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STUDY OF DEFORMATIONS IN SHEET PILES UNDER THE INFLUENCE OF DIFFERENT VARIABLES

Hayder Hasan Ali ALI

Master's Thesis

Supervisor

Assoc. Prof. Dr. Sepanta NAİMİ

Istanbul, 2023

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The thesis titled STUDY OF DEFORMATIONS IN SHEET PILES UNDER THE INFLUENCE OF DIFFERENT VARIABLES prepared by HAYDER HASAN ALI ALI and submitted on 10/04/2023 has been **accepted unanimously** for the degree of Master of Science in Civil Engineering

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I hereby declare that all information presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Hayder Hasan Ali ALI

Signature

DEDICATION

First and foremost, I would like to thank God for inspiring me and giving me the ability, patience, and faith to do and finish this modest work.

Besides, I would like to express my sincere gratitude to my advisor Assoc. Prof. Dr. Sepanta NAİMİ, and my Co-Supervisor Dr. Ahmed Al-Janabi for their continuous support, encouragement, enthusiasm, distinctive perspective, and immense knowledge on the research of my M.Sc. study. their guidance helped me in all the time research. I could not have imagined having a better advisor and mentor for my M.Sc. study.

My sincere thanks also go to my father's soul, my great mother, my brother Yousif, my sisters, my lovely wife Marwah, and my children for supporting me spiritually throughout my academic pursuits and my life in general.

PREFACE

This study aims to develop better procedures and research ideas in our countries, as well as design tools to help future generations overcome access constraints.

I could not have reached my current level of success without the assistance of a strong support network. First and foremost, I want to thank my family for their love and understanding. Second, my supervisor, who has advised and guided me throughout the study process.

Thank you for your unending support.

ABSTRACT

STUDY OF DEFORMATIONS IN SHEET PILES UNDER THE INFLUENCE OF DIFFERENT VARIABLES

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Due to the trend toward building tunnels, roads, parking garages, and most of the services, it has become necessary to study the methods of supporting the soil and know the quality of the loads and stresses that affect the supporting panels and what deformations can occur on these panels and how they behave. The goal of this research, which focuses on theory and application, is to help geotechnical engineers worldwide choose and use the finest modelling tools, thereby bridging the gap between theory and practice. Utilizing the program PLAXIS 2D, analyzing the distortions to which he is subjected in the sheet pile is crucial to comprehending the geotechnical behavior of the soil on the panels. Additionally, different mathematical relationships can be obtained by altering the levels of study, such as soil type and characteristics, locations for installing sheet piles, excavation depth, groundwater level, and others, to study one or more of these variables and their effects on the design.

This thesis investigated the behavior of the cantilever and anchorage sheet pile under the influence of various factors. Among the most important factors investigated were dredge level, water table level, the distance of anchors from the ground surface, the distance between anchors, and the number of anchors. Sheet pile and different levels of these variables mentioned know the deformations in the sheet pile under these factors and variables where this study uses different types of soil with different degrees of saturation. The main focus of this thesis was on calculating the bending moments resulting from the difference of these factors in the case of the constant load imposed on the soil using a computer program called PLAXIS 2D Connect Edition v20, which is based on the theory of finite elements and is used to determine the behavior of sheet piles by studying horizontal displacements, maximum bending moments, and driven depth of two types of sheet piles, cantilever and anchorage sheet piles. Also, compare these results to those of the PROSHEET program to get more reliable and realistic results.

Keywords: Deformations, Sheet Piles, Plaxis 2d, Prosheet, Variables.

TABLE OF CONTENTS

Pages

LIST OF TABLES

Pages

LIST OF FIGURES

Pages

ABBREVIATIONS

p	:	Plastic Strains
H	:	The Free Height of the Sheet Pile
D_O	:	The Penetration Depth of the Cantilever Sheet Pile
D_1	:	The Penetration Depth of the Anchored Sheet Pile
y	:	The Distance Between the Ground Surface and the First Anchor
S	:	The Distance Between the First and the Second Anchor
Le	:	The Effective Length
Lg	:	The Grouted Length

LIST OF SYMBOLS

φ	:	The Friction Angle of the Soil
τ	:	The Shear Strength
γ_{dry}	:	Soil Dry Unit Weight
γ_b	:	Soil Unsaturated Unit Weight
γ_{sat}	:	Soil Saturated Unit Weight
c	:	Cohesion
E	:	Young’s Modulus
υ	:	Poisson’s Ratio
(Kx, Ky)	:	Permeability
Ψ	:	Dilatancy Angle
R_{inter}	:	Strength Reduction Factor Inter
H	:	Depth
K_o	:	Coefficient of Earth Pressure
I	:	Moment of Inertia
A	:	Area

1. INTRODUCTION

1.1. GENERAL

The world’s population is constantly increasing. This increase requires developments and expansions in various fields to be accommodated. There may be a need to figure out how to distribute food and water as part of this issue. In other words, more provision is required for various services such as energy, electricity, fuel, internet, and sanitation. It may also seek to provide more infrastructure, such as roads, bridges, garages, parking lots, and subways, as well as train stations, housing, and administrative facilities, in order to be able to cover this increase[1-4].

Civil engineering plays a crucial role in these developments and expansions. Due to urban progress in general and the limited spaces in the existing cities, they need to be developed. The required flats and horizontal expansions may not always be available. So, the best alternative solution is vertical expansion. Vertical expansions mean dealing with the layers of the earth and soil at various depths or great heights.[5-7]

Soil mechanics engineering is the field concerned with the study of soils and their breakdown and subsidence and their effects on structures. It is also the field of access to safe facilities for economic purposes and preserving human lives. It is also concerned with the soil support methods, the soil’s ability to deal with different loads, and finding a solution to the deformations that can occur to all supporting structures.[8-12]

One of the most important of these supports is sheet piles, as shown in Figure 1.1, which are defined as one of the types of supporting structures and are used in supporting the sides of the excavation to protect the work area from the collapse of the surrounding soil. There are different types used in areas where the soil is saturated with water or in ports, or it can be reused more than once in the case of temporary use. The sheet pile wall is the magic solution for supporting the foundations, as it does not require large areas. Besides, it is designed to resist bending and shearing.[13-16]

Computer programs such as PLAXIS 2D are one of the most crucial geotechnical analysis programs used in soil mechanics applications, including the attribution of drilling aspects. It aims to analyze and design two-dimensionality to study the deformation and stability of the pillar panels, the various variables, and their impact on these panels and find appropriate solutions to such problems. Researchers in soil mechanics engineering seek to study all the conditions that can affect the sheet piles and how to deal with them or develop a plan to deal with them when they occur.[17-20]

Figure 1.1: Sheet Piles.[13]

1.2. HISTORY OF SHEET PILES

Larsen Pyle, chief engineer in Germany in the early nineteenth century, made history in his hometown of Berlin, where he invented the sheet pile to protect the excavation’s sides from landslides and floods. It was used in Germany and changed over time until it had a U-shaped shape and was connected. This shape became known as the Larsen sheet pile (Figure 1.2 and Figure 1.3).[21-25]

This fundamental invention spread throughout Europe very quickly. Many facilities and projects have not been completed due to the collapsed cases in the soil. Thus, Larsen’s invention was a lifeline and a cornerstone in dealing with one of the biggest soil problems.[26-28] The methods of sheet pile development continued until they reached the beginning of the nineties, a period of a paradigm shift in construction. It was the same period in which advanced methods were used in sheet piles in Poland, where they became easy to design, quick to implement, and safe. It has recently been developed and is used in tunnels and excavations for communications projects and for supporting dam and railway projects. It is used in the biggest tunnelling and drilling projects in Holland, Germany, Denmark, Japan, and other places.[29-32]

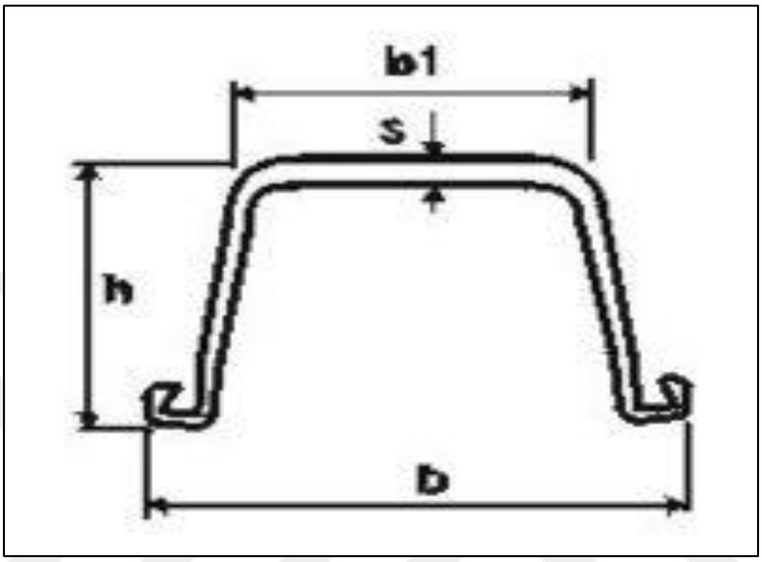


Figure 1.2: Cross Section of Larassan Sheet Piles.[21]

Figure 1.3: Sheet Piles as Foundation Elements – Overbridge in Swarzędz.[25]

1.3. PROBLEM STATEMENT

Due to the continuous urban progress and the lack of spaces allocated for horizontal expansion, the trend has become to build tunnels, roads, and parking garages. Most of the services, infrastructure, and metro roads prevent soil erosion, subsidence and collapse. The collapse of these facilities, as well as its impact on the structures above the surface of the ground (buildings and others), may lead to as a result of enormous human and economic losses.[33-36]

It became necessary to study the methods of supporting the soil and know the quality of the loads and stresses that affect the supporting panels, what deformations can occur on these panels, and how they behave. In addition, it is essential to study the locations of the necessary supports, the locations and the quality of the sheet piles used to install these panels and predict these behaviours to prepare an integrated design that meets all requirements to provide a significant economic cost. Moreover, it enriches scientific research in universities by highlighting the most critical factors affecting the calculation of this type of distortion and understanding the best ways to be followed when carrying out these works to obtain the highest quality and lowest cost.

1.4. METHODOLOGY OF STUDY

Only the development of user-friendly software and the global adoption of personal computers has led to the widespread usage of computers in engineering. One may even argue that developing (high-level) facilities without a computer is becoming more uncommon. In order to design a complex building in the best way possible, you need to use modern software and computers.[37-39]

The current research focuses on theory and application. It seeks to help narrow the gap between theory and practice by contributing to using and selecting the best modelling programs used by geotechnical engineers globally. As a result, fellow engineers will be able to use these programs and deal with the results that can be obtained from them. The study of the distortions that he is exposed to in sheet piles is very necessary. It helps understand the geotechnical behaviour of the soil on the panels by using a program called PLAXIS 2D. The program is changing the levels of study, such as soil type and characteristics, places for installing sheet piles, depth of excavation, groundwater level, and others, to obtain various mathematical relationships for studying one or more of these variables and their impact on the design. Furthermore, this thesis can study all the factors that affect the two main axes of our study: soil and sheet piles. [40]

1.5. CONTENT OF THE THESIS

The thesis topic is divided into five chapters, and references, as shown below:

i. Chapter 1- Introduction

ii. Chapter 2- Literature Review

iii. Chapter 3- Practical Section

iv. Chapter 4- Parametric Study

v. Chapter 5- Discussion and Recommendations

vi. References

2. LITERATURE REVIEW

2.1. GENERAL BACKGROUND

As mentioned earlier, a sheet pile wall is one of the most important solutions for soil support. Soil scientists and researchers strive to find the best way to create a suitable sheet pile wall design that can bear the maximum loads set on it or support all different types of soil. This is a bigger plus and important addition to important projects' foundations as a way to solve problems[41, 42].

Because the foundations are the mainstay of the establishments, everything related to them is studied. Therefore, studying the soil and its reaction or mechanism of action with the foundations helps solve recurring or expected problems. One of the keys to solving soil problems is the sheet pile wall; therefore, it was necessary to study the surrounding medium. Studying all the different factors that affect sheet pile walls. Studying different types of soil at different depths and knowing the deformations. Also being investigated are various loads, groundwater levels, and their effects at various depths. Studying the installation sites for the pile panels and the type and locations of the piles helps to know the behaviours of the sheet pile wall. So, from all of the above, in addition to the fact that other variables can be studied, it is possible to know the type of deformations, how the sheet piles behave, and the design methods to be followed to avoid failure. [43-46]

Software programs were used to make a sheet pile wall model considering all the surrounding conditions and the factors that affect this model, and thus it is possible to deduce the reaction of the sheet pile wall. Much research is being conducted to study all aspects of things. Various research and studies will be presented to learn the outcomes of various experiments and recommendations. In this chapter, this thesis will address four main headings that cover the whole topic to know the factors affecting sheet pile walls and the different methods of design, whether analytical or numerical, and the headings are as follows: [47, 48]

i. Type of sheet pile wall.

ii. Factor effect on the sheet pile wall.

iii. Deformation analysis of sheet pile wall.

iv. The behaviour of sheet pile wall.

2.2. TYPES OF SHEET PILE WALL

This study investigated the types of sheet pile walls and the applications in which the sheet pile is implemented. The study was conducted on anchored sheet pile walls, cantilevered sheet pile walls, and vertical cuts of excavation sheet pile walls. The different shapes, types, and materials from which sheet pile walls are made, whether wooden, metal or concrete, were studied. The researcher also presents an improved variant with a higher stress resistance called HAT-TYPE Sheet pile 900.[49, 50] The study's findings revealed that sheet pile applications, such as retaining walls, settlement prevention, waterway, and various water tightening, can be expanded to improve their properties. The research results also showed that steel sheet piling wall is the most common type due to its various advantages, such as low cost, flexibility in installation, ease of design, and high resistance to the loads that drive its use in other fields. (See Figure 2.1 to Figure 2.3)[19, 51, 52]

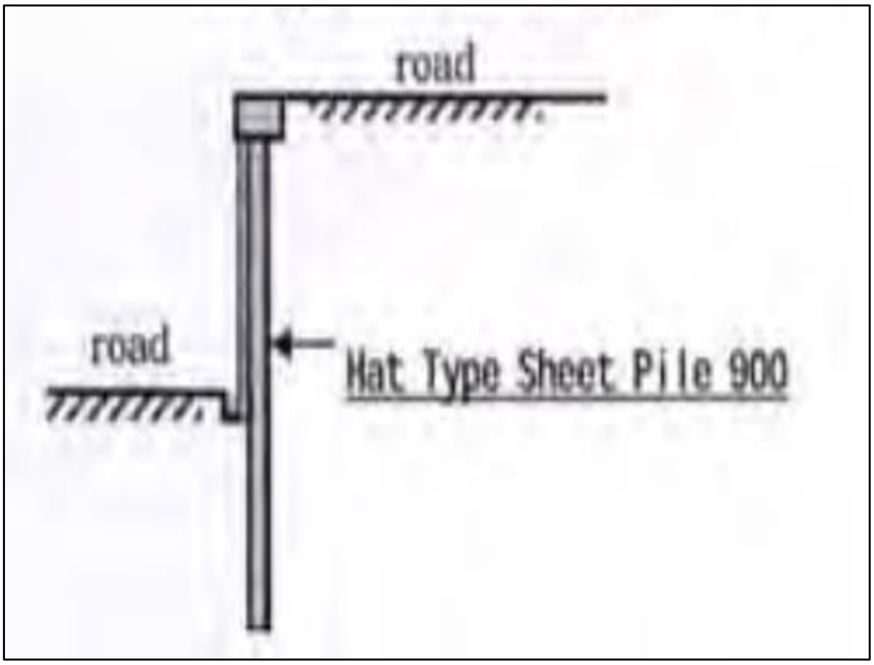


Figure 2.1: Retaining Wall for a Road. [51]

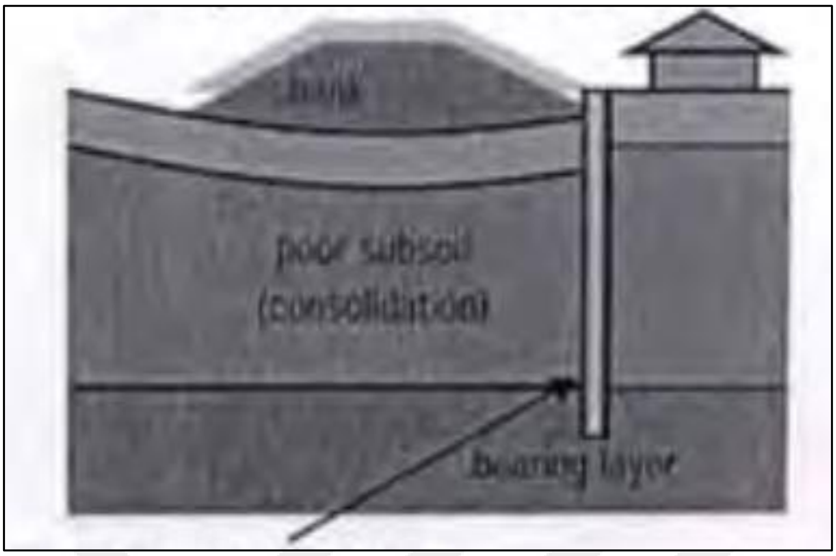


Figure 2.2: Settlement Prevention. [51]

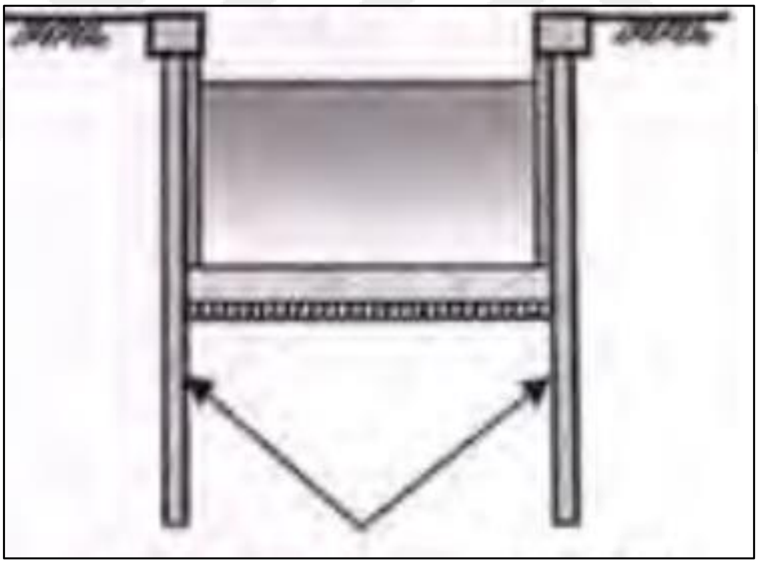


Figure 2.3: Waterway. [51]

Because of the importance of the sheet pile, it is used in many fields, perhaps beyond the fields of engineering and soil. The uses of sheet piles in general, particularly the steel sheet pile in ports and docking of ships, have been studied[53-56].

Various forms and raw materials from which they are made have been studied. The study showed two types, the first of which is the Z-shaped section, which is the most commonly used type in different applications. The second U-shaped section is very similar in use to the Z-shaped section, as shown in Figure 2.4 and Figure 2.5.[57-60]

It was used for large periods in the last century, but because of the way the sheets connected and the presence of weak points, it raised some concerns in the case of high loads. When comparing the two types, the scale swings the Z-section. This is for several reasons, the most important of which is the symmetrical corrugation around its axis, which gives greater workability and saves time and cost during installation due to the larger width of the section than the U-section.[61-63]

The study proved that the use of steel sheet piles is characterized by durability, operability, and resistance to loads with the possibility of using them in different soil conditions, the most important of which are rocky but at close depths. On the other hand, the disadvantages of using sheet pile walls are mentioned, as it is difficult to use them in permanent buildings. It cannot be used in loose or rocky soil, as it cannot be used to great depths.[64-66]

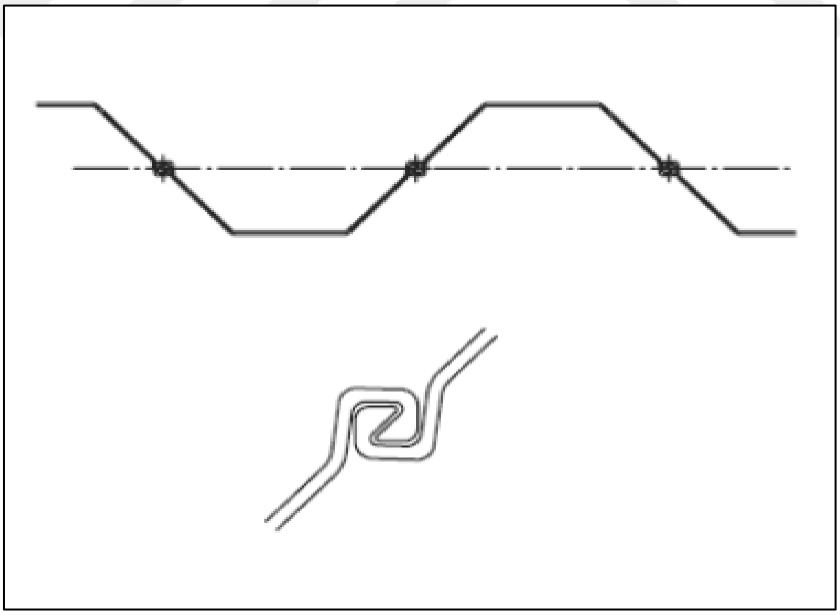


Figure 2.4: U-section Sheet Pile. [64]

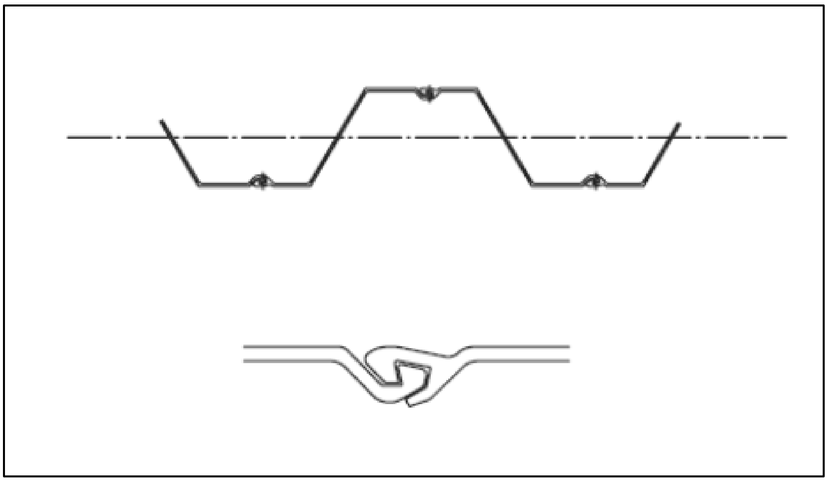


Figure 2.5: Z-section Sheet Pile. [64]

There is a real crisis in the field of mechanical engineering of the soil concerning drilling at great depths in the presence of a neighbour. Fear of soil collapse or tilting requires studying solutions to implement the required safely and stably.[67, 68]

A study was conducted to analyze and design different types of strutted shoring for sandy soil with a depth of 15 meters. The researchers used Genetic Algorithm to improve the system using the Finite Element Method. This improvement includes cost reduction, considering the specification of deformation and soil pressure. The experience has proven that the following tables are shown the sectors that purpose all the specified objectives of cost, resistance to deformation and pressure. The results proved that the best sheet pile wall is Larsen 604. While the best section for the strut is pipe No. (368). Also, the best section for a concrete diaphragm wall is Wall section No. (4).[69, 70]

Table 2.1: Sections for Sheet Pile Wall. [69]

Section No	Section Name	Width, mm	Height, mm	Back thickness	Web thickness	Inertia (cm4/m)
1	Larssen 600	600	150	10.0	9.9	4050
2	Larssen 601	600	310	8.0	6.8	12245
3	Larssen 602	600	310	8.7	8.4	13640
4	Larssen 603	600	310	10.2	8.5	19375
5	Larssen 604	600	380	10.5	9.2	31675
6	Larssen 605	600	420	13.0	9.2	43890
7	Larssen 606	600	435	14.9	9.4	55900
8	Larssen 607	600	452	19.5	10.8	73900

Table 2.2: Sections for Concrete Diaphragm Wall. [69]

Section No	Thickness cm	Length, cm	Area, cm2	Inertia (cm4/m)
1	40	100	4000	533*104
2	50		5000	1041*104
3	60		6000	1800*104
4	70		7000	2858*104
5	80		8000	4266*104
6	90		9000	6075*104
7	100		10000	8333*104
8	110		11000	11091*104

Table 2.3: Sections for Struts Pipes. [71]

Section No	Pipe No	Thickness cm	Area, cm2	Radius of Gyration (cm)
1	325	8	79.7	11.2
2	325	10	99.0	11.1
3	368	8	90.5	12.7
4	368	10	112.0	12.7
5	419	10	128.0	14.5
6	419	12	153.0	14.4
7	529	9	147.0	18.4
8	529	10	163.0	18.4

2.3. FACTORS AFFECT ON SHEET PILES WALL

A study was conducted to clarify the relationship between soil cohesion and internal friction angle and their effect on sheet pile walls, as the value of soil cohesion ranged from 70 to 280 kilonewtons per square meter. In contrast, the soil friction angle ranged from 0 to 40 degrees. A sheet pile wall with a thickness of approximately 27 mm was used. A numerical model was made, where the results showed a clear, direct relationship between soil cohesion, friction angle and excavation depth. The deviation when reaching a depth of 12 meters increased by 41%, while when reaching a depth of 16 meters, it increased by 80%.[71, 72]

Guharay conducted a study on five sheet pile wall models with a change in factors affecting them. The physical properties of this wall were studied in cases of different soil types and groundwater levels. A new parameter called the probabilistic risk factor (Rf) was proposed to study the role of factors affecting the design of sheet pile walls stably and safely. [73]

The study proved that the friction angle between the backfill and the foundation soil and soil cohesion are the main factors in obtaining a safe sheet pile wall. The groundwater level determines the optimum embedment depth, as there is a clear, direct relationship between embedment depth and the groundwater level. The lowest depth of the sheet pile wall occurs when the water is on the surface. The study also proved that non-cohesive soil is better for sheet piles than cohesive soil.[74]

On the other hand, the parameters affecting the sheet pile wall design were studied using a software program called ABAQUS/Standard. The angle of expansion and the coefficient of friction between the backfill and the foundation soil with the distribution of soil pressure on the wall and the extent of deformation that occurred in it as a result of these pressures were studied. The program's results proved that the abovementioned factors significantly impact the sheet pile wall. [75]

The relationship between the deformations in the wall and the friction angle is inverse, as increasing the angle of friction reduces the deformations. It was also shown that the soil's friction angle between 260 to 300 behaves completely differently than if the friction angle of the soil was between 360 to 460. A relationship was deduced through which the distribution of ground pressures on the sheet pile wall can be calculated more realistically, as its results can be relied upon if a quick initial picture is desired. (Figure 2.6 and Figure 2.7)[76]

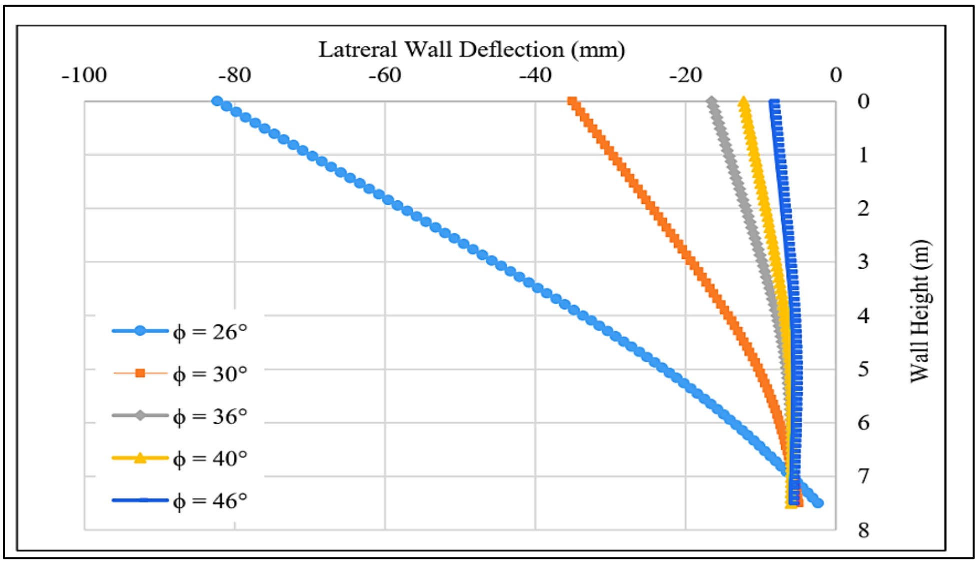


Figure 2.6: Lateral Wall Deformation.[76]

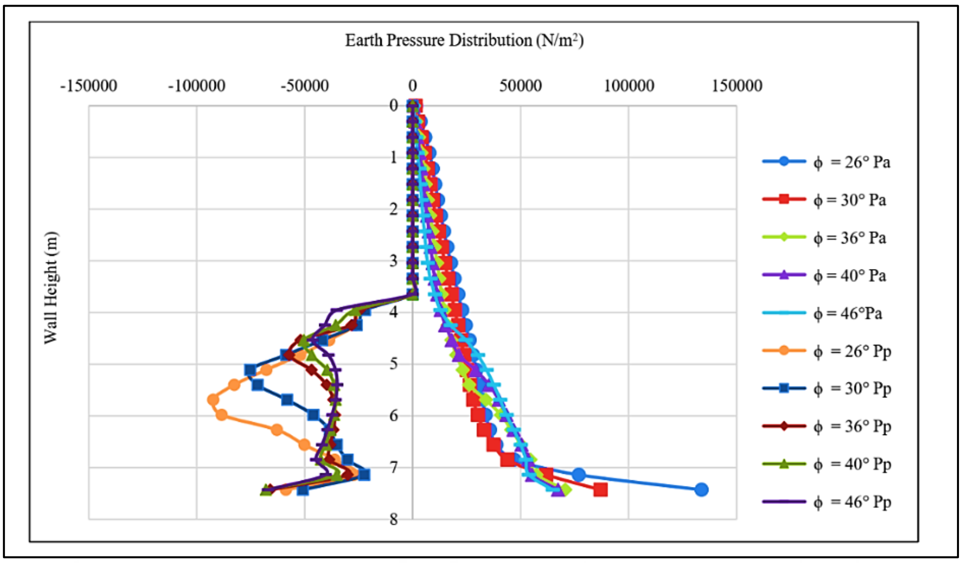


Figure 2.7: Earth Pressure Distribution from the FEA Method.[76]

In China, a study was conducted on several factors that significantly impact the mechanical properties and deformations of sheet pile walls. Twenty-eight models were made to conduct tests and analyses on retaining wall structures. The tests were conducted with and without the unloading board. The results showed that in the absence of external loads, the greater the depth of the unloading board, the more the width had a clear effect on the wall deformations. In the case of the unloading plate, it helps to reduce or prevent deformation affecting the wall. As for the presence of external loads, the unloading panel has a very shallow depth, which makes it hard for the wall's width to reduce the deformations.[77]

2.4. DEFORMATION ANALYSIS SHEET PILE WALL

A study was conducted to determine the effect of the length of sheet piles wall on the amount of bearing foundations resting on piles when affected by horizontal and vertical loads. A model was made for the deep foundations based on the piles, and they were presented to the mound and vertical loads. The results showed that the presence of 4 sheet piles around the foundations increases the bearing capacity of the foundations, as it helps to increase the foundations' bearing of vertical loads by 46 per cent. In contrast, it helps to increase the foundations' bearing of horizontal loads by 33 percent. This means that sheet piles play a significant role in improving and supporting the foundations. (Figure 2.8)[78]

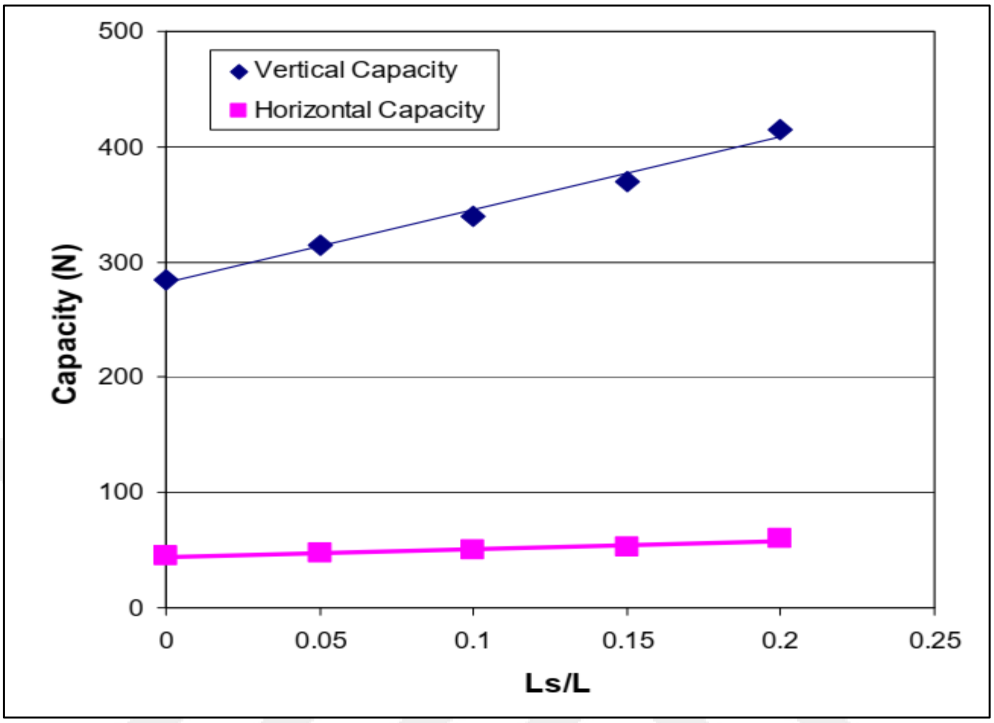


Figure 2.8: The Capacity of Improved Foundations With Different Sheet Pile Lengths. [78]

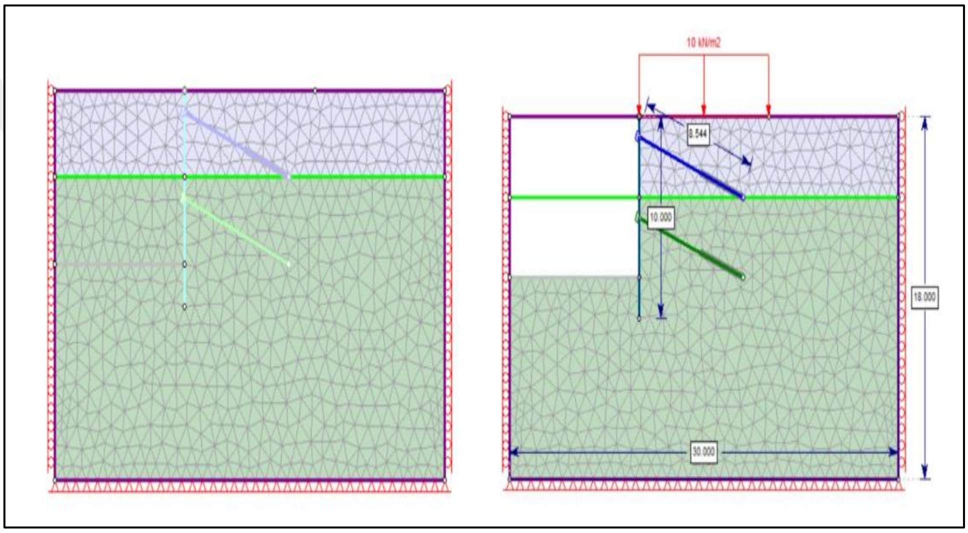
Sheet pile wall is used as soil support in excavation operations, as shown in Figure 2.9, as it is used to maintain the soil's survival and reduce the pressure expected from the ground on the foundation. For this study, a sheet pile wall model was developed for analysis. However, the problem was simulating the sliding cases between the sheet pile wall and the soil. It was necessary to find a solution to the occurrence of this slip in order to obtain real and clear results. Many studies show that the three-dimensional analysis is better than the binary analysis as it best reflects the real cases on the site.[79]

Table 2.4: Material Properties for Soil Model Stiffness Parameters. [79]

Properties	Sand	Medium Clay
Unit weight, kN/m2	20	17
Poisson's ratio	0.3	0.25
Young's Modulus, kPa	15,000	20,000

Table 2.5: Material Properties for Soil Model Strength Parameters. [79]

Properties	Sand	Medium Clay
Peak cohesion, kPa	5	10
Peak friction angle (°)	35	25
Peak tensile strength, kPa	0	0



a b

Figure 2.9: Soil Model a) Before Excavation and b) After Excavation with Anchored Sheet Pile. [79]

Due to the overcrowding, high density, and quest for expansion, there are many problems related to excavation work with the foundations. In the old areas, it may be necessary to build underground floors, and therefore it is necessary to ensure the stability of the foundations of the neighbouring facilities. It may require disposal or passage of groundwater, and therefore a sheet pile wall was the best solution to protect the foundations of the neighbourhood.

The study was conducted to develop engineering concepts for sheet pile walls that can support the soil and foundations of underground buildings. The study showed that the sheet pile wall has many advantages, as it is easy to transport and install and has no problems related to unplanned downtime. It is also low in cost and easily connected.

Despite that, it enjoys high flexibility as experiments have been conducted on dams for over a hundred years, and they enjoy the same durability. However, on the other hand, there are some concerns, as in the case of deep excavations with high density. It could cause the soil around it to collapse if the sheet pile wall cannot reach layers that are hard to dig into or problems that change as the work continues. (See Figure 2.10 and Figure 2.11)[29]

Figure 2.10: Sheet Pile Wall for Tunnel.[29]

Figure 2.11: Anchored Sheet Pile Wall for Excavation Shoring.[29]

The constant quest to study the sheet pile wall makes researchers search for the best way to analyze its behaviour. There is a team that seeks the traditional analytical study, and there is another team that seeks the numerical study. Each team studies what it thinks is the best analysis. Melentijevic et al.[80] conducted one research study to compare the two points of view and what the results led to. They reviewed both methods and dealt with sheet pile walls and soil material.

The results proved that the analytical method might exaggerate respect to the sheet pile wall's flexural and shear strength values due to its inability to define the soil material and its properties optimally. While the normal method, each element is applied in its real form by employing a computer program such as GEOWALL, PLAXIS or PROSHEET, as these programs take into account many things in the work of the model that was not taken into account in the analytical aspect.

There was a clear difference in the views of the lateral ground pressure affecting the sheet pile wall and the precise analytical ability with or without groundwater. The results came as expected. There is a clear discrepancy in the results between the numerical and analytical methods. The results ranged from 7 to 11 percent in bending forces and 26 percent in shear forces.[80]

There are many theories about soil and sheet pile walls. Such theories are studied for a comprehensive and complete study, and various models are made. These models are tested, and each model's reaction is recorded to evaluate the real behaviour of the sheet pile wall and its relationship to soil. This is due to the importance of the relationship between the soil and the sheet pile wall, as the soil has a role in shaping the shape of the deformation in the wall. It is beyond debate those numerical methods are the best way to explain, analyze, and predict the soil-wall relationship.

The numerical method can deduce the degree of response to the wall with the pressure distribution applied. The study proved that the deformation and stresses on the sheet pile wall depend mainly on the technology chosen for the design. It also makes sure that there is no general guide that can be referenced in order to determine the exact specifications of this matter. It also proved that to ensure a good design and obtain accurate results. In order to make a good model, accurate data on the properties of all the materials used must be added, and cases must be chosen that reflect how the sheet pile wall acts.[81]

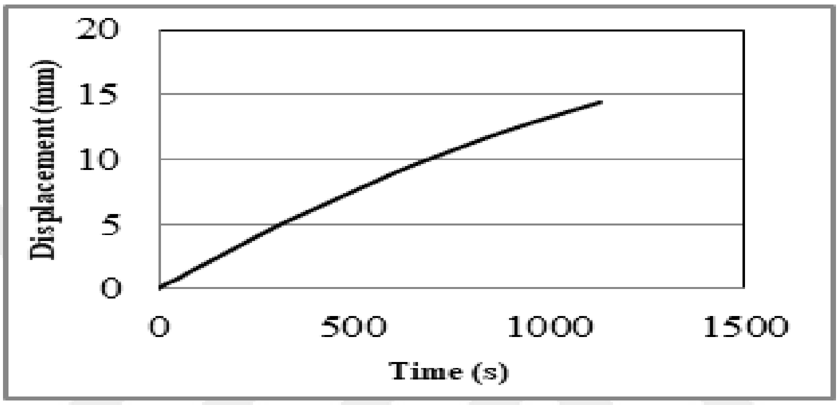
This thesis is still comparing the analytical and numerical methods, whereas a deep excavation was investigated using the infinite element method. The study was carried out in three layers of soil. One layer is a loose soil layer. Three different models were made so that the loose soil layer is the first layer in the first model, the second layer in the second model, and the third layer in the third model. The modelling was done by the numerical method.

The results proved that a loose layer over two layers of high hardness reduces the deformations of the soil and sheet pile wall, but the changes are slight. It was also demonstrated that the thickness of the loose layer increased shear strength by 50%. The results showed that the presence of a depth equal to twice the depth of the loose layer helped to increase the bending moment on the sheet pile wall in clay soil by 70% and in sandy soil by 110%. The presence of a loose layer has a pronounced effect on the lateral movement of the soil. The presence of a loose layer changes the location of the deformations on the sheet pile wall. So, it is 0.7H instead of 0.89H in sand and 0.55H instead of 0.74H, where H is the height of the sheet pile wall from the ground surface.[82]

In this study, a special investigation was conducted into the displacement of the sheet pile wall located at a distance from the bases. This investigation was conducted, and tests were conducted on the numerical method. The distance between the foundations and the sheet pile wall ranged from 10 to 20 cm. The depth of the sheet pile wall did not change with the distance change. During the experiments, the deformation of the sheet pile wall at different distances was looked at, and a graph was made to show how it changed as the touch changed.

The results of the experiment were compared with the numerical results expected from the programs. The results showed that at the fixed depth of 25 cm, the displacement values were 6.72 mm at a distance of 10 cm, 5.52mm at a distance of 15 cm, and 2.99 at a distance of 20 cm. In the case of analyses resulting from the normal method, the displacement values were 6.17 mm at a distance of 10 cm, 5.65mm at a distance of 15 cm, and 2.76mm at a distance of 20 cm. The average difference between the values from the experiment and the numerical method values is eight percent, two percent, and eight percent, respectively. The displacement value obtained at a distance of 10 cm was 125 percent of the displacement value at 20 cm.

In comparison, the value of the displacement at a distance of 15 centimetres amounted to an increase of 85 percent of the value of the displacement at a distance of 10 cm. The sheet pile wall between the foundation and the sheet pile wall reduces the displacement value. It can also be concluded that the values obtained by the numerical method are very close to the results of the experiments. (Figure 2.12 and Figure 2.13)[83]



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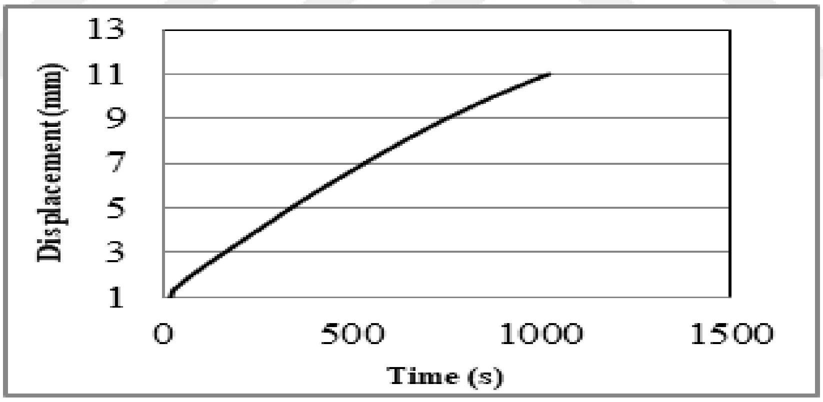

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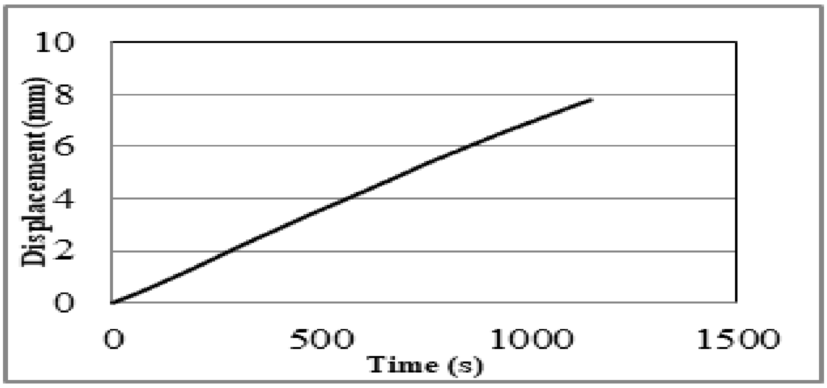

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Figure 2.12: a), b), c) Time – Displacement Graph of Sheet Pile (Experimental Results).[83]

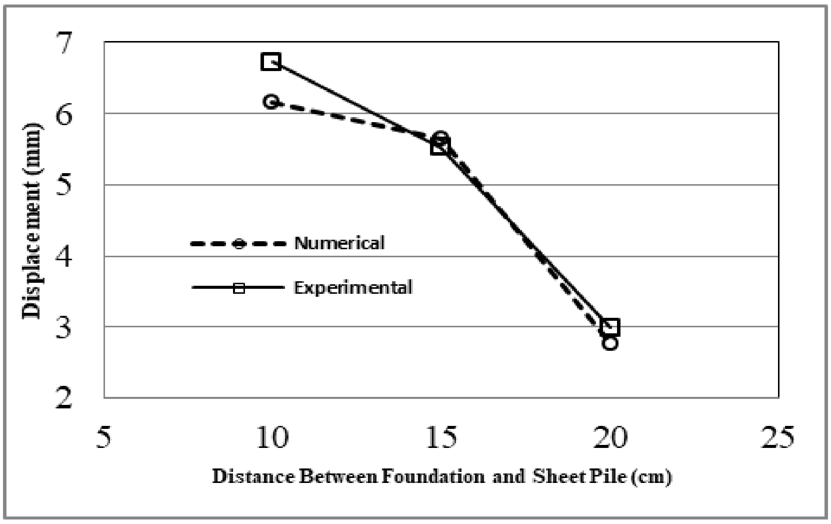


Figure 2.13: Distance Between Sheet Pile Penetration Depth – Sheet Pile Displacement (Numerical and Experimental).[83]

2.5. BEHAVIOUR OF SHEET PILE WALL

After this thesis mentioned the types of sheet pile walls and the factors affecting them, the behaviour and performance of the sheet pile walls were studied with other structures.

A study was conducted using sheet pile walls in the form of pipes, as shown in Figure 2.14. Two were installed at the front and end of the structure. Experiments were carried out with non-cohesive soil, and each of them was subjected to lateral loads, and the reaction of each of them was studied. The result showed that the bearing capacity of the front pipe sheet pile wall for side loads is greater than that of the rear by 10%. It was also observed that the maximum bending moment is achieved in the front pipe sheet pile wall due to its greater distance from the active zone. The displacement of the rear pipe sheet pile wall is much larger than the front, and that causes the rear pipe sheet pile wall to have less bearing capacity for lateral loads.[84]

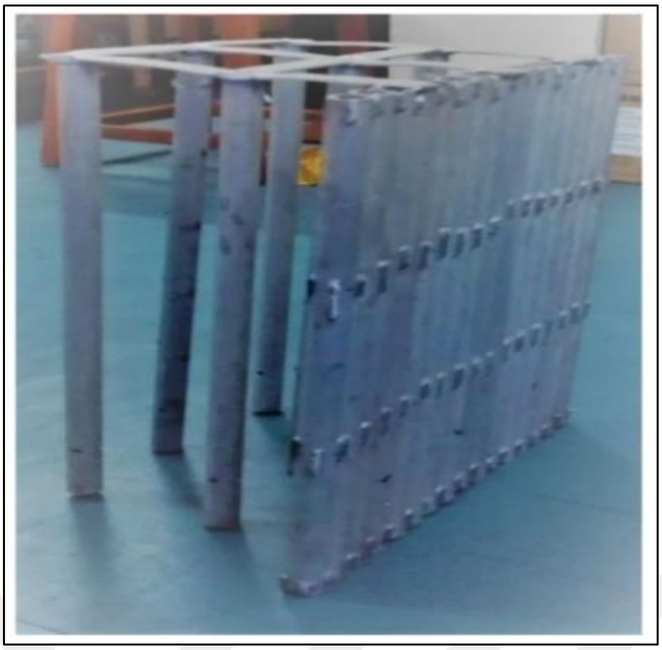


Figure 2.14: Perspective View of the Model. [84]

Another study was carried out in different environmental conditions. A braced sheet pile wall was used, powered by vibrators, in soft clay soil and the presence of a groundwater level. The excavation depth was up to 6 meters, and the dimensions of the scheme were 24 m x 29 m. The retaining wall behaviour was measured and compared with the predictions and analyses reached by the numerical method and using the PLAXIS program's finite element. The results showed great agreement while measuring what was obtained from the software. The results proved that vibrating motors could be used with braced sheet pile walls, provided they are not in sandy or gravel soils of large thicknesses. It is better to get all the details and information about the soil and the different working environments to get accurate predictions and analyses from the PLAXIS program.(See Figure 2.15 and Figure 2.16)[85]

Figure 2.15: Lateral Support System. [85]

Figure 2.16: Vibratory Sheet Pile Driver. [85]

Certainly, earthquakes have a clear impact on the sheet pile wall and the structures supported by it. An earthquake design study and its impact on steel sheet pile walls were conducted. The free height of this wall was 18 meters. It was applied to two supporting soil types: dense sandy in the first case and hard clay in the second case, as shown in Figure 2.17. The wall was subjected to seismic tremors at different levels and degrees at design acceleration ag between 0.15g and 0.5g. Design and calculations are done with simple, old-fashioned methods, so the results do not match reality because they do not consider all the factors.

In contrast to using ABAQUS programs, PLAXIS uses a finite element model that gives the relatively accurate results and analyses. The modelling found that the wall in solid soil performs to a large extent in medium and high tremors. The results also showed how much groundwater needs to be taken care of so that the wall does not have to carry as much weight. (Figure 2.18 and Figure 2.19)[86]

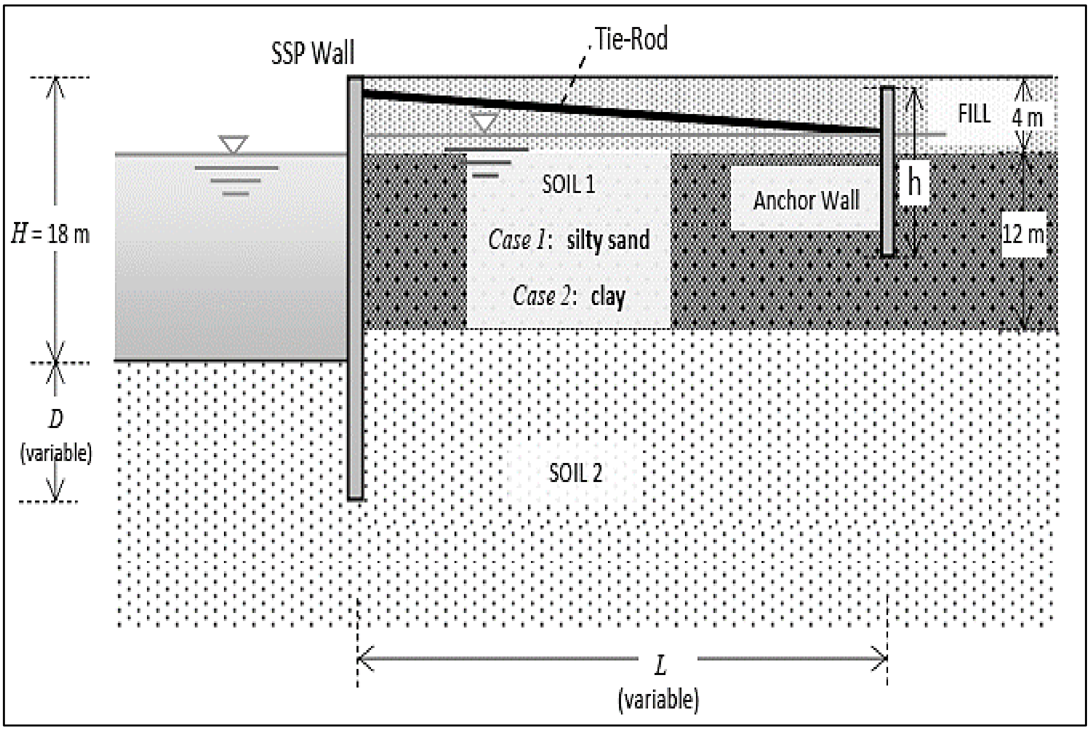


Figure 2.17: Example Sheet-Pile Wall System Used in the Study.[86]

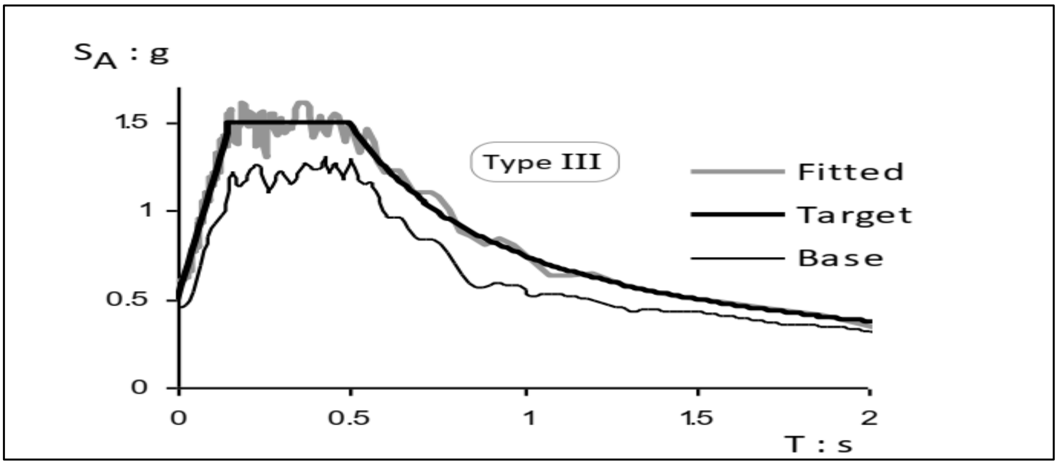


Figure 2.18: Comparison of the “Rock-Outcrop” Target and Fitted Spectra with the Computed “Base” Motion Spectrum (for Comparison).[86]

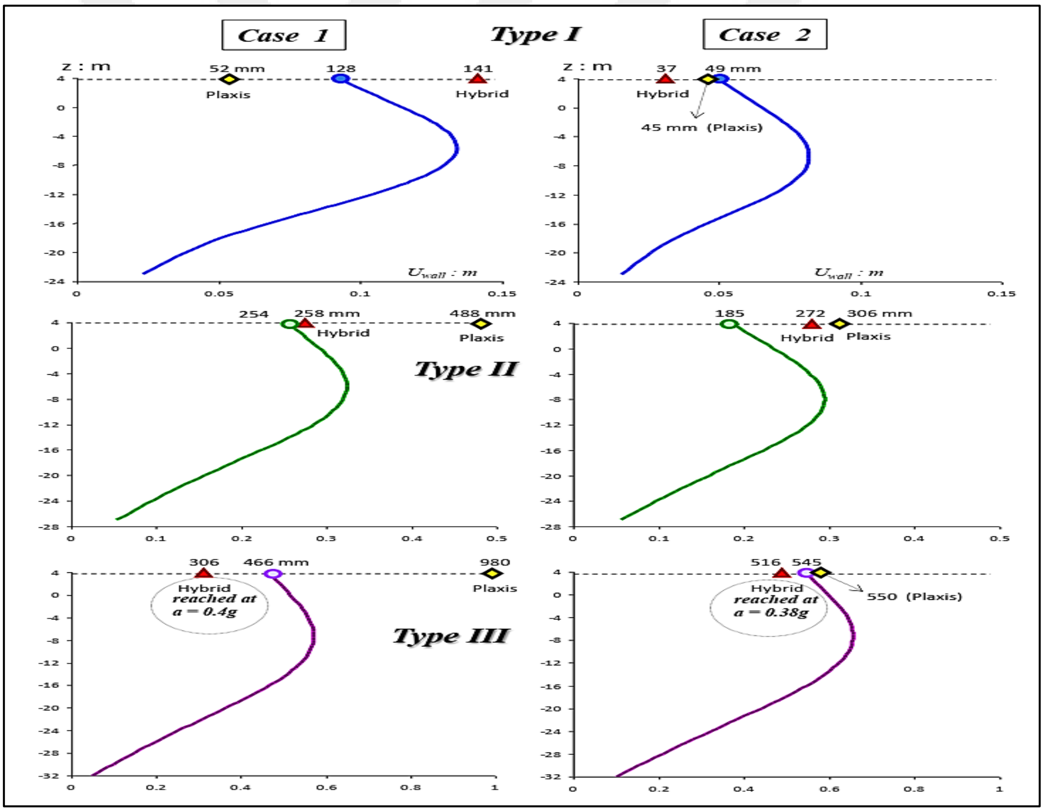


Figure 2.19: Comparison of the Lateral Deflection of the Main SSP Wall for Both Cases and All Three Types of Motion (Obtained at the Instance of Maximum Lateral Deflection at the Top of the SSP Wall).[86]

As this thesis mentioned earlier, there are many materials from which sheet pile walls are made, such as steel, concrete, or wood. As this study previously talked about steel sheet pile walls, this thesis is now talking about concrete sheet pile walls in a study conducted in Vietnam. As the Mekong River erodes the foundations of the facilities overlooking the Mekong River, which has caused huge economic losses, and these losses also prolong social conditions. Furthermore, researchers in general and in Vietnam needed to find a solution to such a big problem.

The solution was to build dams supported by concrete sheet pile walls with special specifications. A model was made, and tests were conducted on it, and the results showed that the concrete sheet pile wall reinforced with semi-continuous pipes, as shown in Figure 2.20 and Figure 2.21, saved the cost of the steel pipe pile wall by 40%. The appropriate depth of the wall can be calculated from the equation L2 = (0.6÷ 0.7) L1, where L1 is the length of the spun concrete pile and L2 is the preliminary selection of pile length.[87]

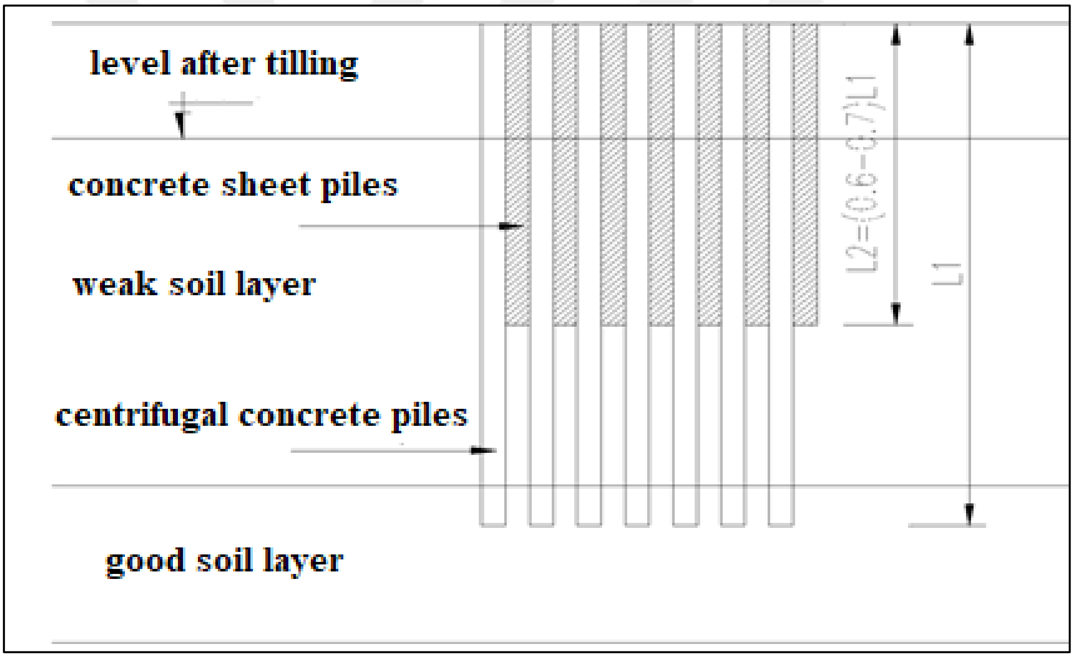
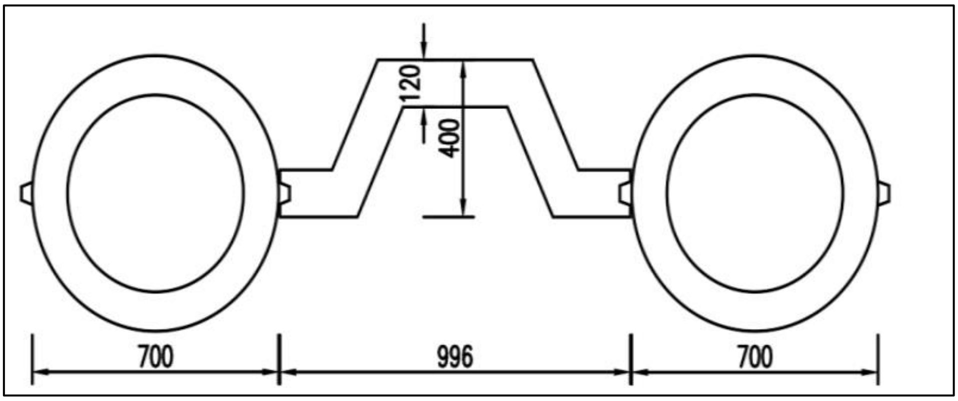


Figure 2.20: Preliminary Selection of the Length of Semi-Continuous Pipe-Sheet Pile Wall. [87]



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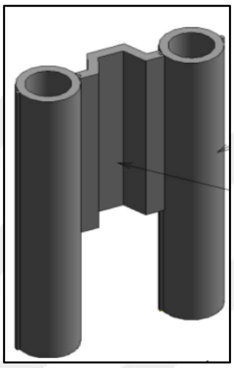


b

Figure 2.21: (a) Plan, (b) Cross-Section of the Semi-Continuous Pipe-Sheet Pile Wall. [87]

3. PRACTICAL SECTION

3.1. MODELLING USING THE FINITE ELEMENT METHOD

The finite element method was used to determine the behaviour of sheet piles. The PLAXIS 2D Connect Edition v20 program is considered one of the essential software in geotechnical engineering, based on the theory of finite elements. It is used to determine the behaviour of sheet piles by studying horizontal displacements, maximum bending moments, and driven depth of sheet piles, cantilever and anchorage sheet piles.

To design an accurate case model using PLAXIS 2D Connect Edition v20, it is essential to understand how to draw the model and enter dimensions in PLAXIS 2D. It offers two methods for determining dimensions:

3.1.1. Asymmetry

Axisymmetry is suitable for determining circular models with specific diameters. The researcher works in the cross-section defined by the y-axis and the x-axis, but the program will consider the direction out of the plane (z), assuming that all strains are equal in the two directions $\varepsilon x = \varepsilon z$ (Figure 3.1) (Tjie-Liong, 2014).

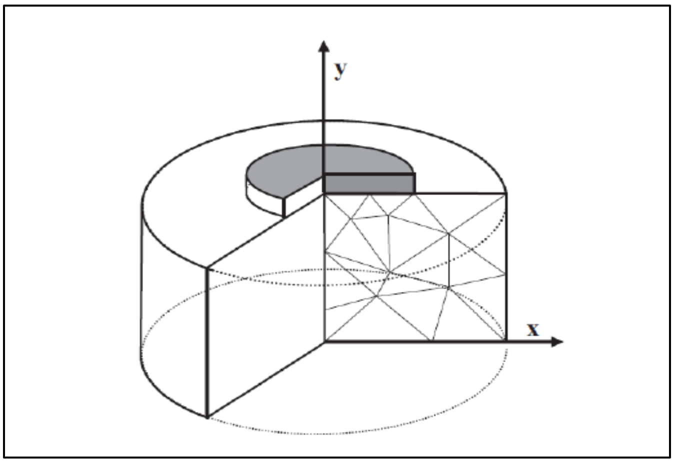


Figure 3.1: The Model's Dimensions Using the PLAXIS Program Using the Axisymmetry Method.[88]

3.1.2. Plane Strain

Plane strain is used for cases where the segment is regular outside the studied plane. This option was often used to model extended roads or excavations with greater length than width, so plane strain was considered in this thesis (Figure 3.2).

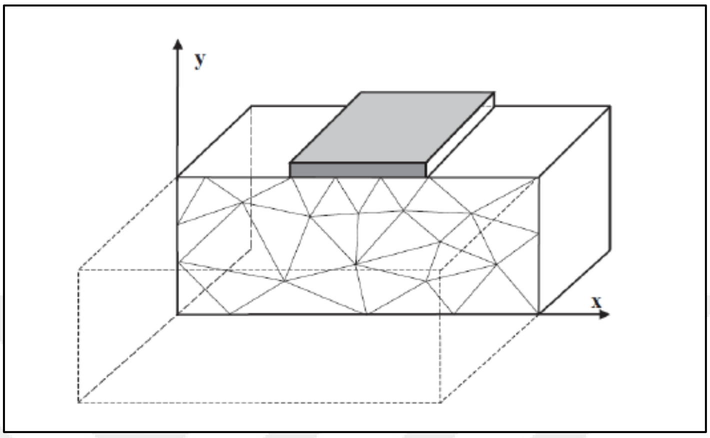


Figure 3.2: Dimensions of the Model Using the PLAXIS Program by Using the Plane Strain Method[88].

3.2. MATERIAL MODEL

PLAXIS 2D suggests that the mechanical behavior of soils and rocks can be modelled with varying degrees of accuracy, as shown in many experiments and studies of soil behavior (PLAXIS V20, 2020).

3.2.1. Linear Elastic Model (LE)

This model depends on Hooke's law for the homogeneous resonance of materials; that is, the relationship between strain and stress is linear. The required model parameters are E, the soil's Young's modulus, and Poisson's ratio μ [89]. Even though this is not how grounds usually act, it is a good way to start simple modelling to understand how the system works before moving on to more complex modelling.

3.2.2. Mohr-Coulomb (MC) Soil Model

A basic, linear, elastic, and completely plastic model called the Mohr-Coulomb Soil is used to represent the behavior of soil.

The Mohr-Coulomb model's linear elastic component is governed by Hooke's law of isotropic elasticity. On the other hand, the ideal plastic component is determined by the Mohr-Coulomb failure criteria[90]. The following equation determines the Mohr-Coulomb failure criterion:

$$\tau = c + \sigma' tan\varphi \quad (3.1)$$

Where c is the cohesion, φ is the friction angle of the soil, τ is the shear strength, and σ' is the effective normal stress.

The stress-strain diagram displayed in Figure 3.3 explains the linear elastic completely plastic behavior. Elastic and plastic strains are denoted by the letters "e" and "p," respectively.

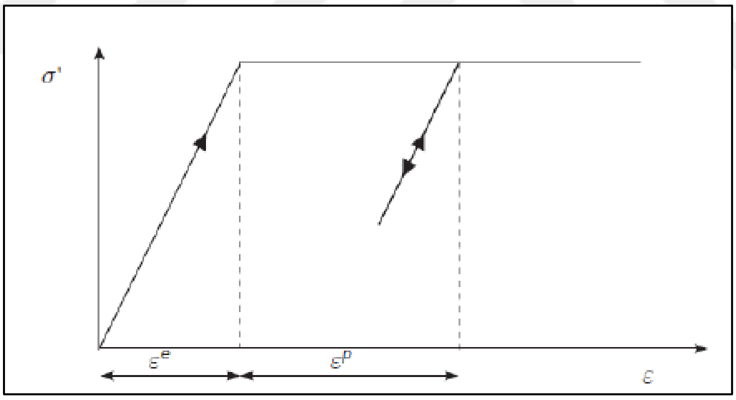


Figure 3.3: Basic Linear Elastic Plastic Behaviour [90].

3.3. NUMERICAL MODELLING USING PLAXIS2D FINITE ELEMENT:

This program works within the Windows operating system. It relies on the finite element method to analyze and study the deformations of soils and rocks under the influence of different loads and soil structures. The PLAXIS 2D program consists of four main programs, which are, in order:

3.3.1. Input Procedure

The stage of work within this program is the pre-treatment stage, which is used to enter the primary data necessary to describe the issue under study. It figures out the size and shape of the engineering model, describes the properties of the different materials that make up the model, defines the effective loading system, and figures out the initial and boundary conditions for the issue being studied, including groundwater.

3.3.2. Calculation Step

The main advantage of this program's calculations and processing is to make accurate models of the different stages of building a project. This lets you figure out the stress and distortions of each step on its own.

3.3.3. Output Step

It is a post-processing stage concerned with outputting the results of the calculations, as it presents the studied finite element network model and the stresses affecting it in its various forms. The program also provides the ability to display the results in tables.

3.3.4. Curves Program

A program is used to show the relationship curves between the loads and deformations, the relative stresses and distortions, and the paths of stresses and deformations at certain points of the engineering model, with the option of showing the distribution of groundwater pressures.

3.4. NUMERICAL MODELLING OF A SHEET PILE

3.4.1. Material Model and Material Parameters

The geotechnical behaviour of retaining structures was studied using numerical modelling of cantilever and anchored sheet pile walls at various dredge height (H) values. The plane strain model was used with 15 node elements. The program generated a fine mesh. For lateral loads acting on sheet piles or earth pressure on sheet piles under static load, the Mohr-

Coulomb model is considered a suitable model that can be used to simulate the nonlinear behaviour of the soil in general due to its simplicity.

This thesis will deal with dry and saturated soil by changing water table levels. The parametric study used three different types of soil, and the following tables characterized the properties of soil. The first soil is sandy. Its properties are presented in Table 3.1.

Table 3.1: Sandy Soil Properties.

Parameter	**Symbol**	**Value**	**Unit**
Friction angle	φ	35.3	°
Soil dry unit weight	γ_{dry}	16.8	KN/m^3
Type of behaviour	drained	-	-
Soil unsaturated unit weight	γ_b	18	KN/m^3
Soil saturated unit weight	γ_{sat}	20.5	KN/m^3
Cohesion	C	0.001	KN/m^2
Young's modulus)	E	30000	KN/m^2
Poisson's ratio	υ	0.3	-
Permeability	(Kx, Ky)	0.2	m/day
Dilatancy angle	Ψ	0	°
Strength reduction factor inter	R_{inter}	0.67	-

The second soil is clay, and its properties are presented in Table 3.2.

Table 3.2: Clay Soil Properties.

Parameter	Symbol	Value	Unit
Friction angle	φ	0.043	°
Type of behaviour	undrained	-	-
Soil unsaturated unit weight	γ_b	15	KN/m^3
Soil saturated unit weight	γ_{sat}	16	KN/m^3
Cohesion	C	25	KN/m^2
Young's modulus	E	30000	KN/m^2
Poisson's ratio	υ	0.3	-
Permeability	(Kx, Ky)	0.0001	m/day
Strength reduction factor inter	R_{inter}	0.67	-

The third soil is sandy clay. Its properties are presented in Table 3.3.

Table 3.3: Sandy Clay Soil Properties.

Parameter	Symbol	Value	Unit
Friction angle	φ	35	°
Type of behaviour	undrained	-	-
Soil dry unit weight	γ_{dry}	16	KN/m^3
Soil unsaturated unit weight	γ_b	18	KN/m^3
Soil saturated unit weight	γ_{sat}	20	KN/m^3
Cohesion	C	25	KN/m^2
Young's modulus	E	25600	KN/m^2
Poisson's ratio	υ	0.2	-
Permeability	(Kx, Ky)	0.002	m/d ay
Dilatancy angle	Ψ	6	°
Strength reduction factor inter	R_{inter}	0.67	-

The characteristics of the sheet pile wall, including the dredging height (H), the penetration depth of the cantilever sheet pile (Do), the penetration depth of the anchored sheet pile (D1), the distance between the ground surface and the first anchor (y), the distance between the first and the second anchor (S), the effective length (Le), and the grouted length (Lg) are presented in Figure 3.4 and Figure 3.5.

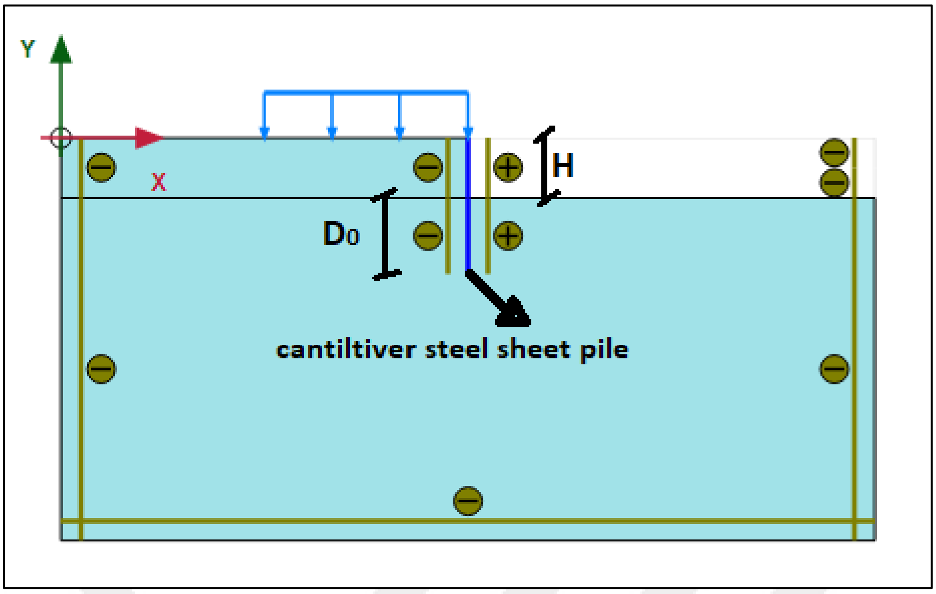


Figure 3.4: The Geometry of the 2D PLAXIS Model for Cantilever Sheet Pile.

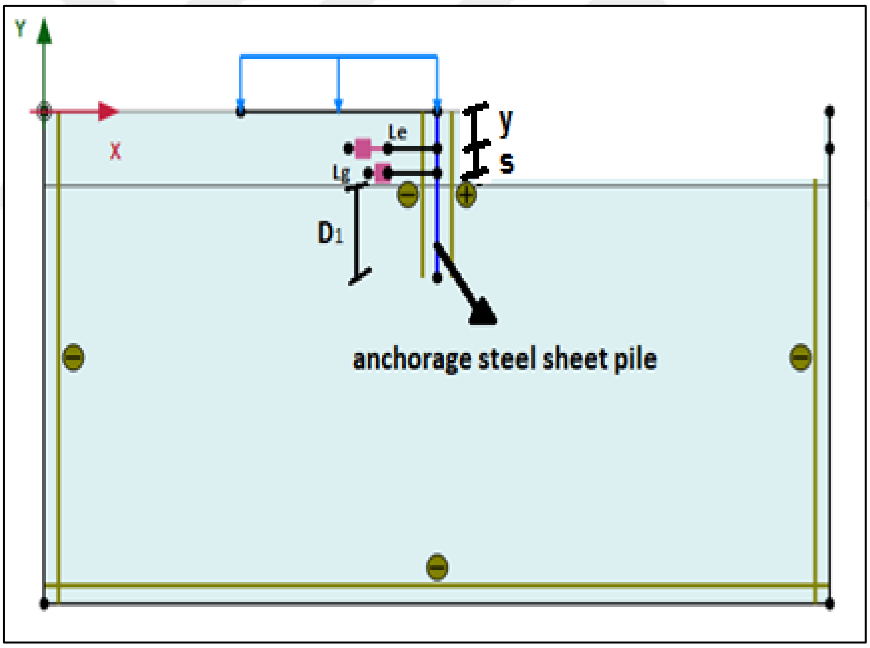
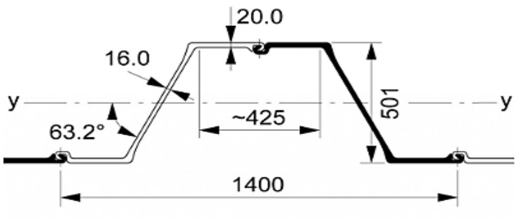


Figure 3.5: The Geometry of the 2D PLAXIS Model for Two Anchored Sheet Piles.

The structural properties are chosen for the steel sheet pile section: AZ46-700N, shown in the following figure:



Metric units Imperial units

AZ 46-700N

	A	G	I_y	$W_{el,y}$	r_g	A_L
	cm^2	kg/m	cm^4	cm^3	cm	m^2/m
Per S	200.9	157.7	80 760	3 220	20.05	1.03
Per D	401.8	315.4	161 520	6 450	20.05	2.06
Per m of wall	287.0	225.3	115 370	4 605	20.05	1.47

A	Sectional area
G	Mass per m
I_y	Moment of inertia about the main neutral axis y-y
$W_{el,y}$	Elastic section modulus
r_g	Radius of gyration about the y-y axis
A_L	Coating area. One side, excludes inside of interlocks
S	Single pile
D	Double pile

Figure 3.6: Steel Sheet Pile Section AZ46-700N. [91]

Moreover, the required properties of sheet piles in PLAXIS 2D are given in Table 3.4. Table 3.5 demonstrates the characteristics selected for the anchor system.

Table 3.4: Properties of Sheet Pile.

Symbol	value	Unit
EA	10.5E6	kN/m
EI	0.22E6	$kN/m^2/m$
W	2.2	KN/m
d	0.501	m
υ	0.15	-

Table 3.5: Properties of Anchors.

Parameter	Name	Value	Unit
Normal stiffness	EA	2E5	kN/m

Type of behaviour	Material type	Elastic	-
L spacing		1	m

Table 3.6: Properties of the Grout Body.

Parameter	Name	Value	Unit
Normal stiffness	EA	1.E5	kN/m
Type of behaviour	Material type	Elastic	-
L spacing		1	m

3.4.2. Variables and Ranges Used in the Parametric Study

3.4.2.1. Studying dry and saturated soils

3.4.2.2. Studying the different levels of groundwater and its impact on different depths (dry condition -saturated condition)

3.4.2.3. Studying the effects of different levels in dredge depth by considering the free height of sheet pile

$$\left(\frac{1}{3}H - \frac{2}{3}H - H\right) \tag{3.2}$$

Where H is the free height of the sheet pile

3.4.2.4. Studying the effects of the number of anchors, the distance between anchors (S) and the distance between the ground surface and the first anchor (Y). Table 3.7 lists the variables and ranges used in the parametric study.

Table 3.7: Variables and Ranges.

Case	Variable	Range
free height	H	3m,5m,6m
NO. of anchor	NO.	2

Table 3.7: Variables and Ranges. "Table Continued"

One anchor	Y	0.2H-0.3H--0.5H
Two anchored	S	(0.2 H, 0.3 H, and 0.5 H) at constant y=0.2 H

3.4.3. Procedure Stages of Model

3.4.3.1. Example in PLAXIS 2D:

An example will be applied to an anchorage sheet pile and subjected to a uniformly distributed load where the distributed load is 10 KN/m^2, 6 m of excavation above the dredge line, 5.25m depth below the dredge line, and the soil behind the sheet pile are sandy. The sheet pile has anchoring elements and grout material to resist soil thrust. This thesis will explain the modelling steps and the specification of the material properties in detail.

i. Initially, a model will be developed with a plain strain model, 15 nodes were selected for the greatest accuracy, and the model dimensions used (X_{min}=0, X_{max}=50m, Y_{min}=0, Y_{max}=40) were determined (Figure 3.7).

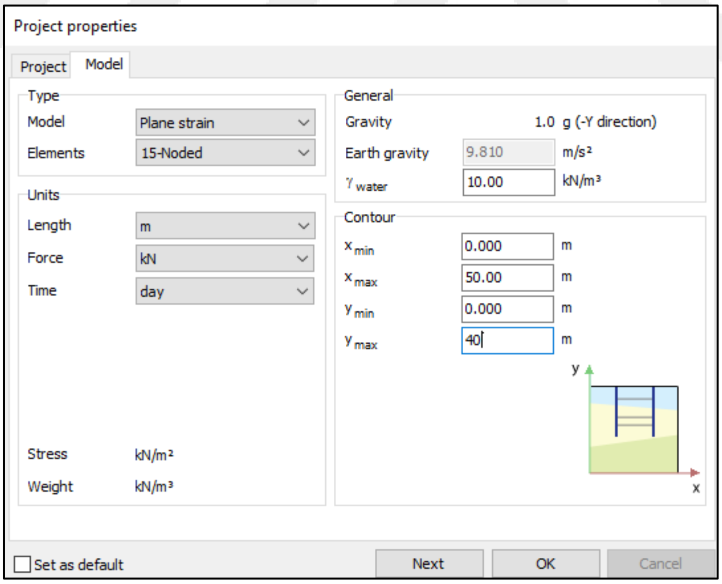


Figure 3.7: Dimension of the Model.

ii. After determining the model's dimensions, a borehole will be made with a depth of 40m, and a water table will be placed at a depth of 2m from the top of the sheet pile (Figure 3.8).

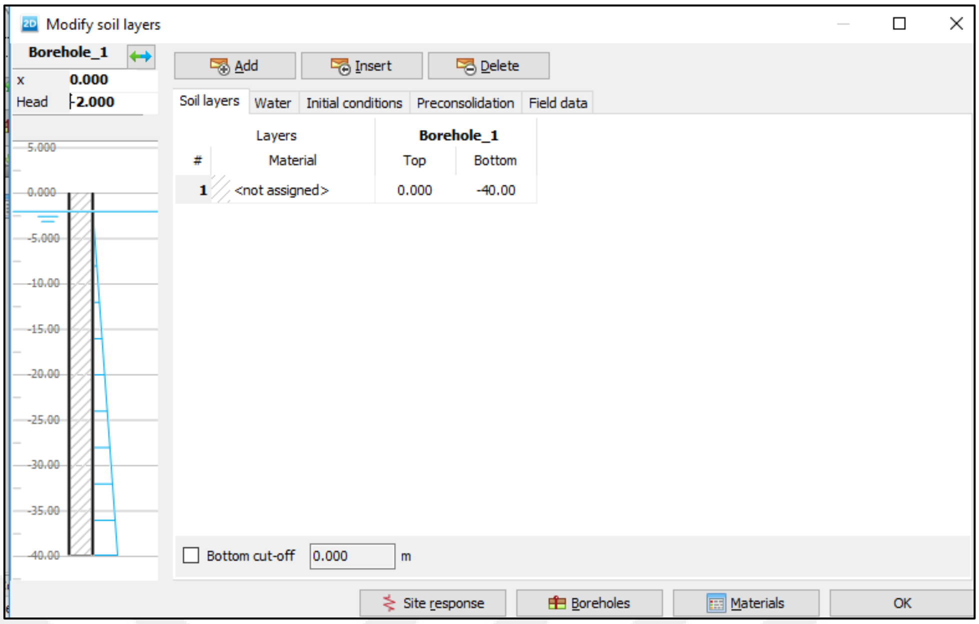


Figure 3.8: Bore Hole Depth.

iii. The soil characteristics were determined and used in the sheet pile behind and in front of the sheet, where three different types of soil will be modelled, and the effect of each type on the sheet pile will be studied. In the current example, the sandy soil was made in two characters, bulk and saturated unit weight.

Figure 3.9 shows the properties, including cohesion, friction angle, elasticity factor, and Poisson’s ratio.

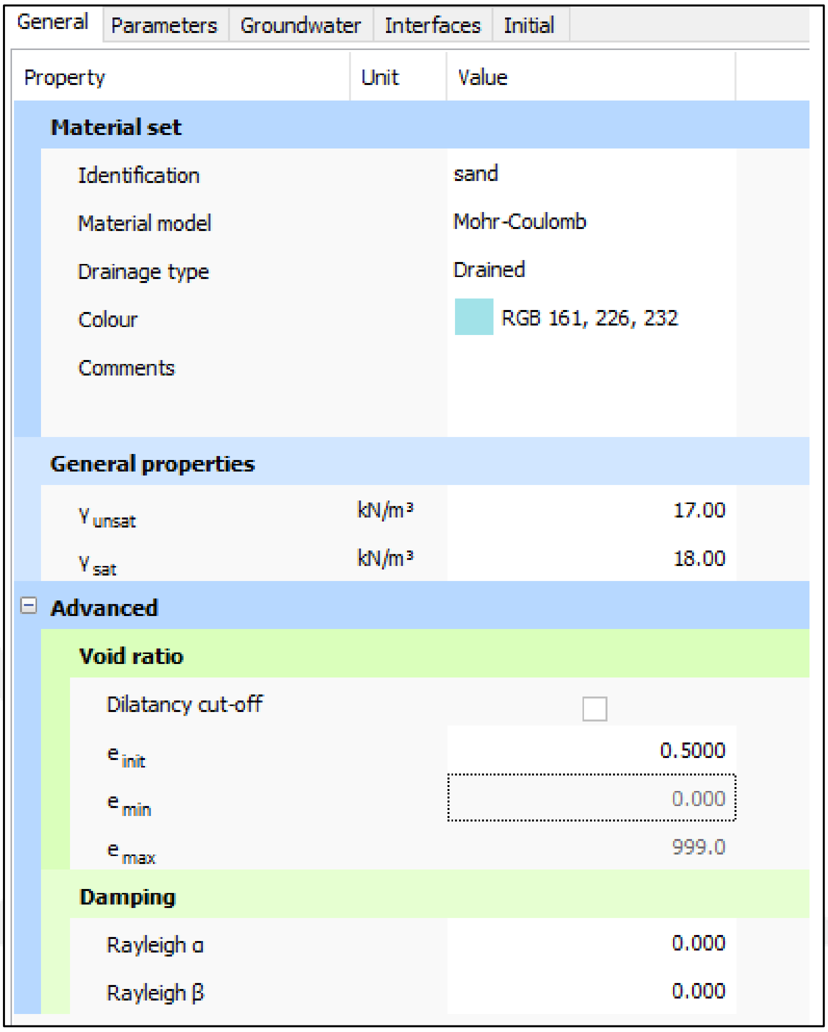


Figure 3.9: General Properties of Soil.

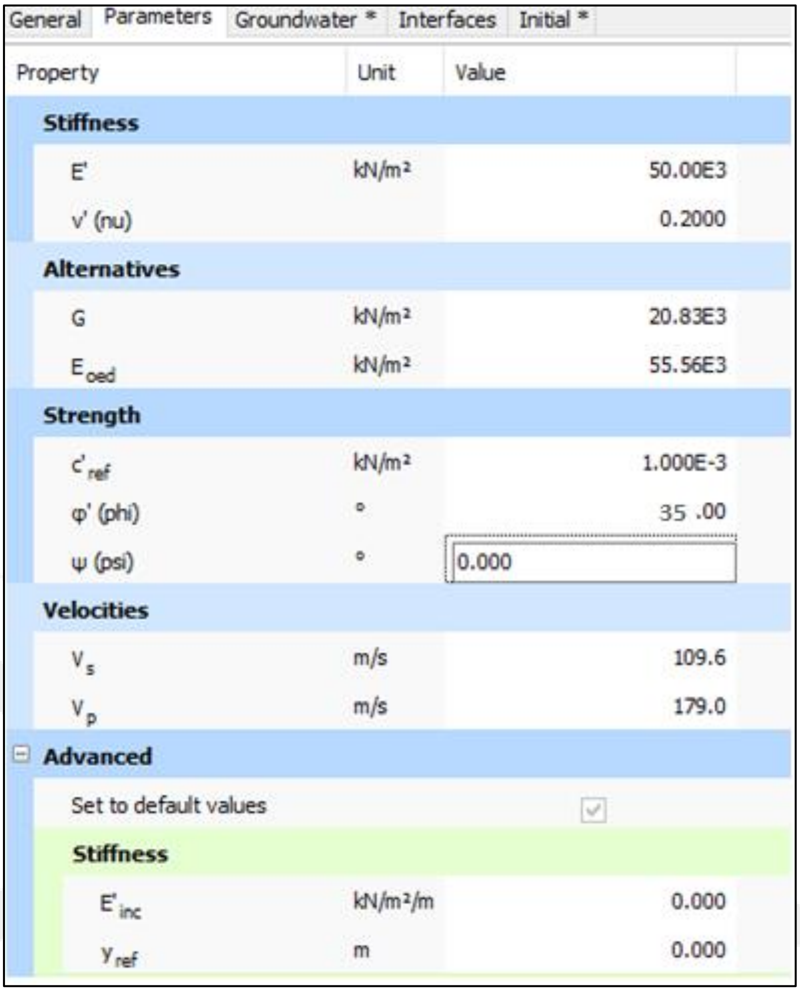


Figure 3.10: Parameter's Properties of Soil.

Figure 3.11 shows the input of permeability coefficient Kx, Ky.

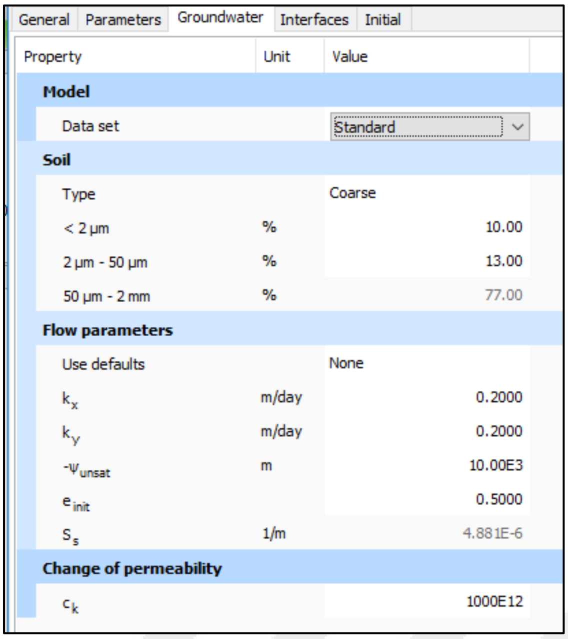


Figure 3.11: Ground Water Properties.

The interaction between the sheet pile and soil was studied by applying interfaces along the sheet pile, in addition to choosing the appropriate value of R_{int}. (Figure 3.12)

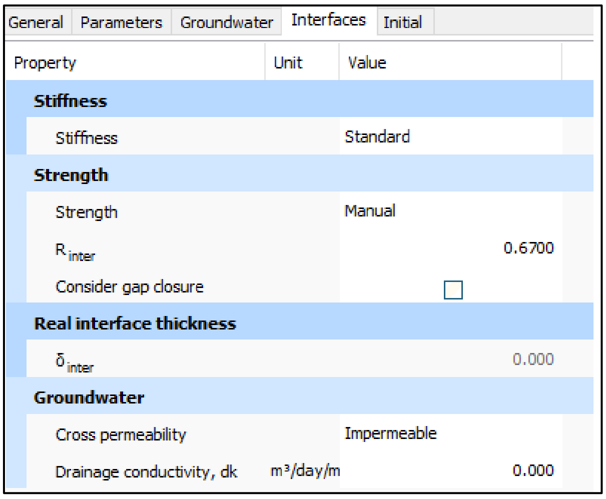


Figure 3.12: Interfaces Properties.

iv. The next step was the Structure window after completing the properties of the soil. The steel sheet pile will be modelled and drawn in the middle of the model and defined as a plate, and the create plate command will draw it from the Structure-Show Materials-Plate command. (Figure 3.13)

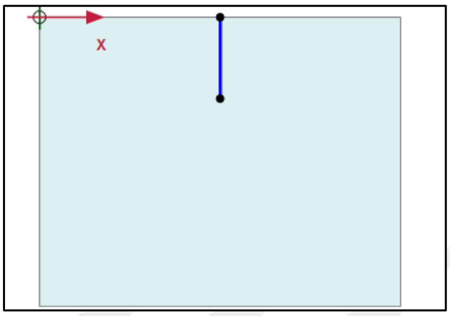


Figure 3.13: Steel Plate.

The plate will be defined with the properties shown in Figure 3.14.

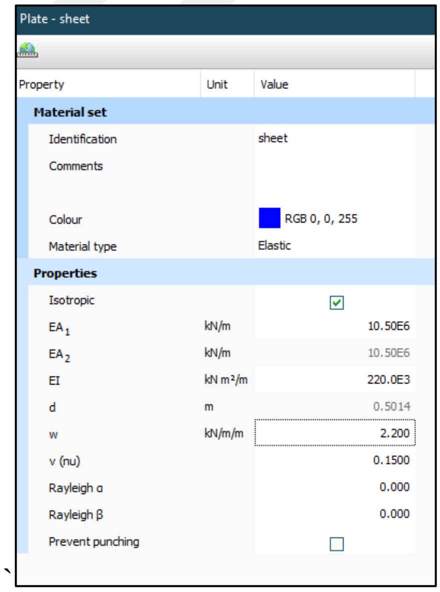


Figure 3.14: Steel Sheet Pile Properties.

v. At this stage, a uniformly distributed load will be placed on the surface of the soil above and behind the plate, where the load will be drawn with the command "Create line load," and the location of this load is determined at a value of 10KN/m^2. (Figure 3.15)

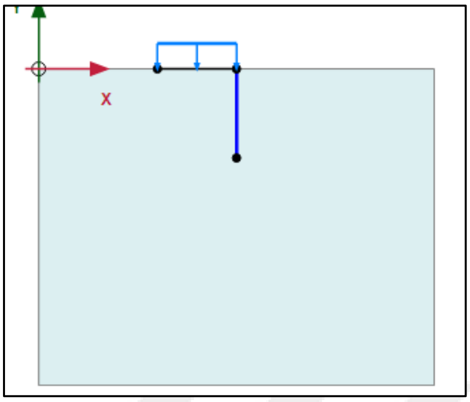


Figure 3.15: Load on Soil.

vi. Cantilever sheet pie and anchorage sheet pile are the two types of sheet piles. In our example, the two anchor elements were drawn at the height of 2m and 4m, respectively, from the top of the plate through the command "Creat" node to node anchor, and it was drawn by placing the appropriate dimensions for its location and length of Initial 6 m, where the length of the element will be variable during the stages of the study.

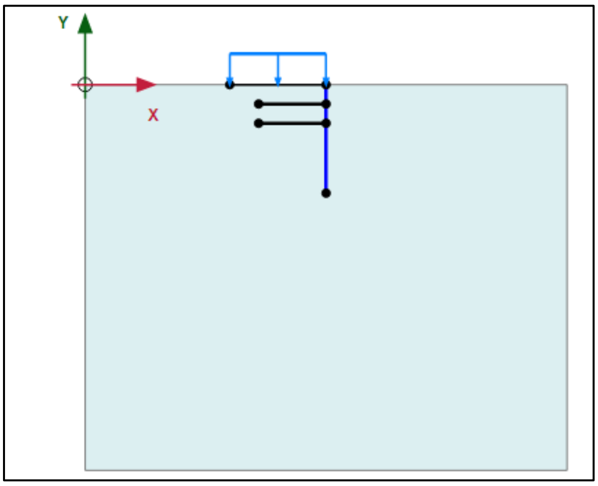


Figure 3.16: Anchor on Plate.

vii. This element has properties shown in the following figure by adopting L spacing=1m, where these elements are studied on a metric slide. These properties were modelled from the command “Structure-Show materials-Anchor.”

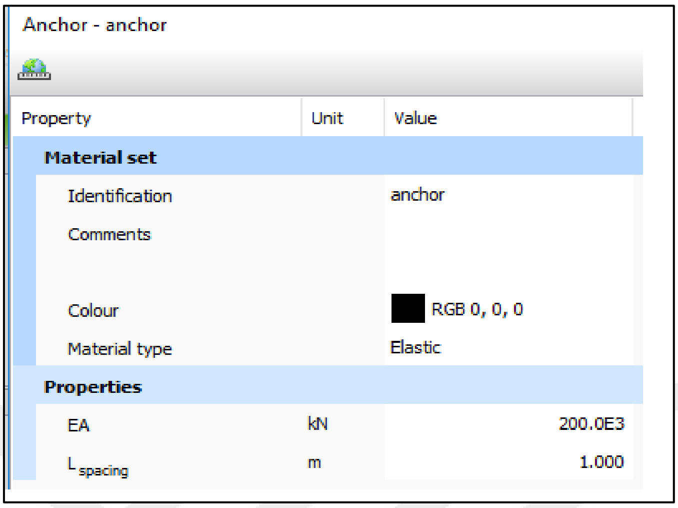


Figure 3.17: Anchor Properties.

viii. These elements are reinforced and fixed with grout, a cement material injected into the soil at the end of the anchoring element, where it is modelled with a length of 2 m behind the element through the command “Create embedded beam row”.

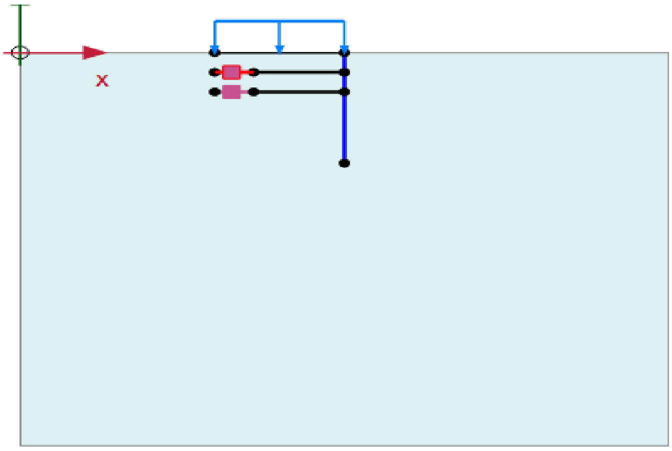
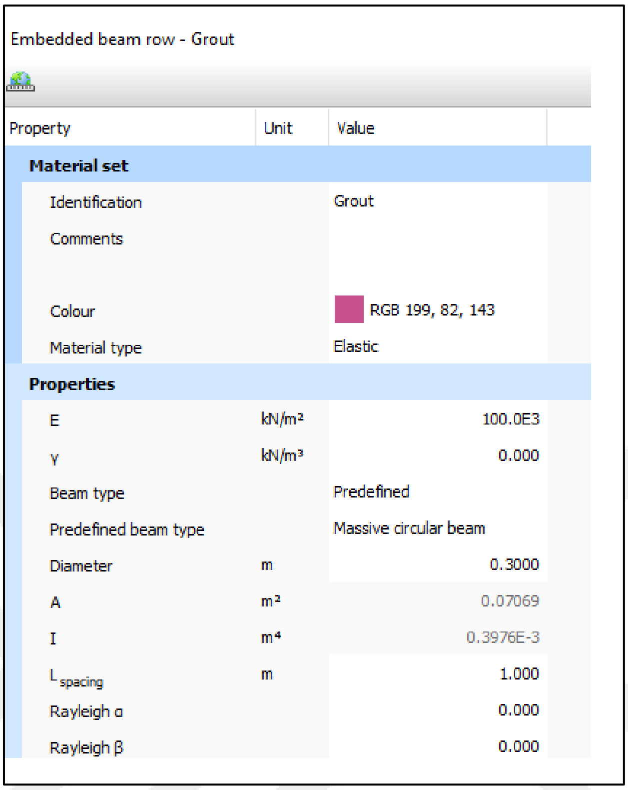


Figure 3.18: Anchor and Grout on Plate.

ix. A diameter of 0.3m was set for the material, and this material has the properties modelled by the command: structure Show materials Embedded beam row.



Embedded beam row - Grout

Property	Unit	Value
Material set		
Identification		Grout
Comments		
Colour		RGB 199, 82, 143
Material type		Elastic
Properties		
E	kN/m^2	100.0E3
γ	kN/m^3	0.000
Beam type		Predefined
Predefined beam type		Massive circular beam
Diameter	m	0.3000
A	m^2	0.07069
I	m^4	0.3976E-3
$L_{spacing}$	m	1.000
Rayleigh α		0.000
Rayleigh β		0.000

Figure 3.19: Grout Properties.

x. The Mesh window divides the element into small and fine elements. In this window, there are several options for dividing the triangular mesh (Medium, Fine, Very (fine)), and fine division will be adopted in order to obtain more accurate results

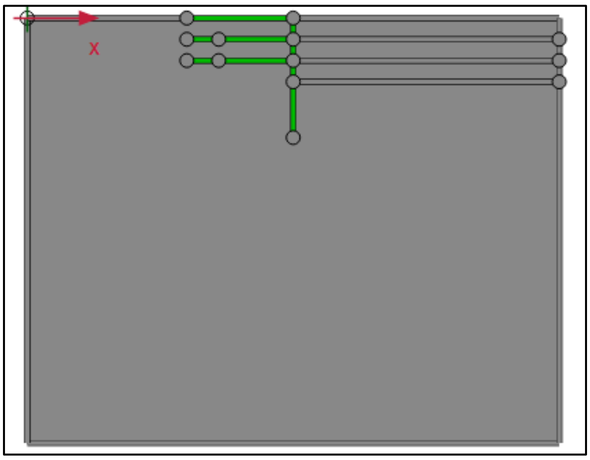


Figure 3.20: Generating Mesh.

xi. Three separating lines will be drawn at three different drilling depths 2m, 4m, and 6m. These depths represent 0.33H, 0.66H, and H, where:

Where H= Free Hight of Sheet Pile

The water table will be variable in the study. In our example, a water table was drawn at a depth of 2 m, and when excavation was done, the water table level in front of the sheet pile should be reduced, as illustrated in Figure 3.21.

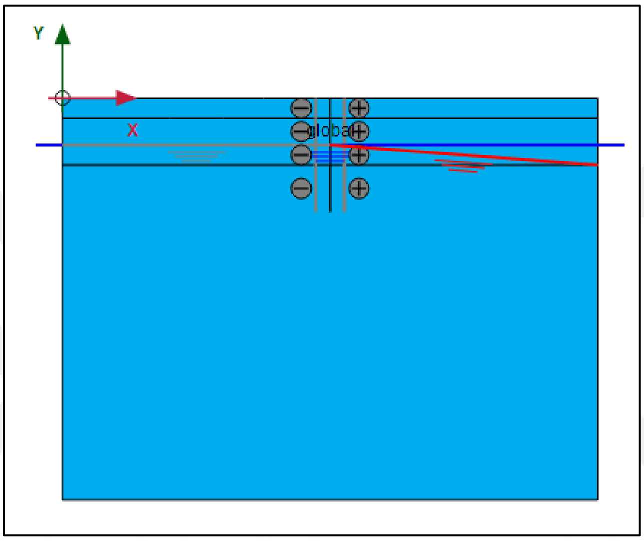


Figure 3.21: The Model with the Water Table.

xii. In the last stage, before the analysis, several phases are modelled that express the construction phases of the model, as the program assumes the Initial phase, which expresses only soil modelling.

The phases are added, with phase1 activating the plate and surcharge load together.

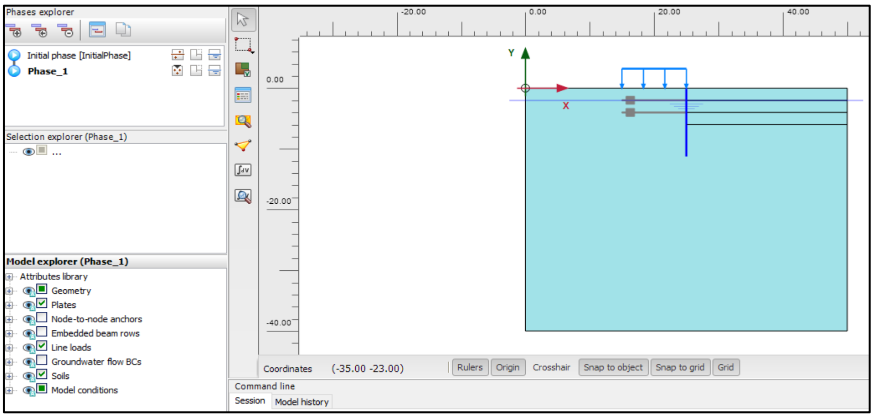


Figure 3.22: Phase 1 Activating Plate and Surcharge Load.

xiii. In phase 2, the first excavation with a depth of 2 m is deactivated

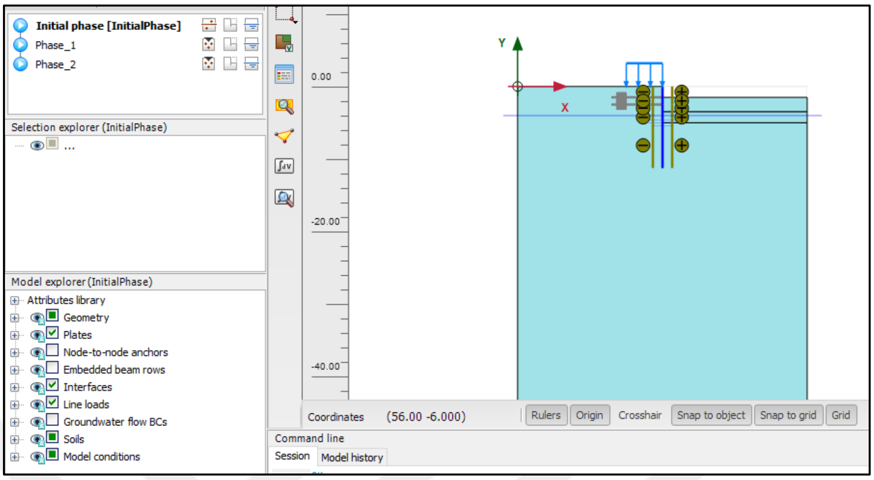


Figure 3.23: Deactivating First Excavation.

xiv. In phase 3, Node to node anchor and Embedded beam row options will be activated to activate the effect of the anchors and grout.

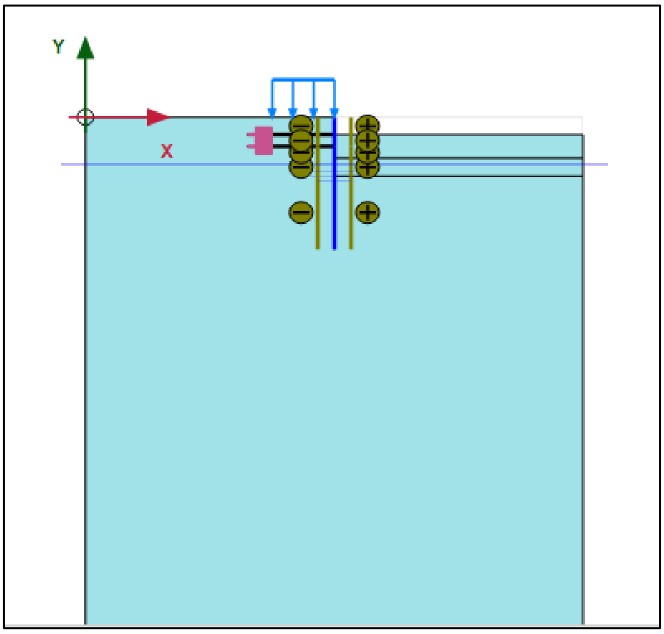


Figure 3.24: Phase 3 Activating Anchors and Grout Body.

xv. As for phase 4, the previous cut will be added to the soil to a depth of 2m in front of the plate so that the excavated depth will be 4m.

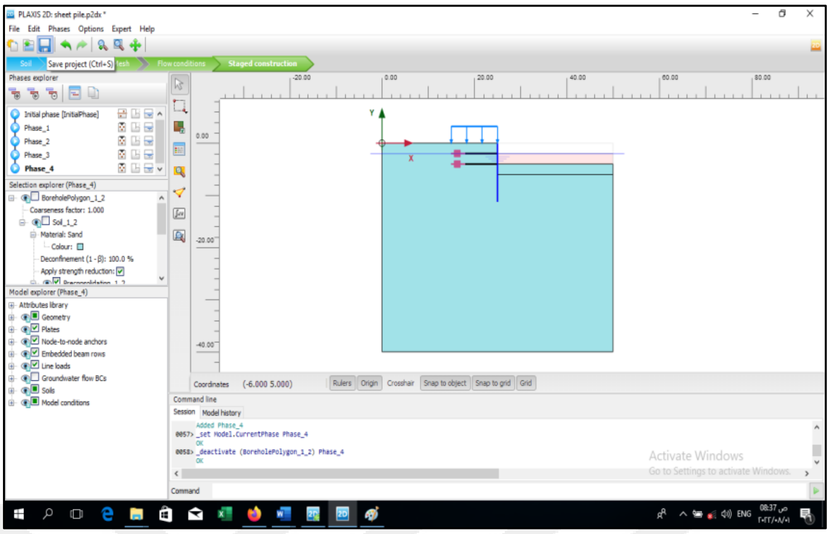


Figure 3.25: Phase 4 Properties

xvi. In the last phase 5, an additional 2m will be excavated in front of the plate so that the excavated depth will be 6m, and this level represents the total depth of excavation of the soil in front of the plate

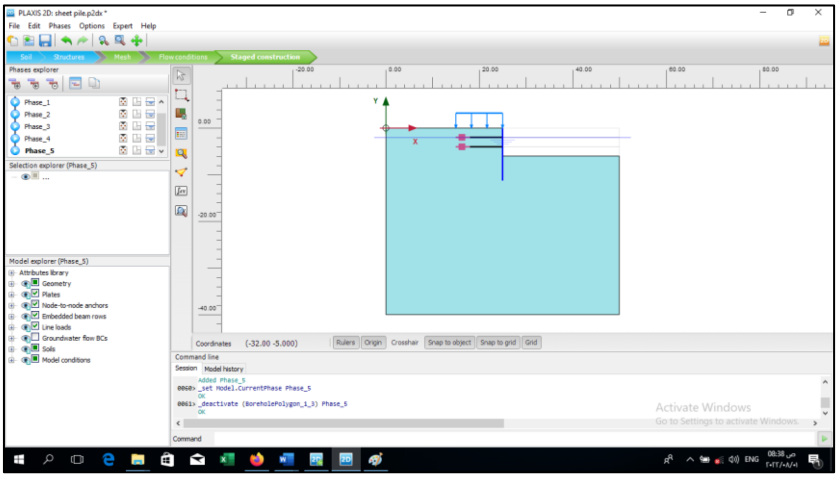


Figure 3.26: Phase 5 Properties.

xvii. After completing the definition of all phases, the analysis process begins through the Calculate command. After completing the analysis, the results are reviewed by pressing the view calculation results command. These results show that the deformation-deformed mesh command can display the deformed shape.

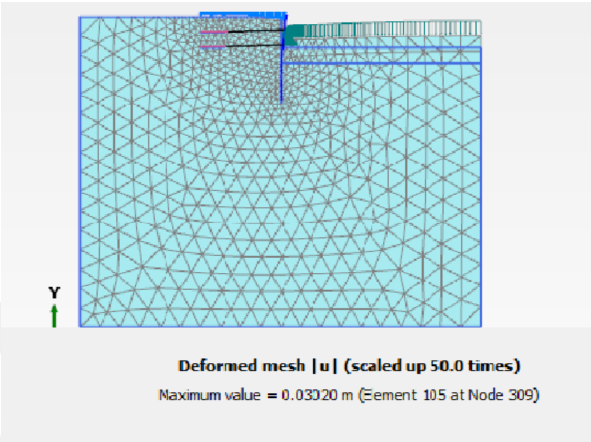


Figure 3.27: Deformed Shape.

xviii. The values of horizontal displacements can be viewed through the command: Deformation-Total displacement-Ux.

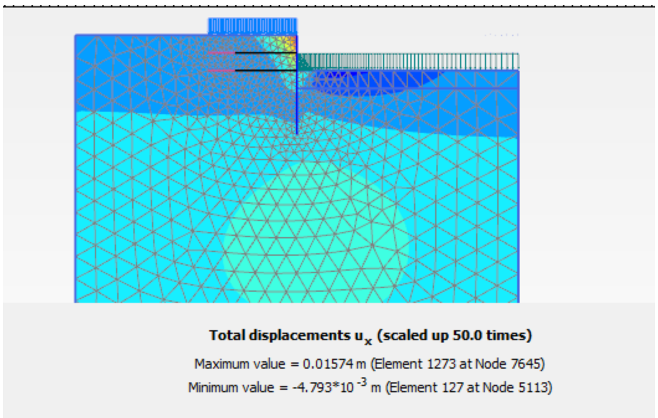


Figure 3.28: Total Displacements U_x.

xix. The Bending moment applied to the plate is also calculated, this diagram is drawn, and the maximum value of the bending moment is known.

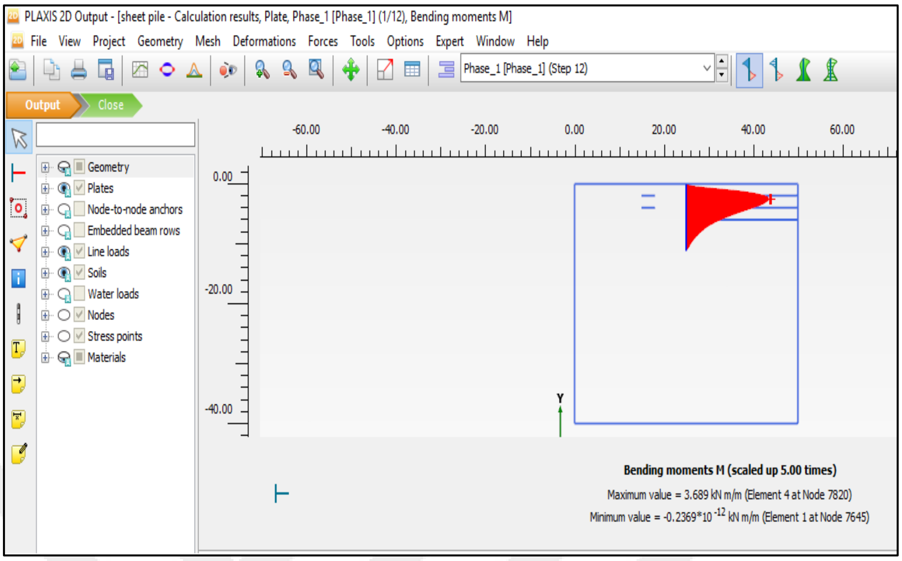


Figure 3.29: Bending Moment.

In this thesis, all cases were studied by adopting the damping ratio equal to zero because the study was conducted under static conditions to achieve more accuracy and realism, a certain value was added to the damping ratio, and because all the conditions and loads studied in this study are static, therefore, there must be no change in the results, and this is what has been verified by comparing the tables of values of moments and displacements.

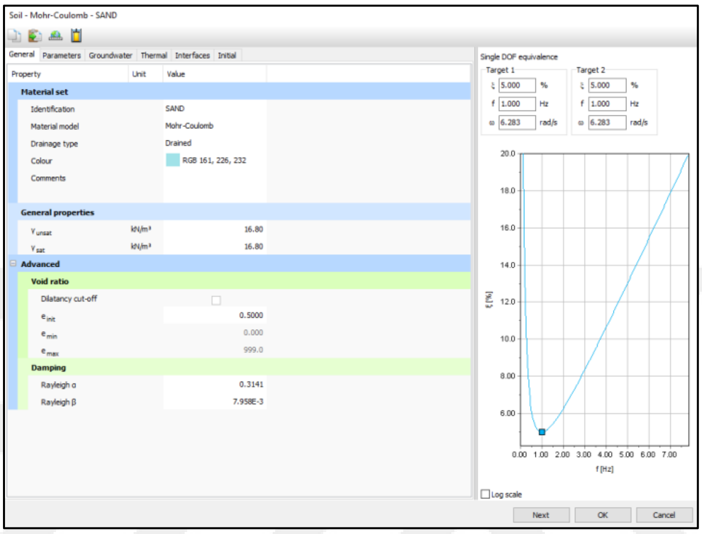


Figure 3.30: Values of Damping Ratio.

The values of horizontal displacements and moments along the cantilevered piles and anchor piles were imported from PLAXIS 2D program. These results were compared with the results after adding the damping ratio in all cases. No change was found; therefore, the results were adopted.

3.5. DESIGN SOFTWARE PROSHEET

To ensure the reliability of the results calculated in the PLAXIS 2D program, the outcomes calculated from the PLAXIS 2D program are compared with design software ProShee2.2, version August 2017.

A complete sheet pile design tool for cantilever and single-supported retaining walls is called PROSHEET. It is based on the Blum theory, a limit equilibrium strategy.

It is an easy tool to calculate all the forces needed to design a sheet pile retaining wall, making it perfect for conceptual designs. With the exception of granular soils with very high internal friction angles, the soil pressure and resistance components are calculated using the Caquot and Kérisel theory, which produces findings comparable to those of the Coulomb theory.

3.5.1. Calculate Steps in the Prosheet Program

i. Each of the following data is entered into the geotechnical data window:

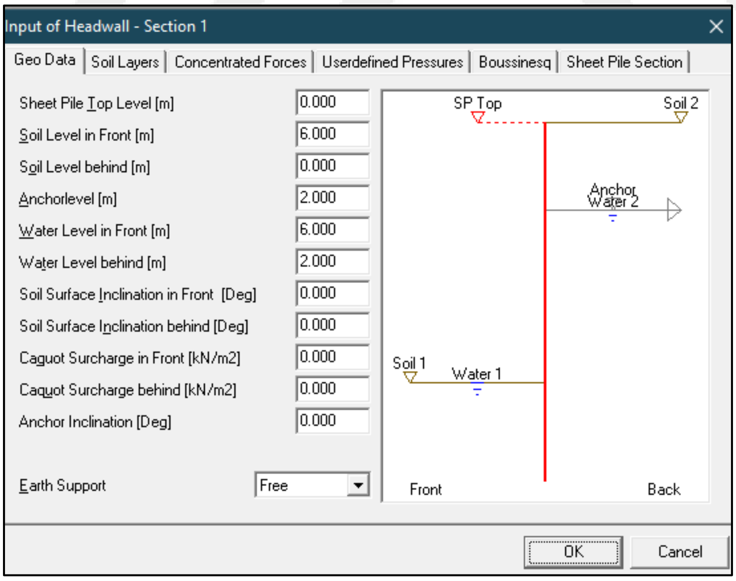


Figure 3.31: Geo Date in PROSHEET Program.

This window requires entering the following values: the level of the sheet pile, the level of soil and water behind the sheet pile, the level of soil and water in front of the sheet pile, and the level of the anchoring element.

It also gives one of the following options if the sheet pile is tied: Free or Fixed, and if the sheet pile is cantilevered, this study choose the cantilever option.

ii. The soil layer window was moved, and all the properties were entered for each soil layer behind and in front of the sheet pile.

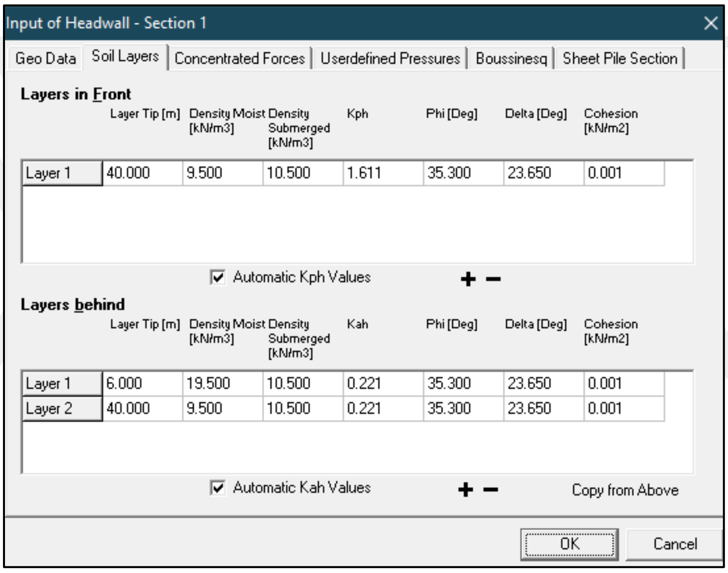


Figure 3.32: Soil Layers in the PROSHEET Program.

iii. The surcharge load value, width, and distance were entered from the sheet pile by the following window:

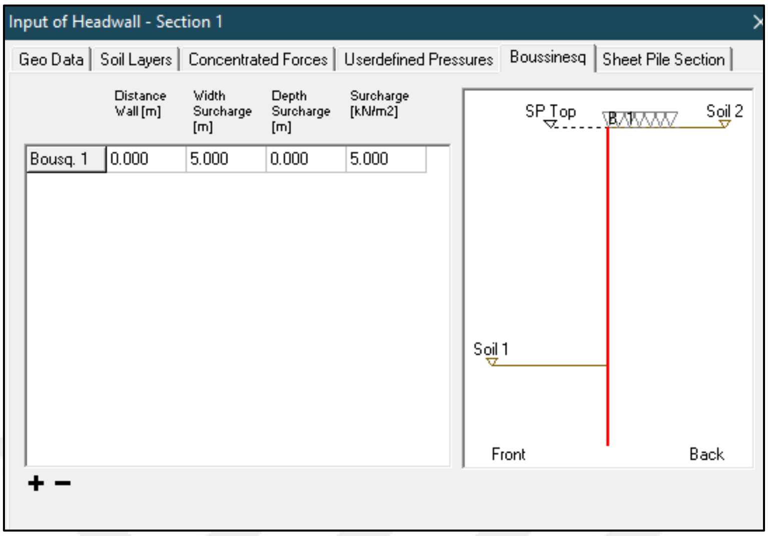


Figure 3.33: Surcharge Load Window.

iv. In the final step, the sheet pile section was entered by choosing AZ46-700 N sheet pile with steel grades S355GP.

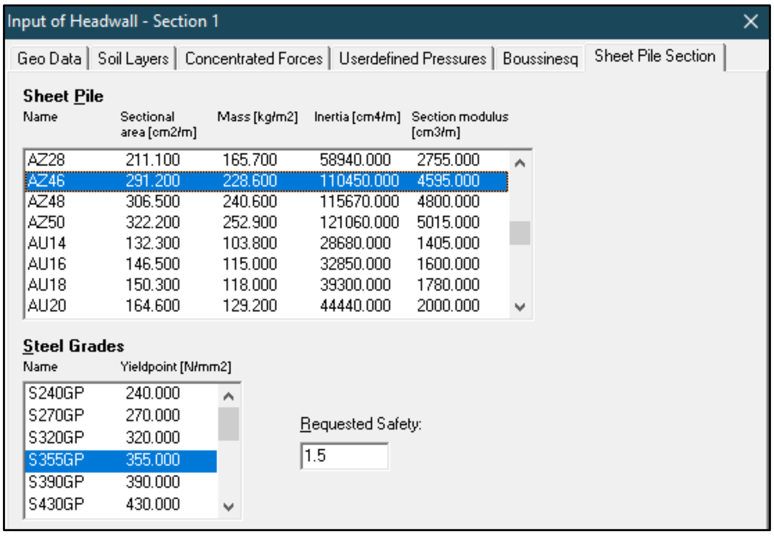


Figure 3.34: Sheet Pile Section.

v. After entering all required data in the input window, the PROSHEET gives results by drawing a horizontal deflection diagram, driven depth, horizontal pressure, static water pressure and moment diagram as illustrated in Figure 3.35 and Figure 3.36.

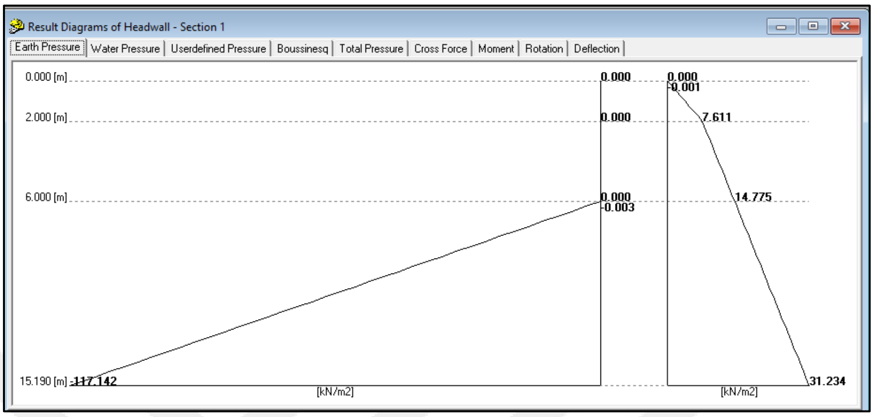


Figure 3.35: Earth Pressure Diagram.

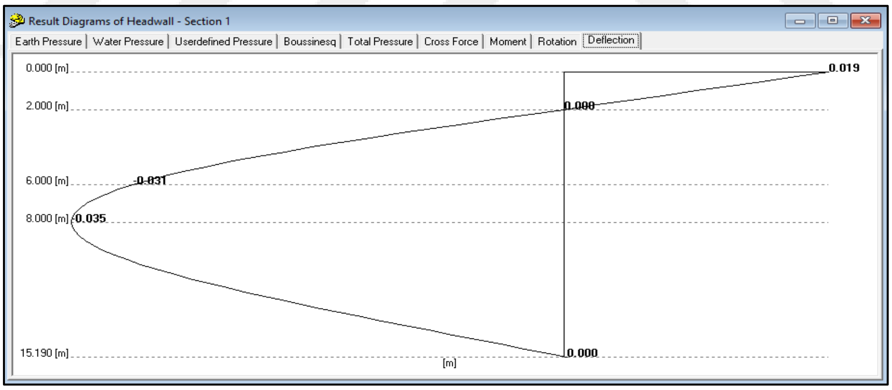


Figure 3.36: Deflection Diagram.

However, the PROSHEET program does not study the effects of more than one anchor so that all cases will be compared in both programs only by one anchor.

4. PARAMETRIC STUDY

In this research, there are two basic types of sheet piles (cantilever and anchorage sheet piles), and these sheet piles will be studied for three different types of soil in the absence of a water table and the presence of a water table with different depths.

4.1. THE FIRST CASE (SANDY SOIL)

4.1.1. Water Table at a Deep Depth: Dry Sand

Sandy soil was applied to two cantilever anchorage sheet piles for several dredge depths (0.3h-0.67h-h) with a surcharge load of 10 kN/m^2. The surcharge load was considered constant for all cases. The properties of the sheet pile for dredge level h=3m were different from the dredge level (h=5-6m) because, for h=5 m, there was instability when AZ46-700 N SO was used.

A higher properties section of the sheet pile is needed at the dredge level starting from 5m.

Table 4.1: Properties of Soil and Sheet.

Sandy soil	Sheet (h=3m)	Sheet (h=5m)	Sheet (h=6m)
Φ=35.3	EA=10.5E6 KN/m	EA=1.008E9 KN/m	EA=1.008E9 KN/m
$\boldsymbol{\gamma}_{dry}$=16.8 KN/$m^3$	EI=0.22E6 KN/m^2	EI=2.133E6 KN/m^2	EI=2.133E6 KN/m^2
C=0.001 KN/m^2	d=0.501m	d=0.503m	d=0.503m
E=30000 KN/m^2	υ=0.15	υ=0.15	υ=0.15
υ=0.3			
R_{inter}=0.67			

These different dredge depths in sandy soil restrained by a cantilever sheet were studied in the PLAXIS 2D program. The economic penetration depths were calculated for all cases, as well as calculating the obtained horizontal displacements, calculating the maximum moment values, and comparing these results with the Pro Sheet program for studying the sheet piles. The results are illustrated in Figure 4.1.

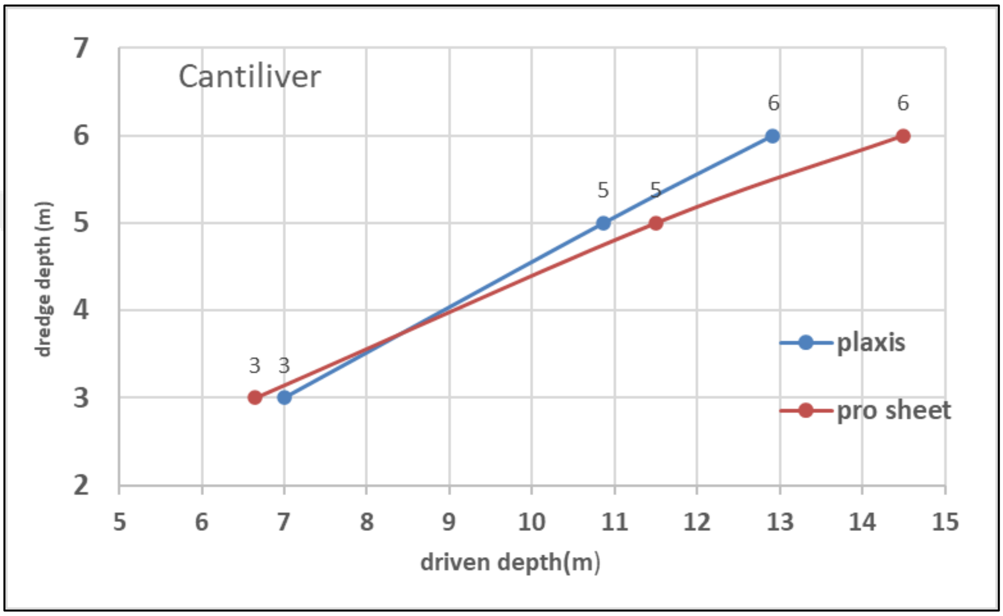


Figure 4.1: Economic Driven Depth of Cantilever Sheet Pile.

From the previous curve, the driven depth increases with the increase in the dredge level and the convergence of the values of the two programs significantly.

Values of horizontal displacements and moments along the sheet pile were imported from the PLAXIS 2D program. An excel chart drew these values to represent horizontal displacements and moments along the sheet pile, as shown in Figure 4.3 and Figure 4.4.

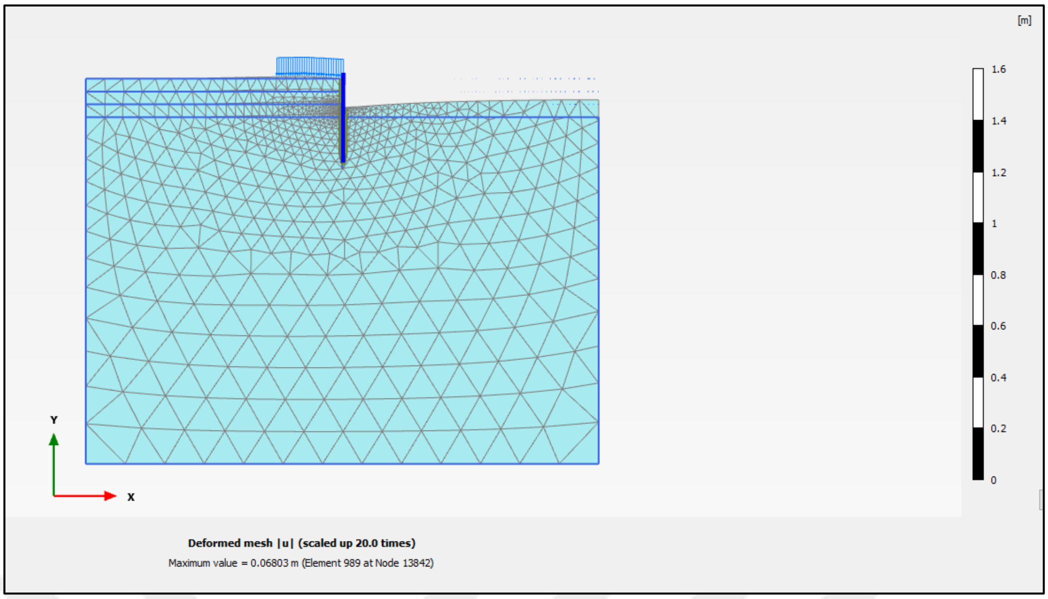


Figure 4.2: Deformed Mesh [u].

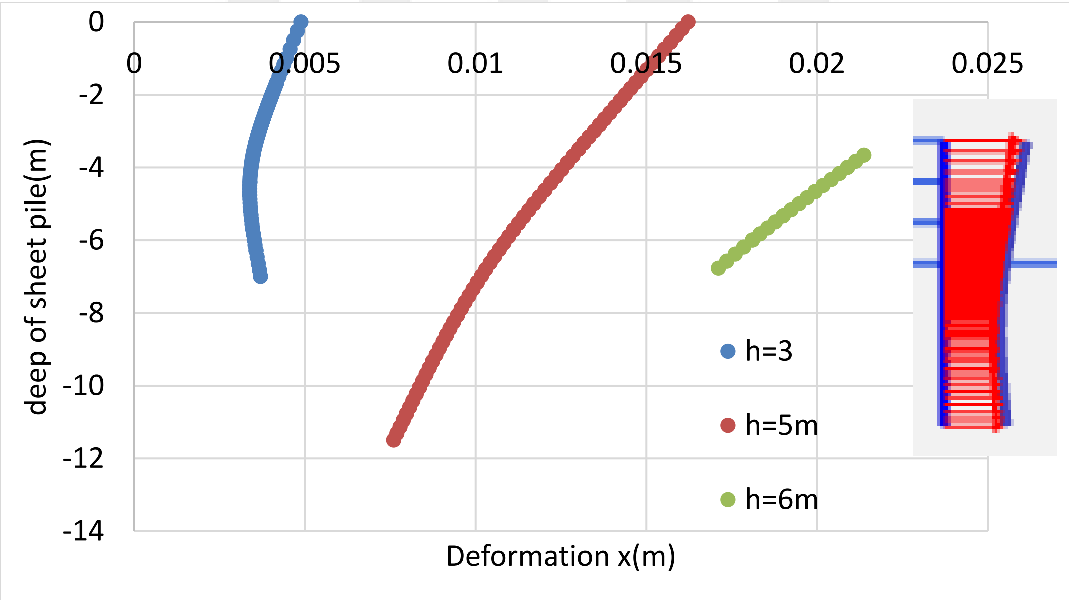


Figure 4.3: Horizontal Displacement Diagram of Sheet Pile for Different Dredge Levels.

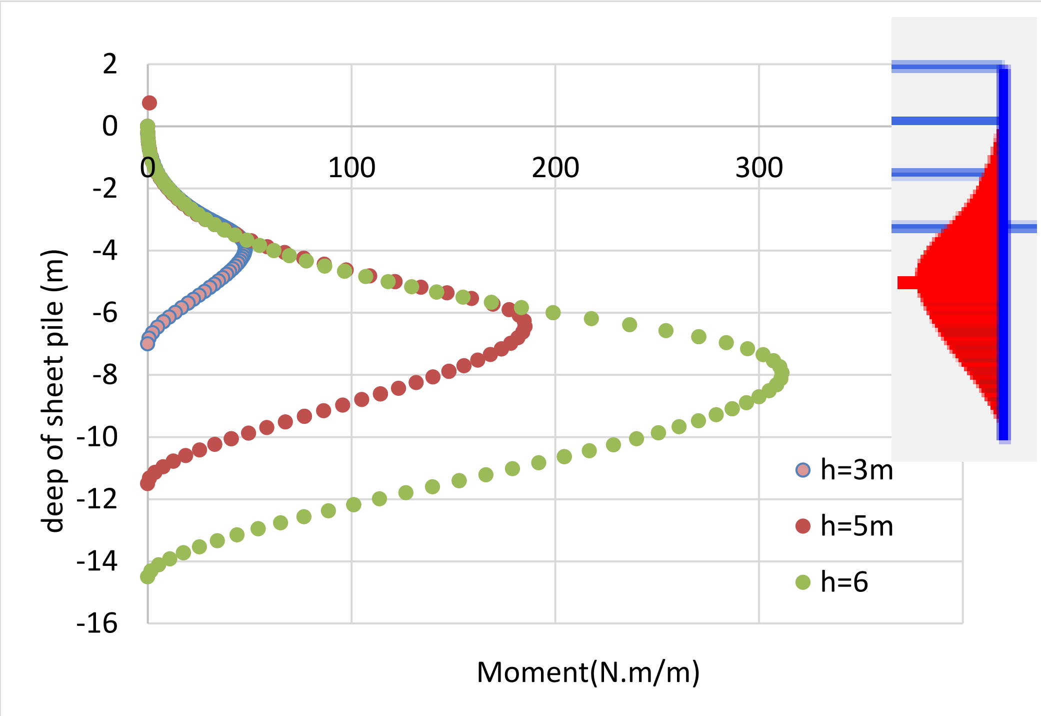


Figure 4.4: Moment Diagram of Sheet Pile for Different Dredge Levels.

The maximum values of moments and displacements of cantilever sheet piles in Figure 4.3and Figure 4.4 were compared with the maximum values of the PROSHEET program as illustrated in Figure 4.5 and Figure 4.6.

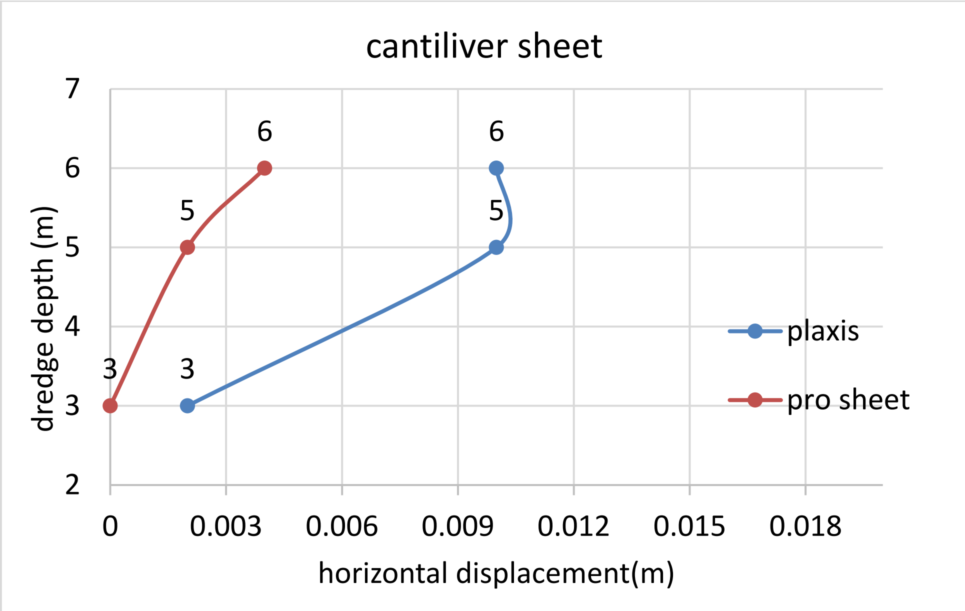


Figure 4.5: Deformation of Cantilever Sheet.

The displacement values increased with the increase in the dredge depth, and the values of the PLAXIS 2D program gave greater results for the displacement than the values of the pro sheet program.

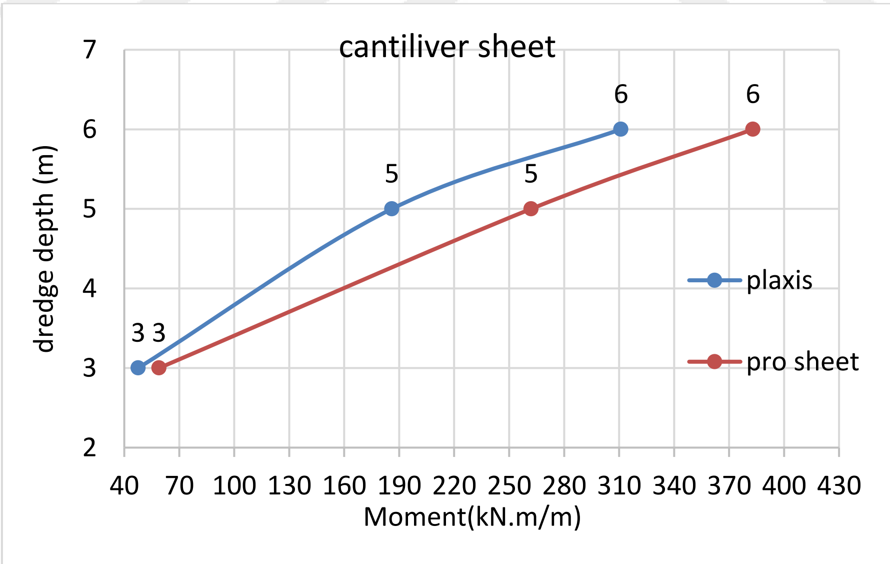


Figure 4.6: Moment of Cantilever Sheet Pile in Case of Different Dredge Depths.

The same was for the values of the maximum moments in Figure 4.5, where this study notice an increase in the value of the maximum moments with the increase in the values of the dredge depth and the convergence of the values of the moments for the two studied programs.

The same cases were looked at again, but this time for anchorage sheet piles. This was done to see how adding an anchor element to grouts affects driven depth, displacement, and maximum moment values for dredge depths.

The properties of anchors and grouted bodies are listed in Table 4.2 and Table 4.3.

Table 4.2: Properties of Anchor.

Anchor Properties (H=3m)	**Anchor Properties (H=5m)**	**Anchor Properties (H=6m)**
EA=50E3 KN/m	EA=2E5 KN/m	EA=200E3Kn/m
L=1.5m	L=3m	L=4m

Table 4.3: Properties of Grout.

Grout Properties (H=3m)	**Grout Properties (H=5m)**	**Grout Properties (H=6m)**
D=0.05m	D=0.3m	D=0.3m
L=1m	L=2m	L=3m

The PLAXIS 2D program calculated the driven depths, horizontal displacements, and moments, and all these values were compared with the pro sheet program. The curves for the sheet with the anchor are as follows.

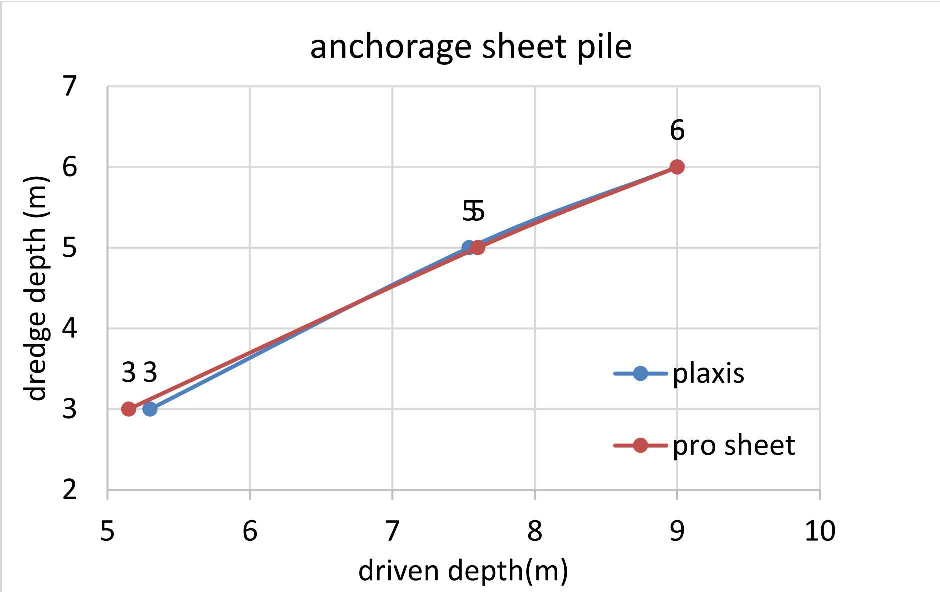


Figure 4.7: Driven depth of Sheet with Anchor.

Upon comparing Figure 4.1 and Figure 4.7, it was noticed that the driven depth in the case of the anchorage sheet pile is less than one in the cantilever sheet pile.

As this study did in the cantilever sheet pile, values of horizontal displacements and moments along the anchorage sheet pile were imported from the PLAXIS 2D program. An excel chart drew these values to represent horizontal displacements and moments along the anchorage sheet pile, as shown in Figure 4.9 and Figure 4.10.

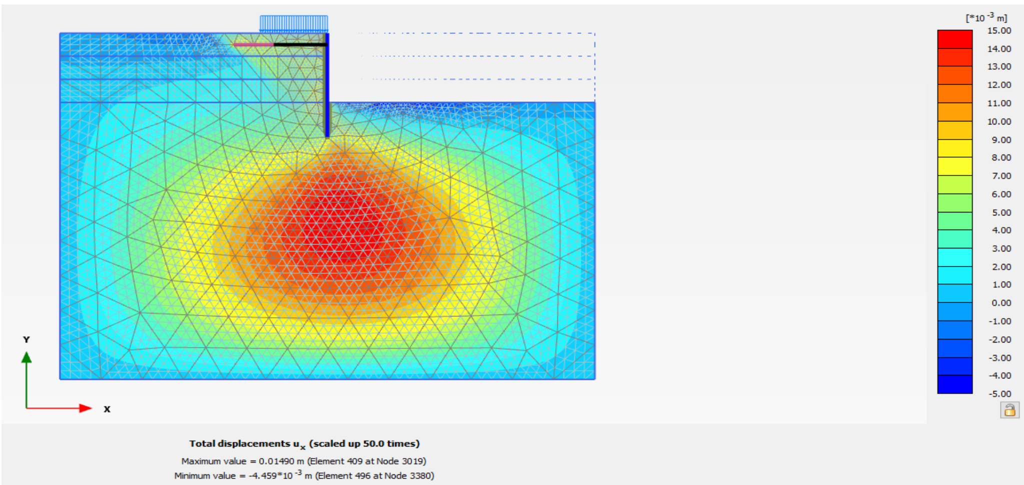


Figure 4.8: Total Displacement U_x.

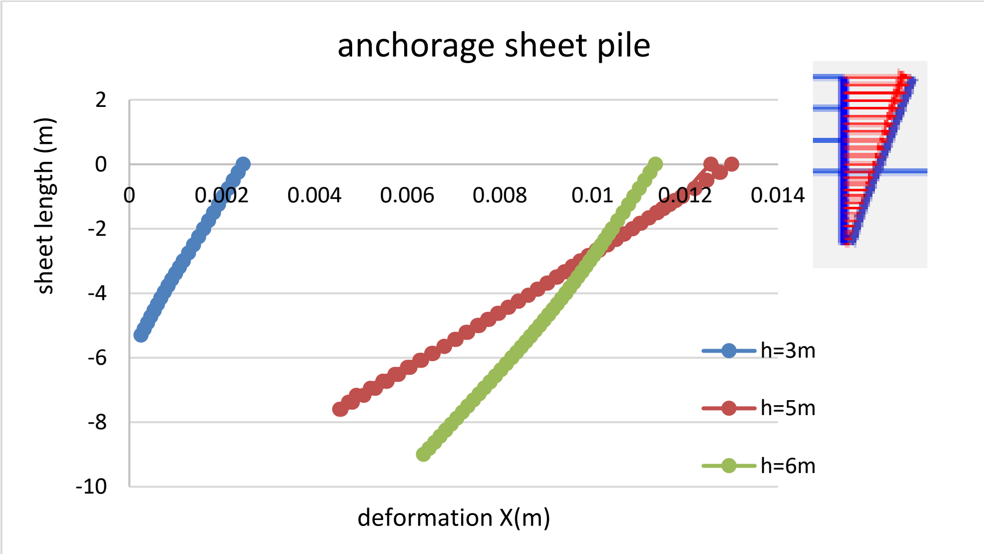


Figure 4.9: Deformation Diagram of Anchorage Sheet.

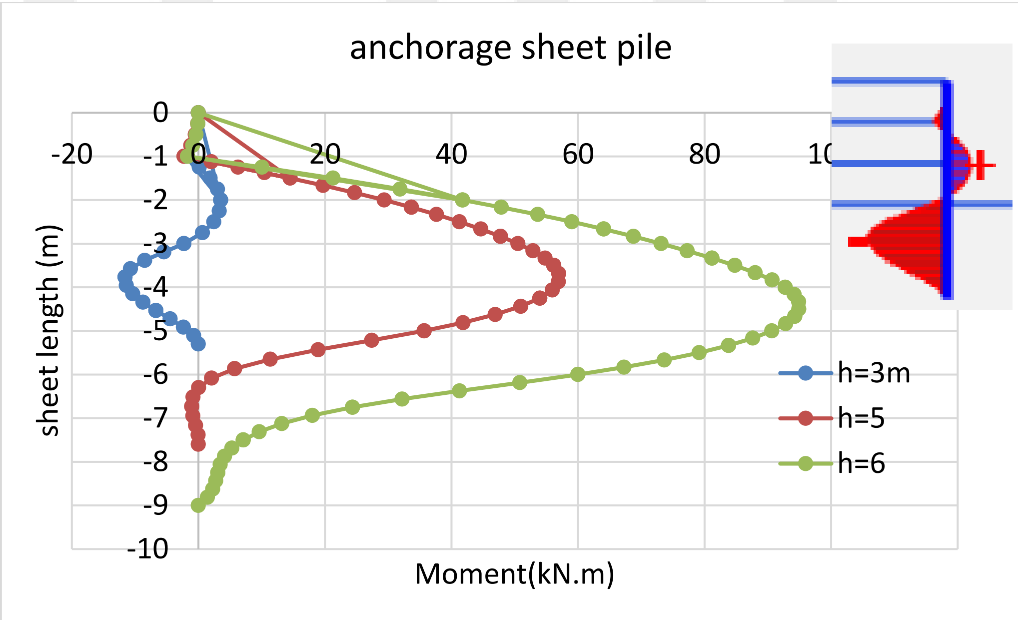


Figure 4.10: Moment Diagram of Anchorage Sheet.

The maximum values of moments and displacements of anchorage sheet piles in Figures 4.9 and 4.10 were compared with the maximum values of the PROSHEET program as illustrated in Figure 4.11 and Figure 4.12.

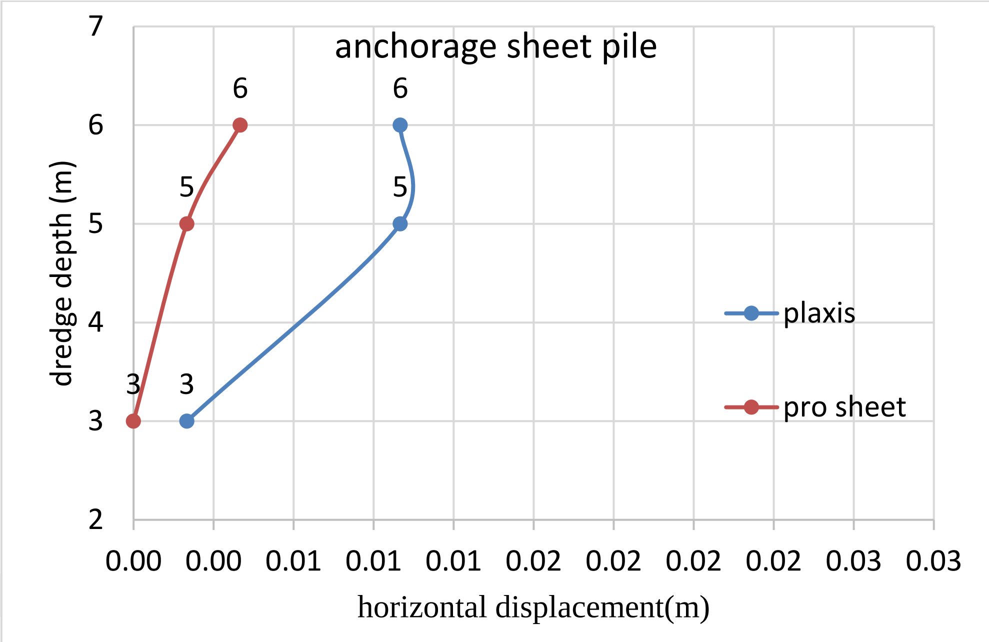


Figure 4.11: Deformation of the Sheet with Anchor.

The values of the horizontal displacement of anchorage sheet piles were less than in the Cantilever sheet pile. The PLAXIS 2D program gave a higher value for the displacement than the values of the pro sheet program.

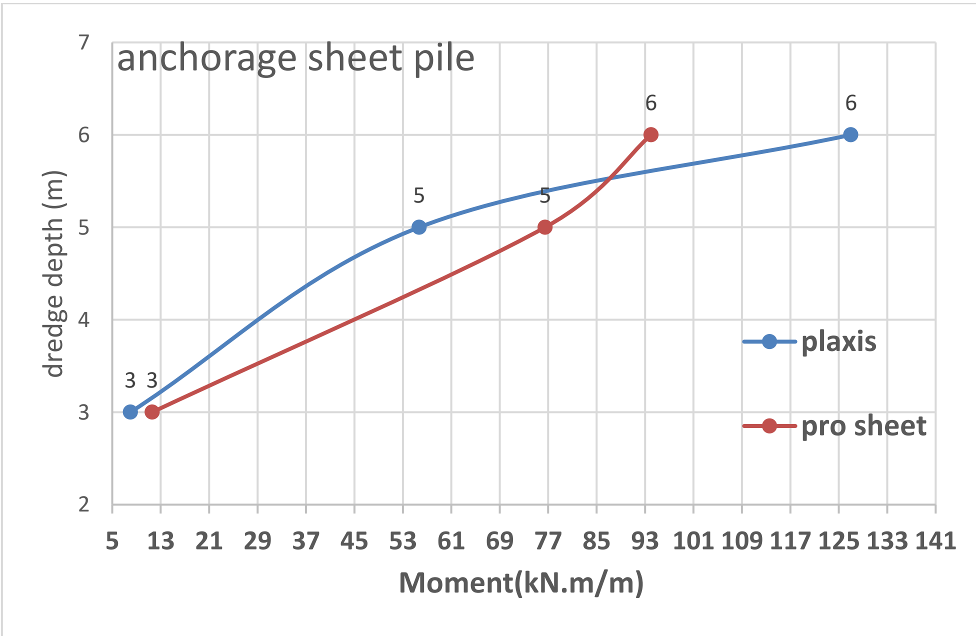


Figure 4.12: Moment of the Sheet with Anchor.

Also, the values of the maximum moments in the anchorage sheet were less than in the cantilever plates.

4.1.2. Water Table Effects:

In this case, the same type of soil was studied on the two types of cantilever sheet pile, anchorage sheet, and for several dredge depths, in the case of a water table with different depths to show the effect of the presence of water on the driven depths, moments, and displacements. The numerical study was carried out utilizing the PLAXIS 2D, and the outcomes were compared to the PROSHEET program results.

First, the cantilever sheet pile was studied at different water table levels (hw=1.5,3.5,5 m from the ground surface), and the following table shows the properties of the soil and the sheet pile used.

Table 4.4: Properties of Soil and Sheet Pile with Water Table Case.

Sandy soil	Sheet
Φ=35.3	EA=12E6KN/m
γ_b=19.5 KN/m^3	EI=5.75E6KN/m^2
γ_{sat}=20.5KN/m^3	υ=0.15
C=0.001 KN/m^2	w=20 KN/m
E=30000	
υ=0.3	
R_{inter}=0.67	

Values of Horizontal displacements and moments along the cantilever sheet pile were imported from the PLAXIS 2D program, and these values were drawn by excel chart to represent horizontal displacements and moments along the cantilever sheet pile in the case of water table presence as shown in Figure 4.13 and Figure 4.14.

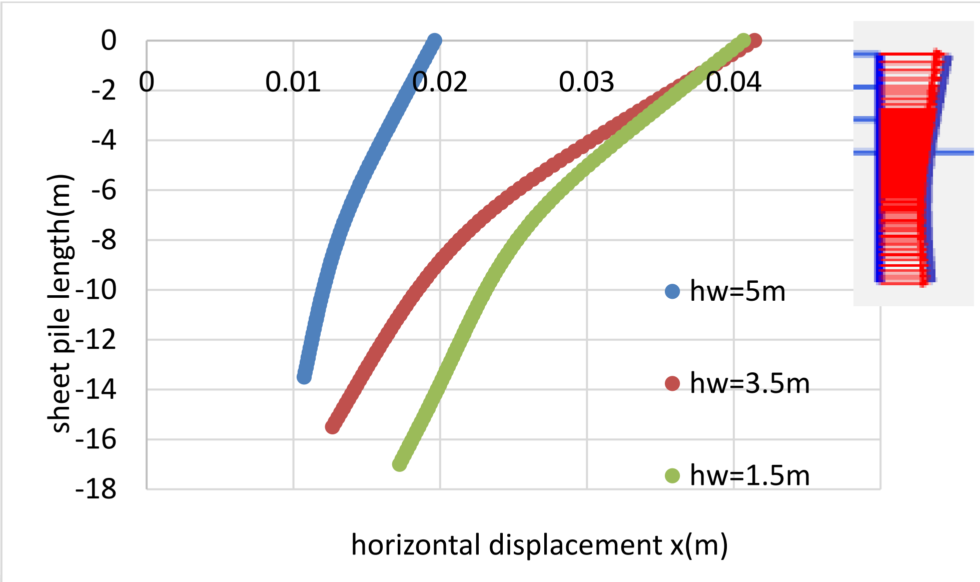


Figure 4.13: Deformation X Curves of Cantilever Sheet with Water Table.

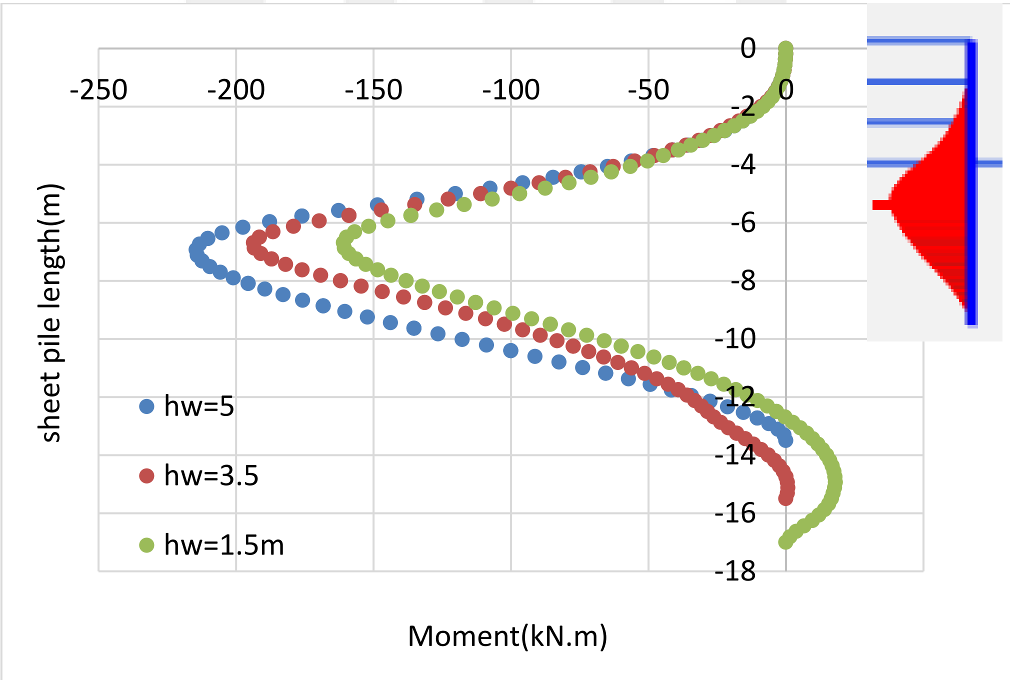


Figure 4.14: Moment Curves of Cantilever Sheet with Water Table.

The penetration depths and horizontal displacements were compared between the two programs for different water table levels and by applying a homogeneously distributed loadings on top of the sheet pile of 5 KN/m^2.

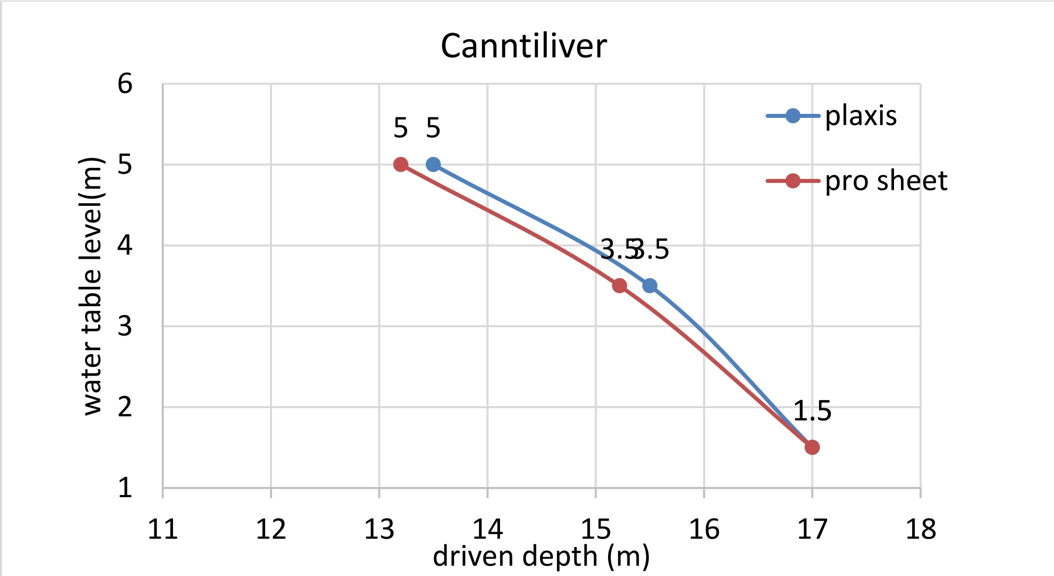


Figure 4.15: Driven Depth of Cantilever Sheet Pile by Water Table Case.

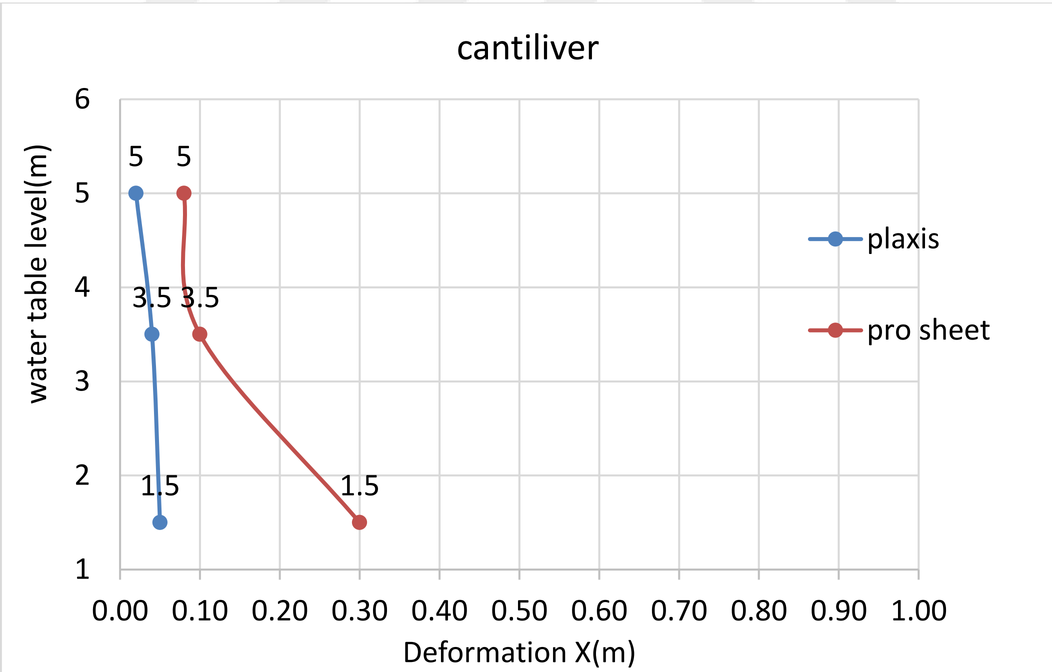


Figure 4.16: Deformation X of Cantilever Sheet by Water Table Case.

It was noticed from the previous two curves that the driven depth and displacements increase with increasing water table level in the case of a water table presence.

Also, the anchorage sheet pile was studied by placing the anchor element and the grout material, where the optimum economic values of the anchor and grout element were calculated in various water table levels by applying a homogeneously distributed loading of 5kN/m^2 on top of the sheet pile the following table shows the characteristics of the sheet pile, anchor, and grout**.**

Table 4.5: Properties of Sheet Pile and Anchor and Grout with Water Table.

Sheet pile with anchor	Anchor properties	Grout properties
EA=12E6 KN/m	EA=3E5 KN/m	D=0.4m
EI=5.75E6 KN/m^2	L=8m	L=4m
υ=0.15		
w=20 KN.m		

Values of Horizontal displacements and moments along the anchorage sheet pile were imported from the PLAXIS 2D program. An excel chart drew these values to represent horizontal displacements and moments along the cantilever sheet pile in case of water table presence, as shown in Figures 4.15 and 4.16.

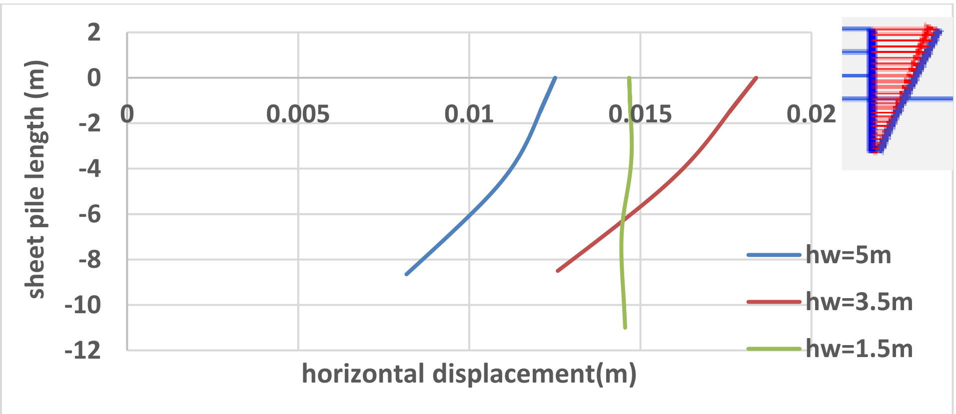


Figure 4.17: Deformation X Curves of Sheet with Anchor with Water Table.

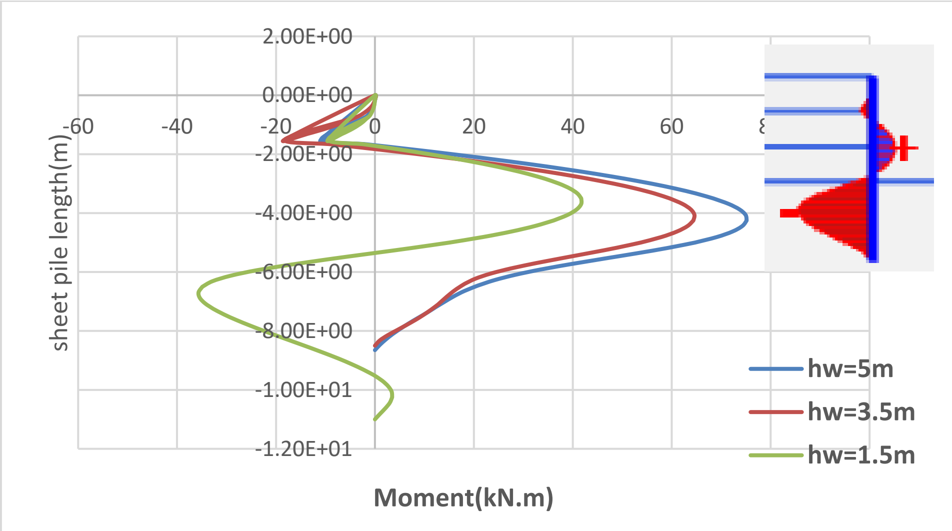


Figure 4.18: Moment Curves of the Sheet with an Anchor with Water Table.

As in the cantilever sheet pile, this thesis studied the driven depth and the horizontal displacements in the anchorage sheet pile, and compared the results between the program PLAXIS 2D and PROSHEET.

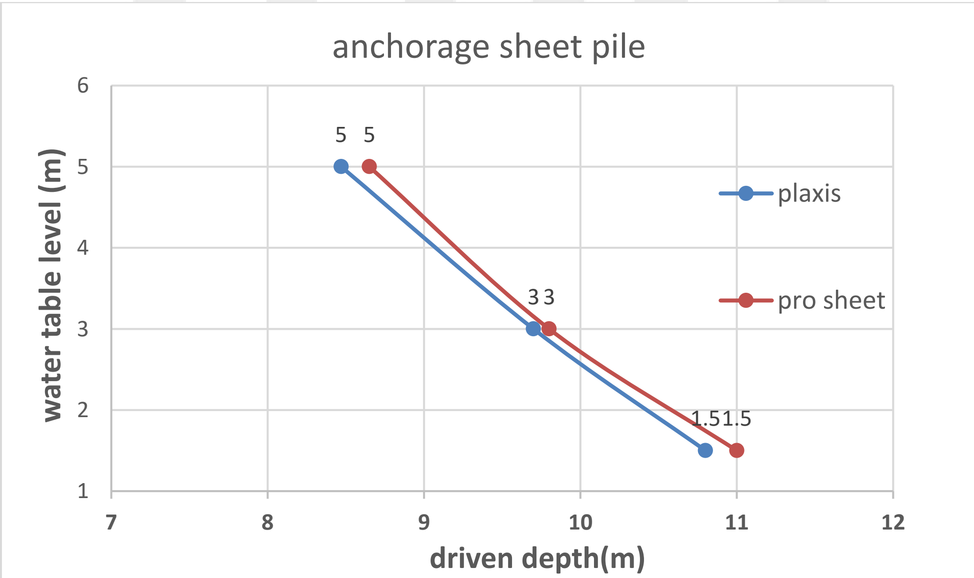


Figure 4.19: Driven Depth of Anchorage Sheet Pile with Water Table.

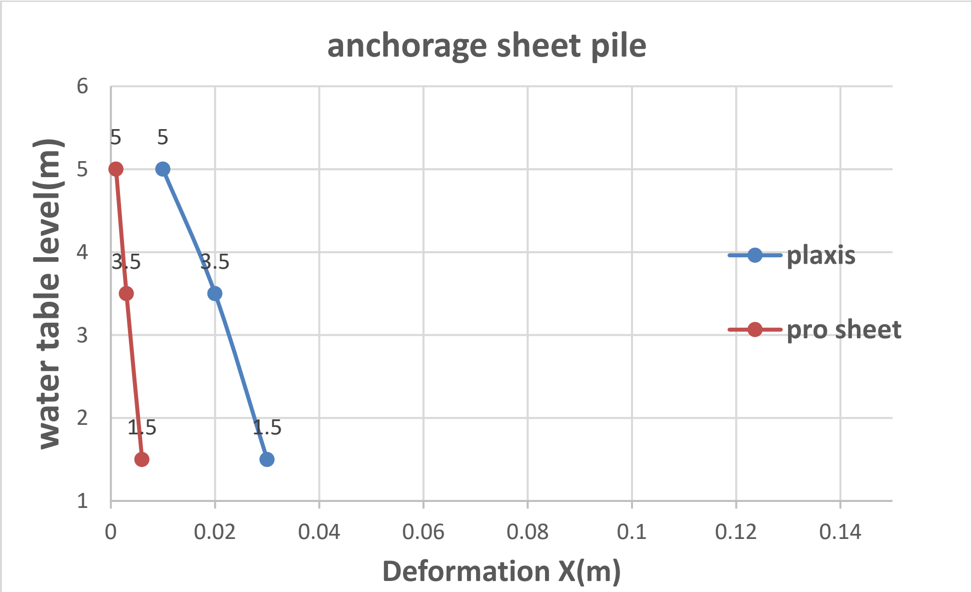


Figure 4.20: Deformation X of Anchorage with Water Table.

As in the anchorage sheet pile case, the driven depth and displacements increase with the water table level in the case of a water table in the anchorage sheet pile.

4.1.3. Effects of Anchor Distance from Surface Ground (y):

To know the effects of anchor distance from the surface ground (y) in the case of anchorage sheet pile restrain dry sand soil by considering the water table at a deep depth from the surface ground. As this thesis mentioned, anchor distance was taken (0.2h-0.3h-0.5h) as a variable to study this case, which (h) represents dredge level, as this study mentioned before. The dredging depth was constant (H), equal to 5m, and the driven depth was 2.6m. The properties of sheet pile, anchors, and grout body are illustrated in Table 4.6.

Table 4.6: Properties of Anchorage Sheet Pile in Case of Anchor Distance from Ground.

Sheet pile	Anchor	Grout
EA=100.2E6 KN/m	EA=2E5 KN/m	D=0.3m
EI=2.096E6 KN/m^2	L=3m	L=2m

Table 4.6: Properties of Anchorage Sheet Pile in Case of Anchor Distance from Ground. "Table Continued"

υ=0.15		
w=20 KN/m		
d=0.501m		

Values of horizontal displacements and moments along the anchorage sheet pile were imported from the PLAXIS 2D program. An excel chart drew these values to represent horizontal displacements and moments along the cantilever sheet pile in the case of water table presence, as shown in Figures 4.21 and 4.22.

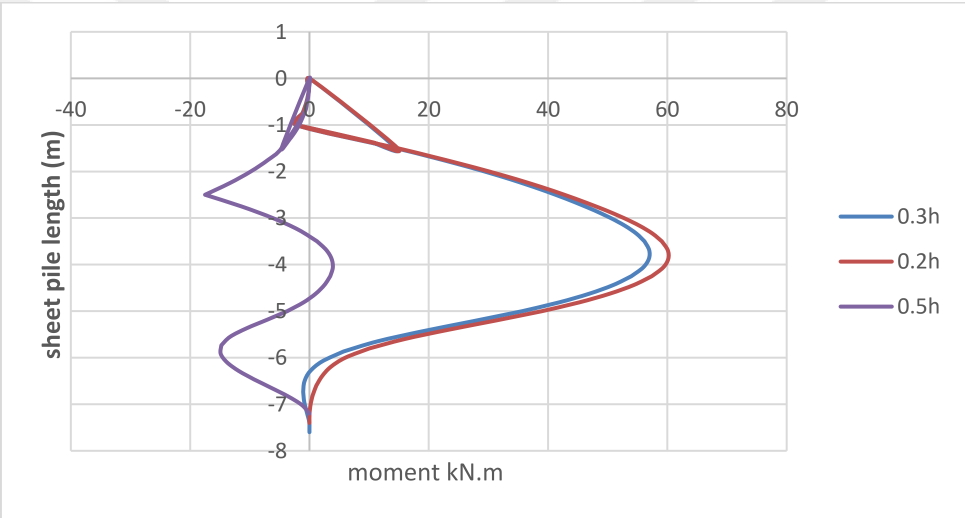


Figure 4.21: Moment Diagram of Anchorage Sheet Pile (Case Anchor Distance).

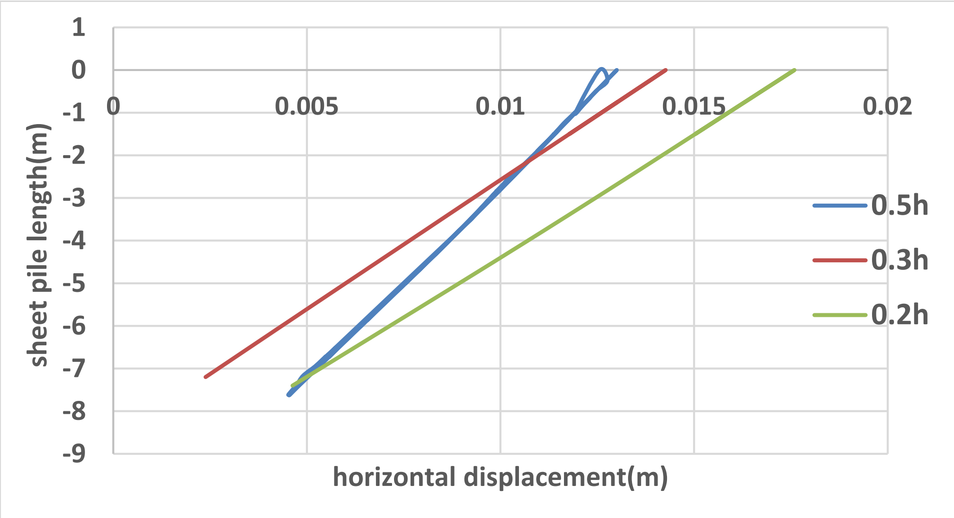


Figure 4.22: Horizontal Displacement Diagram of Anchorage Sheet Pile (Case Anchor Distance).

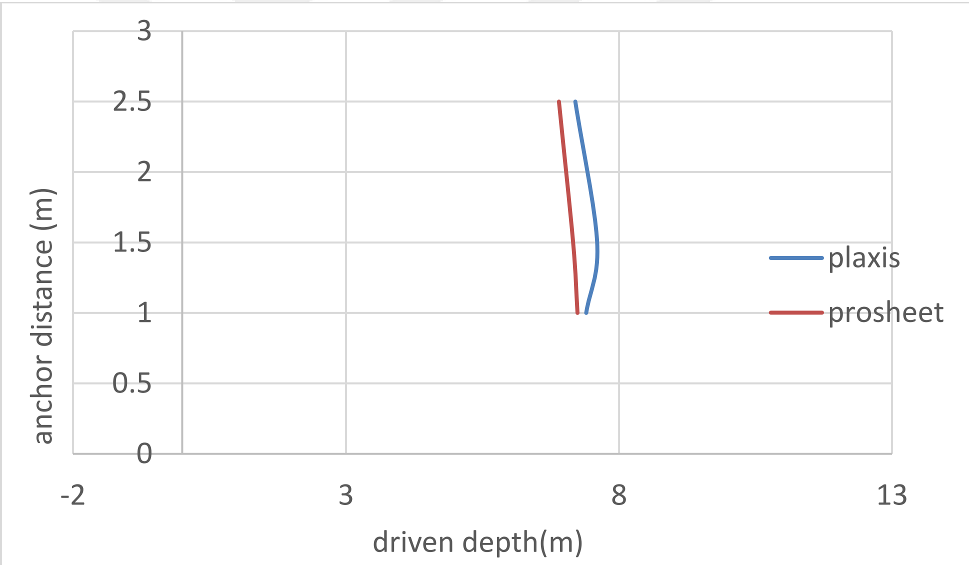


Figure 4.23: Driven Depth of Anchorage Sheet Pile (Case Anchor Distance).

Figure 4.23 shows that the distance of the anchor from the ground surface has little effect on driven depth, which slowly decreases by increasing the distance from the ground surface. Also, PROSHEET and PLAXIS 2D give close results.

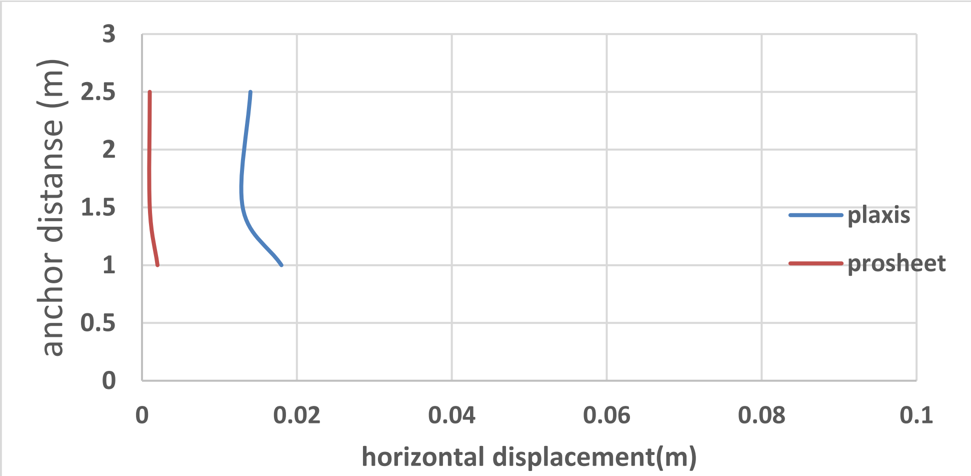


Figure 4.24: Horizontal Displacement of Anchorage Sheet Pile (Case Anchor Distance).

Figure 4.24 shows that horizontal displacement is constant in changing the anchor distance from the surface ground, which means there are no effects of changing the anchor distance from the surface ground.

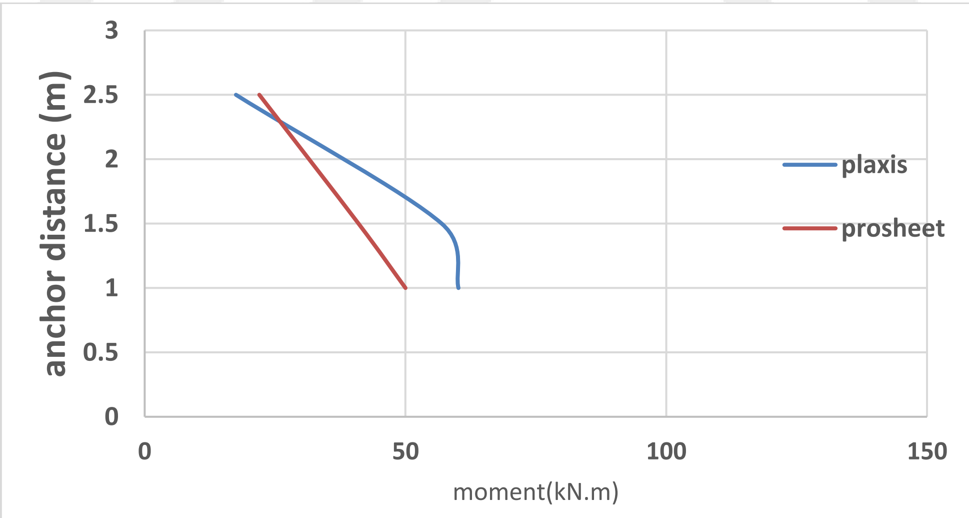


Figure 4.25: Moment of Anchorage Sheet Pile (Case Anchor Distance).

Figure 4.25 shows a decrease in the maximum moment, whereas the distance of the anchor from the surface increased. In addition, the two programs' values convergence was significantly enhanced.

4.1.4. Number of Anchors Effects

In this section, the number of anchors was studied by comparing the behavior of sheet pile in the case of one and two anchors by calculating moments, deformation, and driven depth in two cases.

The cases were studied only in the PLAXIS 2D because the PROSHEET does not consider more than one anchor. The sheet pile, anchors, and grouted body properties are illustrated in Table 4.6.

The first anchor was set at a depth of 1.5 m, while the second was set at a depth of 2.5 m below the earth.

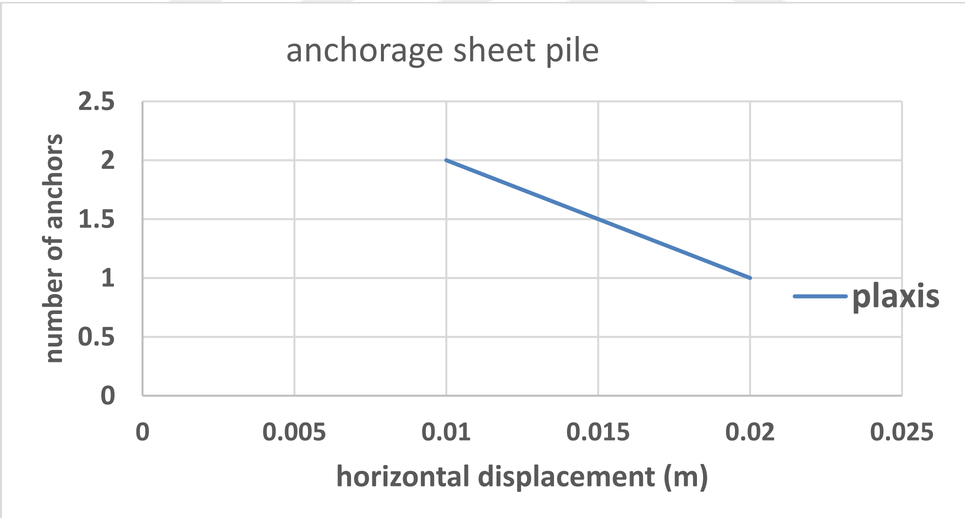


Figure 4.26: Horizontal Displacement of Anchorage Sheet Pile (Case Number of Anchor).

Figure 4.26 shows that a remarkable decrease in horizontal displacement is caused by an increasing number of anchors.

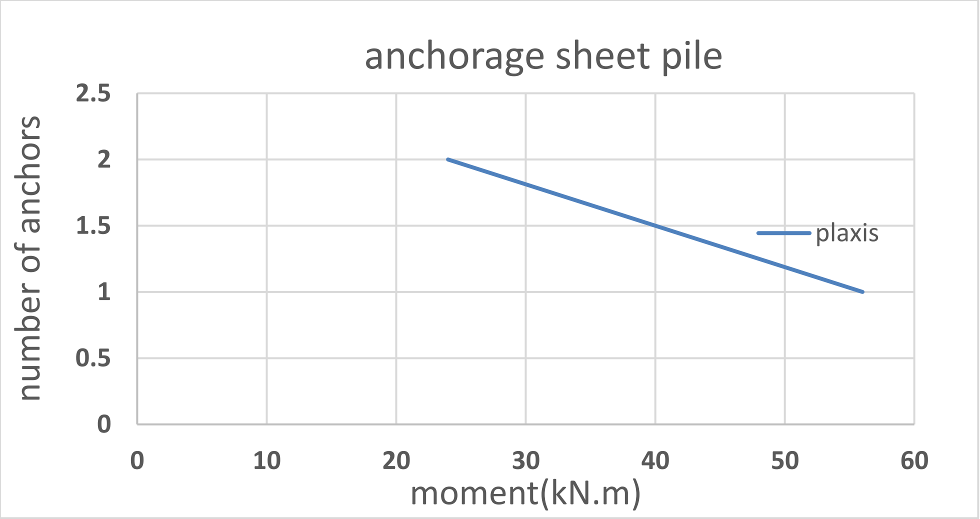


Figure 4.27: Moment of Anchorage Sheet Pile (Case Number of Anchor).

Figure 4.27 shows that maximum moment is reduced by 50 % when two anchors are used.

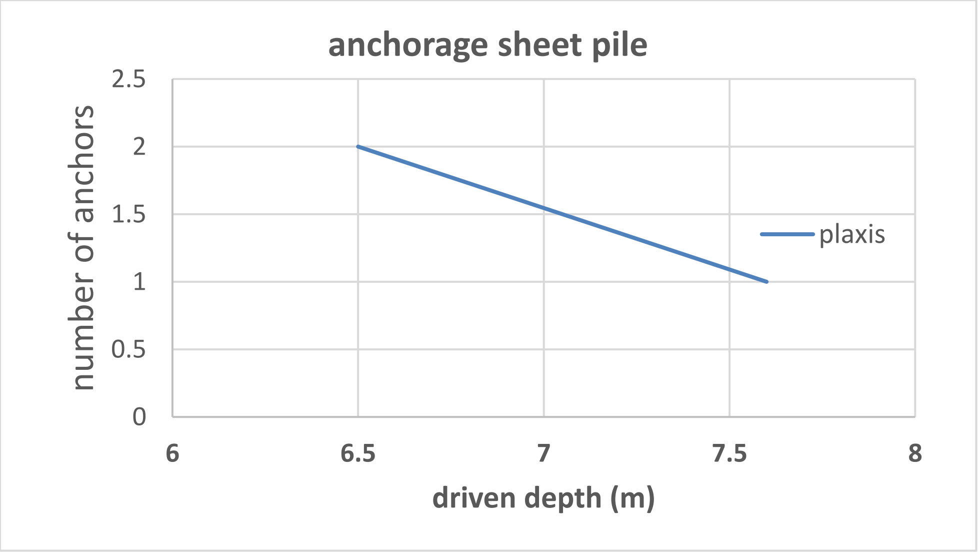


Figure 4.28: Driven Depth of Anchorage Sheet Pile (Case Number of Anchor).

Also, Figure 4.28 shows that the driven depth was reduced 1m by using two anchors.

4.1.5. Distance Between Anchors Effects

In this section, several anchors were studied by comparing the behavior of sheet piles in the case of one and two anchors by calculating moments, deformation, and driven depth in two cases.

The cases were studied only in the PLAXIS 2D because the PROSHEET does not consider more than one anchor. Table 4.6 shows what the sheet pile, the anchors, and the grouted body are like.

The distance of the first anchor from the ground surface was 1.5m and the second anchor from the ground surface was 2.5 m.

The distance between anchors had no effect on the driven depth because the economical driven depth was a constant value of 7.6m.

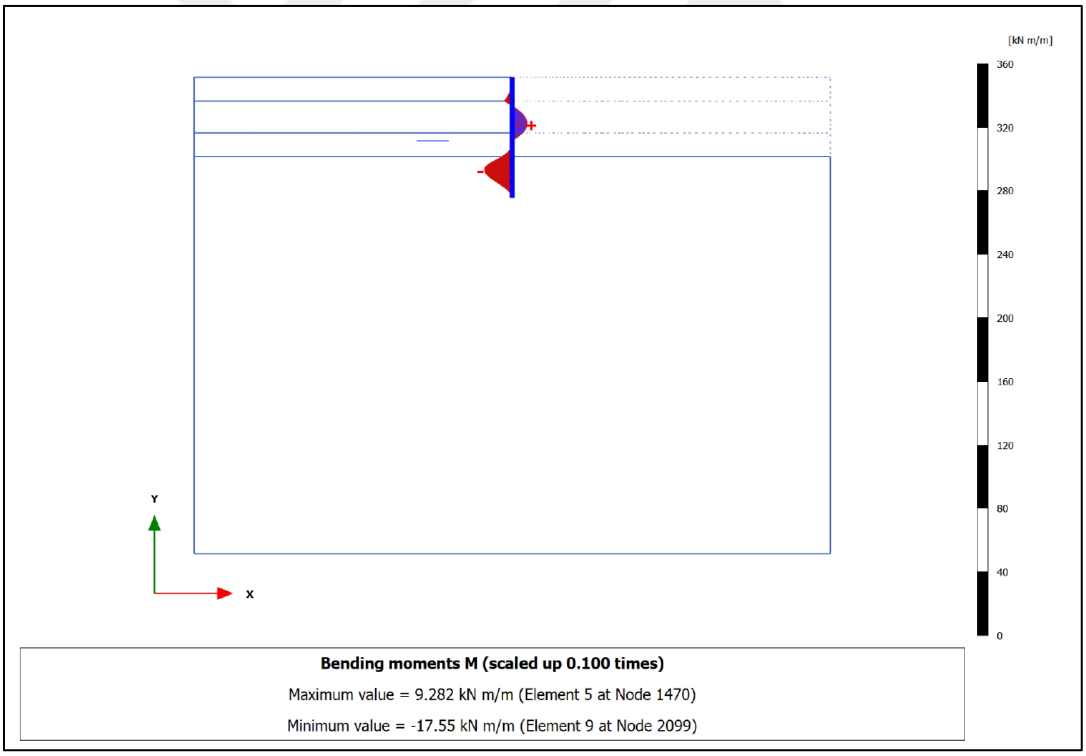


Figure 4.29: Bending Moments M.

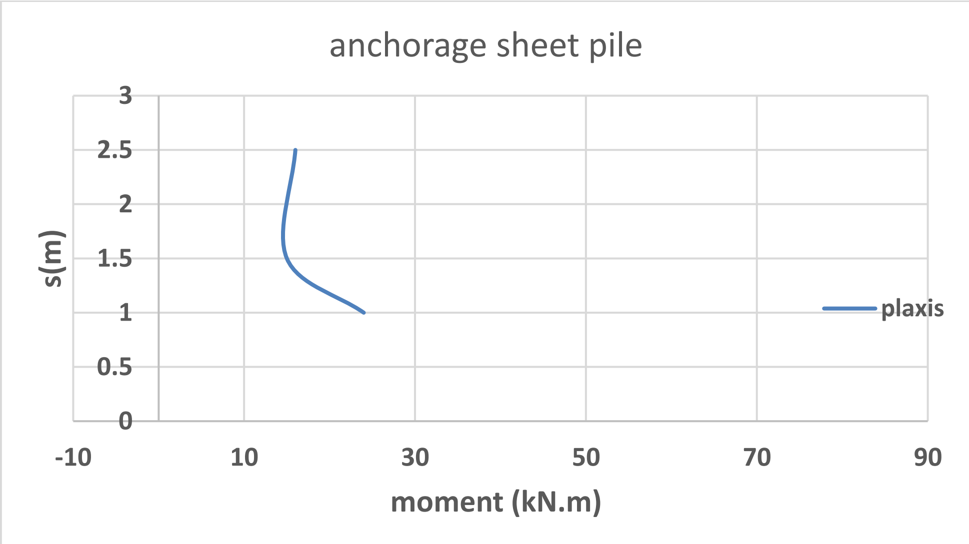


Figure 4.30: Moment of Anchorage Sheet Pile (Case Distance Between Anchors).

Also, Figure 4.30 shows little reduction in the moment with increasing distance between anchors. Consequently, the distance between anchors has not much effect on the moment.

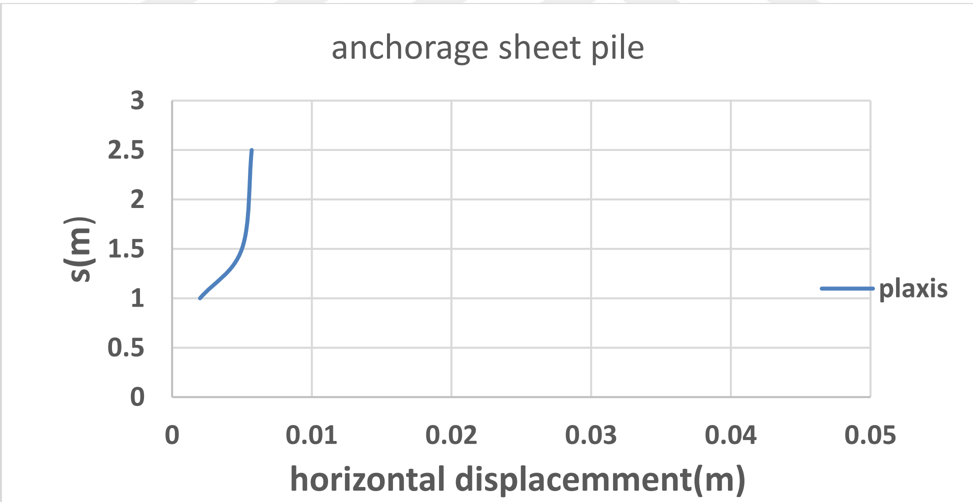


Figure 4.31: Horizontal Displacement of Anchorage Sheet Pile (Case Distance Between Anchors).

Figure 4.31 shows that the distance between anchors has not had much effect on horizontal displacement.

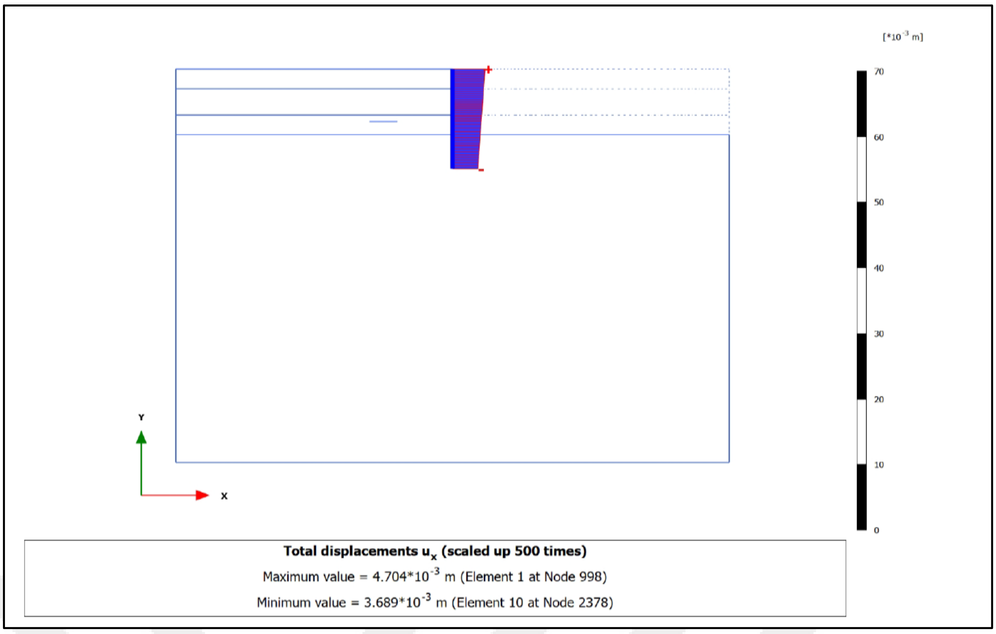


Figure 4.32: Total Displacement U_x.

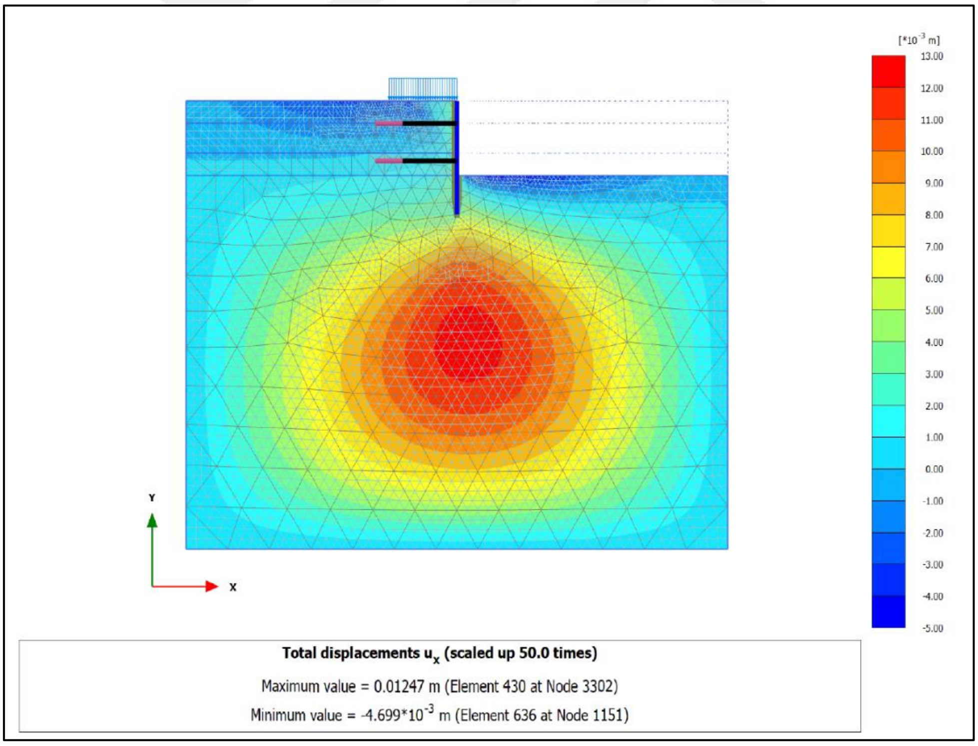


Figure 4.33: Total Displacement U_x.

4.2. SECOND CASE (SANDY CLAY SOIL)

4.2.1. Water Table Effects

In this case, the same type of sandy clay soil was studied for two types: cantilever sheet pile and anchorage sheet pile. Different water table levels were investigated for several dredge depths (0.3H-0.67H) to demonstrate the effect of water table presence on calculating driven depth, moments, and horizontal displacements.

The numerical study was carried out using the PLAXIS 2D and compared to the PROSHEET program results. First, the cantilever sheet pile was studied at different depths of water (h_w=1.5,3.5,5m from the ground surface), and the following table shows the properties of the soil and the sheet pile used**.**

Table 4.7: Properties of Soil and Sheet Pile with a Water Table.

Sandy clay soil	**Sheet**
Φ=35	EA=12E6 KN/m
$\boldsymbol{\gamma_b}$=18 KN/m^3	EI=5.75E6 KN/m^2
$\boldsymbol{\gamma_{sat}}$=20KN/$m^3$	υ=0.15
C=25KN/m^2	w=20KN/m/m
E=25600 KN/m^2	
υ=0.3	
R_{inter}=0.67	

Economical penetration depths and horizontal displacements were compared between the two programs at different dredge levels (0.3H-0.67H-H) and by applying a homogeneously distributed loading on top of the plate at 5 kN/m^2.

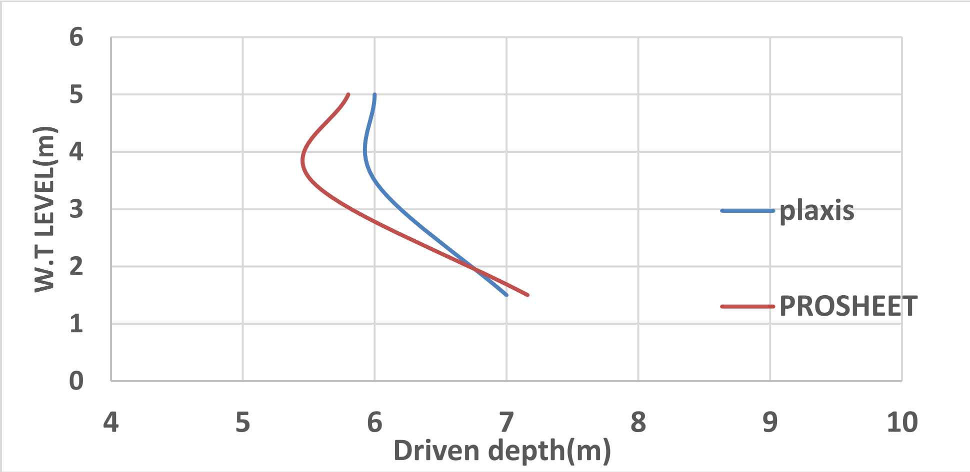


Figure 4.34: Driven Depth of Cantilever Sheet Pile (Case Water Table).

This study notices from the previous figure that the driven depth increases with increasing water table level in the case of a water table presence.

Values of moments along the sheet pile were imported from the PLAXIS 2D program, and these values were drawn by excel chart to represent moments along the cantilever sheet pile as shown in figure 4.35.

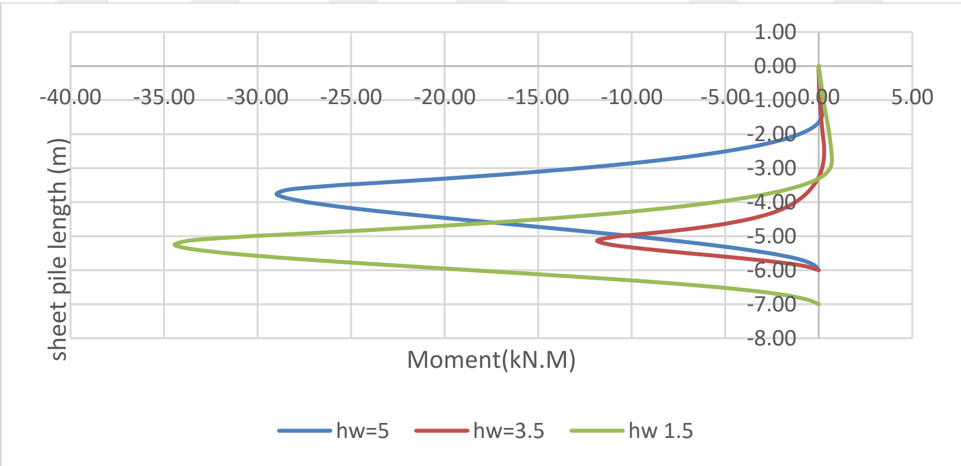


Figure 4.35: Moment Diagram of Cantilever Sheet Pile (Case Water Table).

Figures 4.36 and 4.37 show how the maximum values of moments in cantilever sheet piles from the PLAXIS 2D program were compared with the maximum values from the PROSHEET program.

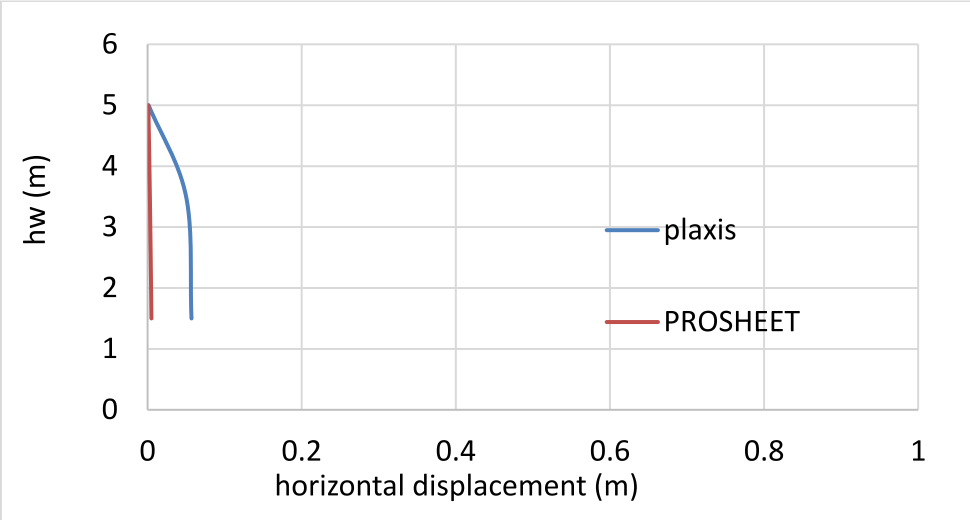


Figure 4.36: Horizontal Displacement of Cantilever Sheet Pile (Case Water Table).

It was noticed from Figure 4.36 that there is no effect on horizontal displacement in the case of different levels of the water table. Horizontal displacement is almost constant for the two programs.

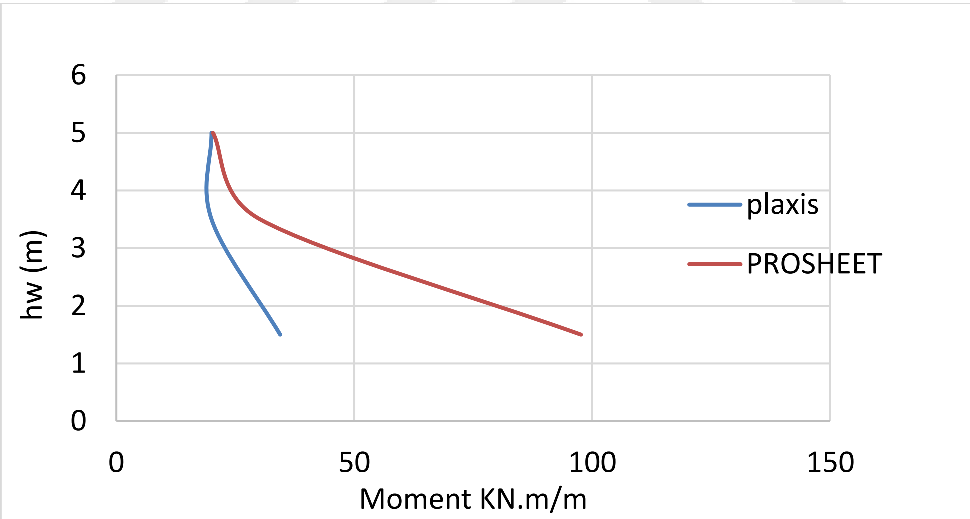


Figure 4.37: Moment of Cantilever Sheet Pile (Case Water Table).

It was noticed from Figure 4.37 that the moment increases with an increasing water table level in the case of a water table presence.

Also, the anchorage sheet pile was studied by placing the anchor element and the grout material, where the optimum economic values of the anchor and grout element were calculated at various dredge levels by applying a uniformly distributed load 5kN/m^2on top of the sheet pile, and table 4.5 shows the characteristics of the sheet pile, anchor, and grout.

Values of moments along the sheet pile were imported from the PLAXIS 2D program, and these values were drawn by excel chart to represent moments along the cantilever sheet pile, as shown in Figure 4.38.

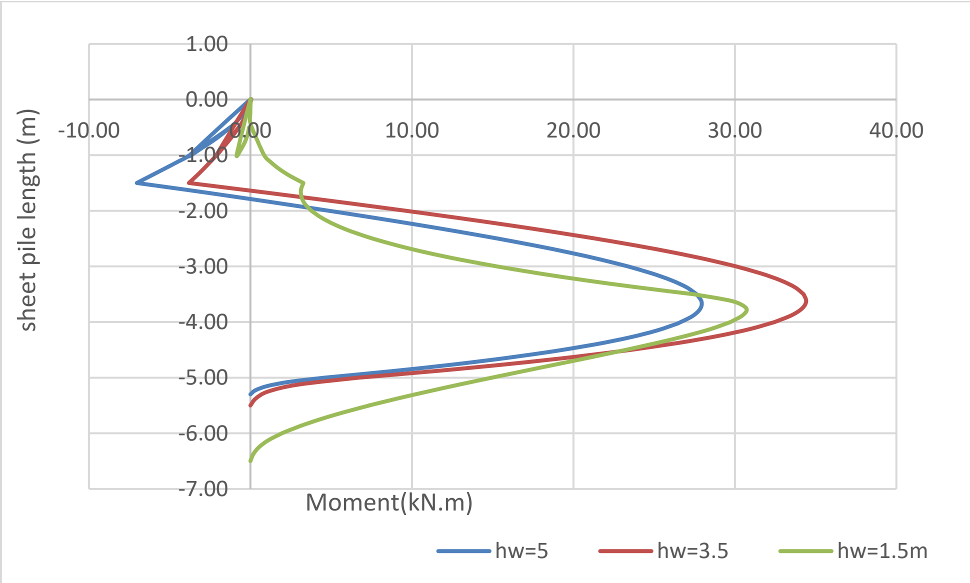


Figure 4.38: Moment Diagram of Anchorage Sheet Pile (Case Water Table).

As in the cantilever sheet pile, this thesis studied the driven depth, horizontal displacements, and moments in the anchorage sheet pile. The results were compared between the programs PLAXIS 2D and PROSHEET.

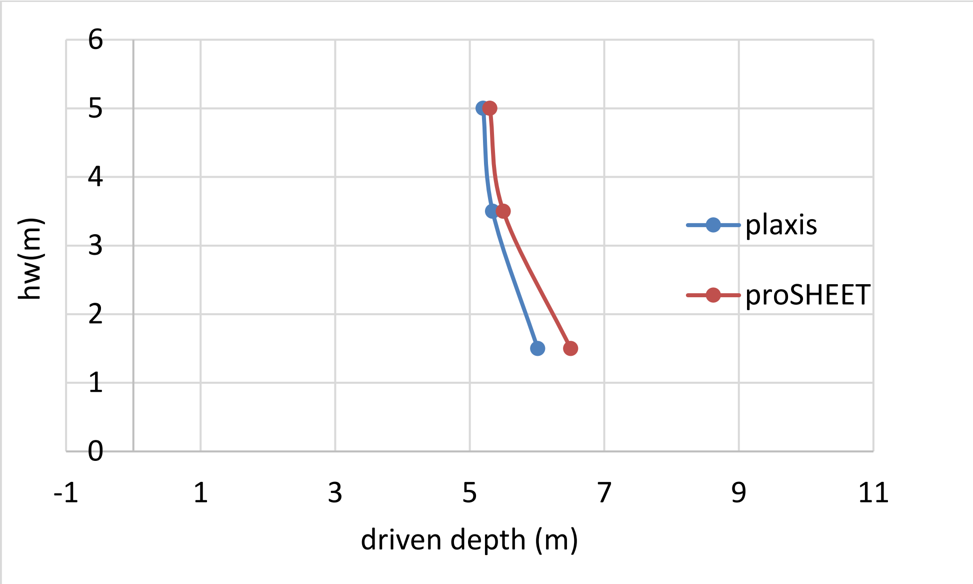


Figure 4.39: Driven Depth of Anchorage Sheet Pile (Case Water Table).

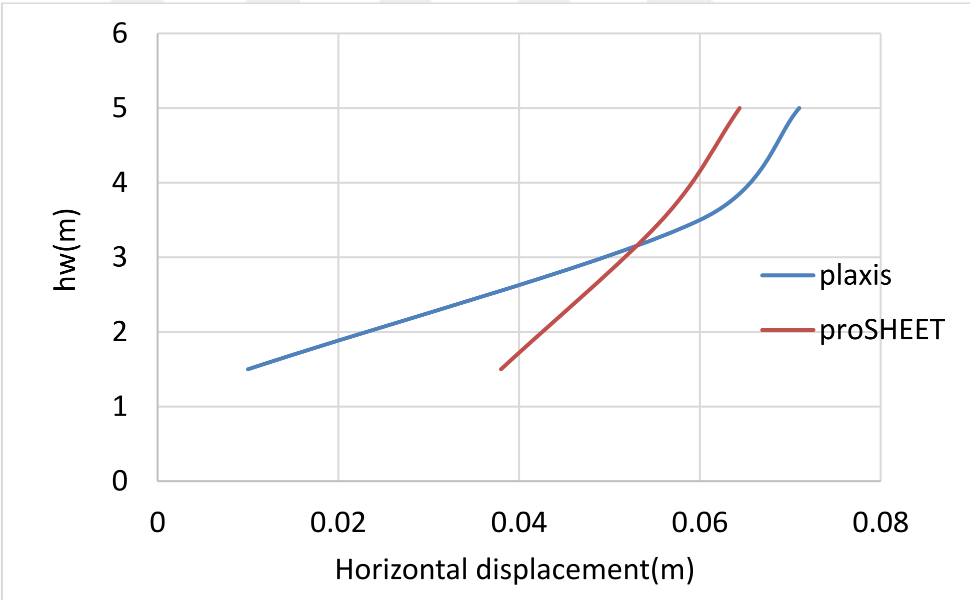


Figure 4.40: Horizontal Displacement of Anchorage Sheet Pile (Case Water Table).

It was noticed from Figures 4.39 and 4.40 that the driven depth increases, but displacements decrease with increasing water table level in the case of a water table presence.

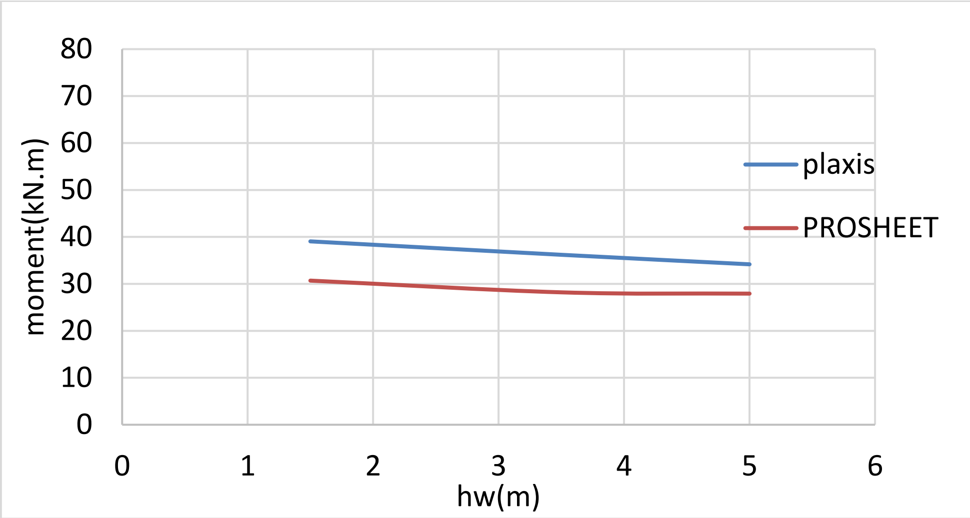


Figure 4.41: Horizontal Displacement of Anchorage Sheet Pile (Case Water Table).

Figure 4.41 shows an increase in the maximum moment with an increasing water table level, significantly converging the values of the two programs.

4.2.2. Effects of the Distance of Anchor from the Ground Surface

In this section, the anchorage sheet pile was studied by changing the distance of the anchor from the ground surface, where the optimum economic values of the anchor and grout body were calculated at various dredge levels by applying a homogeneously distributed loading 5kN/m^2 on top of the sheet pile, Table 4.6 shows the characteristics of the sheet pile, anchor, and grout.

The water tables were at a deep depth from the surface of the ground. Values of moments and horizontal displacements along the sheet pile were imported from the PLAXIS 2D program. An excel chart drew these values to represent moments along the cantilever sheet pile, as shown in figures 4.42 and 4.43.

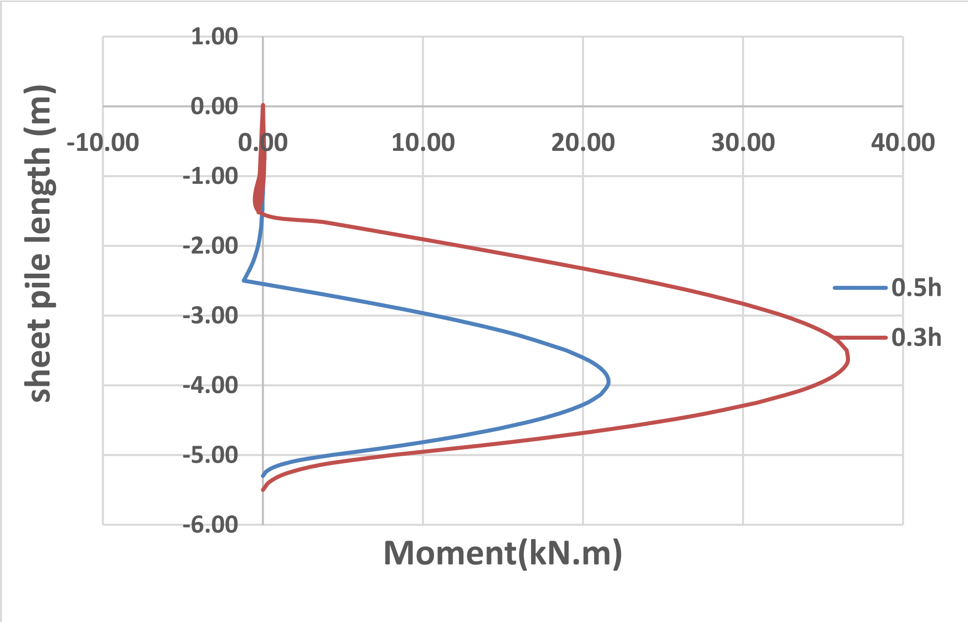


Figure 4.42: Moment Diagram of Anchorage Sheet Pile (Case Distance Ground).

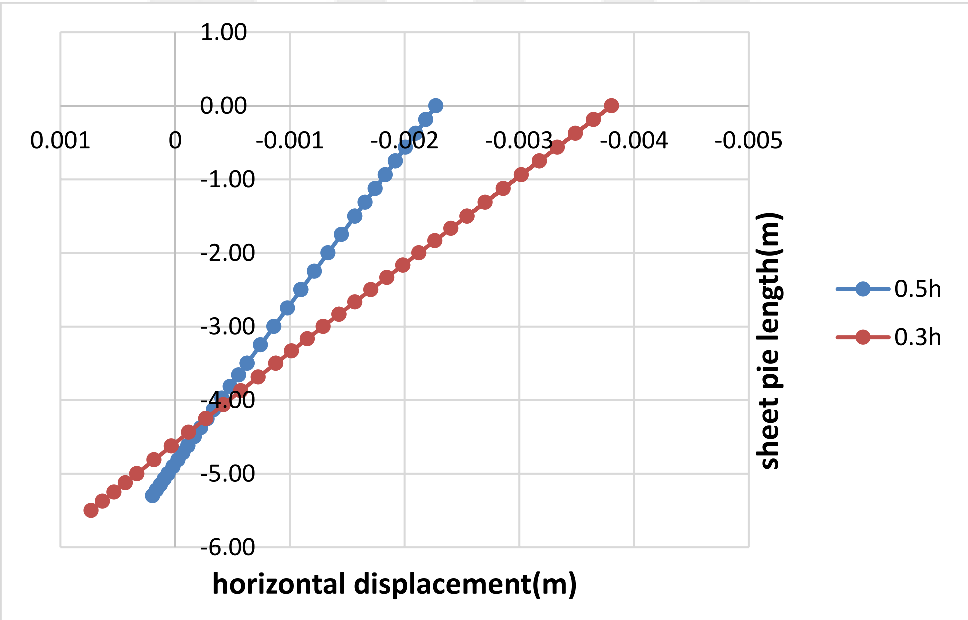


Figure 4.43: Horizontal Displacement Diagram of Anchorage Sheet Pile (Case Distance Ground).

The driven depth, horizontal displacements, and moments were studied in the anchorage sheet pile, and compared the results between the programs PLAXIS 2D and PROSHEET.

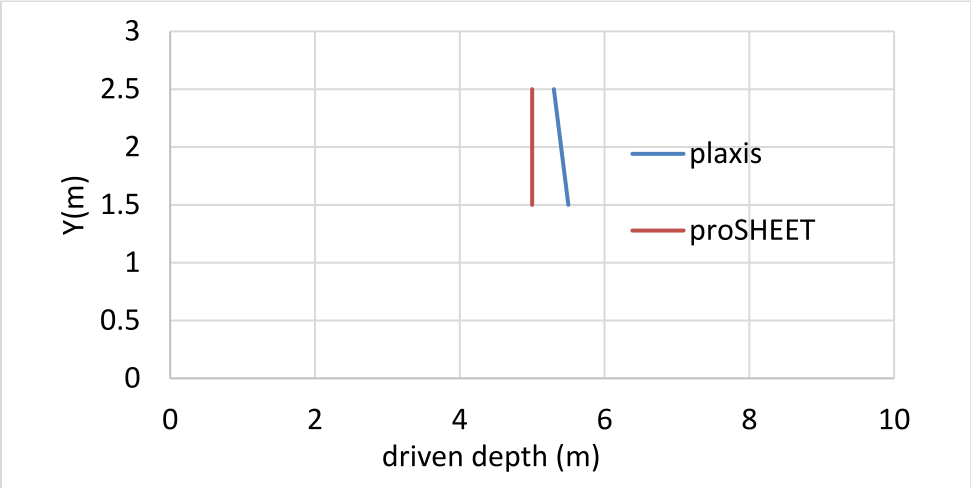


Figure 4.44: Driven Depth of Anchorage Sheet Pile (Case Distance Ground).

It was noticed from Figure 4.44 that the driven depth is constant in the PROSHEET program, but as for the PLAXIS 2D, there is a minimal decrease in driven depth in the case of increasing the distance of the anchor from the surface ground. In addition, both programs have closed results.

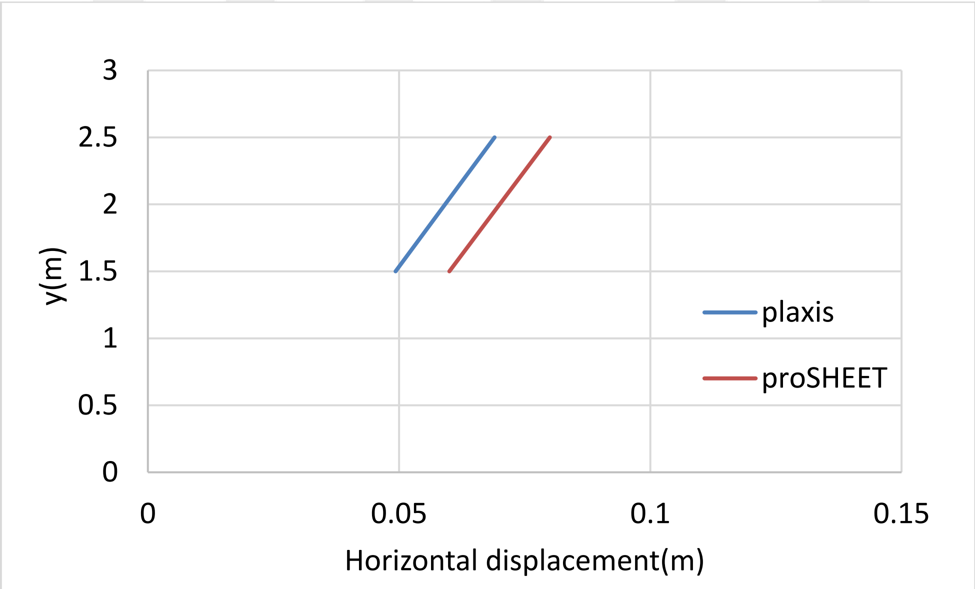


Figure 4.45: Horizontal Displacement of Anchorage Sheet Pile (Case Distance Ground).

Figure 4.45 shows that for two programs, the horizontal displacement increases by increasing the distance between two anchors. In addition, both programs give closed results.

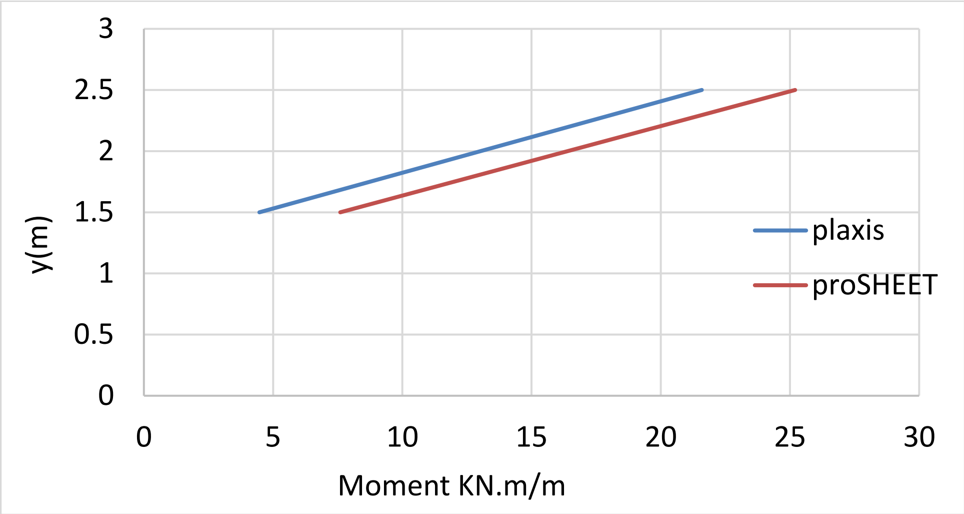


Figure 4.46: Moment of Anchorage Sheet Pile (Case Distance Ground).

Also, by increasing the distance anchor from the surface ground, the moment of sheet pile increases, and this increase is shown in Figure 4.46 in two programs.

4.2.3. Effects of the Distance Between two Anchors

In this section, the anchorage sheet pile was studied by changing the distance between two anchors, where the optimum economic values of the anchor and grout body were calculated at various dredge levels by applying a homogeneously distributed loading 5kN/m^2 on top of the sheet pile, and Table 4.6 shows the characteristics of the sheet pile, anchor, and grout. Because the PROSHEET affects only one anchor, the study was limited to the PLAXIS 2D.

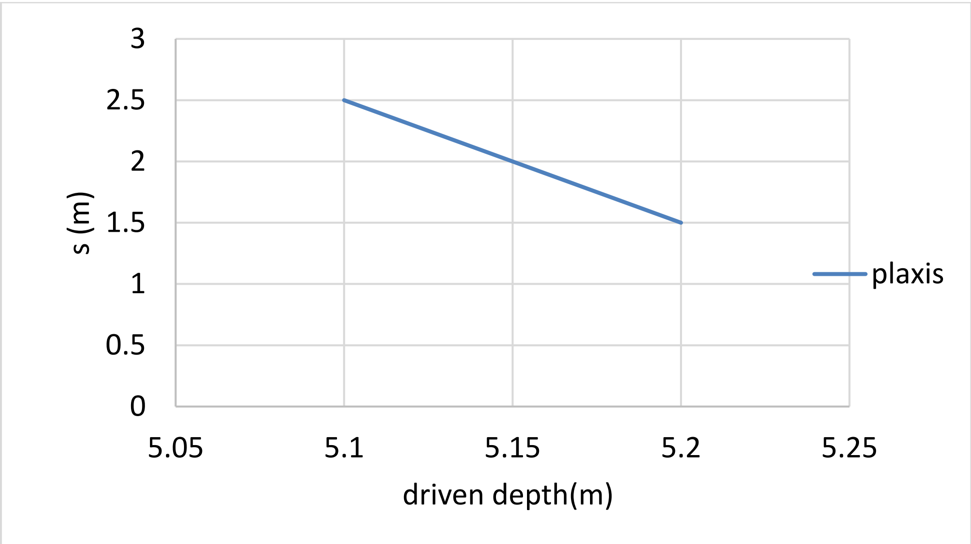


Figure 4.47: Driven Depth of Anchorage Sheet Pile (Case Distance Between Anchors).

Figure 4.47 shows that the driven depth decreases with an increasing distance between two anchors.

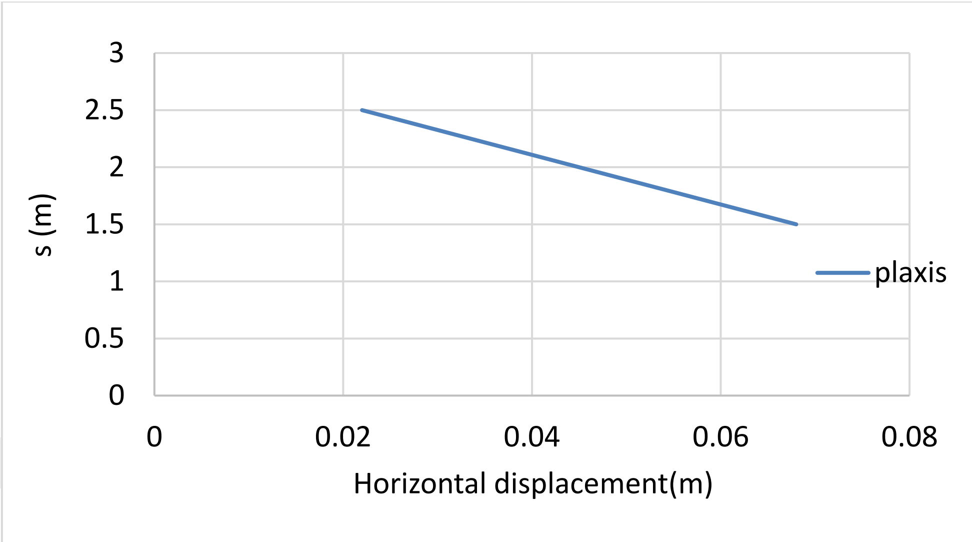


Figure 4.48: Horizontal Displacement of Anchorage Sheet Pile (Case Distance Between Anchors).

Figure 4.48 depicts horizontal displacement decreasing as the distance between two anchors increases.

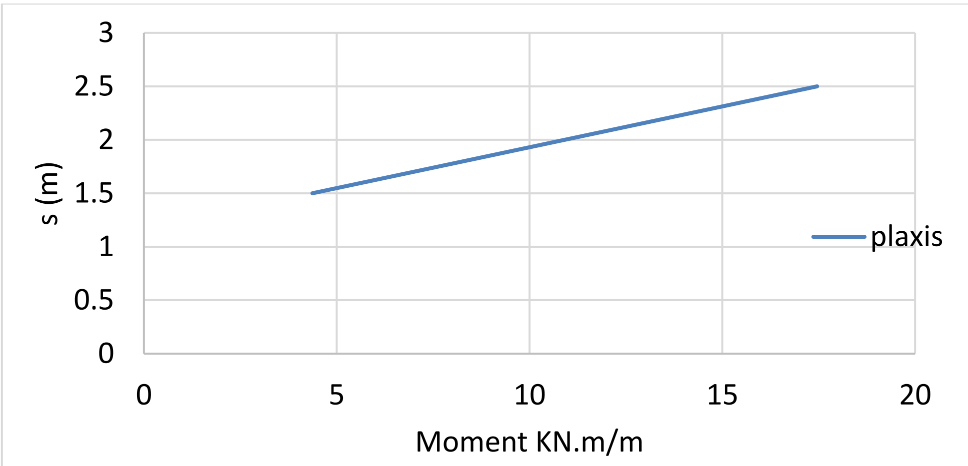


Figure 4.49: Moment of Anchorage Sheet Pile (Case Distance Between Anchors).

Figure 4.49 shows the moment increase with increasing distance between two anchors.

4.2.4. Effects Number of Anchors

In this section, the number of anchors was studied by comparing the behavior of sheet piles in case one and case two anchors by calculating moments, deformation, and driven depth in two cases.

The cases were studied only in PLAXIS 2D because the PROSHEET does not consider more than one anchor. Table 4.6 shows what the sheet pile, the anchors, and the grouted body are like. The distance of the first anchor from the ground surface was 1.5 m, and the second anchor from the ground surface was 2.5 m. The water tables were regarded to be at a deep depth below the ground surface.

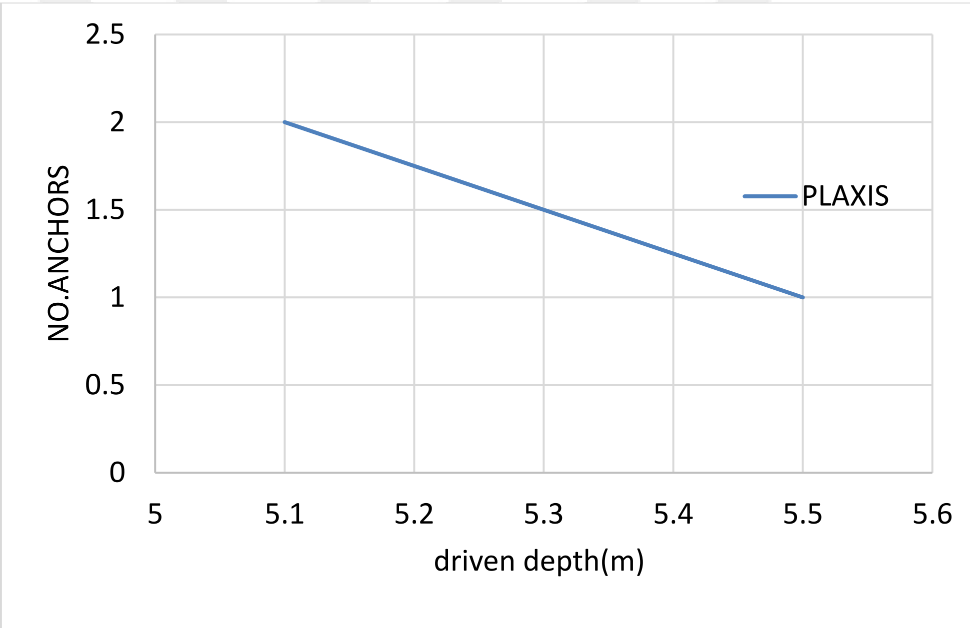


Figure 4.50: Driven Depth of Anchorage Sheet Pile (Case Distance Between Anchors).

The driven depth will increase if the number of anchors increases by increasing the number of anchors.

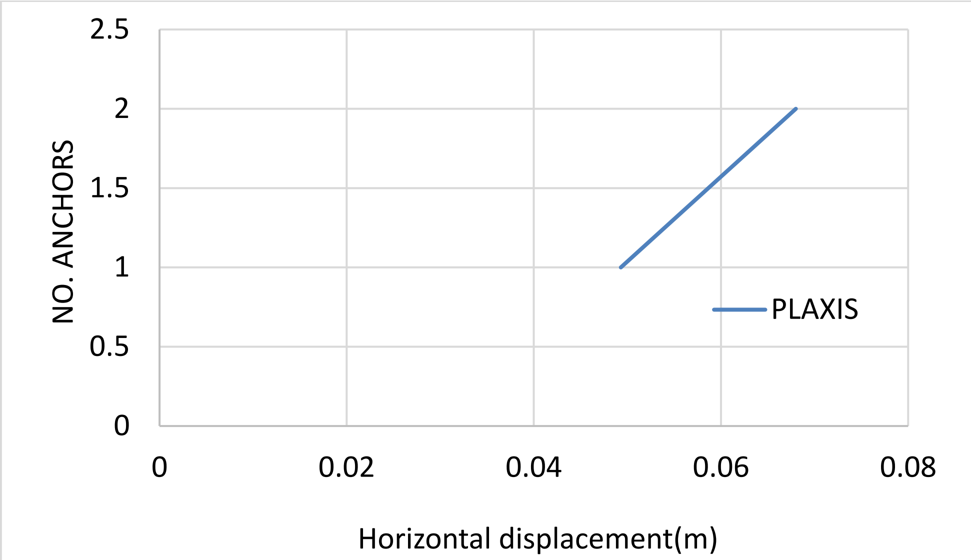


Figure 4.51: Horizontal Displacement of Anchorage Sheet Pile (Case NO. Anchors).

The horizontal displacement will be reduced if the number of anchors is reduced by increasing the number of anchors.

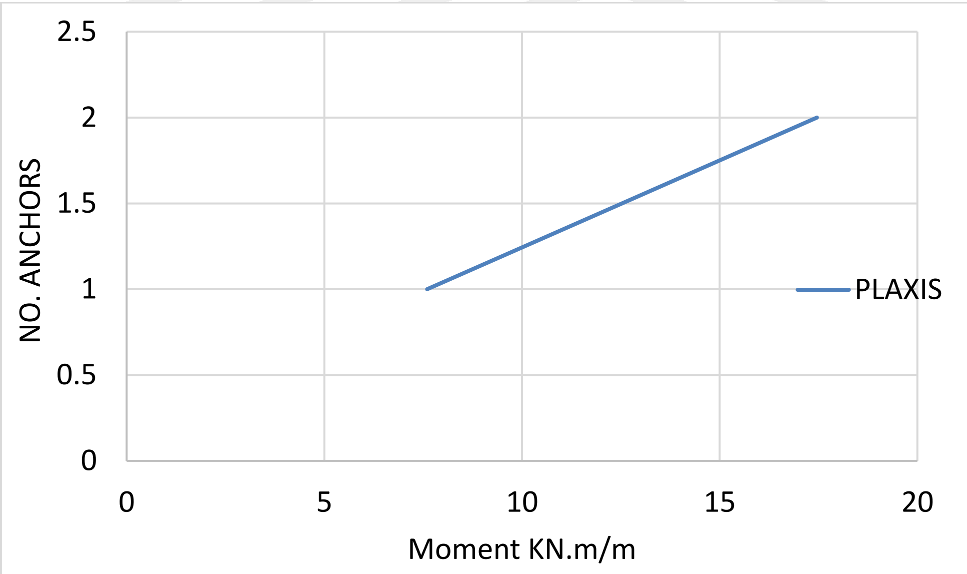


Figure 4.52: Moment of Anchorage Sheet Pile (Case NO. Anchors).

4.3. THIRD CASE (SATURATED CLAY SOIL)

4.3.1. Water Table Effects

In this case, the same type of clay soil was studied for two types: cantilever sheet pile and anchorage sheet pile. Different water table levels were investigated for several dredge depths (0.3H-0.67H) to demonstrate the effect of water table presence on calculating driven depth, moments, and horizontal displacements.

The numerical study was performed utilizing the PLAXIS 2D, and the results were compared to the PROSHEET program results. First, the cantilever sheet pile was studied at different depths of water (h_w=1.5,3.5,5m from the ground surface), and the following table presented the characteristics of the soil and the sheet pile used**.**

Table 4.8: Characteristics of Soil and Sheet Pile with the Water Table.

Sandy clay soil	Sheet
Φ=0.043	EA=12E6 KN/m
$\boldsymbol{\gamma_b}$=15 KN/m^3	EI=5.75E6 KN/m^2
$\boldsymbol{\gamma_{sat}}$=16 KN/$m^3$	υ=0.15
C=25KN/m^2	w=20KN/m/m
E=30000 KN/m^2	
υ=0.3	
R_{inter}=0.67	

Economical penetration depths and horizontal displacements were compared between the two programs at different dredge levels (0.3H-0.67H-H) and by applying a uniformly distributed load on top of the plate of 5 kN/m^2.

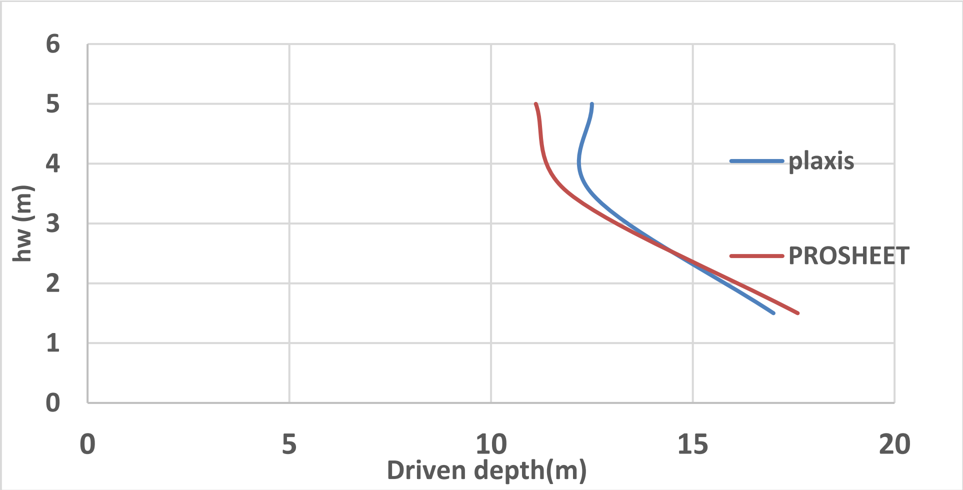


Figure 4.53: Driven Depth of Cantilever Sheet Pile (Water Table Level).

Figure 4.53 shows an increased driven depth with an increasing water table level. In addition, both programs give closed results.

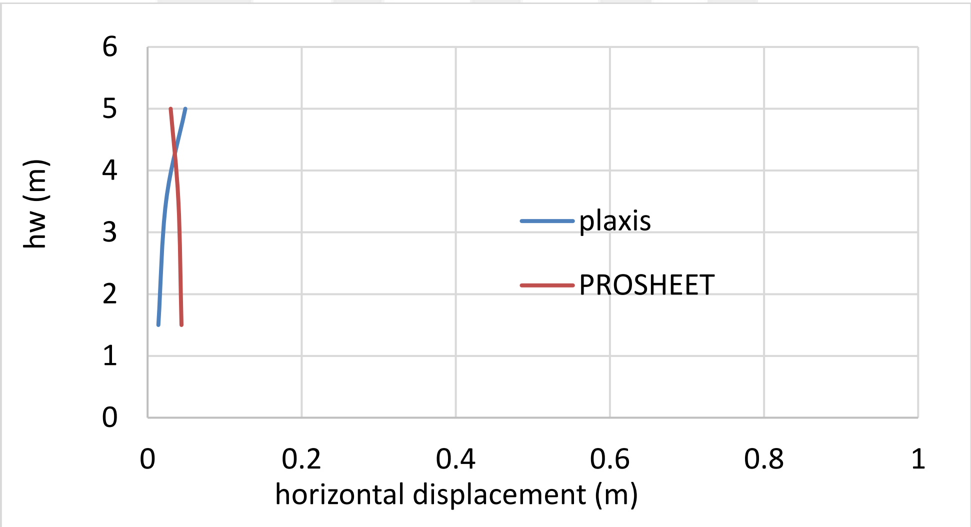


Figure 4.54: Horizontal Displacement of Cantilever Sheet Pile (Water Table Level).

Figure 4.54 shows no effect of the water table on increasing horizontal displacement in the PLAXIS 2D and PROSHEET. In addition, the two programs' value convergence is significant.

As in the cantilever sheet pile, this thesis studied the driven depth and the horizontal displacements in the anchorage sheet pile and compared the results between the program PLAXIS 2D and PROSHEET.

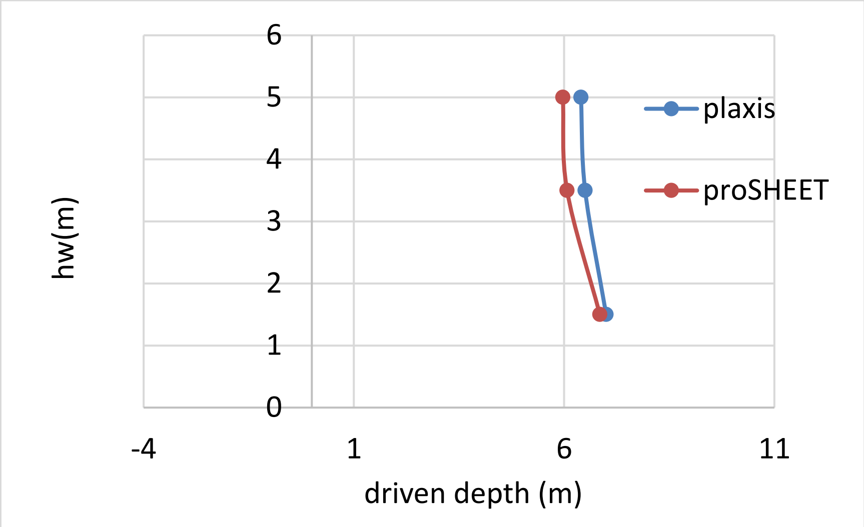


Figure 4.55: Driven of Anchorage Sheet Pile (Water Table Level).

Figure 4.55 shows increased driving depth with an increasing water table level. In addition, both programs give closed results.

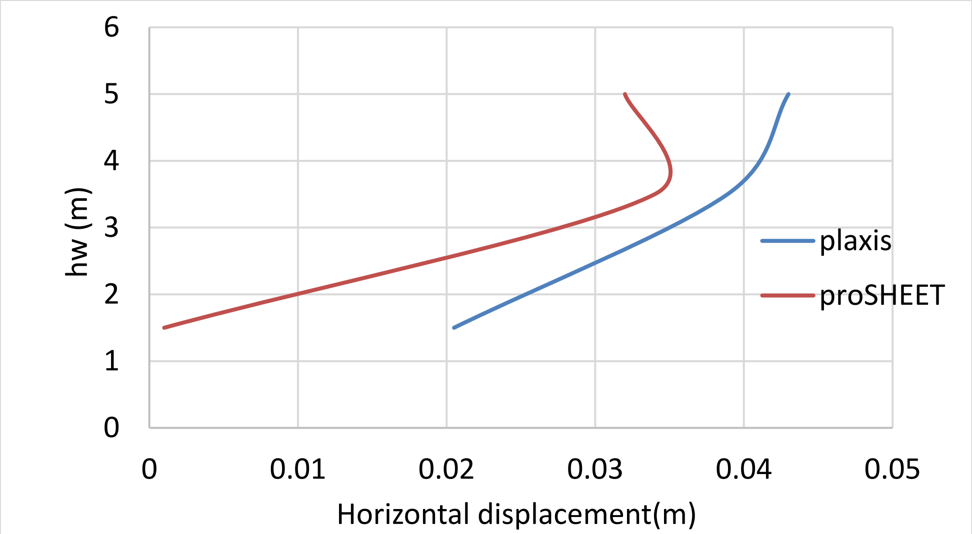


Figure 4.56: Horizontal Displacement of Anchorage Sheet Pile (Water Table Level).

4.3.2. Effects of Distance Anchor from the Ground Surface

In this section, the anchorage sheet pile was studied by changing the distance of the anchor from the ground surface, where the optimum economic values of the anchor and grout body were calculated at various dredge levels by applying a homogeneously distributed loadings 5kN/m^2 on top of the sheet pile. Table 4.6 shows the characteristics of the sheet pile, anchor, and grout. There was a significant drop down in water level from the surface to the subsurface.

Values of moments along the sheet pile were imported from the PLAXIS 2D program, and these values were drawn by excel chart to represent moments along the cantilever sheet pile as shown in Figures 4.54 and 4.55.

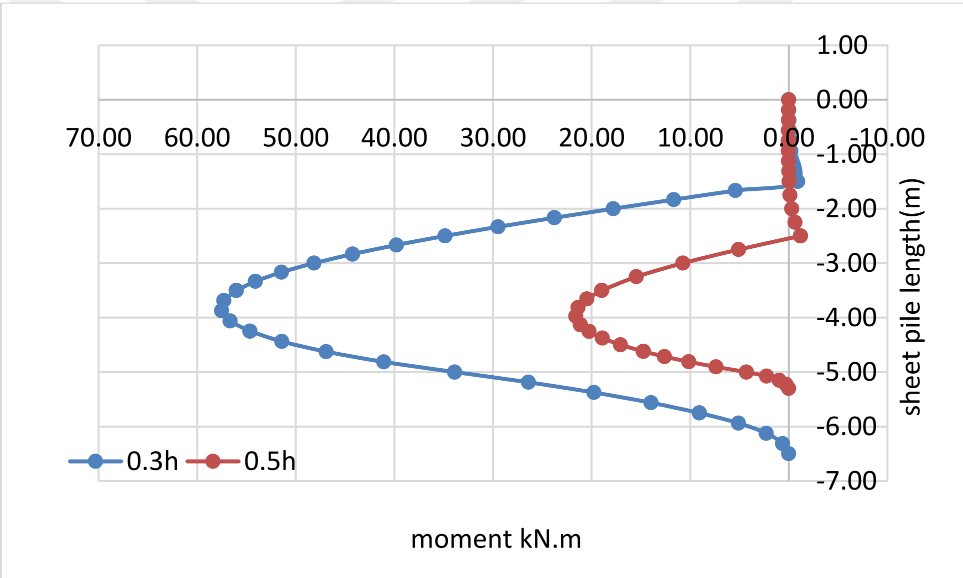


Figure 4.57: Moment Diagram of Anchorage Sheet Pile (Water Table Level).

In the anchorage sheet pile, this study looked at the driven depth, the horizontal displacement, and the moments. This thesis compared the results from the PLAXIS 2D and pro sheet.

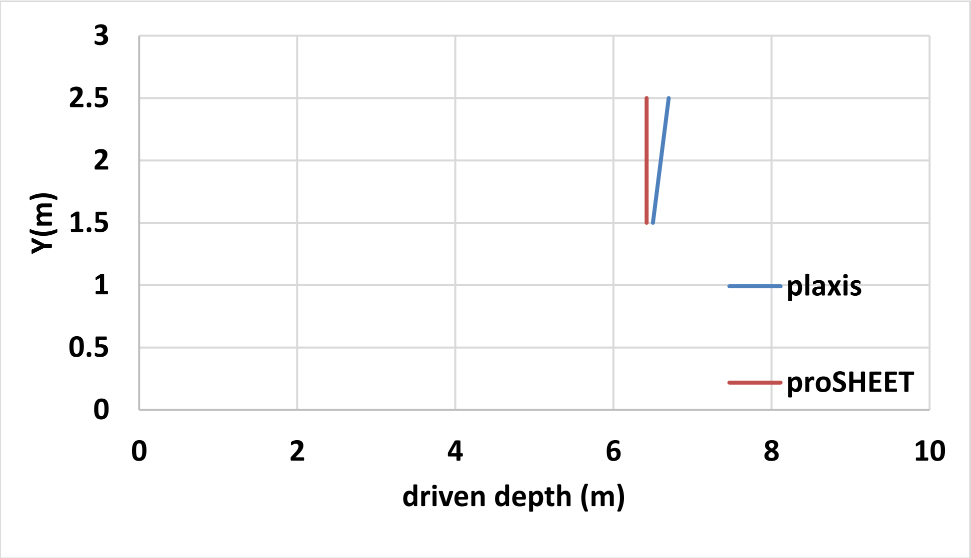


Figure 4.58: Driven Depth of Anchorage Sheet Pile (Case Anchor Distance).

Figure 4.58 shows no effect of anchor distance from the ground surface on the driven depth of the anchorage sheet pile. In addition, both programs give a closed result.

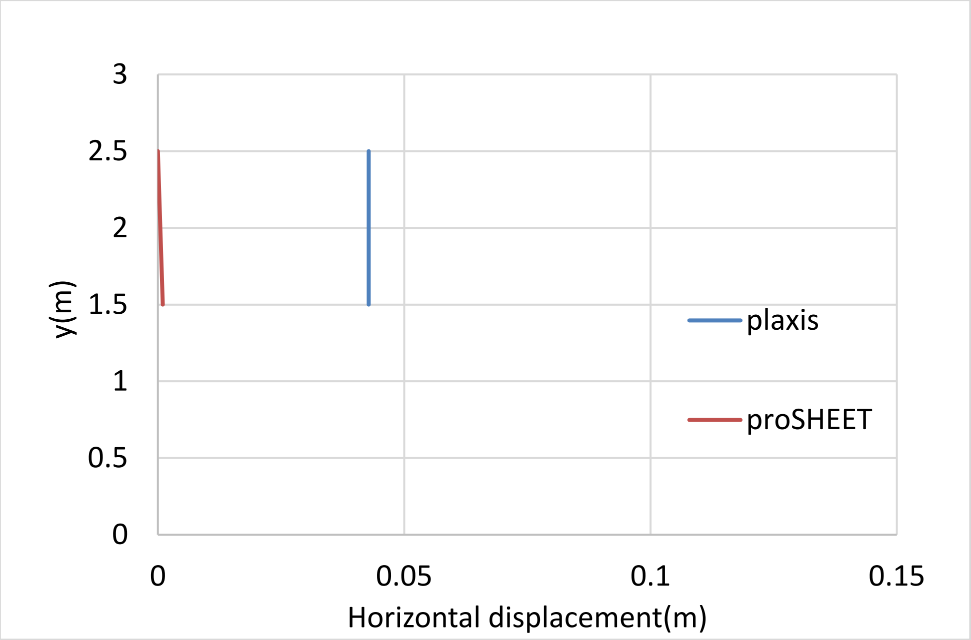


Figure 4.59: Horizontal Displacement of Anchorage Sheet Pile (Case Anchor Distance).

Figure 4.59 shows no effect of anchor distance from the ground surface on the horizontal displacement of the anchorage sheet pile. Figure 4.54 decreases with increasing anchor distance from the ground surface.

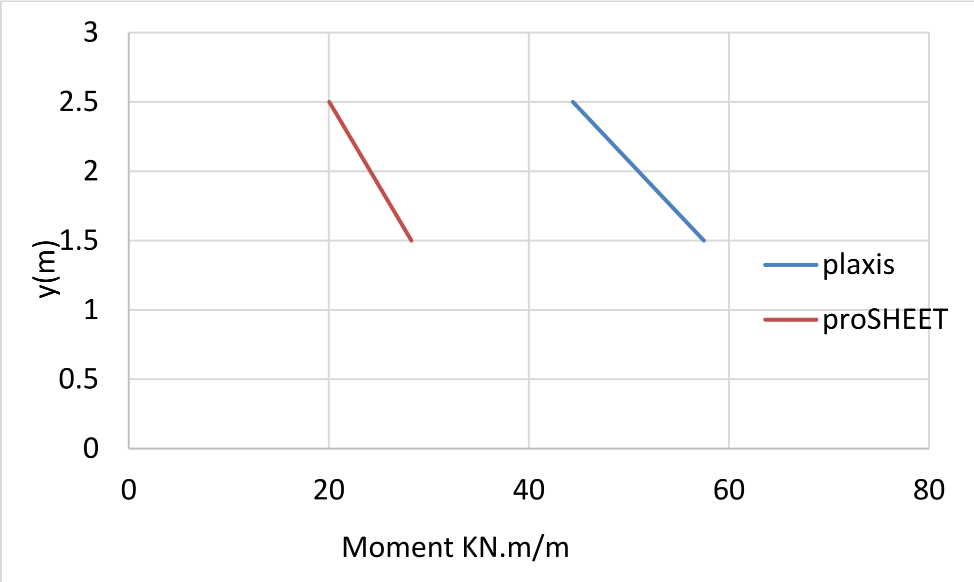


Figure 4.60: Moment of Anchorage Sheet Pile (Case Anchor Distance).

5. DISCUSSION AND RECOMMENDATION

5.1. DISCUSSION OF RESULTS

i. When dry sandy soil was studied, and in the case of the cantilever sheet pile, this thesis noted that the driven depth increases with the increase in dredge depth, and the horizontal displacement also increases with the increase in dredge depth behind the sheet pile, as well as the maximum moment. These increases were proportional to the percentage increase in the dredge depth.

ii. It was noticed that when the cantilever sheet pile was studied in sandy soil, the results converged between the Pro sheet and the PLAXIS 2D program, where the PROSHEET program gave results with greater values for the moment and driven depth. As for the displacement values, the values of the PLAXIS 2D were greater.

iii. In the case of the sandy cantilever sheet pile, with a depth of 5 to 7 meters dredges level, this study has adopted the properties of an enormous sheet pile in terms of rigidity and flexibility to achieve balance and not collapse the sheet pile.

iv. For the same type of sandy soil and anchorage sheet pile, this study noticed a considerable congruence in the values between the two programs regarding the driven depth and horizontal displacements. As for the maximum moments, the values were different between the two programs.

v. In dry sandy soil, and by comparing the two types of sheet piles used, this thesis note that the presence of the anchor improved the driven depth in the anchorage sheet pile. The percentage improvement was 25% and was less than its value in the cantilever sheet pile at the dredge depth of 3 meters. In contrast, it improved by 30% in the cases of dredge depths of 5 and 7 meters, which indicates that the presence of anchors and grouts has reduced the driven depth of sheet pile, which means it is more economical.

vi. In the case of sandy soils, for a depth of 5 meters and the cantilever sheet pile, this thesis found that when the groundwater level changes, the depth of penetration decreases as the groundwater level decreases by approximately 14%. Also, the PLAXIS 2D and PROSHEET programs' values were very close.

vii. When the groundwater level has changed in the case of sandy soil and the anchorage sheet pile, there was a need for an anchor length of 8 meters and a grout length of 4 meters with a diameter of 0.4 meters to stabilize the sheet pile.

viii. The presence of the anchor in the case of the presence of a water table level reduced the value of the driven depth to 38%, and this means more economical

ix. When the spacing between the anchor elements was studied in the case of dry sandy soil, this study found that changing the values of the spacing between the elements did not affect the driven depth while increasing the spacing between the elements decreased the value of the maximum moment, which indicates that in the design process and when there is more than one anchor element, it is preferable to put the spacing up to 0.5h from the height of the sheet pile in order to reduce the value of the moment as much as possible.

x. In the case of clay sandy soils restrained by cantilever sheet piles, this thesis notice a decrease in the value of the driven depth, which decreased by 15% when the water table level decreased from 1.5 to 3.5. At the same time, it does not change the water level. At 5 m, it was at the level 3.5 m, and the maximum moment decreased by 40% when the water table level decreased from 1.5 to 3.5 meters, while it did not change for the 5-meter water table level.

xi. In the case of an anchorage sheet pile restraining clay sandy soil, the values of the depth of penetration decreased by 11% when the water table level decreased from 1.5 to 3.5 m. At the same time, it was not affected by the depth of the rug level of 5 m, but the moment values were close in all three cases.

xii. The presence of the anchor in this type of soil and the case of a water table has reduced the value of the driven depth by 10% in the three cases of placing water table level.

xiii. In the instance of clay sand soil, the driven depth value was not noticeably different depending on how far the anchor element was from the ground. At the same time, it increased the moment by increasing the anchor distance from the surface ground.

xiv. Also, when the spacing between the anchor elements was studied, the values of the driven depth did not differ clearly. At the same time, the moment had an apparent effect the farther the distance between anchors changes, in the case of sandy clay soil.

xv. Placing two anchor elements instead of one improved the driven depth values and reduced them by 10%. At the same time, it had the opposite effect on the horizontal displacement. It increased the horizontal displacement by 2 cm, but that was still within the allowed range.

xvi. In the case of clay soil and when using a cantilever sheet pile and changing the water table level from 1.5 m to 3.5 m, this study noticed a decrease in the value of the driven depth by up to 27%, while the driven depth did not change when the water table level changed to 5 m. As for the moment values, this thesis found that the values of the moments were close in all three cases of placing the water table level.

xvii. When using the anchorage sheet pile instead of the cantilever in the case of clay soil, this study found that the value of the driven depth decreased by 8% when the water table level decreased from 1.5 to 3.5, while the driven depth did not change by 5 meters.

xviii. By comparing the sheet piles, the cantilever, and the anchorage sheet pile, the presence of the anchor has reduced the value of the driven depth by more than 50%, and this indicates the tremendous economic effectiveness of the presence of an anchor in the case of clay soil.

xix. When the spacing of the anchoring element from the ground has been studied in the case of clay soil, the value of the driven depth of the sheet pile inside the ground increased slightly by 2% when changing the distance of the anchor element from the ground from 0.3 to 0.5. In contrast, the values of the horizontal displacement were not affected, which indicates that the distance changed. As far as can be seen, the distance between the anchor element and the ground surface does not seem to affect the sheet pile.

5.2. RECOMMENDATIONS

This thesis dealt with the studied behavior of the cantilever and anchorage sheet pile under various factors. The most critical factors studied are dredge level, water table level, anchor distance from the ground surface, the distance between anchors, and the number of anchors. This study was carried out under static conditions, so this thesis recommend further work on the following:

i. Study the behavior of sheet piles in seismic conditions using development methods such as the earthquake’s time history to achieve the best seismic design of sheet piles.

ii. Upgrading the performance of sheet piles by using economic and safe techniques.

iii. Make field experiments that simulate reality and compare them with modern methods to reach the best and safest design of sheet piles.

iv. Study how water flows when the level behind and in front of the sheet pile changes and look into how water flows through pipes to make sure the sheet piles stay stable if water flows.

v. Investigate the effect of the inclination of backfill behind the sheet pile.

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