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INFLUENCE OF CONSTRUCTION PROCEDURE AND ANCHOR INCLINATION ON THE BEHAVIOR OF MULTI-ANCHORED SHEET PILE WALL

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INFLUENCE OF CONSTRUCTION PROCEDURE AND ANCHOR INCLINATION ON THE BEHAVIOR OF MULTI-ANCHORED SHEET PILE WALL

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Influence of Construction Procedure and Anchor Inclination on the Behavior of Multi-Anchored Sheet Pile Wall

BY

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DECLARATION

This is certify that the thesis entitled "Influence of construction procedure and anchor inclination on the behavior of multi-anchored sheet pile wall", submitted in partial fulfillment of the requirements for the degree of master of science in geotechnical engineering under faculty of civil and water resource engineering Bahir Dar Institute of Technology, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this thesis have been duly acknowledged.

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Approval of thesis for defense result

I hereby confirm that the changes required by the examiners have been carried out and incorporated in the final thesis.

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As members of the board of examiners, we examined this thesis entitled "Influence of Construction Procedure and Anchor Inclination on the Behavior of Multi- Anchored Sheet Pile Wall "by Bethlehem Beyene Asefa. We hereby certify that the thesis is accepted for fulfilling the requirements for the award of the degree of Masters of Science in "Geotechnical Engineering".

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ABSTRACT

Sheet pile walls are one of the oldest earth retaining structures constructed to retain earth, water or any other fill material in civil engineering projects. They are used in a wide variety of both temporary and permanent building applications, including excavation support system, cofferdams, cut-off walls under dams, slope stabilization, water front structures and flood walls.

Several methods can be used to increase the load carrying capacity of sheet-pilling walls. The use of additional anchored tie rods grouted in to the backfill soil and arranged along the exposed wall height is one of the most practical and appropriate solutions adapted for stabilization and rehabilitation of the existing sheet pile wall. In this work parametric study through the finite difference program, FLAC 2D, version 7was carried out to investigate the influence of construction procedure, grouted body area, length of grouted body, number of anchor and anchor inclination for multi-anchored sheet pile walls in terms of horizontal displacements and moment induced along the sheet pile wall. This study also provide in giving insight in formulating a guide line for specific type of soil by solving the deep excavation benchmark problem with a finite difference based program FLAC and using CY plastic soil model for the sand soil.

The results indicate that for this kind of problem the advanced soil constitutive model (cap-yield plastic soil model) will give realistic deformation. And also the results of the analysis indicate that the optimum angle of anchor inclination is 27 degrees to reduce the maximum bending moment and the maximum horizontal displacement. Variation of construction procedure has a significant effect on the sheet pile wall. As grouted body area increases, the maximum horizontal displacement and the maximum bending moment decrease. As grouted body length increases for not pre stressed anchors, the maximum bending moment and the maximum horizontal displacement decrease but this trend of grouted body length become a complete opposite when the anchors become pre stressed.

Keywords: Multi-Anchored sheet pile wall, Deep excavation, Construction procedure, Anchor inclination, Pre-Stressed, Grouted length.

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NOMENCLATURE

Φ	Un-drained internal friction of the soil
ν	Poisson ratio
α	Angle of anchor inclination
ψ	Dilation of the soil
α_1	Cap yield surface parameter
β	Calibration factor
K_o	Coefficient of lateral earth pressure
K_a	Rankin's active earth pressure coefficient
K_p	Rankin's passive earth pressure coefficient
γ	Soil unit weight
P_{ref}	Reference pressure
E	Young's modulus
C	Cohesion of the soil
m	Power
OCR	over consolidation ratio
R	Multiplier
R_f	Failure ratio
L	Sheet pile length
D	Penetration depth of sheet pile wall
P_c	Cap-pressure

CHAPTER ONE
INTRODUCTION

1.1 Background of the study

Sheet piles and ground anchors have been used in the construction industry since early last century. These piles are used in a wide variety of both temporary and permanent structures, including retaining walls, slope stabilization, seepage control barriers, river and canal frontages, quays, sea walls, dock and harbor works, permanent foundations and ground reclamation works. So far considerable amount of research has been performed and these studies revealed significant technical knowledge and construction expertise.

The digging of an excavation in the ground causes stress changes in the ground. This induced stress indicates a change in the stress distribution particularly around the excavation. These stress changes caused by the excavation bring out the displacements around the excavation which can cause the deformations and loosing of soil especially on the retaining walls. One of the most important application cases is to control these change in stress and deformations with the help of some excavation supports.

The greatest use of anchors is to support both temporary and permanent excavations, sheet pilling and ground anchoring can be utilized in several areas. One of the important applications is to control the lateral displacement of the anchored piles due to the excavation. Load-deformation behavior of anchored sheet piles and anchors is affected by various factors. The performance of an anchored structure depends on how the anchor develops load.

In this research the behavior of the multi-anchored sheet pile wall is investigated using a finite difference method (FDM). The main objective is to investigate the multi-anchored sheet pile wall behaviors in response to construction procedure, anchor inclination, number of anchors, grouted body length and grouted body area parameters using cap-yield plastic soil model which helps to see the effectiveness of advanced plastic soil model than the other soil constitutive models. The program chosen for the analysis is FLAC 2D. FLAC is a robust simulator of geotechnical problems which works on the basis of finite difference method. This software is capable of solving a wide range of problems, from simple linear analysis to highly complex non-linear simulation, particularly, through considering the effect of soil-structure interaction.

1.2 Motivation

During deep ground excavation work the main concern is the stability of the walls around the opining. The stability of the adjacent structure constructed before (E.g. buildings next to the cliff walls, motorways above a tunnel, terminals, etc.) are intern affected by the excavation unless the supporting structures are properly designed.

This study is performed for two major motivations;

a) The use of numerical analysis may provide different results for the same problem due to the assumptions used in modeling like constitutive model, material parameters, and choice of element type for modeling soil, meshing and boundary condition. Therefore, this investigation helps in avoiding unrealistic modeling assumptions of soil constitutive model for deep excavation problems in sand.

b) The most widely used excavation supports are rock bolts and ground anchorages. Even if there are a lot of research studied on sheet pile wall working mechanism there are still some influential parameters which should be studied more. In this study the anchored sheet pile wall behavior is studied focusing the change in construction procedure, inclination of the anchorage, grouted anchor area, number of anchors and length of grouted body of the anchor on the sheet pile wall. Moreover, the effect of these factors on the behavior of the sheet pile walls is analyzed and then the conclusion and recommendation are developed.

1.3 Objective

1.3.1 General objective

The major objective of this research is to study the influence of construction procedure and anchor inclination factor on the behavior of multi-anchored sheet pile wall.

1.3.2 Specific objective

The specific objectives are:

a) To check whether the strain-hardening model results realistic deformations (result of the analysis) for this benchmarking and similar retaining wall problems.

b) To study the influence parameters which are stated in the motivation (see section 1.2).

1.4 Scope of the thesis

Investigation of the stabilization and rehabilitation problem is possible with the determination of several design parameters and the interaction of the parameters which affects the deformations of ground during the excavation, stabilization and rehabilitation studies. Therefore, in this study the following scopes are considered.

This study is a plain strain problem so 2D analysis is used. This study use a multi-anchored (triple anchored) concrete sheet pile wall on medium dense sand backfill with ground water; the diaphragm wall is introduced for the whole height of the soil but Influence of diaphragm wall construction is not included; on the excavated side of the soil, ground water lowering is performed. This study will solve a benchmark problem with finite difference method and Cap-Yield plastic soil model; Static analysis is performed; Bending moment and lateral deformation of the anchored sheet pile wall is investigated. This study will cover the effect of the construction procedure using stepped excavation. The parameters which will be covered is the influence of construction procedure, inclination of the anchorage, grouted body area, length of grouted body and also number of the anchor are investigated. A FDM analysis is considered using FLAC 2D (V7).

1.5 Outline of the thesis

In the first chapter, the problem and the objective of the thesis is defined, the scope of the thesis and the outline of the thesis is also described.

Chapter two gives the background information some literature survey about the sheet pile walls, the anchorage system, about the anchor wall system and design concepts for these anchored walls has been discussed and also their applications.

Chapter three presents the creation of a multi-anchored sheet pile wall model for the specific geotechnical sheet pile wall problem. This chapter presents the validation of the numerical model, as well as advanced modeling of anchored sheet pile wall systems, and also sensitivity analysis of model parameters.

In chapter four the investigation of specific parameter using FLAC software that have 'a real life' effect in the engineering industry and interpretation of the results.

Finally the last chapter presents the overall findings, summary of the conclusion of the thesis and also recommendations for future work are discussed to ensure that this work is clearly defined.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Benchmarking a problem have significant importance in geotechnical engineering due to the reasons; the domain to be analyzed is not clearly defined by the structure; it is not very clear that which type of models (continuum and discontinuum) are more appropriate for the problem going to be analyzed; there are different of constitutive models exist in different studies but there is no approved constitutive model for each type of soil and soil/structure interaction is often important and may lead to numerical problems.

A benchmarking problem, namely a deep excavation in Berlin sand and a tunnel excavation problem are specified by German numerical society of geotechnics. A deep excavation in Berlin sand soil is presented in this thesis. This problem has been idealized problem with very tight specification so little room for interpretation was left to the analyst. The specification was sent to various research institutions and consulting companies and their results shows that the calculated maximum horizontal wall displacement for all results varies between approximately 10 to 65 mm and the shape (the deflection curves) also different from the expected (measured value) some results indicate the maximum deflection slightly above the final excavation level, others show the maximum value at the top of the wall. When the calculated and measured values compared it clearly shows that the simplification introduced in ground water lowering (one step lowering instead of ground water lowering according to the excavation progress) higher deflection, further studies shows that the difference in calculated deflection due to difference in modeling the ground water lowering is very dependent on the constitutive model employed (Schweiger, 2002). The calculated surface settlement also got up to 45mm and a heave up to 15mm which is not satisfactory result comparing to the measured value (reality observed from the inclinometer).

The objective of this chapter of the thesis is to review different literatures related to sheet pile wall and show the gaps on their research.

2.2 Background information

Retaining walls are used to hold back soil and maintain a difference in the elevation of the ground surface. Retaining walls can be classified into two categories of structure: rigid or flexible (Bilgin, 2010). A wall is considered rigid if it moves as a unit and does not produce wall deformation. Most gravity walls such as masonry walls, simple concrete walls or reinforced concrete walls can be considered rigid. Flexible walls, by contrast, undergo wall deformations. Sheet pile walls have tolerance of large deformation due to this behavior they are under the category of flexible walls. Typical examples of these two types of retaining wall are indicated in figure 2-1.

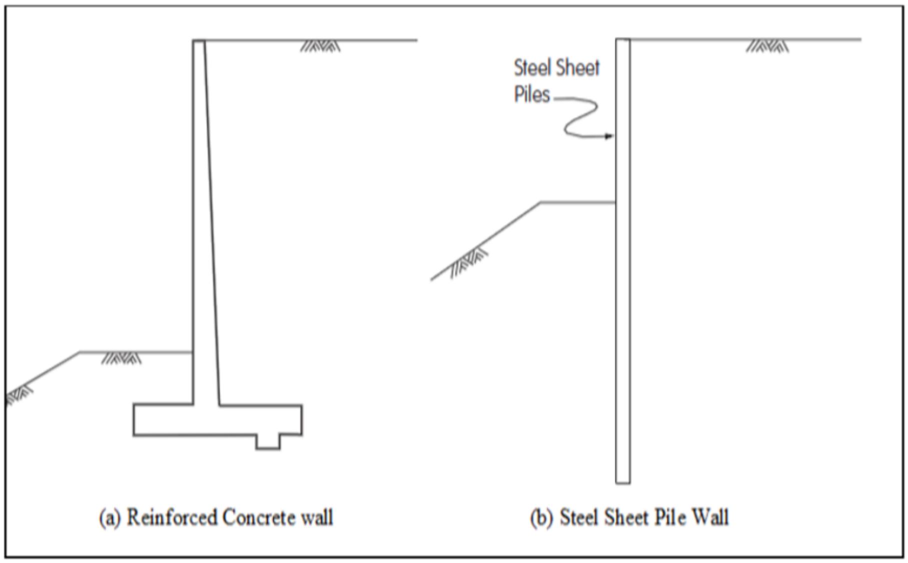

Figure 2-1: Retaining walls; (a) rigid wall, (b) flexible wall(Ramadan, 2013)

Sheet pile walls consist of driven vibrated or pushed interlocking pile segments embedded into soils to resist horizontal pressures(Wood, 2003). The sheet pile walls are constructed by driving the sheet piles into a slope or excavation. They are considered most cost effective where retention of higher earth pressures of soft soils is required; sheet piles have a significant advantage in that they can be driven to depths below the excavation bottom and so provide a control to heaving in soft clays or piping in saturated sand (Bilgin, 2012).

Sheet piles can function as temporary or permanent structures and are most often used in excavation projects. Temporary sheet piling structures are used to control or exclude earth or water and allow the continuation of permanent work. Permanent sheet pilling is commonly used as a retaining structure, and at times as part of the structure of underground buildings (Paikowsky, SG & Tan, 2005).

When sheet pile walls are constructed, important design parameters are introduced that are often difficult to evaluate. Numerical modeling has evolved over the years. Research has found that these numerical methods for the design of sheet pile walls are very useful and can be used to obtain information that is unavailable when using analytical methods for the design of sheet pile walls (Smith 2006;Bilgin 2010) that is, the wall deformation, ground settlement and possible surface failures, this research uses FLAC to develop its numerical model. FLAC is a popular industrially known design tool, used to solve geotechnical problems.

2.2.1 Sheet pile wall materials

Sheet pile walls are made of different kinds of materials such as wood, concrete, steel or aluminum(Ramadan, 2013). The material selection depends on a number of factors, including strength and environmental requirements. The designer must consider the possibility of material deterioration and its effect on the structural integrity of the system. Most enduring structures are constructed of steel or concrete. Concrete is capable of providing a long service life under normal conditions, but has relatively high initial costs when compared to steel sheet pile(Ramadan, 2013). Concrete pilling is also more difficult to install than steel pilling. Long-term field observations indicate that steel sheet piling provides a long service life when properly designed (Ramadan, 2013).

The steel sheet pile alternative is the most popular due to its strength, ease of handling and construction. Steel sheet piles are available in various cross-section shapes. They can have problems with corrosion that can be prevented by coating. They can be used above or below water provided the required protection is applied (Bowles, 1988).

Their advantages are:

- ✓ resistant to high driving stresses
- ✓ relatively light weight
- ✓ reusable
- ✓ long service life
- ✓ easy to increase length by welding
- ✓ joints are less likely to deform
- ✓ they can produce a water tight wall

Other materials such as vinyl, polyvinyl chloride and fiber glass are also available. These pilings have very low structural capacities and function in tieback situations. When compared to other materials, only short lengths of pile available. The designer for each sheet pile application when using one of the above-mentioned materials must carefully evaluate the properties of the specific material obtained from the manufacturer (Paikowsky, SG & Tan, 2005).

Steel and concrete are the most common material used for sheet pile walls.

2.2.2 Construction of sheet pile walls

The construction of sheet pile walls may involve either excavation of soils in front or back filling of soils behind the wall; that is, fill construction or cut construction. Fill wall construction refers to a wall system in which the wall is constructed from the base of the wall up to the top: also called ‘bottom-up’ construction. Cut wall construction refers to a wall system in which the wall is constructed from the top of the wall down to the base, concurrent with excavation operations: known as ‘top-down’ construction (Zhou, 2006). These construction procedures generate different loading conditions in the soil and thus different wall behavior should be expected (Das, 1990).

Sheet pile walls are widely used in excavation support systems, cofferdams and cut-off walls under dams, slope stabilization, waterfront structures and flood walls. Sheet pile walls used to provide lateral earth support could be either cantilever or anchored depending on the wall height. Recently, land owners have been seeking to maximize the usage of their land by designing basements up to their land boundaries, with little regard for the subsoil and site condition restraints. The result is that various deep excavations are cared out in close proximity to existing buildings and infrastructures, increasing the importance in design of considering the safety of neighboring structures (Kasim, 2011).

2.2.3 Cantilever sheet pile walls

Cantilever sheet pile walls are usually used with low wall height between 3 and 6m, and sometimes less due to limitations in availability of certain section modulus and their costs(‘Geotechnical design procedure for flexible wall systems’, 2007), cantilever sheet pile walls are suitable for places with tight space constraints due to the narrow base width of the cantilever wall. This type of sheet pile wall depends on the passive resistance of the foundation material in front of the wall and the moment resisting capacity of the piles for stability.

Therefore, it should not be used where the foundation material may be removed during wall service life(Caltrans, 2004).

2.2.4 Ground anchors

Grouted ground anchors are installed in grout filled drill holes. These anchors are structural elements installed in soil or rock used to transmit an applied tensile load (Sabatini, P.J., 1999). There are three basic components of grouted ground anchors. These are: (1) anchorage; (2) free stressing (unbounded) length; (3) bond length. Figure 2-2 shows all components of grouted ground anchors.

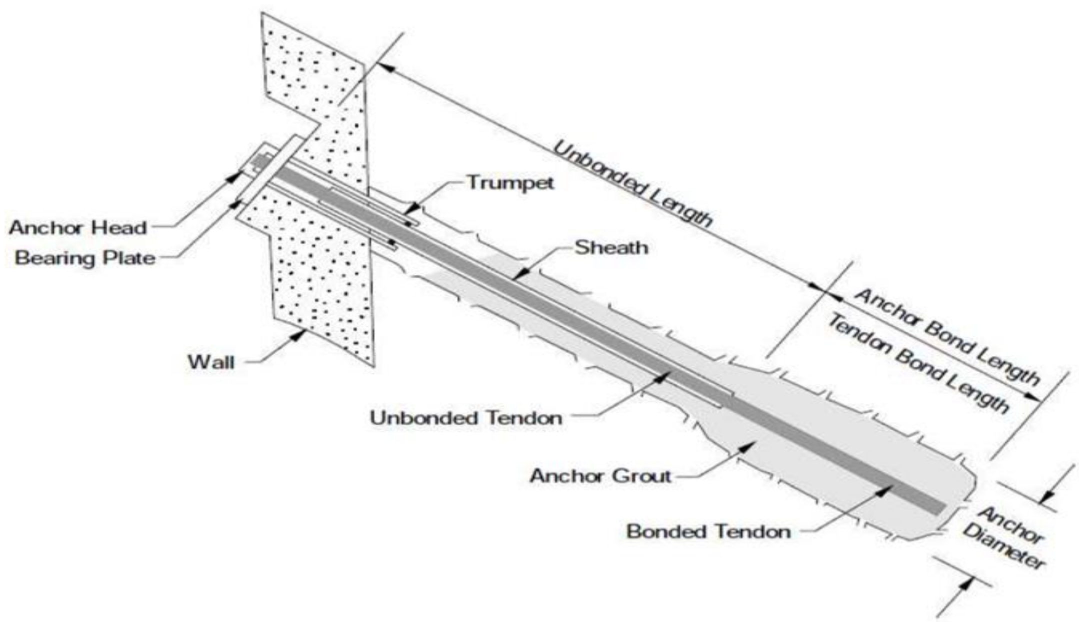

Figure 2-2: Components of a ground anchor

Anchor head, bearing plate and trumpet combined and give anchorage which can transmit the pre-stressing force.

"The unbounded length is that portion of the pre-stressing steel that is free to elongate elastically and transfer the resisting force from the bond length to the structure. A bond breaker is a smooth plastic sleeve that is placed over the tendon in the unbounded length to prevent the pre-stressing steel from bonding to the surrounding grout. It enables the pre-stressing steel in the unbounded length to elongate without obstruction during testing and stressing and leaves the pre-stressing steel unbounded after lock-off. The tendon bond length is that length of the pre-stressing steel that is bonded to the grout and is capable of transmitting the applied tensile load in to the ground. The anchor bound length should be located behind the critical failure surface. A portion of the complete ground anchor assembly is referred to as the tendon. The tendon includes the pre-stressing steel element (strands or bars), corrosion protection, sheaths (also referred to as sheathings), centralizers, and spacers, but specifically excludes the grout. The definition of a tendon, as described in PTI (PTI, 1996), also includes the anchorage ; however, it is assumed here in that the tendon does not include the anchorage." (Mollahasani, 2014)

"The sheath is a smooth or corrugated pipe or tube that protects the pre-stressing steel in the unbounded length from corrosion. Centralizers position the tendon in the drill hole such that the specified minimum grout cover is achieved around the tendon. For multiple element tendons, spacers are used to separate the stands or bars of the tendons so that each element is adequately bonded to the anchor grout. The grout is a Portland cement based mixture that provides load transfer from the tendon to the ground and provides corrosion protection for the tendon." (Sabatini, P.J., 1999)

Basic application of ground anchors are: for highway retaining walls; for slope and land slide stabilization and for tie down structures.

2.2.5 Anchored sheet pile walls

A sheet pile wall height above 6m required to be anchored in order to decrease the penetration depth and to decrease the wall moment by increasing the support (passive pressure in front of the wall) and also in order to limit the lateral defection for design consideration,(Leila , E & Behzad, 2011).

"Anchored sheet pile walls are typically constructed in cut situations, and may be used for fill situations with special design considerations to protect the anchor from construction damage from fill placement or fill settlement."('Geotechnical design procedure for flexible wall systems', 2007)

There are several type of anchors two of them are very common. These are dead-man and grouted tie-backs.('Geotechnical design procedure for flexible wall systems', 2007). The selection of the most suitable type of anchor generally depends on the soil type, presence of ground water and cost considerations (Elias, V & Juran, 1991). The stability of the dead-man anchors is limited to single anchored walls whereas the grouted tie backs can be introduced for all type of anchors (single, double and multi anchored walls) (Caltrans, 2004).

“Grouted tiebacks and dead-man anchors are used when there is available underground space beyond the excavated area. This space should be free from the foundations and the underground utilities of adjacent structures.” (Gulhati, SK & Datta, 2008)

Different researchers studied on anchored sheet pile wall in order to know the effect of different parameters on the stability and also behavior of sheet pile wall.

Bilgin in 2010 studied anchored sheet pile wall behavior constructed in cut and fill conditions. The loading conditions dependent on the construction procedure which makes the wall to generate different behaviors. The conventional methods do not consider the method of construction but the numerical methods incorporate the construction method in the design and analysis of sheet pile walls (Bilgin, 2010).

Bilgin (2010) investigated the effect of the wall construction by varying soil conditions and wall heights using finite element modeling. He concludes that construction using backfilling procedures will give significantly higher bending moments and wall deformations. His findings indicate that more information can be get from numerical analysis.

In 2012 bilgin also studied the effect of lateral earth pressure coefficient for anchored sheet pile wall; the lateral earth pressure coefficient established by the conventional method is based on active and passive earth pressure from limit equilibrium. He carried out the parametric study using both conventional and numerical methods (finite element method was used) to investigate the behavior of single anchored sheet pile wall. The result shows that free earth support method over estimates the bending moment and underestimates the anchor force. As the result new lateral earth pressure coefficient is developed that can consider the stress concentration around the anchor level in to account and give realistic earth pressure distributions acting on the wall and accurate anchor sheet pile wall design (Bilgin, 2012).

The effect of wall penetration depth on the behavior of sheet pile wall is studied by Ramadan in 2013, Ammar Jalil Alimosawi and Karar saleh suhail in 2019 using finite element method.“Important serviceability considerations are not considered when using the limit equilibrium methods. This is because information about the wall deformation cannot be obtained by these analytical methods"(Ramadan, 2013).

Ramadan (2013) investigated behavior and structural response of both cantilever and anchored sheet pile walls by using finite element analysis. From his study he found that both deformation and bending moments reduce with increasing penetration depth for both type of sheet pile walls (Ramadan, 2013).

Ammar jalil almosawi and karar saleh suhail (2019) also conclude the same as Ramadan (2013), in addition they stated that increasing penetration depth has a great effect on cantilever walls than the anchored since it reduce the horizontal displacement by 70% than the anchored sheet pile wall (Suhail, 2019).

In 2013 Torrabadella investigate the influence of initial stress state condition of sheet pile walls. He found that the deformation is minimum at the top of the wall when K_0 become between 0.7 and 0.9 but this deformation may vary up to 40% since the initial stress state depends in soil friction (Torrabadella, 2013).

Torrabadella (2013) also stated that "the limit equilibrium methods corresponded well with the numerical methods for both cantilever and anchored sheet pile walls". Seeing these kinds of result difference and judgment which arise a controversial Helmut F.Schweiger in 2002 studied the effect of constitutive model assumptions for a deep excavation in sand on anchored sheet pile wall. By seeing the effect of constitutive model, element type of soil, element type of wall, interface and domain analyzed he conclude that guidelines and procedures should be defined in order to get reliable numerical model in practical geotechnical engineering (F.schweiger, 2002).

2.3 Numerical Modeling Methods

To understand the complexity of natural phenomena engineers take simplified assumptions to create mathematical models(Pastor, M & Tamagnini, 2004; Wood, 2003).

The improvement of modern technology (computer improvements) leads us to have the ability to undertake different complex engineering problems (Rao, 2005; Zienkiewicz, OC, Taylor, RL & Zhu, 2013; Desai, CS & Christian, 1977). However the numerical models have also their own limitations and uncertainties, because of their uncertainties and assumptions taken by the engineers their results should be valid by analytical methods (Pande, GN & Pietruszczak, 2004).

2.3.1 Background of FLAC Software

“FLAC is a finite difference software program, developed by Dr.Peter Cundall in 1986. This software makes it possible to visualize the behavior of the structure in the soil, rock or any other material that may undergo plastic flow. A grid of the materials can be formed that represents elements or zones that can be adjusted by the user. This explicit, Lagrangian calculation scheme and the mixed-discretization zoning technique used in FLAC ensure the highly accurate modeling of flow and plastic collapse. Large 2D calculations can be made without the need for massive memory requirements due to no matrixes being formed.” (Brits, 2014)

“FLAC was originally developed for geotechnical and mining engineers. This software offers a wide range of capabilities including for solving complex problems in mechanics. The FLAC software has special built-in functions that make it unique. The application range of FLAC is extensive because it is equipped with 11 built-in constitutive models, five optional facilities and several kinds of structure elements as well as a built-in coding language, FISH.” (Brits, 2014)

“Other element structures present in FLAC include beam, anchor, pile and shell structures. These elements are used to create more realistic models of geotechnical engineering problems in the software. It will be use full to design an anchored sheet pile wall model in FLAC. The build-in coding language (FISH) can also be used to define new functions and variables to meet user demands.” (Brits, 2014)

2.3.2 Major FLAC features

The major features of FLAC software are:

“Large strain simulations of continua, with optional interface that is able to distinctively simulate planes along which slip and/or separation can occur; Obtaining stable solutions from the provided explicit solution scheme when compared to unstable physical processes; Availability to model groundwater flow, with full coupling to mechanical calculation (including negative pore pressure, unsaturated flow and phreatic surface calculation); Selection of multiple structural elements (including non-linear material behavior); Full library of material models (e.g. elastic, Mohr-coulomb plasticity, double-yield, stain- softening, modified Cam-Clay, Hoek-Brown and others); Statistical distribution of any property for generating plots of virtually any problem variable with extensive facilitation; Extra user-defined features such as the built-in language FISH.” (‘FLAC 2D online manual’, 2009)

2.3.3 FLAC Software Advantage and Disadvantages

The FLAC software used here to develop a numerical model has several advantages over other methods. These are:

"The mixed-discretization zoning method is more accurate than the reduced integration method generally used to simulate the plastic flow of materials; the explicit methods used decrease the time needed to solve non-linear equations; the full dynamic equation of motion is used, making the software more suitable to simulate problems involving vibration, failure and large deformations. And the element numbering is done in row and column formatting." ('FLAC 2D online manual', 2009)

The disadvantages are:

"More time is needed to reach convergence for a linear problem than when using the finite element methods. And FLAC depends on the ratio of maximum and minimum natural periods of the system for the convergence velocity." ('FLAC 2D online manual', 2009)

Different research has shown that FLAC is excellent software for modeling any geotechnical engineering model. Therefore, FLAC is used to undertake the numerical modeling in this thesis work.

CHAPTER THREE

NUMERICAL ANALYSIS AND CONVERGENCE STUDY

3.1 Introduction

The objective of this chapter of the thesis is to use FLAC to investigate the complex anchored sheet pile wall penetrating sand problem, performing the sensitivity study of the modeling assumptions, discussing the results of the studied modeling assumptions and validating the analyzed model. The studied modeling assumptions are; Influence of ground water lowering, Influence of wall friction, Influence of discretization, Influence of domain analyzed, Influence of wall thickness, Influence of variation in stiffness and strength parameters of soil.

3.2 Problem Description

3.2.1 Assumptions and geometry

The problem is related to an actual project in Berlin. In this thesis the construction sequence used is firstly by lowering the ground water step wisely up to the required level after this is performed the step wise excavation is started. Basic material parameters have been taken from the literature. The general layout can be seen in figure 3-1. The domain analyzed has been chosen as follows; width =150 m, depth =100 m (see section 3.5.4). The mesh consists of 90 zones, which is refined in areas where high stress gradients can be expected (see section 3.5.3). The mesh was deliberately chosen to be fine in order to minimize the meshing error (as seen in section 3.3.1.1, figure 3-3).

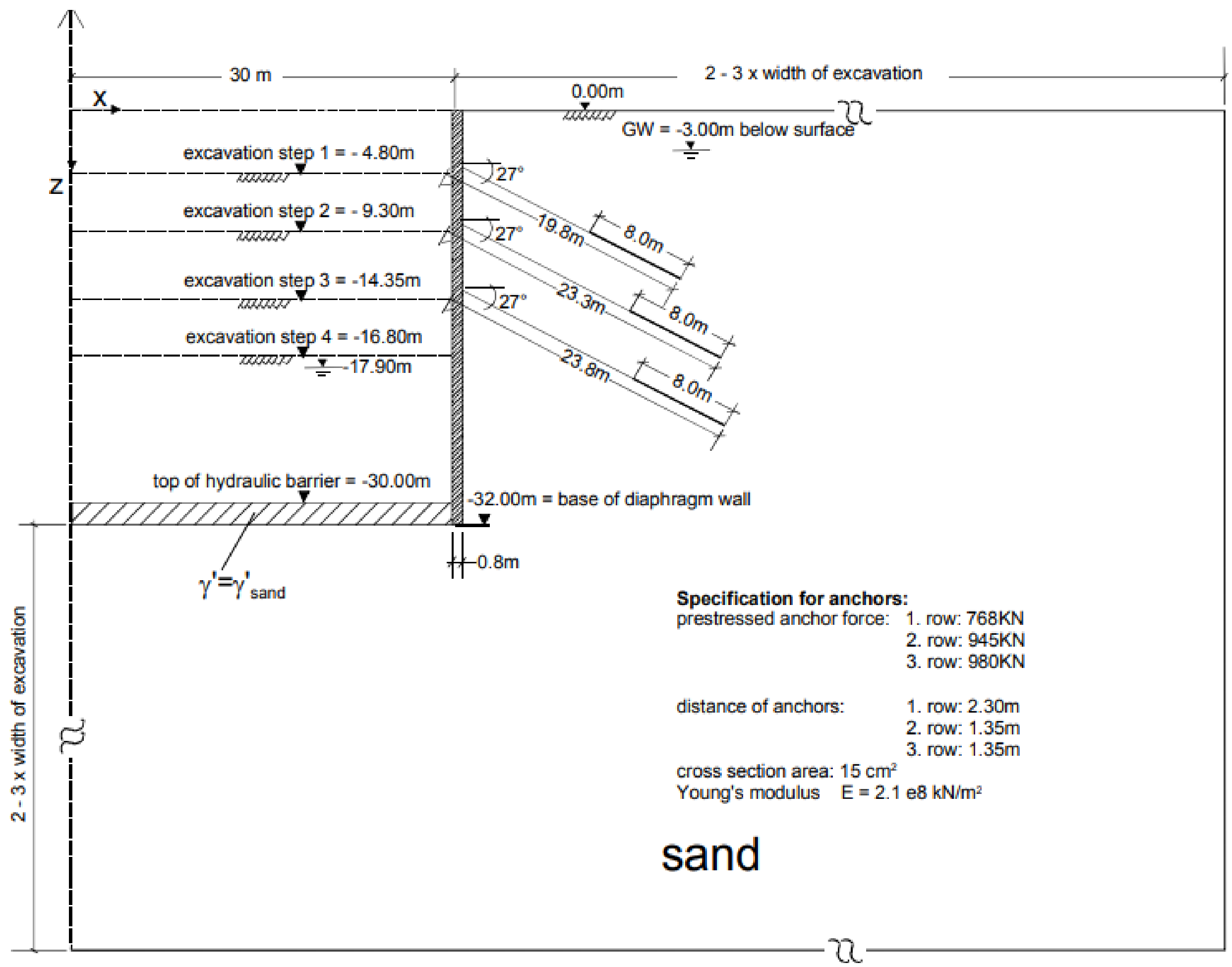

Figure 3-1: Problem geometry

Several model specifications adopted for this thesis from schweiger (2002), are:

a) The problem to be analyzed is a Plain strain problem.
b) The diaphragm wall is modeled and introduced using beam structural element connected with the soil by interface and also the influence of diaphragm wall construction is not considered.
c) In order to avoid seepage analysis horizontal hydraulic cutoff is introduced at 30m having a mechanical property of the same as the surrounding soil.
d) The overall step wise ground water lowering is performed and completed before the step wise excavation is started.
e) The anchors are modeled as a rod and the force shown in figure 3-1 are design loads.
f) Layer 1and layer 2 has 0.43 and 0.38 lateral earth pressure coefficient respectively.

3.2.2 Brief description of FLAC Cap-Yield (CY Plastic Soil) model

"The CY Plastic soil model is a strain-hardening constitutive model characterized by a frictional and cohesive Mohr-Coulomb shear envelope and an elliptic volumetric cap with ratio of axes, defined by a shape parameter α."('FLAC 2D online manual', 2009)

"The motivation for closing the yield surface by a cap on the mean stress axis is to permit plastic behavior in response to an isotropic stress increase. This plasticity effect accounts for grain crushing and rearrangement, and is particular to soils. In the double-yield model, the cap is a plane, normal to the mean stress axis in stress space. The impact of this particular shape on the coefficient of lateral earth pressure, K_O, as predicted by the model in uniaxial compression tests, has been considered to be somewhat restrictive by some users. In that respect, the CY Plastic soil model is a modification of the double-yield model that addresses this issue by accounting for a cap with an elliptic shape in the (p',q) plane" as shown in figure 3-2."The ratio of axes of the ellipse, α, determines the value of K_0 and is a material property for the model. This can be chosen to match a known value in uniaxial compression."('FLAC 2D online manual', 2009)

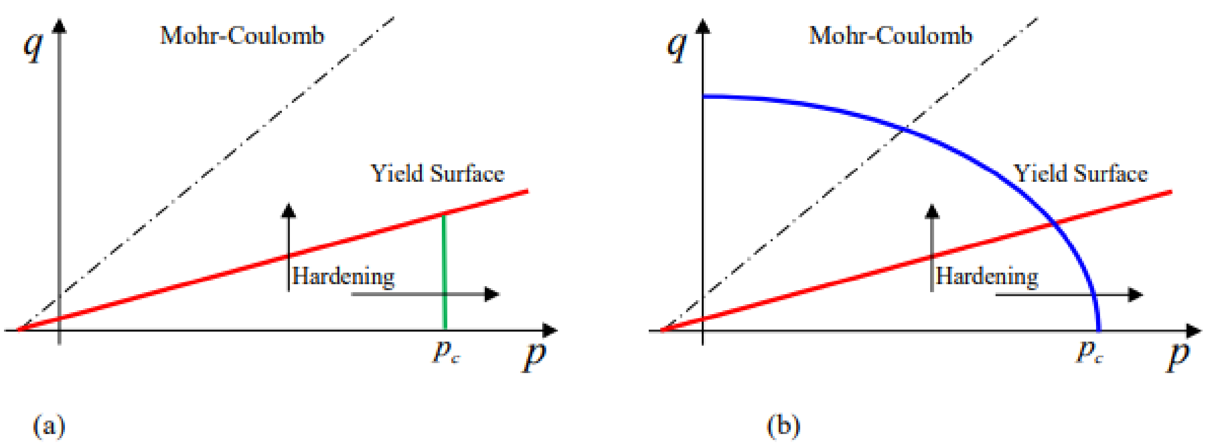

Figure 3-2: (a) The yield surfaces of the Double Yield Material Model; Deviatoric yield surface (red) and the vertical cap (green), (b) The yield surfaces of the CY Plastic Soil Material Model; Deviatoric yield surface (red) and the elliptical cap (blue).

In particular, a planar volumetric cap is obtained as a special case of the CY Plastic soil formulation by assuming a value α>>1.

In addition, when subjected to deviatoric loadings, soils usually exhibit a decrease in stiffness, accompanied by irreversible deformations. In most cases, the plot of deviatoric stress versus axial strain obtained in a drained triaxial test may be approximated by a hyperbola. This feature has been used by Duncan and Chang (1970) to formulate their well-known “hyperbolic soil” model. The hyperbolic soil model of Duncan and Change is a nonlinear elastic model that has been shown to exhibit some drawbacks. These drawbacks include, for example, difficulty in detecting and characterizing unloading/reloading and, in specific cases, producing a nonphysical bulk-modulus value that can lead to an erroneous energy generation in the model. Because the CY Plastic soil model is formulated in the theory of hardening plasticity, it allows for an alternative expression of the hyperbolic behavior (based on friction hardening), which is capable of addressing some of these problems. A simplified version of the CY Plastic soil model, called the CHSoil model, also addresses the difficulties of the Duncan and Chang model and is provided as an alternative to the Duncan and Chang model.

“When tested under drained triaxial conditions, soil generally exhibit shear-induced volume changes that are strongly dependent on soil density. Typically, there is a tendency for the soil to contract under small shear strains, and to dilate under large strains, unless it is very loose”(Byrne et al, 2003). In particular, when fluid fills the pores, it is this tendency of the soil skeleton to contract and dilate that controls its liquefaction response. Also, the shear-stress/ shear-strain response of loose soil may exhibit a softening response under un-drained conditions. “It is the existence of a peak in shear strength which may lead to instability (static liquefaction) during a monotonic load-controlled process”(Boukpeti, 2001). Shear-induced volume changes can be accounted for in the CY Plastic soil model by means of a dilation hardening/softening law.

3.2.3 FLAC Input parameters for CY Plastic soil model

The basic set of material parameters (seen in table 3-1, 3-2, 3-3 and 3-4) used to obtain the analysis of this thesis is based on data available in the literatures and from PLAXIS and FLAC program online manuals.

Table3-1: Berlin sand soil property. Adapted from PLAXIS program online manuals

Properties	**Layer 1**	**Layer 2**
Dry density (Kg/m^3)	1900	1900
Friction angle (degree)	35	38
Dilation angle (degree)	5	6
E^{ref}_{ur} (MPa)	180	300
E^{ref}_{oed} (MPa)	45	75
Reference pressure (MPa)	0.1	0.1
Poisson's ratio	0.2	0.2
Cohesion	0	0
Power, m	0.55	0.55
Over consolidation ratio, OCR	1.0	1.0
Multiplier, R	3.444	3.444
G_{ref}	168.75	281.25
Cap yield surface parameter, α	1.0	1.0
Calibration factor, β	0.5	0.5
Failure ratio, R_f	0.9	0.9

Material parameters for structural elements (pile, diaphragm wall and anchor).

Table 3-2: Pile element properties adapted from Schweiger (2002)

Elastic modulus (Pa)	3.069e10
Height (m)	1
Width (m)	0.8
Friction between sand and sheet pile wall (degree)	0
Total length of sheet pile wall (m)	32
Penetration depth of sheet pile wall (m)	15.2

Table 3-3: Diaphragm wall properties adapted from Schweiger (2002)

Density (Kg/m^3)	2400
Young's modulus (GPa)	30.0
Poisson's ratio	0.15

Table 3-4: Anchor specifications adapted from Schweiger (2002)

Properties	Row 1	Row 2	Row 3
Location depth at wall (m)	4.80	9.30	14.35
Dip (degree)	27	27	27
Total length (m)	19.8	23.3	23.8
Anchored length (m)	8.0	8.0	8.0
Spacing (m)	2.3	1.35	1.35
Prestress anchor force (KN)	768	945	980
Young's modulus (GPa)	210	210	210
Grout shear stiffness (Pa)	1e8	1e8	1e8
Yield strength (Pa)	1e10	1e10	1e10
Intrinsic shear strength (Pa)	1e8	1e8	1e8
Cross-sectional area (m^2)	0.0015	0.0015	0.0015

3.3 Analysis using FLAC

FLAC is a finite difference program and does not approach this problem in the same way as the analytical methods. When using the limit equilibrium methods for solving this problem, the penetration depth of the sheet pile is found as the result of other parameter inputs but FLAC requires the penetration depth of the sheet pile to be entered before determining whether the system is stable or not. Due to this reason some parameters are varied to get more appropriate parameters value which can fit better for the problem analyzed. Thus, the overall soil/pile system behavior can be examined first by varying several input parameters. To obtain more accurate sheet pile wall designs, numerical analysis in FLAC is undertaken.

The analysis in this thesis includes nine general steps (see section 3.4.1.2 for detailed steps):

Stage 1- Initialize stress state; including ground water table 3m below soil surface.

Stage 2- Activate diaphragm wall and lower water level up to -17.90 m.

Stage 3- Excavation step 1 (to level -4.80 m).

Stage 4- Activate anchor row 1 at level -4.30 m and pre stress anchors.

Stage 5- Excavation step 2 (to level -9.30 m).

Stage 6- Activate anchor row 2 at level -8.80 m and pre stress anchors.

Stage 7- Excavation step 3 (to level -14.35 m).

Stage 8- Activate anchor row 3 at level -13.85 m and pre stress anchors.

Stage 9- Excavation step 4 (to level -16.80 m).

3.3.1 Model Creation

The first step is to build the geometry of the problem, assuming an initial length in the x and y directions (see section 3.6.4). The soil layer boundaries and material properties are then defined. Construction element like walls and anchors are placed next. The soil/wall system is then created using interface properties, which are then defined. Finally, the mesh is generated.

3.3.1.1 Modeling procedure

Step 1: creating the model grid, define the two sand layers and four excavation stages, and assign boundary conditions.

Step 1-1: this stage is where the project will be set. Ground water flow, total stress, structural element and advanced constitutive model will be adjusted.

Step 1-2: geometry builder will be activated and set outer boundaries of the model at $-30<x<120$; $-100<y<0$.

Step 1-3: using vertical and horizontal edge option the location of the anchored wall and the boundary between layer 1 and layer 2 at $x=0$, $y_1=-32$, $y_2=0$; $y=-20$ will be added respectively.

Step 1-4: using horizontal edge option the location of the excavation levels at y=-4.8 m, -9.3 m, -14.35 m, -16.8 m and dewatering level of -17.9 m will be added.

Step 1-5: construction line will be created to create a model composed of 16 blocks then assign roller boundaries for both sides and fixed boundaries for the soil model.

Step 1-6: the beam-interface will be set and the wall will be represented by beam element with interface on each side of the beam connecting to the grid. In order to connect the separated blocks by beam/interface or an attached edge through the model attach command will be introduced between the wall and the construction line beneath the wall as.

Step 1-7: meshing will be authorized using automated zoning. Then the grid will be manually adjusted to provide finer zoning around the excavation wall and coarser zoning farther out by introducing "zone size (manual)" and "adjust ratio" options and also regions will be assigned as seen in figure 3-3.

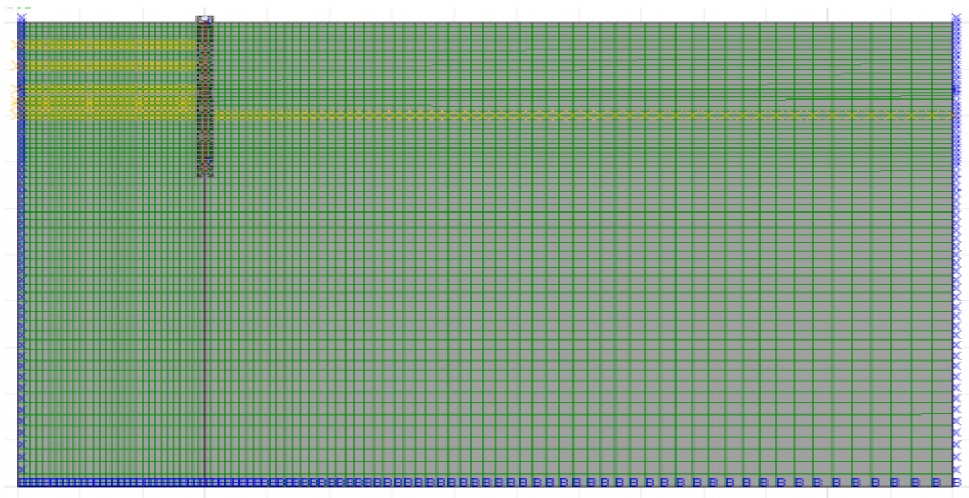

Figure 3-3: State of the model at the end of step 1

Step 2: assign the CY Plastic soil model and properties of sheet pile wall and wall-soil interface properties.

Step 2-1: cap-yield plastic soil model property for layer 1 and layer 2 and soil ground water property will be assigned.

Step 2-2: properties for the interfaces on both sides of the beam and beam properties will be assigned.

According to the FLAC manual, an interface between the soil/wall systems is represented as normal, and there is shear stiffness between the two planes (figure 3-4). For either side of the interface, FLAC uses contact logic similar to that used by the finite element method.

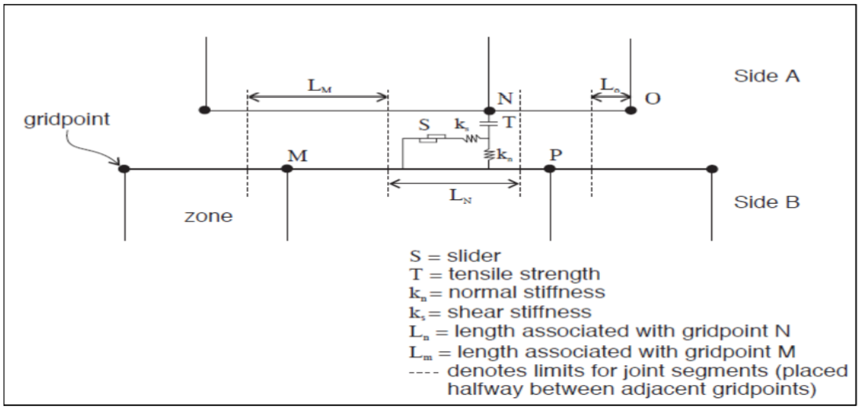

Figure 3-4: An Interface Represented by sides a and b, connected by sear (ks) and normal (kn) stiffness springs (‘FLAC 2D online manual’, 2009)

At this stage unbounded interface for both sides of the beam is introduced. The friction used for the interface is the average of the wall and the soil friction.

Step 2-3: turning off ground water flow calculation; the gravity and water density value will be set and initialize stress and pore pressure for the two layers.

In order to model the soil mass in FLAC the soil mass is solved to reach equilibrium using the ‘solve elastic’ at the first instance, thus automatically creating the initial stresses due to the weight of the soil mass.

Step 3: calculating the initial in-situ stress with the ground water level at elevation y=-3m.set the stress-dependent CY Plastic soil model properties.

Step 3-1: water table elevation at -3.0 m and k_o value for layer 1 and layer 2, 0.43 and 0.38 respectively will be set using fish function then pore pressure distribution will be plotted as shown in figure 3-5.

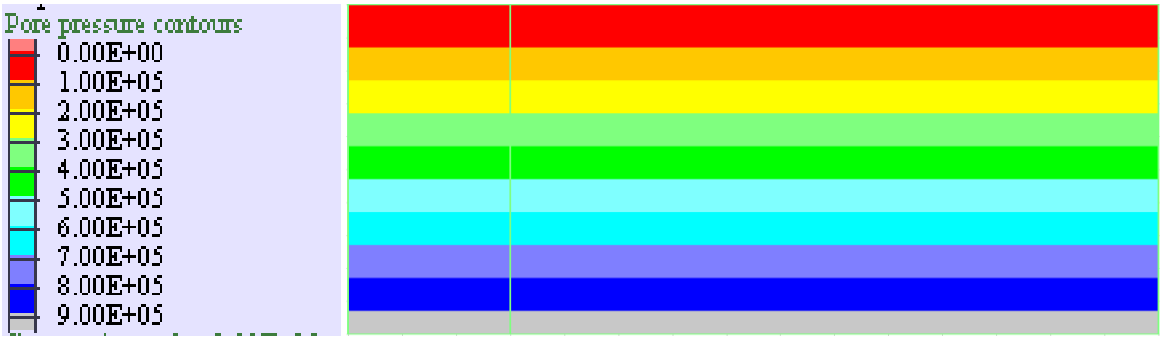

Figure 3-5: Pore pressure before lowering of the water level

Step 3-2: cap pressure, mobilized friction, upper bound shear modulus and plastic shear strain will be executed using fish function and solve for initial equilibrium to initialize insitu stress.

Step 4: simulate the wall construction by adding the weight of the beam and solving for the equilibrium state.

Step 5: simulate dewatering of the excavation region by initializing saturation and pore pressures in the dewatering region. Dewatering is performed in five stages.

Step 5-1: the saturation and pore pressure will be set to zero for the first excavation region. Linear pore pressure distribution from the bottom of the first excavation region to the level y= -30m will be set.

Step 5-2: after the first excavation region dewatered and solved for mechanical equilibrium the same dewatering process will be performed up to -17.9m.

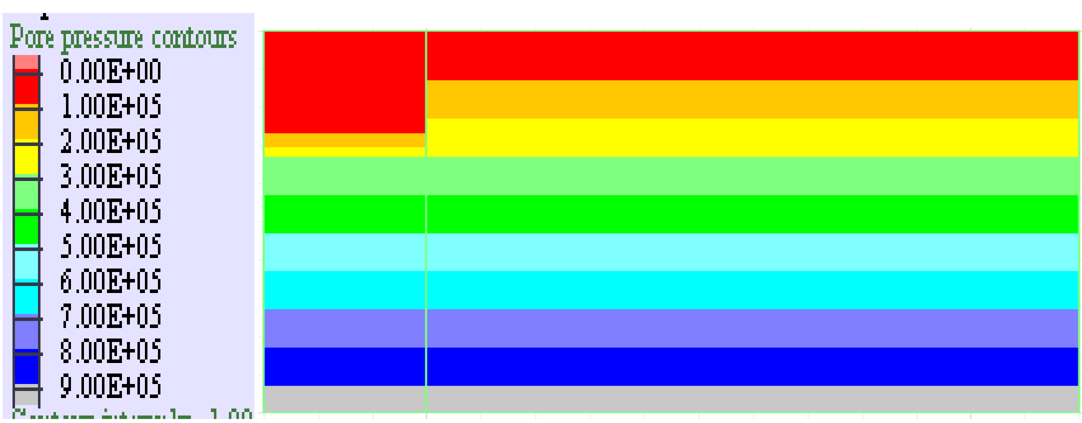

Figure 3-6: Pore pressure after lowering of water level to -17.90 m

The purpose of the diaphragm wall is dewatering (lowering of the water level) of the soil after the model is solved for elastic equilibrium and before the excavation of the soil starts and the purpose of the hydraulic cut off is to control seepage. The ground water lowering takes place up to -17.90 m in pit and the pore pressure become as shown in figure 3-6.

Step 6: simulate the four excavation stages. The pre stressed anchors are added at the first three excavation stages.

Step 6-1: The required depth above the dredge line to the left of the sheet pile was then excavated step by step using 'model null' command. After excavating the soil, the model was solved again using the 'solve' command to investigate the effects and behavior of the sheet pile wall by interpreting specific FLAC outputs.

Step 6-2: at this stage the first anchor will be introduced, the properties will be assigned, the pretension force will be applied and the model will be solved to the equilibrium. The anchors are modeled as cable elements because cable elements can be grouted at a specific point and develop force along its length as other grids deform. They can carry tension and compression forces and also they can be pre tensioned .due to this reason cable elements are perfect feet for modeling tiebacks.

Step 6-3: the second, third and fourth excavation and the second and third anchor introduction will be done accordingly as shown in figure 3-7.

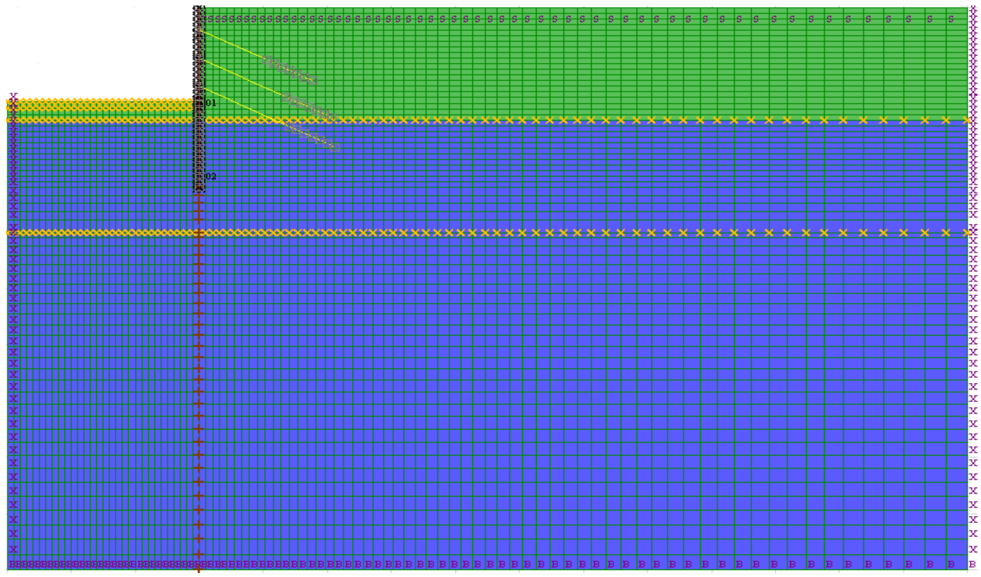

Figure 3-7: FLAC model for installation of triple anchored sheet pile wall excavation in Berlin sand soil

Step 7: compare the results with schweiger's (2002) results and actual measured deflection which is measured by inclinometer.

3.3.2 FLAC Results

Establishing whether the created model is correct forms part of the model validation process.

Failure Surface

Plotting the failure surface on shear strain rate plot gives a good indication of whether the grid size of the model is acceptable.

Due to specimen weakness or imperfect boundary conditions, inhomogeneous deformations occur strains thus become concentrated in to narrow zones, also known as 'shear bonds'. Figure 3-7 is initially assumed model grid. The failure surface in figure 3-8 is fully contained within the initially assumed model grid this indicates that the grid size is acceptable.

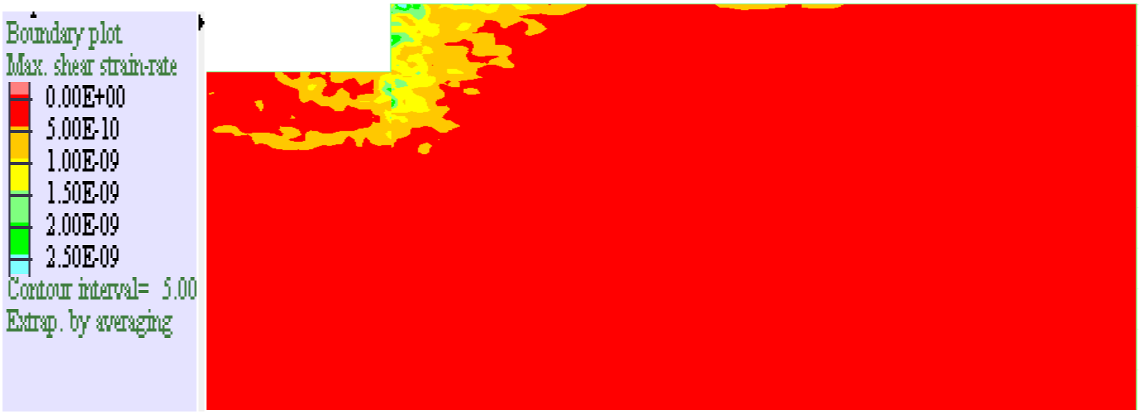

Figure 3-8: Failure surface for fine mesh model

Soil Mass Failure

The failure of the soil mass can be examined by plotting the plasticity graph in FLAC. This plot indicates which elements are at yield or have undergone plastic deformation.

The overall purpose of analyzing plasticity plot is to determine whether the system fails. It is thus crucial to examine the plot of plasticity indicator for each element prone to failure. The soil mass is found to fail when the plasticity elements on one side of the sheet pile connect the ground surface to the ground surface on the other side of the sheet pile via extending around the sheet pile tip. Failure also occurs when the plastic elements extend far beneath the sheet pile tip in to the outer boundary of the plot.

Figure 3-9: State of the model

By examining figure 3-9, which shows the state of the model clearly indicates that there is no any plastic deformation occurrence every deformation is in elastic rage. Thus it is reasonable to conclude that the anchored sheet pile wall penetrating 32 m of sand soil is safe as failure is not occurring.

Maximum Bending Moment and Horizontal Wall Displacement

According to past research, numerical methods such as FLAC are very accurate when compared to analytical solutions(Smith, 2006; Bilgin, 2010). Accuracy of results is very important for design engineers. If the forces exerted on the structure are underestimated, structure failure may result, which leads to lives being lost and the design engineer being held accountable.

By analyzing the anchored sheet pile wall behavior in FLAC, it was possible to obtain the maximum bending moment exerted on the sheet pile wall (see figure 3-10) and the maximum horizontal wall displacement (see figure 3-11). As already mentioned, these out puts are extremely important for stability and structural design purposes.

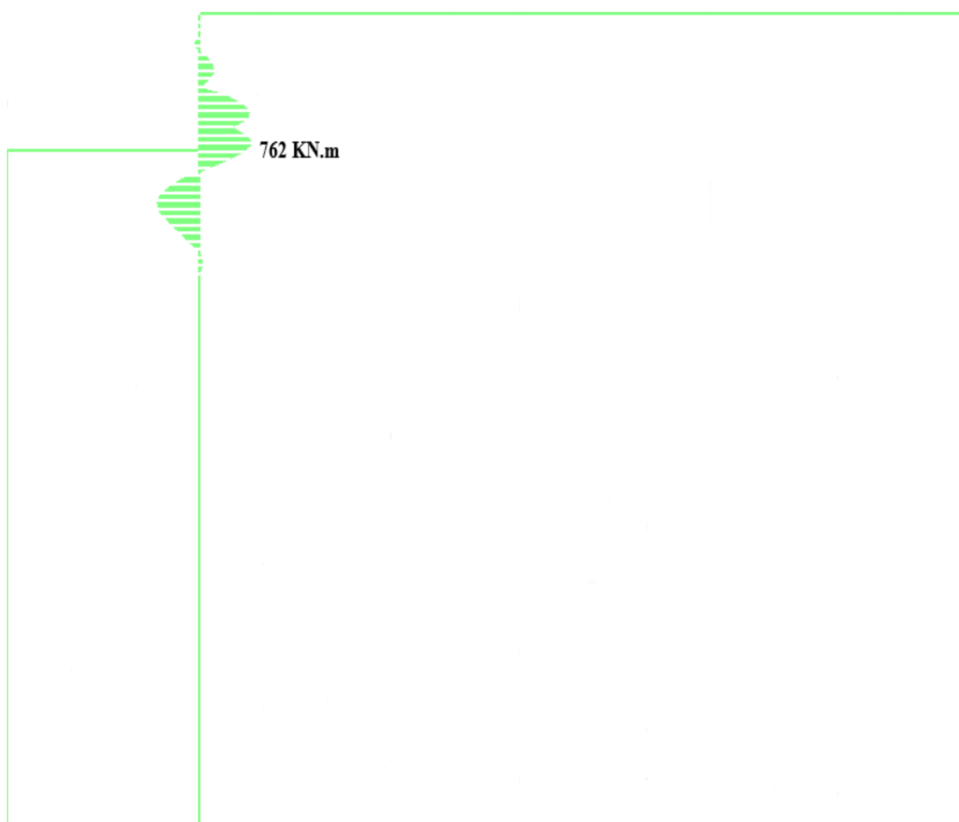

Figure 3-10: Maximum Bending Moment

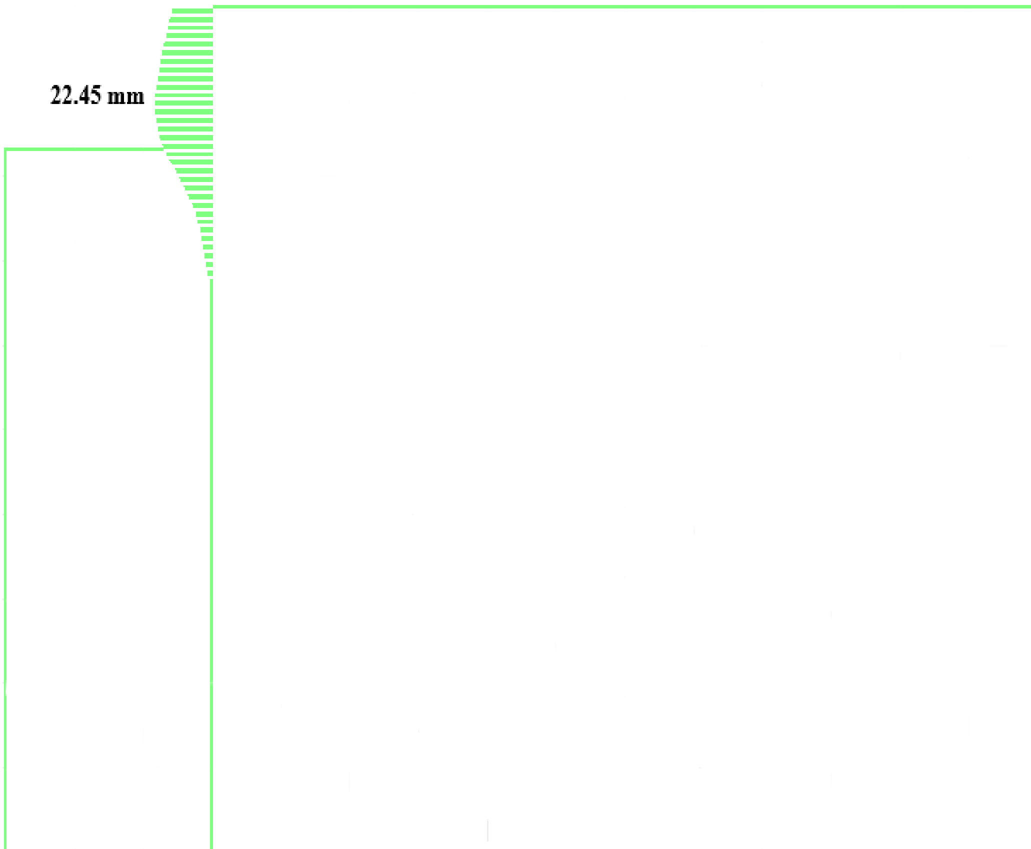

Figure 3-11: Maximum X-Displacement

Containing these visual outputs certainly gives a good indication of the soil-wall system; however, determining the quality of the result outputs is what is important.

3.4 Validation of FLAC Model

The validation of this model is an important step with in this chapter as it ensured the quality of the result being obtained. This validation is done by comparing the FLAC outputs of horizontal displacement (deflection) and vertical displacement (settlement) obtained from the analysis with the measured actual deflection by using inclinometer and the vertical displacement obtained from schweiger's study (2002) using PLAXIS program.

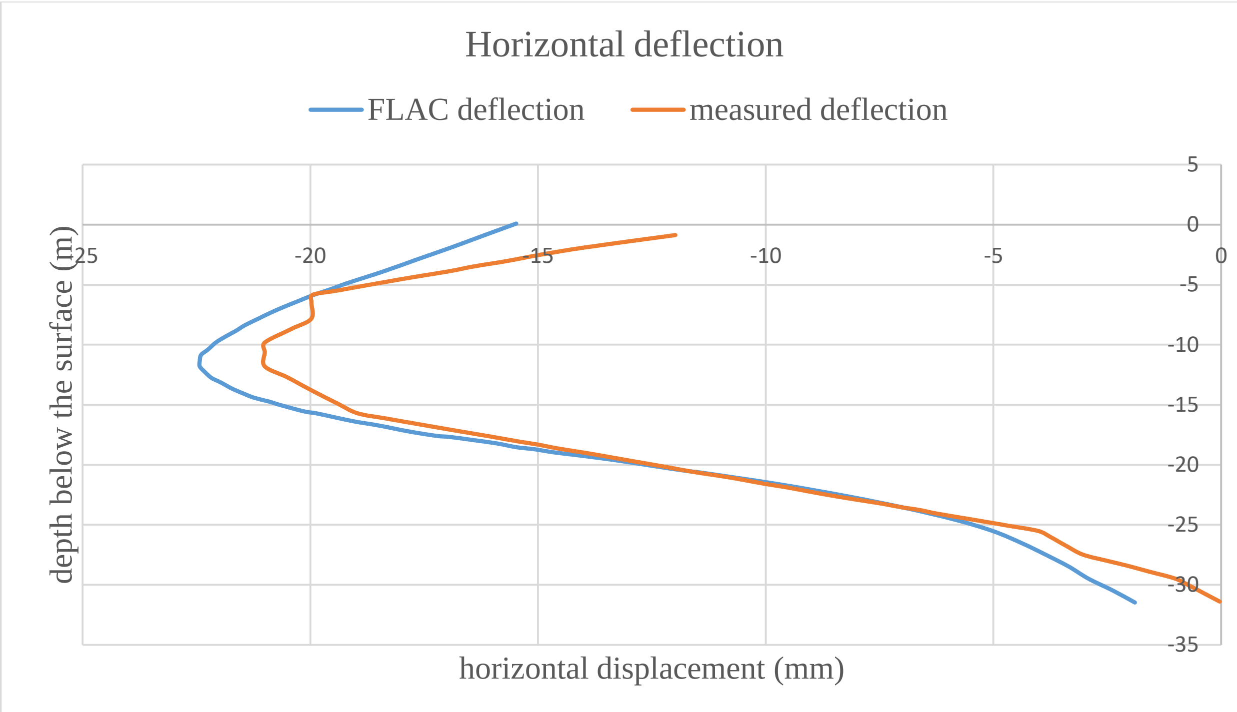

Figure 3-12: Visual comparison of maximum deflection

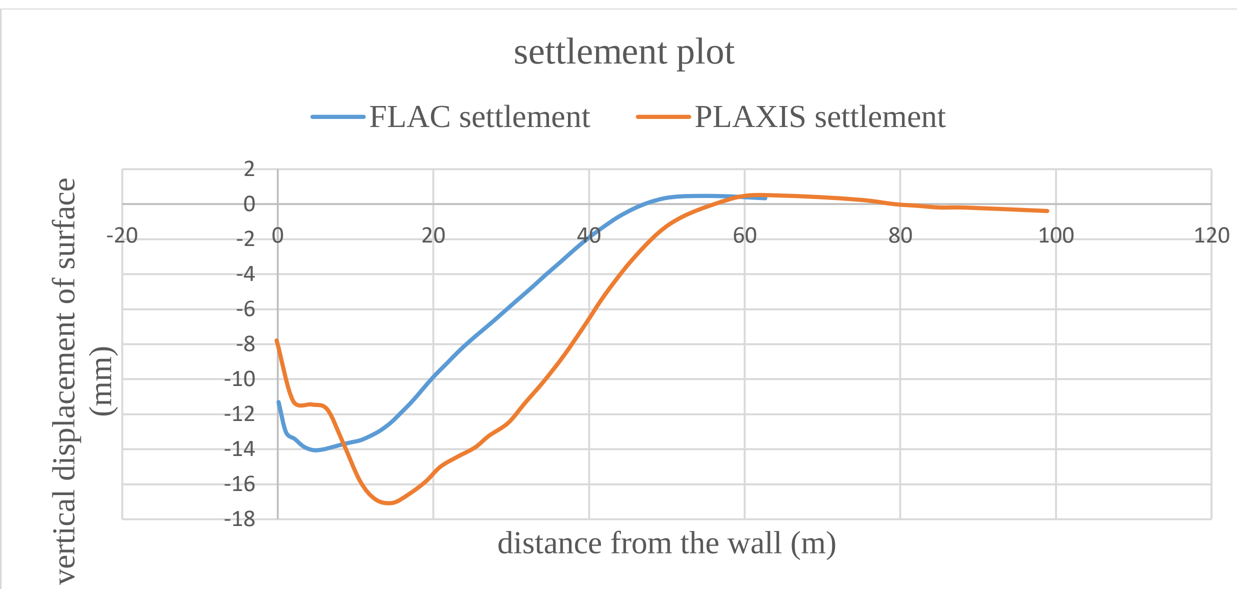

Figure 3-13: Visual comparison of maximum settlement

As shown in table 3-5, the maximum deflection obtained from FLAC sees only a 6.47% increase from the horizontal deflection obtained from the measurements. This gives a 93.53% comparison between the obtained solutions from FLAC and measured one. And also as shown in table 3-6, the maximum settlement obtained from FLAC sees only a 17.7% reduction from the maximum settlement obtained from PLAXIS by schweiger's study. This gives an82.3% comparison between the obtained solution using FLAC and the obtained solution using PLAXIS which is done by schweinger in 2002 G.C.

Table 3-5: Comparison of maximum deflection

Wall depth (m)	FLAC solution (mm)	Measured deflection (mm)	Percentage difference (%)
32	-22.45	-20.998	6.47

Table 3-6: Comparison of maximum settlement

Distance from the wall (m)	FLAC solution (mm)	PLAXIS solution (mm)	Percentage reduction (%)
120	-14.04	-17.0595	17.7

This close comparison indicates that the results compare very well, strongly suggesting the validity of the results obtained from FLAC.

3.5 Sensitivity analysis

This sensitivity study focuses primarily on studying the effect of the modeling assumptions such as influence of ground water lowering, wall friction, meshing, domain analyzed, wall thickness, variation in stiffness and strength parameters of soil.

3.5.1 Influence of ground water lowering

To investigate the ground water lowering, two ways of ground water lowering was used and performed before the excavation starts. The two ways are one step lowering and step wise lowering up to 17.90. the step wise lowering was performed in 5 steps, from top to 4.8 m, 4.8 m to 9.3 m, 9.3 m to 14.35 m, 14.35 m to 16.8 m and 16.8 m to 17.9 m these steps was performed (refer section 3.3.1.1 to see the pour pressure distribution) accordingly.

Lowering the ground water in one step from top to 17.9 m at once will increase the settlement by approximately8 mm and the wall deflection by 17 mm. the results of the analysis can be seen in Figure 3-14 and Figure 3-15.

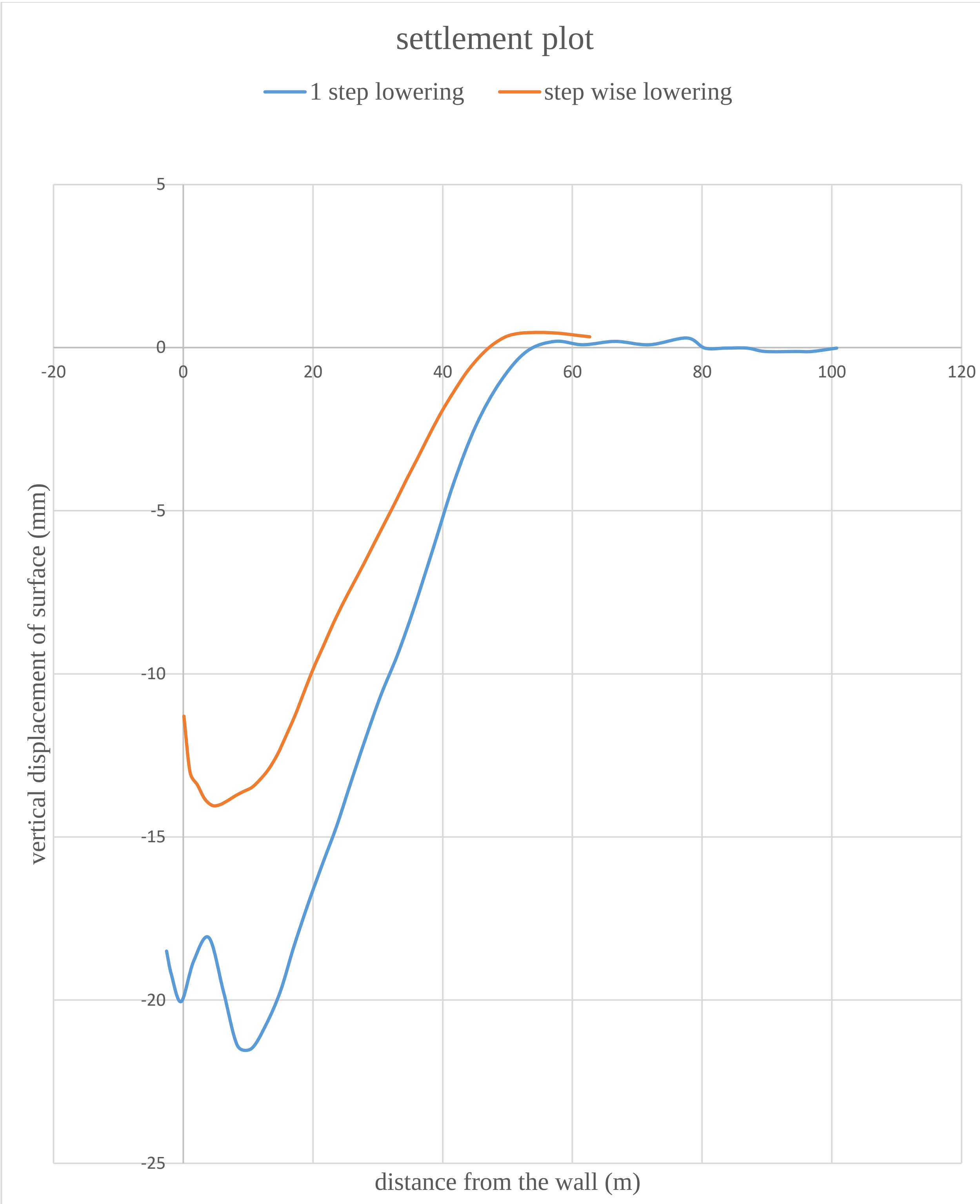

Figure 3-14: surface settlements – influence of ground water lowering

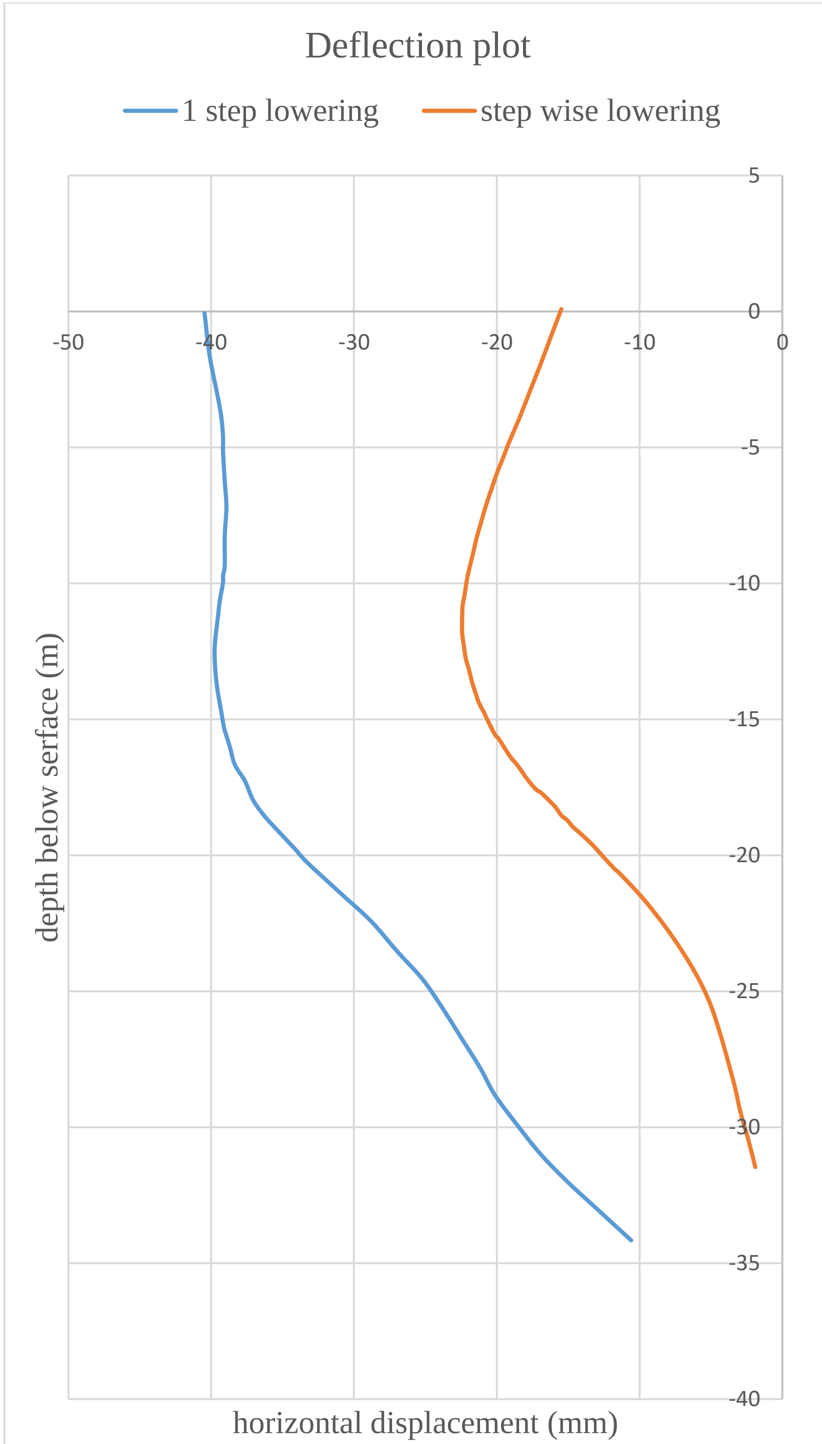

Figure 3-15: wall deflection – influence of ground water lowering

Due to the analysis results and in actual ground work the soil loses the water slowly step by step. Because of these two reasons, for this work step by step ground water lowering is adopted.

3.5.2 Influence of wall friction

In order to investigate this parameter an analysis had been performed by changing R_{inter} from 0.5 to 0.8.Inthis analysis the result shows that the horizontal displacement of the top of the wall decreased by approximately 32 mm and settlement behind the wall by approximately 11 m as shown in Figure 3-17 and Figure 3-16 respectively.

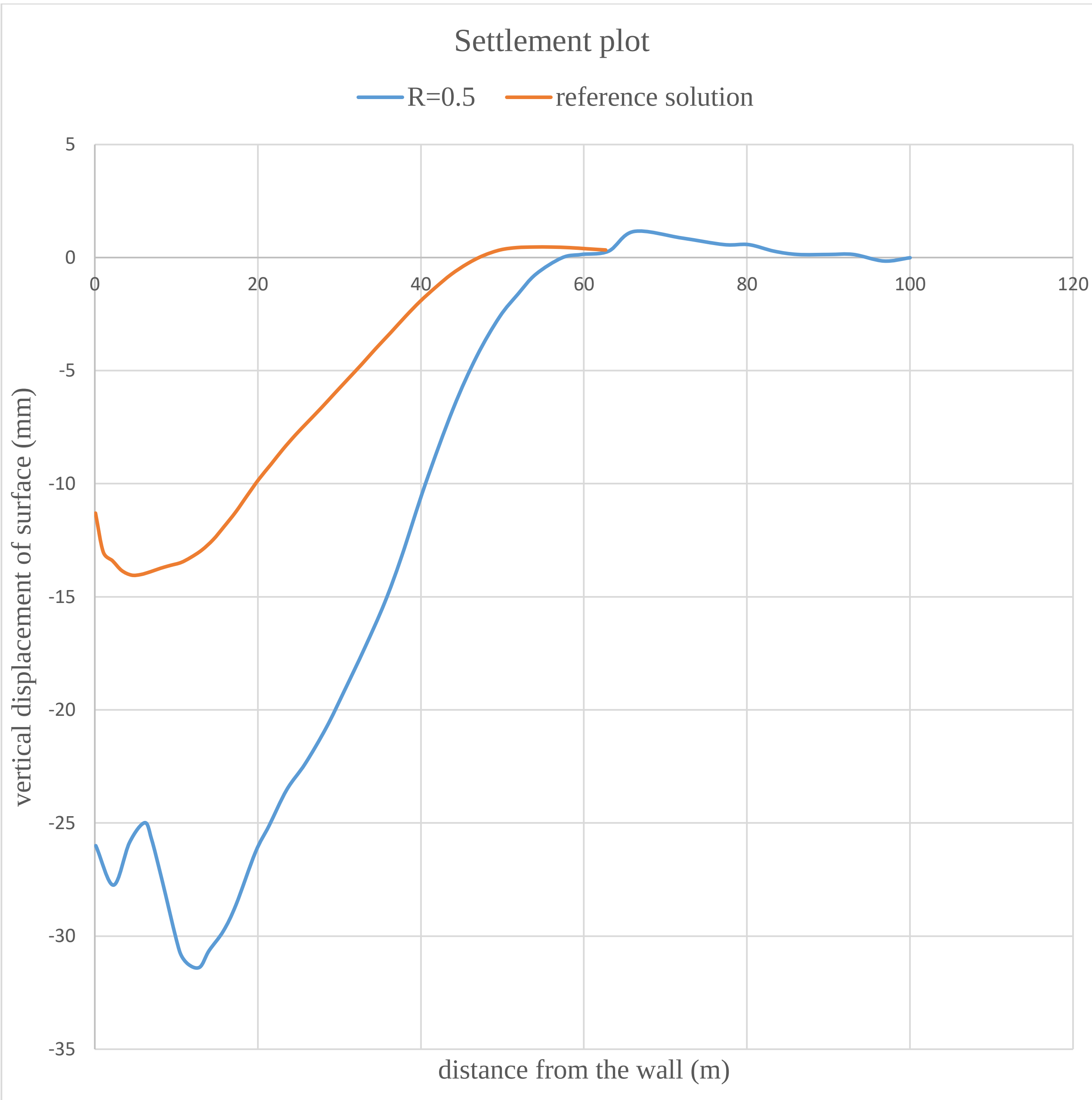

Figure 3-16: surface settlement – influence of wall friction

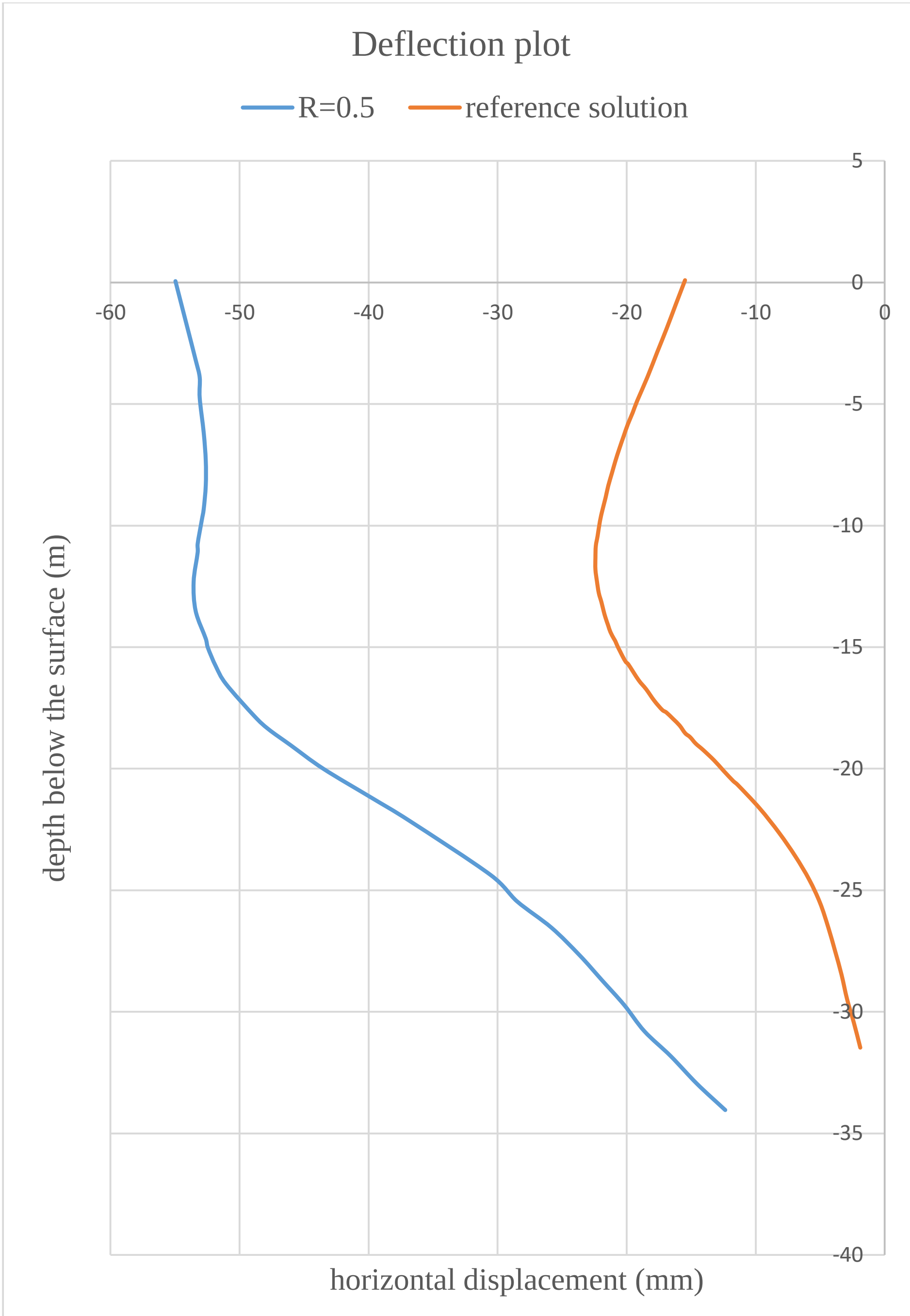

Figure 3-17: wall deflection – influence of wall friction

For this thesis the value of the interface was assumed based on the analysis result and other literatures which performed their analysis using FLAC software.

3.5.3 Influence of discretization

For this thesis coarse mesh with 20 zones, medium mesh with 40 zones, fine mesh with60 zones and finer mesh with 90 zones horizontally are computed for the sensitivity analysis (see table 3-7).

Table 3-7: Effect of mesh size

Model	Mesh coarseness	Zones (horizontal direction)	Maximum settlement (mm)
Model 1	Coarse	20	10.4
Model 2	Medium coarse	40	12
Model 3	Fine	60	13.6
Model 4	Finer	90	14.04

The results obtained from this sensitivity analysis and FLAC online manual shows that the finer the mesh the discretization error decreases which means the results become more accurate. Because of these two reasons the finer mesh with 90 zones is adopted.

3.5.4 Influence of domain analyzed

In order to study the influence of the discretized domain the following domains are chosen for these thesis, W x D =150 x 70, W x D =150 x 100, W x D = 100 x 100, W x D = 100 x70 and W x D = 200 x 150m. As seen from figure 3-18 and figure 3-19 the surface settlement and deflection of the wall is affected by the domain analyzed.

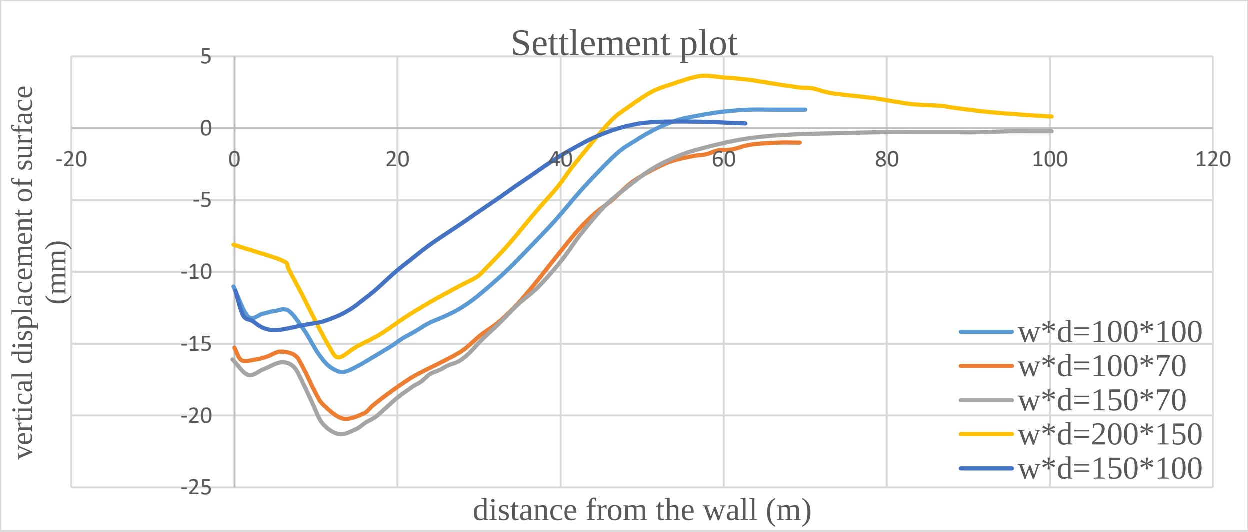

Figure 3-18: surface settlement – influence of domain analyzed

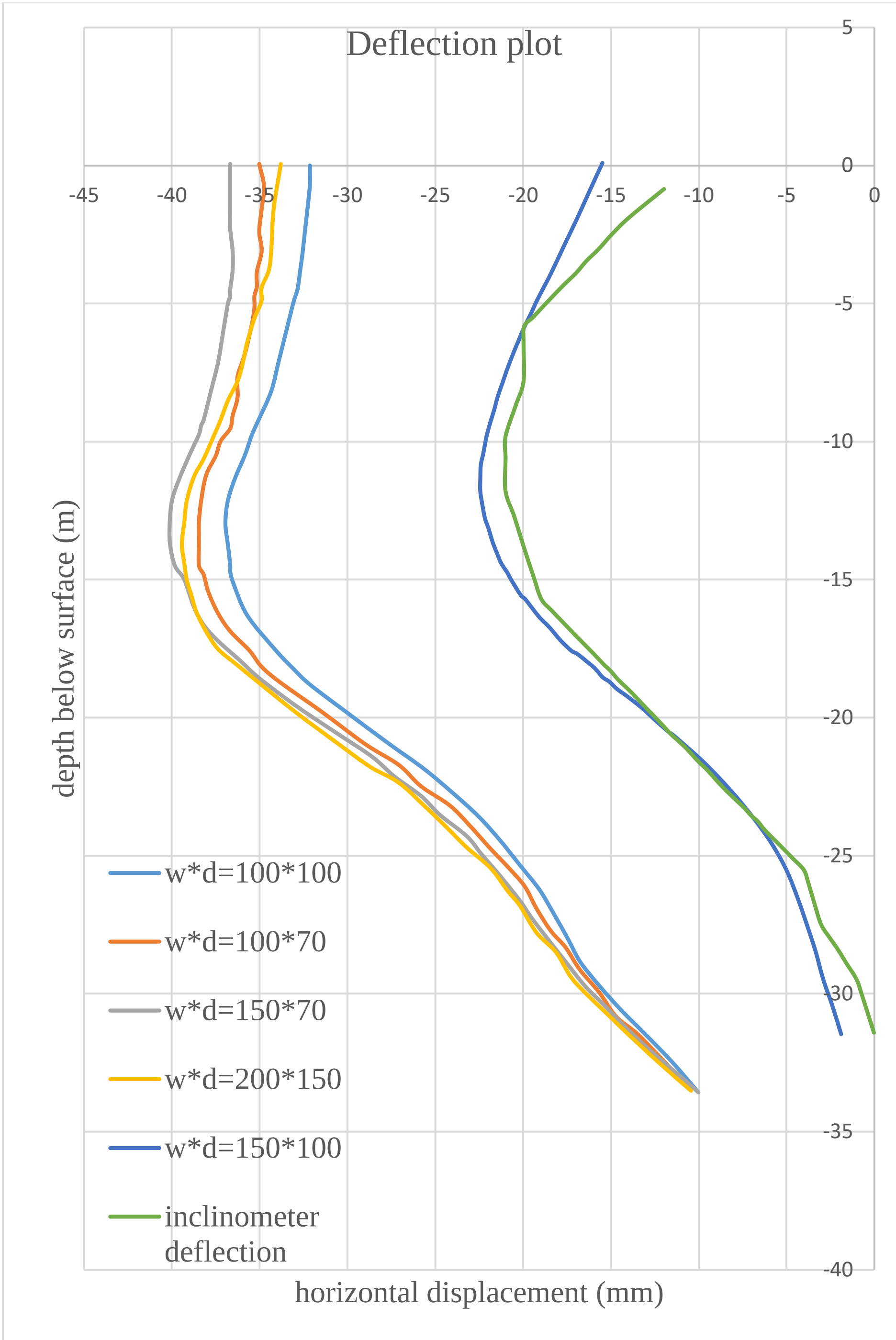

Figure 3-19: wall deflection – influence of domain analyzed

Due to the results obtained from the analysis and comparing with schweiger's (2002) analysis result, the domain W x D = 150 x 100 m gives the result close to the deflection in inclinometer. Because of the above reasons domain 150 x 100 m is adopted for this thesis and checked by getting the plasticity plot (see section 3.3.2).

3.5.5 Influence of wall thickness

In order to study this parameter a wall thickness of d= 0.8 m and d = 1.2 m was analyzed. The analysis showed that the maximum deflection and maximum settlement obtained from using a wall thickness of 0.8 cm is -22.45mm and -14.04 mm respectively. When the wall thickness changes to 1.2 cm the maximum deflection becomes -25.5 mm. So the increase in wall thickness does reduce the maximum horizontal displacement, but not significantly and surface settlement does not change much.

The results obtained from the sensitivity analysis of the wall thickens of 0.8 cm doesn't have a significant difference with 1.2 cm wall thickens. Because of the reason that the engineering designs should be both safe and economical, 0.8 cm wall thickness is adopted for this thesis.

3.5.6 Influence of variation in stiffness and strength parameters of soil

In order to study these parameters, the stiffness parameters have been varied by +/-25% and strength parameters by +/- 10% from the mostly used Berlin sand soil parameters (see section 3.2.3) respectively. In the latter case the friction angle for all layers has been varied, but the dilatancy angle has been kept same. The variation in the stiffness parameters introduced in this sensitivity analysis is by changing E_{50}^{ref}, E_{oed}^{ref} and E_{ur}^{ref} for all layers accordingly. The results shows that the large difference in calculated horizontal displacements and settlements emphasize that careful considerations are required in determine appropriate input parameters.

The result of the analysis shows that the maximum deflection for stiffness +25% and friction +10% become 5mm and 8mm less than the maximum deflection get from the mostly used Berlin sand property of stiffness and friction respectively, while -25% and -10% give greater maximum deflection by 10mm and 12mm respectively.

The result of the analysis shows that the maximum settlement for stiffness +25% and friction +10% become 5mm and 10mm less than the maximum settlement get from the mostly used Berlin sand property of stiffness and friction respectively, while -25% and -10% give greater maximum settlement by 8mm and 10mm respectively.

Due to this effect the Berlin sand soil parameters used in this thesis is adapted from PLAXIS manual and also the adapted soil parameters are also mostly used in literatures for Berlin sand.

3.6 Conclusion

The wall behavior was investigated through the wall displacement, bending moment and surface settlement. The finite difference method, FLAC was used to analyze this sheet pile wall behavior and to investigate the effect of some parameters on the model created. Influence of ground water lowering, wall friction, discretization, and domain analyzed, wall thickness and variation in stiffness and strength parameters are parameters which investigated to establish the numerical model.

It was obtained that using finer mesh grids led to more accurate results as well as being able to obtain out puts that can easily be analyzed thus leading to more qualitative results. The solution can be considered as a good approximation because care has been taken in establishing the numerical model and choosing input parameters. Due to the results obtained from the sensitivity analysis and literatures, the numerical model (see section 3.4) is established.

Validating the model is the most critical part of numerical modeling. The results of the numerical model was compared and validated with the inclinometer measurement (horizontal displacement or deflection) and with Schweiger's study (2002) (surface settlement).

The validation shows that the results are very comparable which leads to the conclusion that the numerical model is acceptable and ready to perform and investigate further parametric studies.

CHAPTER FOUR

PARAMETRIC STUDY

4.1 Introduction

This chapter of the thesis includes the investigation of the influence of some parameters on anchored sheet pile wall. The parameters are: anchor inclination, grouted body length with pre stressed and not pre stressed anchors, grouted body area, number of anchors and construction procedure with the pre-stressed anchor.

The investigation takes place using a finite difference program FLAC.

4.2 Analysis and results

It is concluded from parametric studies that all parameters pertaining to sheet pile walls system in this study have a significant effect on the behavior of the structure. In the following sub sections the results of these analyses in terms of wall deformations and wall bending moments obtained from different parameters is presented.

4.2.1 Study of the influence of the construction procedure

For the study of the influence of the construction procedure a range of cases has been considered. The aim is to recognize a trend in the relation between the stages followed, the bending moment and wall movement. This parameter is studied because location of grouted anchor from ground surface is one of the most important factors affecting the behavior of the anchored sheet pile walls. The methodology consists of the following steps.

a) Represent the geometry of the model which permits a staged excavation.
b) Installation of the anchors when the anchor level is reached in the excavation.
c) Steeply increase the excavation depth before placing the anchors and applying the load.

Cases considered for the study of construction procedures are stated in Table 4-1.

Table 4-1: Cases considered for the study of construction procedure

Cases	Excv1 (m)	% excv1	Anchor1 (m)	Excv2 (m)	Anchor2 (m)	Excv3 (m)	Anchor3 (m)
Case1	2	12 %	1	6	5	11	10
Case2	3	18 %	2	7	6	12	11
Case3	4	24 %	3	8	7	13	12
Case4	4.8	29 %	4.3	9.3	8.8	14.35	13.85
Case5	7	42 %	6	11	10	16	15
Case6	8	48 %	7	12	11	16.8	16
Case7	9	54 %	8	13	12	16.8	16

Table 4-2 results for construction procedure cases shows the results for 7 cases considered. The maximum horizontal displacement is minimum for the case 4 and maximum for the case 7.

Table 4-2: Results for construction procedure cases

Cases	% excv (%)	Max. U_x (mm)	Max. M (kN.m)
Case 1	12	-41.62	1840
Case 2	18	-38.09	1565
Case 3	24	-35.71	1251
Case 4	29	-22.45	762
Case 5	42	-68.63	-929.7
Case 6	48	-121	-1167
Case 7	54	-200.1	-1523

The construction procedure of anchored sheet pile walls has a critical influence over the movement of the wall, particularly at the top. The later the anchors are placed and pre-stressed, the more deflection occurs in the wall, and so large movements are registered at the top. The maximum horizontal displacement is not located at the top of the wall but in a certain depth. As the anchors applied proportional to the excavated height a minimum value of maximum horizontal displacement and maximum bending moment is registered, this is seen in case 4, but as the anchors introduced disproportional to the excavated depth like when the more height is not anchored at the top or at the bottom as seen at case 7 and case 1 the maximum bending moment and horizontal displacement become high.

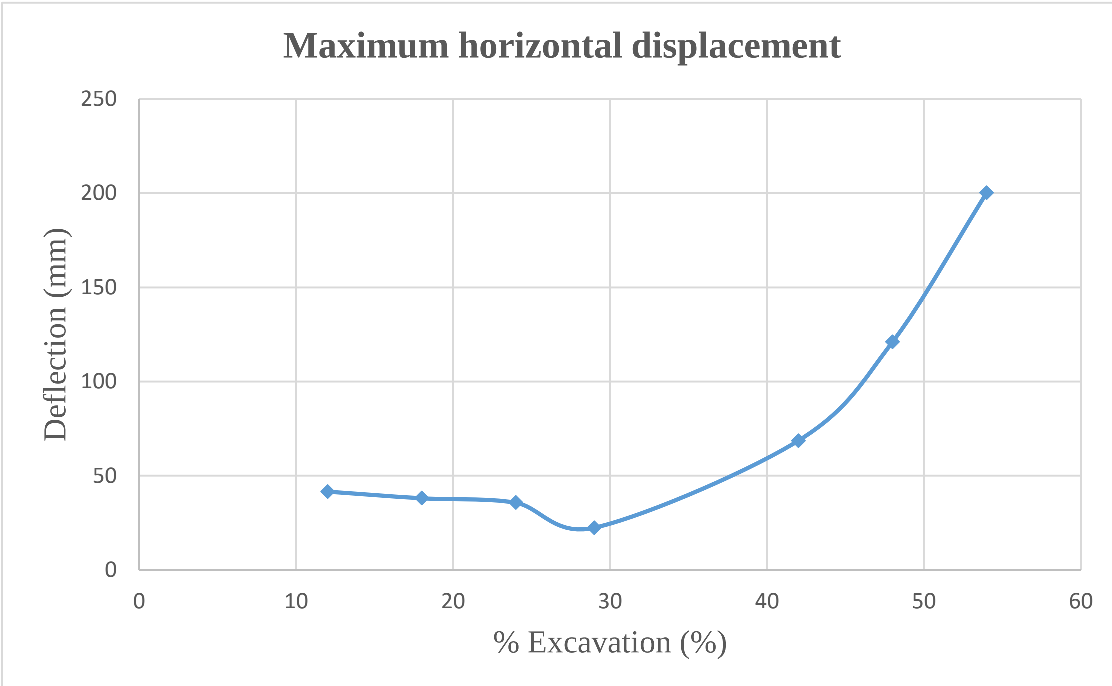

Figure 4-1: maximum horizontal displacement for the 7 cases considered

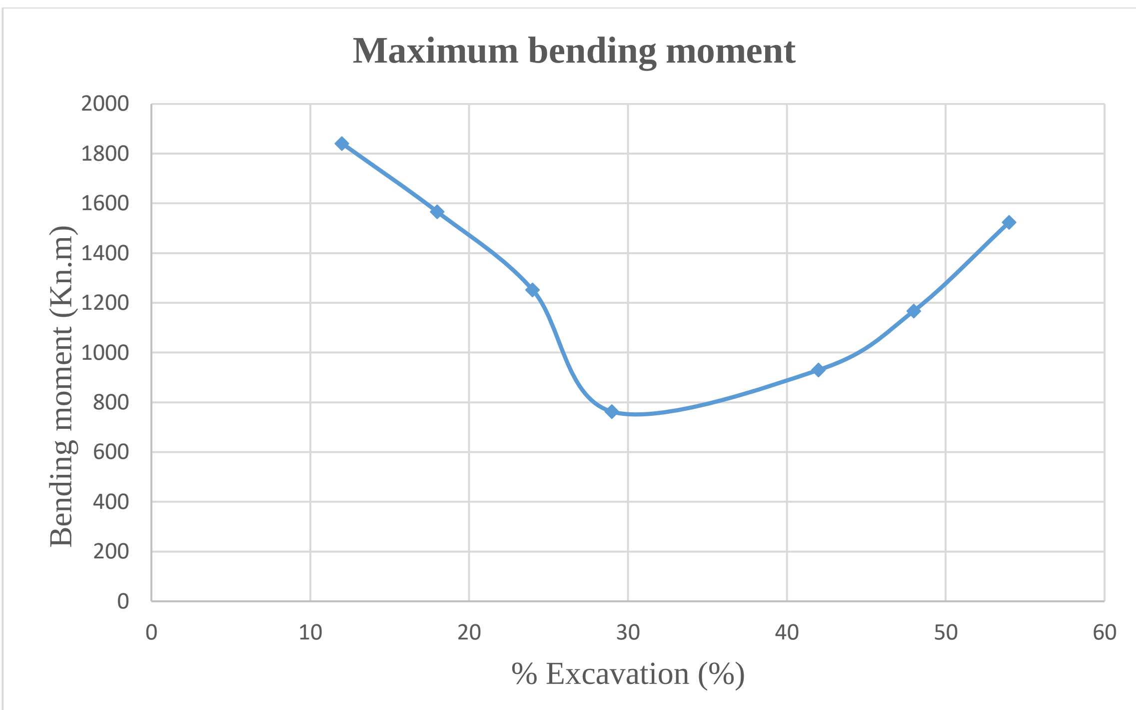

Figure 4-2: maximum bending moment for the 7 cases considered

As seen from table 4-2 and figure 4-1 and also figure 4-2, both the bending moment and the deflection decrease up to case 4 and increase after that. This shows that for this type of problem the anchor location has high effect and also the deflection and the moment is greater when the more excavation takes place the higher the deflection and moment.

4.2.2 Influence of the number of anchors

For this parameter, cantilever, single, double and triple anchored were studied as shown in table 4-3. It is common to put the first anchor at the top of the wall on the depth greater or equal to 0.2H to control the top movement of the wall (where H is the retained depth above the dredge level) (Das, 2010). The geometry and properties used for this analysis is described in chapter 3.

Table 4-3: Comparison between the results for cantilever, single, double and triple row anchors

Cases	Number of anchor	Max. U_x (mm)	Max. M (KN.m)
Cantilever	----	-2659	12830
Single row	1	-123.2	2925
Double row	2	-43.72	1884
Multi row	3	-22.45	762

The results shows that using single row anchor reduces the maximum bending moment by77.2% and the maximum deflection decreases by 95.4%, using double row anchor reduces the maximum bending moment by 85.3% and decreases the maximum deflection by 98.4%, using triple row anchor reduces the maximum bending moment by 94.1% and decreases the deflection by 99.2% than using cantilever sheet pile walls.

4.2.3Influence of grouted anchor inclination (α)

To represent the effect of the grouted anchor inclination on the internal forces of this type of structure, six values of α were studied, (α = 0°, 9°, 18°, 27°, 36° and 45°). The other parameters of the model were kept constant.

Figure 4-3 and 4-4 present the effect of the grouted anchor inclination on the internal forces of the structure. The result shows that an increase of α up to 27° leads to a decrease in the maximum bending moment and horizontal displacement of the wall. After that by increasing the anchor inclination α, the maximum bending moment and the horizontal displacement increases.

These observations indicate that, for this case study, increasing the angle of inclination α up to 27° enhance the performance of the structure and generally improve the efficiency of the wall.

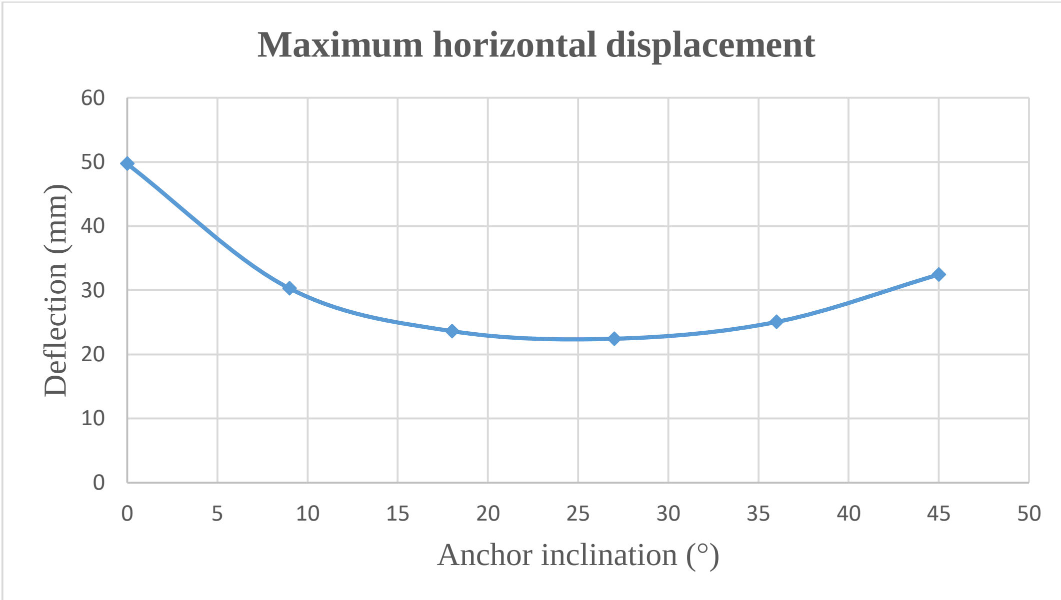

Figure 4-3: Maximum horizontal displacement versus anchor inclination degree

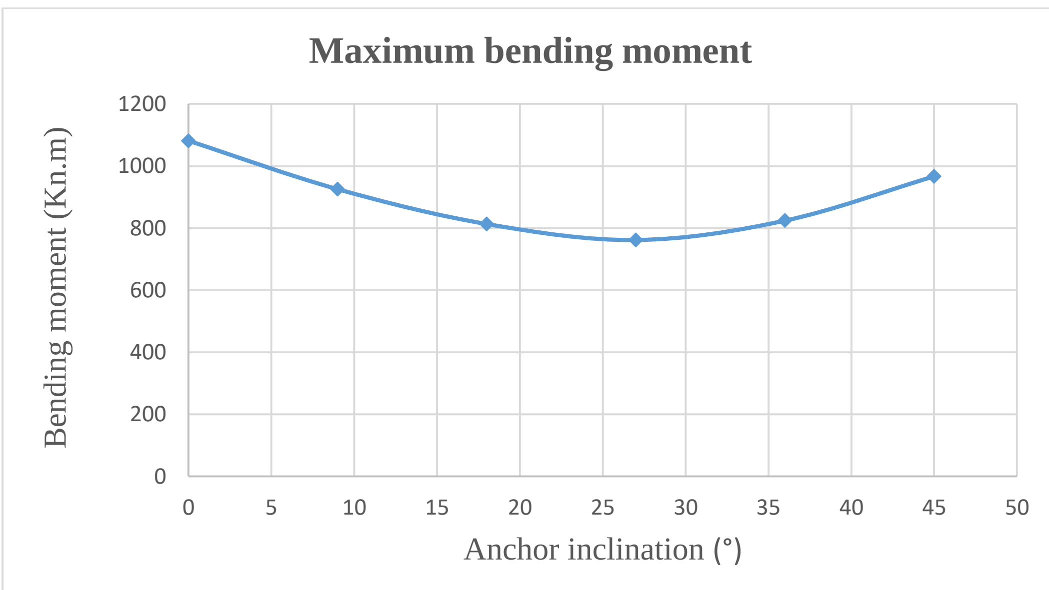

Figure 4-4: Maximum bending moment in sheet pile versus anchor inclination degree

4.2.4 Influence of grouted body area (A_g)

Using grouted anchors in the enhancement of sheet pile wall leads to a considerable reduction in the maximum bending moment and maximum horizontal displacement of the sheet pile wall. To study the effect of grouted body area on the enhancement of the structure, six different values of A_g were examined (D = 10, 20, 30, 43.7, 50 and 60 mm). The other parameters of the model were kept constant.

Table 4-4 summarizes the results of different values of grouted body area, A_g increased, the maximum bending moment decreased. Similarly, the maximum horizontal displacement will decrease with the increase of A_g. This enhancement could be caused by the grouting ties area, which helps to increase the overall stiffness of the structure and thus decrease the internal forces induced in the sheet pile wall system.

Table 4-4: Summary of effect of grouted body area on sheet pile wall

Cases	**Diameter (mm)**	**Max. U_x (mm)**	**Max. M (Kn.m)**
Case 1	10	-31.38	910.6
Case 2	20	-26.59	823.6
Case 3	30	-24.27	785.1
Case 4	43.7	-22.45	762
Case 5	50	-21.99	749
Case 6	60	-21.23	746.7

4.2.5 Influence of grouted body length (L_g)

The location of the critical potential failure surface must be evaluated since the anchor bond zone must be located sufficiently behind the critical potential failure surface so that load is not transferred from the anchor bond zone into the “no-load” zone. For walls constructed in cohesion less soils, the critical potential failure surface can be assumed to extend up from the corner of the excavation at an angle of 45° +Φ/2 from the horizontal (i.e., the active wedge) (Sabatini, P.J., 1999). To study the effect of grouted body length to the behavior of the structure, six different values of L_g were considered (L_g = 2, 4, 6, 8, 10 and 12 m) for each pretension and not pretension row of anchors.

Table 4-5 presents the results of different values of grout length L_g for not pre stressed anchors. From these results, it can be noticed that the increase of L_g enhances the performance of this type of sheet pile walls. Also, it reduces the maximum bending moment and horizontal displacement of the sheet pile wall. These observations indicate that increasing the grout length, L_g leads to increase in fixity of the structure and then enhances the performance of the wall. The results also show that the reductions in the internal forces are not significant when the grout length, L_g is greater than 8 m.

Table 4-6 presents the results of different values of grouted length for pretension anchors. The results show that increasing the values of L_g will increase the maximum bending moment and horizontal displacement of the sheet pile wall. These observations indicate that increasing the grout length leads to decrease of fixity of the structure and then decrease the performance of the wall. The result also shows that the increase in the internal force is not significant up to 8 m grout length.

Table 4-5: Summary of the effect of grouted body length for not pre stressed anchors on the sheet pile wall

Grouted body length L_g (m)	**Maximum deflection (mm)**	**Maximum moment (KN.m)**
2	-87.43	-1629
4	-81.44	-1619
6	-75.52	-1558
8	-70.5	-1509
10	-68.23	-1473
12	-66.39	-1463

Table 4-6: Summary of the effect of grouted body length for pre stressed anchors on the sheet pile wall

Grouted body length L_g (m)	**Maximum deflection (mm)**	**Maximum moment (KN.m)**
2	-17.69	715.3
4	-18.22	742.5
6	-20.30	751
8	-22.45	762
10	-25.48	782
12	-29.07	816.1

4.3 Conclusion

A numerical study using finite difference analysis was conducted to investigate the effect of grouted body area, length of grouted body, anchor inclination, number of anchors and construction procedure on the behavior of multi – anchored sheet pile walls. Based on the results of present parametric study, several conclusions can be drawn; the rehabilitation of sheet pile walls using additional grouted tie-rods has a significant role on the performance of sheet pile wall systems. The anchored wall system and surrounding soil show more stabilized behavior when the grouted anchors are used. The maximum bending moment and horizontal displacement occurring along the sheet pile wall have been considerably reduced by the increasing the pertaining parameters of the system but obviously, this leads to an increase of the maximum original anchor force. Therefore, a trade-off is required to balance the increase of original anchor force and the reduction of maximum bending moment and horizontal displacement. Results also show that the grouted anchor inclination and the number of anchors has a great effect on the system's performance and the anchor's inclination up to 27° increases the performance enhancement of the system. furthermore, the optimal length of the grouted anchor, in this case study, is in the range between 6 m and 8 m. and also pre stressing anchors reduces the deflection and moment of the sheet pile wall significantly than the not pre stressed anchors. So pre stressing anchors is recommended before applying the anchors on the sheet pile walls.

CHAPTER FIVE

DISCUSSION AND CONCLUSION

6.1Discussion

As seen in section 3.5 of the thesis and from registered results of previous studies, the influence of ground water lowering by taking one step lowering and step wise lowering cases, the influence of wall friction by taking R_{inter} of 0.5 and 0.8 cases, influence of discretization by taking coarse, medium coarse, fine and finer cases, influence of domain analyzed by taking width * depth (W*D) of 150m*70m, 150m*100m, 100m*100m, 100m*70m and 200m*150m cases, influence of wall thickness by taking 0.8 m and 1.2 m cases and influence of variation in stiffness and strength parameters of soil by taking the stiffness parameter +/-25% and the strength parameter +/-10% from the mostly used Berlin sand soil parameters is studied and checked for their convergence and used for the analysis.

It was obtained that using finer mesh grids led to more accurate results as well as being able to obtain out puts that can easily be analyzed thus leading more qualitative results. The analysis is claimed that the solution can be considered as a good approximation because care has been taken in establishing the numerical model and choosing input parameters. Due to the results obtained from the sensitivity analysis and literatures, the numerical model (see section 3.3) is established and validated as seen in section 3.4 and the CY Plastic soil model is used for modeling the Berlin sand soil, the calculated surface settlement increased approximately 6 mm for the first stage to over 14 mm to the final stage, which also can be considered possible result and also the calculated horizontal displacement is actually very close to the measured horizontal displacement using inclinometer.

The validation shows that the results are very comparable which leads to the conclusion that the numerical model is acceptable and ready to perform and investigate further parametric studies as seen in chapter 4. Due to this reason a numerical study using finite difference analysis was conducted to investigate the effect of grouted body area, length of grouted body, anchor inclination, number of anchors and construction procedure on the behavior of multi – anchored sheet pile walls. Based on the results of present parametric study, several conclusions aredrawn; the rehabilitation of sheet pile walls using additional grouted tie-rods has a significant role on the performance of sheet pile wall systems. The anchored wall system and surrounding soil show more stabilized behavior when the grouted anchors are used. The maximum bending moment and horizontal displacement occurring along the sheet pile wall have been considerably reduced by the increasing the pertaining parameters of the system but obviously, this leads to an increase of the maximum original anchor force. Therefore, a trade-off is required to balance the increase of original anchor force and the reduction of maximum bending moment and horizontal displacement. Results also show that the grouted anchor inclination and the number of anchors has a great effect on the system's performance and the anchor's inclination up to 27° increases the performance enhancement of the system. furthermore, the optimal length of the grouted anchor, in this case study, is in the range between 6 m and 8 m. and also pre stressing anchors reduces the deflection and moment of the sheet pile wall significantly than the not pre stressed anchors. So pre stressing anchors is recommended before applying the anchors on the sheet pile walls as seen in chapter 4 of this thesis.

Based on this thesis result and also the ones which is shown in 2002 schweiger's report it is argued that there is a strong need for defining guide lines and procedures to achieve at a reliable numerical models in practical geotechnical engineering.

6.2 Conclusion

A series of numerical studies using finite difference analysis were conducted to investigate the behavior of anchored sheet pile walls. The effect of several parameters on the wall and lateral deflection and bending moment of the structures was investigated. The parameters considered were; anchor inclination, grouted body length, grouted body area, number of anchors and construction procedure. Based on the results of this study several conclusions are drawn:

1. It was found that finite difference based program, FLAC is a powerful tool for investigating the behavior of a stabilized wall by soil anchorage and sheet pile wall.
2. The maximum bending moment and horizontal displacement occurring along the sheet pile wall have been considerably reduced by increasing pertaining parameters of the system (the grouted body area, number of anchors and length of grouted body for not pre stressed anchors), this leads to an increase of the maximum original anchor force. Therefore, a trade-off is required to balance the increase of original anchor force and the reduction of maximum bending moment and horizontal displacement.

3. For pre stressed anchors increasing length of grouted body length results in increasing the maximum bending moment and also horizontal displacement which shows the decrease in fixity of the structure which also mean a decrease in performance of the structure because of a decrease in anchor force. Therefore, a trade-off also required here to balance the decrease in original anchor force and the increase in maximum bending moment and horizontal displacement.
4. For deep excavation up to 16.8m, it is recommended to use two-rows of anchors to reduce the maximum horizontal displacement and maximum bending moment which may be practical and economical for wall of height 32 m.
5. The grouted anchor inclination has a significant effect on the anchored sheet pile wall system performance and an inclination up to 27° increases the performance stability of the system for this study.
6. The construction procedure of anchored sheet pile walls has a critical influence over the movement of the wall. When the anchors introduced at a proportional location with the excavated depth of the sheet pile wall, the registered maximum bending moment and maximum horizontal displacement become a minimum value.
7. The results illustrate that the elastic perfectly plastic constitutive models such as the Mohr-coulomb model are not well suited for analyzing deep excavation problems and more advanced models are required to obtain realistic results. Strain hardening plasticity models are in general a better choice.
8. The Cap-Yield Plastic soil model provided a competent result. This was directly due to the model's incorporation of deviatoric and volumetric hardening mechanisms, stress-path dependent stiffness, soil dilatancy and the expansion or contraction of the yield surface with respect to plastic straining.

6.3 Recommendation

The present study can be developed and refined and a deeper study in this specific subject would be of great interest. It would also be preferable to perform field measurements in order to determine the real behavior of the sheet pile wall. Therefore, by comparing the measured field results with the various constitutive models a better understanding of the behavior of these anchored sheet pile walls will be conclude and also will help in formulating a guideline and recommendations on how to model typical geotechnical problems in practice.

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