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Development of P-Y Curves for Monopiles in Clay using Finite Element Model Plaxis 3D Foundation

Dhruba Lal Pradhan

Geotechnics and Geohazards
Submission date: June 2012
Supervisor: Gudmund Reidar Eiksund, BAT
Co-supervisor: Liv Hamre, DNV

Norwegian University of Science and Technology
Department of Civil and Transport Engineering

Report Title: Development of P-Y Curves for Monopiles in Clay using Finite Element Model Plaxis 3D Foundation	Date: June 2012 Number of pages (incl. appendices): 71			
	Master Thesis	√	Project Work	
Name: Dhruba Lal Pradhan				
Professor in charge/supervisor: Prof. Gudmund Reidar Eiksund				
Other external professional contacts/supervisors: Liv Hamre (Det Norske Veritas, Oslo)				

Abstract:

The monopiles with typical diameters of 4-6m are mostly used as foundations for the offshore wind turbine structures to resist the vertical and horizontal loads. The response of the laterally loaded pile depends upon the soil and pile behavior and also on the interaction between them. Various methods for the development of p-y curves exist and the accuracy of such methods depends upon the data from which it was developed. The accuracy of the analysis of the pile depends on the accuracy at which the p-y curve represents the soil response to the lateral pile deflection because most of the commonly used p-y curve criteria are based on a very limited number of tests.

The p-y curve recommended by API (American Petroleum Institute) code which is widely used by geotechnical engineers for the analysis of laterally loaded piles; however the method was developed for the slender piles with diameters up to approximately 2m. Hence several authors have claimed that p-y curves should be revised to be applicable for large diameter rigid pile.

The thesis presents the finite element model (FEM) analysis of monopiles in marine clay with the diameter from 1m to 6m by means of the Finite Element program Plaxis 3D Foundation. To avoid the influence of the pile flexibility and pile rotation, lateral translation of rigid piles is analyzed.

The rigid pile and soil with hardening soil parameter is modeled in FEM Plaxis 3D Foundation. Piles are loaded with lateral loads to obtain the soil response on pile and pile deflection at different stages which in turn is used for the development of p-y curve and are compared with the API p-y curves. The result does not show any diameter effect in the initial stiffness but the initial stiffness of soil is very low in comparison to that given by the p-y curve (API code). Low stiffness compared to API p-y curve may be due to the selected parameters of the soil model.

As the result shows difference in p-y curve from FEM 3D plaxis foundation and API code, some field test results for larger diameter will be fruitful to decide which method is valid for the analysis of the larger diameter monopiles.

Key Words:

1. Development of P-Y Curve
2. Lateral Displacement
3. FEM Plaxis 3D Foundation
4. Secant Stiffness

NTNU

Fakultet for ingeniørvitenskap og teknologi
Institutt for bygg, anlegg og transport

MASTER DEGREE THESIS

Spring 2012

for

Student: Dhruba Lal Pradhan

Development of P-Y Curves for Monopiles in Clay using Finite Element Model Plaxis 3D Foundation

BACKGROUND

Wind energy is a renewable energy source believed to have potential for delivering a significant amount of the future energy demands. Offshore wind turbines are one possibility for development of this energy source. The wind turbines are exposed to large cyclic loads from wind and waves while installation and maintenance of offshore structures are costly. It is therefore important that the foundation methods are both robust and economical optimal. A frequently used foundation method for wind turbines is monopiles. Typical monopile dimensions are 3 – 6 m in diameter and 20 to 50 m penetration depth. The dominating design practice for the monopiles is to use “P-Y” curves recommended by API. The API “P-Y” curves are originally developed for smaller and more flexible piles.

TASK DESCRIPTION

The objective for this thesis research is to compare results from 3D finite element analysis of monopiles with results from the “P-Y” approach recommended by API. This topic was investigated in a project work in 2011. In the project report it was concluded that the existing “P-Y” curves may not be applicable for large diameter monopiles and that this topic could further investigated in a thesis work were more parameter variations can be included.

This thesis will include the following activities:

- A review of proposed P-Y curves
- Background and motivation for the parameter variations
- Evaluation of the selected parameters for the soil material model in relation to the parameters for the “P-Y” curves
- Presentation of the 3D finite element model
- Presentation and evaluation of the results
- Recommendations for development of P-Y curves for monopiles

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Professor in charge: Gudmund Reidar Eiksund

Other supervisors: Liv Hamre, DNV

Department of Civil an Transport Engineering, NTNU

Trondheim, June 06, 2012.

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Professor in charge (sign)

Acknowledgement

This report is prepared for the result of the Geotechnical Master Thesis at Norwegian University of Science and Technology (NTNU) spring 2012. The thesis is based on the theoretical background and analyses of laterally loaded monopiles for offshore wind turbines in FEM PLAXIS 3D Foundation.

The project was proposed by the Det Norske Veritas (DNV) and would like to thank **Professor Gudmund Eiksund** and **Liv Hamre** (DNV) for their valuable guidance and suggestions.

I would like to thanks Professor Thomas Benz, Professor Lars Grande, Professor Steinar Nordal, Assistant Professor Arnfinn Emdal for the literature and guidance in the graduate year at NTNU.

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Dhruba Lal Pradhan

June 2012, Trondheim

Abstract

The monopiles with typical diameters of 4-6m are mostly used as foundations for the offshore wind turbine structures to resist the vertical and horizontal loads. The response of the laterally loaded pile depends upon the soil and pile behavior and also on the interaction between them. Various methods for the development of p-y curves exist and the accuracy of such methods depends upon the data from which it was developed. The accuracy of the analysis of the pile depends on the accuracy at which the p-y curve represents the soil response to the lateral pile deflection because most of the commonly used p-y curve criteria are based on a very limited number of tests.

The p-y curve recommended by American Petroleum Institute (API) code which is widely used by geotechnical engineers for the analysis of laterally loaded piles; however the method was developed for the slender piles with diameters up to approximately 2m. Hence several authors have claimed that p-y curves should be revised to be applicable for large diameter rigid pile (Augustesen, Sorensen, & Ibsen, 2010), (Achmus, Abdel-Rahman, & Kuo, 2008).

The thesis presents the finite element model (FEM) analysis of monopiles in marine clay with the diameter from 1m to 6m by means of the Plaxis 3D Foundation. To avoid the influence of the pile flexibility and pile rotation, lateral translation of rigid piles is analyzed.

The rigid pile and soil with hardening soil parameter is modeled in FEM Plaxis 3D Foundation. Piles are loaded with lateral loads to obtain the soil response on pile and pile deflection at different stages which in turn is used for the development of p-y curve and are compared with the API p-y curves. The result does not show any diameter effect in the initial stiffness but the initial stiffness of soil is very low in comparison to that given by the p-y curve (API code). Low stiffness compared to API p-y curve may be due to the selected parameters of the soil model.

As the result shows difference in p-y curve from FEM 3D Plaxis foundation and API code, some field test results for larger diameter will be fruitful to decide which method is valid for the analysis of the larger diameter monopiles.

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List of Symbols

Symbol	Explanation	Unit
p	Lateral soil resistance	KN/m^2
y	Lateral pile displacement	m
k_i	Initial soil stiffness	KN/m^3
p_u, p_{ult}	Ultimate lateral soil resistance	KN/m^2
y_c, y_u, y_{50}	Ultimate lateral pile deflection	m
y_e	Maximum displacement of pile for linear portion of p-y curve	m
p_e	Maximum soil resistance for linear portion of p-y curve	KN/m^2
Z	Depth below soil surface	m
Z_{cr}	Critical depth below soil surface	m
Z_R	depth below soil surface to bottom of reduced resistance zone	m
D, d	Diameter of pile	m
ε_{50}	Strain at 50% of maximum shear stress in unconfined undrained triaxial test	
S_u	Undrained shear strength	KN/m^2
N_p	Ultimate lateral soil resistance coefficient	
σ_z'	Effective overburden stress at depth Z	KN/m^2
J	API (1987) lateral resistance factor. Normal value from 0.25 to 0.8	
γ'	Effective unit weight of soil	KN/m^3
Su_{avg}	average undrained shear strength from ground surface to depth Z	KN/m^2
γ_{avg}	average effective unit weight from ground surface to depth Z	KN/m^3
A	empirical parameter used in unified clay criteria	
F	empirical reduction factor representative of soil strength degradability	
F_s	empirical reduction factor representative of soil strength degradability for static loading	
L_c	Critical pile length	m
E_pI_p	Bending stiffness of pile	KNm^2
E_p	Young's modulus elasticity for pile material	KN/m^2
E_s	Young's modulus of soil	KNm^2

u	Dummy variable used in Beizer's equation varies from 0 to 1	
E_{50}^{ref}	Stiffness modulus for primary loading in drained triaxial test	KN/m^2
E_{oed}^{ref}	Stiffness modulus for primary loading in oedometer test	KN/m^2
E_{ur}^{ref}	Stiffness modulus for unloading/reloading in drained triaxial test	KN/m^2
m	Modulus exponent for stress dependency	
ν	Poisson's ratio	
γ_{sat}	Saturated unit weight	KN/m^3
γ_{unsat}	Unsaturated unit weight	KN/m^3
ϕ	Internal Friction Angle of soil	degree
ψ	Dilation Angle	degree
V	Shear force on pile at depth Z	kN
M	Bending moment at depth Z	kN-m

1. Introduction

1.1 Background

Pile foundations are commonly used to support a range of heavily loaded structures like electrical transmission towers, high-rise buildings, bridge foundations, retaining structures and wind turbines (Kodikara, Haque, & Lee, 2010). Monopile is one of the foundation options for offshore wind turbines employed in shallow water up to the depths of 30m. Since, these piles are often subjected to heavy vertical and lateral loads; they should be designed to resist both vertical and lateral loads without failure or excessive lateral deflection. It is important to understand the load-displacement response of the laterally loaded pile for the design purpose. Recently large diameter monopiles have been used as foundation for the offshore wind turbine to resist the large lateral loading (Augustesen, et al., 2009). The diameters of such monopiles are around 4-6m and embedded length of 20-30m depending upon the magnitude of loads and the soil conditions.

In the analysis of piles supporting offshore structure, the key element in predicting the response to lateral loads is the determination of the appropriate lateral load-deformation relationships (p-y curves) for the soil. The present practice of constructing the p-y curves are based on the result of lateral load tests on instrumented piles and strength deformation characteristics of the soil.

The pile analysis method commonly used in practice is the p-y approach (Reese et al. 1974) and p-y approach (Matlock, 1970), where the p-y curves represents the relationships between the lateral load (p) and the displacement (y) at a point in the pile.

This report will describe and summarize a number of different methods for analysis and designed of laterally loaded pile foundation and mostly focused on the development of the p-y curve for the laterally loaded monopile embedded in marine clay using finite element program 3D Plaxis foundation.

1.2 Choice of Subject

The subject “Development of p-y curve for monopiles in marine clay” is the continuation of the project work with subject “A Parametric study of monopile Wind turbine Foundation” which was chosen in cooperation with Det Norsk Veritas (DNV).

The project work was focused on the comparison of lateral displacement of the pile under static loading calculated from FEM Plaxis 3D Foundation and traditional p-y method (Geosuite 2010, Pile Analysis). The results for the combination of different diameter and embedded length of pile were compared, which shows that the traditional p-y curve suggested by API code gives almost the same result for the 2.5m diameter pile but more lateral displacement for 5m and 6m diameter pile in comparison to result obtained from the FEM 3D Plaxis Foundation. The kick back effect can also be seen in larger diameter pile. Some results from the project work are attached in appendix (A.2).

Development of the p-y curve for the monopiles in marine clay using FEM 3D Plaxis Foundation is therefore of the interest.

1.3 Objectives

The main objectives of this thesis are:

1. A review of the proposed p-y curves for clay.
2. Evaluation of the selected parameters for the soil material model in relation to the parameters for the p-y curves given by API code
3. Development of the soil response-displacement curves for the monopile in clay using FEM 3D Plaxis Foundation
4. Study on effect of pile diameter in soil response and pile displacement
5. Comparison of the result with the p-y curve suggested by API code.

2. Methods for p-y curve Development

2.1 Introduction

Some studies have been done for developing the p-y curve for the pile in different times and some have been ongoing continuously to improve the existing methods. A number of different methods have been proposed for the development of the p-y curves. The p-y curve which is originated from the subgrade reaction method represents the lateral load per unit length, p, which is an integral of the shear and normal pressure acting on a pile segment when the pile is translated laterally into the soil by a displacement of y (Matlock, 1970).

Because of the complexity of the manner in which unit soil resistance is mobilized, its characteristics have generally been determined empirically from the results of full scale and model pile load tests. Empirical determination of the p-y behavior from load test result is valid and reasonable in most cases but it is important to recognize the limitation of such empirical approach. The accuracy of such empirical methods depends upon the data from which it was developed. The reliability of the approach is based on the number of tests (Kramer, 1988). The most commonly used p-y curve criteria (Matlock, 1970) is based on a very limited number of tests.

This chapter will discuss the general characteristic of p-y curve and describe the different methods proposed for developing p-y curve for different soil condition.

2.2 Characteristics of P-y Curve

The p-y curve which is originated from the subgrade reaction method represents the lateral load per unit length, p, which is an integral of the shear and normal pressure acting on a pile segment when the pile is translated laterally into the soil by a displacement of y (Matlock, 1970).

The p-y curve simply relates the unit soil resistance to pile deflection. Theoretically, it is normally assumed that the soil in the back and front of the pile will remain in contact with reference to the pile during lateral displacement. Typical representation of p-y curve applicable to the single pile in the clayey soil is shown in **Figure 1**. The slope of p-y curve at any deflection represents the tangent soil stiffness at that deflection. The ratio p/y at any deflection represents the secant soil stiffness corresponding to that deflection (Kramer, 1988).

Matlock (1970) developed the empirical expression to represent the p-y curve defined by the power function of deflection normalized by pile deflection at 50% of the ultimate soil reaction. Integrated clay criteria (O'Neill & Gazioglu, 1984) proposed three expressions to represent the different segment of the p-y curve.

The reference displacement (y_c) is taken as the displacement of pile that will occur at 50% of the ultimate soil resistance. The ultimate soil resistance occurs at a displacement of y_u and beyond these remains constant for ideally plastic clays (Kodikara, Haque, & Lee, 2010).

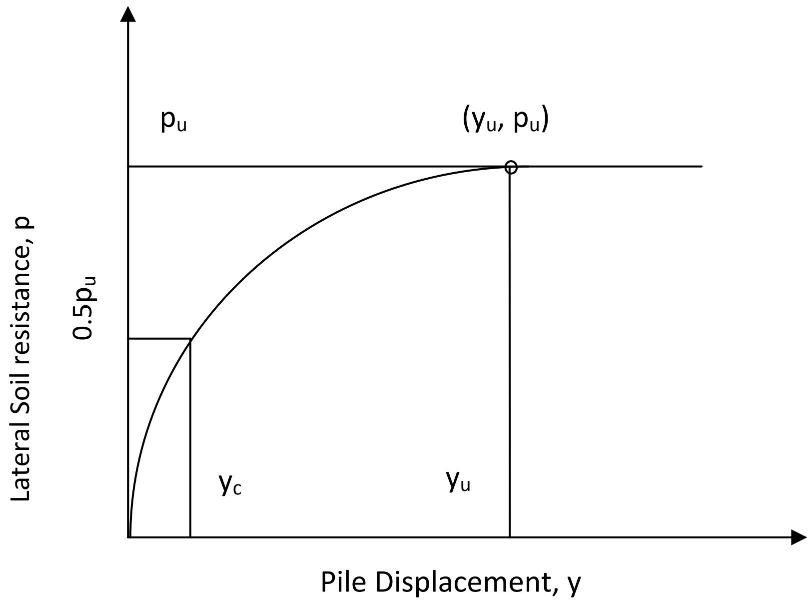

Figure 1: Characteristics p-y Curve for short-term Static Load

2.3 Failure Mechanism of Soil Surrounding the Pile

The magnitude of ultimate soil resistance i.e. the soil resistance under fully plastic behavior p_u is related to the undrained shear strength and varies with the depth and will depend upon the governing type of failure mechanism of soil surrounding the pile. For laterally loaded piles, two types of failure mechanism are considered. The first type of failure mechanism usually occurs at relatively shallow depths involves the failure of a wedge of soil in front of the pile with a gap forming behind the pile. The second type of failure mechanism occurs at greater depth and represented by plastic flow of the soil around the pile as it deflects laterally (Randolph & Susan, 2011). The depth at which these two failure mechanism predict the same ultimate soil resistance is known as critical depth (Z_{cr}). The ultimate soil resistance up to critical depth varies with depth but below critical depth it is taken constant.

The two failure mechanisms are illustrated in **Figure 2** and **Figure 3** below.

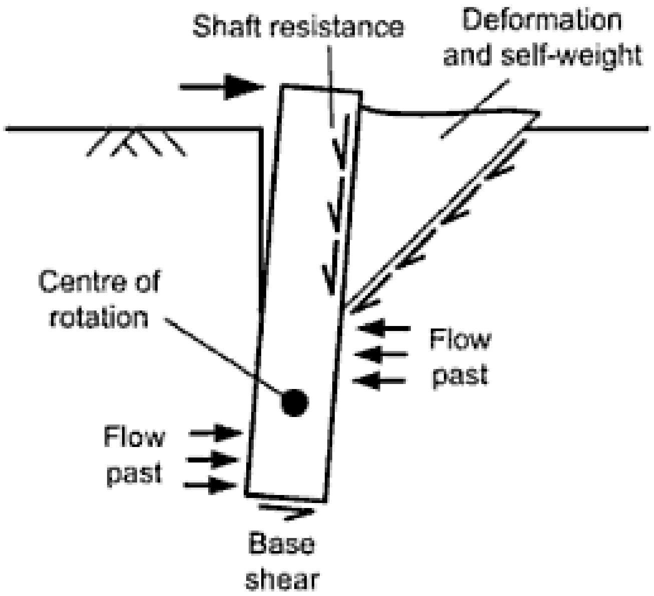

Figure 2: Components of Lateral resistance in clay close to ground surface (Randolph & Susan, 2011)

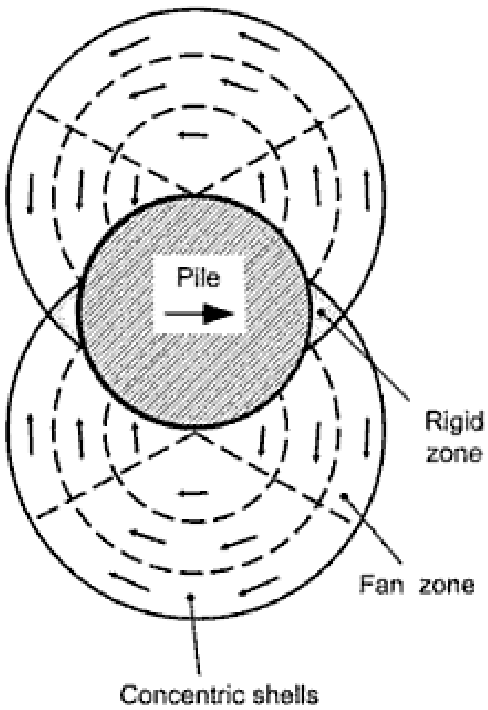

Figure 3: Flow round mechanism for deep lateral resistance in clay (Randolph & Susan, 2011)

2.4 P-Y Curve Criteria for Clays

Many p-y criteria are proposed for the development of the p-y curve for clays. These criteria have been developed based on the result of full scale lateral load tests for static and cyclic loading conditions. Some criteria are reviewed in this section.

2.4.1 Soft clay criteria (Matlock, 1970)

Matlock (1970) proposed a procedure for the development of p-y curves for piles in soft, saturated clays. The strain hardening criteria are based on the results of four lateral load test performed on a fully instrumented 12.75 inch diameter pile driven into soft to medium silty clays at two different sites (Stevens & Audibert, 1979).
The parameters used for calculation are:
P = lateral soil resistance
p_u = ultimate lateral soil resistance
y = lateral pile deflection
$y_c = 2.5*\varepsilon_{50}*d$ .... (1)
ε_{50}= strain at one half the maximum deviator stress in undrained test
d = pile diameter.

The ultimate soil resistance, p_u, is calculated as

$p_u = N_p*S_u*d$ .... (2)

Where, S_u = undrained shear strength of soil
N_p = ultimate lateral soil resistance coefficient
Matlock suggested that N_p =9 for the great depths where sufficient confinement exists that corresponds to horizontal flow of the soil around the cylindrical pile. But near the surface the soil in front of pile is not well confined and as the pile deflects the soil is pushed up and away from the pile N_p = 3 at the surface and increases with depth with the following relationship

$N_p = 3 + \sigma'_z/S_u + J*Z/d$ .... (3)

Where, σ'_z = effective overburden stress at depth z.
S_u = undrained soil shear strength at depth z
J = an empirical constant with an approximate value of 0.5 for the soft offshore clays and a value of 0.25 for somewhat stiffer clays.

2.4.2 Above Water Table (AWT) Stiff Clay Criteria (Reese & Welch, 1975)

Reese and Welch (1975) developed p-y curve criteria for piles embedded in stiff clays above the water table on the basis of one full scale field lateral load test. The load test was performed on a 30-inches diameter drilled shaft in which a 10.75-inches diameter instrumented pipe was embedded. The authors recommended that the reference deflection and the ultimate soil resistance calculated as for soft clay using equations **(1)**, **(2)** and **(3)**. The ultimate soil resistance is considered to be mobilized at deflections greater than or equal to 16 times the reference deflection. At smaller deflection, the shape of the p-y curve is as shown in **Figure 4**.

The p-y curves for the short term static load case may be generated from the following expression:

$p/p_u = 0.5*(y/y_c)^{(1/4)}$ .... (4)

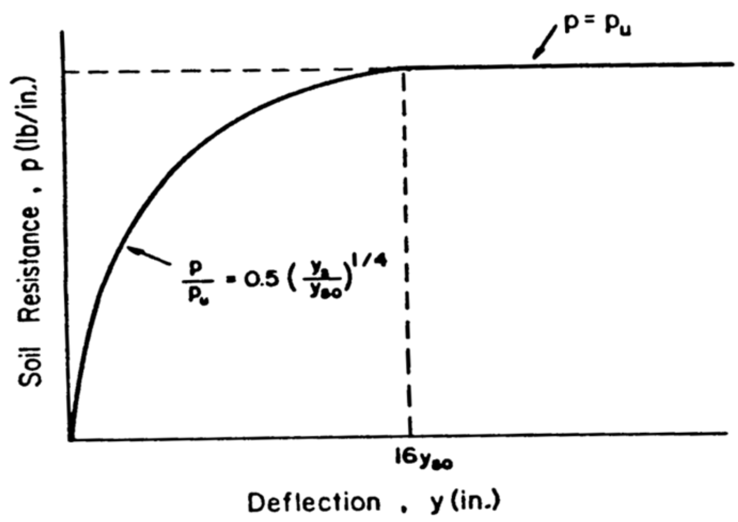

Figure 4: p-y curve for above water table stiff clay criteria (Static Loading)

2.4.3 Below Water Table (BWT) Stiff Clay Criteria (Reese et al, 1975)

Reese, et al. (1975), proposed a procedure for the development of p-y curve for piles embedded in stiff clays below the water table. Development of a strain softening clay criteria for p-y curves was based on the results of lateral load test on two fully instrumented 24 inches and one 6 inch diameter piles driven into stiff clays with shear strengths between 1 and 5 tsf.

Reese developed separate expressions for the ultimate soil resistance for two distinct mechanisms by which the pile was assumed to move through the soil. Based on the failure of wedge of soil in front of pile and on the plastic flow of soil around the pile in a horizontal plane, the ultimate lateral soil resistance, p_u, per unit length of the pile is determined as the lesser of the following equations

$p_u = 2*S_u*d + \sigma'_z*d + 2.83*S_u*Z$ .... (5)

or, $P_u = 11*S_u*d$ .... (6)

Where, σ'_z = effective overburden stress at depth Z

S_u = undrained soil shear strength at depth Z

d = pile diameter

The deflection at one half the ultimate soil resistance is given by:

$y_c = \varepsilon_{50} * d$ .... (7)

ε_{50}= strain at one half the maximum deviator stress in undrained test

d = pile diameter

The shape of the p-y curve for static loading condition generated by below water table stiff clay criteria is shown in **Figure 5**.

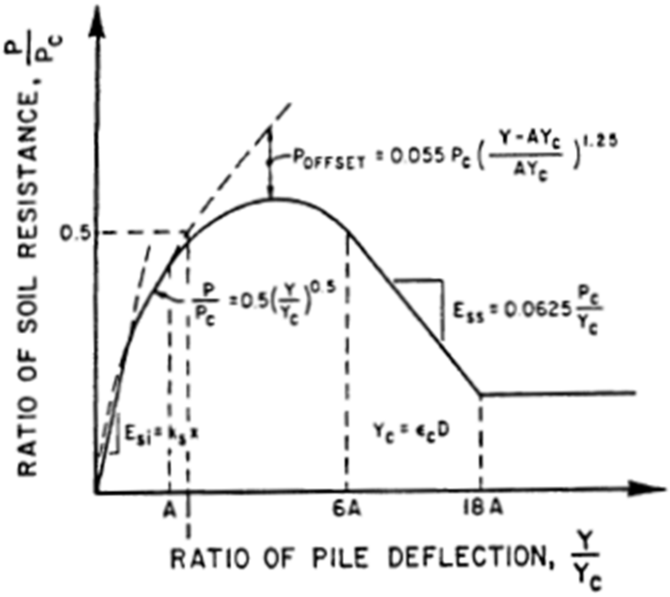

Figure 5: p-y curve for below water table stiff clay criteria (Static Loading)

2.4.4 Design codes recommendations for P-y curve (API, 1993)

American Petroleum Institute (API, 1987, 1993) and Det Norske Veritas (DNV 2007) have recommendations for design of piles in offshore industries. The design regulations for pile in soft and stiff clay are based on the work of (Matlock, 1970) and (Reese, Cox, & Koop, 1974). The only difference is variation of N_p with depth. The API introduces a new term Z_R to relate the variation of N_p depending upon the depth. The N_p values near the mud line are presumed to vary linearly from zero at mud line to nine at depths equal or greater than Z_R. The relation for Z_R given as:

$Z_R = 6d/(\gamma' d/S_u+J)$ .... (8)

For static lateral loads the ultimate unit lateral bearing capacity of soft clay p_u has been found to vary between $8S_u$ and $12S_u$ except at shallow depths where failure occurs in a different mode due to minimum overburden pressure. Cyclic loads cause deterioration of lateral bearing capacity below that for static loads. In the absence of more definitive criteria, the following is recommended:

p_u increases from $3S_u$ to $9S_u$ as Z increases from 0 to Z_R according to:

$$p_u = 3 * Su + \gamma' * Z + J * \frac{Su*Z}{d}$$ .... (9)

And

$$p_u = 9 * Su \text{ for } Z > Z_R$$ .... (10)

Where, p_u = ultimate resistance, (kPa)

S_u = undrained shear strength for undisturbed clay soil samples, (kPa)

d = pile diameter (m)

γ' = effective unit weight of soil, kN/m^2

J = dimensionless empirical constant with values ranging from 0.25 to 0.5 having been determined by field testing.

Z = depth below soil surface, (m)

Z_R = depth below soil surface to bottom of reduced resistance zone in (m). For a condition of constant strength with depth,

For undrained shear strength varying with depth, Z_R, is found by plotting equations (9) and (10) with depth and Z value at the intersection is used. In general, minimum values of Z_R should be about 2.5 times pile diameter.

Lateral soil resistance–deflection relationships for piles in soft clay are generally nonlinear. The p-y curves for the short term static load case may be generated from the following expression:

$p/p_u = 0.5*(y/y_c)^{(1/3)}$ .... (11)

which gives the non-dimensional values for the generation of static p-y curve as presented in the **Table 1.**

Table 1: P-Y curve for Short term static load for soft clay

p/p_u	y/y_c
0.00	0.0
0.23	0.1
0.33	0.3
0.50	1.0
0.72	3.0
1.00	8.0
1.00	∞

Where,

p = actual lateral resistance, (kPa)

y = actual lateral deflection, (m)

$y_c = 2.5*\varepsilon_{50}*d$, (m)

ε_{50} = strain which occurs at one half the maximum stress on laboratory unconsolidated undrained compression tests of undisturbed soil samples.

For the case where equilibrium has been reached under cyclic loading, the p-y curves may be generated from the following table:

Table 2: P-Y curve for the case where equilibrium is reached under cyclic load

$Z > Z_R$			$Z < Z_R$	
p/p_u	y/y_c		p/p_u	y/y_c
0.00	0.0		0.00	0.0
0.23	0.1		0.23	0.1
0.33	0.3		0.33	0.3
0.50	1.0		0.50	1.0
0.72	3.0		0.72	3.0
0.72	∞		$0.72*Z/Z_R$	15
			$0.72*Z/Z_R$	∞

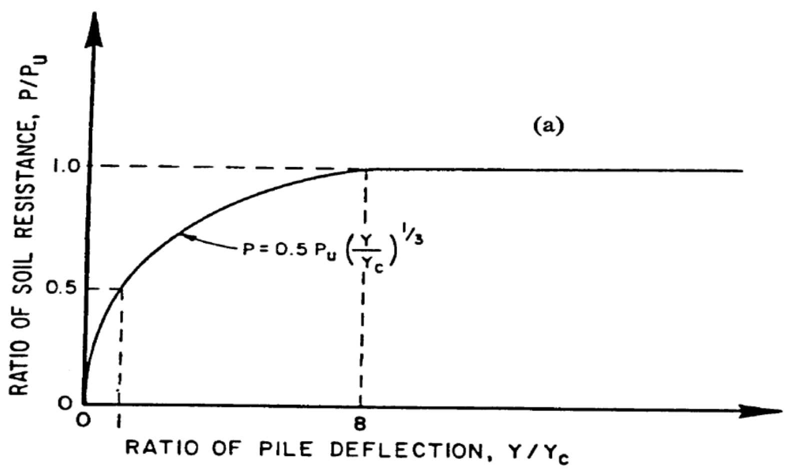

Figure 6: Characteristic shape of P-y curve for soft clay given by API code (Static loading)

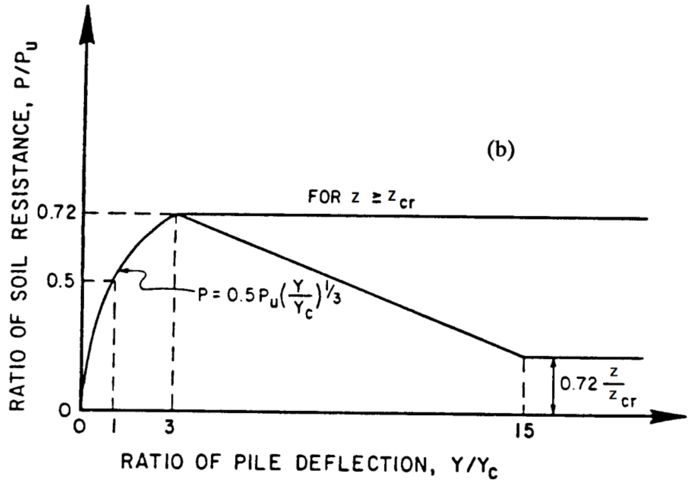

Figure 7: Characteristic shape of P-y curve for soft clay for cyclic loading

2.4.5 Unified Clay Criteria (Sullivan, Reese, & Fenske, 1980)

Sullivan et. Al. (1980), proposed a unified approach to p-y curve development for clays. This method is based upon the soft clay criteria proposed by Matlock and stiff clay criteria proposed by Reese, et al., and consequently on the lateral load test data from which they were developed. It is recommended for use in pile design in any clay soil. Sullivan, et al., reviewed the expressions for p_{ult} developed by a number of investigators and recommended that the ultimate unit soil resistance be taken as the smallest value computed by the following three relationships:

$P_{ult} = (2+ \gamma_{avg}*z/S_{uavg}+0.833/d*Z)*S_{uavg}*d$ .... (12)

$P_{ult} = (3+ 0.5/d*z)*S_u*d$ .... (13)

$P_{ult} = 9S_u*d$ .... (14)

Where, γ_{avg} = average effective unit weight from ground surface to depth z

d = pile diameter

S_{uavg} = average undrained shear strength from ground surface to depth z

S_u = undrained shear strength at depth z

Like the stiff clay criteria, the unified clay criteria proposes an initial linear portion followed by a curved portion, which is described by the cubic equations relating pile deflection to a critical deflection y_{50}, defined as

$y_{50} = A*\varepsilon_{50} *d$ .... (15)

where A is an empirical parameter that is equal to 2.5 for Matlock's tests in soft clay and 0.35 for test in stiff clay.

The shape of p-y curve given by unified clay criteria is shown in **Figure 8**. The user of this criterion is still required to judge whether the soil is soft or stiff for the evaluation of the empirical parameters A and F. The parameter F has been estimated as 1.0 at a soft clay site and 0.5 for the stiff clay site.

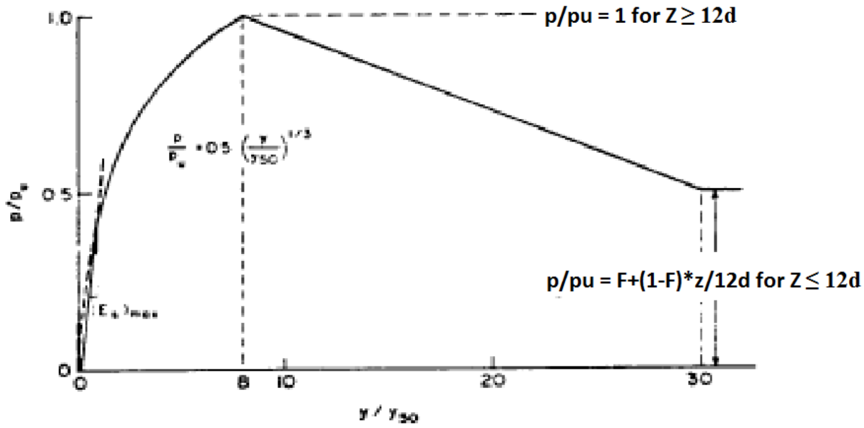

Figure 8: p-y curve for unified clay criteria (Static Loading)

2.4.6 Integrated Clay Criteria (O'Neill & Gazioglu, 1984)

O'Neill and Gazioglu (1984) proposed a p-y curve development procedure that would be applicable to all clays to remove the subjective distinction associated with characterization of cohesive soils as either soft clays or stiff clays. This procedure is based on the result of the 21 field lateral load tests at 11 different locations. The field lateral load tests used to develop the integrated clay criteria were selected to include available high quality tests on a wide range of soils. The integrated clay criteria is developed by making a number of reasonable assumptions regarding the influence of factors like pile diameter, pile length and soil stiffness and by optimizing the several parameters to produce a procedure that provides the best agreement with the available field data.

The following steps can be used to construct the p-y curve by integrated clay criteria.

The ultimate soil resistance is given by

$P_{ult} = F*N_p*S_u*d$ .... (16)

Where, F = empirical reduction factor representative of soil strength degradability

Factor	UU Triaxial Compression Failure Strain		
	< 0.02	**0.02 - 0.06**	**> 0.06**
F (Static Loading)	0.5	0.75	1.00

$N_p = 3+6*(Z/Z_{cr})$ for $Z \leq Z_{cr}$ .... (17)

$Np = 9$ for $Z \geq Z_{cr}$

Z_{cr} = critical depth $=L_c/4$

L_c = critical pile length = $3.0*(EI/E_s*d^{0.5})^{0.286}$ .... (18)

The critical deflection is calculated using the following expression:

$y_c = 0.8*\varepsilon_{50}*d^{0.5}*(EI/E_s)^{0.215}$ .... (19)

The shape of p-y curve for static loading which is shown in **Figure 9** is determined from the following equations,

$p = 0.5*p_u*(y/y_c)^{0.387}$ for $y < 6y_c$ .... (20)

$p = p_u*(Fs+(1-Fs)*Z/Zcr)$ for $y > 6y_c$ and $Z < Z_{cr}$ .... (21)

$p = p_u$ for $y > 6y_c$ and $Z > Z_{cr}$ .... (22)

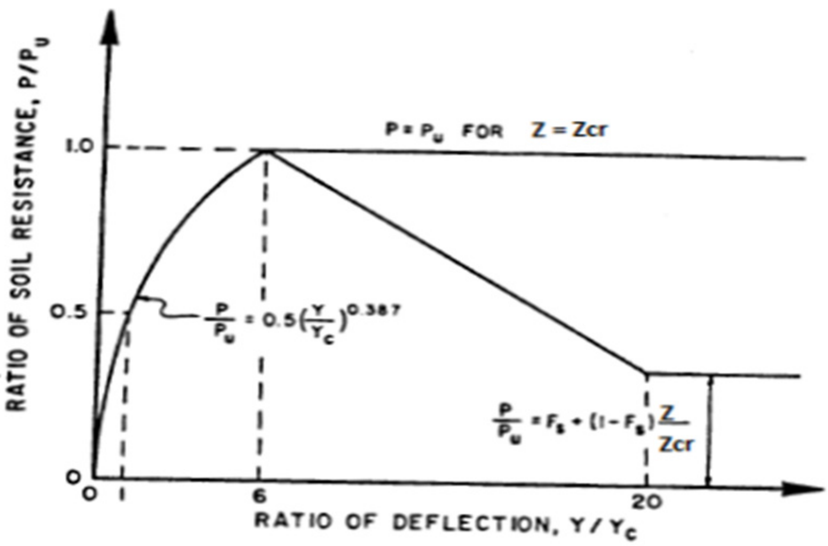

Figure 9: p-y curve developed by integrated clay criteria (Static loading)

2.4.7 Use of Bezier Equations to Represent p-y Curve (Kodikara, Haque, & Lee, 2010)

The typical representation of p-y curve applicable to the single pile in the soft clayey soil is shown in **Figure 10**. The curve is characterized by three segments; an initial segment has a linear portion up to a displacement y_e characterized by stiffness K_i (MPa) signifying the linear elastic behavior of the soil, a curved segment between y_e and y_u and the final linear segment featuring the ultimate failure after reaching the ultimate soil resistance p_u (KN/m) that occurs at a displacement of y_u. The middle curve segment needs to be asymptotic to the two linear segments. For $y > y_u$, the resistance is considered to be constant for ideally plastic clay. Therefore, for the accurate representation of p-y curve, all these parameters (y_u, y_e, K_i, and p_u) need to be evaluated.

The family of curves known as de Casteljau's algorithm introduced by the French engineer Pierre Bezier, in the 1970s (Mortenson 1985) and currently used in automotive design was found to be worthy of consideration. For the prediction of the p-y curve in **Figure 10**, one can consider that

$(y_1, p_1) = (y_e, p_e) = (y_e, K_i*y_e)$,

$(y_2, p_2) = (1/K_i*p_u, p_u)$ and

$(y_3, p_3) = (y_u, p_u)$.

On this basis, entire p-y curve can be represented by the following segments

$y \le y_e$ $\quad p = K_i*y$ .... (23)

$y_e \le y \le y_u$ $\quad y = (1-u)^2 *y_e+2u(1-u)*1/K_i*P_u+u^2*y_u$ $\quad$ for $0 \le u \le 1$ .... (24)

$p = (1-u)^2 *Ki*ye+2u(1-u)*P_u+u^2 p_u$ $\quad$ for $0 \le u \le 1$ .... (25)

$y \ge yu$ $\quad p = p_u$ .... (26)

where u is the continuous dummy variable between 0 and 1.

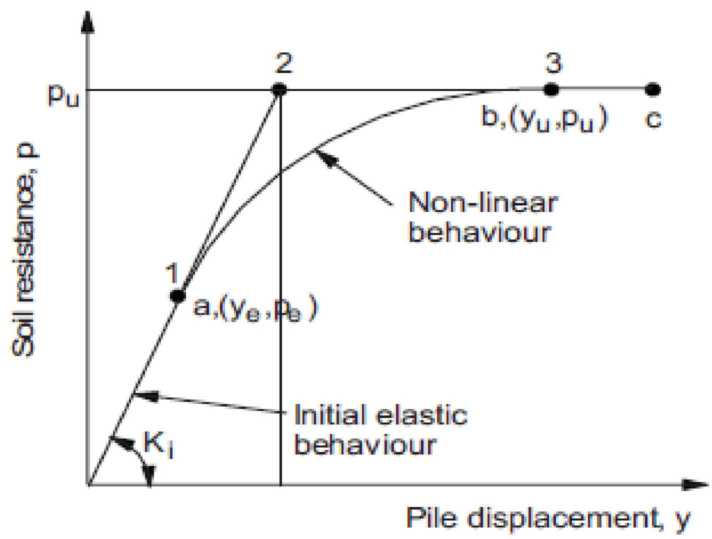

Figure 10: Typical Representations of p-y Curve (Bransby 1996) and Beizer Technique

2.5 Discussion on Different Clay Criteria

Matlock soft clay criteria used the strain at one half the deviator stresses in undrained test and diameter to calculate the reference deflection (y_c). Empirical expression defined by power function of deflection normalized by pile at 50% of ultimate soil reaction is used to represent the p-y curve. This criterion does not take into account shear modulus, poison's ratio, tensile stress of soil, initial stress level. The ultimate lateral soil resistance is calculated using undrained shear strength, ultimate lateral soil resistance coefficient which varies with depth from 3 to 9 and diameter of the pile.

The above water table stiff clay criteria also used the same relation as Matlock to calculate the ultimate soil resistance and ultimate lateral deflection but the ultimate soil resistance is considered to be mobilized at deflection greater than or equal to 16 times the reference deflection.

In below water table stiff clay criteria, Reese developed the separate expression for the ultimate soil resistance based on the mechanism by which the pile is moved in soil. The ultimate soil resistance varies from 2*Su*d to 11*Su*d. The reference deflection is taken as the product of strain at one half the maximum deviator stress in undrained test and diameter of pile. The initial portion of the p-y curve is considered to be linear with an initial soil modulus. This criterion also gives an expression to consider the reduction of soil response beyond the ultimate stress stage.

API code recommendation is based on the work of Matlock and Reese. The only difference is the variation of the ultimate soil resistance coefficient. API introduces a new term Z_R to relate the variation of the N_p depending upon the depth. The ultimate soil resistance is considered to be mobilized at deflection greater than or equal to 9 times the reference displacement.

Unified clay criteria give three relationships to calculate the ultimate soil resistance and the minimum value is considered. It introduced the average shear strength and average effective unit weight term for the calculation of ultimate soil strength. So it is also applicable to the layered soil. The reference deflection is calculated as the product of ε_{50} and diameter of pile with empirical coefficient which depends on the type of clay. This criterion also considered the initial portion of p-y curve to be linear and reduction of soil response beyond the ultimate point is taken into account.

The integrated clay criteria calculated the ultimate soil resistance and reference deflection based on the shear strength, diameter of pile, stiffness of pile and young's modulus of soil. Based on the critical depth and 6 times the reference deflection it gives separate relationships to calculate the soil response at different deflection.

Pierre Beizer characterized the p-y curve by three segments and introduces three equations to describe these three portions of p-y curve. The initial portion is considered to be linear.

Even there are numbers of methods to describe the p-y curve for clay; the API code method is most widely used by geotechnical engineer. This method is only method that is well described in the design standard code and easy to use. It is better to follow the standard codes for the analysis of pile which is accepted by all.

3. Description of Model

3.1 Introduction

For the development of p-y curve, Finite Element 3D Plaxis Foundation is used for the analysis purpose. Soil pile modeling is done in three dimensional finite element Plaxis Foundation to investigate the lateral deformation of pile and soil reaction.

Nowadays FEM 3D Plaxis foundation is one of the mostly used programs by geotechnical engineers to analyze the foundation of different structure. The existing empirical expressions of p-y curves for the monopiles were proposed based on the field test. This numerical analysis is done to check the applicability of FEM Plaxis 3D foundation for the analysis of the laterally loaded monopile by comparing result with the existing empirical expressions. In reality the monopile is loaded with vertical load, lateral load and overturning moment at the head of monopiles. When the monopile is analyzed with these loads in 3D Plaxis, it shows the kick off effect at the tip of the pile and also influenced by the pile flexibility which makes difficult to study the soil reaction and pile displacement effect. So for the study of the soil reaction and pile displacement relation of the soil through the soil depth, it is decided to apply the loads both at head and tip of the rigid pile to achieve the pure lateral translation of the pile.

The sketch of the typical model used for analysis is shown in ***Figure 11*.**

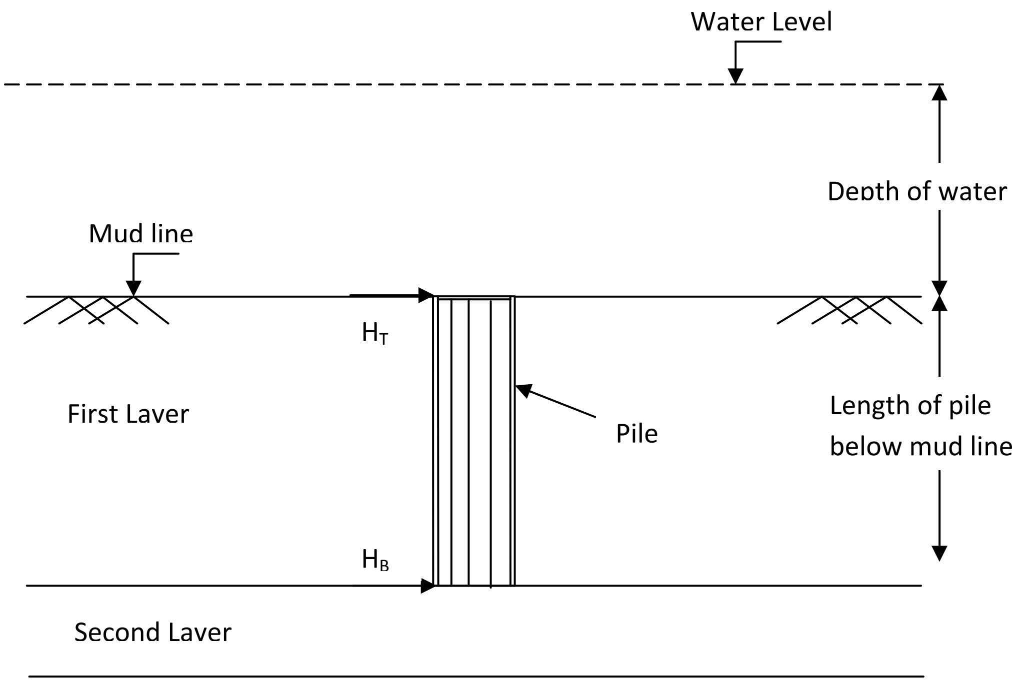

Figure 11: Sketch of the typical model

3.2 Soil Condition

The marine clay is considered for the soil profile. The soil is modeled in two layers of soil for the analysis. The soil model above the tip of the pile is considered as first layer and below the tip of the pile is considered as second layer. The properties of the first layer soil are described by the undrained hardening soil model and the undrained shear strength is kept constant throughout the layer. For the second layer the linear elastic soil model is used to describe the soil properties.

The study is focused in the soil response and pile displacement in the first layer. There is problem in modeling the pile with the free lateral translation of pile tip without including the soil below the tip. So a layer soil below the tip of pile is included. For the soil with hardening soil model below tip result greater shear resistance at the tip of the pile, so the soil below the tip is modeled with assumed linear elastic parameters to reduce the shear resistance at the tip of the pile during the lateral translation.

The equivalent soil parameters required to explain the hardening soil model of the first layer is determined from the Plaxis soil test for the soil with undrained shear strength (S_u) of 100kPa and strain at half maximum strength value (ε_{50}) of 0.45%. The Plaxis test model is presented in the appendix **A.1**.

The soil parameters of different layers are presented in **Table 3** and **Table 4**.

Table 3: The soil parameters for first layer soil

SN	Parameters	Value	Unit
1	E_{50}^{ref}	18.75E+03	KN/m^2
2	E_{oed}^{ref}	18.75E+03	KN/m^2
3	E_{ur}^{ref}	56.25E+03	KN/m^2
4	m	1	
5	Undrained Shear Strength (S_u)	100	kPa
6	Unit weight (γ_{sat})	20	KN/m^3
7	Internal Friction Angle (ϕ)	0	degree
8	Dilation Angle (ψ)	0	degree

Table 4: The soil parameters for the second layer soil

SN	Parameters	Value	Unit
1	E_{ref}	1000	KN/m^2
2	ν	0.35	
3	Unit weight (γ_{sat})	20	KN/m^3

3.3 Pile Properties

Monopiles of steel are used as the foundation for the offshore wind turbines. In the analysis the pile is modeled as a solid cylindrical beam with interface element between pile and soil. Nowadays monopile of 4-6m diameter are typically used. A high stiffness is assigned for the pile to make it rigid so that the bending of the pile becomes negligible. The bending stiffness E_pI_p is kept constant along the pile length. This is done to get the uniform displacement throughout the depth when lateral load is applied. The unit weight of the pile material is taken same as soil to avoid the vertical settlement of the pile in the analysis.

The solid cylindrical pile with diameters of 1m, 2m, 3m, 4m, 5m and 6m were considered for the analysis to study the effect of pile diameter. The length to diameter ratio (L/D) in between 5 to 10 is taken to avoid the slender pile effect. Hence the length of the pile 10m, 15m, 20m, 25m, 35m and 45m for respective pile diameter are considered in the analysis.

The parameters used for the pile is presented in **Table 5**.

Table 5: The parameters used for equivalent solid pile in analysis

SN	Parameters	Value	Unit
1	Young's Modulus of Elasticity (E_p)	2.15E+12	KN/m^2
2	Poissons ratio (ν)	0.3	
3	Unit weight (γ_p)	20.0	KN/m^3

3.4 Loads

The monopile is normally designed to carry the vertical load, lateral load and bending moment. But in the analysis only the static lateral load is considered. For the development of the soil resistance-pile displacement curves the loads are applied in steps. The load model consists of two point loads one at the head and other at the tip of the pile. The loads were increased in steps. The top and bottom loads were adjusted in such a way that the lateral displacement of the pile achieved to be uniform throughout the length. The point loads were finalized by trial and error method. The combination of loads applied in each step for different diameter of piles is presented in the tables below.

Table 6: Load combination for 1m diameter Pile.

Load Steps	Lateral Load Applied at	
	Head of the Pile (kN)	Tip of the Pile (kN)
1	2	2.1
2	25	26
3	98	100
4	200	200
5	400	400
6	800	800
7	1000	1000

Table 7: Load combination for 2m diameter Pile

Load Steps	Lateral Load Applied at	
	Head of the Pile (kN)	Tip of the Pile (kN)
1	10	11
2	100	105
3	420	430
4	840	855
5	1680	1710
6	3360	3450
7	4200	4330

Table 8: Load combination for 3m diameter Pile

Load Steps	Lateral Load Applied at	
	Head of the Pile (kN)	Tip of the Pile (kN)
1	25	27
2	250	265
3	1000	1060
4	2000	2120
5	4000	4240
6	8000	8480
7	10000	10900

Table 9: Load combination for 4m diameter Pile

Load Steps	Lateral Load Applied at	
	Head of the Pile (kN)	Tip of the Pile (kN)
1	50	53
2	475	495
3	1900	2100
4	3800	4000
5	7600	8050
6	15200	16350
7	19000	20400

Table 10: Load combination for 5m diameter Pile

Load Steps	Lateral Load Applied at	
	Head of the Pile (kN)	Tip of the Pile (kN)
1	80	84
2	800	860
3	3125	3250
4	6250	6500
5	12500	12900
6	25000	27800
7	31250	34800

Table 11: Load combination for 6m diameter Pile

Load Steps	Lateral Load Applied at	
	Head of the Pile (kN)	Tip of the Pile (kN)
1	100	95
2	1000	925
3	4000	3780
4	8000	7625
5	16000	15600
6	32000	34000
7	48000	52400

3.5 Modeling and Analysis in Plaxis 3D Foundation

Soil pile modeling is established in three dimensional numerical models to investigate the lateral deformation and soil reaction on pile during the horizontal loading. The computations are carried out by means Finite Element program 3D Plaxis Foundation.

Due to symmetry of loading condition and material model, only one half of the pile and its surrounding soil are modeled for the analysis which helps in the saving calculation time.

The soil is modeled as a cylindrical with outer diameter larger than 30 times diameter of pile. For each analysis, the mesh with 15 noded elements is considered to be sufficient. The study is focused on the lateral displacement and soil reaction, the pile is designed as solid cylinder pile with high stiffness to reduce the local deformation. The linear elastic material with 15 noded continuum elements is used to model pile elements in finite element model. The pile head is kept at the level of mud line. The unit weight of the pile is considered same as the soil model to avoid the vertical settlement of the pile.

The soil and pile properties are described as the parameters presented in ***Table 3***, ***Table 4*** and **Table 5**. The value of interface coefficient is taken as 1.

The analysis is executed stepwise. First the initial stress state is established in the entire model using submerged unit weight for both the soil element and the element that later becomes the pile. A K_0 procedure is employed to establish the initial horizontal effective stress. As the internal frictional angle for the soil is assumed to be zero, the appropriate K_0 value 0.65 is assigned.

In the second step, the pile is generated by replacing the soil element that now becomes the pile with the adjusted strength and stiffness parameter. Between the pile element and the soil element, an interface is established to model the soil-pile interaction. The system is brought to equilibrium. The combinations of lateral loads are applied in each stage to get the uniform lateral displacement. The horizontal loadings for each stages of different diameter of piles are assigned as given in **Table 6** to **Table 11.**

The stepwise modeling in Plaxis 3D foundation is shown in figures bellow:

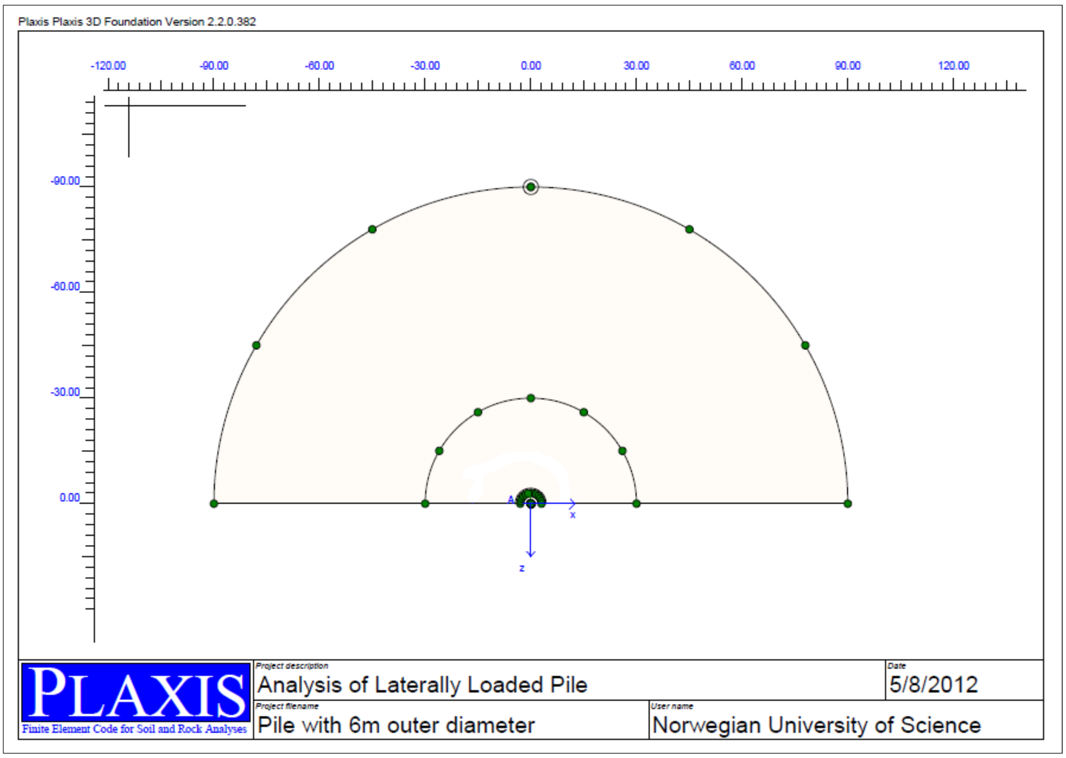

Figure 12: Defining the Different Cluster for Soil Modeling

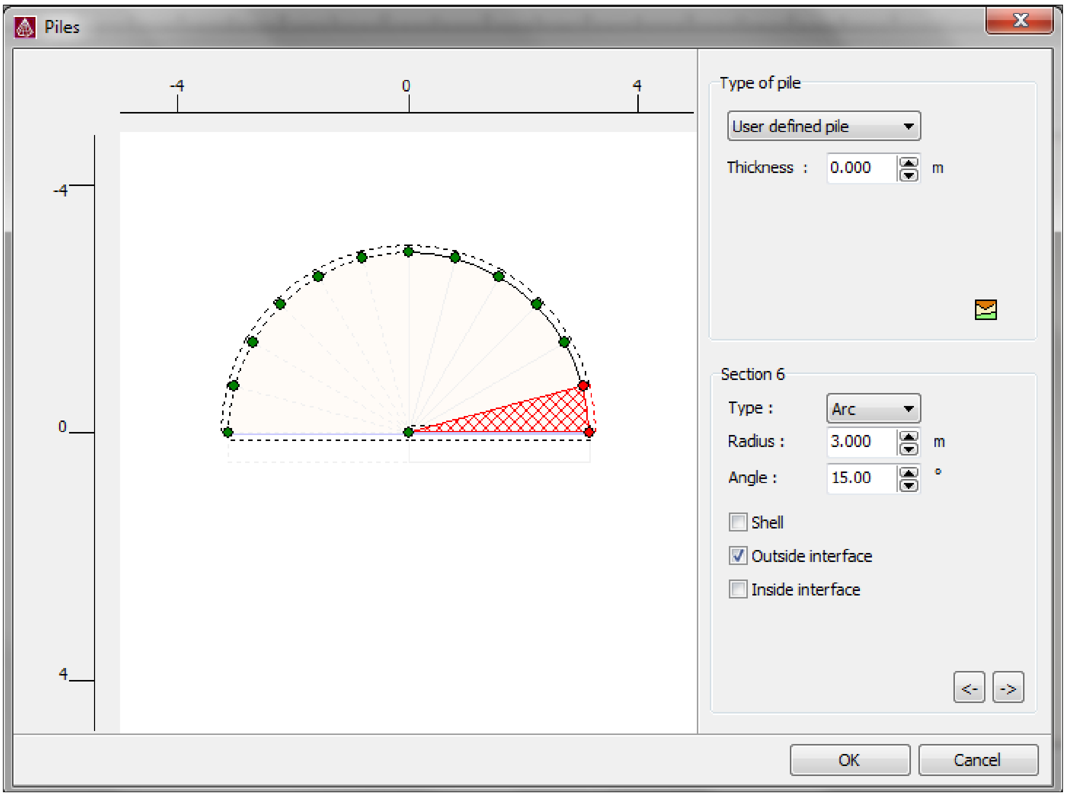

Figure 13: Pile Modeling

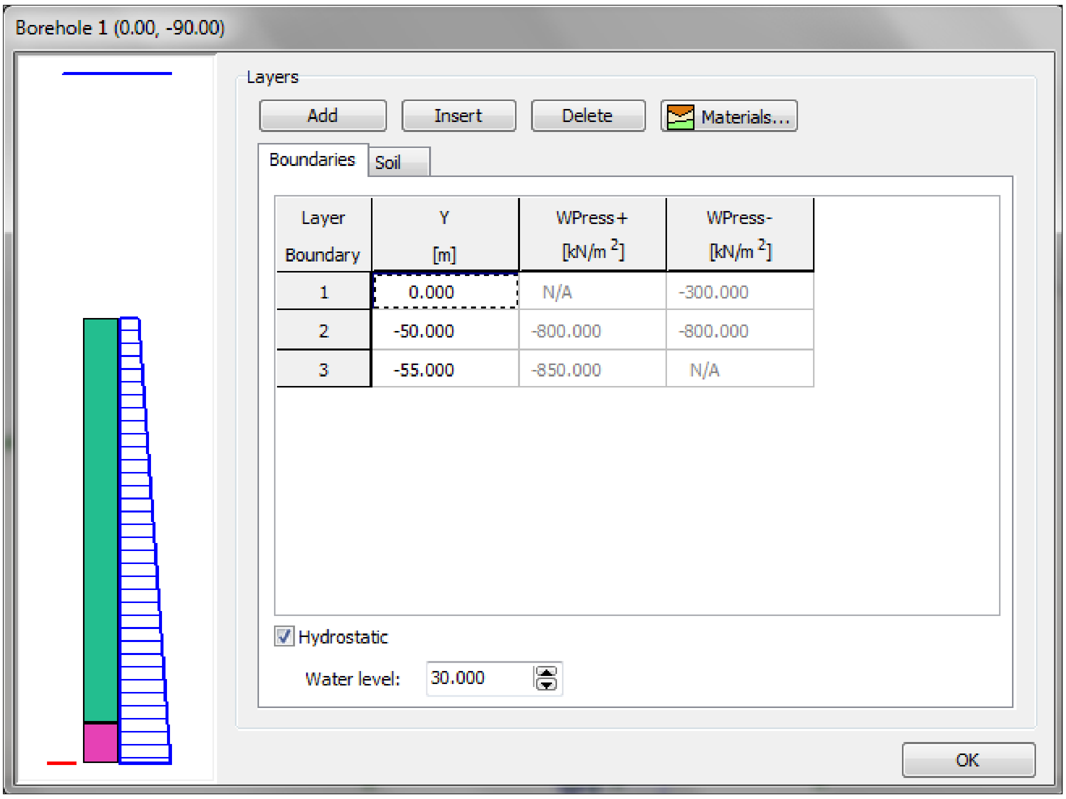

Figure 14: Borehole Properties for the Analysis

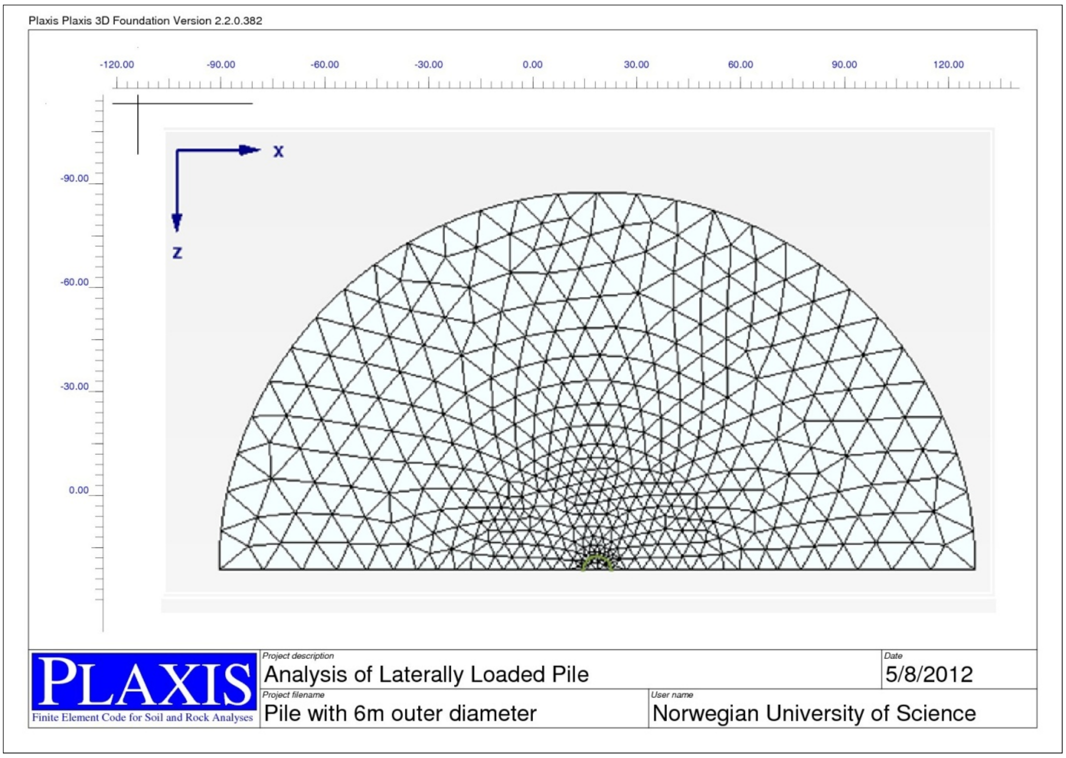

Figure 15: Meshing in Horizontal Direction

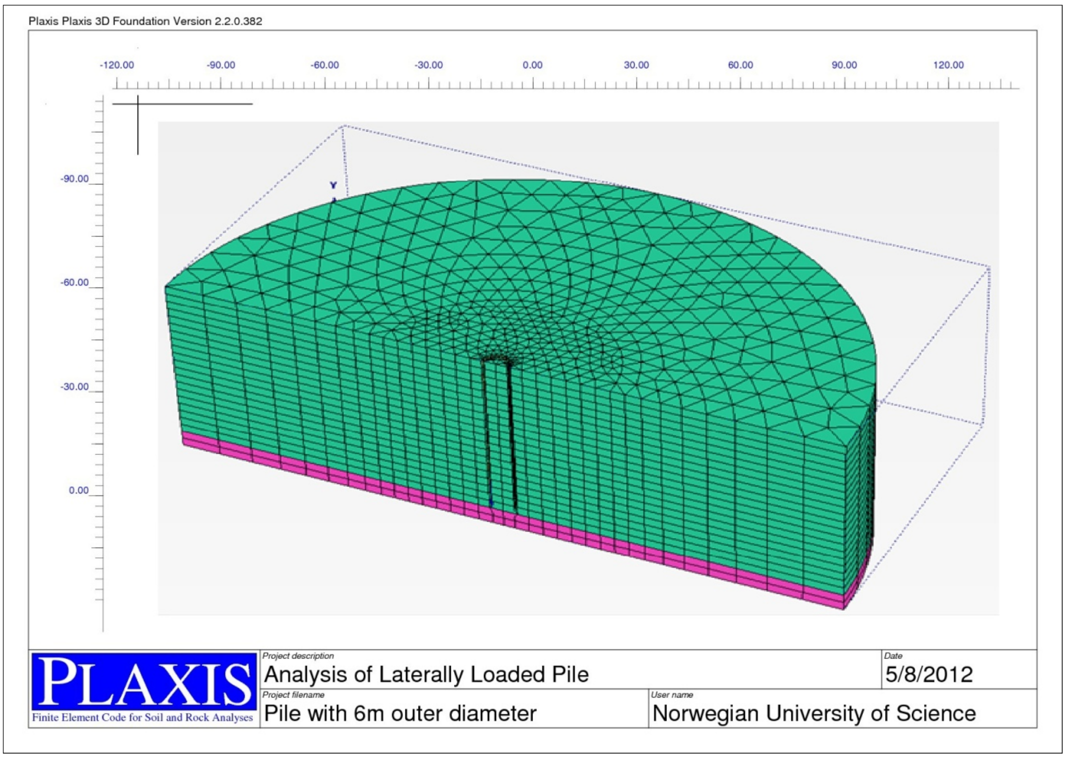

Figure 16: Three Dimensional Models of the Soil and Pile with Meshing

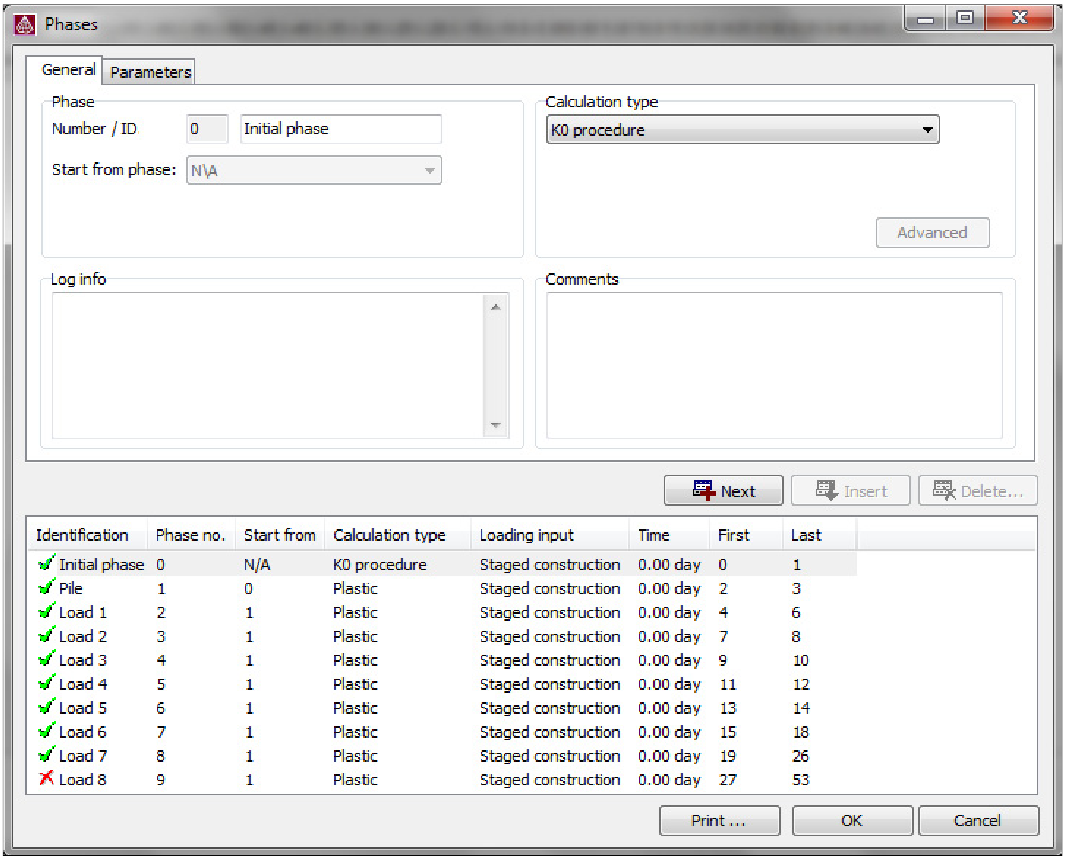

Figure 17: Different Phases for the Analysis

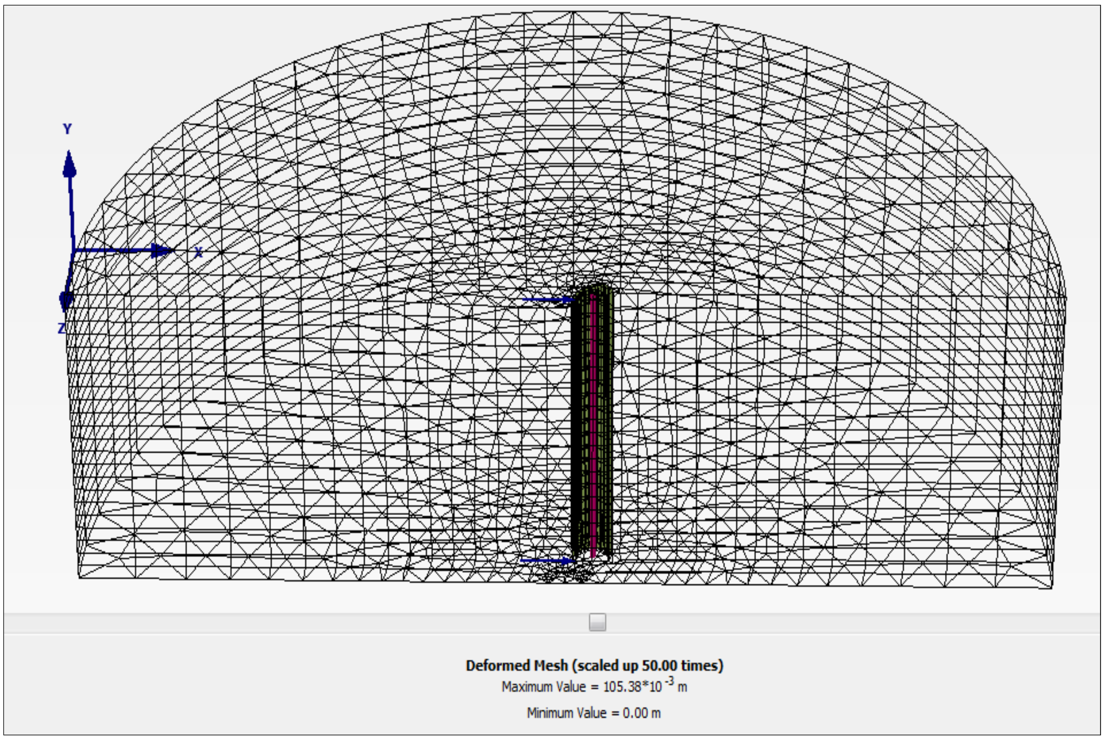

Figure 18: Deformed Mesh

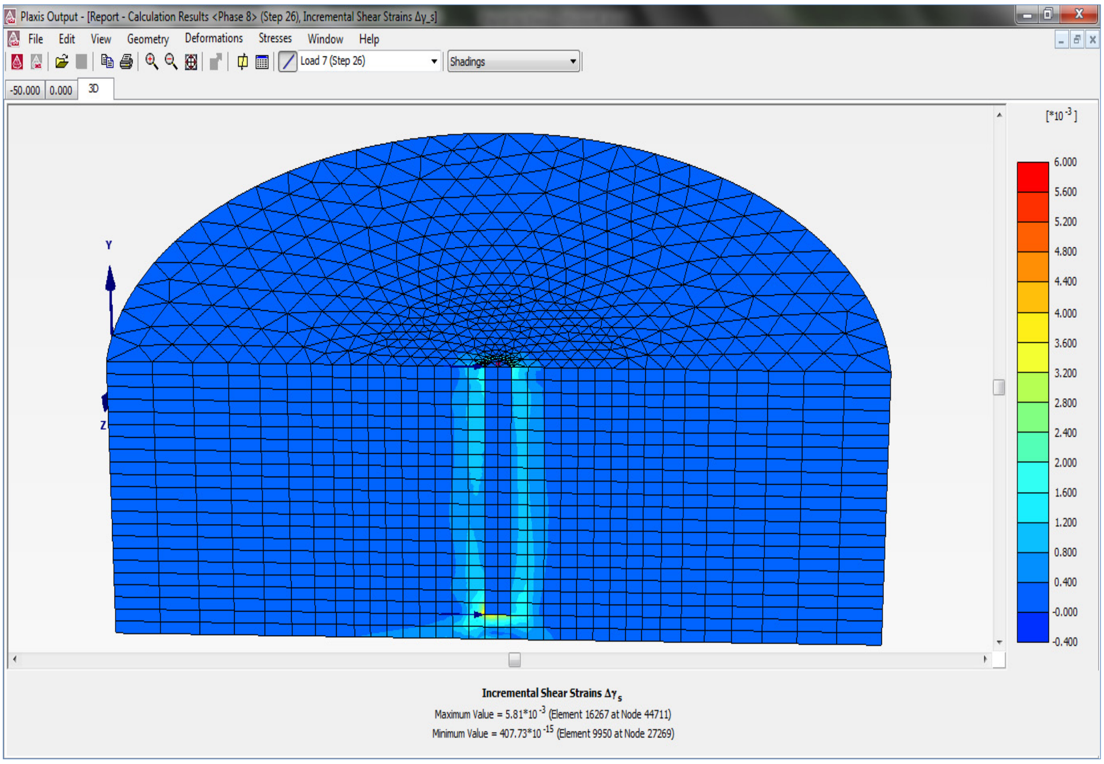

Figure 19: Incremental Shear Strain

After completing the analysis, the output related to stress and lateral displacement for the central beam element of the pile is taken and used for the further calculation.

4. Results

The results from the analyses of laterally loaded piles in the Finite Element Program Plaxis 3D Foundation are presented in this chapter. The analysis is done for static loading only. The soil reaction is plotted with the corresponding displacement and compared with the p-y curve given by API code.

Derivation of the p-y curves using output data from Finite Element Plaxis 3D Foundation involve the mathematics. The soil resistance per unit length, p, of the pile can be derived using the differentiation technique on the shear force-depth profile or bending moment –depth profile (Brown & Shie, 1990). It can be expressed as

$$P = dV/dZ \quad \text{or} \quad \text{………………. (27)}$$

$$P = d^2M/dZ^2 \quad \text{………………. (28)}$$

Where p = net soil resistance per unit length of the pile at depth Z and

V = the shear force at depth Z

M = the bending moment at depth Z

The lateral displacement of the pile is analyzed using the finite element program 3D Plaxis foundation. The analysis is done for the piles with different diameter. The analysis focused on the pure lateral displacement to determine the soil reaction for the different displacement. The soil response is calculated using the shear force acted upon the pile from the soil. As the pile is modeled as solid cylinder with very high stiffness, the central element of the pile behaves like beam element. The central node element is connected to the circumferential nodes of the piles, so the shear force and bending moment and displacement of the central element is representatives for the pile. Hence the shear force and bending moment on this central element can be used for the calculation of the soil response on pile using the expressions given in 27 and 28.

The lateral displacement, y, along the depth was directly obtained from the output of the Finite Element 3D Plaxis Foundation. The obtained soil reaction is plotted with respect to the respective lateral displacement to get the p-y curve.

The groups of soil resistance vs lateral displacement curves are plotted for the each diameter of pile at the depth of 1*Diameter, 2*Diameter, 3*Diameter, 4*Diameter and 5*Diameter. But the soil resistance vs lateral displacement curves from plaxis result along with the p-y curves obtained by the relation provided by API code were plotted only for the depth of 1*Diameter and 5*Diameter.

The soil reaction and lateral displacement for different diameter of pile at the depth corresponding to about 1*Diameter and 5*Diameter were presented in the **Table 12** to

Table 23 which are used for the comparison purpose. The secant stiffness at different load steps are also calculated and presented in these tables. The secant stiffness corresponding to respective lateral displacement obtained from FEM analysis is also calculated from the API code and is presented for the comparison.

Table 12: Soil Resistance, Pile Displacement and Secant Stiffness for 1m Diameter Pile at 1.05m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000014	0.39	28575	18.33	1262300
2	0.000174	5.04	28910	42.55	234385
3	0.000712	18.81	26430	67.20	93975
4	0.001530	39.01	25500	85.64	57850
5	0.003250	82.06	25250	109.83	35175
6	0.007420	161.89	21820	144.86	20220
7	0.009775	201.55	20620	159.22	16735

Table 13: Soil Resistance, Pile Displacement and Secant Stiffness for 1m Diameter Pile at 5.0m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000015	0.41	28130	18.75	1206625
2	0.000182	5.11	28170	43.25	226880
3	0.000715	20.23	28285	67.32	93600
4	0.001480	42.14	28465	84.42	59530
5	0.003122	80.38	25740	107.90	36440
6	0.007164	161.64	22560	142.65	20850
7	0.009512	202.90	21330	157.34	17140

Table 14: Soil Resistance, Pile Displacement and Secant Stiffness for 2m Diameter Pile at 2.25m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000042	1.29	30430	43.30	1021735
2	0.000433	13.38	30930	93.94	217110
3	0.001891	55.43	29310	153.59	81210
4	0.003964	107.26	27055	196.56	49580
5	0.008598	228.25	26545	254.44	29590
6	0.021146	444.50	21020	343.45	16240
7	0.029571	560.01	18940	384.06	12985

Table 15: Soil Resistance, Pile Displacement and Secant Stiffness for 2m Diameter Pile at 10.13m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000048	1.43	29585	45.12	937145
2	0.000464	13.67	29430	96.17	207130
3	0.001924	56.43	29335	154.46	80295
4	0.003890	114.63	29470	195.33	50210
5	0.008348	231.87	27775	251.95	30180
6	0.020766	465.03	22395	341.38	16440
7	0.029184	583.70	20000	382.78	13100

Table 16: Soil Resistance, Pile Displacement and Secant Stiffness for 3m Diameter Pile at 3.0m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000081	2.44	30135	71.28	880500
2	0.000821	24.99	30440	154.28	187955
3	0.003391	98.26	28975	247.56	73000
4	0.007095	185.17	26100	316.63	44625
5	0.015869	379.87	23940	414.07	26090
6	0.040317	780.50	19360	565.01	14015
7	0.050877	795.13	15630	610.57	12000

Table 17: Soil Resistance, Pile Displacement and Secant Stiffness for 3m Diameter Pile at 15.0m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000091	2.63	28840	74.16	813420
2	0.000896	25.77	28770	158.85	177300
3	0.003601	103.51	28745	252.56	70135
4	0.007287	210.27	28855	319.46	43840
5	0.015743	433.19	27515	412.98	26230
6	0.040943	866.66	21170	567.92	13870
7	0.050158	980.26	19545	607.68	12115

Table 18: Soil Resistance, Pile Displacement and Secant Stiffness for 4m Diameter Pile at 3.75m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000131	3.94	30095	103.04	787270
2	0.001260	38.30	30395	219.20	173985
3	0.005144	148.14	28800	350.33	68110
4	0.010871	280.42	25795	449.59	41355
5	0.024236	604.74	24950	587.32	24230
6	0.065018	1188.50	18280	816.09	12550
7	0.101835	1513.35	14860	947.74	9305

Table 19: Soil Resistance, Pile Displacement and Secant Stiffness for 4m Diameter Pile at 20.0m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000145	4.11	28330	106.64	735030
2	0.001354	38.22	28235	224.51	165840
3	0.005780	164.50	28460	364.23	63010
4	0.011059	312.77	28280	452.16	40885
5	0.024103	659.41	27360	586.25	24320
6	0.065685	1343.07	20450	818.86	12465
7	0.101096	1656.76	16390	945.44	9350

Table 20: Soil Resistance, Pile Displacement and Secant Stiffness for 5m Diameter Pile at 5.25m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000151	4.52	30010	131.50	872715
2	0.001513	45.34	29970	283.68	187545
3	0.006092	186.06	30545	415.33	71090
4	0.012622	344.57	27300	575.39	45585
5	0.027765	655.92	23625	748.31	26950
6	0.069941	1356.67	19400	1018.19	14555
7	0.105214	1716.92	16320	1166.66	11090

Table 21: Soil Resistance, Pile Displacement and Secant Stiffness for 5m Diameter Pile at 25.38m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000165	4.63	28090	135.48	822190
2	0.001686	47.48	28170	294.10	174480
3	0.006398	179.21	28010	458.78	71700
4	0.012873	360.21	27980	579.17	44990
5	0.026457	741.58	28030	736.38	27832
6	0.070999	1621.63	22840	1023.30	14410
7	0.106364	2014.03	18935	1170.89	11010

Table 22: Soil Resistance, Pile Displacement and Secant Stiffness for 6m Diameter Pile at 6.25m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000124	4.17	33620	142.79	1150795
2	0.001309	43.00	32840	313.19	239200
3	0.005537	174.63	31535	506.47	91465
4	0.011482	331.88	28905	645.85	56250
5	0.024088	598.02	24825	826.79	34320
6	0.055121	1165.61	21145	1089.51	19765
7	0.101103	1796.04	17765	1333.66	13190

Table 23: Soil Resistance, Pile Displacement and Secant Stiffness for 6m Diameter Pile at 30.0m Depth below Mud line

Load Steps	Lateral Displacement (y), m	FEM 3D Plaxis Foundation		API code	
		Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y	Soil Resistance (p), kN/m^2	Secant Stiffness K_i =p/y
1	0.000143	3.86	26880	149.88	1044480
2	0.001307	36.35	27805	313.01	239465
3	0.005584	150.35	26925	507.90	90950
4	0.011443	304.57	26615	645.12	56375
5	0.024024	639.89	26635	826.05	34385
6	0.055286	1409.85	25500	1090.59	19725
7	0.101481	2130.64	20995	1335.32	13160

The **Figure 20, Figure 21, Figure 22, Figure 23, Figure 24 and Figure 25** shows the soil resistance vs. lateral displacement curves for the pile diameters of 1m, 2m, 3m, 4m, 5m and 6m respectively. Each figure includes the soil resistance vs. lateral displacement curves for the different depth of soil profile.

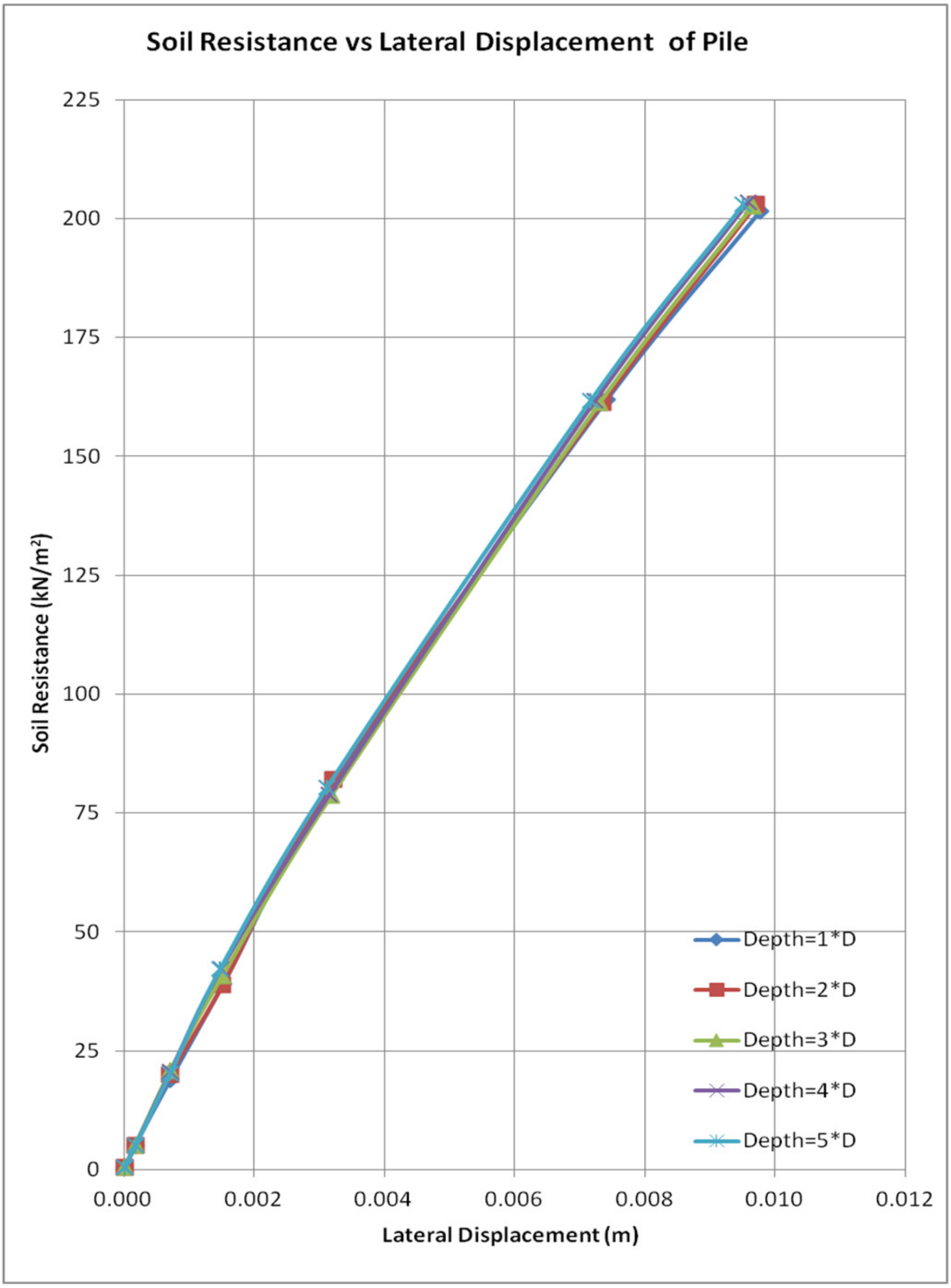

Figure 20: Soil Resistance vs. Lateral Displacement Curve for the Pile of 1m Diameter

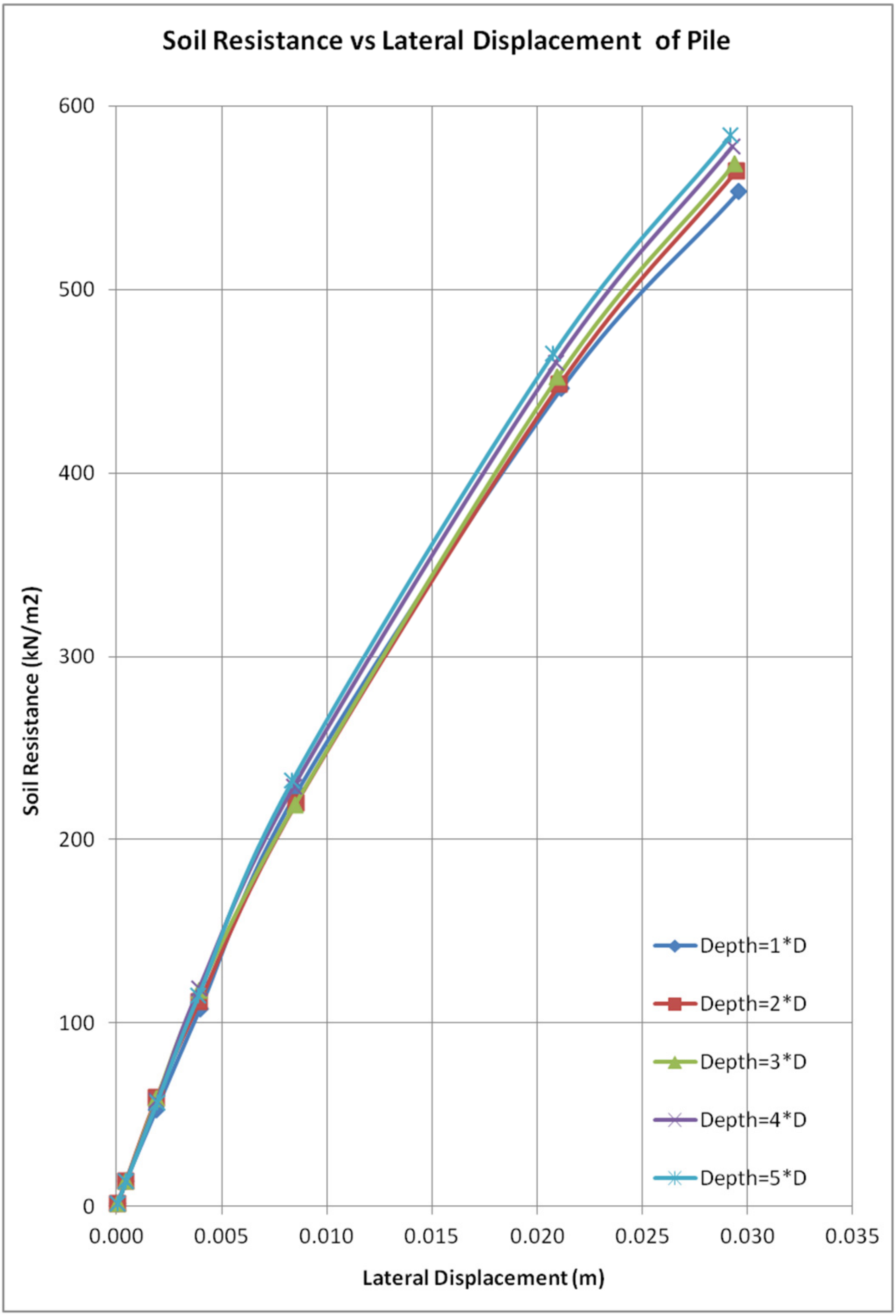

Figure 21: Soil Resistance vs. Lateral Displacement Curve for the Pile of 2m Diameter

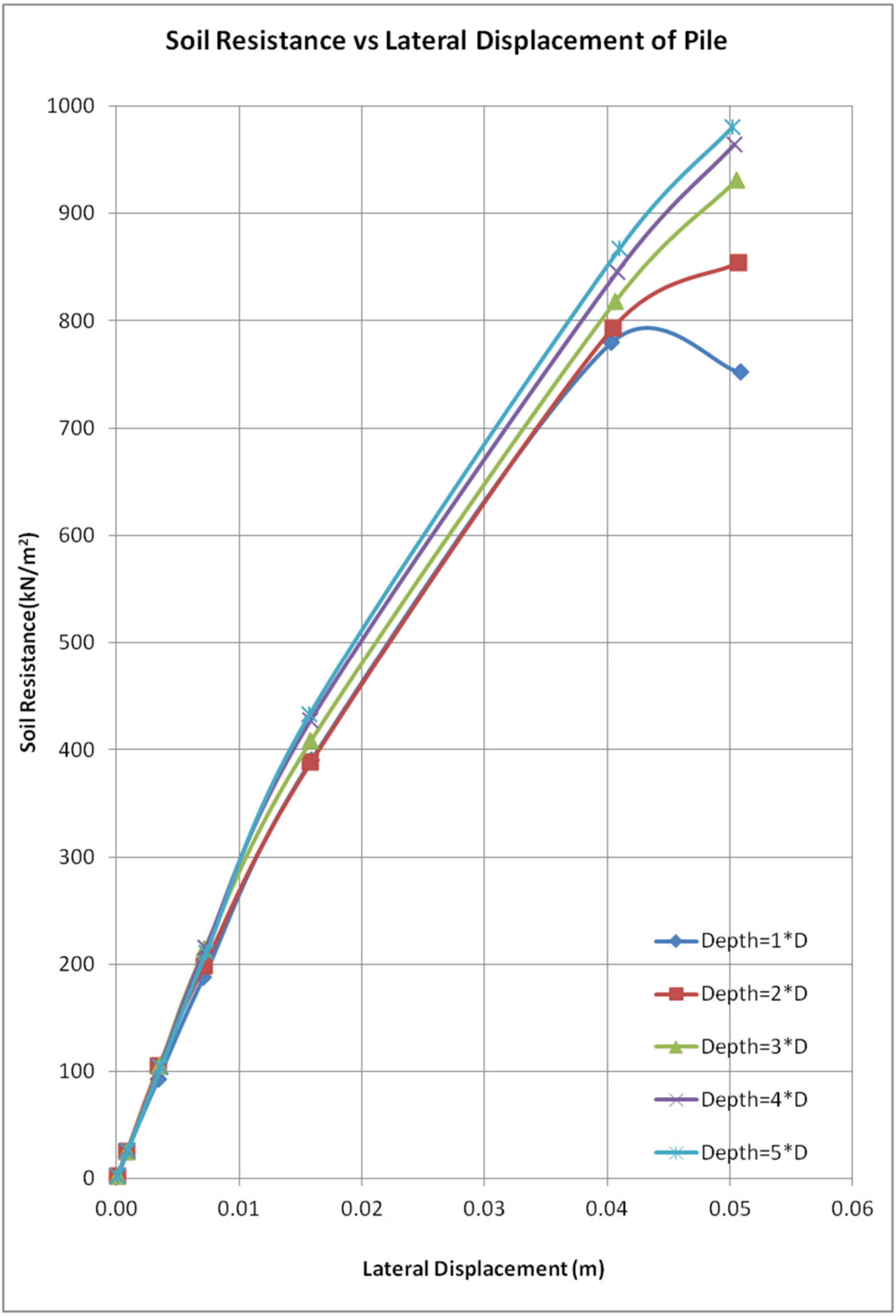

Figure 22: Soil Resistance vs. Lateral Displacement Curve for the Pile of 3m Diameter

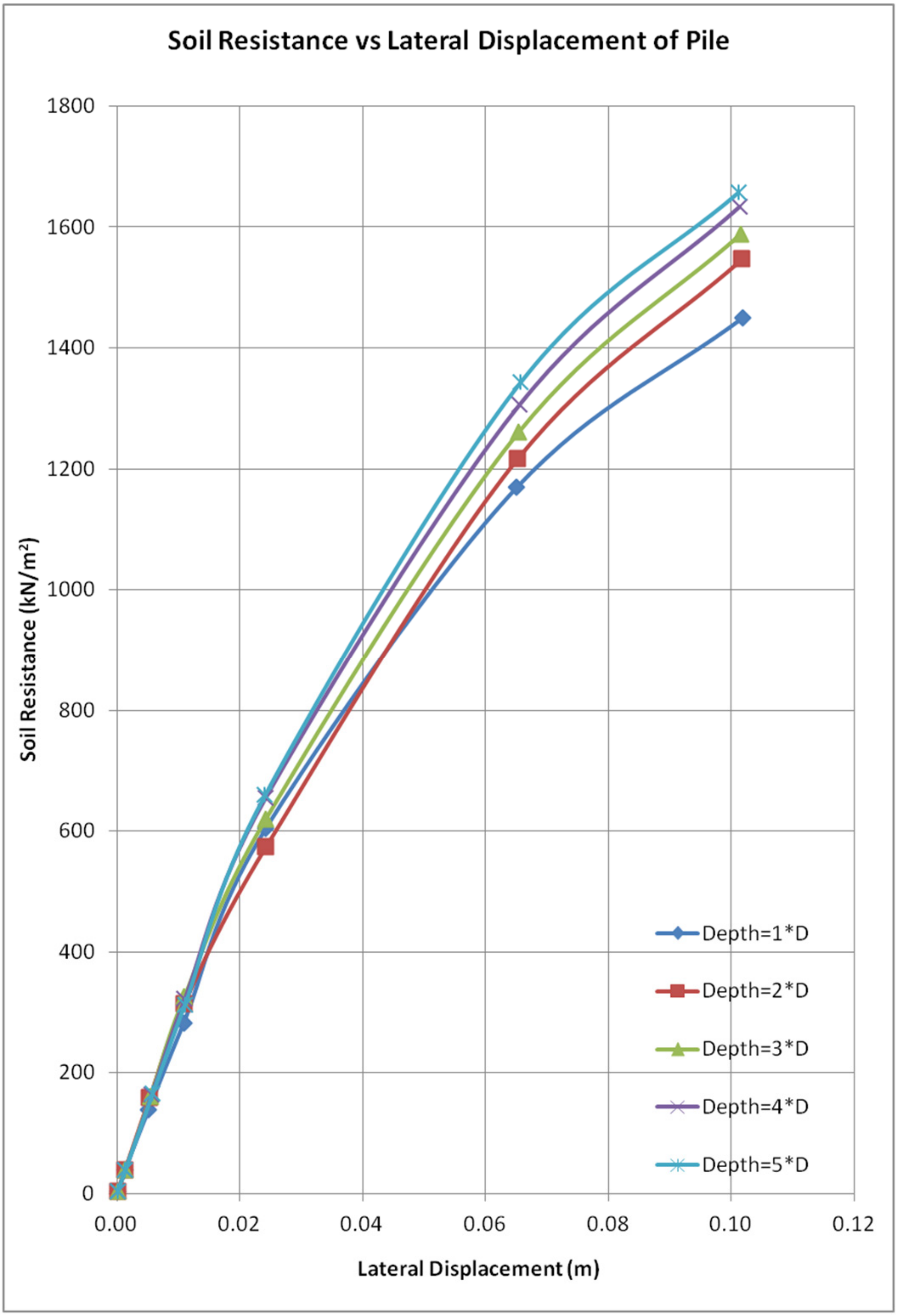

Figure 23: Soil Resistance vs. Lateral Displacement Curve for the Pile of 4m Diameter

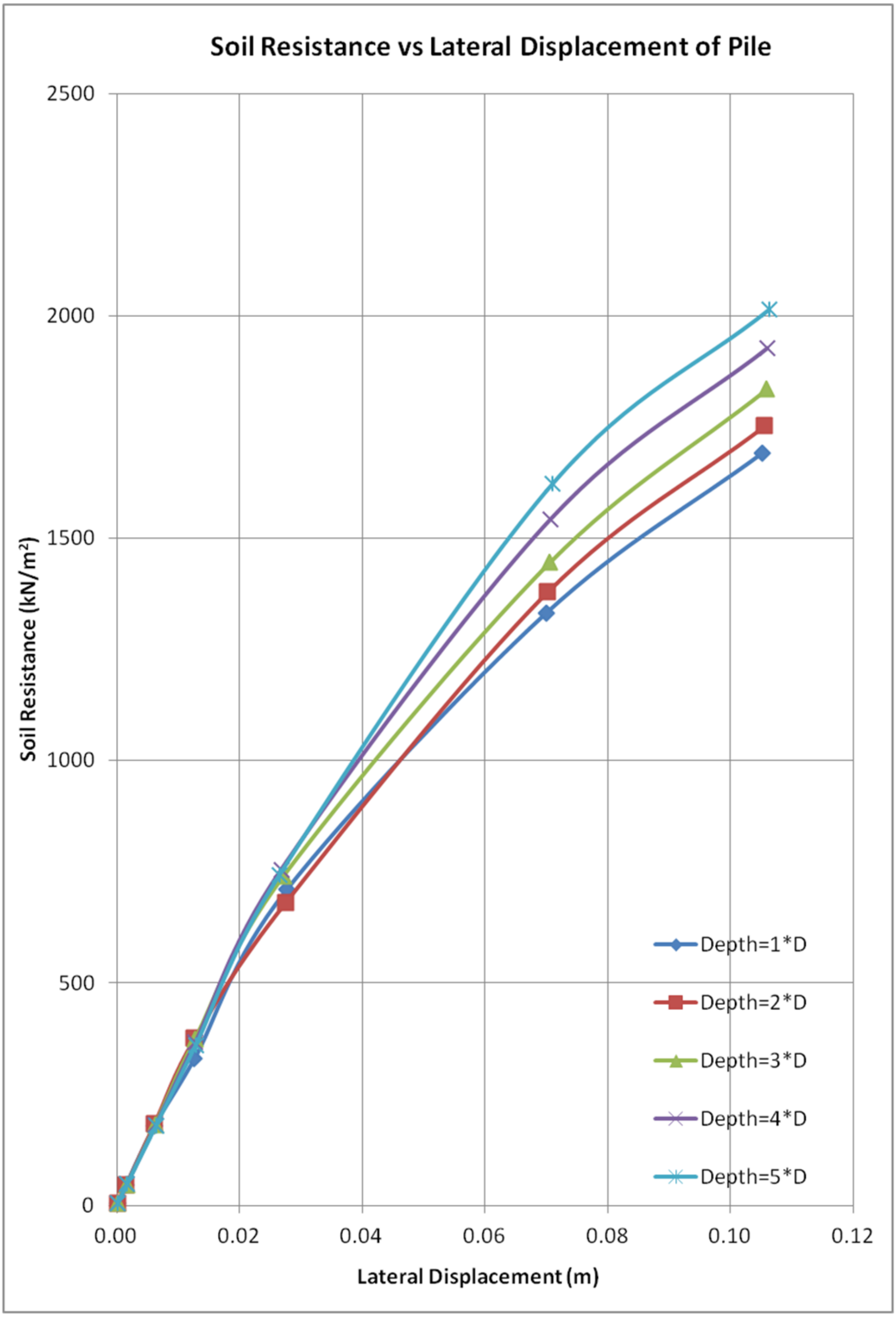

Figure 24: Soil Resistance vs. Lateral Displacement Curve for the Pile of 5m Diameter

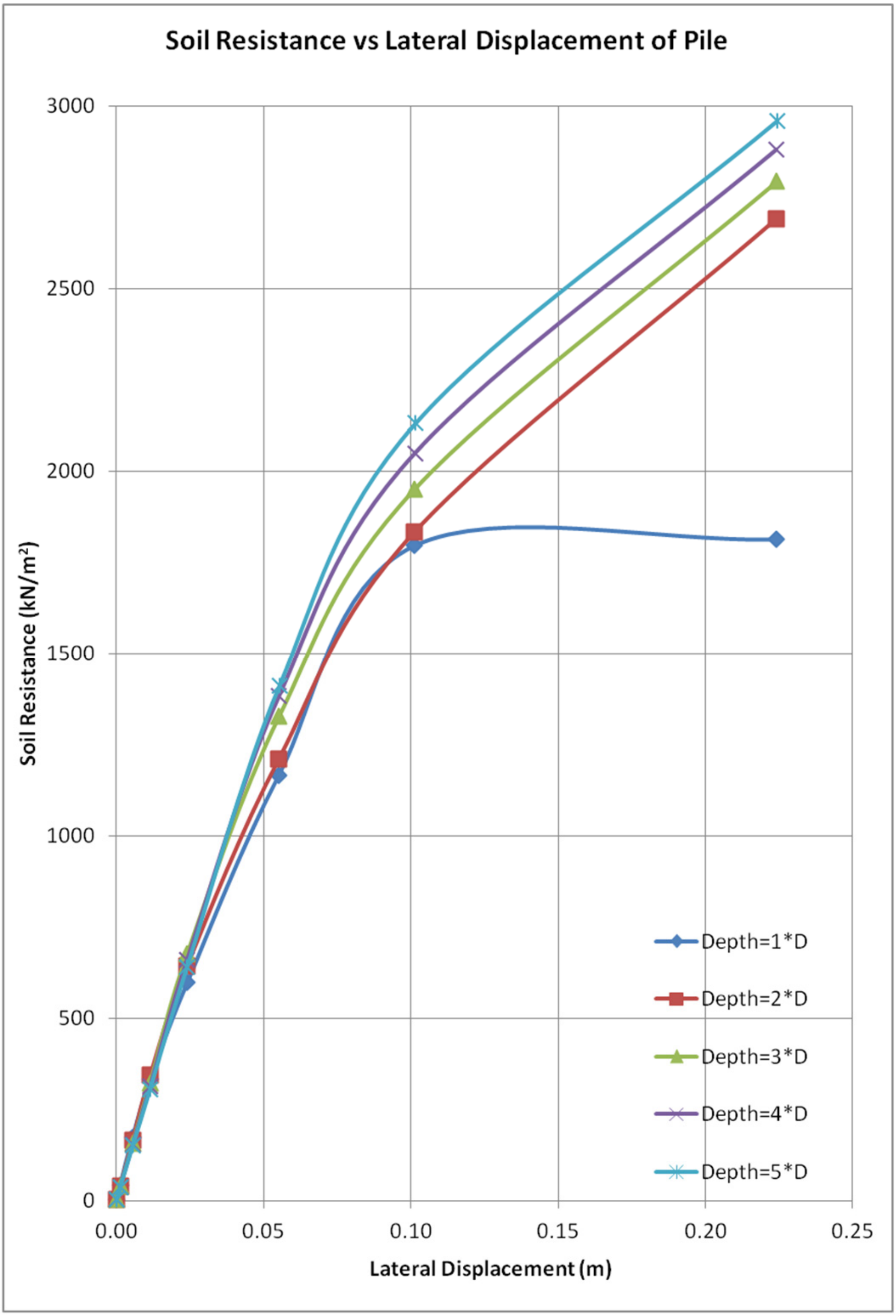

Figure 25: Soil Resistance vest Lateral Displacement Curve for the Pile of 6m Diameter

The **Figure 26** to **Figure 37** shows the comparison of soil resistance vs. lateral displacement curve developed using the result from FEM 3D Plaxis Foundation and the p-y curve based on the relation given by API code. P-y curve is plotted for the depth of approximately one times diameter of pile and five times diameter of the pile.

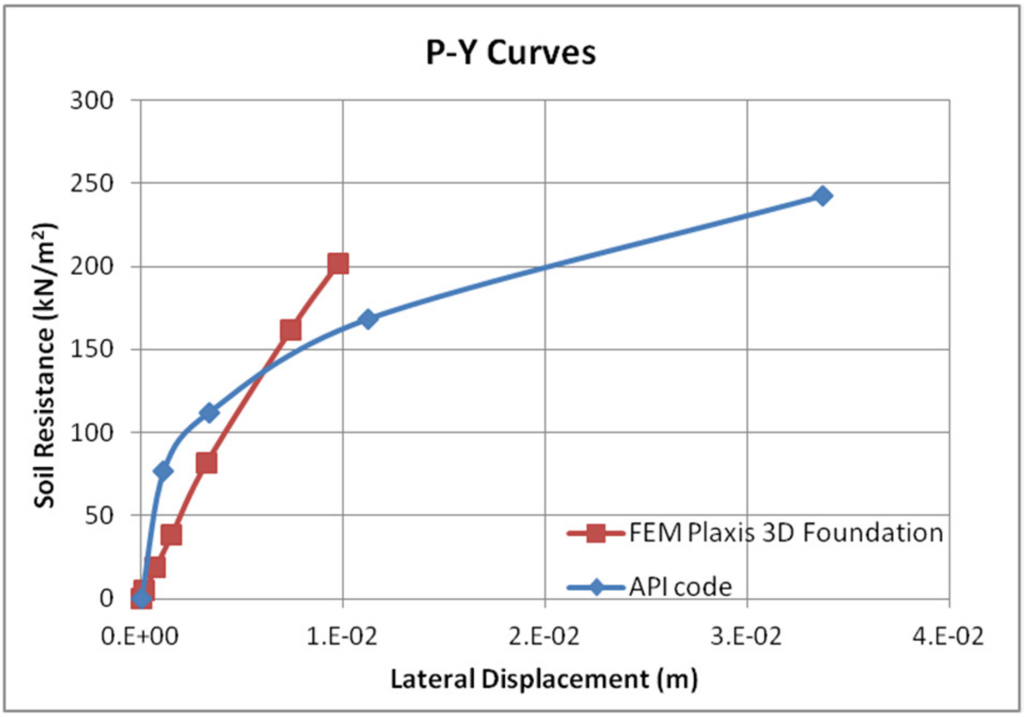

Figure 26: P-Y curves for the pile with 1m diameter at 1.05m depth

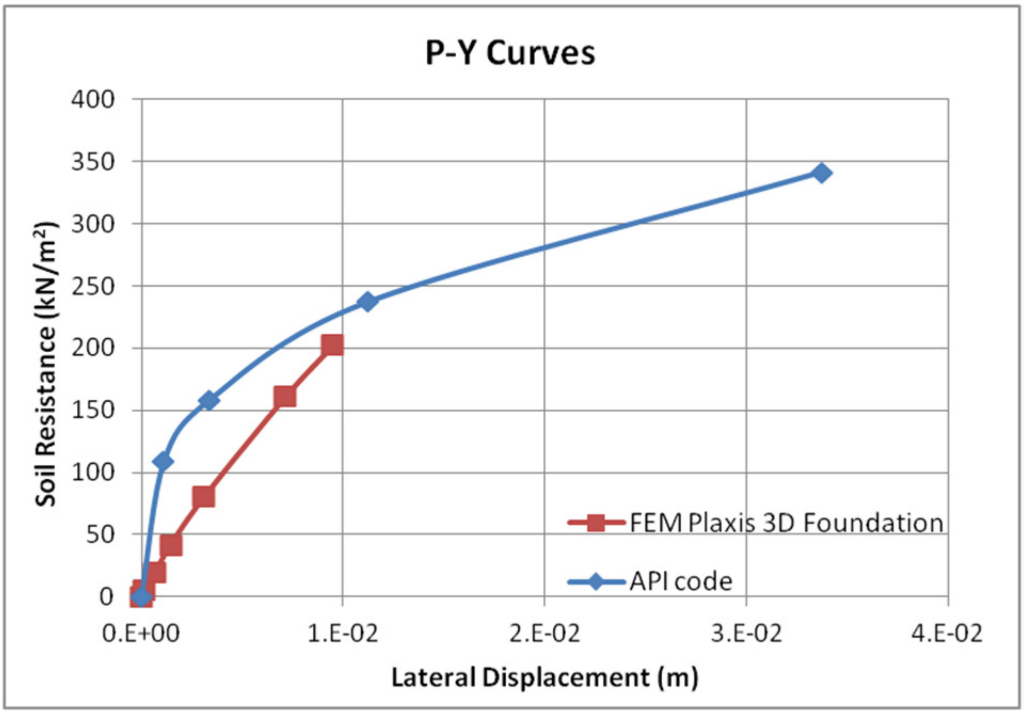

Figure 27: P-Y curves for the pile with 1m diameter at 5.0m depth

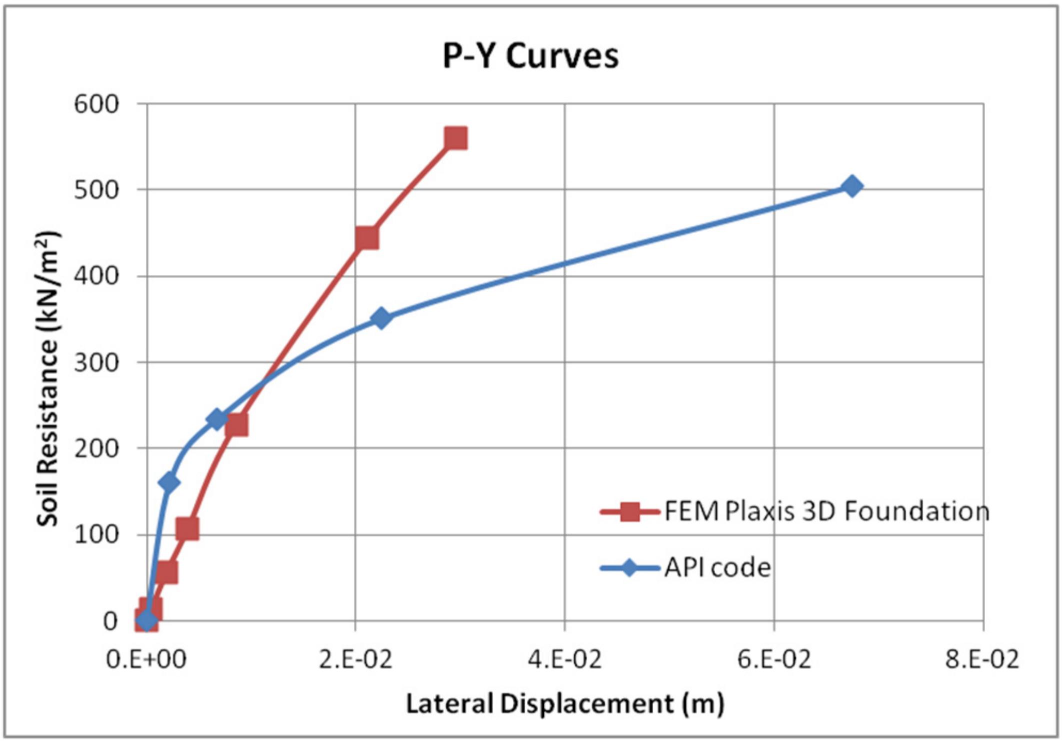

Figure 28: P-Y curves for the pile with 2m diameter at 2.25m depth

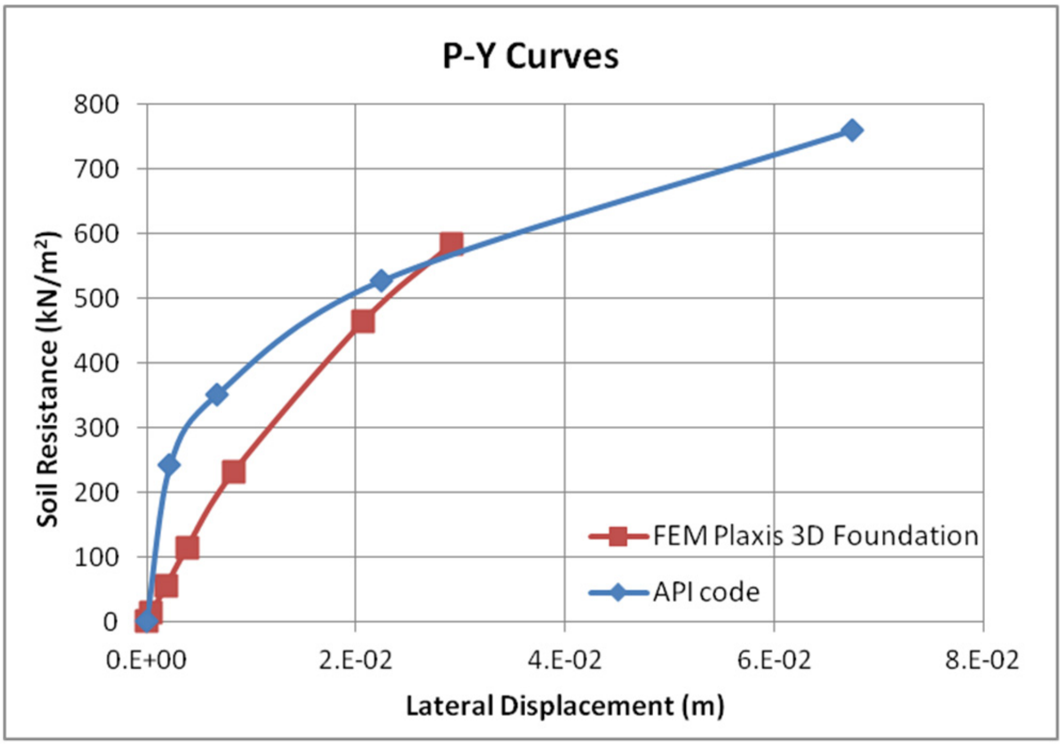

Figure 29: P-Y curves for the pile with 2m diameter at 10.13m depth

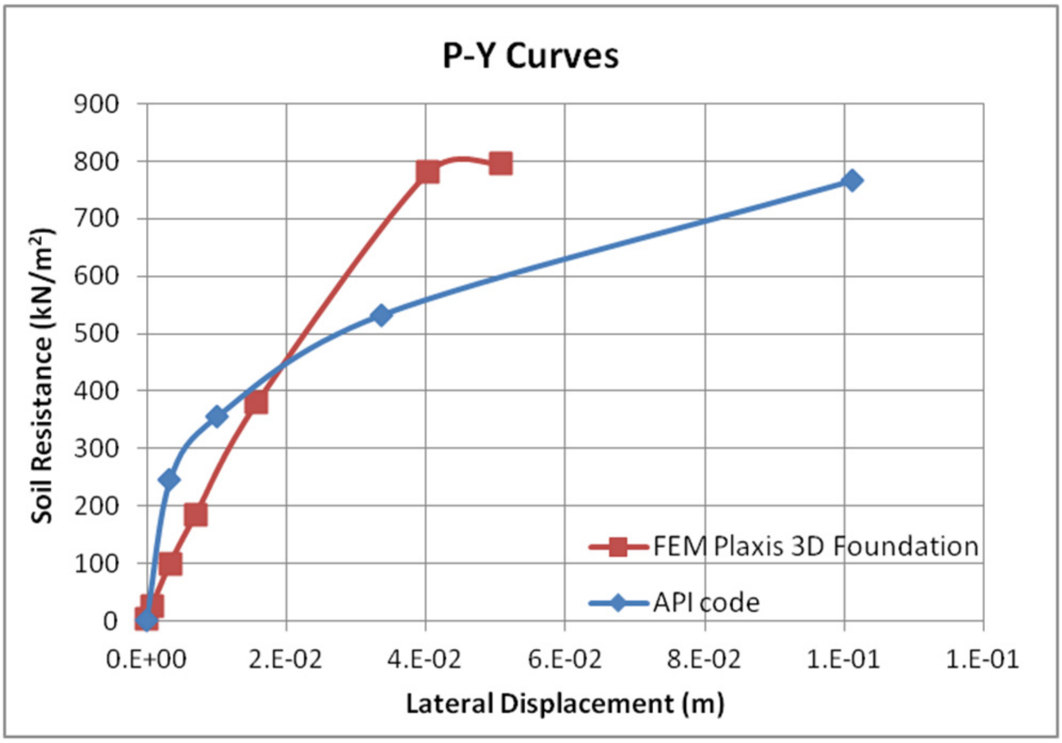

Figure 30: P-Y curves for the pile with 3m diameter at 3.0m depth

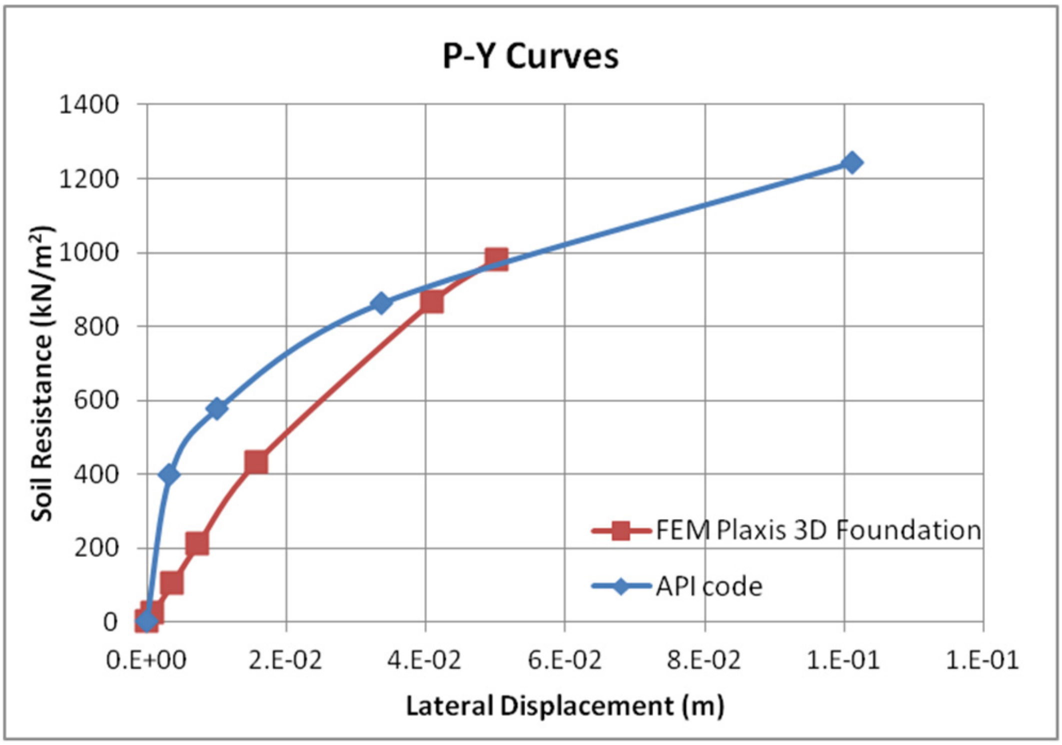

Figure 31: P-Y curves for the pile with 3m diameter at 15.0m depth

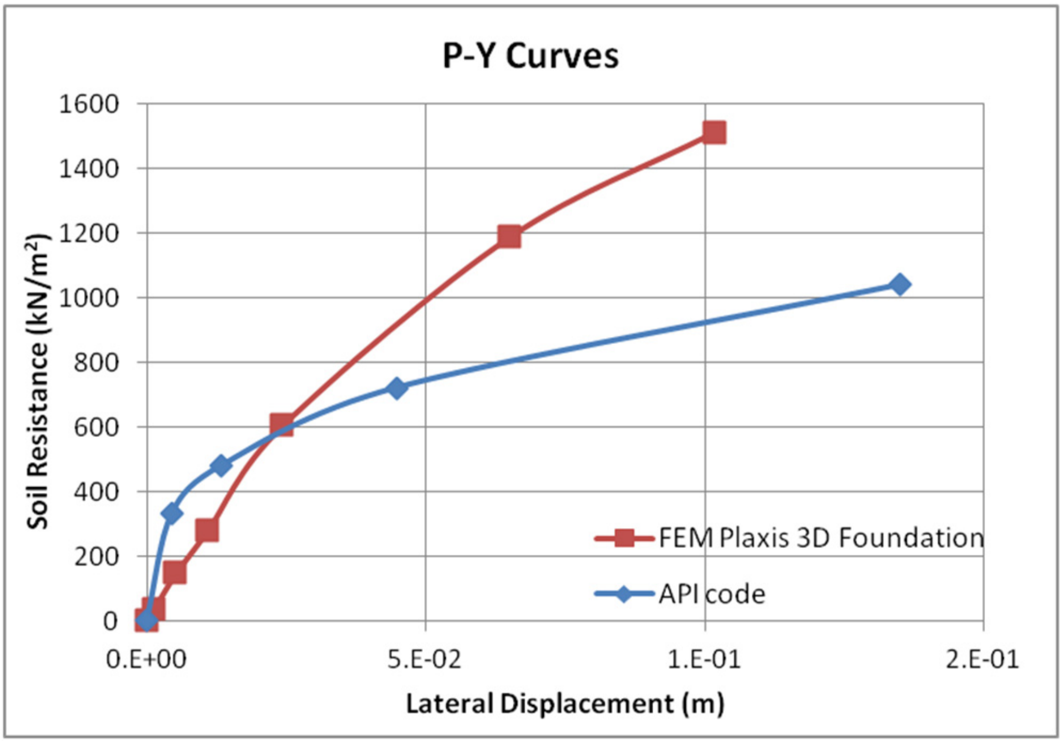

Figure 32: P-Y curves for the pile with 4m diameter at 3.75m depth

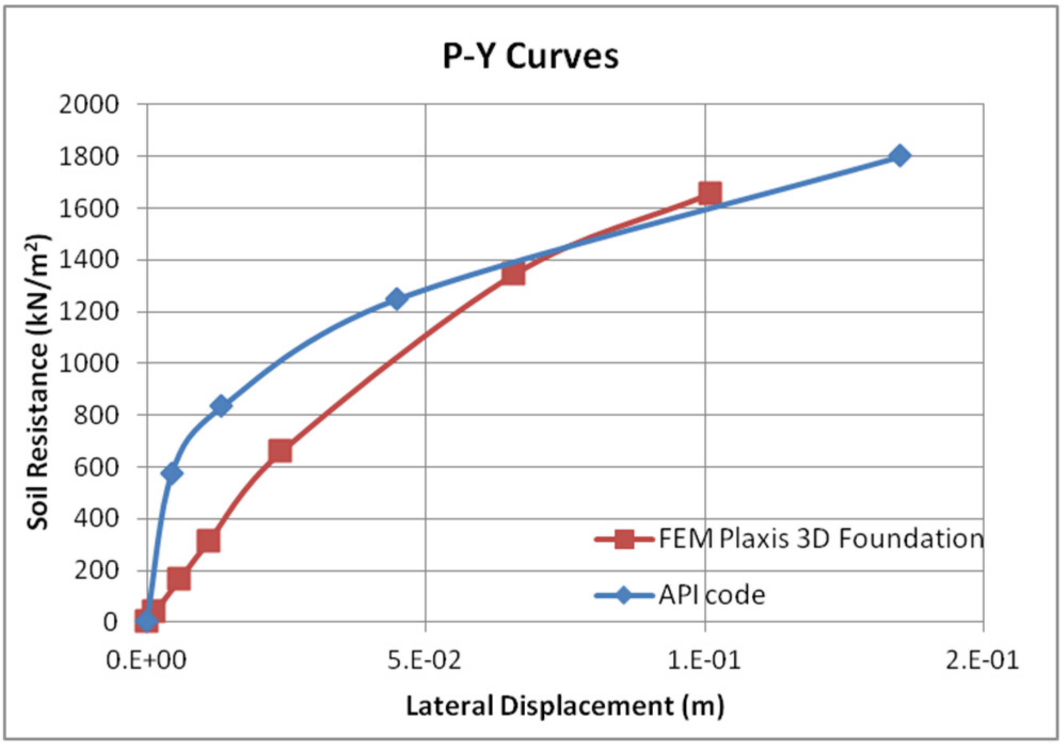

Figure 33: P-Y curves for the pile with 4m diameter at 20.0m depth

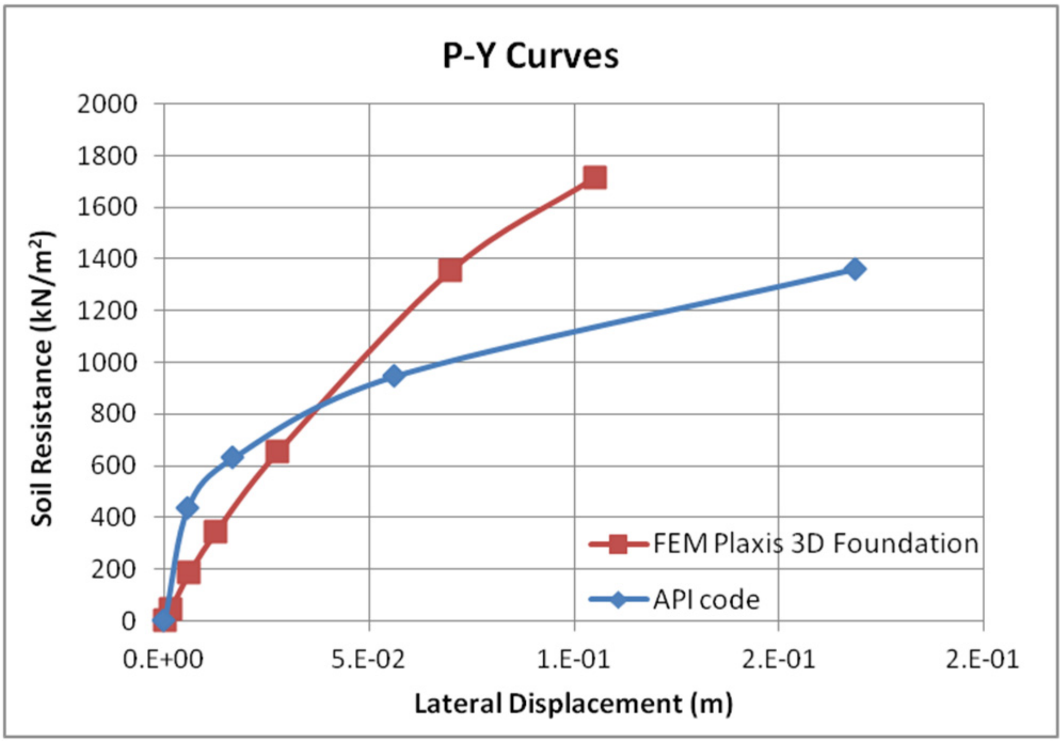

Figure 34: P-Y curves for the pile with 5m diameter at 5.25m depth

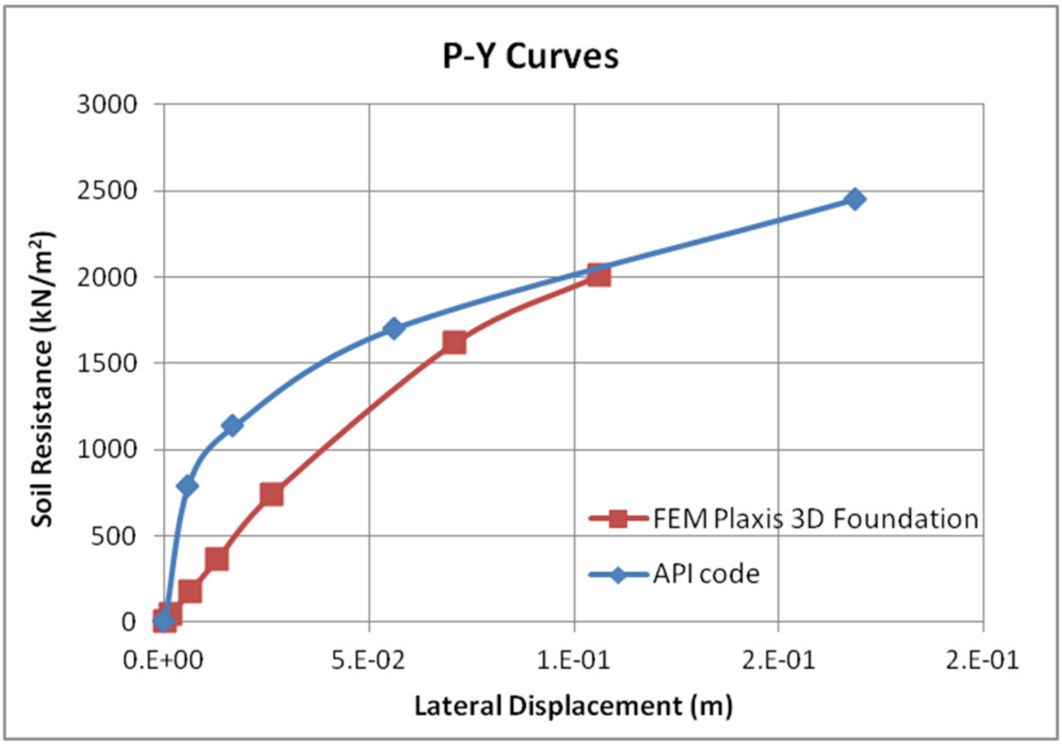

Figure 35: P-Y curves for the pile with 5m diameter at 25.38m depth

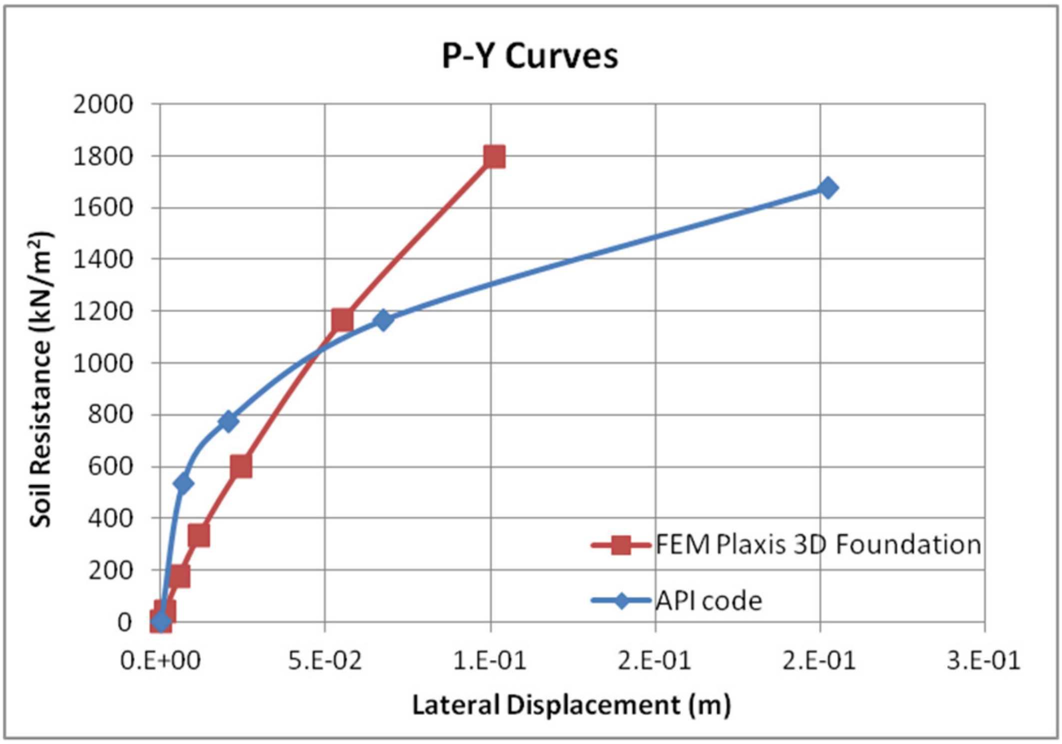

Figure 36: P-Y curves for the pile with 6m diameter at 6.25m depth

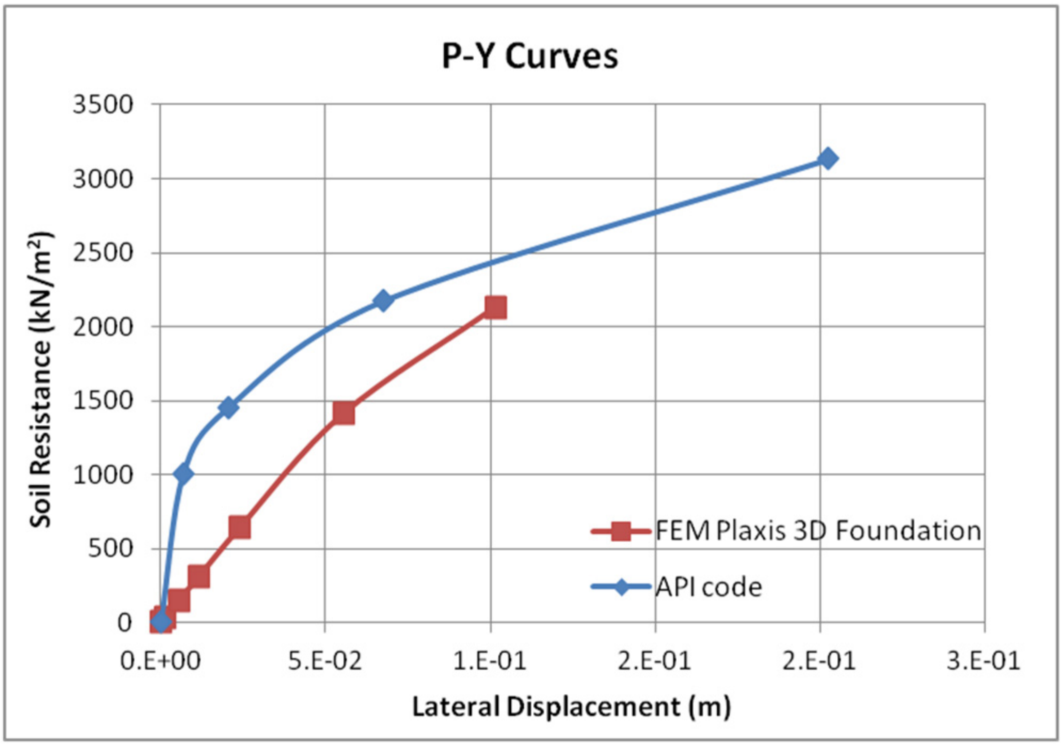

Figure 37: P-Y curves for the pile with 6m diameter at 30.0m depth

5. Discussion

The laterally loaded monopile with different pile diameters embedded into marine clay is modeled and analyzed in finite element model Plaxis 3D Foundation. The output from the program is used to develop the soil resistance–pile displacement curves and is compared with the p-y curve given by API code.

The soil resistance pile displacement curves do not reach the ultimate capacity for all load combination. To reach the ultimate capacity further loads can be applied. As the analysis takes a lot of time to reach ultimate stage and the study is focused in initial stiffness of soil, the analysis is not done for further load combinations.

The **Figure 20** to **Figure 25** shows the relation between the soil resistance and pile deflection for different pile diameter at various soil depths. The **Figure 20, Figure 21**, **Figure 23** and **Figure 24** indicate that the soil reaction is below the ultimate capacity. The initial part of the curve is almost linear.

But in the **Figure 22**, the p-y curve developed for the depth of 1*D and 2*D indicate the initiation of the failure of soil, but the p-y curve for depth 3*D, 4*D and 5*D is not reached in failure situation. Similarly in **Figure 25**, for the depth 1*D the soil reached to the ultimate capacity but for depth 2*D, 3*D, 4*D and 5*D soil is not reached to the ultimate capacity. This indicates that the soils have lower ultimate capacity at shallow depths and it increases gradually in greater depths. This is due to the wedge failure mode i.e. shallow depth failure of the soil. There is reduction on ultimate capacity of soil at depth of 1*D for the 3m diameter of pile. It is due to the softening of soil resulting from the initiation of failure at greater depth i.e. at depth of 2*D. The reduction of ultimate capacity of soil is not started at depth of 1*D for 6m pile diameter because the ultimate capacity of soil below this depth is not reached.

The **Figure 26** to **Figure 37** present the comparison of p-y curves obtained from FEM 3D Plaxis foundation and API code for different diameters of pile at 1*D and 5*D depth. The p-y curve plotted for the API code shows that the secant stiffness is very high in the initial segment of curve and reduced to very low value for the ultimate stage. But in p-y curve obtained from FEM 3D Plaxis, the secant stiffness is not changed significantly from initial segment to ultimate stage. The secant stiffness obtained from the FEM Plaxis 3D foundation is lower than that from API code for the initial part but greater at the larger displacement. Analytically the initial stiffness is approximately 4 times shear modulus (4*E/3 = 4*18750/3=25000) (Kodikara, Haque, & Lee, 2010), which is closer to the result obtained from analysis in Plaxis. This shows that the calculation from the Plaxis is relevant. This difference in stiffness from two methods may be due to the parameters that are selected to explain the soil properties in the model and analysis.

The pattern of the p-y curve is similar for all the diameter of pile. Referring **Table 12** to **Table 23**, the initial secant stiffness for all diameter of pile in almost same. This indicates that the influence pile diameter is not significant in the initial stiffness of the clay for the rigid pile.

The pattern of the curves for all diameter of pile is similar in both methods. But there is difference in curves. The project work (Appendix A.2) shows that the lateral displacement of the pile is almost same for both methods for small pile diameters, while the displacement from API code was greater in comparison to the FEM 3D Plaxis foundation result for larger pile diameter. This may be due to the rigidity of pile because large diameter pile behaves almost like rigid and the p-y curve for API code is actually derived from the results of flexible pile.

6. Conclusion

This thesis work is focused on the development of soil resistance –pile displacement curve and to evaluate the effect of diameter in the p-y curve of clay through FEM 3D Plaxis foundation modeling. To avoid the influence of the pile flexibility and pile rotation, lateral translation of rigid pile is analyzed. The p-y curve for different diameters of pile is developed based on the result from static loading of pile in 3D Plaxis foundation analysis and compared with the p-y curve given by API code. From this study the following results are concluded:

The initial stiffness of p-y curve from the FEM 3D Plaxis foundation analysis is very low in comparison to that given by API code. This may be due to the selected parameters for the soil model.

This study shows that the initial secant stiffness for all diameters of pile is almost same. This indicates that the influence of the pile diameter is not significant in the initial stiffness of p-y curve for the clay and rigid piles obtained from the FEM 3D Plaxis foundation analysis.

This study shows that there is difference in the p-y curve for all diameter of pile from two methods. The project work (Appendix A.2) shows that the lateral displacement of the pile is almost same for both methods for small pile diameters, while the displacement from API code was greater in comparison to the FEM 3D Plaxis foundation result for larger pile diameter.

The p-y curves developed from FEM 3D Plaxis need to be verified with some field test result for lager diameter.

7. References

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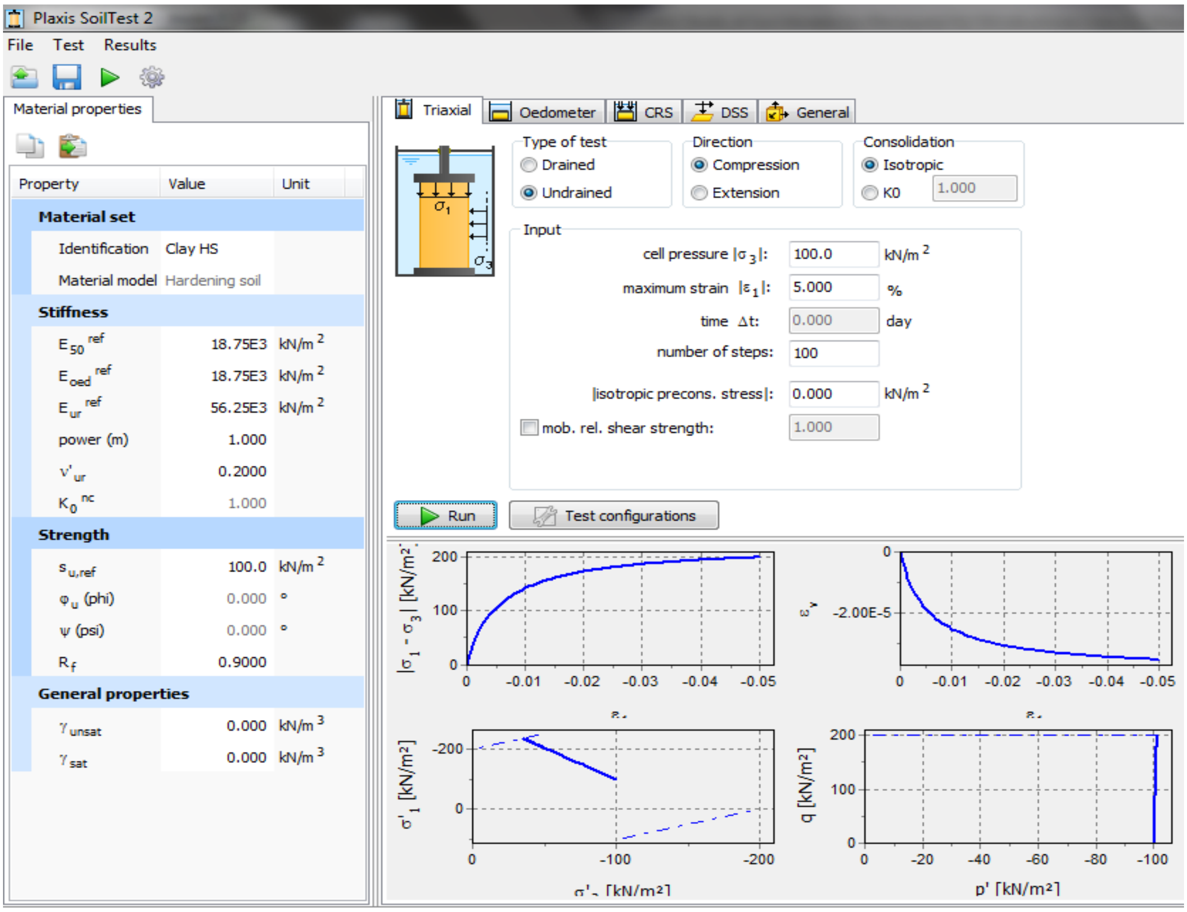
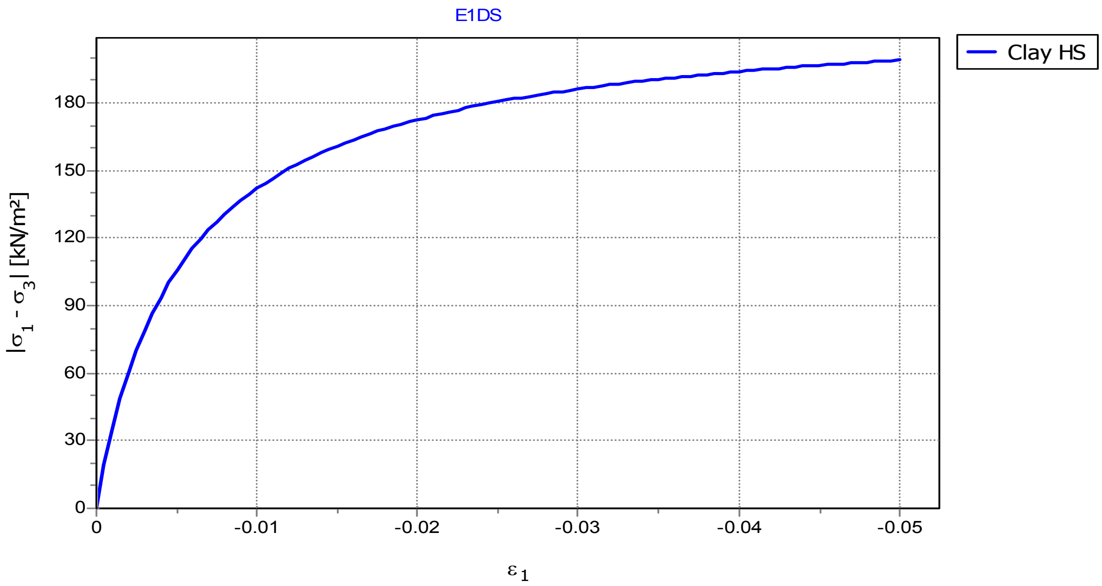
Appendices

A.1 Back calculation of HS soil parameter

Back calculation of HS soil parameter based on undrained Shear strength and Strain at half maximum strength using FEM Plaxis soil test.





A.2 Result from project work

During the project work the pile with diameters 2.5m and embedded length 30m and 5m, 6m and 7m with embedded length of 20m, 30m and 40m were analyzed in SPLICE (Geosuite2010) and FEM Plaxis 3D Foundation.

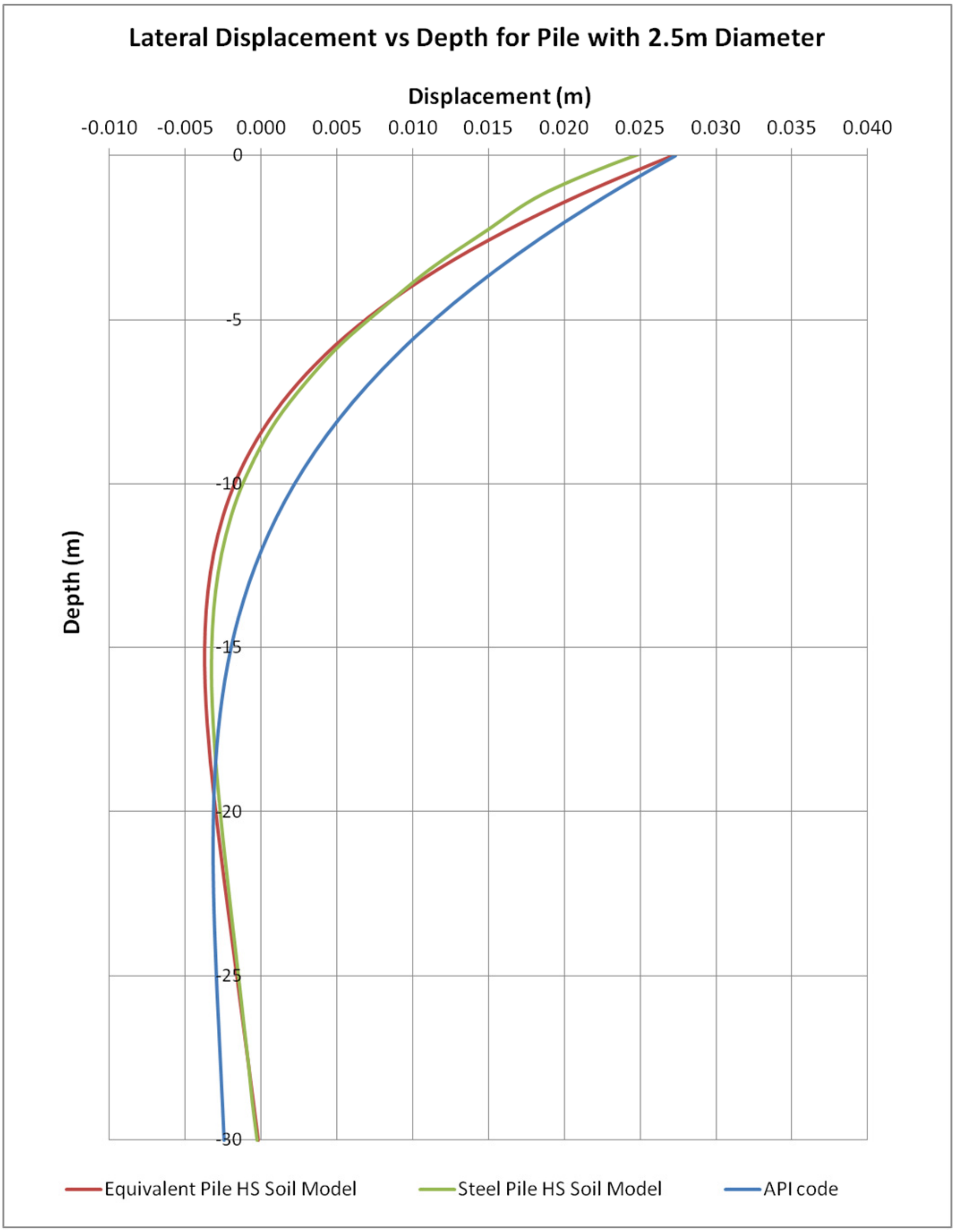
Calculation of Lateral displacement of pile using FEM Plaxis3D Foundation with following combination of soil-pile model is done.

- Equivalent Pile with HS soil Model
- Equivalent Pile with MC soil Model
- Steel Pile with HS soil Model
- Steel Pile with MC soil Model

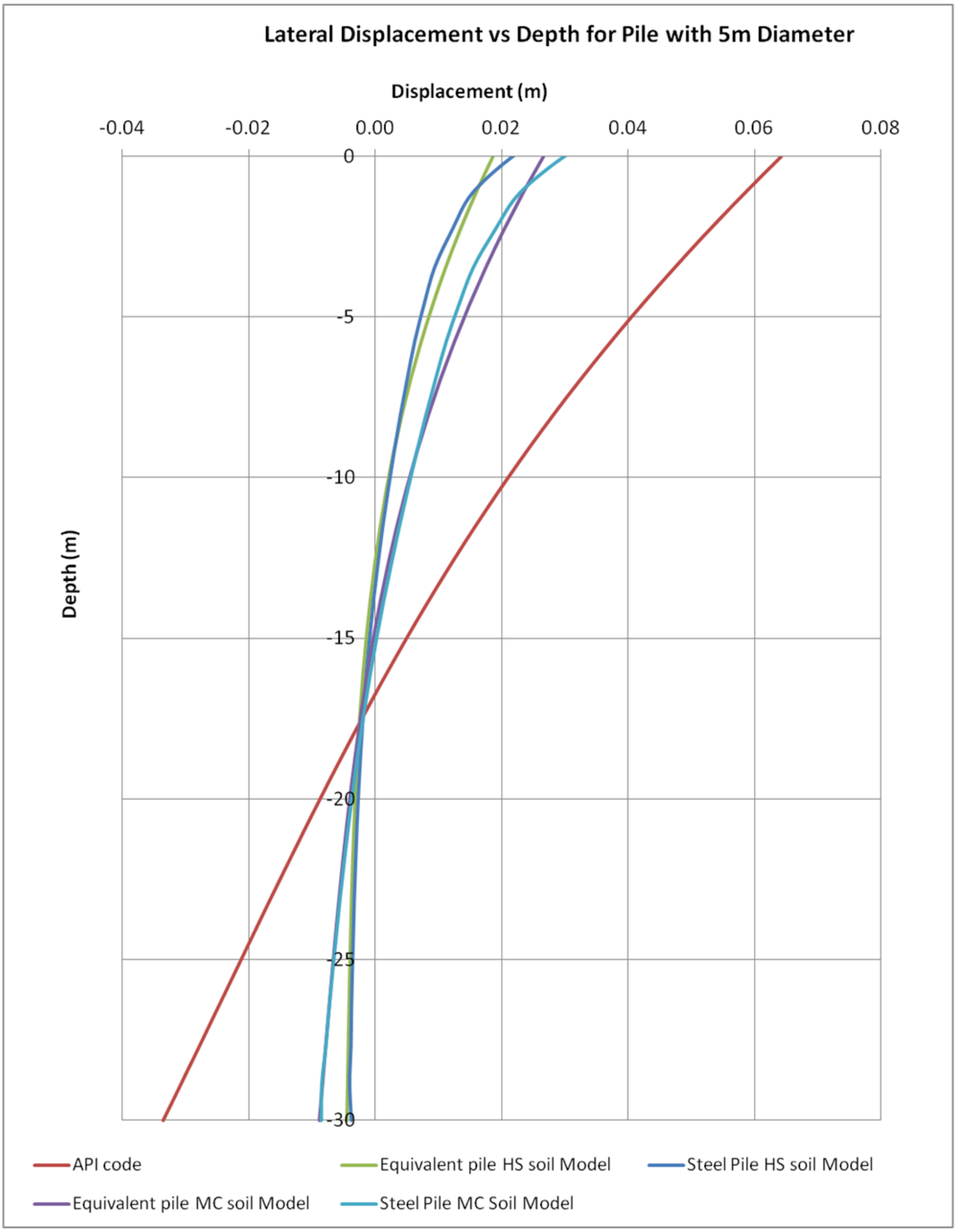
The comparison of lateral displacement of pile calculated using API code (SPLICE, Geosuite 2010) and FEM 3D Plaxis Foundation are presented below for:

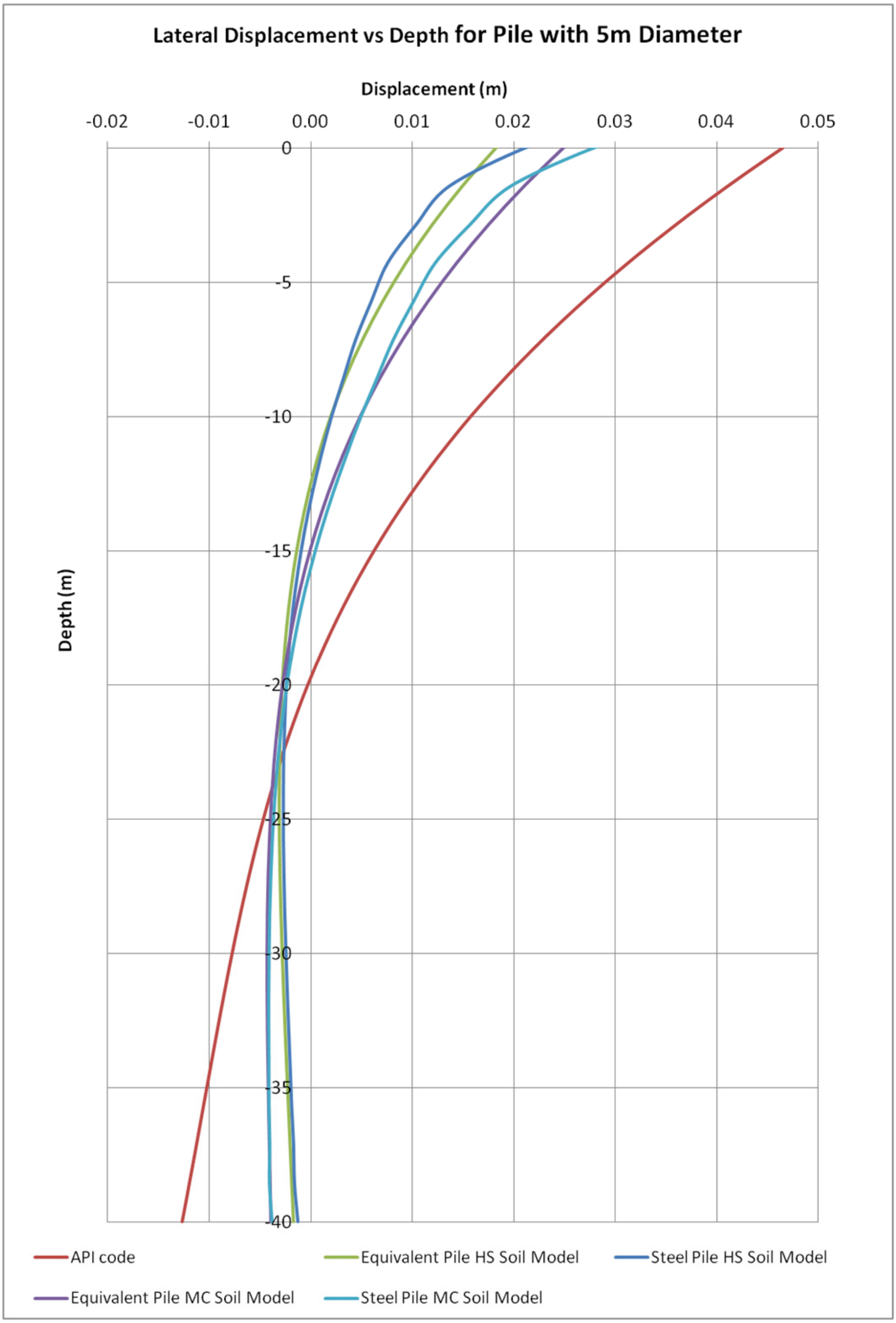
- 2.5m Pile diameter and 30m embedded length
- 5.0m Pile diameter and 30m embedded length
- 5.0m Pile diameter and 40m embedded length
- 6.0m Pile diameter and 20m embedded length
- 6.0m Pile diameter and 30m embedded length
- 6.0m Pile diameter and 40m embedded length

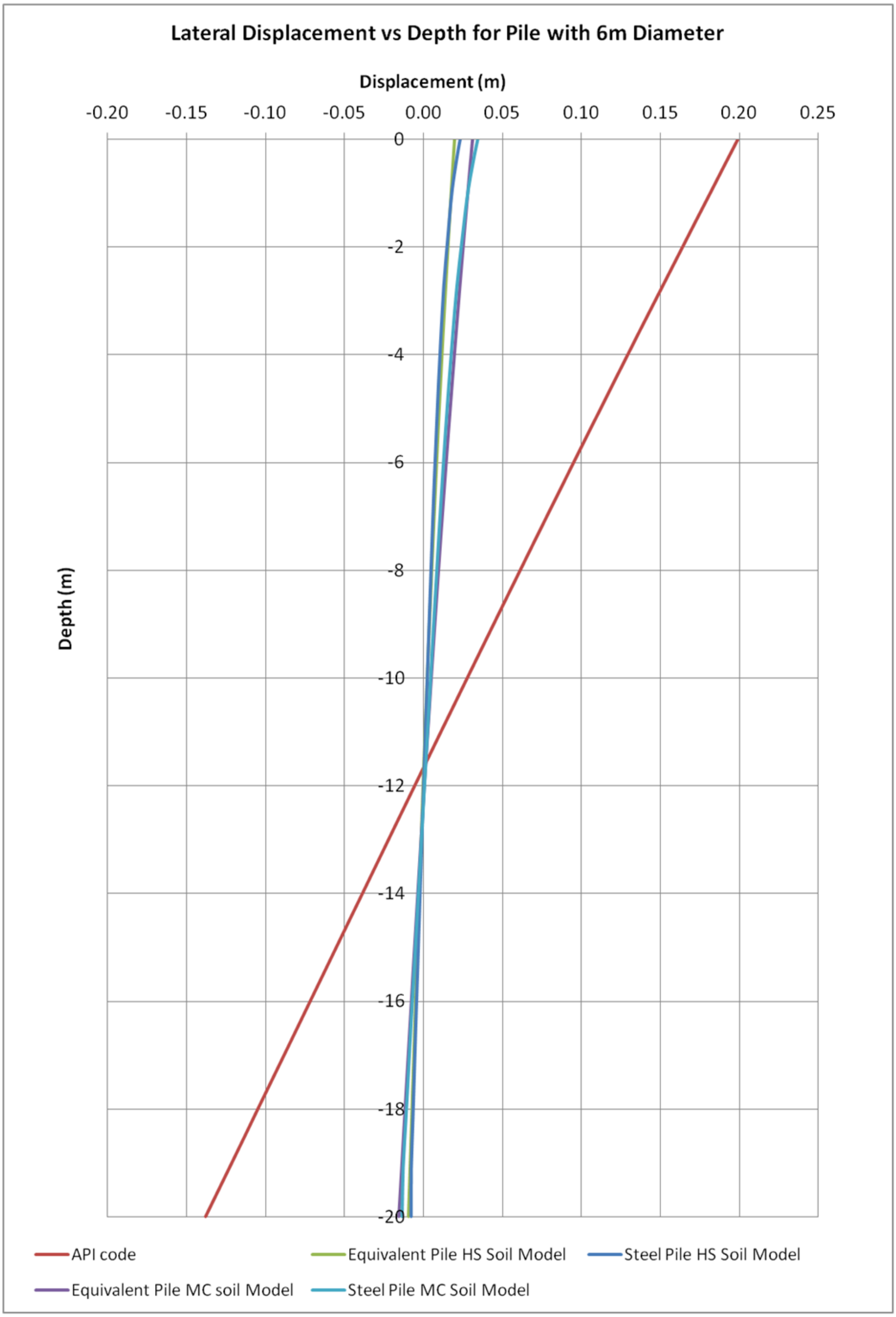
The result shows that the lateral displacement of the monopile calculated using API code and FEM 3D Plaxis Foundation is almost same for small diameter monopiles. But for larger diameter monopile the lateral displacement calculated from API codes is higher in comparison to result obtained from FEM 3D Plaxis Foundation. This indicates that the API code is only useful for the analysis of small diameter slender monopiles and needs further research to use it in the analysis of larger diameter monopiles.

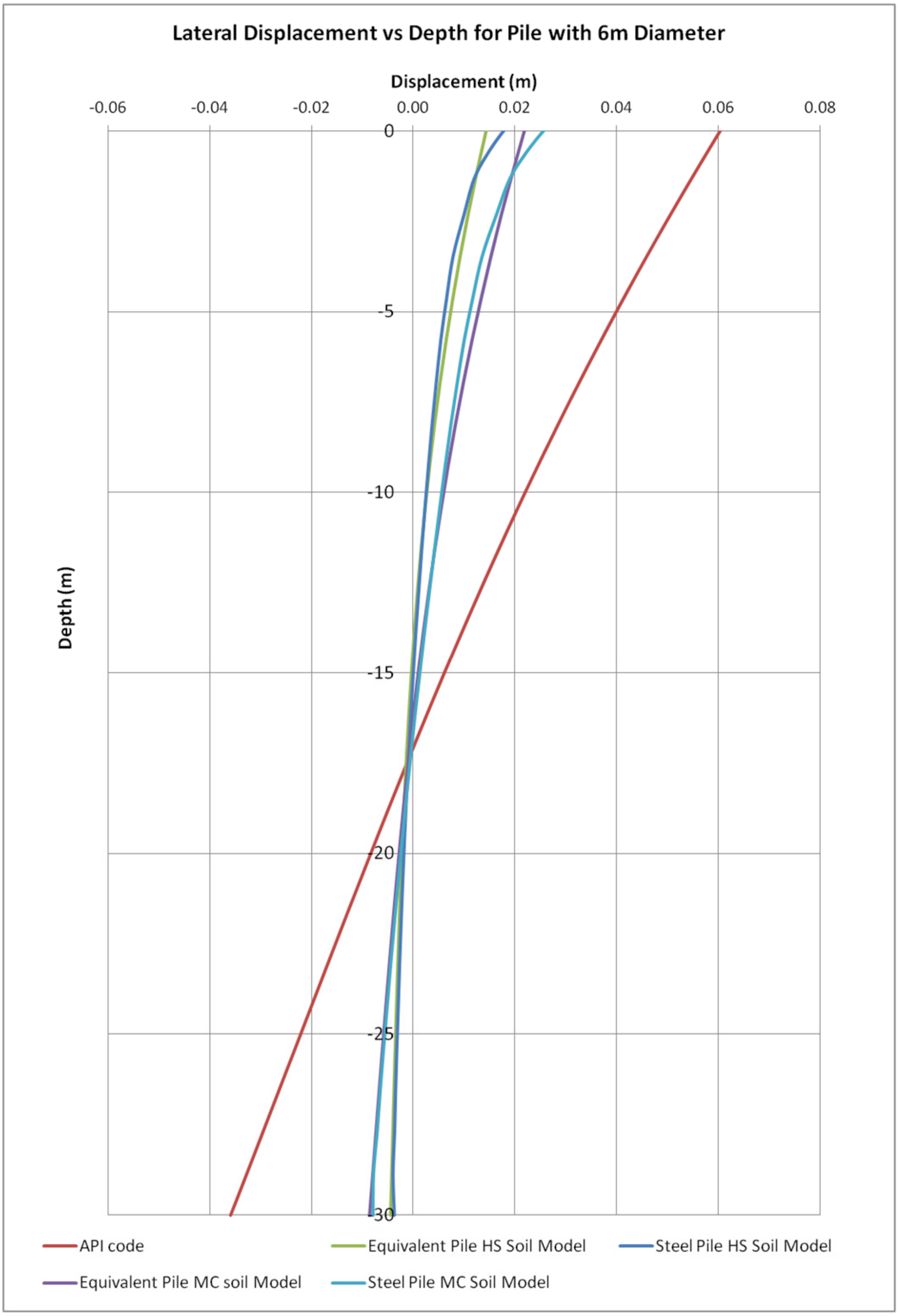


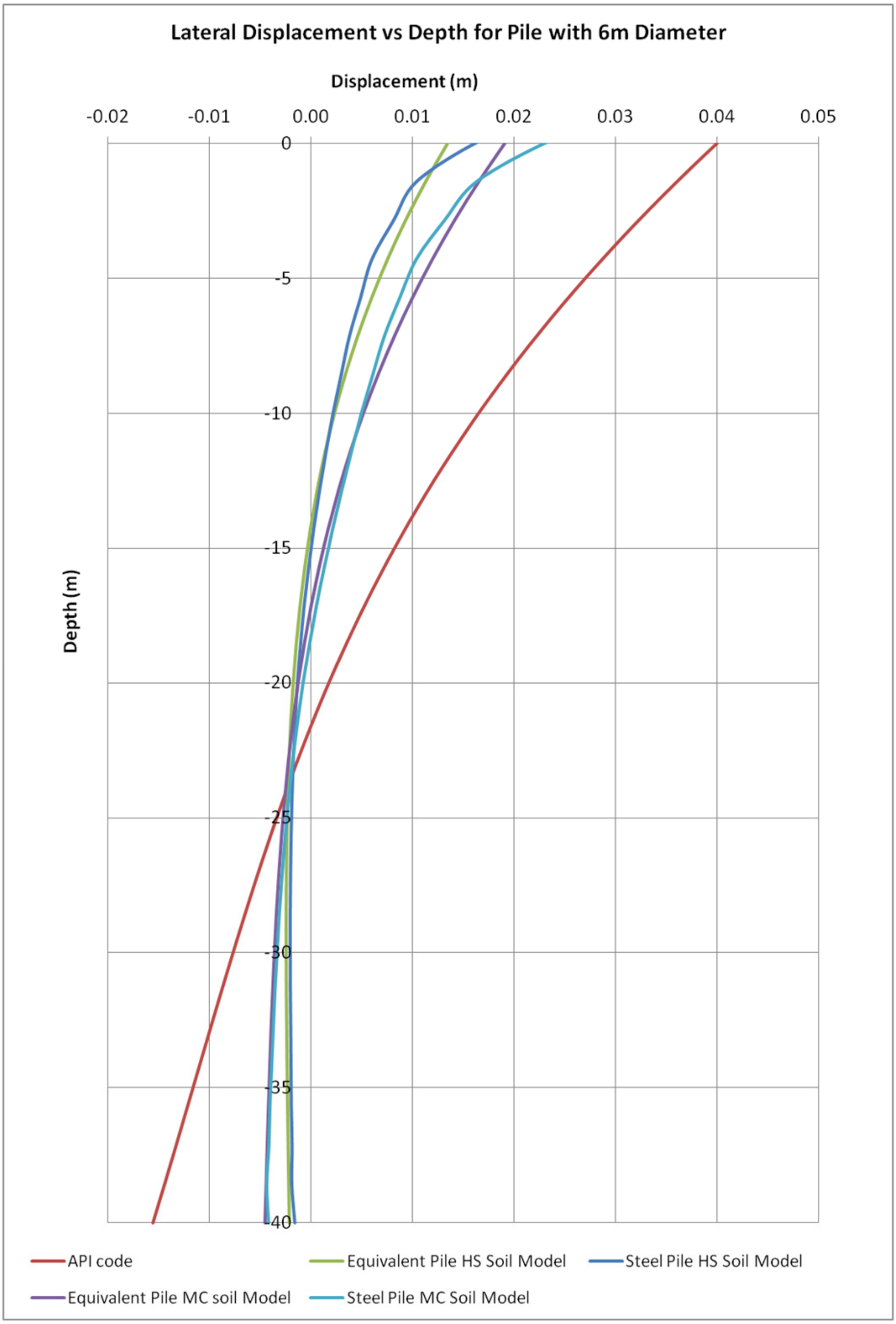
Lateral Displacement vs Depth for Pile with 2.5m Diameter
Displacement (m)
-0.010
-0.005
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
Depth (m)
0
-5
-10
-15
-20
-25
-30
Equivalent Pile HS Soil Model
Steel Pile HS Soil Model
API code


Lateral Displacement vs Depth for Pile with 5m Diameter
Displacement (m)
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
Depth (m)
0
-5
-10
-15
-20
-25
-30
API code
Equivalent pile HS soil Model
Steel Pile HS soil Model
Equivalent pile MC soil Model
Steel Pile MC Soil Model


Lateral Displacement vs Depth for Pile with 5m Diameter
Displacement (m)
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
0
-5
-10
-15
-20
-25
-30
-35
-40
Depth (m)
API code
Equivalent Pile HS Soil Model
Steel Pile HS Soil Model
Equivalent Pile MC Soil Model
Steel Pile MC Soil Model


Lateral Displacement vs Depth for Pile with 6m Diameter
Displacement (m)
-0.20
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
Depth (m)
API code
Equivalent Pile HS Soil Model
Steel Pile HS Soil Model
Equivalent Pile MC soil Model
Steel Pile MC Soil Model


Lateral Displacement vs Depth for Pile with 6m Diameter
Displacement (m)
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0
-5
-10
-15
-20
-25
-30
Depth (m)
API code
Equivalent Pile HS Soil Model
Steel Pile HS Soil Model
Equivalent Pile MC soil Model
Steel Pile MC Soil Model


Lateral Displacement vs Depth for Pile with 6m Diameter
Displacement (m)
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
0
-5
-10
-15
-20
-25
-30
-35
-40
Depth (m)
API code
Equivalent Pile HS Soil Model
Steel Pile HS Soil Model
Equivalent Pile MC soil Model
Steel Pile MC Soil Model