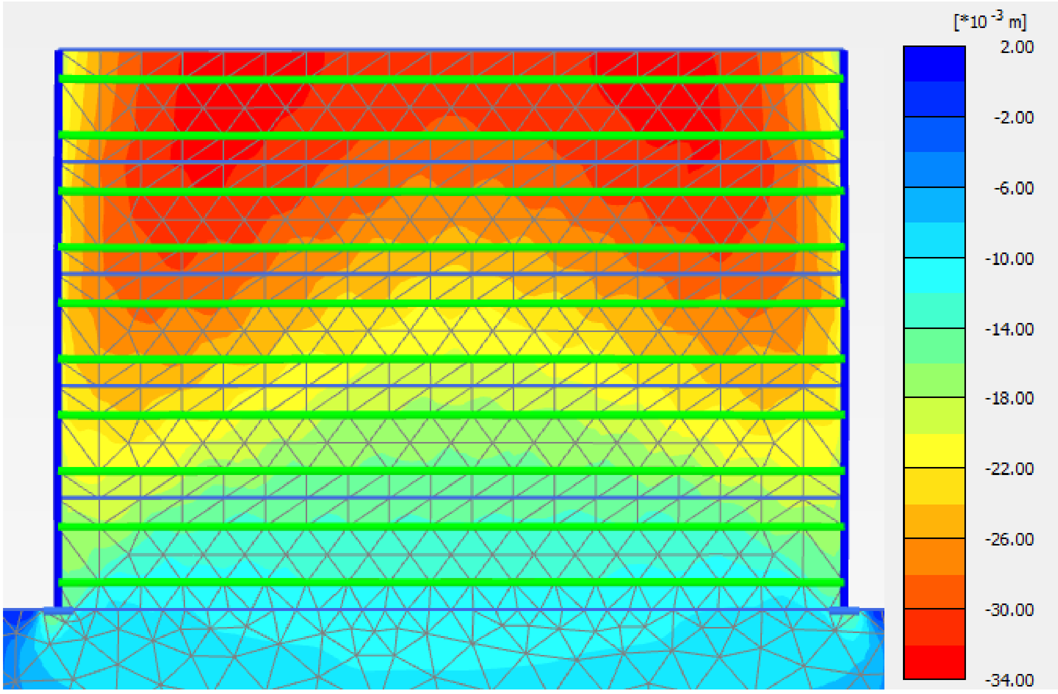


Figure 4-31: X3 Total vertical displacements

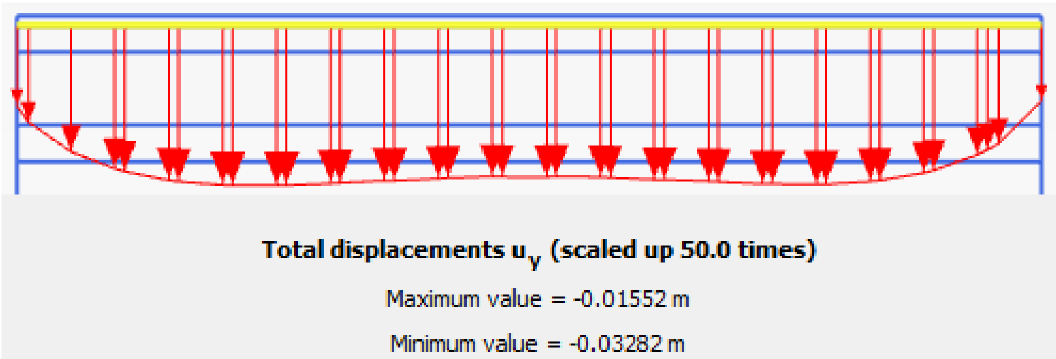


Figure 4-32: X3 Cross section of total vertical displacements near surface of MSEW

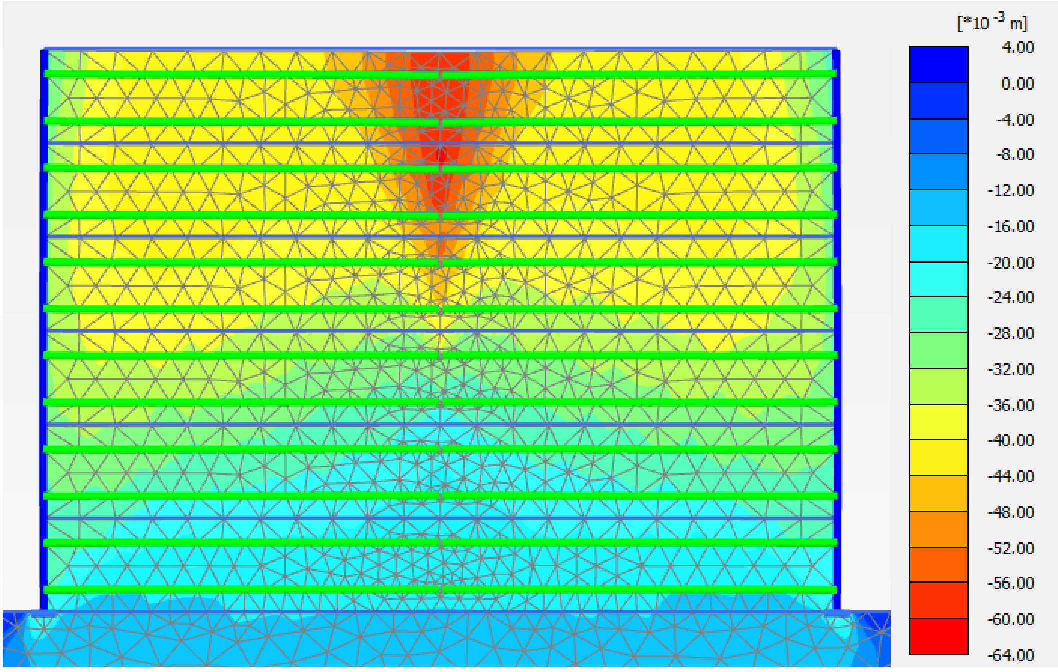


Figure 4-33: Y2 Total vertical displacements

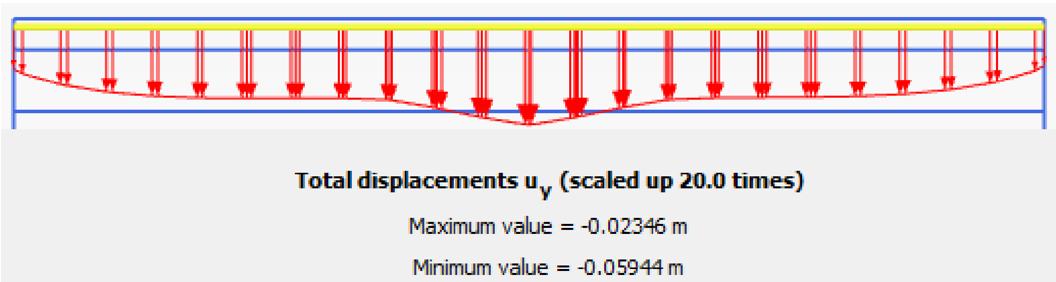


Figure 4-34: Y2 Cross section of total vertical displacements near surface of MSEW

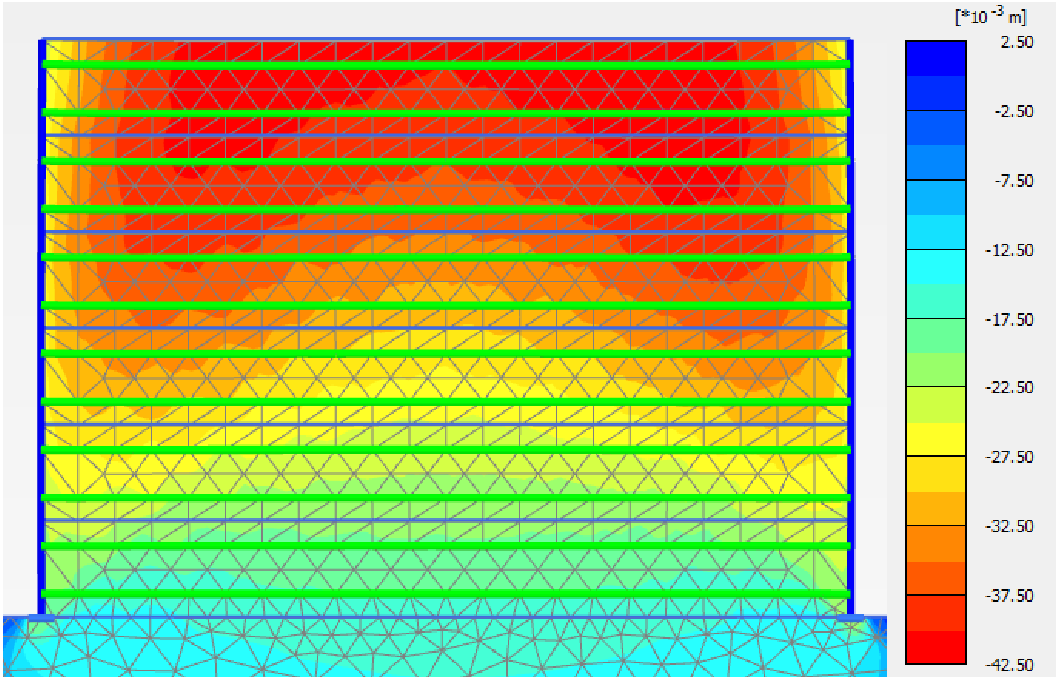


Figure 4-35: Y3 Total vertical displacements

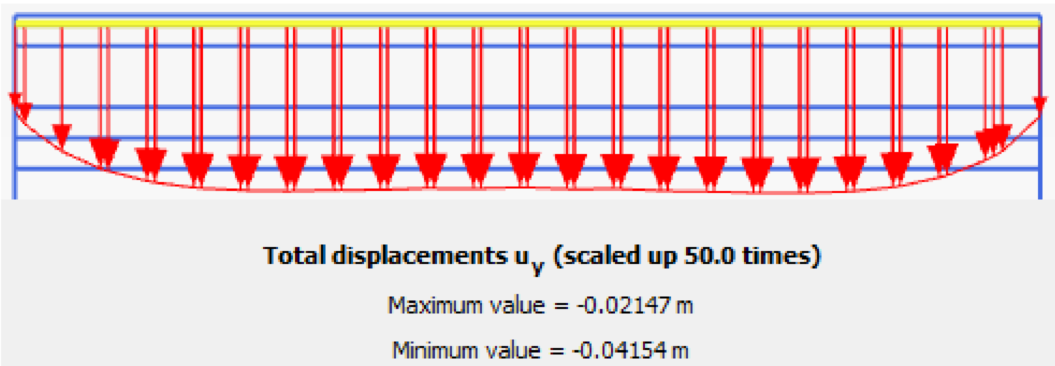


Figure 4-36: Y3 Cross section of total vertical displacements near surface of MSEW

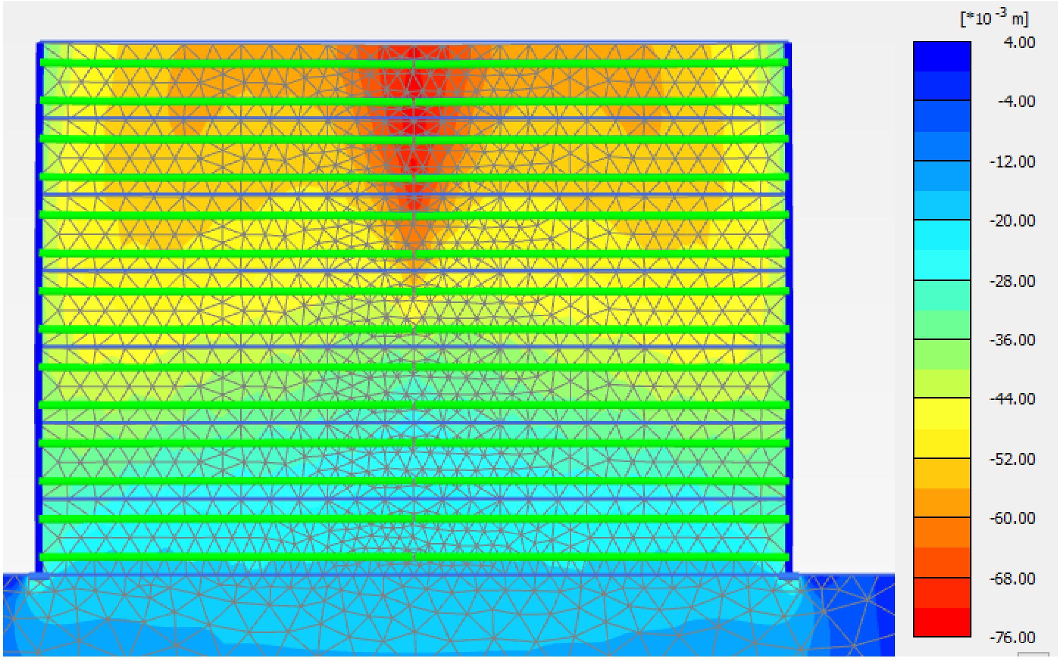


Figure 4-37: Z2 Total vertical displacements

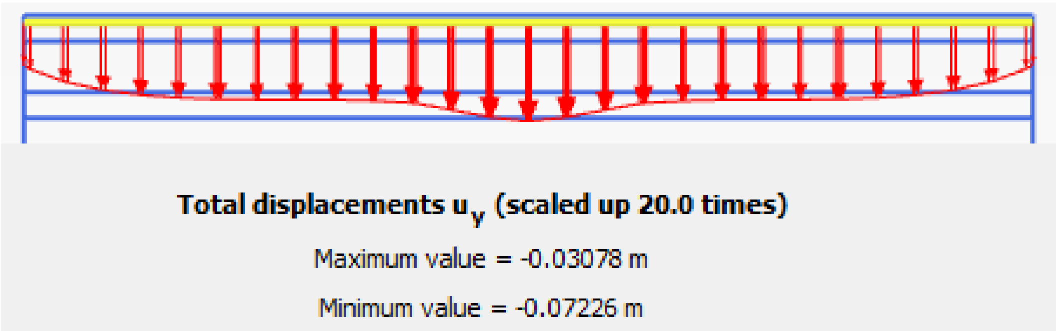


Figure 4-38: Z2 Cross section of total vertical displacements near surface of MSEW

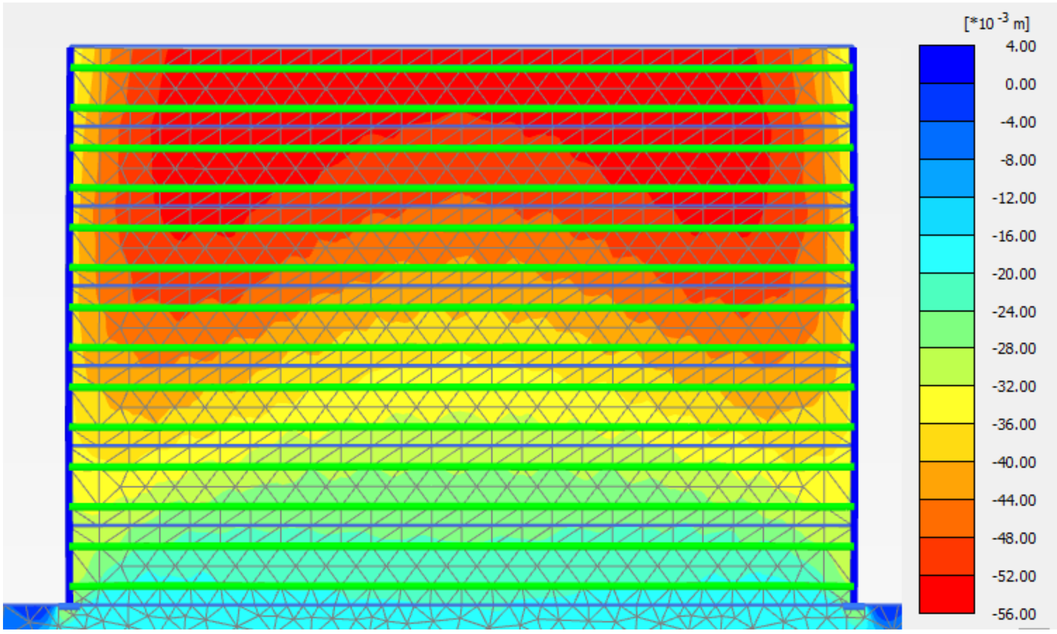


Figure 4-39: Z3 Total vertical displacements

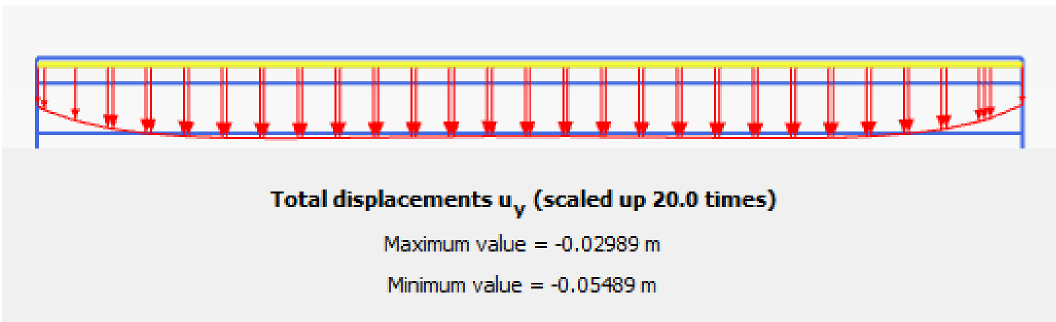


Figure 4-40: Z3 Cross section of total vertical displacements near surface of MSEW

Table 4-19 below shows the maximum, mimimum, and differential settlement experienced near the surface of the MSEW's for X2, X3, Y2, Y3, Z2, and Z3.

Table 4-19: Settlement near the surface of MSEW's for X2, X3, Y2, Y3, Z2 and Z3

Vertical Settlement near surface (mm)			
Case	**Minimum**	**Maximum**	**Differential**
X2	15	38	24
X3	16	33	17
Y2	23	59	36
Y3	21	42	20
Z2	31	72	41
Z3	30	55	25

It is clear from Table 4-19 and Figure 4-29 to Figure 4-40 above, cases with independent reinforcement (X2/Y2/Z2) experience a higher vertical settlelement near the surface of the MSEW's when compared to cases with contiuous reinforcement (X3/Y3/Z3) and the cases with independent reinforcement (X2/Y2/Y3) experiences the most displacement at the center of the back to back MSEW. The cases with continuous reinforcement (X3/Y3/Z3) has a more even distribution of vertical settlement when compared to the cases with independent reinforcement (X2/Y2/Z2).

The maximum horizontal displacement (of the facing panel) and location (from the base of the MSEW) for X1/X2/X3, Y1/Y2/Y3 and Z1/Z2/Z3 are shown below in Figure 4-41, Figure 4-42, and Figure 4-43 respectively.

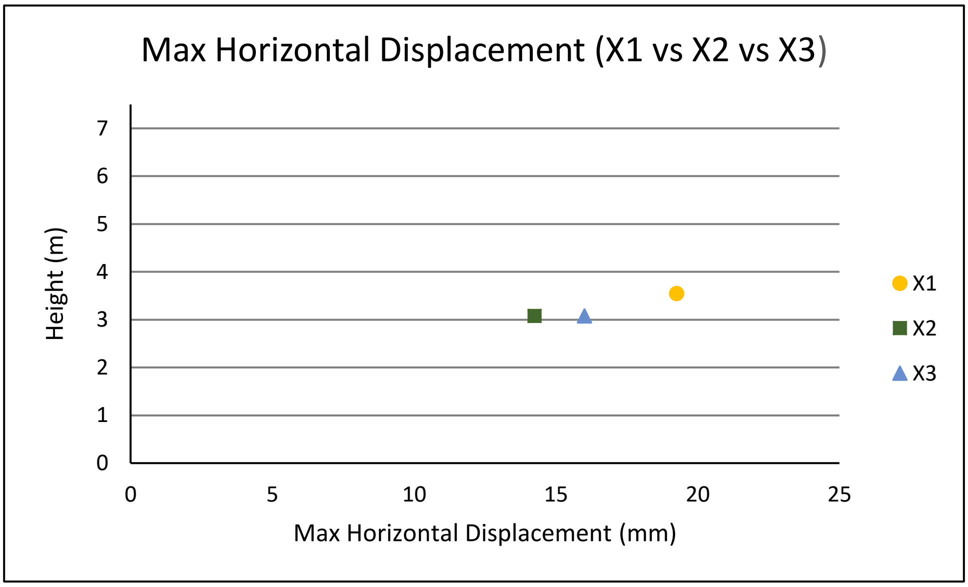


Figure 4-41: Comparison of maximum horizontal displacement for X1, X2, and X3

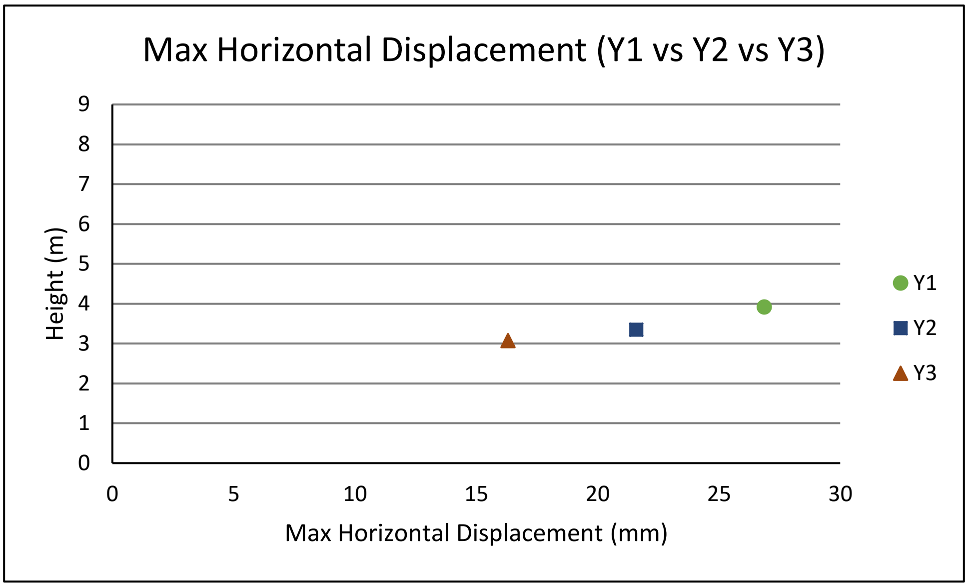


Figure 4-42: Comparison of maximum horizontal displacement for Y1, Y2, and Y3

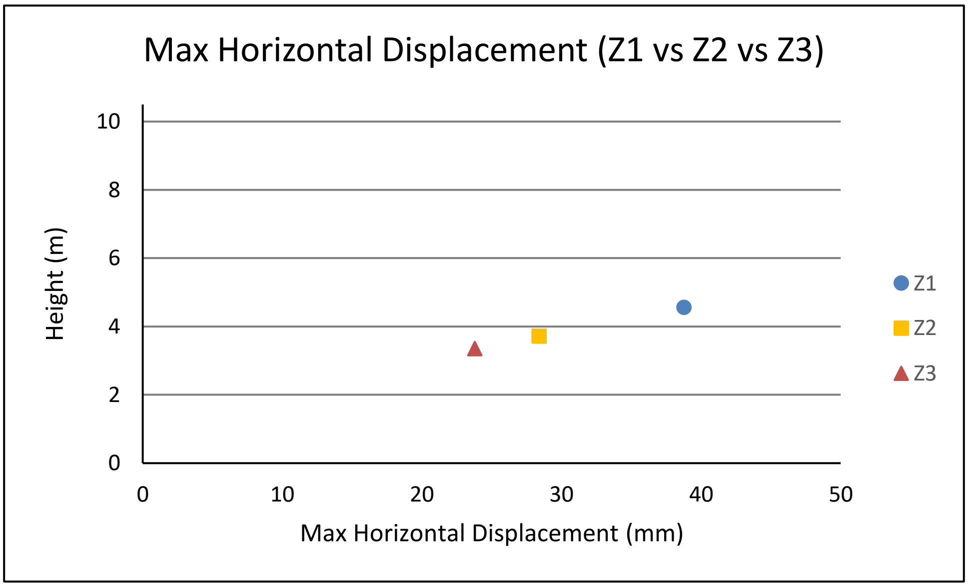


Figure 4-43: Comparison of maximum horizontal displacement for Z1, Z2, and Z3

It is clear from Figure 4-41 to Figure 4-43 above that the location of the maximum horizontal displacement is higher in single sided MSEW's (X1/Y1/Z1) when compared to back to back to back MSEW's (X2/X3/Y2/Y3/Z2/Z3). The general trend follows that single sided MSEW's (X1/Y1/Z1) have the highest horizontal displacement followed by back to back MSEW's with independent reinforcement (X2/Y2/Z2) and thereafter back to back MSEW's with continuous reinforcement (X3/Y3/Z3).

4.6.3 Type 2 with distance between back to back MSEW equal to 1.0H

This section will compare back to back MSEW's that have the distance between the back to back walls equal to 1.0H and have their reinforcement continuous or overlapping. X4, X5, Y4, Y5, Z4, and Z5 fall into this category and can only be analysed using FEM if they are analysed as a whole. If these MSEW's are designed to BS8006-1:2010 they would have been designed as independent MSEW's with the same geometry. In carrying out any comparisons, it was therefore decided to include the forces that would have been generated if the MSEW's had been designed to BS8006-1:2010.

Table 4-20, Table 4-21, and Table 4-22 below shows the forces generated in the reinforcements for X1-BS8006/X4/X5, Y1-BS8006/Y4/Y5, and Z1-BS8006/Z4/Z5 at the ULS respectively.

Table 4-20: Force generated in reinforcements for X1-BS8006, X4, and X5

Reinforcement Level (m)	Force (kN/m)		
	X1-BS8006	X4	X5
7.125	9.73	12.62	12.55
6.375	16.27	17.72	15.03
5.625	22.11	20.29	20.93
4.875	27.07	20.84	22.52
4.125	32.00	32.62	26.21
3.375	36.61	33.25	28.74
2.625	40.69	37.10	34.14
1.875	44.21	36.75	35.48
1.125	49.17	39.37	35.60
0.375	53.84	48.30	41.67

Table 4-21: Force generated in reinforcements for Y1-BS8006, Y4, and Y5

Reinforcement Level (m)	Force (kN/m)		
	Y1-BS8006	Y4	Y5
8.625	9.63	13.66	13.92
7.875	16.16	15.72	16.81
7.125	22.00	22.11	22.91
6.375	27.04	23.38	25.19
5.625	31.49	32.09	29.53
4.875	35.81	34.23	29.04
4.125	39.52	45.69	37.09
3.375	41.31	42.90	38.76

Reinforcement Level (m)	Force (kN/m)		
	Y1-BS8006	Y4	Y5
2.625	47.04	48.79	43.67
1.875	53.39	46.04	44.51
1.125	60.24	49.99	46.75
0.375	66.72	63.98	59.76

Table 4-22: Force generated in reinforcements for Z1-BS8006, Z4, and Z5

Reinforcement Level (m)	Force (kN/m)		
	Z1-BS8006	Z4	Z5
10.125	9.57	14.51	14.40
9.375	16.05	17.29	18.28
8.625	21.92	24.30	25.24
7.875	27.01	25.84	29.04
7.125	31.31	32.89	32.34
6.375	35.33	33.60	35.82
5.625	38.85	46.44	36.61
4.875	41.73	46.50	38.80
4.125	45.81	53.73	47.38
3.375	51.65	52.73	51.29
2.625	57.81	57.86	54.75
1.875	64.35	55.80	55.75
1.125	71.28	61.92	57.76
0.375	77.65	77.16	71.81

Figure 4-44, Figure 4-45, and Figure 4-46 below contains the comparison carried out for X1-BS8006/X4/X5, Y1-BS8006/Y4/Y5, and Z1-BS8006/Z4/Z5 respectively which shows the forces generated in the reinforcement versus the height of the reinforcement from ground level at the ULS.

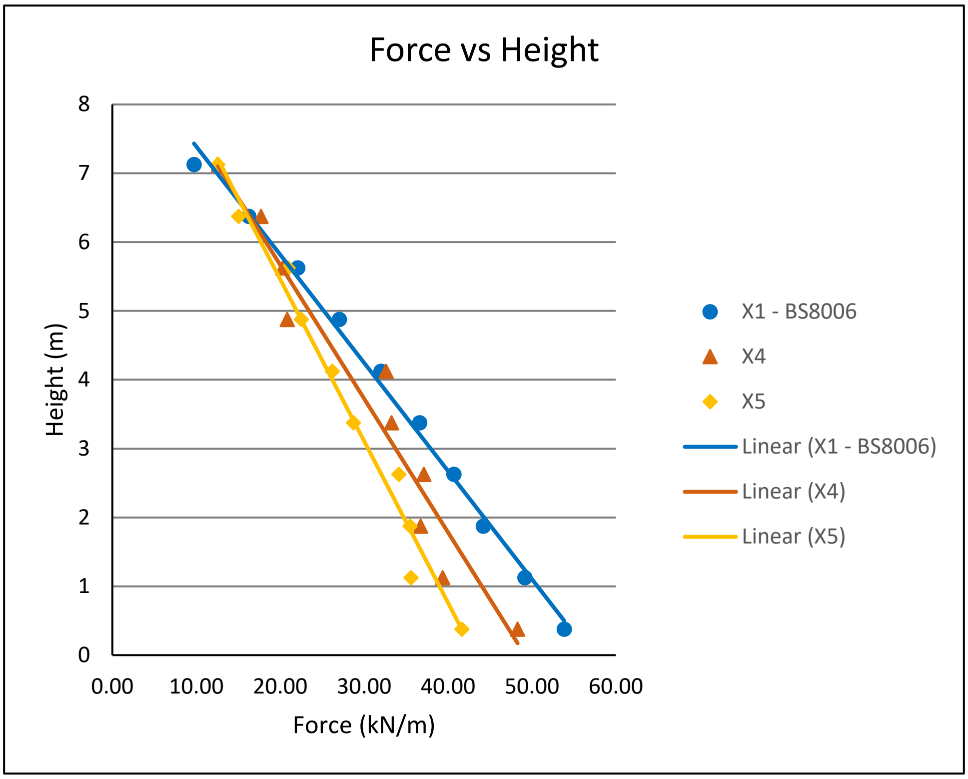


Figure 4-44: X1-BS8006 versus X4 versus X5

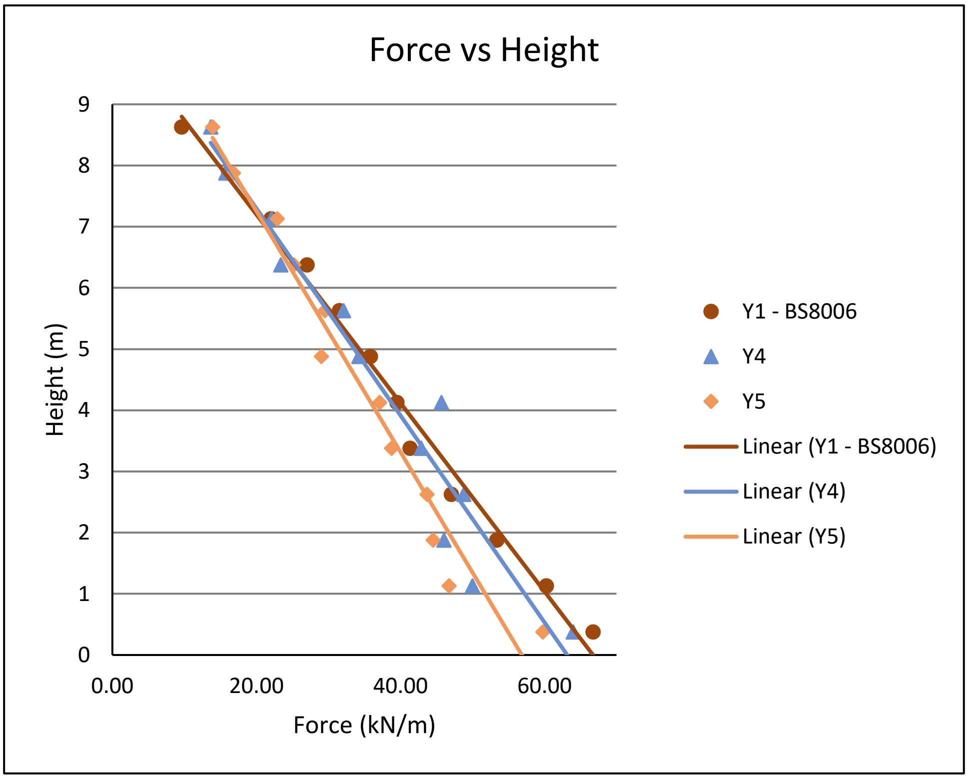


Figure 4-45: Y1-BS8006 versus Y4 versus Y5

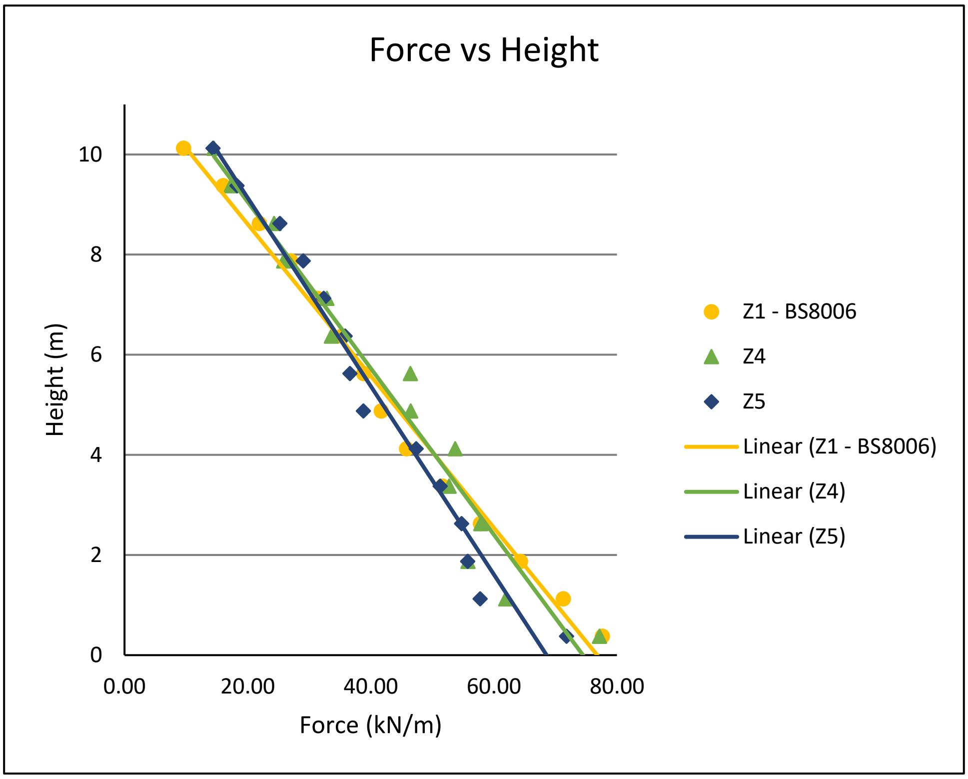


Figure 4-46: Z1-BS8006 versus Z4 versus Z5

The linear trendlines (of the forces calculated) shown in Figure 4-44 to Figure 4-46 above shows that the forces calculated behave as follows:

- X1-BS8006 is generally larger followed by X4 and then X5
- Y1-BS8006 is generally larger followed closely by Y4 and then Y5
- Z1-BS8006 follows Z4 closely in the lower half and is higher than Z5 in the lower half. In the upper half, Z4 and Z5 follow each other closely with both having slightly higher forces than Z1-BS8006

The force distribution along the length of the reinforcement for X1/X4/X5, Y1/Y4/Y5, and Z1/Z4/Z5 are shown below in Table 4-23, Table 4-24, and Table 4-25 respectively and should only be used to compare the shape of the force distribution along the length of the reinforcement. Figure 4-27 (applies to X1/X5/Y1/Y5/Z1/Z5) and Figure 4-28 (applies to X4/Y4/Z4) shows the side of the MSEW facing, the location of the maximum force in the reinforcement, the reinforcement, and the force distribution. The results of the forces of the right-hand side of MSEW X5/Y5/Z5 are not shown since the results were symmetrical to the left-hand side. X4/Y4/Z4 has two MSEW facings since it had continuous reinforcement between the back to back MSEW.

Table 4-23: Force distribution along reinforcement for X1, X4 and X5

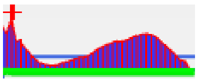
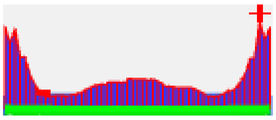
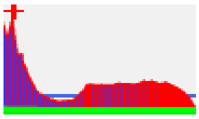
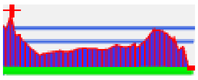
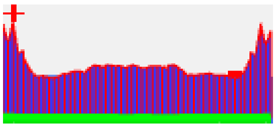
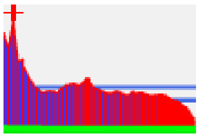
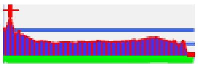
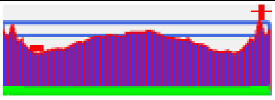
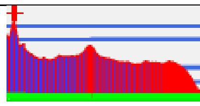
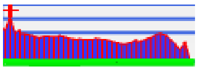
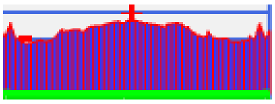
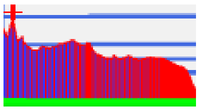
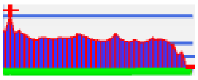
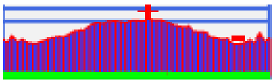
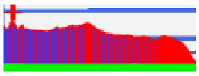
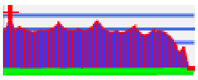
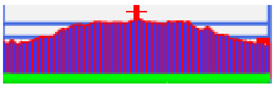
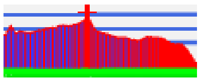
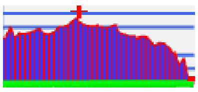
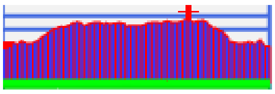
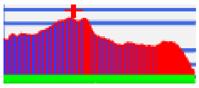
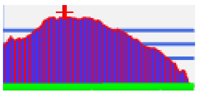
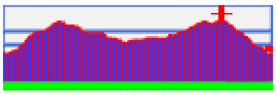
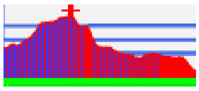
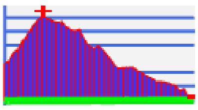
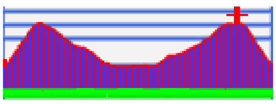
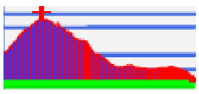
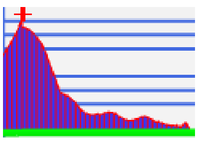
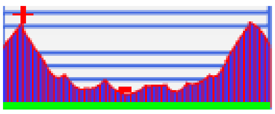
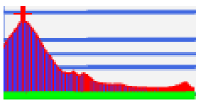
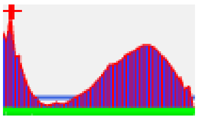
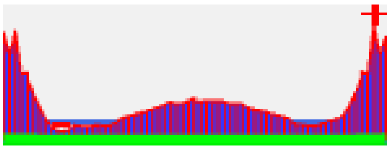
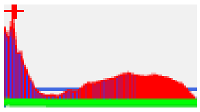
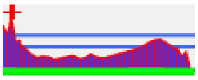
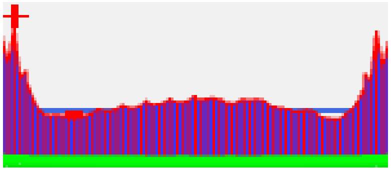
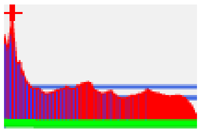
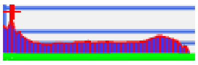
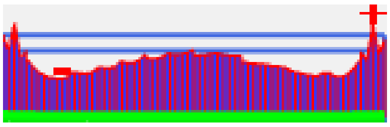
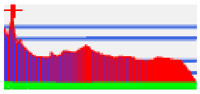
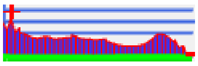
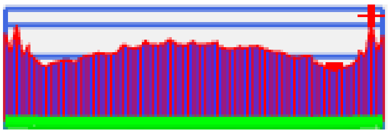
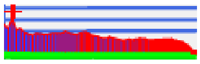
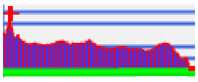
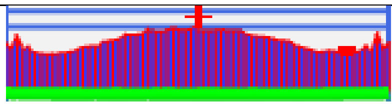
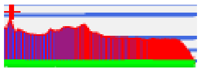
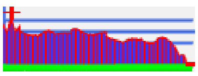
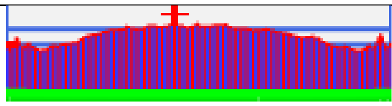
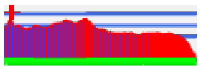
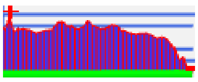
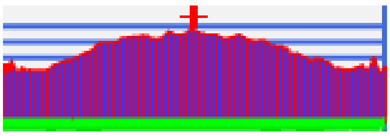
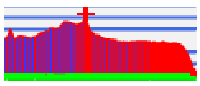
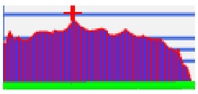
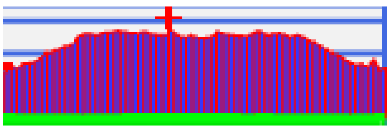
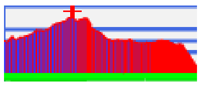
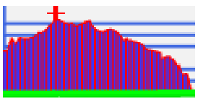
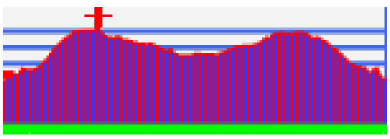
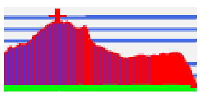
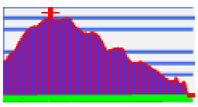
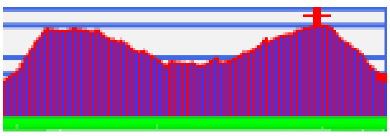
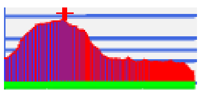
Level (m)	X1	X4	X5
7.125			
6.375			
5.625			
4.875			
4.125			
3.375			
2.625			
1.875			
1.125			
0.375			

Table 4-24: Force distribution along reinforcement for Y1, Y4 and Y5

Level (m)	Y1	Y4	Y5
8.625			
7.875			
7.125			
6.375			
5.625			
4.875			
4.125			
3.375			
2.625			
1.875			

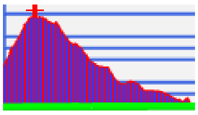
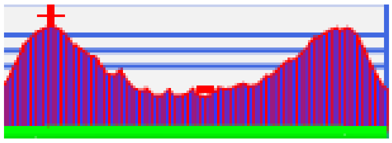
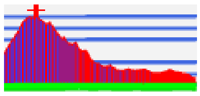
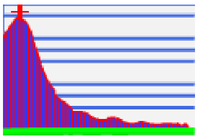
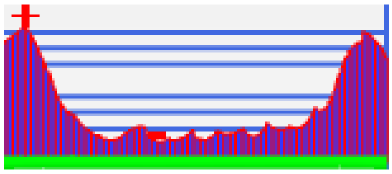
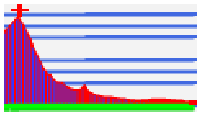
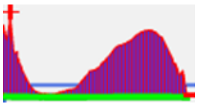
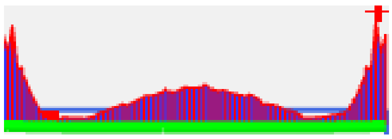
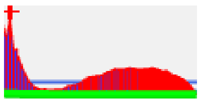
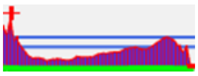
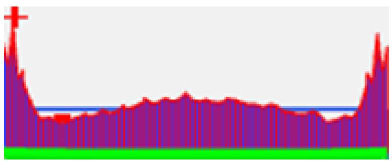
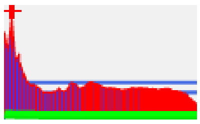
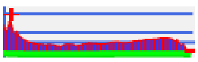
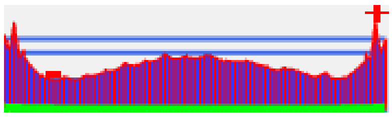
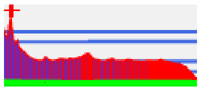
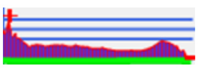
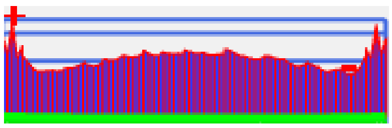
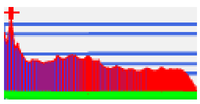
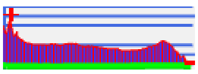
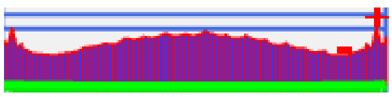
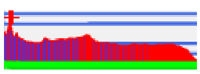
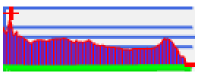
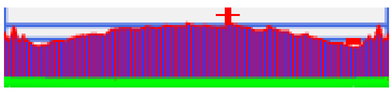
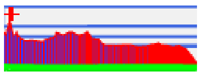
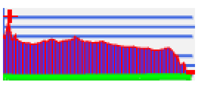
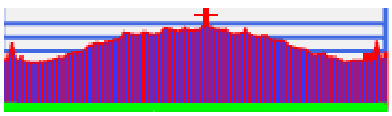
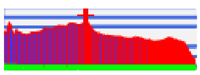
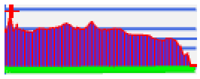
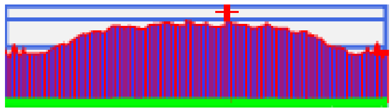
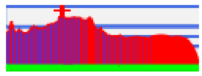
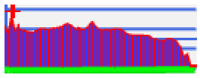
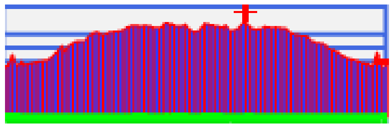
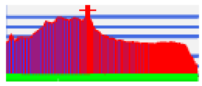
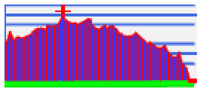
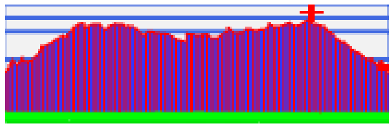
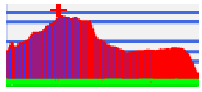
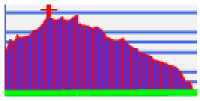
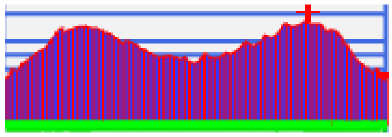
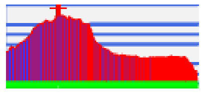
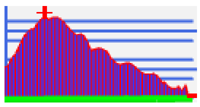
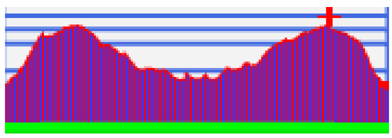
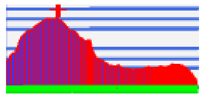
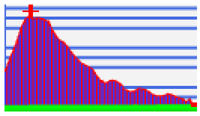
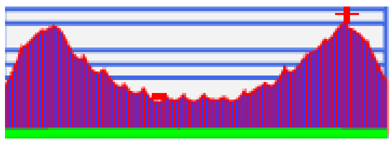
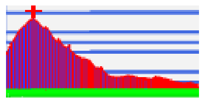
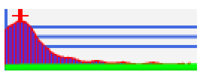
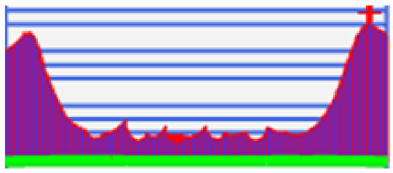
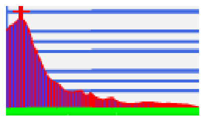
Level (m)	Y1	Y4	Y5
1.125			
0.375			

Table 4-25: Force distribution along reinforcement for Z1, Z4 and Z5

Level (m)	Z1	Z4	Z5
10.125			
9.375			
8.625			
7.875			
7.125			
6.375			
5.625			

Level (m)	Z1	Z4	Z5
4.875			
4.125			
3.375			
2.625			
1.875			
1.125			
0.375			

According to Table 4-23 to Table 4-25 above, it can be seen that the force distribution along the reinforcement and the location of the maximum force (shown by the + symbol) experienced are generally similar for single sided MSEW's (X1/Y1/Z1) and back to back MSEW's with overlapping reinforcement (X5/Y5/Z5).

The force distribution along the reinforcement for X4, Y4, and Z4 is different since it is continuous from each face of the back to back MSEW. Due to the continuous reinforcement, the force does not reduce to zero as there are no free ends however, the shape of the force generated along the reinforcement varies as follows:

- The upper half generally starts off as concave up, then concave down before becoming concave up again
- The lower half generally starts off as concave down, then concave up before becoming concave down again.

The total vertical displacement of the FEM models obtained using Plaxis 2D for the SLS are shown in Figure 4-47, Figure 4-49, Figure 4-51, Figure 4-53, Figure 4-55 and Figure 4-57 for X4, X5, Y4, Y5, Z4, and Z5 respectively. Cross sections were taken just below the top of the MSEW's in order to view the vertical settlement that would be experienced in the MSEW's near the surface. These cross sections are shown in Figure 4-48, Figure 4-50, Figure 4-52, Figure 4-54, Figure 4-56, and Figure 4-58 which apply to X4, X5, Y4, Y5, Z4, and Z5 respectively.

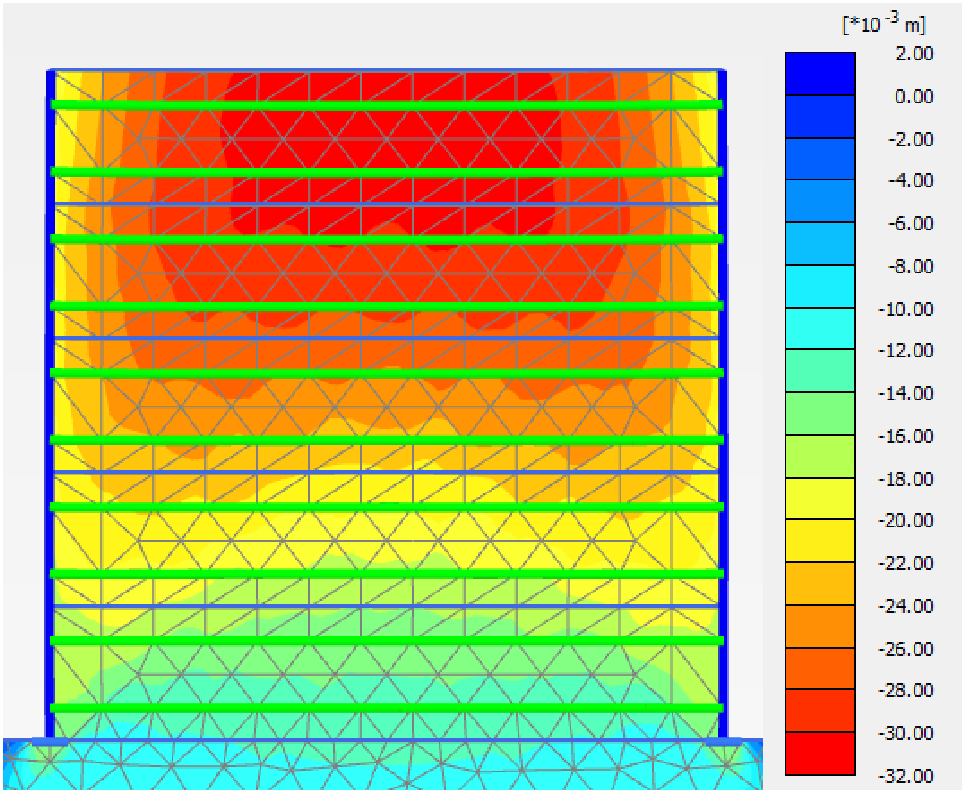


Figure 4-47: X4 Total vertical displacements

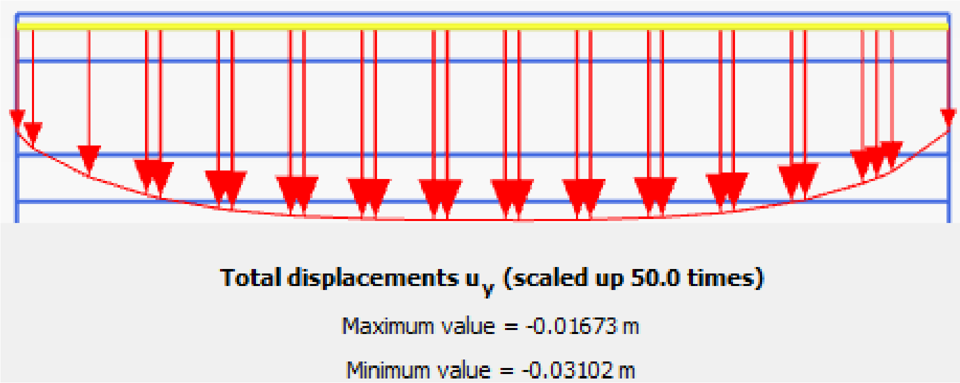


Figure 4-48: X4 Cross section of total vertical displacements near surface of MSEW

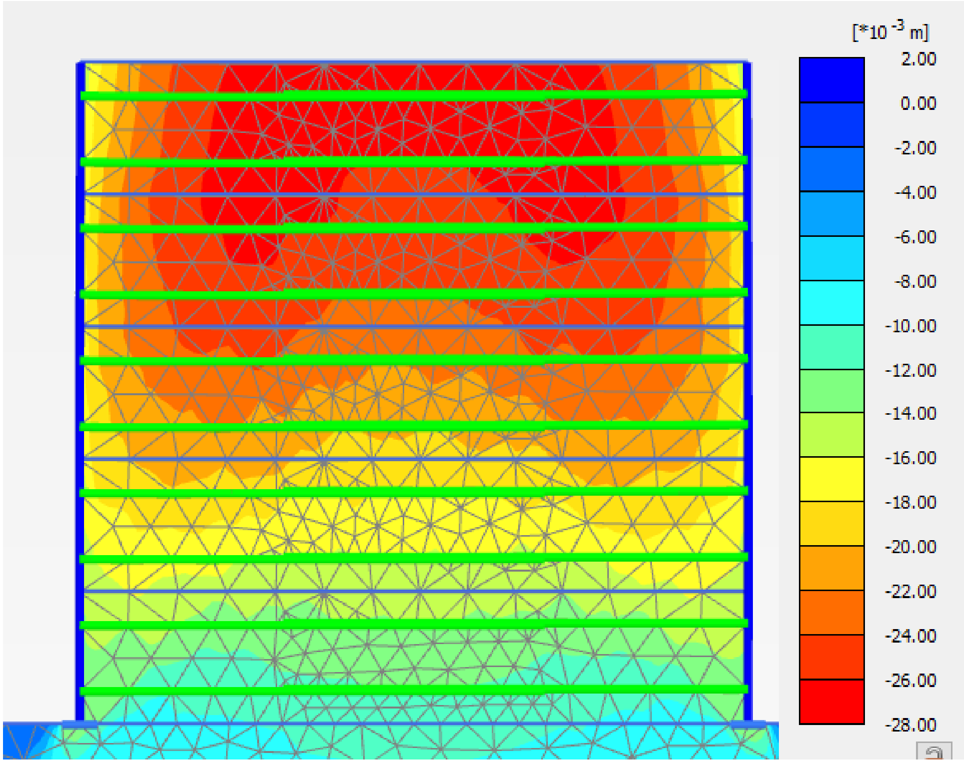


Figure 4-49: X5 Total vertical displacements

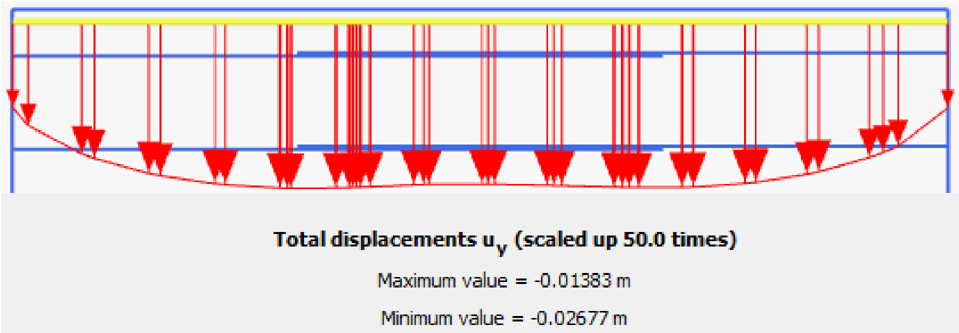


Figure 4-50: X5 Cross section of total vertical displacements near surface of MSEW

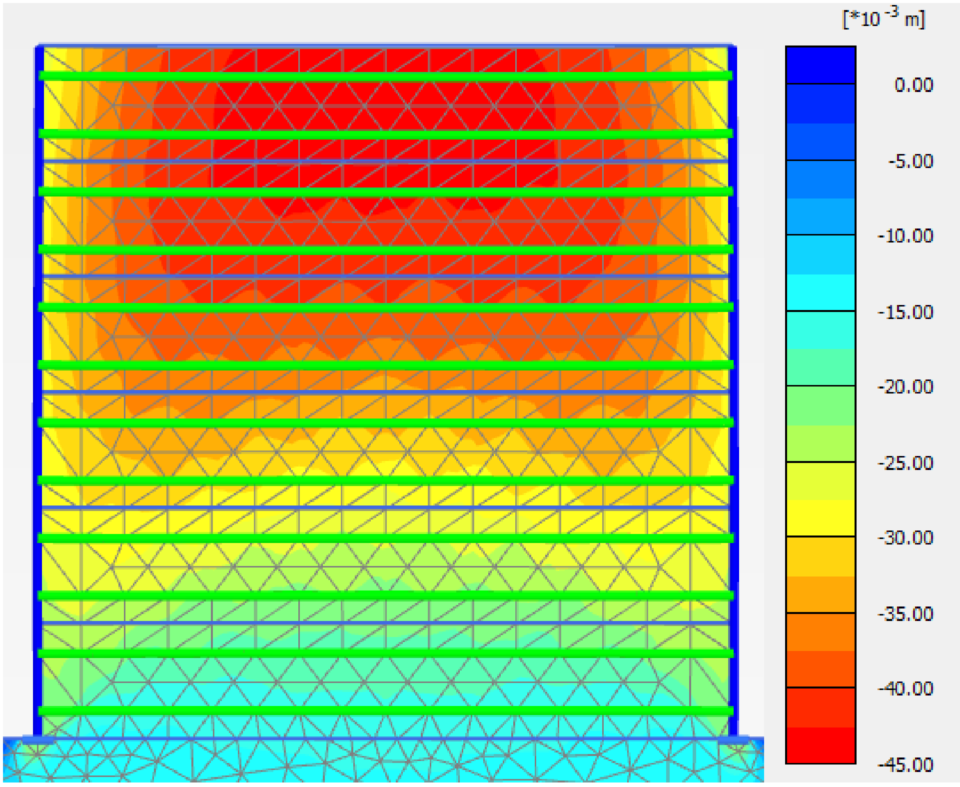


Figure 4-51: Y4 Total vertical displacements

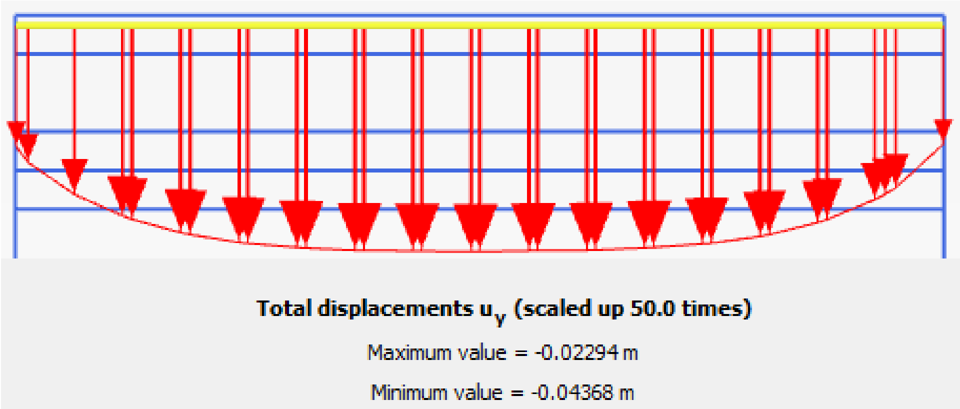


Figure 4-52: Y4 Cross section of total vertical displacements near surface of MSEW

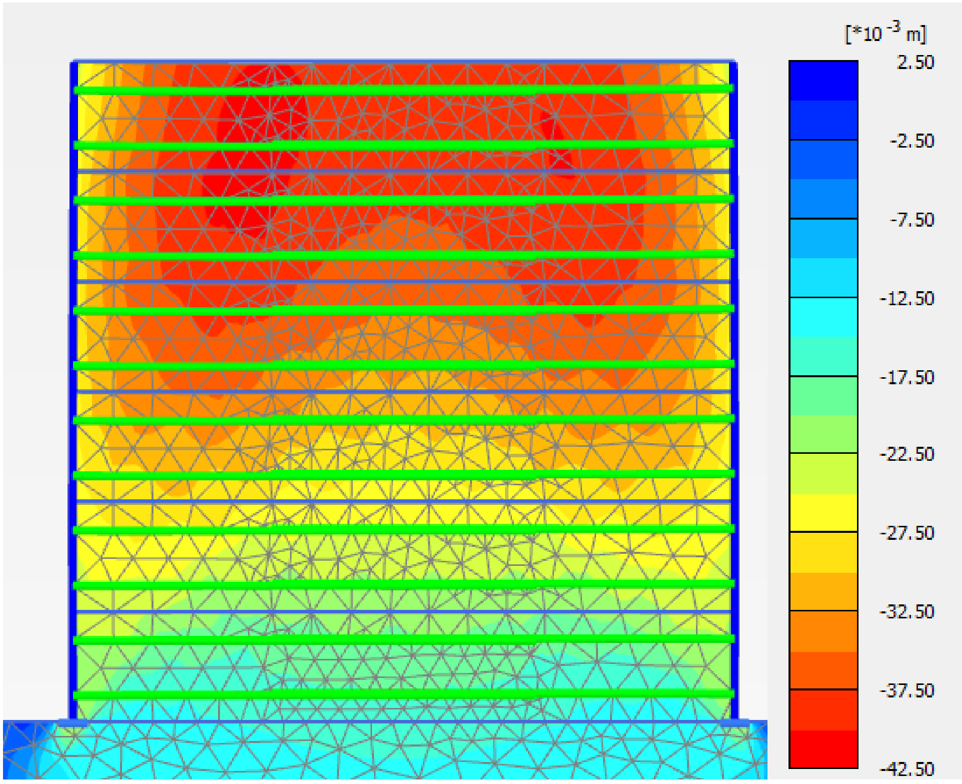


Figure 4-53: Y5 Total vertical displacements

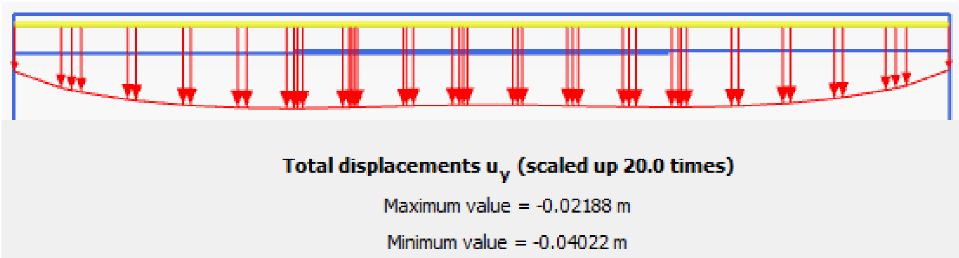


Figure 4-54: Y5 Cross section of total vertical displacements near surface of MSEW

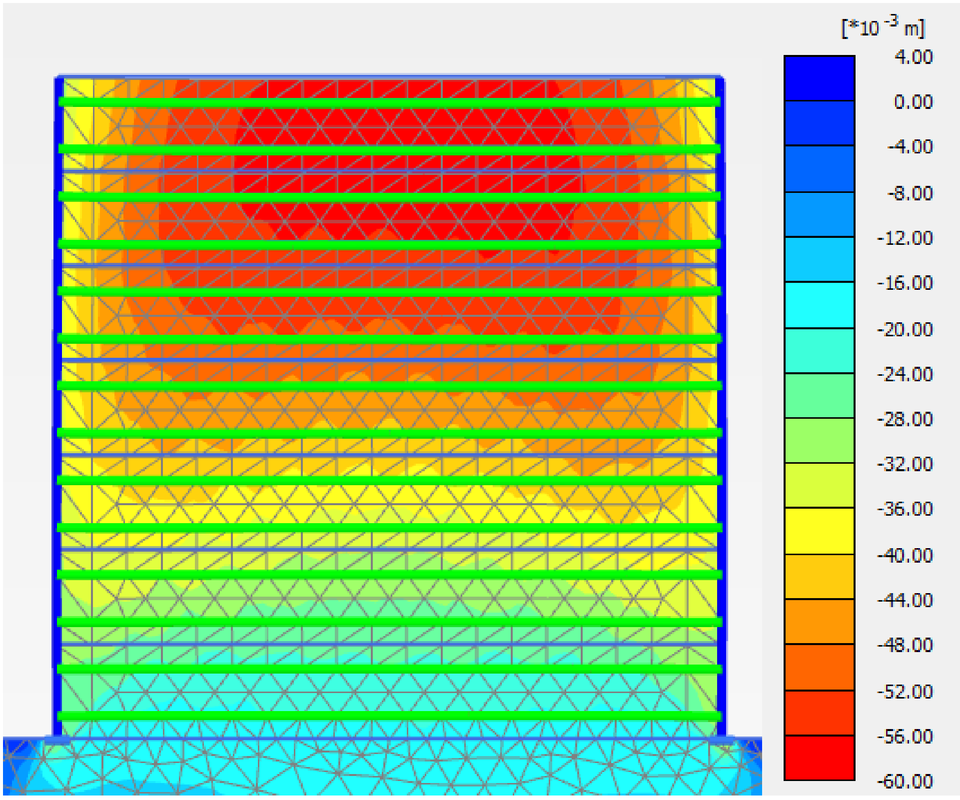


Figure 4-55: Z4 Total vertical displacements

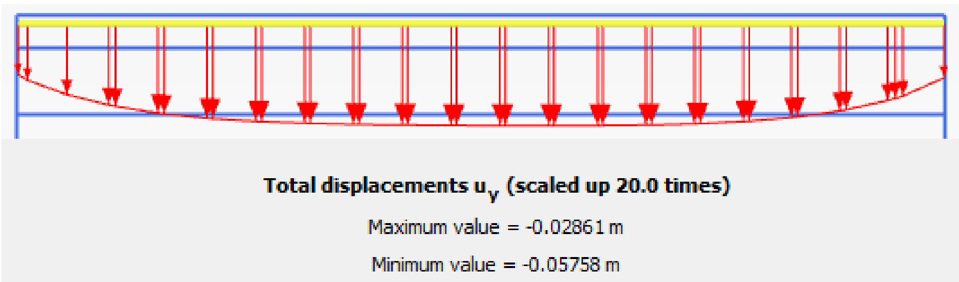


Figure 4-56: Z4 Cross section of total vertical displacements near surface of MSEW

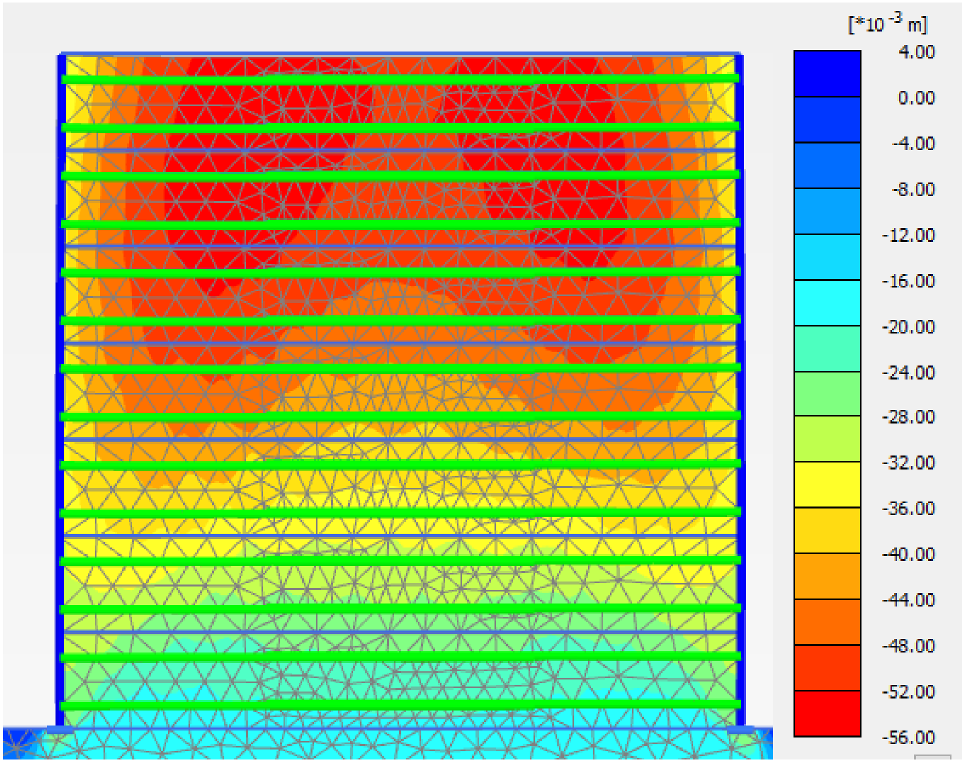


Figure 4-57: Z5 Total vertical displacements of MSEW

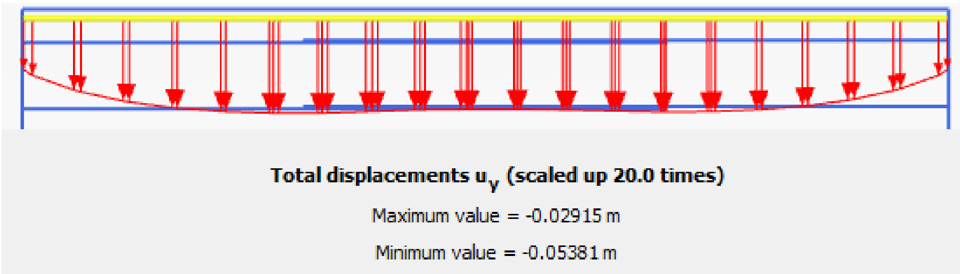


Figure 4-58: Z5 Cross section of total vertical displacements near surface of MSEW

Table 4-26 below shows the maximum, mimimum, and differential settlement experienced near the surface of the MSEW's for X4, X5, Y4, Y5, Z4, and Z5.

Table 4-26: Settlement near the surface of MSEW's for X4, X5, Y4, Y5, Z4 and Z5

Vertical settlement near surface (mm)			
Case	**Minimum**	**Maximum**	**Differential**
X4	17	31	14
X5	14	27	13
Y4	23	44	21

Vertical settlement near surface (mm)			
Case	**Minimum**	**Maximum**	**Differential**
Y5	22	40	18
Z4	29	58	29
Z5	29	54	25

It is clear from Table 4-26 and Figure 4-47 to Figure 4-58 above, cases with continuous reinforcement (X4/Y4/Z4) experience a slightly higher vertical settlelement near the surface of the MSEW's when compared to cases with overlapping reinforcement (X5/Y5/Z5). The cases with overlapping reinforcement (X5/Y5/Z5) has a more even distribution (barely) of vertical settlement when compared to the cases with continuous reinforcement (X4/Y4/Z4).

The maximum horizontal displacement (of the facing panel) and location (from the base of the MSEW) for X1/X4/X5, Y1/Y4/Y5, and Z1/Z4/Z5 are shown below in Figure 4-59, Figure 4-60, and Figure 4-61 respectively.

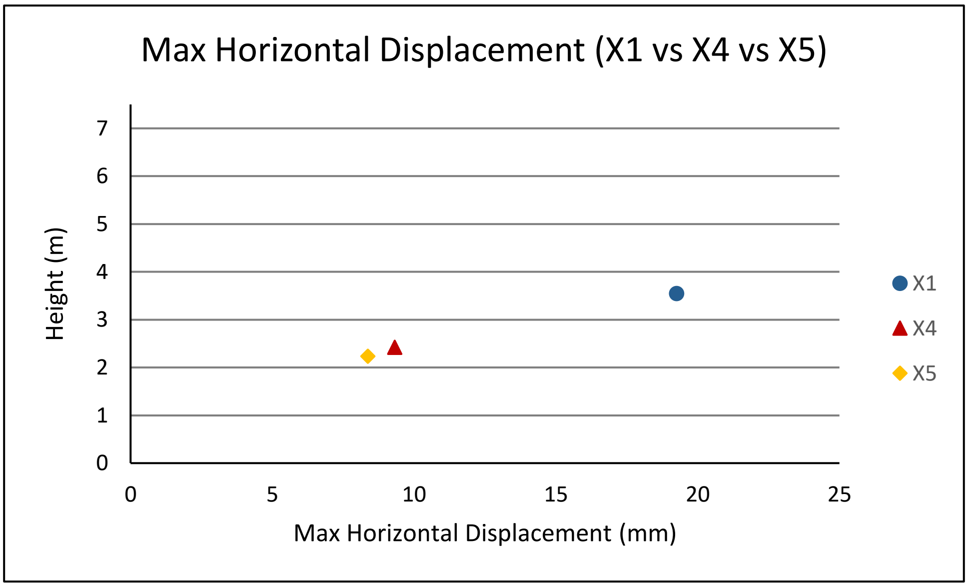


Figure 4-59: Comparison of maximum horizontal displacement for X1, X4, and X5

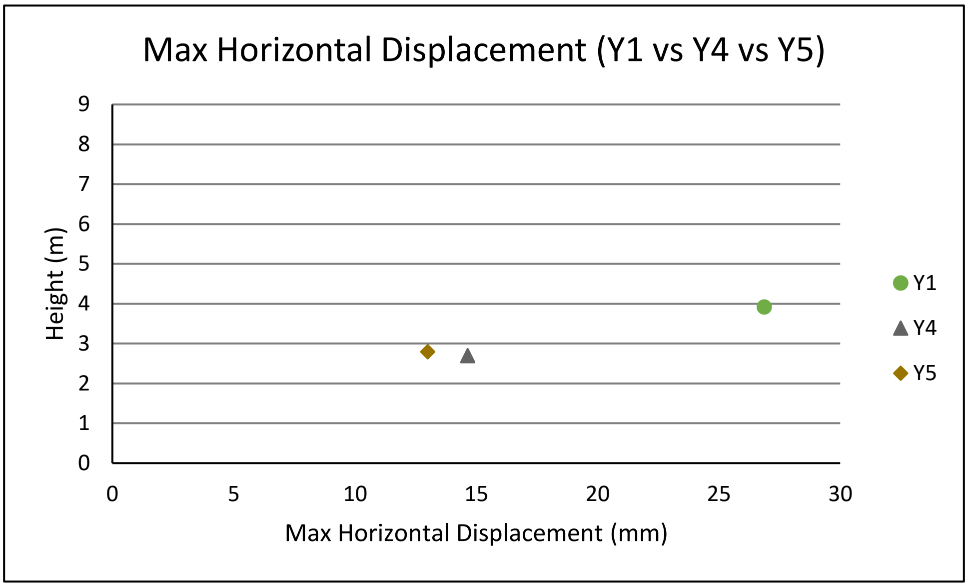


Figure 4-60: Comparison of maximum horizontal displacement for Y1, Y4, and Y5

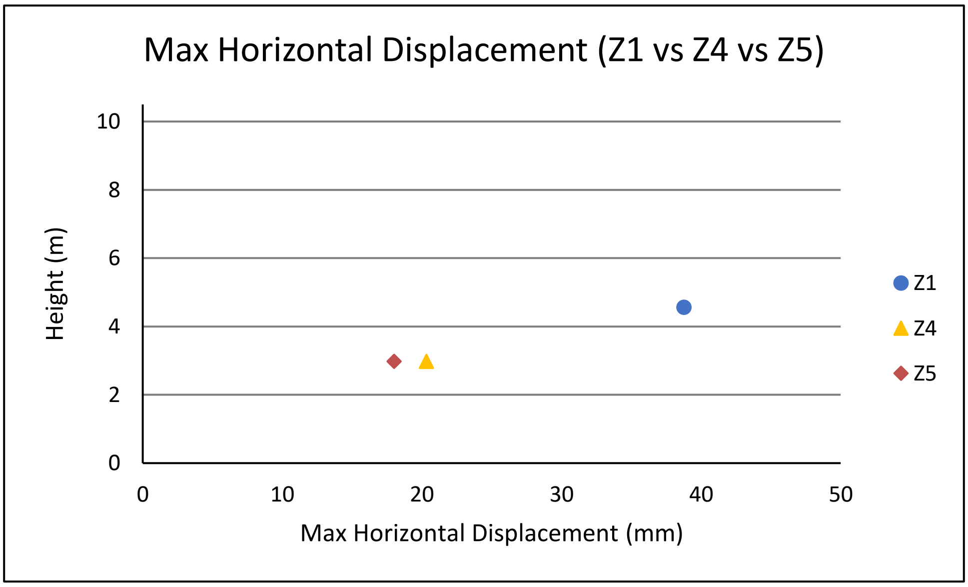


Figure 4-61: Comparison of maximum horizontal displacement for Z1, Z4, and Z5

It is clear from Figure 4-59 to Figure 4-61 above that the location of the maximum horizontal displacement is higher in single sided MSEW's (X1/Y1/Z1) when compared to back to back to back MSEW's (X4/X5/Y4/Y5/Z4/Z5). The general trend follows that single sided MSEW's (X1/Y1/Z1) have the highest horizontal displacement followed by back to back MSEW's with continuous reinforcement (X4/Y4/Z4) and thereafter followed closely by back to back MSEW's with overlapping reinforcement (X5/Y5/Z5).

4.7 Summary

Chapter 4 provides the basis of the analysis, presents the case study analysis (Mt Edgecombe Interchange) and contains a comparative analysis of various geometries of MSEW's. An analysis of the case study is carried out by designing a back to back MSEW from the case study using analytical methods (BS8006-1:2010) and FEM. Various geometries of single sided MSEW's are then also analysed using BS8006-1:2010 and FEM. The results of the analyses indicate that there is good agreement between the two methods of analysis (BS8006-1:2010 and FEM) with regard to the forces generated in the reinforcing elements providing confidence in using FEM to further investigate geometries not covered by BS8006-1:2010 such as back to back MSEW's.

A comparative analysis of various geometries of MSEW's was then carried out which were grouped according to the wall heights and distance between back to back MSEW's. They were grouped and compared as follows:

- single sided MSEW's versus back to back MSEW's with independent reinforcement versus back to back MSEW's with continuous reinforcement
- single sided MSEW's versus back to back MSEW's with continuous reinforcement versus back to back MSEW's with overlapping reinforcement

The following results of the comparative analysis were presented in this chapter for each case of MSEW's analysed:

- Forces generated in the reinforcing elements
- Force distribution along the reinforcement
- Vertical settlement near the surface of the MSEW's
- Maximum horizontal displacement of the facing panel of the MSEW's

A discussion and summary of the results obtained in this chapter is presented in the following chapter 5.

CHAPTER 5 : DISCUSSION AND CONCLUSION

5.1 Introduction

This chapter contains the discussion of the results obtained from the FEM analysis carried out on various configurations of MSEW's with a particular focus on the forces generated in the reinforcing elements of the MSEW. This chapter also concludes the dissertation providing insight for further studies required and recommendations regarding the use of back to back MSEW's with continuous reinforcement.

5.2 Discussion

An analysis of the following cases was carried out in the previous chapter.

- Type 1
- Type 2 with distance between the back to back MSEW equal to 1.4H
- Type 2 with distance between the back to back MSEW equal to 1.0H

Generalised remarks are presented here which have been compiled after analysing the results obtained.

5.2.1 Forces generated in reinforcement

- The trend of the forces generated in the reinforcement when designing using BS8006-1:2010 are generally higher or similar when compared to the results obtained from the FEM analysis for all configurations containing independent reinforcement, continuous reinforcement, and overlapping reinforcement.
- The analyses also showed that the continuous reinforcement produced smaller forces in the reinforcing elements when compared to the configurations containing independent reinforcement or overlapping reinforcement which is contrary to what is mentioned in (Berg, et al., 2009) whereby it is mentioned that back to back MSEW's with continuous reinforcement are expected to have higher forces when compared to back to back MSEW's with independent reinforcement from each wall.

Figure 5-1 below shows the force distribution of the single layer of reinforcement in an MSEW according to BS8006-1:2010. It can be seen that there the force at the connection to the facing is above zero which then increases to a maximum before reducing to zero at the free end of the reinforcement. This force distribution would apply to single sided MSEW's.

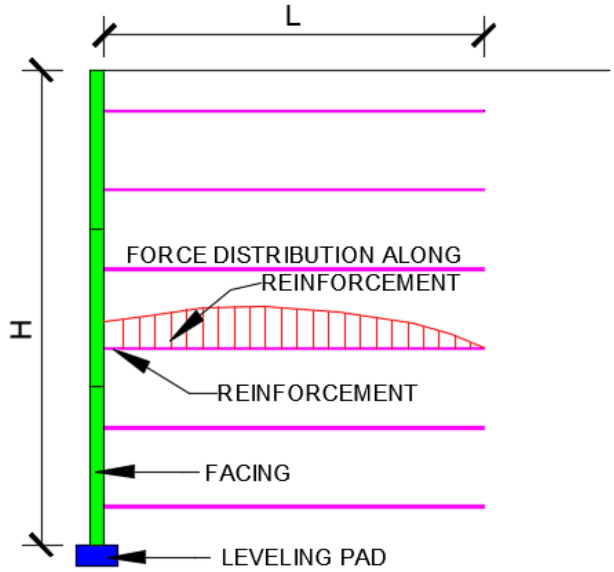


Figure 5-1: Force distribution of MSEW in the reinforcement

According to the analyses carried out, the following points can be made regarding the force distribution along the reinforcement:

- The force distribution along the reinforcement for single sided MSEW's do not explicitly follow the shape shown in BS8006-1:2010. However, the shape is fairly similar in the lower zones.
- It was noticed that the force distribution of the back to back MSEW's with independent reinforcement and the back to back MSEW's with overlapping reinforcement had a similar shape and they both had some zones that followed the BS8006-1:2010 shape.
- Back to back MSEW's with continuous reinforcement unlike back to back MSEW's with independent or overlapping reinforcement did not reduce to zero since there were no free ends. The shape of the force generated along the reinforcement for continuous reinforcement was like a back to back mirror of the independent or overlapping reinforcement at the same level except that the reinforcement did not have a zone that reduced to zero. It may be deduced that the reinforcement utilisation for continuous

reinforcement is higher when compared to independent or overlapping reinforcement (in back to back MSEW's).

5.2.2 Displacements

Although not a main focus of this dissertation, the settlement of the MSEW and the outward movement of the MSEW facing was investigated as well. The following points of interest were noted:

- The single sided MSEW has similar settlements over the reinforced zone before reducing as one moves further away from the MSEW facing.
- Back to back MSEW's with continuous reinforcement experience lower vertical settlements near the surface of the MSEW when compared to back to back MSEW's with independent reinforcement that meet at the centre.
- The vertical settlement profile (near the surface) of MSEW's with continuous reinforcement and overlapping reinforcement is fairly consistent between each face of the back to back MSEW. Back to back MSEW's with independent reinforcement show that there are higher settlements at the point whereby two reinforcements meet but don't overlap. Having continuous reinforcement or overlapping reinforcement is therefore more favourable since they produce smaller differential settlements near the surface of the back to back MSEW.

The maximum horizontal displacement of the MSEW facing panels were investigated in order to see which configurations produced the least horizontal outward movement. The following points summarise the findings.

- Single sided MSEW's produced the highest horizontal movements of the MSEW facing panels when compared to all other configurations.
- Back to back MSEW's with continuous reinforcement produced smaller horizontal movement of the MSEW facing panels when compared to back to back MSEW's with independent reinforcement that meet at the centre and were only marginally higher than back to back MSEW's with overlapping reinforcement.

5.3 Summary and Conclusions

The analysis of back to back MSEW's with continuous reinforcement was the main focus of this dissertation. The dissertation followed a process of providing a literature review and methodology focused on MSEW's. A case study of a back to back MSEW with continuous reinforcement was then investigated using analytical and FEM methods which showed good agreement between the results obtained for the forces generated in the reinforcing elements. Thereafter, a study was carried out whereby various geometries of MSEW's were investigated. A study using single sided MSEW's was first carried out using analytical methods and then FEM methods which showed that both methods produced similar forces in the reinforcement. This provided confidence in using the FEM to investigate other configurations (such as back to back MSEW's) whereby the geometry was varied as follows:

- Continuous reinforcement between back to back MSEW's
- Independent reinforcement between back to back MSEW's
- Overlapping independent reinforcement between back to back MSEW's

The various configurations mentioned above were designed using FEM and then compared to results (forces in the reinforcement at the ULS) obtained from designing according to BS8006-1:2010. Since BS8006-1:2010 has no separate method to design back to back MSEW's, they are designed as single sided MSEW's. This comparison yielded many talking points which are discussed further below.

1. The forces generated in the reinforcing elements using FEM for single sided walls agreed well with the forces calculated using the methods described in BS8006-1:2010. The case study also further validated that the FEM analysis gives similar results to BS8006-1:2010.
2. Contrary to (Berg, et al., 2009) the force in the reinforcements for back to back MSEW's with continuous reinforcement was actually similar to and mostly lower than the forces calculated using BS8006-1:2010.
3. The study showed that it is possible to have continuous reinforcement instead of overlapping reinforcement in back to back MSEW's which goes against the minimum reinforcement length requirement specified in BS8006-1:2010.
4. A trend was noticed for the forces generated in the reinforcement whereby forces generated using BS8006-1:2010 was mostly higher than the forces generated for every other configuration.

5. The analyses showed that the stress distribution along the reinforcement can vary from the shape provided in BS8006-1:2010 with the maximum force generated sometimes falling close to the connection to the facing which is contrary to BS8006-1:2010.
6. Although not a focus of this dissertation it was noticed that the back to back MSEW's with continuous reinforcement produced less differential settlement near the surface of the MSEW when compared to back to back MSEW's with independent reinforcement meeting at the centre.
7. The maximum horizontal displacement of the facing panels for back to back MSEW's with continuous reinforcement was lower than back to back MSEW's with independent reinforcement.

In conclusion, this dissertation successfully showed that there is indeed a scope for designing back to back MSEW's with continuous reinforcement. The use of this type of MSEW's can positively impact construction and economics. Further studies utilising instrumented case studies would be beneficial to determine the actual mechanics and behaviour of the system in order to propose an analytical method of design. For now, it is recommended that the design of back to back MSEW's be carried out in conjunction with the relevant design code pertaining to the country and the option of having continuous reinforcement should then be analysed using FEM. Construction of back to back MSEW's with continuous reinforcement should be constructed with instrumentation to monitor the behaviour to ensure that the structure is acting as required.

In order for the design of back to back MSEW's with connected reinforcement to be more widely acceptable, a rigorous study into the behaviour of the MSEW's would need to be conducted. The studies should comprise of the following:

- Instrumented back to back MSEW's with continuous and independent reinforcement
- Various types of MSEW's need to be analysed comprising varying facings and reinforcement types
- Various soil types need to be assessed along with their impact on the behaviour of back to back MSEW's

A design procedure and standard can then be produced which will then give designers more confidence in using back to back MSEW's with continuous reinforcement.

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