

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING**



**THREE DIMENSIONAL FINITE ELEMENT MODELING OF Laterally  
LOADED SINGLE PASSIVE PILE IN SANDY SOILS**

**A thesis submitted to the School of Graduate Studies of Addis Ababa  
University in Partial fulfillment of the Degree of Master of Science in  
Geotechnical Engineering.**

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## Declaration

I, the undersigned, declare that this thesis is my original work performed under the supervision of my research advisor Dr.-Ing. Henok Fikre and has not been presented as a thesis for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

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## Abstract

In this thesis, the behavior of a single passive pile subjected to uniform and/ or triangular lateral soil movement has been carried out by means of a three-dimensional finite element numerical model using PLAXIS 3D software. The Mohr-Coulomb constitutive material law, and linear elastic - plastic model was used to model the surrounding soil and the embedded pile respectively. The accuracy of the three dimensional finite element analysis were validated using published model laboratory test results, and also with a three dimensional finite difference analysis software, FLAC<sup>3D</sup>. It was concluded that the 3D finite element analysis results agree with published laboratory test results, and FLAC<sup>3D</sup> results in terms of the shape, and magnitude of the maximum bending moment, shear force and pile deflection profile curves. A parametric study was carried out to investigate the effect shape of soil movement profile, soil stiffness, pile diameter and the ratio of  $L_m/L_s$ . The results of the parametric study were in good agreement with published laboratory results. The numerical results indicated that the distribution of the bending moment and pile deflection along with the depth of the pile vary considerably, and the results were in good agreement the real pile behavior when adopting a variation of soil stiffness with depth instead of choosing a constant soil stiffness value.

**Key words:** embedded pile, Mohr coulomb, passive pile, lateral soil movement, 3D finite element analysis.

Dedicated to My Family!

## Acknowledgment

First and foremost, I would like to thank my advisor, Dr. Henok Fikre, for his support, inspiring ideas, and advices. I am truly indebted to him for being my advisor and for directing me to go through all the challenges of accomplishing this research. And without his backing, this work would have been far from complete.

I am indebted to Engineer Molla Teshome for his guidance and help during modeling of the problem using PLAXIS 3D software and also vital suggestions I needed.

I would like to express my special gratitude to my parents; my mother Yimenashu Bogale and my elder brother Zewdu G/meskel for their continuous support and encouragement. I am grateful for their understanding and patience in every level of my research.

I would like to thank my close friends who endured me and gave courage especially in difficult times. Their continuous support and friendship are deeply appreciated.

Finally, I praise God for giving me the strength and wisdom to complete my study.

# Table of Contents

|                                                                 |            |
|-----------------------------------------------------------------|------------|
| <b>Abstract .....</b>                                           | <b>III</b> |
| <b>Acknowledgment .....</b>                                     | <b>V</b>   |
| <b>Table of Contents .....</b>                                  | <b>VI</b>  |
| List of Figures .....                                           | VIII       |
| <b>Abbreviations .....</b>                                      | <b>XI</b>  |
| <b>Symbols .....</b>                                            | <b>XII</b> |
| <b>Chapter One: 1. Introduction .....</b>                       | <b>1</b>   |
| 1.1. Background .....                                           | 1          |
| 1.2. Statement of the Problem .....                             | 4          |
| 1.3. Objectives .....                                           | 5          |
| 1.3.1. General Objective.....                                   | 5          |
| 1.3.2. Specific Objectives.....                                 | 5          |
| 1.4. Scope of the Study .....                                   | 6          |
| 1.5. Methodology Overview .....                                 | 7          |
| 1.6. Organization of the Thesis .....                           | 8          |
| <b>Chapter Two: 2. Review of Literature .....</b>               | <b>9</b>   |
| 2.1. General.....                                               | 9          |
| 2.2. Types of Laterally Loaded Passive Piles.....               | 9          |
| 2.3. Failure Mechanism of Passive Laterally Loaded Piles .....  | 10         |
| 2.4. Analysis Methods .....                                     | 12         |
| 2.4.1. Theoretical Studies .....                                | 12         |
| 2.4.2. Experimental Studies.....                                | 20         |
| <b>Chapter Three: 3. 3D FEA Methods and Procedures .....</b>    | <b>26</b>  |
| 3.1. Introduction.....                                          | 26         |
| 3.2. Model Properties.....                                      | 26         |
| 3.2.1. Model Soil Properties .....                              | 27         |
| 3.2.2. Embedded Pile Model Properties .....                     | 29         |
| 3.2.3. Pile-Soil Interaction .....                              | 30         |
| 3.4. 3D Finite Element Mesh Generation .....                    | 35         |
| <b>Chapter Four: 4. Verification of 3D FEA and Results.....</b> | <b>38</b>  |

|                                                                                     |           |
|-------------------------------------------------------------------------------------|-----------|
| 4.1. General.....                                                                   | 38        |
| 4.2. Shear Box Model.....                                                           | 38        |
| 4.3. FLAC <sup>3D</sup> Analysis .....                                              | 40        |
| 4.4. Finite Element Analyses .....                                                  | 42        |
| 4.4.1. PLAXIS 3D Model of a Laterally Loaded Pile .....                             | 42        |
| 4.4.2. Mesh Generation.....                                                         | 43        |
| 4.4.3. Calculation Process.....                                                     | 43        |
| 4.5. Comparison of PLAXIS 3D Results and Discussion.....                            | 45        |
| 4.5.1. PLAXIS 3D Results Validation Using Rectangular Soil Movement Profile .....   | 47        |
| 4.5.2. PLAXIS 3D Results Validation Using Triangular Soil Movement Profile...       | 50        |
| 4.6). Concluding Remarks .....                                                      | 53        |
| <b>Chapter Five: 5. Parametric Study .....</b>                                      | <b>54</b> |
| 5.1. Introduction.....                                                              | 54        |
| 5.2. Effect of Pile Diameter .....                                                  | 54        |
| 5.3. Effect of Soil Stiffness.....                                                  | 56        |
| 5.4. Effect of Soil Movement Profile .....                                          | 59        |
| 5.5. Effect of Thickness of Moving Soil Mass .....                                  | 61        |
| 5.6. Summary of the parametric study.....                                           | 63        |
| <b>Chapter Six: 6. Conclusion and Recommendation for Future Research Work .....</b> | <b>65</b> |
| 6.1. Conclusions.....                                                               | 65        |
| 6.2. Recommendations for Future Research Work.....                                  | 67        |
| 7. References.....                                                                  | 68        |
| 8. Appendixes.....                                                                  | 72        |

## List of Figures

|                                                                                                                       |           |
|-----------------------------------------------------------------------------------------------------------------------|-----------|
| <i>Figure 1. 1: Examples of passive piles [3] .....</i>                                                               | <i>2</i>  |
| <i>Figure 2. 1: (a) Active Pile [10](b) Passive piles in embankment [10] .....</i>                                    | <i>10</i> |
| <i>Figure 2. 2: failure mechanism of the short rigid pile due to lateral load [13] .....</i>                          | <i>11</i> |
| <i>Figure 2. 3: failure mechanism of long pile under lateral load [13] .....</i>                                      | <i>11</i> |
| <i>Figure 2. 4: Subgrade reaction model of soil around the pile [16] .....</i>                                        | <i>14</i> |
| <i>Figure 2. 5: Laboratory Model test [24] .....</i>                                                                  | <i>21</i> |
| <i>Figure 3. 1: Geometric illustration of the shear box model .....</i>                                               | <i>27</i> |
| <i>Figure 3. 2: Shear resistance and tip resistance [28]. .....</i>                                                   | <i>31</i> |
| <i>Figure 3. 3: Boundary surfaces fixity condition for unstable soil layer .....</i>                                  | <i>34</i> |
| <i>Figure 3. 4: Typical mesh generation of the 3-D FEM model in PLAXIS 3D for coarse mesh .....</i>                   | <i>35</i> |
| <i>Figure 3. 5: Typical mesh generation of the 3-D FEM model in PLAXIS 3D for medium-mesh .....</i>                   | <i>36</i> |
| <i>Figure 3. 6: 3D finite element mesh used for model the soil [37] .....</i>                                         | <i>37</i> |
| <i>Figure 4. 1: physical model test setup [8] .....</i>                                                               | <i>39</i> |
| <i>Figure 4. 2: Mesh of soil and pile used in FLAC3D analysis [9] .....</i>                                           | <i>41</i> |
| <i>Figure 4. 3: Construction Phases in PLAXIS 3D .....</i>                                                            | <i>44</i> |
| <i>Figure 4. 4: soil movement profile with a moving layer .....</i>                                                   | <i>46</i> |
| <i>Figure 4. 5: PLAXIS 3D, FLAC<sup>3D</sup> and Model test Bending Moment response Along the Pile length ...</i>     | <i>47</i> |
| <i>Figure 4. 6: PLAXIS 3D, FLAC<sup>3D</sup>, and Model test shear force response Along with the Pile length ....</i> | <i>48</i> |
| <i>Figure 4. 7: PLAXIS 3D, FLAC<sup>3D</sup>, and Model test pile deflection response Along the Pile length .....</i> | <i>49</i> |
| <i>Figure 4. 8: PLAXIS 3D and Model test Bending Moment response Along the Pile length .....</i>                      | <i>51</i> |
| <i>Figure 4. 9: PLAXIS 3D and Model test shear force response Along the Pile length .....</i>                         | <i>52</i> |
| <i>Figure 4. 10: PLAXIS 3D and Model test pile deflection response Along the Pile length .....</i>                    | <i>53</i> |

|                                                                                                                                      |    |
|--------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 5. 1: shows the change in pile bending moment for three pile diameter with depth in sand. ....                                | 55 |
| Figure 5. 2: shows the change in pile deflection for two pile diameter with depth in sand. ....                                      | 56 |
| Figure 5. 3: shows the change in pile bending moment with constant and varying soil stiffness with pile depth in sand. ....          | 57 |
| Figure 5. 4: shows the change in pile deflection with constant and varying soil stiffness with pile depth in sand. ....              | 58 |
| Figure 5. 5: shows the distribution of bending moment along with the pile length for three types of soil displacement profiles ..... | 59 |
| Figure 5. 6: shows the distribution of deflection along the pile depth for three types of soil displacement profiles. ....           | 60 |
| Figure 5. 7: shows the distribution of bending moment along with the pile depth with various $L_m/L_s$ ratios.....                   | 62 |
| Figure 5. 8: shows the distribution of deflection along with the pile depth with various $L_m/L_s$ ratios...                         | 63 |

## List of Tables

|                                                                                                                          |           |
|--------------------------------------------------------------------------------------------------------------------------|-----------|
| <i>Table 2. 1: summary of two-dimensional numerical studies on piles subjected to lateral soil movements [8].....</i>    | <i>17</i> |
| <i>Table 2. 2: summary of three- dimensional numerical studies on piles subjected to lateral soil movements [8].....</i> | <i>19</i> |
| <br>                                                                                                                     |           |
| <i>Table 3. 1: material properties of unstable and stable soil [8] .....</i>                                             | <i>28</i> |
| <i>Table 3. 2: material properties of embedded piles [8] .....</i>                                                       | <i>29</i> |
| <i>Table 3. 3: Node model for the pile-soil interaction [28]. .....</i>                                                  | <i>32</i> |
| <i>Table 3. 4: Surface boundary fixities for unstable soil layer. ....</i>                                               | <i>34</i> |
| <br>                                                                                                                     |           |
| <i>Table 4. 1: calculation phases for shear box and FLAC 3D case verifications. ....</i>                                 | <i>44</i> |
| <br>                                                                                                                     |           |
| <i>Table 5. 1: PLAXIS 3D models at different Lm/Ls ratio .....</i>                                                       | <i>61</i> |

## Abbreviations

FLAC<sup>3D</sup> – Fast Lagrangian Analysis Continua in three dimensions

2D – Two Dimensions

3D – Three Dimensions

FEM – Finite Element Methods

FEA – Finite Element Analysis

M<sub>+max</sub> – Maximum positive bending moment

M<sub>-max</sub> – Maximum negative bending moment

## Symbols

$c$  – Cohesion for the Soil

$\gamma$  -Unit weight of the soil

$\nu$  - Poisson's ratio

$d$  – Pile diameter

$E_p$  - Young's Modulus of the pile

$E_s$  -Young's Modulus of the soil

$E$  – Elastic Young Modulus

$I_p$  – Second moment of inertia of the pile

$K_0$ – Coefficient of lateral earth pressure at rest

$K_R$  – Pile flexibility factors

$L$  – Pile length

$M$  – Pile bending moment

$q$  - Uniformly distributed load

$t$  – Thickness of wall of the pile

$y$  – Lateral pile head displacement

$z$  – Depth below the ground surface

# Chapter One: Introduction

## 1.1. Background

Pile foundations are used when heavy engineering building structures are transfer their superstructure loads to the deep hard strata. However, the majority of these piles are designed to support “active” loads, that is, loads from super structure are directly transferred to the pile foundation by the cap. Most of the time, piles are not designed to withstand “passive” loads, which are created by the deformation and movement of soil surrounding the piles due to the weight of soil and the surcharge.

Earthquakes, landslides, and human activities, such as tunneling and deep excavation in the vicinity of piles might cause irreversible soil movements. These soil movements can generate lateral thrust on the piles supporting both onshore and offshore structures, such as: piles supporting bridge abutments, existing piles adjacent to pile driving, piles used for slope stabilizations, piles near tunneling operations, and piles adjacent to embankments.

The design of such piles may be based on the assumption that forces from moving soil will act against the piles and ‘squeeze’ past the piles. These types of loading are caused by lateral movement of the surrounding soil, and the loading is called passive loading.

The piles subjected to passive loading are called passive piles. As these piles will experience additional stress and strain, failure to assess the effect in design will result in unacceptable pile movement or stress or both. In extreme cases, they might damage the piles and compromise the serviceability and stability of the supporting structures.

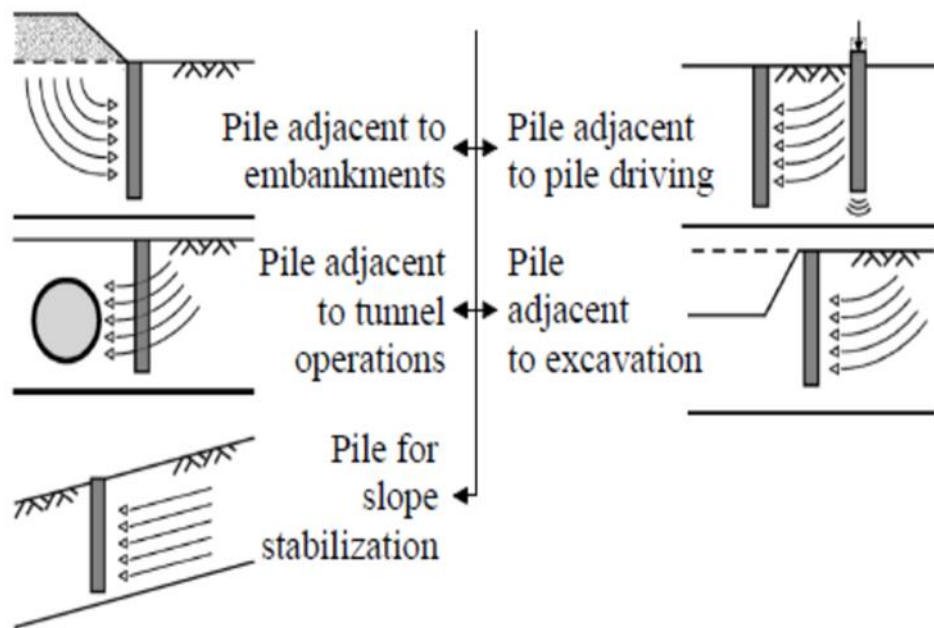


Figure 1. 1: Examples of passive piles [1]

The design of these passive piles for lateral soil movement has to depend on the soil movement mechanism, soil properties, pile head condition, superstructure loading, and ground support by lower stable stratum. The analysis of the load transfer mechanism in a single passive vertical pile under lateral loading is therefore an essential basis for pile foundation design. The physical interaction between pile and soil should be carefully studied. The settlement analysis is also fundamental. The maximum allowable settlement of a pile foundation is the most important criterion in its design. Thus, it should be estimated accurately. The most famous damages caused by lateral soil displacement is the collapse of 13- storey building in China in 2009 under nearby surcharge loading and excavation works [2]. Most researches in the area of piled foundations are as settlement reducers and external load supports. Although this is true in the case of stable soil layers, knowledge of deformations caused by external vertical and horizontal loads only may not be enough for those buildings existing adjacent to soil movement activities. The behavior of single pile under lateral loading, as far as load distribution and settlement along the pile are concerned, has been analyzed through numerous methods. One of the methods is numerical methods using a commercial package finite element, FEM is powerful and very useful tools when used

carefully and calibrated with the appropriate tests. Several analytical simulations with 2D or 3D analyses have been used to assess the behavior of piles to lateral soil movements. For example, [3] investigates the response of single pile due to soil movement using 2D finite element environment, [4] proposed 2D finite element package PLAXIS modeling for the case of the axially loaded single pile under axis-symmetric conditions in two-layered soil. [5] proposed a 3D finite element analysis to study the response of piles adjacent to a surcharge load, [6] proposed three-dimensional analysis response of pile subjected to oblique loads.

This paper describes a numerical solution for predicting the lateral response of "passive piles" subjected to horizontal soil movements by utilizing a three-dimensional finite element software PLAXIS 3D 2013. The three-dimensional finite element PLAXIS 3D enables to predict the complex pile-soil interaction. An embedded pile is used to predict the behavior of a single pile under soil movements. The embedded pile is a beam element covered by special interfaces to represent the pile-soil interaction. Therefore, using this feature leads to a great reduction in the number of elements in the analysis compared to the volume pile. Hence, the time required to perform the analysis is considerably decreased. Comparing the response of this type of piles for axial loading shows a good agreement with volume pile and real pile behavior [7].

## 1.2. Statement of the Problem

In many cases, piles are not designed to sustain lateral soil movement, though such movements may occur in piles adjacent to an embankment, unstable soil layers or nearby vertical excavation activities, pile driving operations, surcharge loads, piles supporting bridge abutments, pile foundations in moving slopes and tunneling operations. On the other hand, piles may be purposely designed to restrain soil movements when they are used to stabilize unstable slopes or potential landslides. Because the lateral loads and relative soil-pile displacements resulting from soil movements induce deflections and bending moments in piles, which can cause serviceability problems and even damage to the passive piles.

To investigate the induced bending moments and deflection along with the depth of the piles, extensive experimental modeling, and analytical analysis carried out, to improve our understanding of the performance of single passive pile undergoing lateral soil movement, many issue are still not clear due to the complexity of soil-pile interactions; such as:

- estimation of lateral shear forces caused by soil movements;
- response of single passive piles in progressive moving soils;
- mechanism of mobilization of soil reaction on piles due to lateral soil movements;
- effects of various soil movement profiles and soil sliding depth and
- In a two dimensional environment, the single pile is modeled as an infinitely long wall, the shear flows of soil around the pile tend to be neglected, hence underestimating the maximum moment acting along with the pile.

Following this, a three-dimensional finite element environment analysis is essential for a single pile to identify the contribution of the increased moment due to the discussed shear flow around the pile and in predicting the non- linear response of pile to soil movements.

## 1.3. Objectives

### 1.3.1. General Objective

The main objective of this study is to investigate the response of laterally loaded single piles subjected to lateral movement of the surrounding soil in sandy soil using a three-dimensional finite element PLAXIS 3D software. To understand the single pile behavior the parameters contributing to the response of single passive pile first needed to be identified.

### 1.3.2. Specific Objectives

The specific objectives of this study are:

- To model the response of a single pile subjected to lateral soil displacement using PLAXIS 3D software.
- To verify the accuracy of the three-dimensional finite element analysis, and model using published laboratory test and FLAC<sup>3D</sup> results in terms of the pile deflection, bending moment and shear force-induced along with the depth of a single pile in sandy soil due to soil movements.
- To investigate the effect of some factors such as shape of soil movement profiles, pile diameter, soil stiffness, and the ratio of  $\frac{L_m}{L_s}$  affect the analysis and modeling of a single passive pile using a three-dimensional PLAXIS 3D software.

## 1.4. Scope of the Study

This study investigates the response of single laterally loaded passive pile behavior by using three-dimensional finite element software PLAXIS 3D 2013. Due to time constraint, the scope of this research is limited to the following features:

- A. Linear elastic pile materials
- B. Single passive piles
- C. Uniform soil layering.
- D. Single pile subjected to lateral soil movement

The non-linearity properties of material increase the complexity of the problem. Due to this, the concept of non-linearity is not implemented in the modeling of pile and soil.

## 1.5. Methodology Overview

This study started by reviewing various literature / previously done researches to model the response of laterally loaded passive pile subjected to lateral soil movement. Various analytical and numerical analysis methods used to model the response of single laterally loaded pile due to soil movement were reviewed and concisely presented. Having done this, a three- dimensional finite element analysis was carried out to model the response of laterally loaded single passive pile due to soil movement using PLAXIS 3D 2013 software. Consequently, the three-dimensional numerical model has been developed, the validation of the three-dimensional numerical model carried out using the laboratory model test result carried out by [8] and the 3D numerical model results obtained for the laterally loaded single pile were compared with laboratory model test results of [8] and with three-dimensional finite difference, FLAC<sup>3D</sup> analysis results of [9]. Then a parametric study was carried out to investigate some of the factors that affect the response of laterally loaded pile used in slope stabilizing problem due to soil movement. Finally, reasonable conclusion and recommendation will be given for the three- dimensional finite element analysis.

## 1.6. Organization of the Thesis

This thesis comprises six chapters, the outline for which is described below:

Chapter one outlines the background of the study, the problem of the research, objectives, scope of the study, methodology overview and organization of the research.

Chapter two presents the review of literature relevant to this study, covering the behavior of piles under active loading at their head, passive loading arising due to the horizontal soil movement, and analysis methods used for the analysis of passive piles subjected to lateral soil movement.

Chapter three describes the three- dimensional finite element analysis method and procedure used for the analysis of the response of single laterally loaded piles due to soil movement.

Chapter four presents the verification of the 3D finite element analysis and discussion of results.

Chapter five describes a parametric study conducted to examine the factors that affect the modeling of single piles due to the surrounding soil movement.

Chapter six summarizes the major finding from this research and highlights the area of requiring further research.

## Chapter Two: Review of Literature

### 2.1. General

Extensive research has been conducted into pile-soil deformation of a pile subjected to lateral loads. The main focus of designers on pile subjected to either axially or laterally loaded piles are to satisfy the two basic requirements:

- (i) the pile needs to withstand applied loads without triggering structural or soil failure, and
- (ii) The induced displacements should not affect the functionality of the supporting structure.

For proper estimation of these failure loads and allowable induced pile displacement designers used several analytical and numerical methods. In this chapter, a review is conducted on different existing analytical and numerical methods for predicting ultimate collapse loads and allowable pile displacement in pile foundations, with the main emphasis on passive pile foundations subjected to lateral soil movement.

### 2.2. Types of Laterally Loaded Passive Piles

As [10]indicated, based on the direction of the load transfer between the piles and the surrounding soils, laterally loaded piles may be classified as active or passive piles.

(1) Passive laterally loaded piles: when piles are subjected to hidden loading due to movement of the surrounding soils, these types of laterally loaded piles are called passive piles. In practice, this type of laterally loaded passive piles due to soil movement encountered in piles in supporting bridge abutment, piles adjacent to pile driving, piles adjacent to embankments, piles near unstable slopes, piles near tunneling operation, and so on. Soil movement causes additional deflection and

serviceability problems or damage to Passive piles. Therefore, the design of laterally loaded piles may be based on the assumption that forces from moving soil will act against the piles and 'squeeze' past the piles. (2) Active laterally loaded piles: On the other hand, referred to piles subjected to a direct horizontal load at the head of the pile and transmit this load to the surrounding soil along their lengths. The main focus of this thesis is three- dimensional finite element analysis of a single laterally loaded vertical passive pile subjected to lateral soil movement.

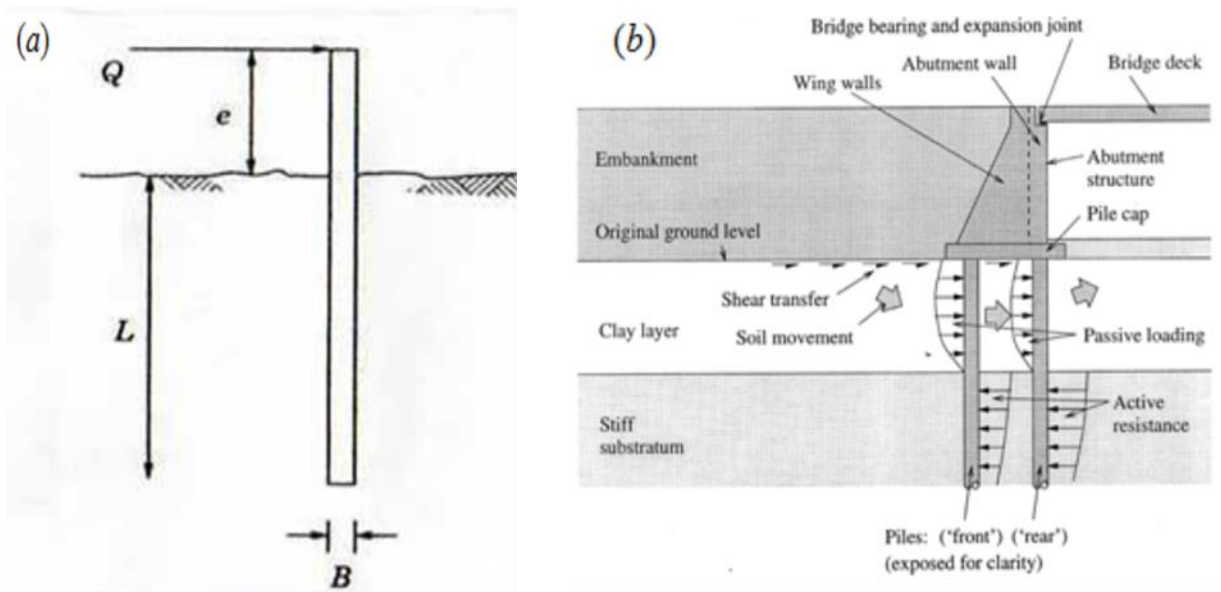
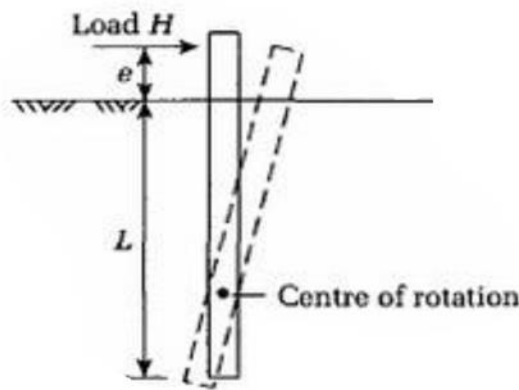


Figure 2. 1: (a) Active Pile [11](b) Passive piles in embankment [12]

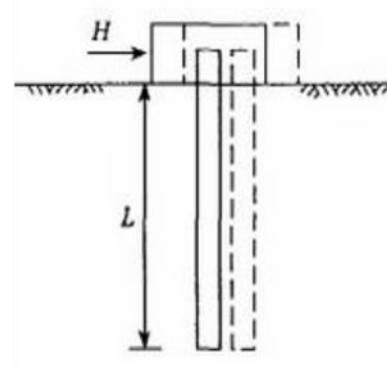
### 2.3. Failure Mechanism of Passive Laterally Loaded Piles

The failure mechanism of a pile can be classified accordingly by long or short pile, in terms of length-to-diameter ratio as their behavior differs for one another. According to [13] a short pile can be described as a pile with length to diameter ratio less than 10-12. When a force is applied to the free head pile, in addition to the passive soil resistance at the opposite side of the head pile, the toe passive resistance also forms at the force acting side. This results in exceeding the optimum values for passive resistance and the pile will start to rotate. The failure mechanism of long pile is different

at the bottom of the pile. The pile acts flexibly as the cumulative passive resistance at the pile bottom is much higher, when compared to short, rigid piles [13]. Hence, a long pile could not rotate as freely as a short pile.

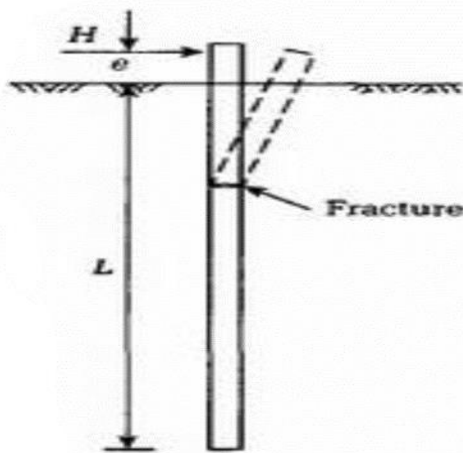


a) Free head

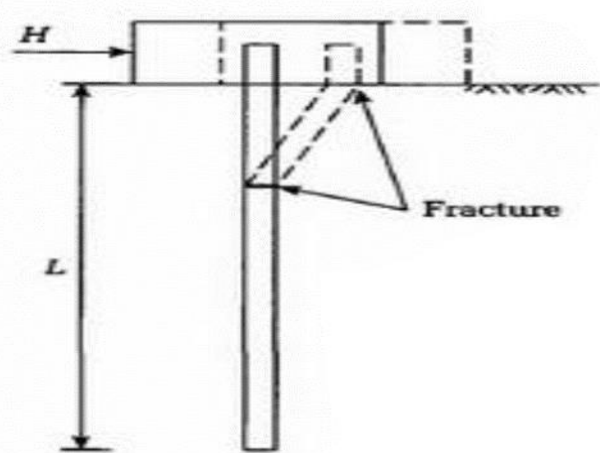


b) fixed head

Figure 2. 2: failure mechanism of the short rigid pile due to lateral load [13]



a) Free head



b) fixed head

Figure 2. 3: failure mechanism of long pile under lateral load [13]

## 2.4. Analysis Methods

Most of the analysis methods available in the literature are developed for active loading, although, most of these methods can be extended to passive loading analyses as well. Analysis methods currently available to analyze piles subjected to lateral soil movement can be categorized as, theoretical and experimental studies.

### 2.4.1. Theoretical Studies

According to [10] the theoretical approaches for analysis of the behavior of laterally loaded passive pile can be classified as 1) Modulus of subgrade reaction method: considering the pile as an elastic beam on a foundation, this method assumed that the soil acts as a series of linearly independent elastic springs. 2) Elastic continuum methods: assuming the soil to be a linear elastic or elastic-plastic material. 3) Finite element methods: simulating the stress-strain behavior of soil with multilinear or hyperbolic approximations.

#### 2.4.1.1. Modulus of Subgrade Reaction Method

Most of the theoretical solutions for laterally loaded piles involve the concept of modulus of subgrade reaction methods (simple and oldest, yet most versatile methods) is based on Winkler's assumption that the soil medium may be approximated by a series of closely spaced independent elastic springs. According to Winkler's hypothesis, the reaction at any point on the base of the beam depends only on the deflection at that point. It is assumed that the beam is supported by a Winkler soil model according to which the elastic soil medium is replaced by a series of infinitely closely spaced independent and elastic springs. This method differs from the elastic

methods [14], in which continuity is not directly accounted for, although the selection of appropriate subgrade moduli approximately, allows the interaction effects.

[15] Assumed piles as beams on an elastic foundation and soil reaction represented by Winkler springs. The behavior of a pile can thus be analyzed using the governing equation for this types of soil-pile system is derived from the classical Hetenyis' solution an elastic beam supported on an elastic foundation and is given by the following equations:

$$EI \frac{d^4 y}{dz^4} + p = 0 \quad (2.1)$$

Where: E= Modulus of elasticity of pile

I= Moment of inertia of pile section

z=Depth along with the pile

y=Lateral deflection of the pile at point z

p=Lateral resistance of soil per unit length of the pile which is equal to  $(k_y y)$ . Equation (2.1) can be rewritten as follows,

$$EI \frac{d^4 y}{dz^4} + kz = 0 \quad (2.2)$$

Where:

k -is the modulus of subgrade reaction (  $z = z_p - z_s$ )

$z_p$  -is the lateral displacement of the pile and

$z_s$  - is the lateral displacement of the soil.

Modification of the subgrade reaction approach to analyze piles subjected to lateral soil movement has been reported by many researchers (Marche, 1973; Byrne et al.,

1984; Maugeri and Motta, 1991; Reese et al., 1992; Frank and Pouget, 2008; White et al., 2008; and Cai and Ugai, 2003).

For example, Maugeri and Motta (1991) extend Reese and Matlock's (1956) and Marche's (1973) methods by linear subgrade reaction,  $k$ , with a non-linear hyperbolic function, together with a limiting load of the soil-pile interaction. Byrne et al (1992) also proposed to represent  $k$  with a non-linear  $p$ - $y$  curve used for the analyses of a laterally loaded pile.

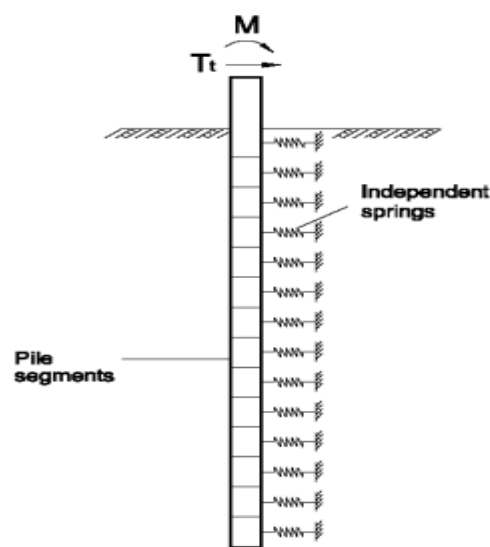


Figure 2. 4: Subgrade reaction model of soil around the pile [16]

#### 2.4.1.2. Elastic Continuum Methods

In this method, the soil is assumed as an ideal elastic continuum. In subgrade reaction methods the continuity of the soil is not taken into account. The Elastic Continuum method is based on a theoretically more realistic approach and can give solutions for varying modulus with depth and layered systems. However, this method suffers from the disadvantage that: it is difficult to determine the appropriate strains in field problems and corresponding modulus and it needs more field verification by applying theory to practical problems.

[14] presented a boundary element method for analysis of single piles embedded in soil undergoing lateral soil movements. This method is an extension approach developed for laterally loaded pile based on elastic continuum theory [17]. The analysis requires an input of the distribution of horizontal soil movement, soil modulus with depth, and ultimate soil pressure on the pile. Parametric studies were conducted to examine the effects of various factors on the pile behaviors, including effect of relative pile flexibility, boundary conditions, soil movement distribution, young's modulus, and limiting pressure distribution. This methods accounts for the continuity of the soil, but a good prediction from the method depends on an accurate estimation of the magnitude of soil movement, and limiting lateral pile-soil pressure, which are difficult to be accurately determined.

[18] applied the methodology of Begemaan and De Leeuw (1972) for the estimation of soil pressures and bending moments on passive piles. In this method, piles are exposed to soil pressure because of the surcharge load at the surface. Horizontal pressures are obtained by considering the effect of the relative flexibility of the pile which is reasonable to adapt because [18]specified that stiff piles may have a restrictive field of application. The soil was considered as linear elastic material in his analyses. It was concluded that if the pile is stiff, maximum pressure methods can be applied; however if the pile is flexible, methods using the pile-soil interaction are needed.

#### 2.4.1.3. Finite Element Method

The behavior of laterally loaded piles is investigated by several researchers using the method of subgrade reaction and elastic continuum approach methods for a long period. However, due to the presence of some variables in laterally loaded pile problems, it is difficult and complex to analyze the factors affecting the real pile–soil interaction using the subgrade reaction methods and an elastic continuum approach methods. In this manner, numerical studies and finite element approaches were

developed and applied to this concept to understand the phenomena more accurately [19], Chen and Poulos 1993, 1997).

Now a day due to the advancement of computer programs made, it is possible to evaluate complex geometries and multilayered soil strata. The finite element method is one this used to calculate pile displacement for different pile geometries in uniform and multi-layered soil and with different constitutive models of soil for single pile and group of piles. This method of analysis is represented by the finite element method in plain-strain analysis. Two and three- dimensional finite element modeling of the problem has been recently used by several researchers to capture actual pile-soil interaction behavior and to propose a feasible design guideline.

[19]used two dimensional (2D) finite element techniques to evaluate undrained soil behavior of slopes reinforced by multi-row pile groups. Effect of piles on the deformation and stability of slope investigated for different pile head fixity and pile stiffness conditions. It was concluded that very stiff piles should be used in slopes to get a considerable effect on slope stability. Increase in pile stiffness, restraints at the top, and tip of the pile enhance the efficiency of the pile. Besides, pile arrangement and soil profile have a significant effect on pile-soil interaction behavior.

[20] carried out a site-specific plane - strain analysis, where the piles were replaced by equivalent sheet pile walls, with flexibility equal to the average of the piles and the soil it replaced. The analysis can be used to analyze piles in a group by incorporating them into finite element mesh.

[21] used a three-dimensional (3D) finite element analysis program ABAQUS to investigate the behavior of a single pile subjected to lateral soil movement. In analyses, the pile was assumed as a linearly elastic material. Von Mises's constitutive model was used to simulate the non-linear stress-strain behavior of moving soil. Pile was modeled as a width of 1m square cross-section and 15 m length. Undrained behavior of cohesive soil was considered in all analyses. Normalized p-y curves and variations of ultimate soil pressures with depth were evaluated for stiff and flexible piles.

[8] identifies the currently published 2D and 3D finite element studies identified in the literature review are summarized as follows.

Table 2. 1: summary of two-dimensional numerical studies on piles subjected to lateral soil movements [8].

| The<br>object<br>ive of<br>the<br>study | Carter<br>(1982)                                | Naylor (1982)                         | Nystran (1987)                                                | Steward<br>(1992)                                   | Chen<br>(1994)                            |
|-----------------------------------------|-------------------------------------------------|---------------------------------------|---------------------------------------------------------------|-----------------------------------------------------|-------------------------------------------|
|                                         | Single<br>piles<br>nearby<br>surface<br>loading | Pile near an<br>embankments           | Effect of soil<br>movement on<br>subsequent<br>axial capacity | Piled bridge<br>embankment                          | Piles<br>subjected<br>to soil<br>movement |
| Soil                                    | Soft<br>stratum                                 | Cohesion less<br>and cohesive<br>soil | Under<br>consolidated<br>clay                                 | Cohesive soil                                       | Cohesion<br>less soil                     |
| Soil<br>model                           | Linear<br>elastic                               | Linear elastic                        | Extended cam-<br>clay                                         | Tresca,<br>modified<br>cam- clay,<br>linear elastic | Elasto-<br>plastic<br>(Tresca)            |
| Pile<br>model                           | Beam<br>element                                 | Equivalent<br>sheet-element           | Solid element                                                 | Beam-column<br>element                              | Rigid<br>element                          |
| progr<br>am                             | -                                               | -                                     | ABAQUS                                                        | AFENA                                               | AVPULL                                    |
| analy<br>sis                            | Axi-<br>symmetry                                | Plane strain                          | Plane strain                                                  | Plane strain                                        | Plane<br>strain                           |

|                           |                                              |                                                                     |                                 |                                                                                         |                            |
|---------------------------|----------------------------------------------|---------------------------------------------------------------------|---------------------------------|-----------------------------------------------------------------------------------------|----------------------------|
| object<br>ive of<br>study | Meyersohn(1994)                              | Bransby(1995)                                                       | Goh et al(1997)                 | Ellis(1997)                                                                             | Chen(2001)                 |
|                           | Piles in liquefaction-induced lateral spread | Piled bridge embankment                                             | Piles near an embankment        | Piled bridge embankment                                                                 | Piles stabilizing slope    |
| soil                      | cohesion less                                | Cohesive                                                            | Cohesion less and cohesive soil | Cohesive soil                                                                           | Cohesion less and cohesive |
| Soil model                | Non-linear elastic                           | Linear elastic, linear elastic-perfectly plastic(Tresca), power law | Non-linear elastic              | Strain dependent Modified Cam-Clay(clay) and linear elastic-perfectly plastic(granular) | Mohr-Coulomb               |
| Pile model                | Beam element                                 | Rigid element                                                       | Beam element                    | Equivalent sheet-pile                                                                   | Beam element               |
| Program                   | B-STRUT                                      | CRISP94                                                             | BCPILE                          | CRISP94                                                                                 | FLAC                       |
| Plain-strain              | Plain-strain                                 | Plain-strain                                                        | Plain-strain                    | Plain-strain                                                                            | Axi-symmetric              |

Table 2. 2: summary of three- dimensional numerical studies on piles subjected to lateral soil movements [8]

| objective of the study | Spring man (1989)           | Chaoui et al (1994)                      | Pan (1998)                                  | Chen (2001)                     | Miao et al (2005)                |
|------------------------|-----------------------------|------------------------------------------|---------------------------------------------|---------------------------------|----------------------------------|
|                        | Piled bridge embankment     | Pile group effect in unstable slopes     | Piles subjected to soil movement            | Piles stabilizing slopes        | Piles subjected to soil movement |
| Soil                   | Soft clay, stiff sand       | Cohesion less                            | Cohesive                                    | Cohesion less and Cohesive soil | Cohesive                         |
| Soil model             | Linear elastic              | Isotropic elastoplastic (Drucker Prager) | Elastic-perfectly plastic (Von Mises model) | Mohr- Coulomb                   | Mohr- Coulomb                    |
| Pile model             | Beam element                | Equivalent sheet- element                | Solid element                               | Beam-column element             | Rigid element                    |
| Program                | CRISP<br>SINPILE<br>SIMPILE | CESAR-<br>LCPC                           | ABAQUS                                      | FLAC <sup>3D</sup>              | ABAQUS                           |
| Analysis               | Finite element              | Finite element                           | Finite element                              | Finite difference               | Finite element                   |

## 2.4.2. Experimental Studies

[22] states that experimental studies have been conducted to understand the actual behavior of laterally loaded single pile or pile groups. Not only do these studies give ideas about the complex behavior of soil and pile systems, but also they provide a reliable comparison tool for the development of theoretical approaches in this concept. Experimental studies can be grouped into two, such as laboratory model tests and in-situ field tests.

Now a day, there are relatively few laboratory and field model tests to model piles due to lateral soil movement. The existing laboratory and field model tests can be classified as follows:

- 1) Lateral soil movement induced in slope stabilization or unstable slope
- 2) Lateral soil movement induced by adjacent pile driving in deep excavation
- 3) Lateral soil movement induced by the construction of an embankment at the soil surface adjacent to piles
- 4) Lateral soil movement induced as a result of tunnel operations

### 2.4.2.1. Laboratory Tests

In addition to theoretical methods, the situation of the pile subjected to lateral soil movements has been investigated with laboratory tests by different researchers. This subsection of this thesis presents the review of laboratory model tests and the design of the testing apparatus used to perform the test.

[23] reported up experimental model tests made by [24] to investigate the effect of horizontal loads on piles due to landslides. A model pile was installed into a rectangular iron model box filled with soil. The box was moved horizontally using a hydraulic jack, as shown in Figure 2.2. This movement simulated a uniform distribution of soil displacement along with depth of pile section embed in the box. The results from the test indicated that the deformed shape of the pile was dependent up on the flexural stiffness of the pile.

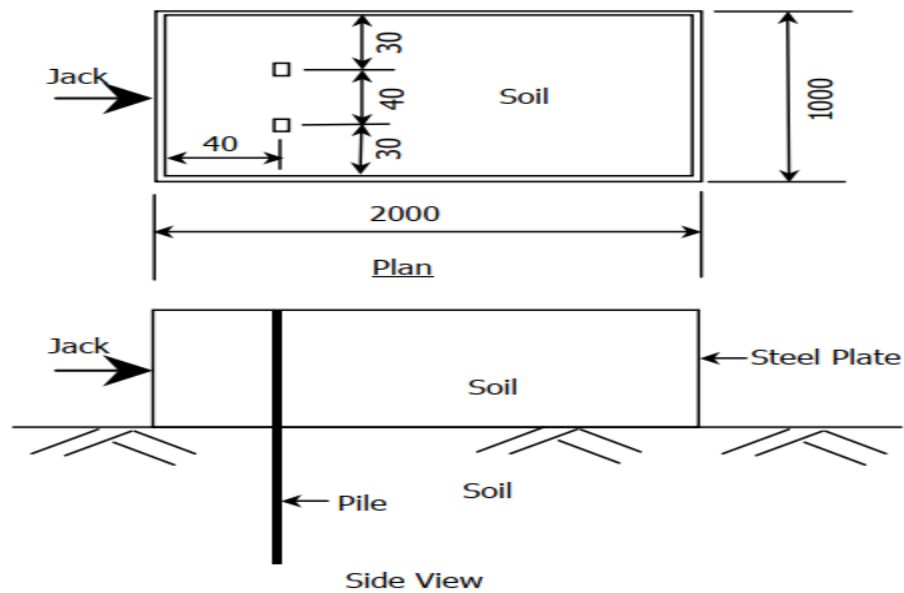


Figure 2. 5: Laboratory Model test [24]

[25] studied on laterally loaded passive pile behavior in a shear box model. Shear box with a 30x30 cm cross- section, maximum depth of 60 cm, and movable part of 15 cm were used in analyses. Pressure distribution on passive piles in cohesive soil was measured using miniature stress cells. Experiments were conducted for different pile penetration depths and soil consistencies.

[26] conducted a laboratory experiment to investigate group action reduction in passive pile groups. The same shear box model with [25] was used in experiments. Two types of material were investigated in analyses as soft clay and stiff clay with an undrained

shear strength of 12kPa and 85kPa respectively. Model piles having 30 cm length and 1cm diameter were inserted into the soil inside the shear box in a row.

[27] investigate bending moment distributions of single and group of piles in cohesion-less soil using model piles. Strain gauges attached to the pile shafts were used to measure bending moments during the test. The maximum bending strain was observed approximately at the depth of  $0.7L$  ( $L$ : Pile length) and maximum negative bending strain measured at the depth of  $0.3L$  for both single pile and pile groups. It was concluded that even if the amount of loading change general behavior of the bending moment distribution remains the same, especially for single piles.

[28] investigate laterally loaded single pile and pile group behavior adjacent to an embankment construction. Model piles were inserted into a soft clay layer underlined by dense sand. The bending moment measurements were obtained during the test from the measurements of strain gages. Bending moment increase was seen at the pile head and interface of soft clay to dense sand layer. It was concluded that centrifuge testing results show very good agreement with the actual field test results.

[8] carried out more model tests to investigate the response of a single in sand subjected to axial load, and a rectangular profile of the soil movement induced by a rectangular loading block. He investigated the effect of pile diameter, density of sand, axial load, and two combinations of the sliding, and stable soil layer depths on the pile responses. He presents the results of single pile tests. He also conducted model tests on pile groups subjected to a uniform soil movement profile by varying the pile diameter, axial load per pile applied on the top of the pile cap, pile arrangement, and pile spacing, and two combination of the ratio of  $L_m/L_s$ . These tests were all conducted in capped-head pile head fixity condition. He concluded that, (1) the maximum bending moment increases with the increase of the ratio  $L_m/L_s$  and pile diameter; (2) the maximum soil pressures acting on the pile in sliding layer and the stable layer of the soil did not exceeds the limiting pressure proposed by Barton (1982); and a linear relationship exists between the maximum bending moment, and shear force.

## 2.4.2.2. In-Situ Test/ Field Tests

The in-situ tests/field tests on the piles loaded laterally by soil movements have been considered as the best practical methods which reflect the real pile behaviors. Field tests are very useful in:

- Evaluating the field performance of piles
- Assessing the effectiveness and improvement of the factor of safety as a result of remedial measures with the use of piles.
- Modifying and verifying the design methods
- Identifying the mechanism of slopes and pile interaction based on a relative pile and soil movement.

Many instrumented field tests have been reported by different researchers, for example, Heyman & Boersma (1962), Heyman (1965), Leussink & Wenz (1969), Nicu (1971). Most of them involved to investigating the response of piles used for slope stabilization and the piles for retaining structures. However, in terms of this part, only two or three researcher reports are mentioned to gain an overview of the pile behaviors. These are:

[29] described a field test relating to a landslide. A reinforced concrete pile with dimensions of 30m in length and 0.79m in diameter was instrumented with pressure cells along the pile shaft and an inclinometer inside. It could be seen from the measurements that, the pile head deformed significantly and the pressures acting on the pile gradually increased.

[30] presented a field test where the steel pile was installed approximately four months after the construction of embankment. The pile was located at the embankment toe and inserted through the soft clay layer & the stiff sand layer. The bending moments and the pile deflections were recorded by vibrating-wire strain-gauges and inclinometer respectively. In short, the measurements showed that the maximum bending moments

acting on the pile could be generally found at the pile top, the middle of the soft layer and the interface between two different layers.

[31] reported about a field investigation scheme on a sliding slope under an embankment. 15 m depth of highly plastic reconsolidated clay movement with an inclination of 5°-8° stopped with 3 m diameter reinforced concrete piers embedding to stable layer into 5m. Earth pressure distributions on piles were recorded with pressure cells. It was observed that measured soil pressures were much smaller than the (only %30) design pressure which had been calculated according to the Brinch Hansen formula.

[32] analyzed the lateral transfer mechanism of an experimental pile undergoing long-duration thrust owing to the moving slopes over 16 years. Experimental  $p \sim \Delta y$  ( $\Delta y = y - y_s$ , is the relative displacement,  $y$  is the pile displacement,  $y_s$  is the free displacement of the soil) curves have been conducted. A Menard pressure meter method and a self-boring pressure meter method are proposed to predict the  $p \sim \Delta y$  curves. Comparison of results from numerical analysis using a three sets of reaction curves derived from the experimental measurement derived from the experimental measurement and the two suggested methods shows that the  $p \sim \Delta y$  curves determined from the Menard pressure method and self-boring pressure meter methods are too stiff. Thus the proposed methods leads to an over estimates of the pile displacements, and bending moment.

This chapter has given a brief review of the wide range of literature concerned with the behavior of piles subjected to lateral loads. Some significant aspects have been covered and conclusions are drawn. Some of the controversial suggestions or even conflicting conclusions about whether a difference in ultimate resistance between active piles and passive pile exists, which requires more research to be carried out.

The current analysis methods have drawbacks, for example, the method of subgrade reaction ignores the continuity of the soils. Whereas, the elastic continuum approaches, it is difficult to determine appropriate strains in a field problem and the corresponding soil moduli.

Laboratory studies directly addressing the response of either single pile or pile groups to lateral soil movements are generally the case- sensitive and insufficient, when compared with the pile failure mode, occurring in the field. The available laboratory test results generally reveal only one mode of pile failure.

Due to the uncertainties of ground conditions and high variations in soils, the current design methods tend to oversimplify the problems, and lead to overdesign. To optimize the design, the load and deformation behavior of a single laterally loaded pile due to soil movement require a thorough investigation. In this research, the 3D FEM software, PLAXIS 3D, will be used to predict the capacity of the single passive pile subjected to lateral soil displacement. Published case studies will be used to calibrate the modeling method, and verify the numerical results.

## **Chapter Three: 3D FEA Methods and Procedures**

### **3.1. Introduction**

In this thesis, three- dimensional finite element analysis software PLAXIS 3D 2013 was used to model the response of laterally loaded single vertical pile in sandy soil due to soil movement. The modeling procedures of PLAXIS 3D were discussed in this chapter along with input parameters.

PLAXIS 3D software is used to model the complex pile-soil interactions and allows the finite element model to be solved quickly. Properties and main functions of the 3D finite element methodology are presented briefly here for a better understanding of the model designs.

### **3.2. Model Properties**

To model the problem, two soil layers (sliding and stable soil layer), embedded pile, and special interface material were used. The properties of the materials used for unstable soil layer, stable soil layer, and embedded piles to model the PLAXIS 3D finite element analyses of these study was directly taken [8] thesis. The following sections present the model soil and model pile properties used for 3D finite element analysis.

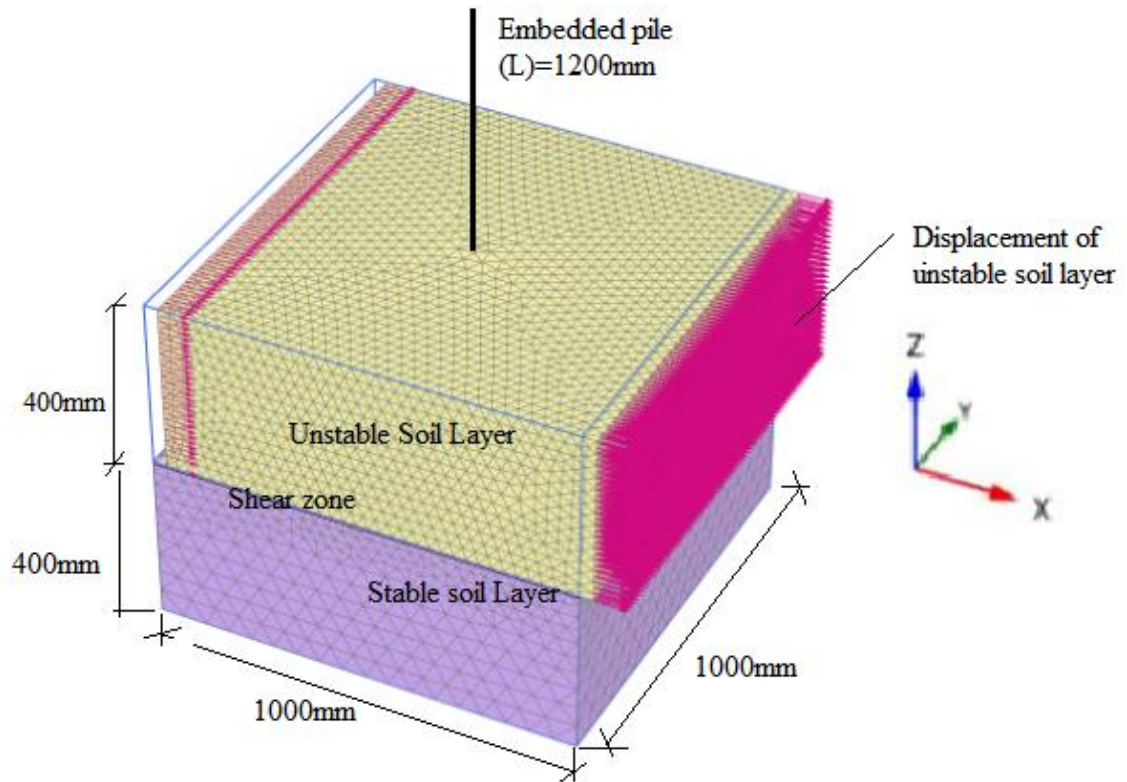


Figure 3. 1: Geometric illustration of the shear box model

### 3.2.1. Model Soil Properties

Similar soil material parameters were used to model unstable and stable soil layers. In this research, the Mohr-Coulomb elastoplastic constitutive model is used as a material model for soils. The Mohr-Coulomb model which is widely used in modeling the geotechnical problem is relatively simpler to be used when compared to other constitutive models. The linear elastic perfectly plastic Mohr-Coulomb model involves five input parameters, i.e. Young's modulus ( $E$ ) and Poisson's ratio ( $\nu$ ) for the soil elasticity; friction angle ( $\phi$ ) and cohesion ( $c$ ) for soil plasticity and ( $\psi$ ) as a dilation angle.

The sand material used for an unstable ( $L_m$ ) and stable ( $L_s$ ) layer had a friction angle of  $\phi = 38^\circ$  and according to [33] dilatation angle ( $\Psi$ ) was estimated by the equation (3.1) as follows:

$$\Psi = \phi - 30^\circ \quad (3.1)$$

After [34] dilation angle ( $\Psi$ ) ranges from  $0^\circ$  to  $20^\circ$  for sand, and  $\Psi = 38^\circ - 30^\circ = 8^\circ$ , which was within the recommended range. Similarly, after [35] the coefficient of earth pressure at rest was estimated by the equation (3.2) as follows and the sand assumed to have a tensile strength of zero ( $Q_t = 0$ ).

$$K_o = 1 - \sin \phi^\circ \quad (3.2)$$

To model unstable and stable soil layer similar materials were used as shown in table 3.1.

Table 3. 1: material properties of unstable and stable soil [8]

| Parameter |                                              |                          | Value        | Unit              |
|-----------|----------------------------------------------|--------------------------|--------------|-------------------|
| General   | Material model                               |                          | Mohr-Coulomb | -                 |
|           | Drainage type                                |                          | Drained      | -                 |
|           | Unit weight                                  | $\gamma_d$               | 16.27        | kN/m <sup>3</sup> |
|           | Coefficient of earth pressure at rest, $K_o$ | $1 - \sin \phi = 0.3843$ |              | -                 |
|           | Deformation modulus                          | $E_s$                    | 572          | kN/m <sup>2</sup> |
|           | Poisson's ratio                              | $\nu_s$                  | 0.3          | -                 |

|                            |                         |        |    |                   |
|----------------------------|-------------------------|--------|----|-------------------|
| Strength<br>paramet<br>ers | Cohesion                | c      | 2  | kN/m <sup>2</sup> |
|                            | Internal friction angle | $\phi$ | 38 | degree            |
|                            | Dilation angle          | $\Psi$ | 8  | degree            |

### 3.2.2. Embedded Pile Model Properties

In PLAXIS 3D software, the embedded pile model can be used to model a structural element, like a shaft in soil. The embedded pile is connected to the adjacent soils by special interfaces named skin interfaces and foot interfaces. The embedded pile was modeled as a linear elastic hollow Aluminum pipe with a length of 1200mm, Young's modulus of  $7.0 \times 10^{10}$  N/m<sup>2</sup>, and poison's ratio of 0.3.

The embedded pile has some benefits than the volume pile which is assigned with soil material. When it is compared to the volume pile, the embedded pile doesn't give influence on the mesh as generated from the geometry model. It also needs a lower mesh refinement, and a reduced time for numerical calculations. Since it is considered as a beam structure, the embedded pile directly gives the results of force in PLAXIS 3D output, which can't be obtained from the volume pile model.

Table 3. 2: material properties of embedded piles [8]

| Parameter              |                       |          | value               | unit              |
|------------------------|-----------------------|----------|---------------------|-------------------|
| Strength<br>parameters | Predefined pile type  | -        | Massive<br>circular | -                 |
|                        | Constitutive models   | -        | elastic             | -                 |
|                        | Unit weight of a pile | $\gamma$ | 27                  | kN/m <sup>3</sup> |
|                        | Deformation modulus   | $E_p$    | $7 \times 10^{10}$  | N/m <sup>2</sup>  |
|                        | Poisson ratio         | $\nu_p$  | 0.3                 | -                 |
|                        | Pile diameter         | D        | 50                  | mm                |
|                        | Pile Length           | L        | 1200                | mm                |
|                        | Wall thickness        | t        | 1                   | mm                |

### 3.2.3. Pile-Soil Interaction

Interface elements were used between the outer perimeter of the model pile and the adjacent soils to model the soil-pile interaction. The behavior of the interfaces is described by an elastic-plastic model. The pile-soil interaction may involve a skin resistance (in a unit of force per length) and a tip resistance (in a unit of force) whose sum is considered as the bearing capacity of the embedded pile.

The following constitutive equation represents the skin resistance of the interface:

$$t^{skin} = K^{skin} * \Delta U_{rel} \quad (3.3)$$

Where

$t^{skin}$  = forces at the integration points

$K^{skin}$  = the interface material stiffness matrix

$\Delta U_{rel}$  = the relative displacement vector between the soil and the pile.

The relative displacement vector between the pile and the soil is given by,

$$\Delta U_{rel} = u^p - u^s \quad (3.4)$$

Where:  $u^p$  - is the displacement of the pile and  $u^s$  - is the displacement of the soil.

In three dimensional (3D) local coordinate system (n, s, t) equation (3.3) can be written as follows:

$$\begin{pmatrix} t_n \\ t_s \\ t_t \end{pmatrix} = \begin{pmatrix} K_n & 0 & 0 \\ 0 & K_s & 0 \\ 0 & 0 & K_t \end{pmatrix} \begin{pmatrix} u_n^p - u_n^s \\ u_s^p - u_s^s \\ u_t^p - u_t^s \end{pmatrix} \quad (3.5)$$

Where:

$t_n$  – The shear stress in the axial direction

$t_s$  and  $t_t$  – The normal stress in the horizontal direction

$K_n$  - The elastic shear stiffness in the axial direction

$K_s$  and  $K_t$  – The elastic normal stiffness in the horizontal direction

$u^p$  – The pile displacement

$u^s$  – The soil displacement

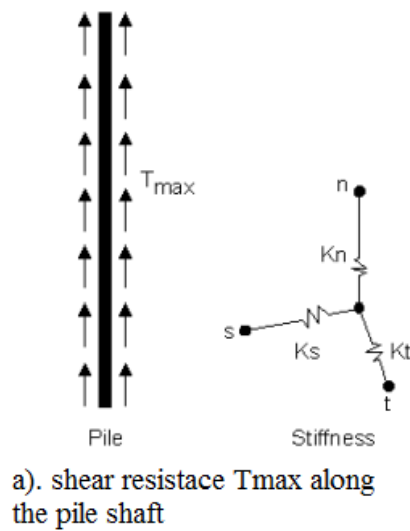


Figure 3. 2: Shear resistance and tip resistance [28].

Constitutive equation (3.3) visualized as shown in figure 3.2a and 3.2b. As shown in figure 3.2a, the skin resistance ( $T_{max}$ ), can be defined as the capacity of the interface to withstand the shear force ( $t_n$ ), along with the pile. In the case of elastic behavior of the shaft, the shear force ( $t_n$ ), at a particular point has to be smaller than the local skin resistance at that point.

$$T_{max}(t_n < T_{max}) \quad (3.6)$$

If  $t_n \geq T_{max}$ , plastic behavior can occur. As shown in figure 3.2b, the tip resistance is governed by a non-linear spring at the pile tip. The tip resistance is the capacity against the maximum force acting at the interaction between the pile tip and the soil and it can be represented by equation 3.7 below.

$$0 \leq F_{tip} = K_{tip} (u_{tip}^p - u_{tip}^s) \leq F_{max} \quad (3.7)$$

Where:

$F_{tip}$  - Force at the pile tip

$K_{tip}$  - Material stiffness matrix of the spring element at the pile tip

$u_{tip}^p - u_{tip}^s$  - Relative displacement vector between the soil and the pile at the foot.

The force at the pile tip,  $F_{tip}$  is zero in case of tension behavior. In the case of compression, the failure will happen when the force at the pile tip,  $F_{tip}$  is equal to the maximum resistance at the pile tip  $F_{max}$ .

The shear resistance of the interface in the axial direction of the pile, which is determined based on a “slide” between the pile node and the soil node. A failure criterion is applied to both the skin resistance and the tip resistance for differentiating between the interface elastic behavior and the interface plastic behavior [36].

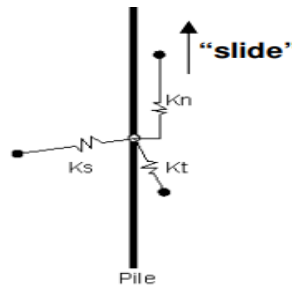


Figure 3. 3: Node model for the pile-soil interaction [28].

In PLAXIS, Skin resistance can be described using linear, multi-linear, or layer dependent traction models. The skin resistance is also, directly related to the strength of the surrounding soil by the interface strength reduction factor  $R_{int}$ , which is set up in the material data set of the soil. These strength reduction factor  $R_{int}$  control the slide in the axial direction of the pile and/ or when the pile subjected to axial loading as shown in figure 3.3.

In this thesis, the skin resistance is represented by the linear traction model and the embedded pile subjected to lateral loading. However, in a laterally loaded pile, it was not clear weather, the  $R_{int}$  value control the pile-soil interaction. It was based on the direction of the node model of the interface as shown in figure 3.3. [36] describes that  $R_{int}$  doesn't give any influence on the displacements in terms of the laterally loaded pile. Because PLAXIS by setting used "slide" to model the pile-soil interaction in the axial direction (n-direction). However, in horizontal directions (t-direction & s-direction), the normal stresses remain elasticity that results in no relative displacement between the pile and the soil in these directions. The interface strength increase as  $R_{int}$  value reduced as recommended by [36]. So for this thesis, a zero slip strength and /or nearly zero slip strength were used by choosing a minimum value of interface reduction factor ( $R_{int}$ ), and also a special interface material (foot interface) was used to model the interaction between unstable and stable soil layer.

### 3.3. 3D FEA Model Boundary Conditions

To define the surface boundaries and to model the embedded pile under lateral soil movement problem, the surface prescribed displacement property was used to define the problem. Proper representation of boundary conditions is vital in the analysis of a single passive pile. To model the boundary fixity of this problem, the movement in three directions must be defined (x, y, and z) direction. The bottom surface of the soil model was restrained to move in X (horizontal direction), Y, and Z (vertical directions), while topsoil surface was free to move. A horizontal (X-direction) uniform or triangular prescribed lateral soil movements of 60mm were applied to the right and left

boundaries in figure 3.3. Those surface boundaries were, also restricted to move in the Y-direction. The surface boundaries parallel to the X-Z plane (front and rear surface boundaries) were restrained from moving in the Y-direction.

Table 3. 4: Surface boundary fixities for unstable soil layer.

| Surface             |            | x-direction                       | y-direction | z-direction |
|---------------------|------------|-----------------------------------|-------------|-------------|
| Unstable soil layer | Front side | Free                              | Fixed       | Free        |
|                     | Rear side  | Free                              | Fixed       | Free        |
|                     | Right side | Prescribed displacement ( $u_x$ ) | Fixed       | Free        |
|                     | Left side  | Prescribed displacement ( $u_x$ ) | Fixed       | Free        |

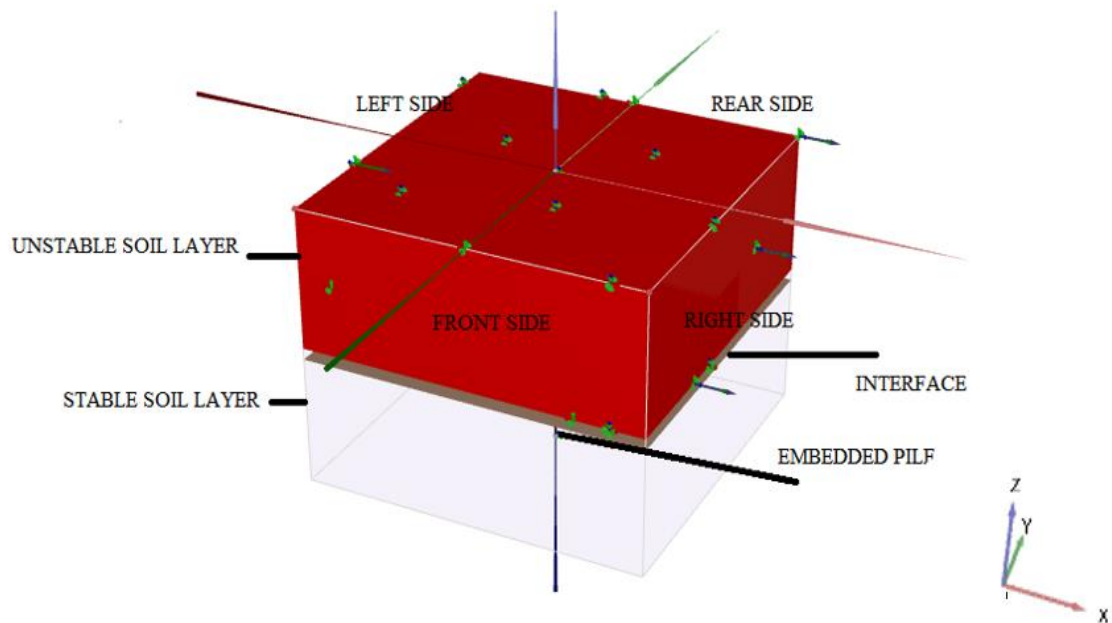


Figure 3. 4: Boundary surfaces fixity condition for unstable soil layer

### 3.4. 3D Finite Element Mesh Generation

In PLAXIS 3D, a fully automatic generation of finite element meshes is allowed. A sufficiently fine mesh should be selected to obtain accurate numerical results. The mesh should be fine enough to get an accurate numerical analysis.

To evaluate mesh dependence, the PLAXIS 3D model is implemented with five types of mesh coarseness. These are very coarse, coarse, medium, fine, and very fine mesh generations.

The optimum size of mesh that best simulates the actual passive pile behavior was determined by investigating calculation time; deformations and structural forces for both pile, and soils.

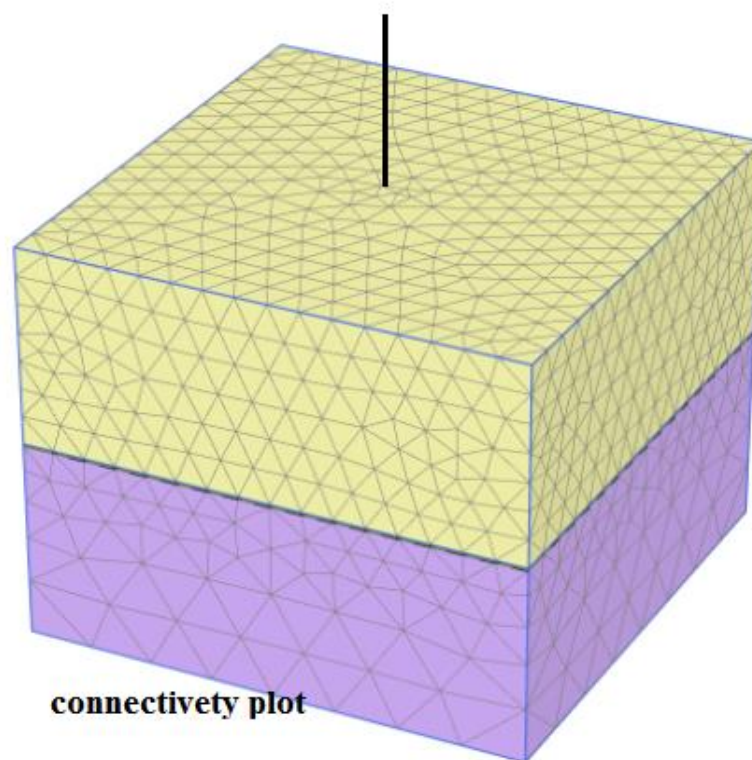


Figure 3. 3: Typical mesh generation of the 3-D FEM model in PLAXIS 3D for coarse mesh

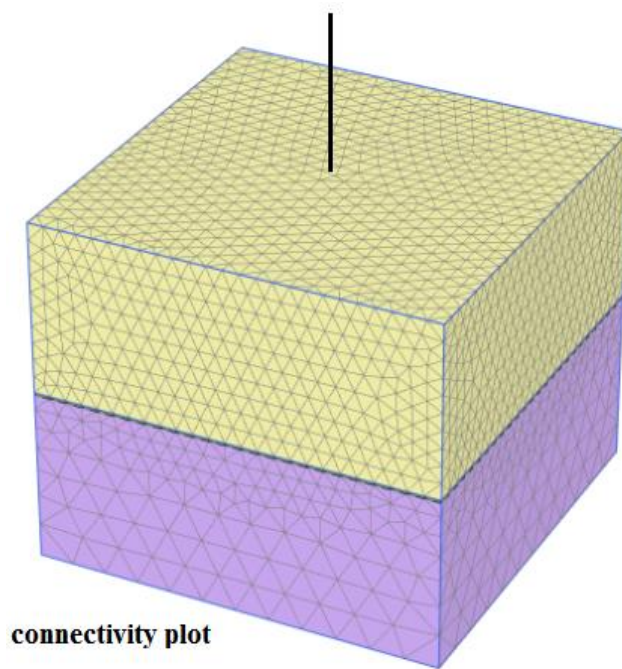


Figure 3. 4: Typical mesh generation of the 3-D FEM model in PLAXIS 3D for medium-mesh

Since coarser mesh contains fewer elements, it is less capable of steep changes in the gradient of deformation. If a finer mesh is used, calculation time and cost of running the model shall be increased.

It is preferred to have a more accurate finer finite element mesh in areas where large stress concentrations are expected while other parts of the geometry might not require a fine mesh.

In this study, medium mesh generation has sufficient degree of fineness, and it gives enough numerical accuracy for the scope of verification, and parametric analysis. Medium mesh could be selected as optimum mesh generation element considering excessive time consumption of fine, and very fine meshes. A 10-node tetrahedral element, as shown in Fig. 4.3, is used to model the soil.

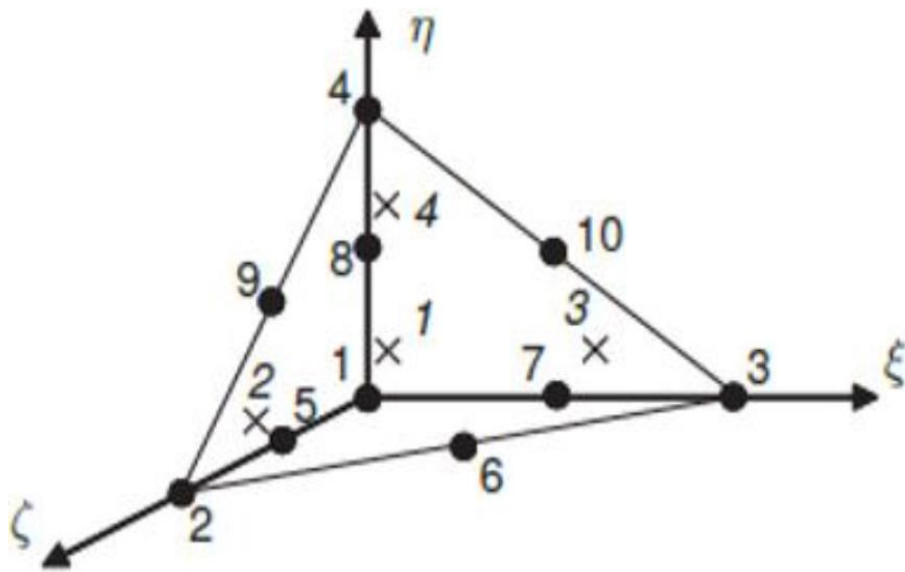


Figure 3. 5: 3D finite element mesh used for model the soil [37]

## Chapter Four: Verification of 3D FEA and Results

### 4.1. General

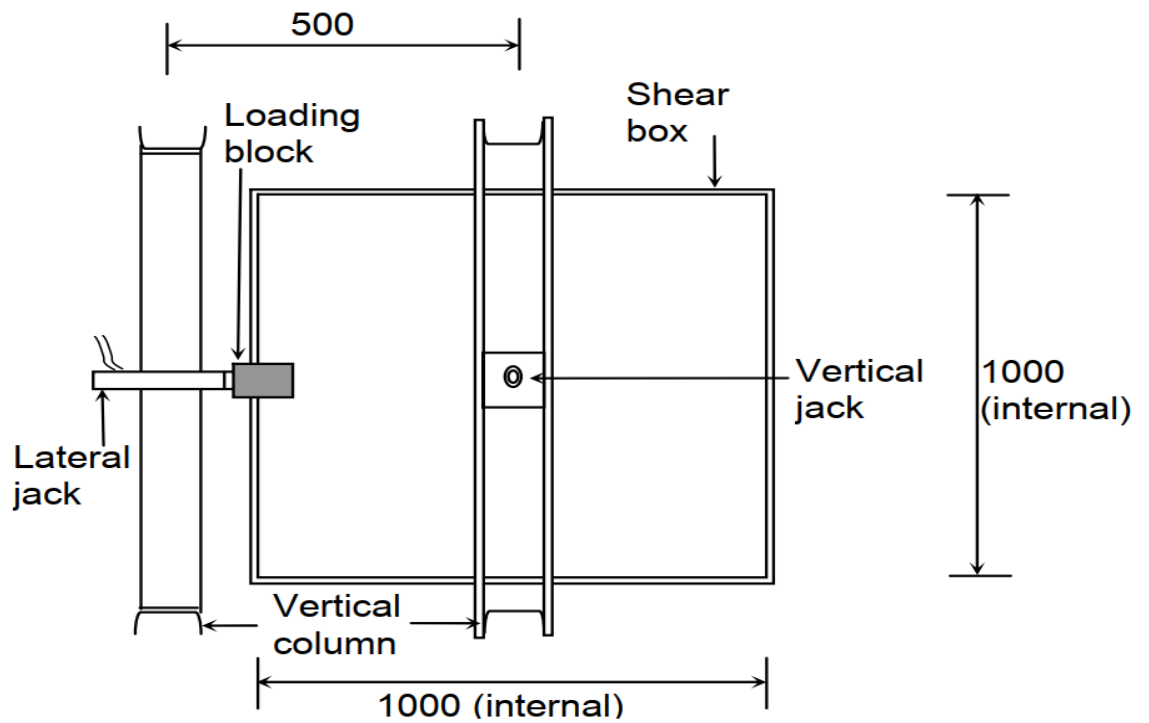
In this chapter, PLAXIS 3D 2013 finite element analysis model is validated using model laboratory test results of [8] for its applicability in modeling problems involving pile undergo lateral soil movement. Besides, the PLAXIS 3D model results are compared with a three-dimensional finite difference (FD) FLAC<sup>3D</sup> analysis is carried out by [9] for the same model with same pile and soil properties.

### 4.2. Shear Box Model

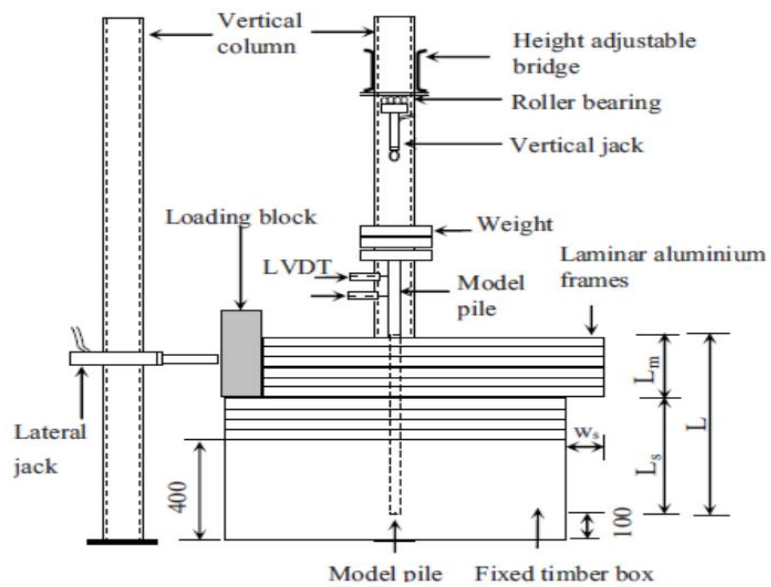
The model laboratory test carried out by [8] was conducted using the shear box. The shear box has internal dimensions of 1000mm by 1000mm, and 800 mm in height as shown in Figure: 4.1. The upper movable part of the box consists of the desired number of 25 mm thick square laminar aluminum frames to achieve a thickness of unstable soil layer ( $L_m$ ) 400 mm(for this research). The lower fixed section of the box is a timber box 400 mm in height, and the desired number of laminar aluminum frames to achieve a stable sand layer of a thickness ( $L_s$ ) 300 mm(for this research).

A loading block is used to apply lateral movements to the laminar Aluminum frames that form the upper section of the shear box. The block is made to different shapes of rectangular, triangular, and trapezoidal (for this research), which are used to simulate corresponding soil movement profiles. The rate of the movement of those frames (thus the soil) is controlled by a hydraulic pumps and a flow control valve. The rate of the movement of the upper shear box (thus the soil) is controlled by a hydraulic pump and a flow control valve. As shown in Figure 4.1(a) and (b), a vertical jack was used to drive the pile into the shear box. In order to restrain the pile head from rotation but not the lateral movement, a roller bearing is used to connect the jack to the loading frame.

Note: all dimensions in the figure are in mm.



a). Plan view



b). Sectional view

Figure 4. 1: physical model test setup [8]

The response of the pile is monitored via strain gauge, and the two linear variable displacement transducers (LVDTs) above the model ground. The test readings are recorded and processed via a data acquisition system and a computer.

The shear box model test was conducted on a single vertical pile subjected to a uniform profile of lateral soil movement. Free-head and free-tip hollow aluminum tube pipe is embedded through the soil box. The pile had an overall length of 1200 mm with an outer diameter of 50 mm and wall thickness of 1.0 mm. Mohr-Coulomb elastic-plastic constitutive model was assumed for the soil. The properties of the sand and embedded pile used in the tests are illustrated in Table 3.1 and Table 3.2 respectively.

### 4.3. FLAC<sup>3D</sup> Analysis

[9] Used a three-dimensional finite difference FLAC<sup>3D</sup> version 2.1 (Fast Lagrangian Analysis of Continua in three Dimensions) to perform the numerical analysis. One of the main features of the FLAC<sup>3D</sup> is that it can operate in small or large strain mode. The large strain mode occurred when the grid point (mesh) coordinates are updated at each strain or movement increment, according to the computed displacement. This is particularly important to the present study involving large soil movements.

The soil strata were modeled with eight-noded brick shape elements and the pile using six-node cylindrical shape elements. For the standard model, with a single pile, the mesh comprised of 1856 elements with 2894 nodes or grid-points.

The bottom face of the mesh in Figure 4.2b was fixed in all three (x, y, and z) directions. Both faces parallel to the y-z plane were fixed in the x-direction and the other faces parallel to the x-z plane were fixed in the y-direction. A uniform rectangular and triangular prescribed displacement of 60mm was applied from the left to right both at left and right side of the model. The thickness of the unstable soil layer ( $L_m$ ) was 400mm and stable soil layer ( $L_s$ ) 300mm as used in the model test. The sand strata were modeled with an elastoplastic Mohr-Coulomb model and using a non-associated

flow rule. The properties of sand and embedded pile as similar to the shear box model, and directly taken from that reported in the model tests by [8].

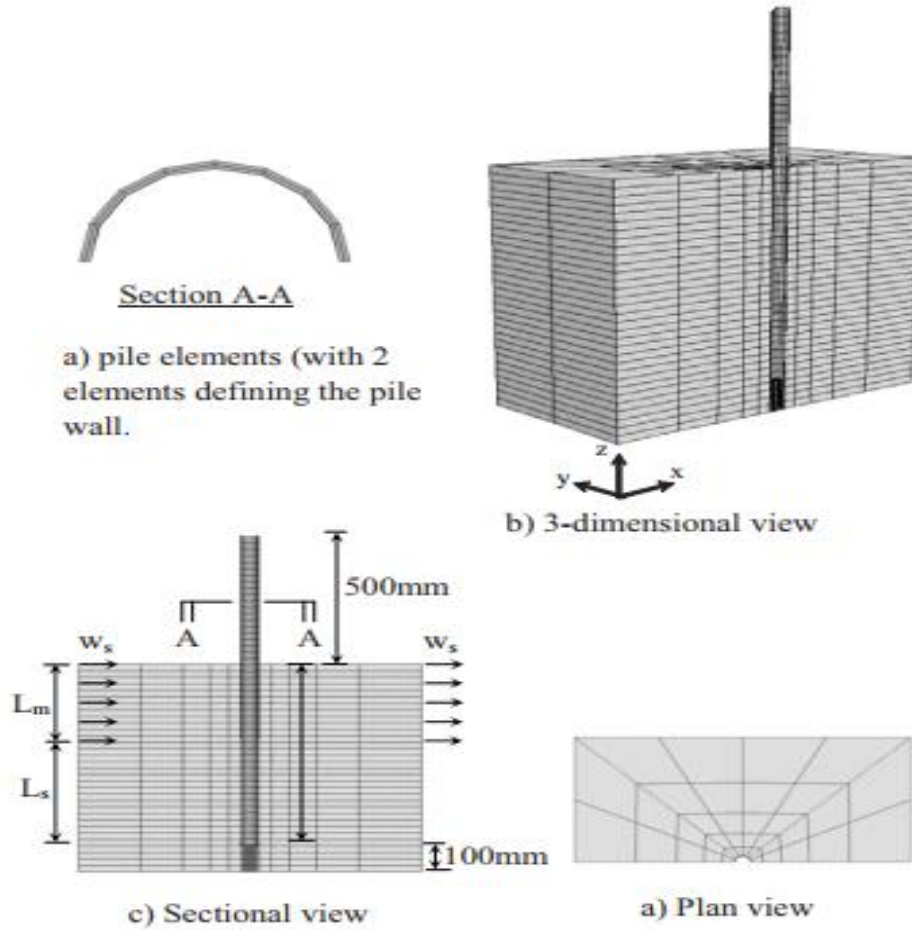


Figure 4. 2: Mesh of soil and pile used in FLAC3D analysis [9]

## 4.4. Finite Element Analyses

### 4.4.1. PLAXIS 3D Model of a Laterally Loaded Pile

In this part of the research, numerical modeling is conducted on a single pile in soil by using the FEM package, PLAXIS 3D 2013. The pile is modeled using an embedded pile model available in PLAXIS 3D. The model geometry can be created with dimensions of 1m in both x and y-directions, and 0.8 m in the z-direction. The soil is assumed to have 0.4m thickness unstable soil layer and 0.4m thickness of stable soil layer. The width (y-axis) and the length (x-axis) of the soil block are pre-defined in the model tab on the project properties window. The limits of the soil contour is defined as the x- min = -0.5m, x - max = 0.5 m, and y min = -0.5m, and y max = 0.5 m.

Once the geometry of the soil model is created, the depth (z-axis) is applied using the “create borehole” button, in this part the groundwater table level can also be selected as  $z = 0$ . The top boundary of the soil layer is at  $z = 0$ , the bottom boundary of the soil layer is at  $z = -0.4$  m for unstable soil layer and at  $-0.8$ m for stable soil layer. Once the soil block is drawn, the soil properties can be assigned to it. The soil is modelled with the Mohr Coulomb model.

The next step is to create the structure phase where the pile is inserted into the soil mass through the “create embedded pile” function. The embedded pile is located at the  $\{0, 0, 0\}$  of the coordinate system with the pile head at the ground surface. The embedded pile has dimensions of 0.05 m in diameter and 1.2 m in length. The material properties of the pile can also be assigned in this mode.

Stiffness properties of the soil profile and embedded pile were assigned regarding the given information and assumptions of [8]. The same materials were used for unstable and stable soils.

#### 4.4.2. Mesh Generation

Once the geometry modeling process is complete, calculations proceed which consist of the generation of meshes and definition of the construction stages. The defined geometry has to be divided into finite elements to perform a FEM calculation. Mesh generation is an important part of a finite element calculation. Meshes should be generated fine enough to obtain accurate results and coarse enough to avoid an excessive amount of calculation times. A mesh is a composition of finite elements that can be created in mesh mode in PLAXIS 3D. A sufficiently fine mesh should be selected to obtain accurate numerical results. In PLAXIS 3D, a fully automatic generation of finite element meshes is allowed. The coarseness of the mesh element distribution can be selected from the sizes that include very coarse, coarse, medium, fine, and very fine. Since coarser mesh contains fewer elements, it is less capable of steep changes in the gradient of deformation. If a finer mesh is used, calculation time and cost of running the model shall be increased.

#### 4.4.3. Calculation Process

In this research, the calculation process was divided into 3 phases to simulate the shear box model as shown in Figure 4.3; i.e. initial phase, pile casting, and uniform lateral displacement application. The effective stresses and pore water pressures are calculated in the soil block during the initial phase. In the next stages, the pile is inserted into the soil. After that, the 60mm uniform rectangular or triangular lateral displacement is applied. The plastic calculation type is used for deformation calculations.

Table 4. 1: calculation phases for shear box and FLAC 3D case verifications.

| Phase Name    | Type of Calculation      | Activated Model properties                                              |
|---------------|--------------------------|-------------------------------------------------------------------------|
| Initial phase | K <sub>0</sub> procedure | Soil                                                                    |
| Phase 1       | Plastic drained          | Soil<br>Interface<br>Embedded pile                                      |
| Phase 2       | Plastic drained          | Soil<br>Embedded pile<br>Interface<br>Uniform lateral soil displacement |

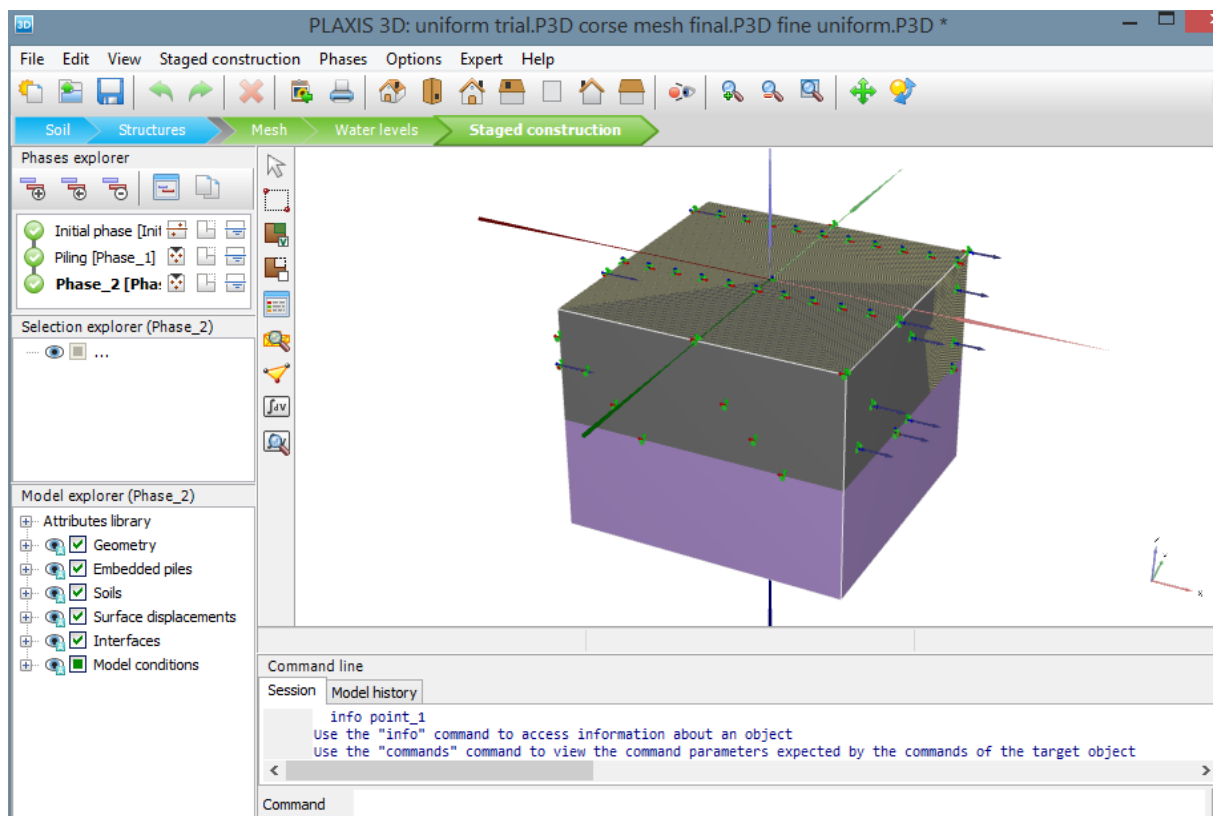


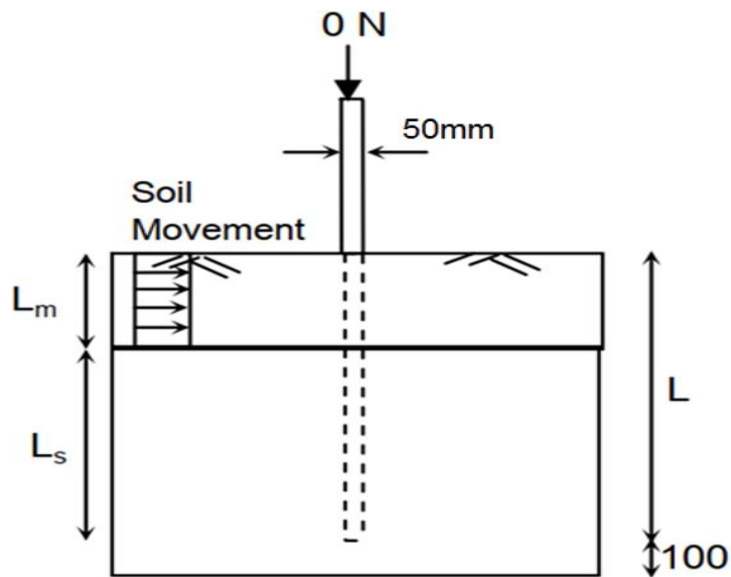
Figure 4. 3: Construction Phases in PLAXIS 3D

In this thesis, the shear force ( $Q_{12}$ ) over the second beam axis and the bending moment ( $M_3$ ) around the third axis was used for validation and parametric study analysis.

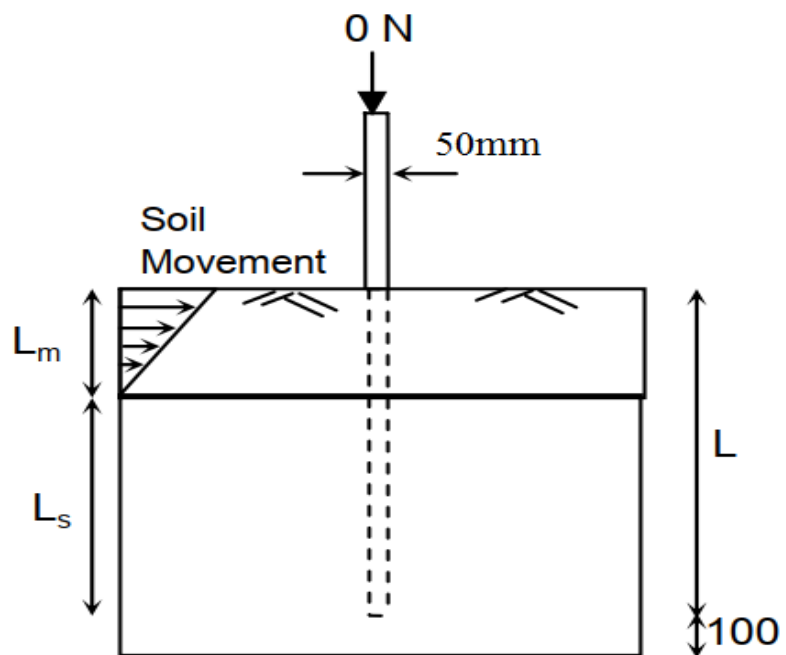
#### 4.5. Comparison of PLAXIS 3D Results and Discussion

The three-dimensional numerical model and analyses carried out by PLAXIS 3D software package validated with the model tests carried out by [8] and FLAC<sup>3D</sup> results carried out by [9]. A uniform or triangular lateral displacement of 60mm was applied to the left and right side boundaries from the ground surface down to the bottom of the unstable soil layer in the numerical analysis as shown in figure 4.4 (a) and (b).

In this part of the research, the numerical results are compared with the laboratory model test results and FLAC<sup>3D</sup> results to evaluate the accuracy and reliability of the 3D finite element method in simulating laterally single pile due to soil movement. The comparison of the three-dimensional numerical model analyses has been conducted with the model laboratory test results represent the bending moment, shear force and pile deflection acting along with the pile depth due to a uniform and triangular lateral displacement of 60mm as shown in figure 4.4 (a) and (b). Another comparison of the validation of the numerical analysis was carried out by FLAC<sup>3D</sup> Finite difference software results carried out by [9] for uniform lateral displacement. The PLAXIS 3D pile results weren't compared with the FLAC<sup>3D</sup> results for triangular lateral soil displacement, since they are not available in [9] study. The following subsection presents the comparison of PLAXIS 3D analyses results in the case of rectangular and triangular lateral soil movement of 60mm.



a). uniform/ rectangular soil movement



b). triangular soil movement

Figure 4. 4: soil movement profile with a moving layer

#### 4.5.1. PLAXIS 3D Results Validation Using Rectangular Soil Movement Profile

##### a) Bending Moment vs Depth Graph

Figure 4.5 shows PLAXIS 3D, FLAC<sup>3D</sup>, and Model test Bending Moment ( $M_3$ ) distribution Along the Pile depth subjected to a uniform lateral displacement of 60mm. If the structure has a local system of axes (1, 2, 3), the first direction is always the axial direction. The other directions (second and third) will always be perpendicular to the structure axis. The bending moment  $M_3$  is the bending moment formed because of the bending around the third axis.

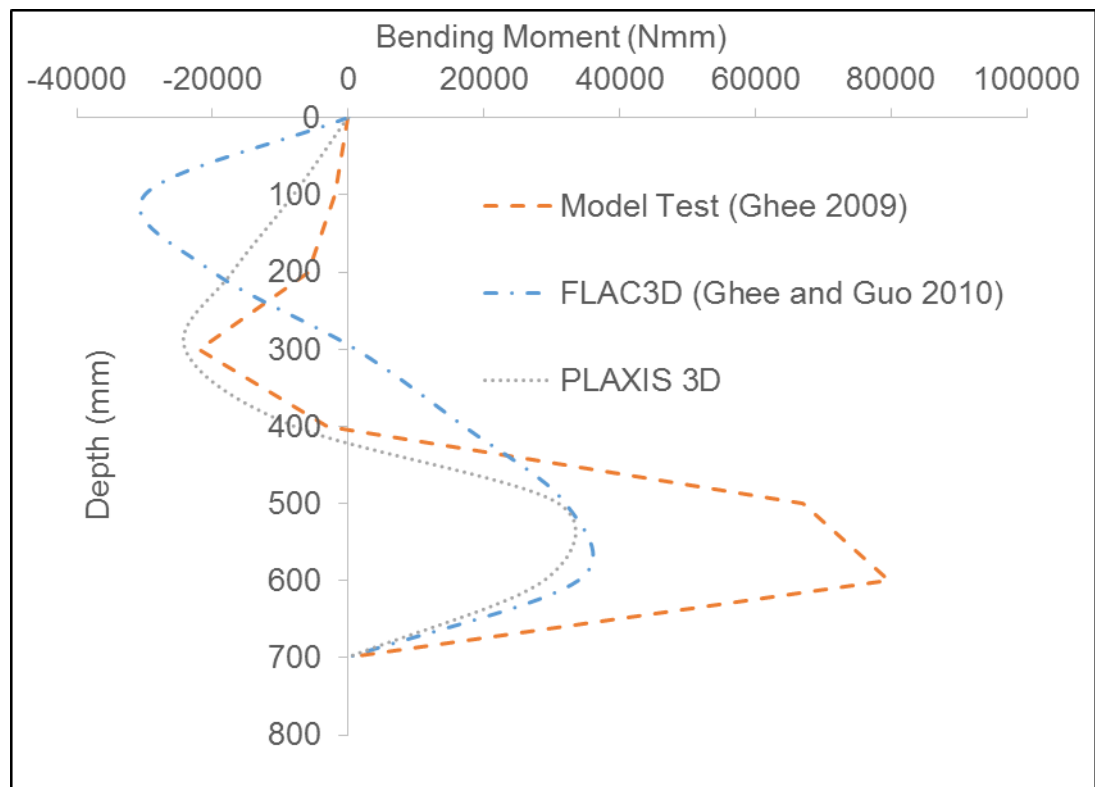


Figure 4. 5: PLAXIS 3D, FLAC<sup>3D</sup> and Model test Bending Moment response Along the Pile length

As shown in Figure 4.5, the bending moment profiles of PLAXIS 3D results show similar shape (double curvature) compared to Ghee's laboratory result and Ghee's and Guo FLAC<sup>3D</sup> results. However, the PLAXIS 3D result shows a 142% difference in

the maximum bending moment (located in the stable layer) with Ghee' lab results and 3.25% with FLAC<sup>3D</sup> results. The variation between PLAXIS 3D results and Ghee's laboratory results was due to the use of the average value of soil stiffness of the soil instead of finding a relationship between soil stiffness and soil depth. The shape of the negative and positive bending moment results of the PLAXIS 3D was in good agreement with Ghee's laboratory result and FLAC<sup>3D</sup> results, except the location of the maximum negative and positive bending moments.

## b) Shear Force vs Depth Graph

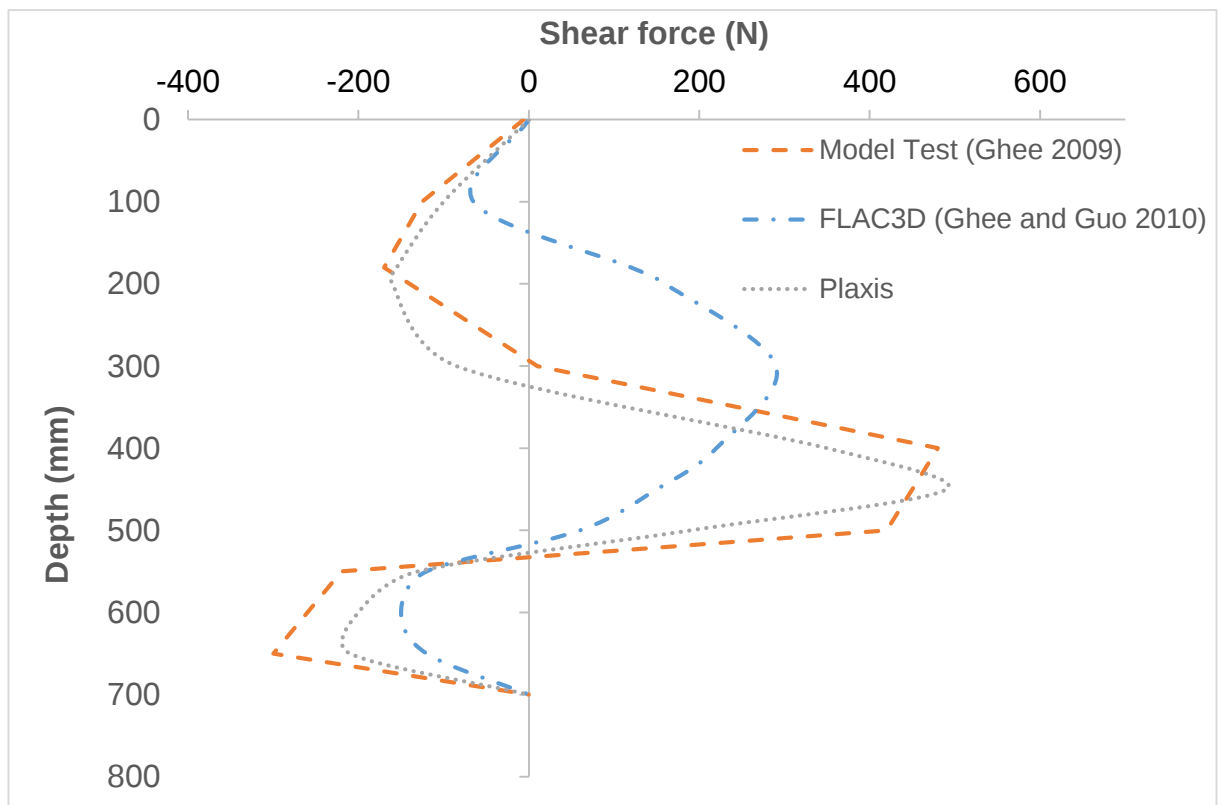


Figure 4. 6: PLAXIS 3D, FLAC<sup>3D</sup>, and Model test shear force response Along with the Pile length

Figure 4.6 present the PLAXIS 3D, FLAC<sup>3D</sup>, and Ghee's laboratory test results of the shear force response Along the Pile length as a result of 60mm uniform lateral displacement. The shear force over the 2<sup>nd</sup> beam axis is denoted as  $Q_{12}$ . As shown in

fig. 4.6 the magnitude and position of the shear force results of PLAXIS 3D were in good agreement with Ghee's laboratory results. Whereas the FLAC<sup>3D</sup> analysis underestimates the shear force as compare to PLAXIS 3D and Ghee's laboratory results. The shear force curve is not as smooth as the bending moment. This may have occurred due to the interface modeling issue between the soil and the pile.

### c) Pile Deflection vs Depth Graph

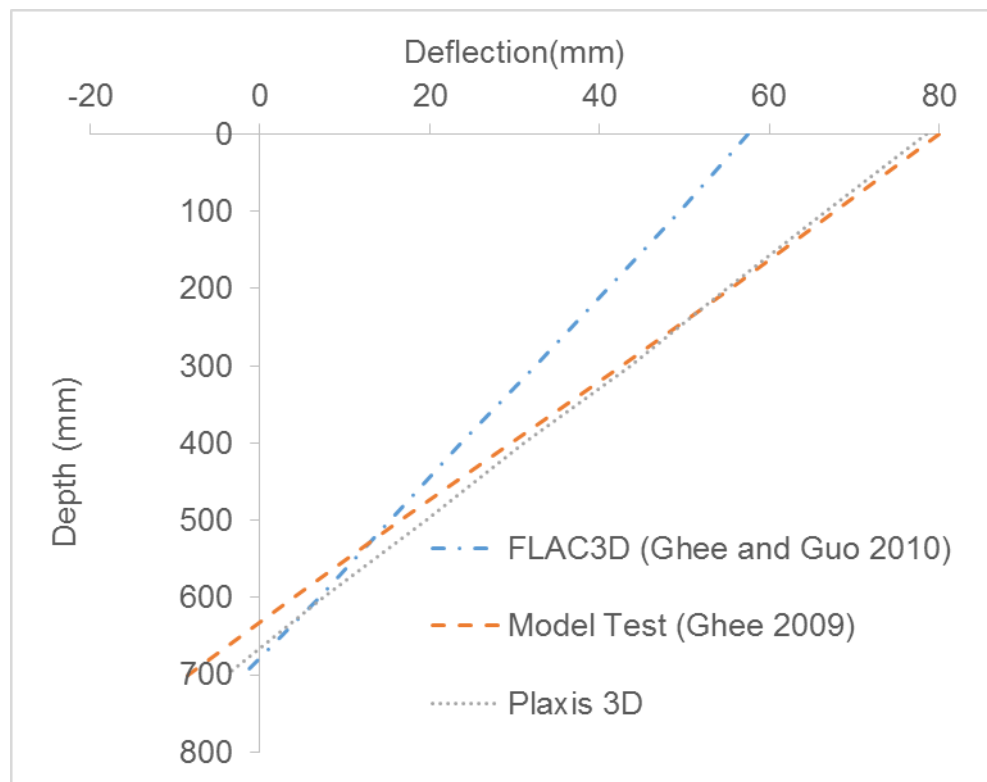


Figure 4. 7: PLAXIS 3D, FLAC<sup>3D</sup>, and Model test pile deflection response Along the Pile length

Figure 4.7 shows that PLAXIS 3D, FLAC<sup>3D</sup> and Ghee' laboratory test results of pile deflection Along the Pile depth due to a uniform lateral displacement of 60mm. The magnitude and deflection profile of the pile were similar for PLAXIS 3D and Ghee's laboratory results. Whereas the results of FLAC<sup>3D</sup> pile deflection at the ground surface is much less than PLAXIS 3D, and laboratory test results. The deflection profiles

indicate that the pile deformed like a rigid pile with a rotation point at the depth between 600 mm and 700 mm.

#### 4.5.2. PLAXIS 3D Results Validation Using Triangular Soil Movement Profile

Another verification of the three dimensional finite element analysis was carried out using a triangular soil movement. The materials used to model the sand, and embedded pile are similar with the previously used uniform model test, except the shape of the soil movement profiles. The comparison with FLAC<sup>3D</sup> is not used, due to absence FLAC<sup>3D</sup> analysis for triangular soil movement profile carried out by [9]. Figure 4.8, 4.9, and 4.10 present the three profiles of the single pile responses subjected to a triangular soil movement of 60mm, which were obtained from both PLAXIS 3D and Ghee's laboratory test results.

### a) Bending Moment vs Depth Graph

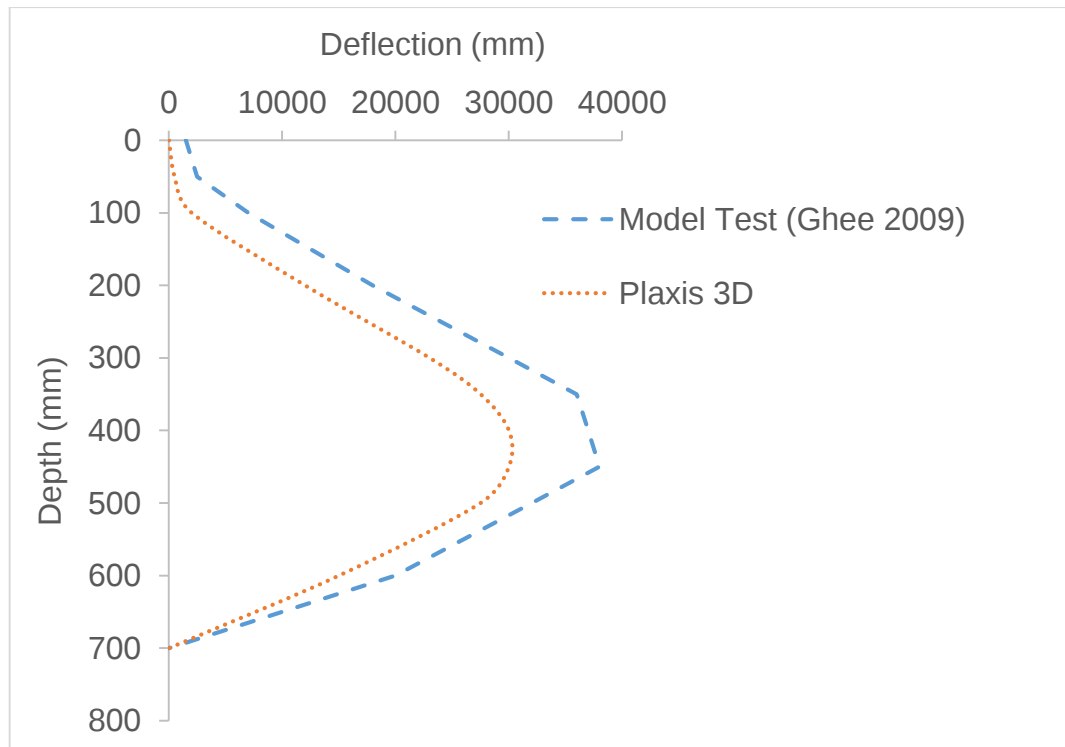


Figure 4. 8: PLAXIS 3D and Model test Bending Moment response Along the Pile length

Triangular soil movement profile was induced using a triangular shape loading block. Figure 4.8 shows PLAXIS 3D, and model test the bending moment ( $M_3$ ) distribution along the pile depth subjected to a triangular lateral displacement of 60mm. The shape of the bending moment was single curvature. The shape and magnitude of bending moment of PLAXIS 3D analyses was in good agreement with Ghee's laboratory results for triangular lateral soil displacement. The maximum bending moment for both Ghee's model test and PLAXIS 3D were located below the unstable soil layer (depth between 400 to 500mm). The difference in the maximum bending moment was 26.7% between the laboratory test and PLAXIS 3D results.

## b) Shear Force vs Depth Graph

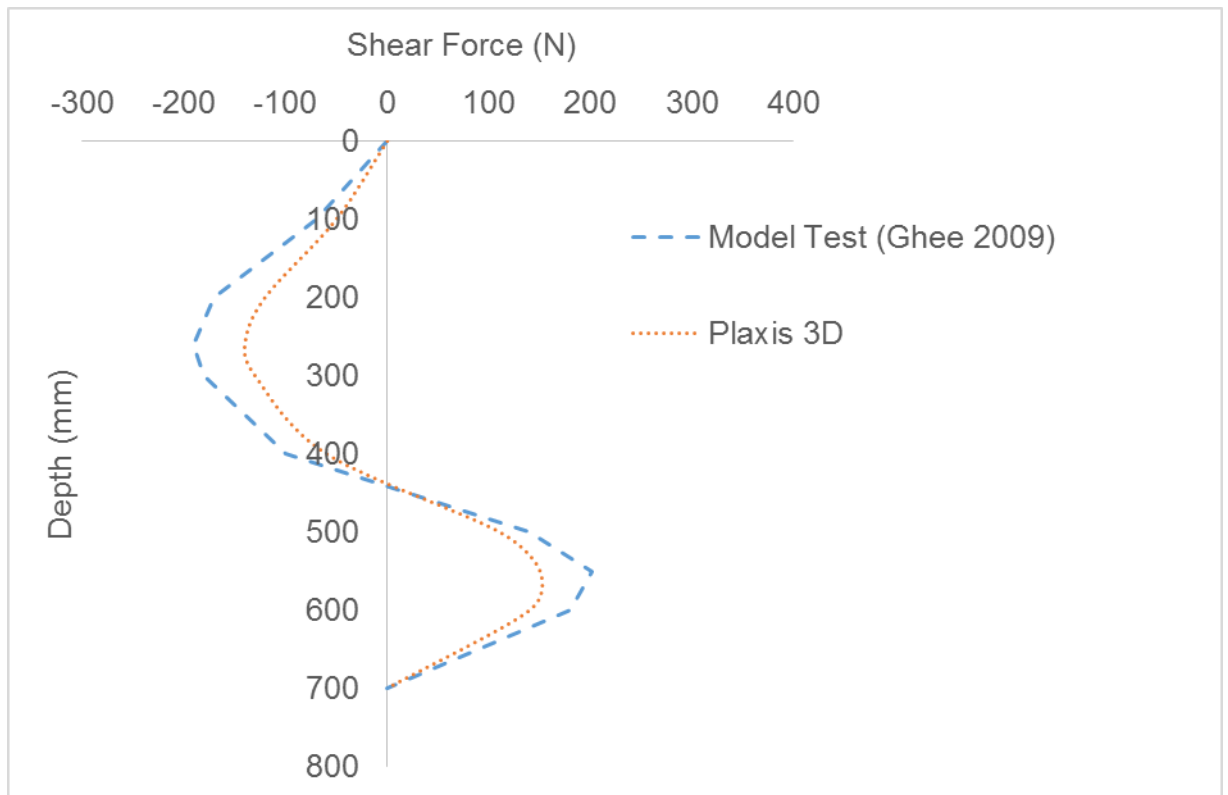


Figure 4. 9: PLAXIS 3D and Model test shear force response Along the Pile length

Figure 4.9 presents the PLAXIS 3D and Ghee' laboratory test results of the shear force response Along the Pile length as a result of 60mm uniform lateral displacement. A similar shape in the maximum negative and positive shear force profiles was noted again for PLAXIS 3D and Ghee's model test results. The shape and magnitude of maximum negative and positive shear force profiles were in good agreement with the model test. The shear force curve is not as smooth as the bending moment. This may have occurred due to the interface modeling issue between the soil and the pile. PLAXIS 3D underestimates the shear force.

### c) Pile Deflection vs Depth Graph

Figure 4.10 shows that PLAXIS 3D and Ghee's laboratory test results of pile deflection Along with the Pile depth due to a triangular lateral displacement of 60mm. Similar to the bending moment and shear force profile PLAXIS 3D underestimates the maximum pile deflection for triangular soil movement profiles.

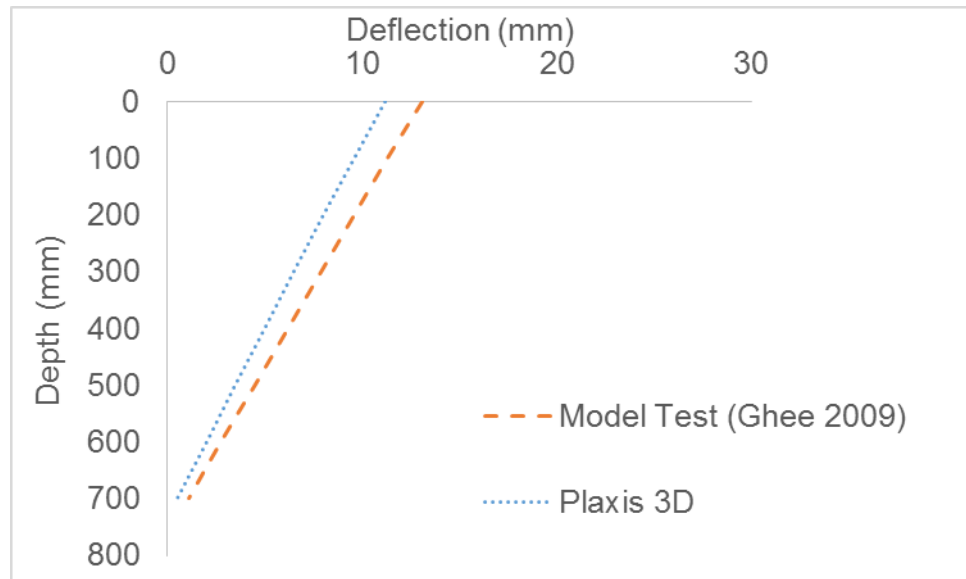


Figure 4. 10: PLAXIS 3D and Model test pile deflection response Along the Pile length

### 4.6). Concluding Remarks

Generally, analyses results show satisfactory agreement with the proposed PLAXIS 3D and measured laboratory test results in pile deflection, bending moment and shear forces for both rectangular, and triangular lateral soil movement profiles. It was concluded that a three-dimensional finite element solution with PLAXIS 3D can accurately model the response of a single laterally loaded pile subjected to lateral soil movement. Therefore, it is a good tool to estimate single passive pile behavior for different variations of pile materials, soil properties, and lateral soil movement, provided that the properties of the soil are accurately represented and the soil movement is correctly inputted.

## Chapter Five: Parametric Study

### 5.1. Introduction

In this Chapter, a parametric study is conducted on a single pile in the sandy soil using PLAXIS 3D. Various factors affecting the passive pile behavior were investigated in a series of parametric analysis for sandy soil. To carry out this study, other properties should be kept constant while the effect of the change in a certain property is being investigated. In the scope of parametric study, the effect of pile diameter, the effect of soil stiffness, soil movement profile, and effect of  $L_m/L_s$  ratio on passive pile response were studied by systematically changing the related parameters.

### 5.2. Effect of Pile Diameter

To investigate the effect of pile diameter on pile response due to uniform soil movement. The pile diameters varied, another factors being constant. Pile with a diameter of 25mm, 32mm, and 50mm was used to investigate the effect of pile diameter on the response of a single laterally loaded pile due to a 60mm uniform prescribed displacement.

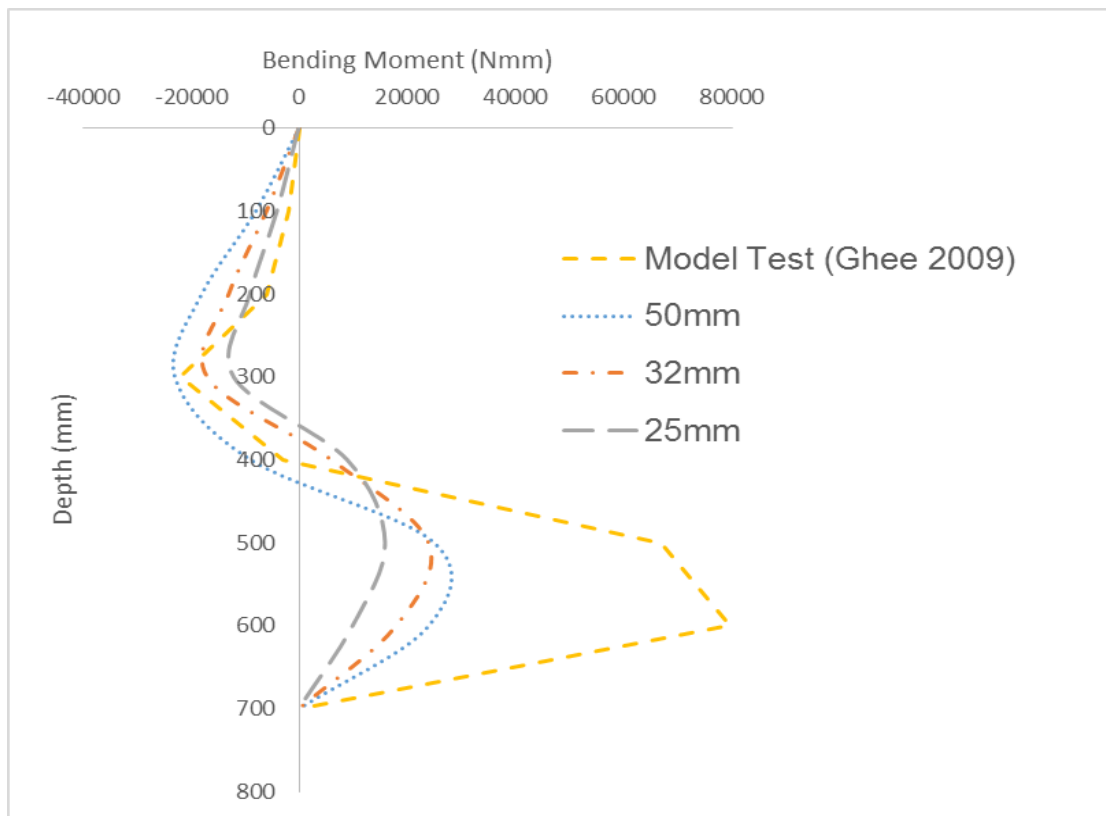


Figure 5. 1: shows the change in pile bending moment for three pile diameter with depth in sand.

The effect of pile diameter can be investigated in case of bending moment and deflection of the pile. The denser a sand bed the more the restraint provided on the pile. The more the restraint at the stable soil layer then causes a negative bending moment above the stable layer. The bending moment profile of the three pile diameter has similar double curvature shapes as shown in figure 5.1. The maximum positive and negative bending moment both increases as the pile diameter increases from 25mm to 50mm.

The maximum bending moment increases with pile diameter; as the pile diameter increases from 25mm to 32mm the maximum bending moment increase by 50%. The further increase in the pile diameter from 32mm to 50mm, the maximum bending moment increased by 33%.

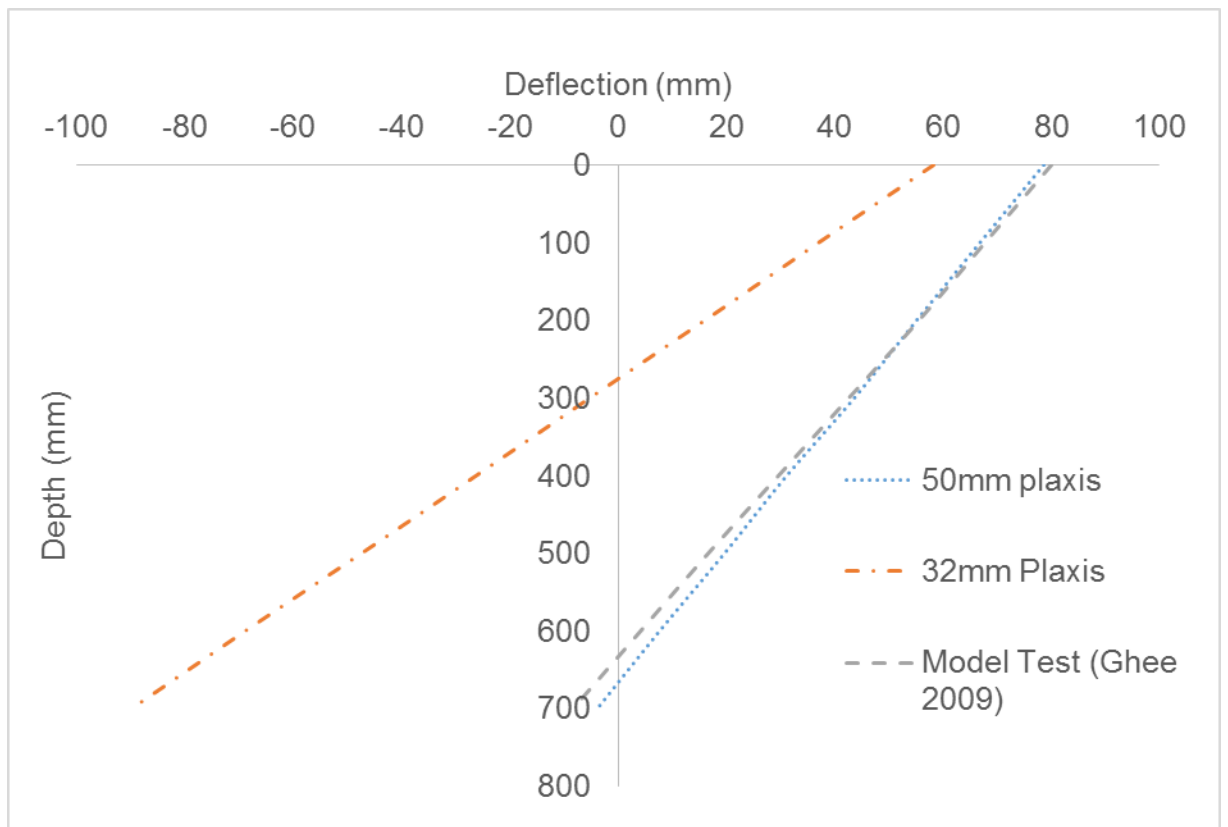


Figure 5. 2: shows the change in pile deflection for two pile diameter with depth in sand.

Figure 5.2 shows the three dimensional finite element analysis results of the pile deflection profiles conducted on the 50mm, and 32mm diameter pile. At the ground surface, the difference in the pile deflection for 32mm diameter pile, when compared to the 50mm diameter pile is 39% and 95.5% at the pile tip. As expected, the deflection of increase as the pile diameter decrease.

### 5.3. Effect of Soil Stiffness

To investigate the effect of soil stiffness a uniform prescribed soil movement of 60mm was applied along the entire embedded length of the pile both at the left and right side boundaries. In sand, it is generally assumed that the strength and soil stiffness of the

sand are increasing with depth. [38] Assumed that the soil stiffness increases linearly with depth for sands and it is possible to obtain acceptable solutions in this way. But in the horizontal direction, the elasticity of the sand can be considered as constant [39].

In this thesis, the effect of the soil stiffness of the sand on the PLAXIS 3D model was investigated using different  $E_s$  (572kPa) values. In the first cases, the investigation should be carried out with  $0.5E_s$ ,  $2E_s$  and  $10E_s$  were set to be constant along with the entire depth of the proposed PLAXIS 3D model, and in the last case, the soil stiffness  $E_s$ , was varied linearly with depth from 334kPa at the sand surface to 744kPa at the depth of 800mm. The bending moment and pile deflection of the above four cases were plotted as shown in figure 5.3 and figure 5.4, respectively.

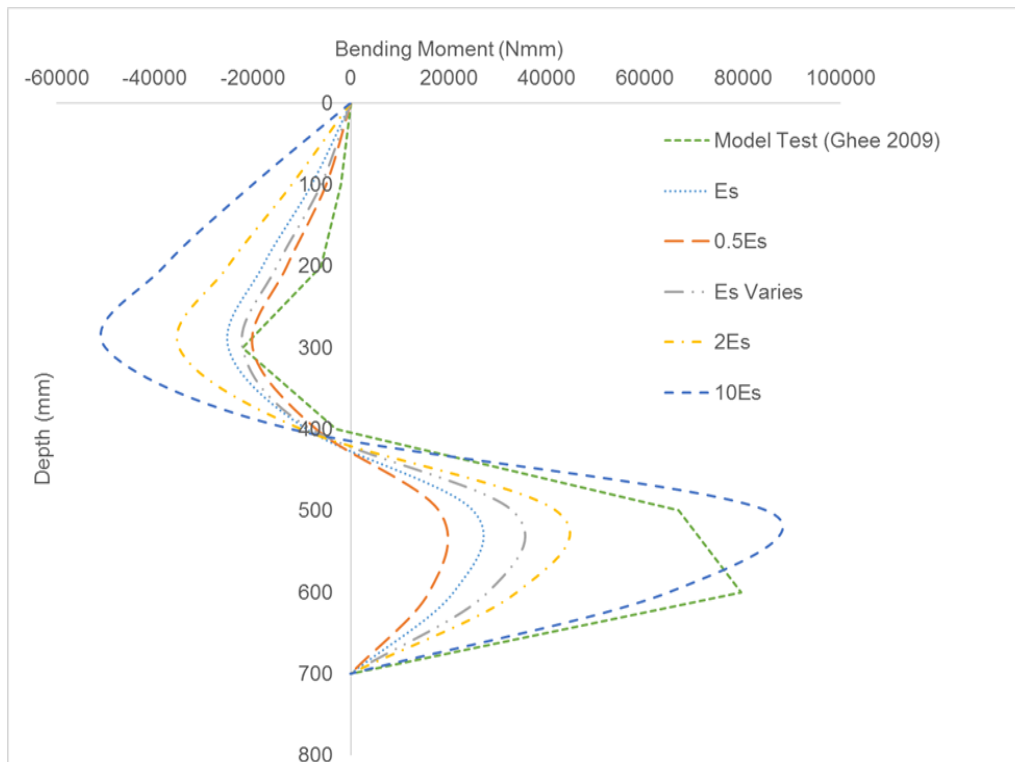


Figure 5. 3: shows the change in pile bending moment with constant and varying soil stiffness with pile depth in sand.

As shown in figure 5.3, as the sand stiffness of the standard model increases from  $0.5E_s$  to  $10E_s$  the bending moment increases. The PLAXIS 3D results increase significantly as compared to a constant  $E_s$ , as  $E_s$  increase from  $2E_s$  to  $10E_s$ . The

difference in the maximum positive bending moment in the sand with  $E_s$ , and  $E_s$  varies with depth are 20.7%. From this, it can conclude that change in soil stiffness had a significant influence on the behavior of the pile, especially in the maximum bending moment. The shape of the bending moment obtained from PLAXIS 3D analysis was in good agreement to that obtained from Ghee's experimental results.

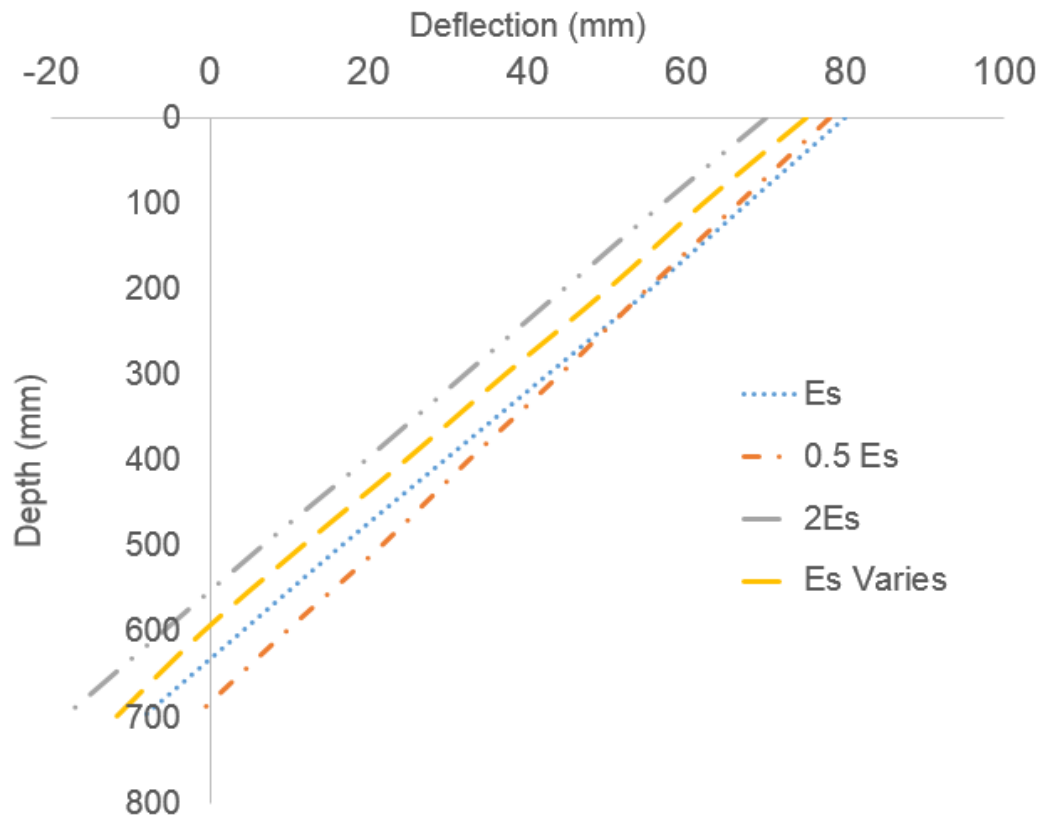


Figure 5. 4: shows the change in pile deflection with constant and varying soil stiffness with pile depth in sand.

Figure 5. 4 shows the change in pile deflection with constant soil stiffness, and varying soil stiffness with pile depth in sand. The mode of the deflection profiles changed as the soil stiffness increases. As expected, when the pile is embedded in stiffer soil ( $2 \cdot E_s$ ), the deflection of the pile reduces to approximately 11.4% from that obtained from least stiff soil ( $0.5 \cdot E_s$ ). At the ground surface, the difference in pile deflection between constant  $E_s$ , and  $E_s$  varies with depth is 4.6%.

## 5.4. Effect of Soil Movement Profile

In the previous analyses, a uniform lateral soil movement profile was assumed to examine the major factors that influence the pile behavior and represented the upper bound conditions. In actual field situations, the soil movements may be non-uniform. Therefore, an additional triangular and trapezoidal soil displacement profile was considered to investigate the effects of soil movement distributions.

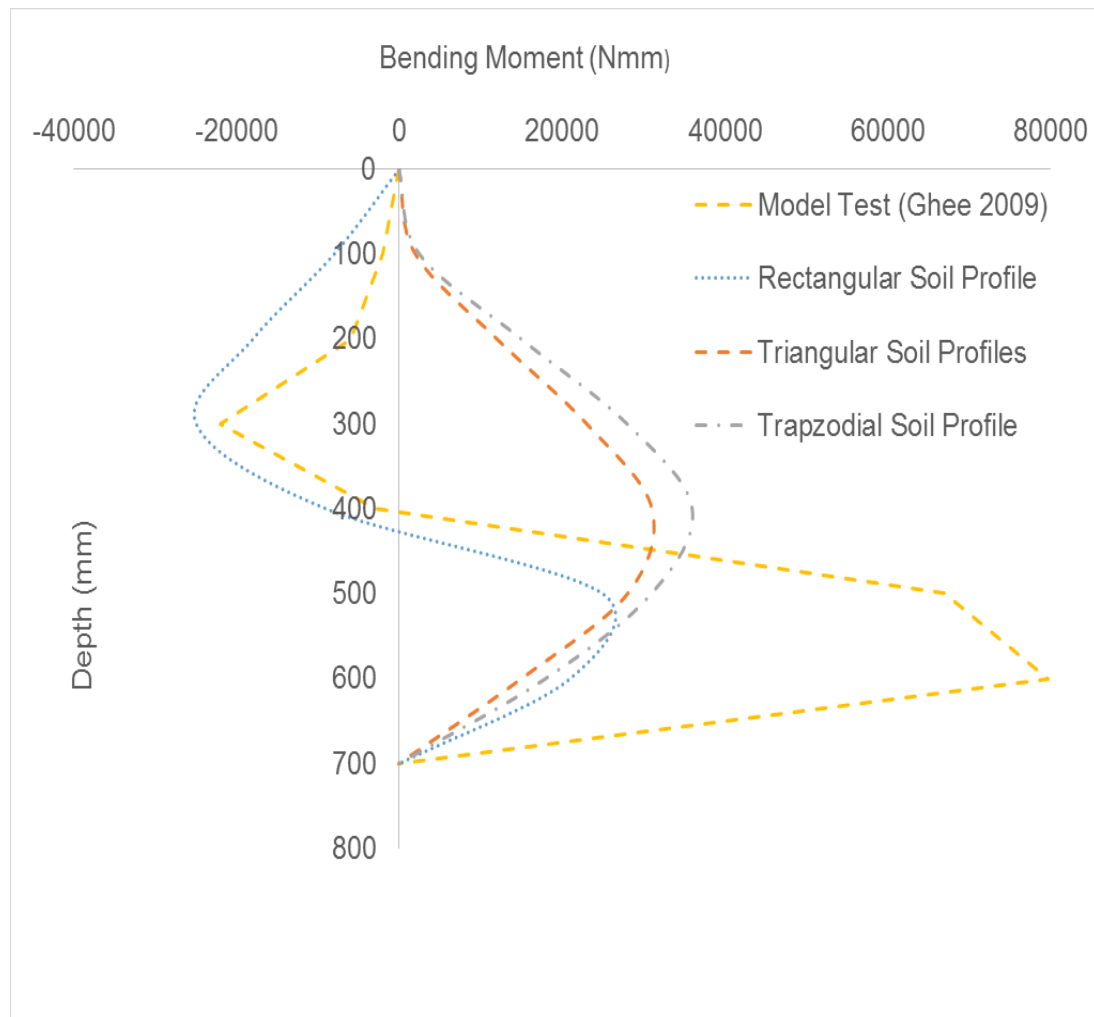


Figure 5. 5: shows the distribution of bending moment along with the pile length for three types of soil displacement profiles

Figure 5.5 shows the distribution of bending moment along the pile length for uniform, triangular and trapezoidal soil displacement profiles with the same lateral movement of soil surface up to 60 mm at both right and left sides of the boundaries. It can be seen that the shape of the bending moment profiles for triangular and trapezoidal are similar in shape to a parabola, indicating single curvature elastic deformation of the pile. Whereas the bending moment profile of uniform soil displacement is double curvatures deformation of the piles. The point of inflection (zero bending moment) was located close to the interface surface, while the point of the maximum bending moment was situated within the stable layer.

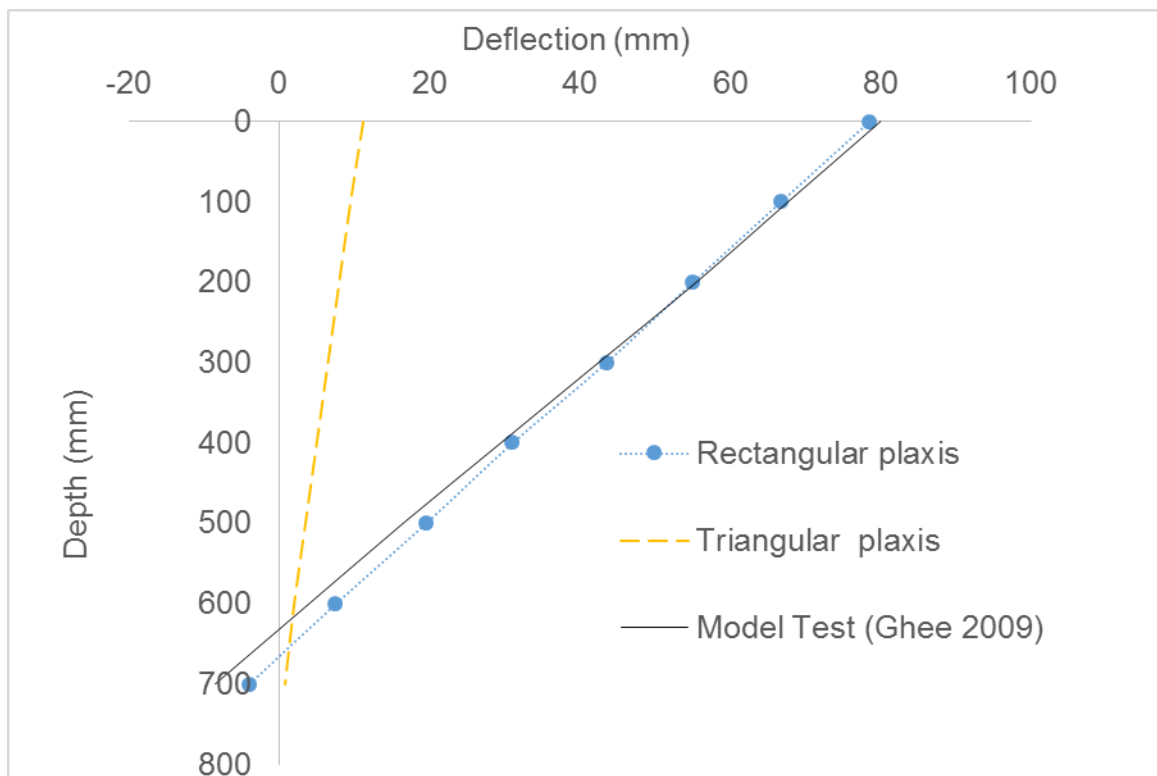


Figure 5. 6: shows the distribution of deflection along the pile depth for three types of soil displacement profiles.

Figure 5. 6: illustrate the distribution of deflection along with the pile depth for uniform and triangular soil movement profiles. The pile deflection modes are relatively complicated, depending on the loading block shape. The piles are mainly deflected by rotation around a certain depth for the PLAXIS 3D model. The pile deflection of the pile

was 78.5mm, and 11.3mm at the ground surface for uniform, and triangular soil movement profiles, respectively. Whereas the deflection at the pile base was about -4mm, and 0.8mm for uniform and triangular soil movement profiles, respectively. The pile deflection at the ground surface for the triangular soil movement profile was less than the rectangular soil movement profile.

## 5.5. Effect of Thickness of Moving Soil Mass

In the previous analyses, the assumed uniform soil movement was applied along the entire embedded length of the pile. In actual field situations, for instance, for piles in moving soil, only the upper part of the pile may be subjected to uniform lateral soil movements. Therefore, additional analyses were carried out for  $L_m/L_s = 0.17, 0.4, 0.75, 1.33, 2.5$ , and 6 to study the influence of the ratio of  $L_m/L_s$ .

Table 5. 1: PLAXIS 3D models at different  $L_m/L_s$  ratio

| Unstable Soil Layer( $L_m$ ) | Stable Soil Layer( $L_s$ ) | The ratio of ( $L_m/L_s$ ) |
|------------------------------|----------------------------|----------------------------|
| 100                          | 600                        | 0.17                       |
| 200                          | 500                        | 0.4                        |
| 300                          | 400                        | 0.75                       |
| 400                          | 300                        | 1.33                       |
| 500                          | 200                        | 2.5                        |
| 600                          | 100                        | 6                          |

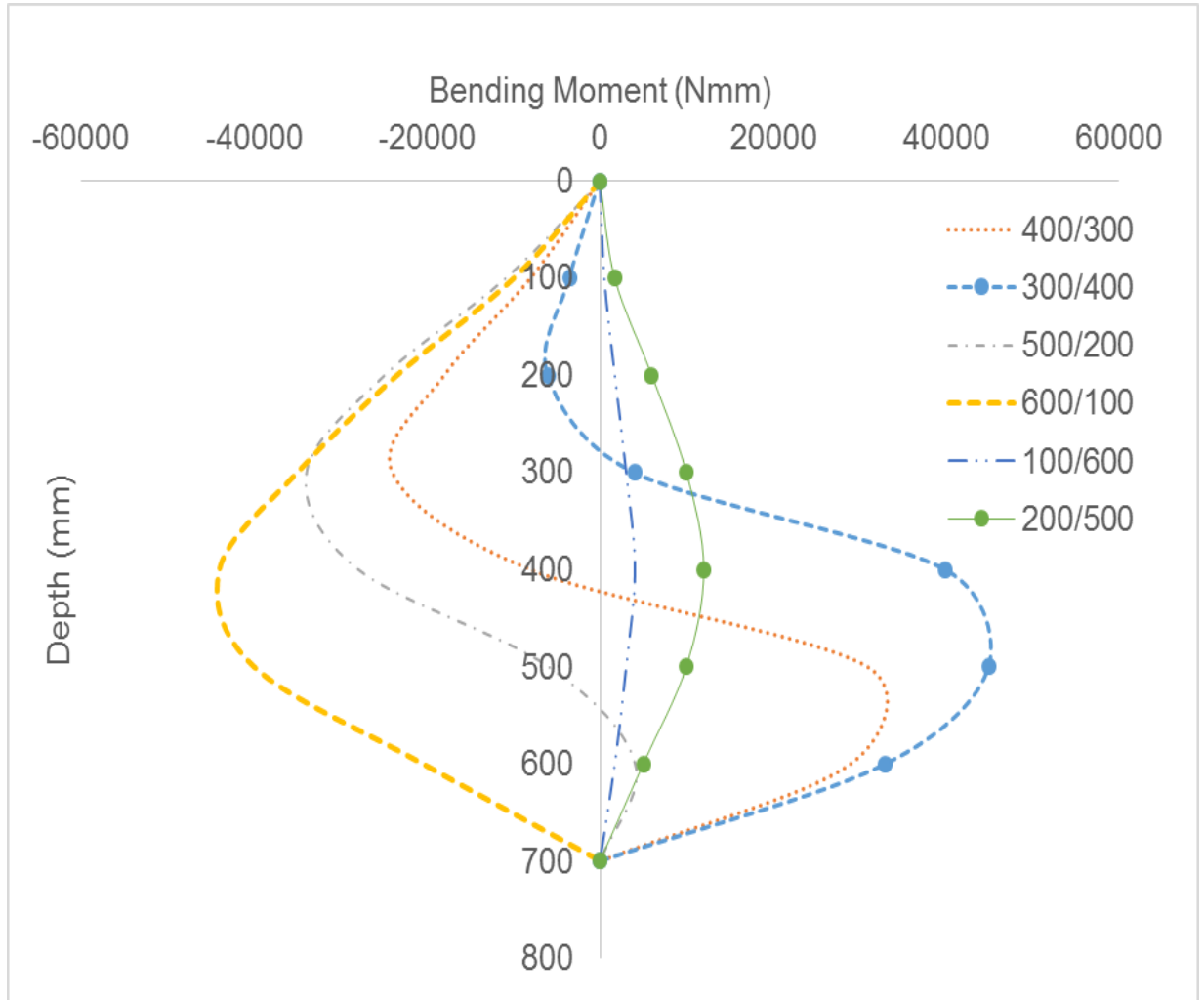


Figure 5. 7: shows the distribution of bending moment along with the pile depth with various  $L_m/L_s$  ratios.

Figure 5. 7 shows the distribution of bending moment along with the pile depth with various  $L_m/L_s$  ratios. It was found that the ratio of  $L_m/L_s$  had a significant influence on the deflection profiles and the bending moment profiles. The shape of the bending moment profiles shows a single curvature at a ratio  $L_m/L_s$  less than or equal to 0.4 and changed to double curvature at  $L_m/L_s$  in between 0.75 to 2.5. Finally, at  $L_m/L_s$  the

bending moment profile shows a single curvature shape with the maximum negative bending moment of -44000Nmm at the depth of 400mm.

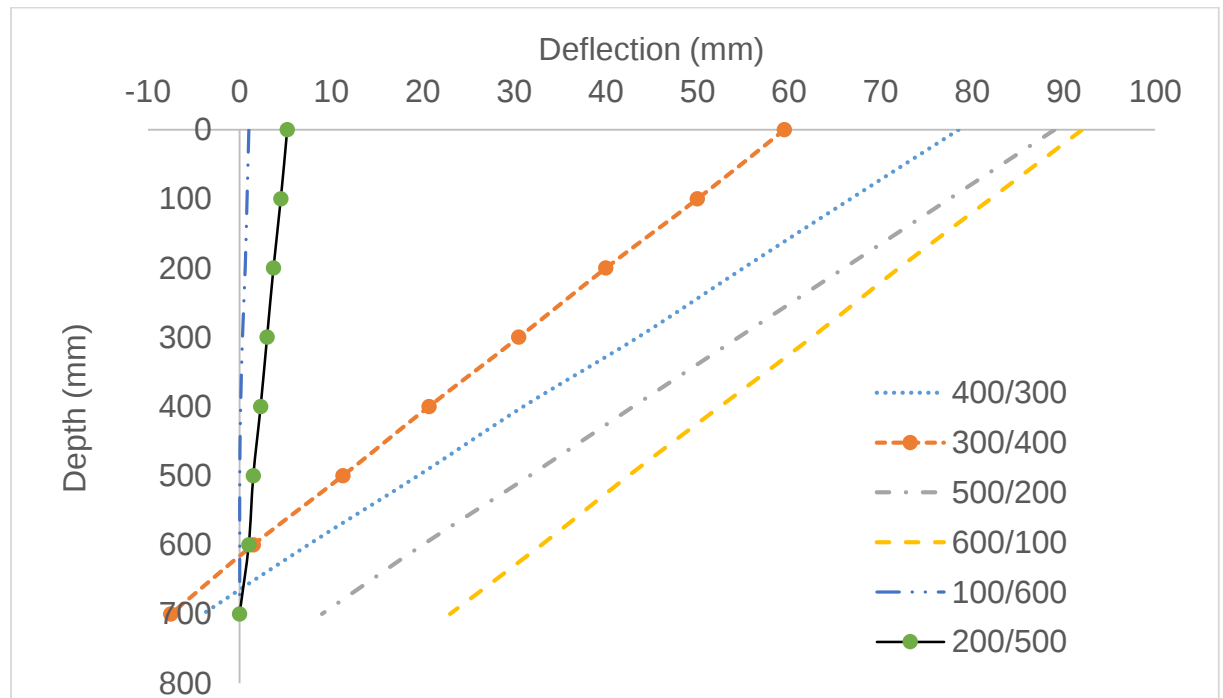


Figure 5. 8: shows the distribution of deflection along with the pile depth with various  $L_m/L_s$  ratios.

Figure 5. 8 shows the distribution of deflection along with the pile depth with various  $L_m/L_s$  ratios. As the ratio of  $L_m/L_s$  equal to or greater than 1.33, the pile may not be stable due to excessive pile deflection. Generally, the maximum pile deflection and bending moment increased as  $L_m/L_s$  ratio increased.

## 5.6. Summary of the parametric study

PLAXIS 3D finite element analysis was successfully used to predict the result of the single model tests that are associated with large deformations subjected to lateral soil movement. The parametric study, performed on a standard model, indicated that the

soil stiffness, pile diameter, the ratio of moving soil layer ( $L_m$ ) to stable soil layer ( $L_s$ ) and shape soil movement profile have a significant influence on the magnitude of the maximum bending moment and maximum pile deflection.

Parametric study analysis, shows that PLAXIS 3D under predicted the maximum bending moment obtained from Ghee's single model test results. This variation in PLAXIS 3D may be contributed from the effect of the initial pile verticality, the way the soil movement applied on the pile, and degree of p-delta effects.

Generally results from the parametric study indicate the following:

- The maximum bending moment mobilized along the pile depth increases with pile diameter and soil stiffness, but the maximum pile deflection decreases.
- The maximum bending moment and pile deflection increases as the ratio  $L_m/L_s$  increases.
- The shape of the bending moment profile was double curvature for rectangular soil movement and single curvature for triangular and trapezoidal soil movement profiles.
- The magnitude of maximum bending moment and pile deflection of rectangular soil movement profile was greater than the triangular and trapezoidal soil movement profiles.

## **Chapter Six: Conclusion and Recommendation for Future Research Work**

### **6.1. Conclusions**

A three-dimensional finite element analyses of PLAXIS 3D 2013 has been carried out to investigate the response of a single pile subjected to lateral soil movements in sandy soil. An elastic–perfectly plastic Mohr–Coulomb model was used to model the sand behavior, and the “embedded pile” approach was used to model the embedded pile. The embedded pile shows good performance in the modeling of a single laterally loaded pile due to lateral soil movement. The accuracy of the three-dimensional PLAXIS 3D model validated using Ghee’s model laboratory test results and a three-dimensional finite-difference analysis, FLAC<sup>3D</sup> carried out by Ghee and Guo. The validation analysis has been conducted on a uniform and triangular soil movement profiles. The analytical results, generally, confirm a reasonable validation of the software. The behavior of the three predicted profiles (bending moment, shear force, and lateral deflection) of piles was in good agreement with those obtained from Ghee’s model laboratory test and FLAC<sup>3D</sup> results. A parametric study has also been conducted to investigate the effect of pile diameter, soil stiffness, shape of soil movement profiles, and the ratio of  $L_m/L_s$  subjected to lateral soil movement.

Based on the numerical model’s results, the following conclusions can be drawn:

- PLAXIS 3D 2013 software can predict the response of a single pile under lateral soil movement with good accuracy. Verification analysis of the PLAXIS 3D model under predicted and slightly over predicted the magnitudes of the pile response (maximum bending moment, shear force, and pile deflection) for both uniform and triangular soil movement profiles as compared to Ghee’s model test and FLAC<sup>3D</sup> results respectively, except the position of magnitude.

- It has been proved that the pile diameter, soil stiffness, shape of soil movement profiles and the ratio of  $L_m/L_s$  had a significant effect on the behavior of single passive pile subjected to lateral soil displacement. The maximum bending moment increases as pile diameter, soil stiffness, and the ratio of  $L_m/L_s$  increases whereas the pile deflection decreases as the soil stiffness, and pile diameter increase. Pile deflection increase with the ratio of  $L_m/L_s$  increases. The magnitude of maximum bending moment and pile deflection rectangular soil movement profile was greater than the triangular and trapezoidal soil movement profiles.

## 6.2. Recommendations for Future Research Work

Even though a great deal of research has been done to investigate the performance of the pile foundation due to soil movement, many uncertainties remain and therefore require further research. Some suggestions for future research studies shall be proceeded by considering the following recommendations.

- The Mohr-Coulomb material model has been used in this research. The results show a satisfactory result in capturing the behavior of pile in soils. However, more advanced material models shall be implemented to see the influence of a material model on the results.
- The differences between the 3D finite element method results, and model laboratory test results are caused by several factors. During the simulations, the soil is assumed to be a uniform soil block, which is different from reality. Besides, the pile is also assumed uniform and perfectly elastic in the modeling, which may not be the same in reality, Even though 3D finite element methods can provide a very satisfactory simulation of the single passive pile due to soil movement.
- Effect of some other factors (such as pile flexibility, the magnitude of soil movement) on pile embedment depth can be investigated in further studies. Factors affecting the design of passive piles such as the location of piles in the finite element model, effect of relative pile flexibility factor, the effect of different pile head fixity conditions, the effect of axial load, the effect of dilation angle of sand and pile materials are some of the topics that need more investigation.
- In this study, rigid piles are used. It is necessary to assess the behavior of relative flexible piles subjected to lateral soil movement. Additionally, different soil may be used, such as clay or silt.
- The present work may be extended to study the effect of axial load on laterally loaded single pile due to soil movement.

- In this study, Investigation should be carried out on a single pile due to soil movement, but it would be good if the present investigation of a single pile extended to pile groups.

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## **Appendices**

## A). Illustration of the Validation Analysis

Additional model illustration of Ghee's model laboratory test results, and FLAC3D were prepared from the calculation result of PLAXIS 3D. Analysis displacements, bending moment, shear force, and cartesian effective stresses in the direction of movement are presented from different views and cross sections.

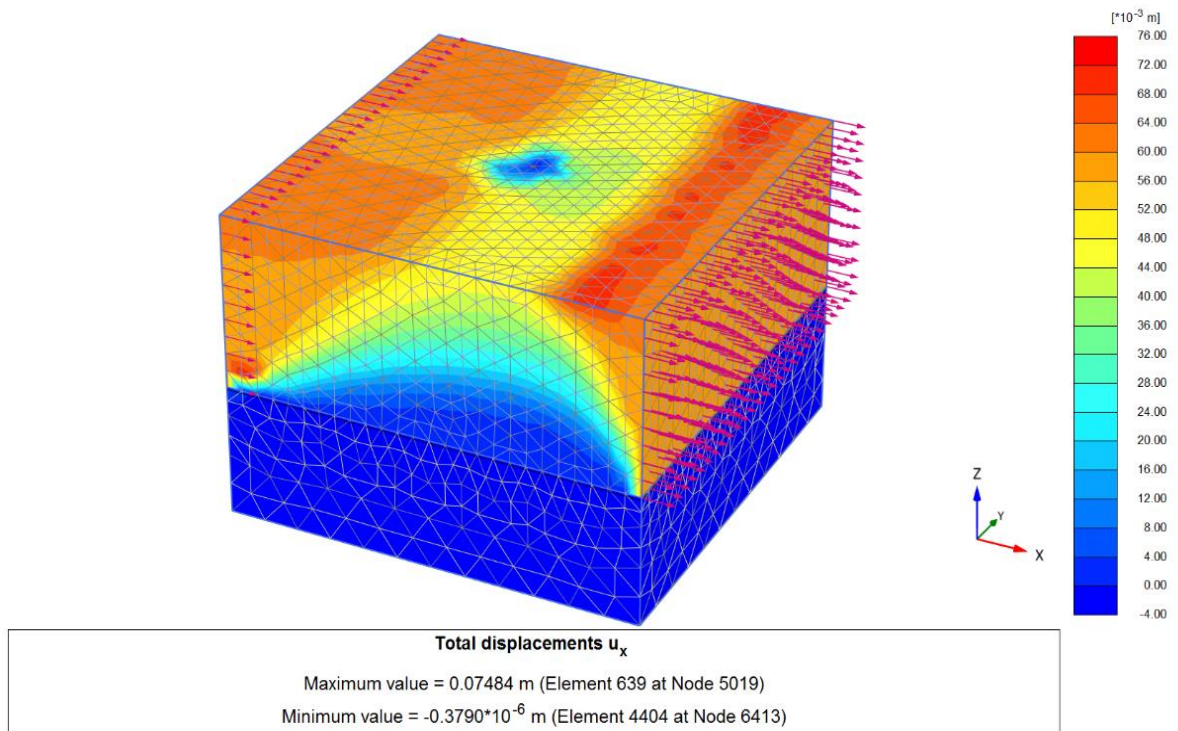


Figure 8.1: Typical total horizontal displacement ( $u_x$ ) after PLAXIS 3D analysis

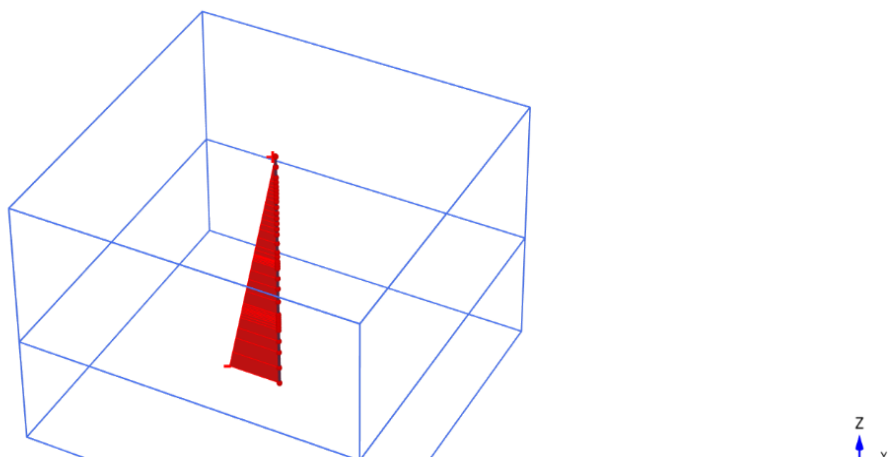


Figure 8.2: Distribution of bending moment along with the pile depth at the end of PLAXIS 3D analysis

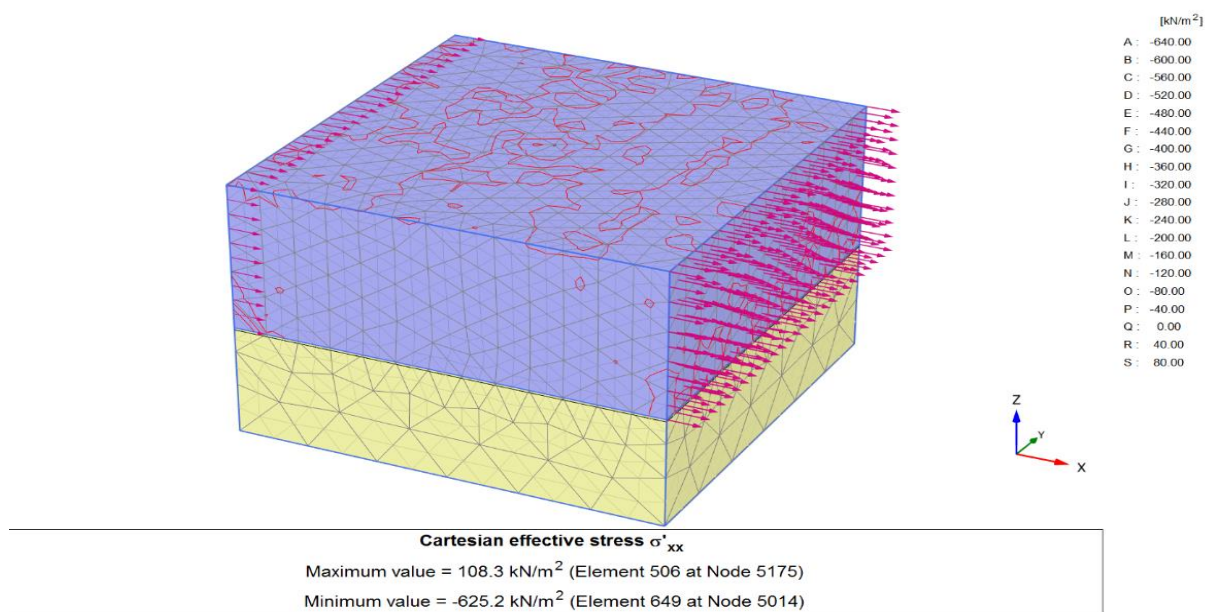
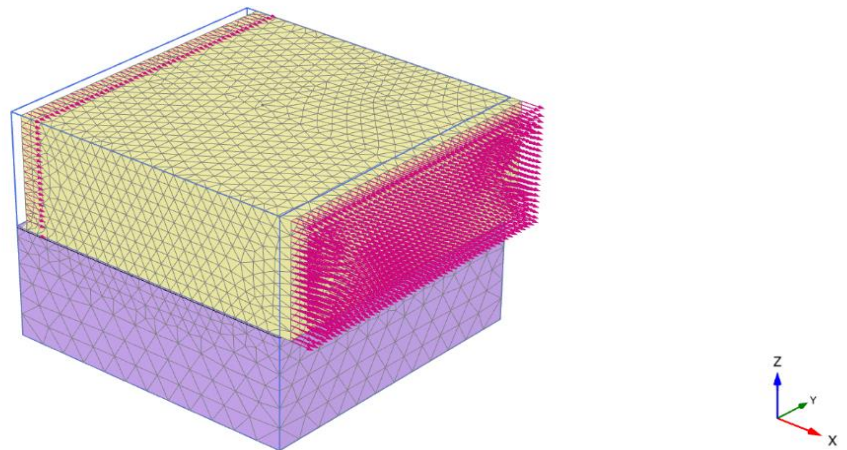


Figure 8.3: Distribution of Cartesian effective stress along with the depth of the pile after PLAXIS 3D analysis



**Deformed mesh |u| (scaled up 5.00 times)**  
Maximum value =  $9.014 \times 10^{-3}$  m (at Node 73271)

Figure 8.4: Typical deformed mesh after PLAXIS 3D analysis