Analysis of Monopile Foundation for Offshore Wind Turbine

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Analysis of Monopile Foundation for Offshore Wind Turbine

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By

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based on research carried out

under the supervision of

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Supervisors' Certificate

This is to certify that the work presented in the dissertation entitled *"Analysis of Monopile Foundation for Offshore Wind Turbine"* submitted by *Anoop Kumar Tiwari*, Roll Number 214CE1047, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of *Master of Technology* in *Civil Engineering (Geotechnical Engineering)*. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

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(Anoop Kumar Tiwari)

Declaration of Originality

I, *Anoop Kumar Tiwari*, Roll Number *214CE1047* hereby declare that this dissertation entitled *"Analysis Of Monopile Foundation for Offshore Wind Turbine"* presents my original work carried out as a Master student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference" or "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in the case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 25, 2016

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ABSTRACT

Load deformation characteristics of monopile are being analyzed in the project. As monopile is a supporting structure for offshore wind turbines. Due to varying environmental conditions exact prediction of load value is not possible but it is important to analyze the load vs deformation relationships to see the behavior of monopile. Monopile structure is subjected to wave, wind load and vertical load for the analysis wave are taken to sinusoidal in nature. The p-y method indicates that the design code recommended p-y curves overestimate for the case of large diameter monopiles the initial stiffness and underestimate the ultimate bearing capacity. When applying the recommended p-y curves as linear springs in a 2D Winkler beam model, the global response of monopole can be calculated regarding load and applied displacement. It is about response based analysis, in which the failure load is being derived from the model developed in MATLAB. In FEM using Abaqus and PLAXIS 3D lateral deflection of the monopile is being seen to visualize the effect of the static lateral load as well as dynamic lateral load with and without vertical loadings. To compare the analysis methods reliability is being calculated using response surface and first order method and the probability of failure is being calculated.

Keywords: Monopile; Winkler Beam model; Probability of failure; FEM modeling

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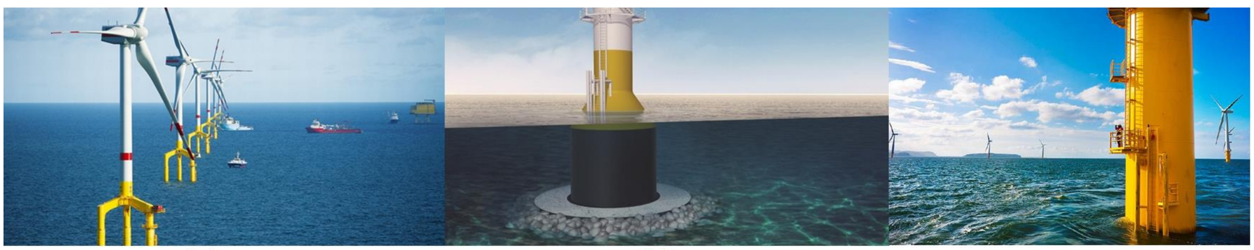
CHAPTER-1

1 INTRODUCTION

1.1 General

Offshore wind energy projects are going to most important part of energy supply in nearest future. It is proving to be a good option to optimize the use of non-renewable recourses of energy. Some offshore wind energy projects are already being installed in countries like Germany, China, Denmark, etc. these projects reduces the pressure on thermal power plants and hydro-electric plants. It is proving to be ecological also as only in UK 925,000 tons of CO_2 is being reduced. Onshore wind energy has also proved its importance and gain a vital recommendation because of certain remedies like noise problem and visibility effects its growth rate is quite low. With the availability of huge area and constant wind current which further increases with distance from shore and less wind fluctuation, offshore wind projects seem to be justified. Foundations other than monopole can also be used for supporting the structure. There are three optional foundation types which can be used. Gravity foundation which is being designed with consideration to avoid the tensile load on supporting structure for achieving this condition sufficient dead weight load is being provided to avoid bending effects which constituted both compressive and tensile force. Tripod Foundation is a steel spatial framed structure transfers the load along the legs of tripod through hollow steel pile. In comparison to the diameter of the monopile they are of small diameter. Among some offshore wind energy projects, one has located in the North Sea and Baltic Sea with a power output of 2MW. These structures are situated at a moderate water depth of 8m, and a smaller distance from the seashore and all these are on monopole foundation. Increasing rate of installation of monopile is because of the simplicity of load transfer mechanism. Analysis of monopile is important as this foundation is going to installed in one of the harshest conditions, the variability of soil is unpredictable in sea and wave, and wind loading has to be sustained along with lateral and axial loads. For the analysis of monopile foundations, API suggested p-y curve is being used its results are not so good when we are analyzing pile diameter of more than 2m. With the uncertainty in the soil conditions and its behavior the prediction of structural response is a hilarious task. Monopile is installed up the water depth of 30m. Most important extent for the analysis monopile behaviors is to get load vs displacement behavior of monopile as along with vertical load it is subjected to lateral loads. Now a day's large diameter monopiles are being used to support larger lateral loadings. The diameter of monopile may be of 4m to 7.5 and embedment depth of 24-30m depending upon soil and loading conditions. Presently the p-y curve is being constructed by pile load test on instrumented pile and strength characteristics of soil beneath the sea level. The analysis methods commonly being used for p-y curve are based on approaches of Reese et al. 1974 and approach by Matlock, 1970 where p-y curve represents lateral load vs displacement.



(a) (b) (c)

Figure 1.1Types of offshore Foundations (a) tripod foundation, (b) gravity foundation and (c) monopole foundation

At seas, the dominating loads are lateral loading and corresponding bending moment from wind and waves. The foundation should be able to carry the loads without causing unacceptable deformations. The most widely used method of calculating laterally loaded piles is the so-called p-y method. Lately, the reliability of the method has been questioned. The main reason is that monopiles originally was used by the petroleum industry in the founding of fixed offshore platforms. Therefore, the p-y method is developed for another type of piles, then the ones used in wind turbine foundation. Monopiles used in wind turbine foundation are often short rigid piles whereas piles used in platform foundations often are long and slender. The monopile structure has to be highly reliable to with stand the non-linear loadings. Some studies have been performed considering the reliability approach. Uncertainties related to this analysis is being of two types one is uncertainty I the consideration of loads and uncertainty related to the stiffness of the material. The consideration of uncertainty of load is because of the a) natural randomness associated with environmental factors such as wind, waves, and current b) model uncertainty which is due to in actual condition monopile is in a state of are-hydro-dynamic condition simulation of such a model is not possible. Strength-related uncertainty is because of natural randomness of the behavior of the materials is in this case soil.

1.2 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 on 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 the plastic flow of the soil around the pile as it deflects laterally (Randolph & Susan, 2011). The depth at which these two failure mechanisms predict the same ultimate soil resistance is known as critical depth (Zcr). The ultimate soil resistance up to critical depth varies with depth but below critical depth, it is taken constantly. The two failure mechanisms are

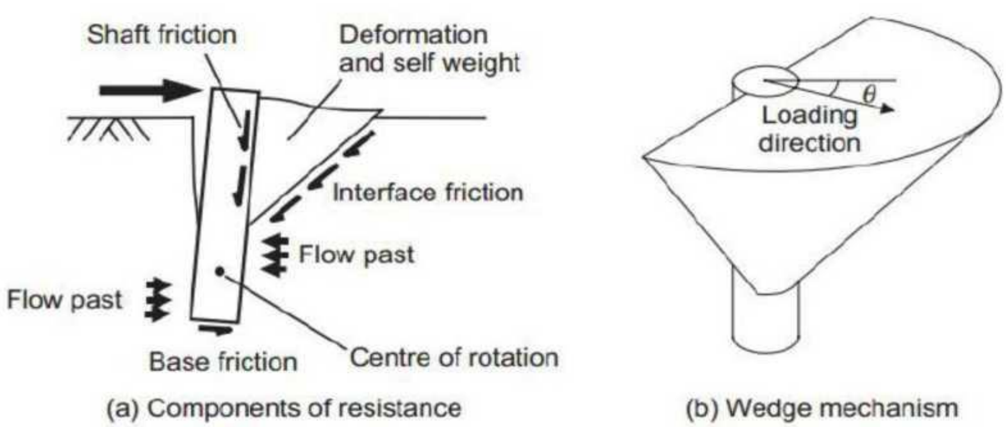


Figure 1.2Failure mechanisms of sand on lateral loading

CHAPTER-2

2 REVIEW OF LITERATURE & METHODOLOGY

2.1 Literature review

There are various exploration papers distributed on analysis of offshore wind energy foundation and reliability considerations [1] has analyzed the behavior of monopile foundations under consideration of lateral load due to wind and wave actions a nonlinear elastoplastic behavior of soil is being considered using Abaqus model and compared it with p-y curve method which is most commonly used for monopile designing works and has concluded that the p-y method proposed by API(2000) has underestimated the deformation characteristics and its validity with larger diameter are under question. [2] uses Abaqus model for the analysis of monopile on cyclic loading for the simulation of soil modal and stress dependency oedometric stiffness modules is being considered along with Mohr–Coulomb failure criterion is taken into consideration. Also determined the variation of displacement at seabed level along with some load cycles and predicted design chart. [3] using the stochastic model they proposed the reliability of monopile foundation for lateral load due to wave and wind load along with uncertainties related to soil loading. Using MATLAB, FAST he investigated the reliability related to soil uncertainty and also found the effect of mode shape using time history dynamic analysis. [4] proposed the efficiency of API p-y curve by conducting static pile and p-y experiments and also compared it with FEM results and found that API p-y curve is not feasible for diameter more than 2m. [5] proposed SBFEM model to investigate monopile behavior under wave loading SBFEM model is being used as it provides solutions in radial directions and found that lateral deflection of monopile is increasing with increasing in wave number, amplitude and with water depth. [6] has compared the p-y curve based on API and based on FEM results for sand and clay on a laterally loaded monopile and also compared the lateral stiffness of the structure. (Singh 2013) proposed FEM model for lateral load vs displacement analysis of monopile for the realistic behavior of soil-pile interaction he used the elastoplastic model in ABAQUS using interaction property he used master-slave interaction and calculated maximum deflection by varying l/d ratio and pile length. [8] performed dynamic analysis on monopile foundation and calculated the response of the structure by applying aerodynamic and hydrodynamic load on monopile foundation using FEM model.

They also considered the variation of the p-y curve along with p-t curve proposed by API. They found that soft-soft design is feasible for the 2MW project but for 5MW project it is infeasible and concluded that soft- stiff design for 2MW project is based on SLS criteria and resonance condition whereas for 5MW projects it is based on SLS as well as fatigue criterion. [9] a series of shake table testes has been performed by him to simulate earthquake, wave action and wind effects on dry low and moderate water conditions. The main preference they have given to nacelle acceleration which could produce high ground motion and random waves.[10] a comparison between different methods of determining bearing capacity has been performed.

As it is a very difficult task to choose the exact method for designing purpose hence a comparison between field results are also being shown by them. [11] they worked on uncertainties related to long-term effects on monopile foundation which are based on thousands of wave and wind current effects they derived a method to simulated any complex wave loading to see term load effect on monopile and its lateral behavior. [12] investigated stiffness to elastic response of soil and monopile model. Some stiffness models have been taken into consideration which are basically based on Winkler' model. For the purpose of calculation of small stress-strain respond of monopile on dynamic loading.[13] calculated head displacement of pile based on numerical approaches taken into consideration that multilayer homogeneous soil is linearly elastic in nature. For the calculation of pile head displacement and rotation, virtual work principle is being used. The equilibrium conditions which are taken into consideration one is for head displacement and pile rotation, and another one is for soil-pile interaction.

2.2 Literature Gap

All these research works have taken into consideration of monopile either for lateral load or vertical load. They haven't considered lateral as well as vertical load consideration of moment caused by lateral load due to wave action is missing. Dynamic load consideration along with vertical load is also missing. Comparison between linearly elastic behavior and Mohr–Coulomb failure criterion has not taken into consideration for such case of loading conditions which has to be investigated. Variation of deflection along with embedment depth in case of dynamic load is also not taken into consideration.

2.3 Problem Formulation

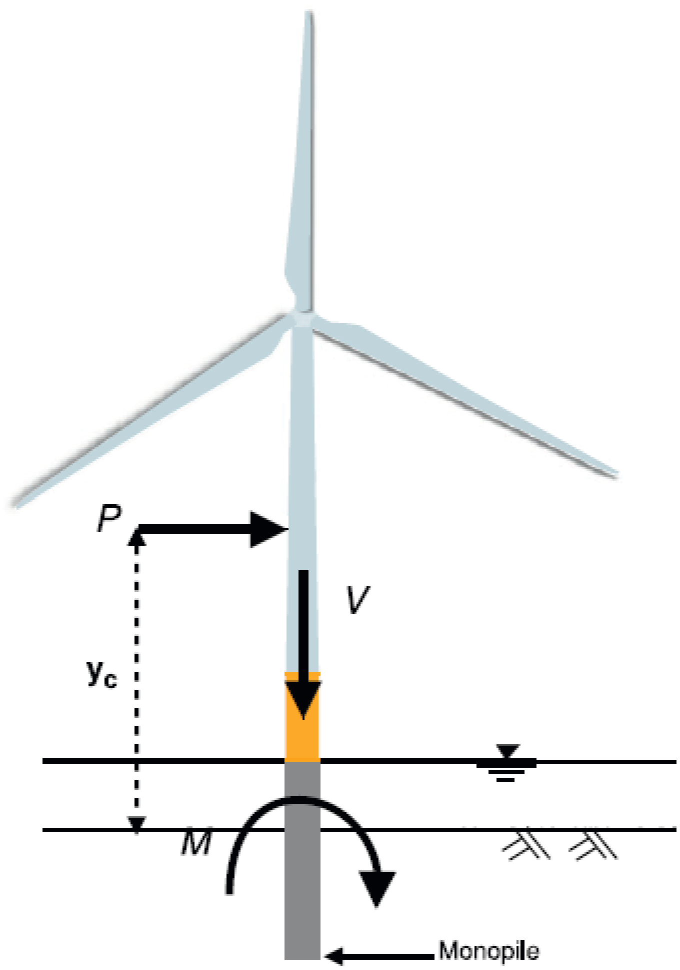


Figure 2.1Loading conditions of Monopile Foundation (Lombardi et al. 2013)

The monopile foundation is stablished is a hashed environmental condition due to the action of wave and wind loading. In general, it is in a state of subjection of vertical load and lateral load which basically dynamic in nature. Three different types of foundation are which can be used for such offshore structure but due to simplicity in load transfer mechanisms monopile is being preferred. The problem related to analysis of monopile is that the soil characteristics at the foundation are variable, and exact prediction of soil data is itself a very difficult task.

It is being analyzed using p-y curve which also under question now a day because of its validity for diameter more than 2m. For heavier loads pile diameter may be up 7.5m on of such is being installed in Germany, world largest project on OWT is under construction in the UK. Variability in natural conditions makes analysis and design of monopile a difficult task many one-dimensional and 3D models are being used to perform the performance studies based on the lateral deflection of monopile. Lateral load at a certain depth from sea bed level due to wave loading induces moment, and a lateral force at sea bed level due to dynamic nature of this load dynamic analysis should have to be performed. Soil conditions above 20m or 30 below sea bed level are also unpredictable, so a probabilistic approach has to need to perform reliability analysis.

2.3.1 Objectives

Along these lines, the principle targets of this study are:

1. An overview of p-y curves given by API for sand.
2. Evaluation of the p-y curve using MATLAB.
3. Study the failure cure of and soil-structure-interaction of the monopile for different diameter and l/d ratio in sand.
4. Soil deformation and structural behavior analysis using PLAXIS and ABAQUS.
5. Comparison of the result with the p-y curve suggested by API code.
6. Comparison of failure profiles of monopile foundation.

2.4 Methodology

Finite Element Method

2.4.1 ABAQUS Modelling

Simulation using ABAQUS is done to see the variation between linearly elastic consideration of soil mass with constant Young’s Modulus of elasticity and oedometric stiffness modules from literature work.

Elemental description

1. Displacements or other degrees of freedom are calculated at the nodes of the element. At any other point in the element, the displacements are obtained by interpolating from the nodal displacements. Elements that have nodes only at their corners, such as the 8-node brick called linear elements or first-order elements.
2. In Abaqus/Standard elements with midside nodes, such as the 20-node brick use quadratic interpolation and are often called quadratic elements or second-order elements.
3. Modified triangular or tetrahedral elements with midside nodes, such as the 10-node tetrahedron use a modified second-order interpolation and are often called modified or modified second-order elements.

2.4.2 PLAXIS Modeling

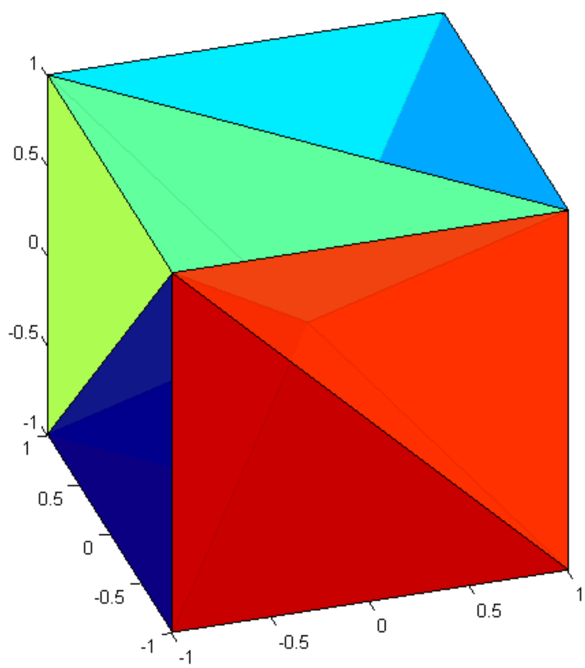


Figure 2.2 Tetrahedron element

PLAXIS 3D uses quadratic tetrahedral 10-noded soil element to. Tetrahedral Element facilities a second order interpolation of displacement. Three local coordinates are for the tetrahedral element. The shape function has a specific property such that function value at considered node is unit and zero at other nodes.

2.4.2.1 Constitutive models

Mohr-Coulomb Model

It is a model for the representation of soil behavior. It is an elastic-plastic behavior. The model is having a functional relationship with five parameters cohesion, the angle of internal friction, dilatancy angle, Young's modulus and Poisson's ratio.

Linear Elastic Model

The model constructed using this are used to simulate the linearly elastic properties. Dependence of this type of model involves with Young's modulus (E) and Poisson's ratio (ν) used for simulation of the pile, footing or rock.

2.4.2.2 Mesh Properties

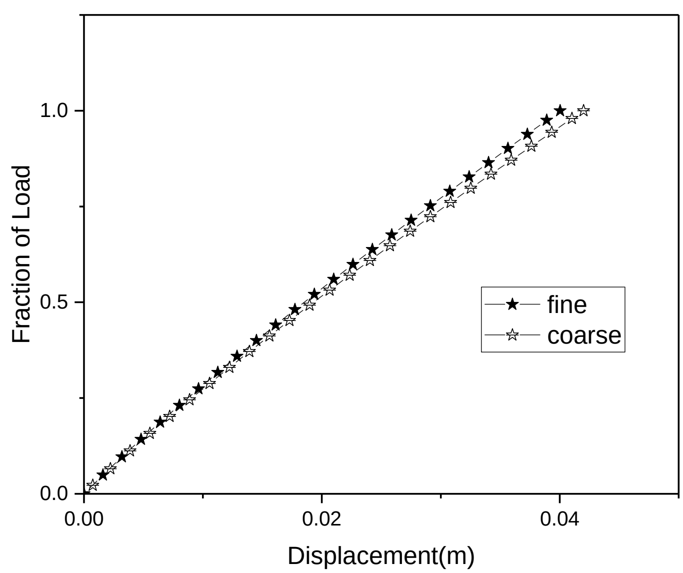


Figure 2.3 Mesh convergence study

Mesh generation in PLAXIS includes the formation of triangular parts. Its optional to have finer or coarse mesh. With increasing finesse in meshing accuracy increases, this provides better results but calculation time also increases so mess convergence may be seen to show which could provide better results. Meshing on monopile model is being shown in fig. 2.3

CHAPTER-3

3. SOLUTIONS BASED ON API AND RELIABILITY ANALYSIS

3.1 Descriptions of API p-y Method

Behavior of laterally loaded pile structure is mainly governed by p-y curves. Each curve represents lateral load (P, load per unit length) and lateral displacement corresponding to the applied load. This method is basically derived by Wrinkler foundation theory, which simulates soil load vs displacement behavior in for of springs. A distributed spring model, based on recommendations of Bush & Manuel (2009) as it is most accurately representing the monopile load deflection response (Bir & Jonkman 2008). Basic assumptions of Winkler's theory are he had considered soil mass as semi-infinite in nature and constant stiffness property of pile as well as soil. For such pile, model x_k is the considered difference between springs. Using p-y curve analysis of monopole considering 6 spring model using MATLAB, to convert it into a model. Finding out the behavior of monopole with the variation of the unit weight of soil, the angle of repose, modulus of subgrade reaction and the distance between springs.

Table 3-1 Properties of Simplified Reference Pile

Symbol	Property	Value
B	Pile diameter	1m
D	Pile depth	10m
Xk	Distance between springs	2.5m

3.2 Application of API Method on Cohesionless Soils

Basic research on offshore pile foundation is being performed by oil & gas industries for offshore supporting structures (LeBlanc et al. 2010). API method for sand to determine p-y curve is given by Reese et al. and checked by Neil & Murchison. The API method is basically a function of angle of internal friction θ, soil unit weight γ and diameter of pile b such that,

$$P = Ap_u \tanh\left(\frac{kx}{Ap_u}\right)y \tag{3.1}$$

where A is either A_s or A_c

$$A_s = \left(3.0 - 0.8\frac{x}{b}\right) \geq 0.9 \tag{3.2}$$

$$A_c = 0.9 \tag{3.3}$$

and initial modulus of subgrade *k* is obtained from the figure as a function water content and angle of internal friction θ,

$$p_u = \min\left(p_{us}, p_{ud}\right) \tag{3.4}$$

$$p_{us} = \left(C_1x + C_2b\right)\gamma x \tag{3.5}$$

$$p_{ud} = C_3 b\gamma x \tag{3.6}$$

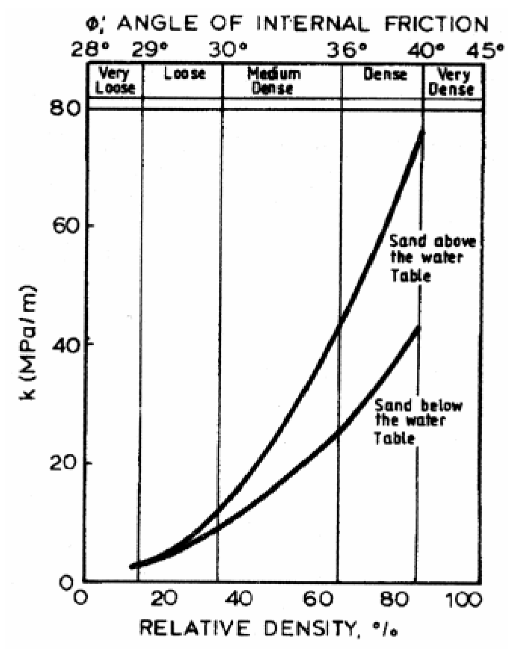
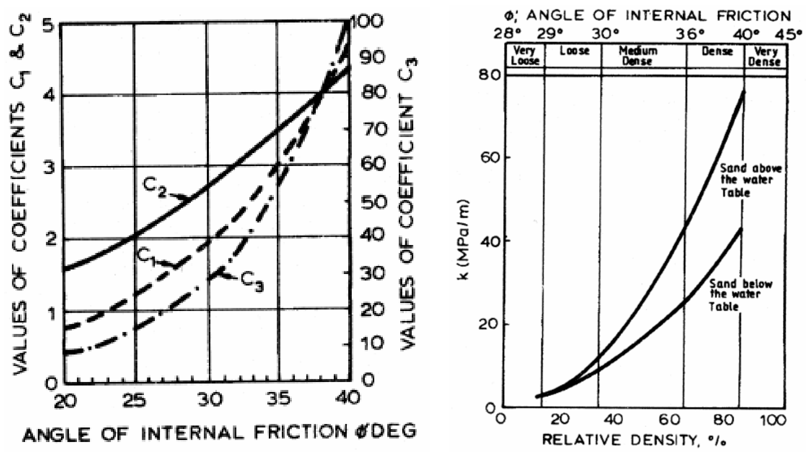


Figure 3.1 Initial Modulus of Subgrade k as a Function of Friction Angle (DNV, 2009)

Where, p_{us} is the ultimate soil resistance at shallower depths, p_{ud} is the ultimate soil resistance at deeper depths, and C_1 and C_2 are coefficients determined as a function of ’



(a) (b)

Figure 3.2 (a) Coefficients as a function of friction angle and (b) initial Modulus k as a function of friction angle (DNV 2009)

For analysis of laterally loaded monopile API methods for sand, Matlock’s method for soft clay and Reese et al.’s method for stiff clay is being used to represent soil-interaction by deriving p-y craves. For the explanation and derivation of the p-y curve of sandy soil using API method reference, properties are listed in Table 3.1 to compare soil properties and pile diameter variation. Using the spring reference model, the soil properties from the table and assuming the water table is located below the pile, the API method yields curves, one for each spring.

Table 3-2 Reference properties for sand

Symbol	Property	Description
B	Friction angle	35
D	Unit weight of soil	17 kN/m^3
Xk	Initial modulus of subgrade reaction	38 MPa

Since the P values are in units of force per unit length, they are multiplied by the length of the pile, x_k to create the curve of lateral force (kN) versus displacement (m). These soil properties are used to see the variation in strength parameter using load vs displacement relationship proposed by API.

3.3 Numerical Simulation of Monopile using API method

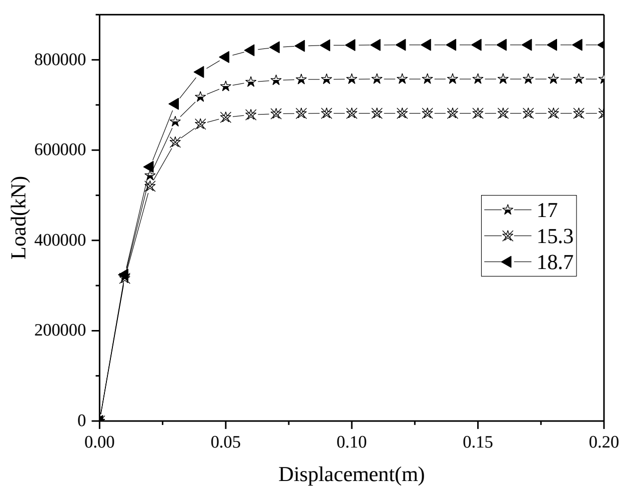


Figure 3.3 Load vs displacement for different specific density

The behaviour of load vs displacement soil and pile parameters took into consideration are being adjusted by ±15%. It is a displacement controlled approach such that displacement is being assured up to serviceability limit, and maximum load is being calculated. Internal friction angle is being varied as 20^0, 30^0, 35^0 and 40^0 classifications of friction angle along can be taken as loose sand, medium sand and dense sand (Reinhold 2002). On varied internal friction angle shape of the curve remains same but strength increases considerably.

From curve plotted using API equation on MATLAB it becomes very clear that initial stiffness of soil is varying linearly with the depth, with increase in soil and pile parameters taken into consideration it can be seen that initial stiffness of soil and strength increases.

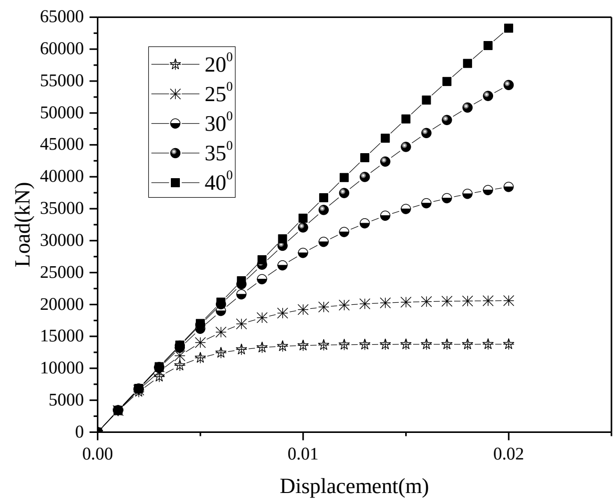


Figure 3.4 Load vs displacement for different friction angle

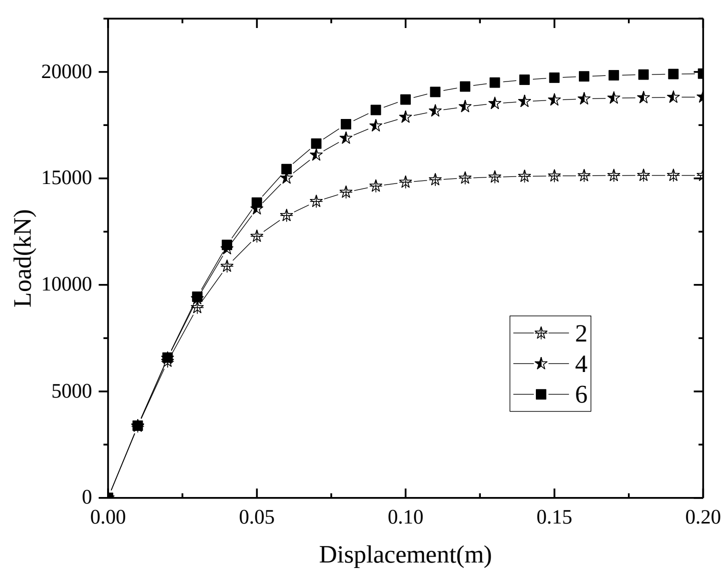


Figure 3.5 Load vs displacement for different friction angle

Considering the results of reliability analysis of the monopole by failure load. By utilizing empirical methods for calculation of reliability and probability density function. To see

Table 3-3 Reference properties for Reliability Analysis

Dry Density (kN/m^2)	Young's Modulus of elasticity (kN/m^2)	Diameter (m)	Deflection (cm)
$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	
13.6	30400	4	4.3131
13.6	45600	6	5.5417
13.6	30400	6	5.4988
13.6	45600	4	4.3205
20.4	30400	4	6.3632
20.4	45600	6	6.3632
20.4	30400	6	7.8978
20.4	45600	4	6.4697

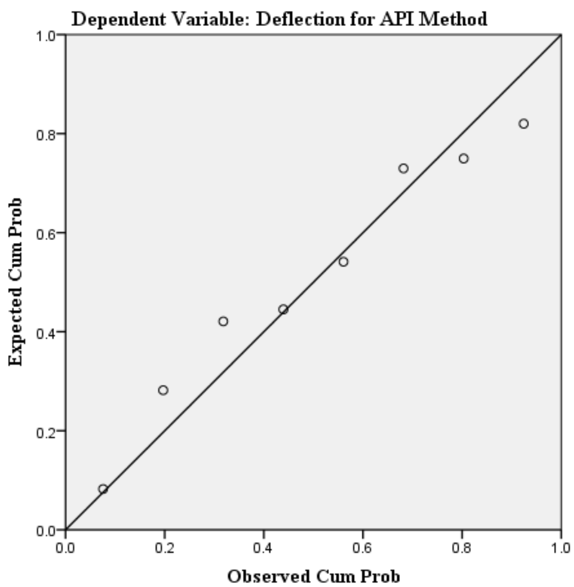


Figure 3.6 Normal P-P Plot of Regression Standardized Residual

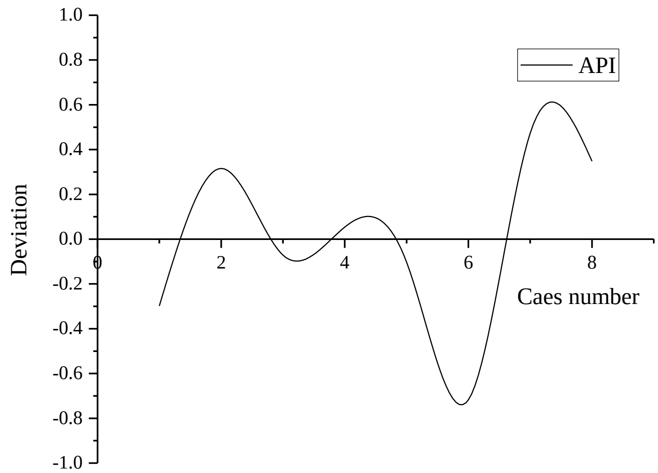


Figure 3.7 Residual deviation vs case plot

variation from residual deviation curve it can be seen that for the case 3, 4 and 5 the actual values are quite closer to that of predicted values but for the case 6, 7 and 8 the actual and predicted values are different. It is a displacement controlled approach such that displacement is being assured up to serviceability limit, and maximum load is being calculated.

From fig. 3.6 it seems clearly that initially the observed values match with the regression mode it shows that initially API values satisfy the regression model. But for 0.2 to 0.5 the API values are over predictive with respect to regression model expected outcomes.

This variation may be due overestimation of stiffness values which is being seen in the API method and being observed from literature works. API values are under predictive also which can be seen from above figure for the probability of 0.7 to 1.

CHAPTER-4

4 FEM BASED MODELING AND RELIABILITY ANALYSIS

4.1 Simulation of Monopile using PLAXIS 3D

A solid cylindrical element with steel material is considered for the analysis which could behave in a similar fashion as monopile with surrounding soil. The length of pile taken into consideration is 35 m. Pile is loaded with lateral load and a moment to simulate this a lateral load of 1252 kN is applied at seabed level to pile and two loads of 10622.9 kN is applied at opposite faces one at the pile tip and other at seabed level.

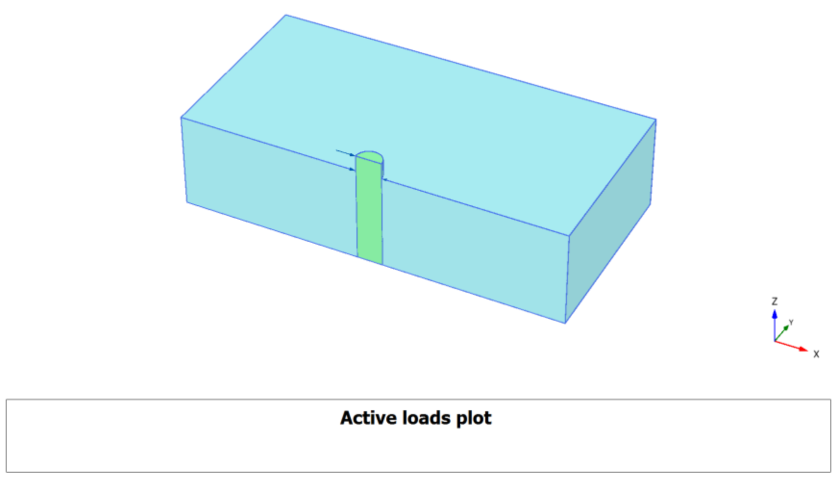


Figure 4.1 Monopile model in PLAXIS 3D

This is done to get the uniform displacement throughout the depth when a 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. After analysis, it can be seen clearly the deformation concentration is mainly on the pile as it is subjected to lateral load and moment. The deformation characteristics are quite similar to that of wedge failure considerations. The stress conditions and deformation characteristics are quite similar to that represented by Achums et al. So as to simulate the condition described by Danish Geotechnical Institute on the basis of data of windmill park at Horns Rev, Denmark. 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 is 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 EpIp is kept constant along the pile length.

4.2 Study of response of Monopile for lateral loading

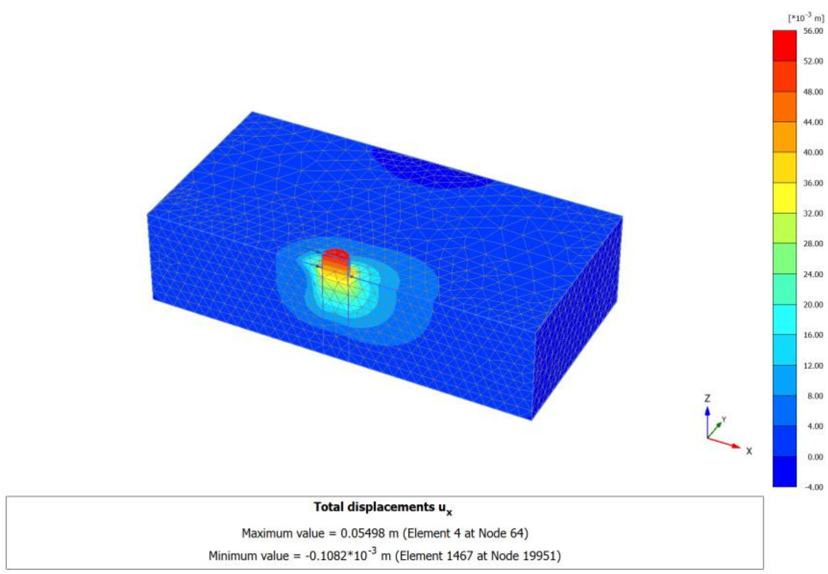


Figure 4.2 Displacement along x-axis

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 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.

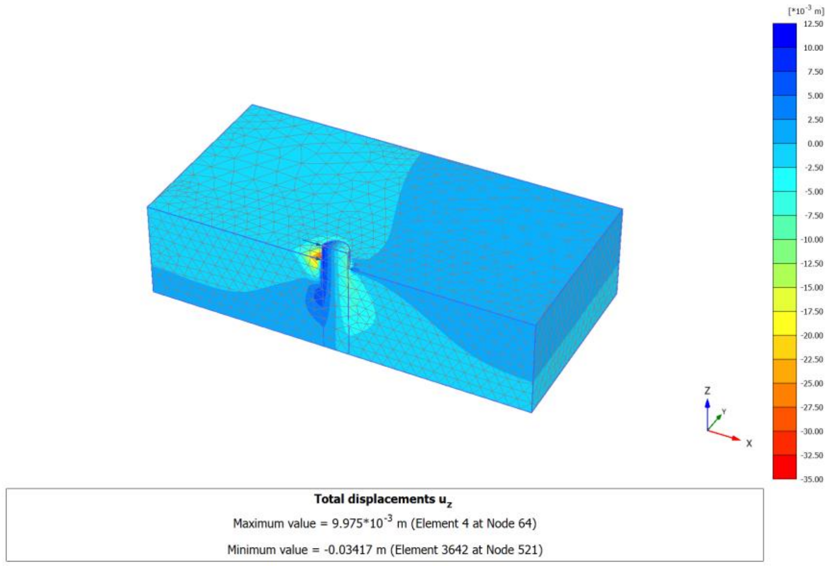


Figure 4.3 Displacement concentration along z-axis

4.3 Regression analysis based on FEM results

16 models are being analyzed to see the variation as 4 properties are selected for calculation of response surface based reliability. The water table is not taken into consideration to see long term effect soil is being considered as drained.

Table 4-1Parameters considered for regression analysis

	MEAN(μ)			
	γ **(kN/m^2)**	**E(MPa)**	**φ^0**	**Diameter**
Reference soil	17	38	35	5
COV%	5	5	5	5

Deformation concentration is not only on opposite side of the loading where actual displacement is happening but also on the side in at which load is being applied. The coefficient of variation being used for regression date is 5 % as per Phoon 2008. By varying each parameter by $\mu \pm \sigma$. 16 cases can be formed by analyzing each case deflection can be computed. Reliability analysis is being performed to find out the probability of failure of the structure if deflection prescribed as per serviceability - criterion is 0.02 m by using response surface method.

Table 4-2 Parameters considered for regression analysis based on PLAXIS 3D results

Friction angle (degree)	Dry Density (kN/m^2)	Young's Modulus of elasticity (kN/m^2)	Diameter (m)	Deflection (m)
$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	
28	13.6	30400	4	4.20E-02
28	13.6	45600	6	1.07E-02
28	13.6	30400	6	1.15E-02
28	13.6	45600	4	3.72E-02
28	20.4	30400	4	3.99E-02
28	20.4	45600	6	1.05E-02
28	20.4	30400	6	1.14E-02
28	20.4	45600	4	3.47E-02
42	20.4	30400	4	3.98E-02
42	20.4	45600	6	1.06E-02
42	20.4	30400	6	1.14E-02
42	20.4	45600	4	3.43E-02
42	13.6	30400	4	4.15E-02
42	13.6	45600	6	1.07E-02
42	13.6	30400	6	1.16E-02
42	13.6	45600	4	3.61E-02

From fig. 4.6 it is being observed that deformation characteristics decrease with increases in diameter as a deflection for 4 m diameter is more for same soil properties same loading conditions. This parameter is also being considered in API. With the increase in diameter, the materialistic strength increases. Embedment depth for the case of monopile should be adequate as it the reason behind characteristic changes. From the literature it is being found for lower embedment depth behavior of load vs displacement characteristics is rigid i.e. its behavior is not exactly elastic. For high embedment depth behavior is elastic.

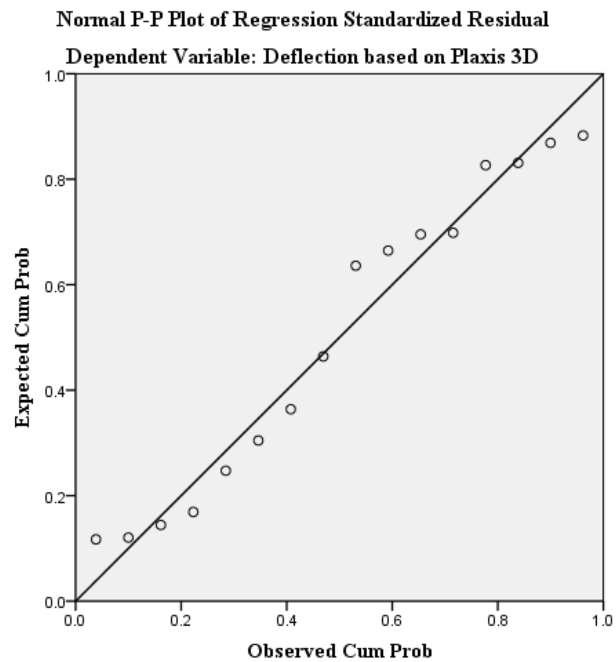


Figure 4.4 Normal P-P Plot of Regression Standardized Residual

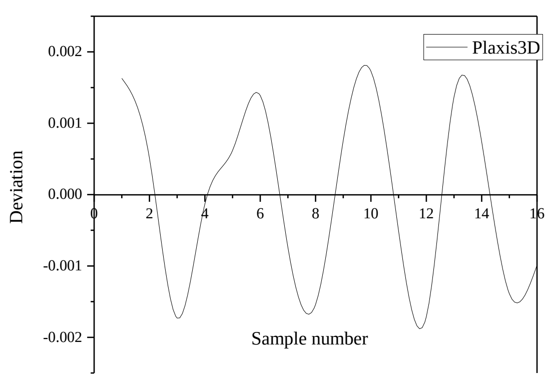


Figure 4.5 Residual deviation vs number of samples

As it is not a linear response dependent variable problem so response curve could not be plotted. The analysis is done using fine mesh node selected to see the deformation is at seabed level we are basically concerned about deflection at seabed level. Fig. 4.5 shows that the error between expected and observed out comes such that it shows the range of samples under which the deviation is maximum and minimum. The deviation on API regression modeling is very low. In the case of PLAXIS results P-P plot shows that the values are within the limits a match is being found up to 0.6 values are under predictive but satisfactory.

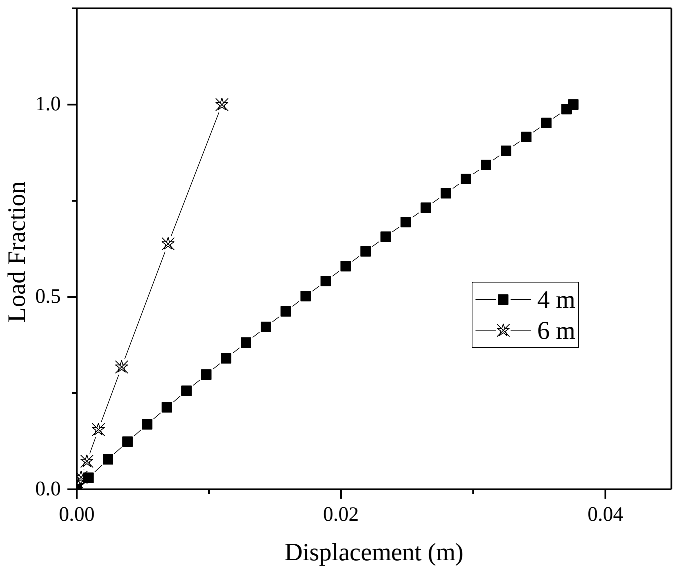


Figure 4.6 load vs Displacement for different diameters

Fig. 4.7 represents the behavior of deflection for same soil characteristics and same loading conditions. It is being seen that slope of each curve representing different embedment depth is different. For lower embedment depth 20 m the displacement is more for the same loading in comparison to that for 25 m and 30 m. For embedment depth of 30 m, the behavior is elastic as the degree of proportionality is quite higher. 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.

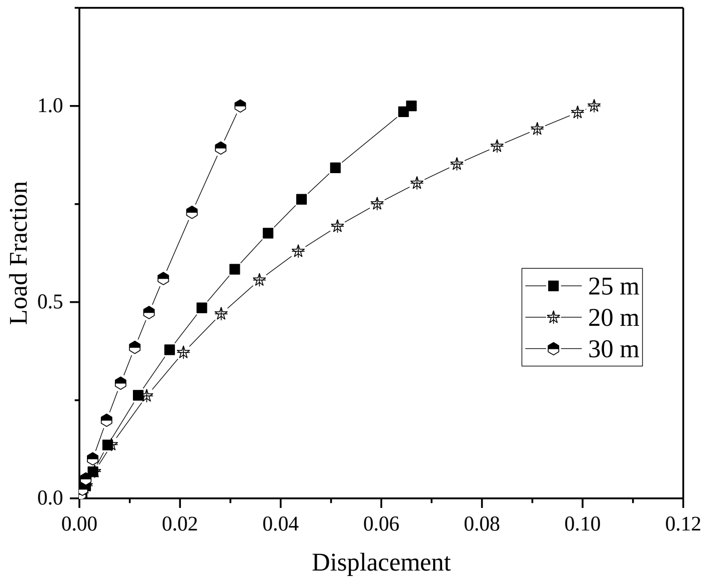


Figure 4.7 Load vs Displacement for varying embedment depthFEM analysis of linearly elastic ABAQUS model

Simulation of monopile on FEM basis is done to compare with the literature works. To see the

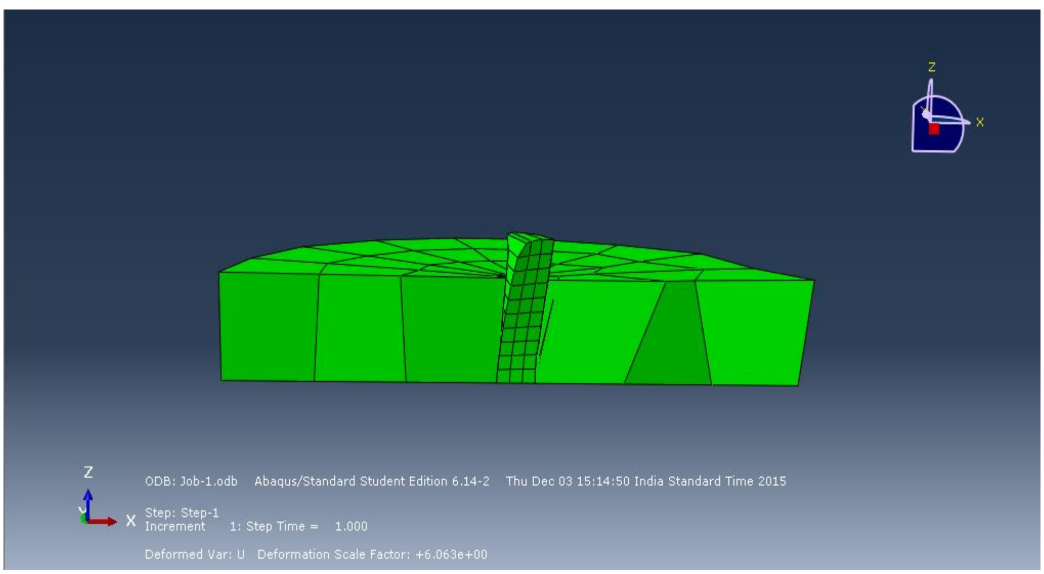


Figure 4.8 Deformed mesh

Load vs displacement behavior with the assumption of soil mass as elastic material monopile of diameter 4m, 5m and 6m is taken into consideration. Lateral load is applied at 5m height above sea bed it induces a moment along with lateral load at sea bed level Interaction property is being defined to simulate the actual condition of pile and soil interaction masters-slave definition is used with a frictional value of 0.35.

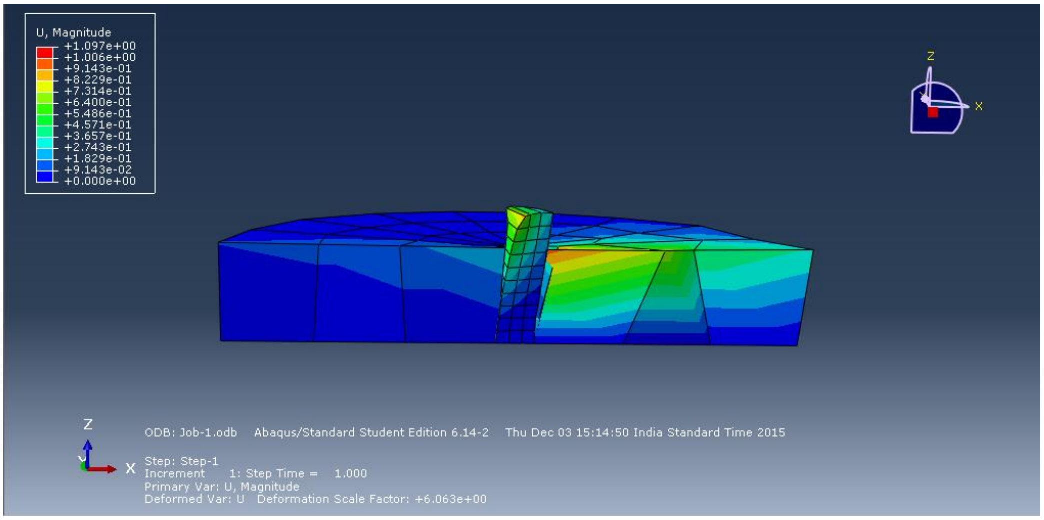


Figure 4.9 Displacement concentration and magnitude

Displacement of monopile is maximum in the U1 direction as the load is also applied in the same direction the failure surface of the soil is similar to that mentioned in the literature. From fig.4.9, the loading behavior along with displacement characteristics can be seen clearly.

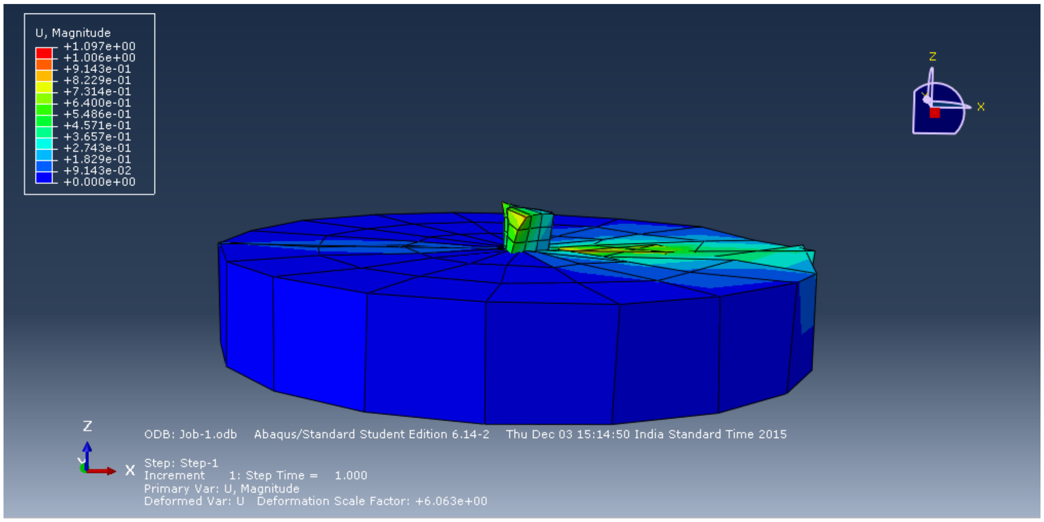


Figure 4.10 Displacement magnitude with mirror image

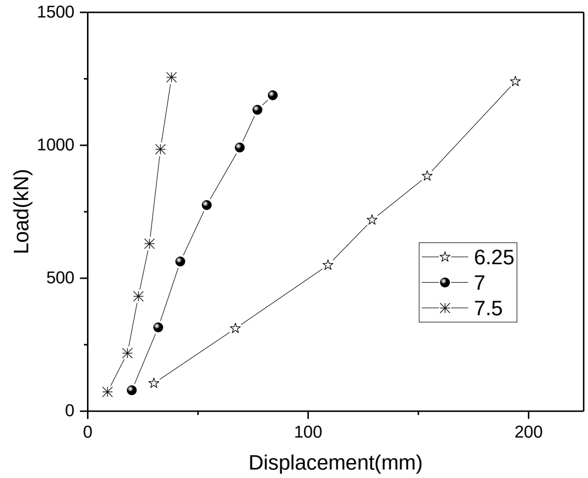


Figure 4.11 Load vs. Displacement response for various l/d ratios

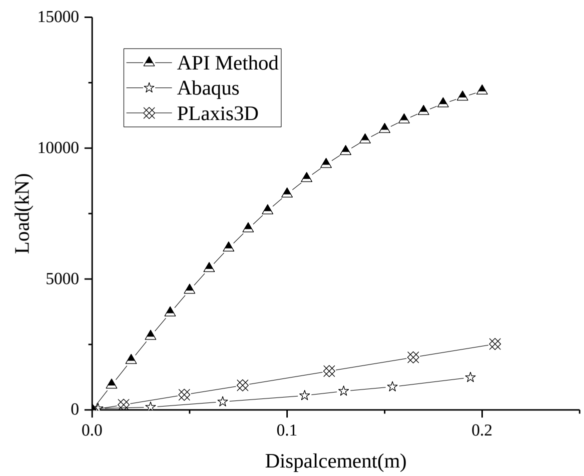


Figure 4.12 Comparison between FEM and API results

With the application of 8MN lateral load at pile tip, the moment induced at seabed level is about 40MNm and a displacement of 20 cm is being observed. To visualize the effect of l/d variation monopile of 6.25, 7 and 7.5 l/d ratio taken into consideration the results are shown in fig. 4.11. From above results, it can be seen the displacement for same applied load decreases with increase in l/d ratios. As API recommendations, l/d ratios should be 5 to 10 for the purpose of avoiding slender pile effect. Comparison between API and FEM results is being done which shows in fig…. that API results are over predictive regarding displacement. API method has ignored the stiffness criteria of the pile. For any type of designing purpose, API results should be checked using numerical analysis methods. For rough calculation soil as linearly elastic can be used to see the displacement of monopile for any prescribed load.

CHAPTER-5

5 DYNAMIC AND ANALYSIS

5.1 Prediction of Dynamic Behaviors

For the dynamic characteristics of monopile, the lateral load is changed to dynamic using sinusoidal characteristic. 1000, 16000, 24000 is the amplitude and 0.25 is the frequency for this analysis is being taken. 0.25 frequencies it means the period of one cycle is around 4 s.

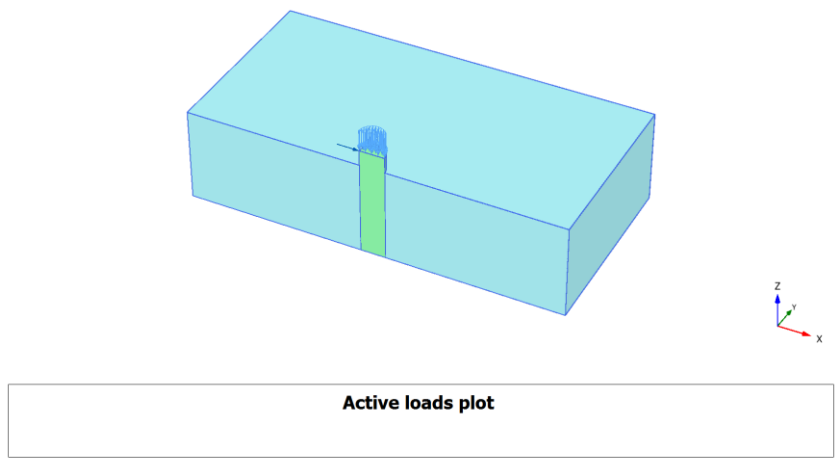


Figure 5.1 loading condition for dynamic analysis

Monopile foundation is subjected to a wave loading which is being taken as static lateral load it is due to wave action of loading for increasing water depth wave height increases it lead to the development of large displacement.

Table 5-1 Loading Descriptions

Loading	Value
Surface Load	1000kN/m^2
Dynamic Load	8MN
Amplitude	24000,1000,160
Frequency	0.25,0.5,0.75

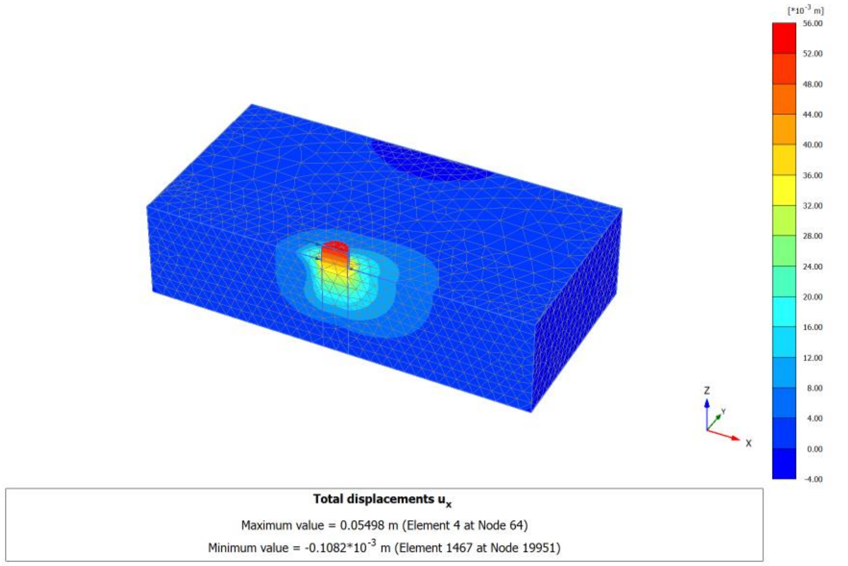


Figure 5.2 Displacement along x- axis

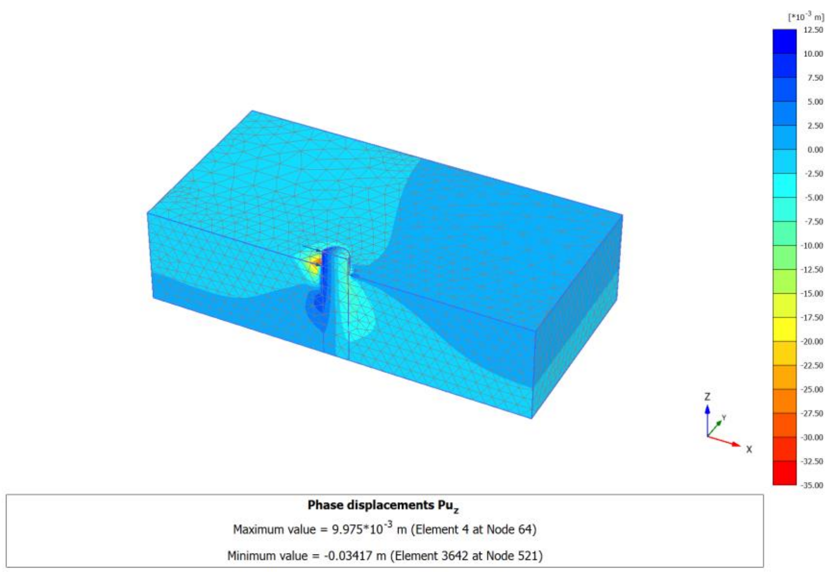


Figure 5.3 Displacement characteristics

A number of the cycle has been varied from 2 to 80 to see the variation in the deformation characteristics. To simulate the actual loading conditions of monopile a surface load along with dynamic loading along lateral direction is also considered.

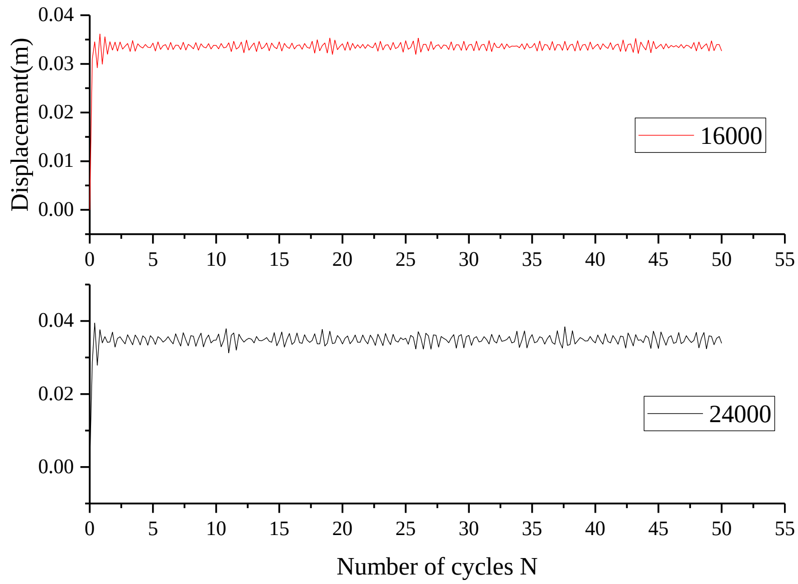


Figure 5.4 Displacement vs Number of cycles N for different amplitude

From the above curve, it can be seen that for the same number of cycles and same frequency deflection behavior of monopile also changes with a change in amplitude but only with large change it is affected because deformation characteristics for 1000 and 16000 amplitudes are quite same.

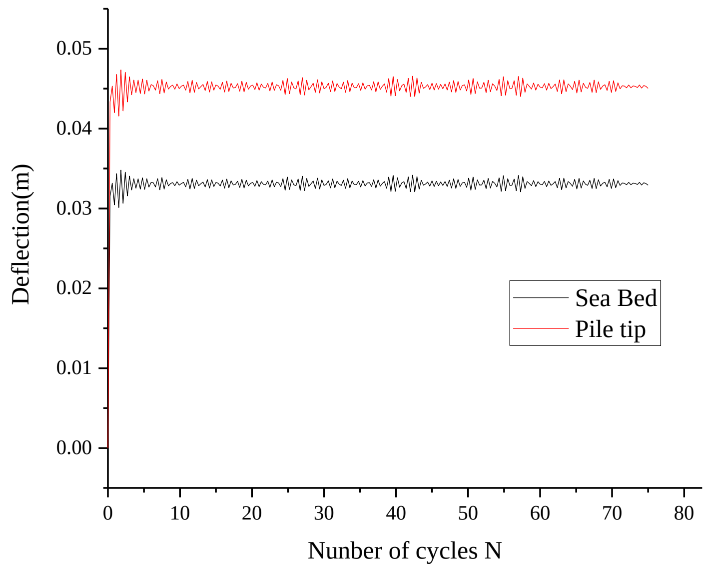


Figure 5.5 Deflection vs Number of cycles at different level with 300s period

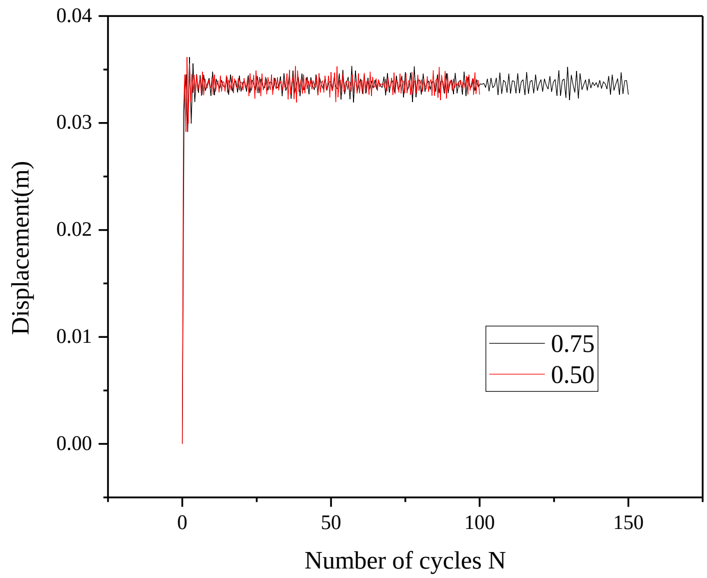


Figure 5.6 Deflection vs Number of cycles for different frequencies

Chapter 6

6 Conclusion

6.1 Conclusion

In the present study lateral load vs deflection characteristics of the monopile foundation is being analyzed as this lateral load is due to the wave action sea water. So dynamic analysis with low frequency is also performed to see the behavior different methods to predict best. API method, FEM based on Mohr–Coulomb failure criterion and for rough estimate using linearly elastic behavior are being compared, and regression analysis is also done

1. From the comparison between API and FEM analysis results both for Mohr–Coulomb failure criterion behavior, it is concluded that API method over predicts deformation characteristics.
2. Variation between h/l indicates an increase in h/l the deformation for same load increases which show that for higher water depth deformation is more as wave height is also increased with water depth.
3. Form API for the case of sandy soil k, C1, C2, and C3 the entire are dependent on the angle of internal friction, so the angle of internal friction is the main parameter to predict deformation characteristics. And dependency of lateral defection on friction angle increase
4. L/D ration variation for same loading conditions with the increase in L/D deformation characteristic changes if ration is varied more than 10 then local buckling may occur with increase in L/D ration it also can be seen elastic nature increases for lower L/D behavior of monopile is similar to small rigid pile.
5. From regression analysis results indicated for API method is the predicted values on the basis of regression is varying highly from the actual value. But for the case of regression using PLAXIS, the variation is little the predicted displacement values are quite of that of actual ones.
6. The failures surface for soil can be considered as a wedge. As from stress and deformation characteristics, it is seen that soil will fail in the form of a wedge.

7. In dynamic loading variation in frequency has more impact on deflection behavior but for same period variation in amplitude only large change in amplitude indicates any noticeable change.
8. The deformation increases with the number of cycles it fluctuates but maximum attained deflection at any interval is more.
9. API method should not be taken into consideration for designing purpose instead of that numerical analysis should be performed to predict the nature of deflection.
10. The reliability based on API method for getting loaded to 8000000 kN attain displacement of 0.02 m is 4.81and reliability based on PLAXIS results to attain a displacement of 0.02 m is 0.33 and probability of failure are 37%.

6.2 Scope for further study

By present research work, it has been seen that a vast study related to this has to be performed.

1. To take into account wind load into account methods to solve wind loading equations has to be studied.
2. As it is a case of dynamic loading also so time history analysis can also be performed for that, a deep study regarding influencing factors has to be performed.
3. To predict the behaviors based on Indian sub-continent study of soil characteristics at sea bed level has to be performed.
4. Find an exact equation to predict soil-pile interaction correctly for any loading condition.

7 References

[1] Abhinav KA, Saha N. Dynamic analysis of an offshore wind turbine including soil effects. Procedia Eng 2015;116:32–9. doi:10.1016/j.proeng.2015.08.261.

[2] Achmus M. Finite element modelling of horizontally loaded monopile foundations for offshore wind energy converters in Germany. Proc, Int Symp Front Offshore Geotech ISFOG 2005:391–6.

[3] Achmus M, Kuo Y-SS, Abdel-Rahman K. Behavior of monopile foundations under cyclic lateral load. Comput Geotech 2009;36:725–35. doi:10.1016/j.compgeo.2008.12.003.

[4] Agarwal P, Manuel L. Wave Models for Offshore Wind Turbines. 46th AIAA Aerosp. Sci. Meet. Exhib., 2008, p. 15.

[5] Ankit A, Datta N, Kannamwar AN. Free transverse vibration of mono-piled ocean tower. Ocean Eng 2016;116:117–28. doi:10.1016/j.oceaneng.2015.12.055.

[6] Arany L, Bhattacharya S, Macdonald JHG, Hogan SJ. Closed form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI. Soil Dyn Earthq Eng 2016;83:18–32. doi:10.1016/j.soildyn.2015.12.011.

[7] Arshad M, Kelly BCO. Model Studies on Monopile Behavior under Long-Term Repeated Lateral Loading. Int J Geomech 2016:1–12. doi:10.1061/(ASCE)GM.1943-5622.0000679.

[8] Bhattacharya S, Nikitas N, Garnsey J, Alexander NA, Cox J, Lombardi D, et al. Observed dynamic soil-structure interaction in scale testing of offshore wind turbine foundations. Soil Dyn Earthq Eng 2013;54:47–60. doi:10.1016/j.soildyn.2013.07.012.

[9] Bisoi S, Haldar S. Dynamic analysis of offshore wind turbine in clay considering soil-monopile-tower interaction. Soil Dyn Earthq Eng 2014;63:19–35. doi:10.1016/j.soildyn.2014.03.006.

[10] Bisoi S, Haldar S. Design of monopile supported offshore wind turbine in clay considering dynamic soil–structure-interaction. Soil Dyn Earthq Eng 2015;73:103–17. doi:10.1016/j.soildyn.2015.02.017.

[11] Cacciola P, Espinosa MG, Tombari A. Vibration control of piled-structures through structure-soil-structure-interaction. Soil Dyn Earthq Eng 2015;77:47–57. doi:10.1016/j.soildyn.2015.04.006.

[12] Carswell W, Johansson J, L??vholt F, Arwade SR, Madshus C, DeGroot DJ, et al. Foundation damping and the dynamics of offshore wind turbine monopiles. Renew Energy 2015;80:724–36. doi:10.1016/j.renene.2015.02.058.

[13] Carswell W, Arwade SR, Myers a T, Hajjar JF. Reliability analysis of monopile offshore wind turbine support structures. Safety, Reliab Risk Life-Cycle Perform Struct

Infrastructures 2013:223.

[14] Cavazzi S, Dutton AG. An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential. Renew Energy 2016;87:212–28. doi:10.1016/j.renene.2015.09.021.

[15] Damgaard M, Andersen L V., Ibsen LB. Dynamic response sensitivity of an offshore wind turbine for varying subsoil conditions. Ocean Eng 2015;101:227–34. doi:10.1016/j.oceaneng.2015.04.039.

[16] Damgaard M, Andersen LV, Ibsen LB, Toft HS, Sørensen JD. A probabilistic analysis of the dynamic response of monopile foundations: Soil variability and its consequences. Probabilistic Eng Mech 2015;41:46–59. doi:10.1016/j.probengmech.2015.05.001.

[17] Damgaard M, Bayat M, Andersen L V., Ibsen LB. Assessment of the dynamic behaviour of saturated soil subjected to cyclic loading from offshore monopile wind turbine foundations. Comput Geotech 2014;61:116–26. doi:10.1016/j.compgeo.2014.05.008.

[18] DNV. DNV-OS-J101 Design of Offshore Wind Turbine Structures. May 2014:212–4.

[19] Esteban MD, Cou??ago B, L??pez-Guti??rrez JS, Negro V, Vellisco F. Gravity based support structures for offshore wind turbine generators: Review of the installation process. Ocean Eng 2015;110:281–91. doi:10.1016/j.oceaneng.2015.10.033.

[20] Gupta BK, Basu D. Analysis of laterally loaded rigid monopiles and poles in multilayered linearly varying soil. Comput Geotech 2016;72:114–25. doi:10.1016/j.compgeo.2015.11.008.

[21] Hokmabadi a. S, Fakher a., Fatahi B. Full scale lateral behaviour of monopiles in granular marine soils. Mar Struct 2012;29:198–210. doi:10.1016/j.marstruc.2012.06.001.

[22] Horgan C. Using energy payback time to optimise onshore and offshore wind turbine foundations. Renew Energy 2013;53:287–98. doi:10.1016/j.renene.2012.10.044.

[23] Jung S, Kim SR, Patil A, Hung LC. Effect of monopile foundation modeling on the structural response of a 5-MW offshore wind turbine tower. Ocean Eng 2015;109:479–88. doi:10.1016/j.oceaneng.2015.09.033.

[24] Kim Y, Jeong S. Analysis of soil resistance on laterally loaded piles based on 3D soil–pile interaction. Comput Geotech 2011;38:248–57. doi:10.1016/j.compgeo.2010.12.001.

[25] Koukoura C, Natarajan A, Vesth A. Identification of support structure damping of a full scale offshore wind turbine in normal operation. Renew Energy 2015;81:882–95. doi:10.1016/j.renene.2015.03.079.

[26] Kuo YS, Achmus M, Abdel-Rahman K. Minimum Embedded Length of Cyclic Horizontally Loaded Monopiles. J Geotech Geoenvironmental Eng 2012;138:357–63. doi:10.1061/(ASCE)GT.1943-5606.0000602.

[27] Labenski J, Moormann C. A comparison of different analytical methods to determine the axial bearing capacity of monopiles. Geomech Energy Environ 2015;under revi. doi:10.1016/j.gete.2016.03.001.

[28] Lee Y-SS, Choi B-LL, Lee JH, Kim SY, Han S. Reliability-based design optimization of monopile transition piece for offshore wind turbine system. Renew Energy 2014;71:729–41. doi:10.1016/j.renene.2014.06.017.

[29] Li L, Gao Z, Moan T, Ormberg H. Analysis of lifting operation of a monopile for an offshore wind turbine considering vessel shielding effects. Mar Struct 2014;39:287–314. doi:10.1016/j.marstruc.2014.07.009.

[30] Li M, Zhang H, Guan H. Study of offshore monopile behaviour due to ocean waves. Ocean Eng 2011;38:1946–56. doi:10.1016/j.oceaneng.2011.09.022.

[31] Lombardi D, Bhattacharya S, Muir Wood D. Dynamic soil-structure interaction of monopile supported wind turbines in cohesive soil. Soil Dyn Earthq Eng 2013;49:165–80. doi:10.1016/j.soildyn.2013.01.015.

[32] Luengo MM, Kolios A. Failure mode identification and end of life scenarios of offshore wind turbines: A review. Energies 2015;8:8339–54. doi:10.3390/en8088339.

[33] Matutano C, Negro V, L??pez-Guti??rrez JS, Esteban MD. Scour prediction and scour protections in offshore wind farms. Renew Energy 2013;57:358–65. doi:10.1016/j.renene.2013.01.048.

[34] Nikitas G, Vimalan NJ, Bhattacharya S. An innovative cyclic loading device to study long term performance of offshore wind turbines. Soil Dyn Earthq Eng 2016;82:154–60. doi:10.1016/j.soildyn.2015.12.008.

[35] Oh KY, Kim JY, Lee JS. Preliminary evaluation of monopile foundation dimensions for an offshore wind turbine by analyzing hydrodynamic load in the frequency domain. Renew Energy 2013;54:211–8. doi:10.1016/j.renene.2012.08.007.

[36] Pang ALJ, Skote M, Lim SY, Gullman-Strand J, Morgan N. A numerical approach for determining equilibrium scour depth around a mono-pile due to steady currents. Appl Ocean Res 2016;57:114–24. doi:http://dx.doi.org/10.1016/j.apor.2016.02.010.

[37] Pappusetty D, Pando M. Numerical evaluation of long term monopile head behavior for ocean energy converters under sustained low amplitude lateral loading. Int J Civ Struct Eng 2013;3:669–84. doi:10.6088/ijcser.201203013061.

[38] Peder Hyldal Sørensen S, Bo Ibsen L. Assessment of foundation design for offshore monopiles unprotected against scour. Ocean Eng 2013;63:17–25. doi:10.1016/j.oceaneng.2013.01.016.

[39] Peng J-R, Rouainia M, Clarke BG. Finite element analysis of laterally loaded fin piles. Comput Struct 2010;88:1239–47. doi:10.1016/j.compstruc.2010.07.002.

[40] Prendergast LJ, Gavin K. A comparison of initial stiffness formulations for small-strain soil-pile dynamic Winkler modelling. Soil Dyn Earthq Eng 2016;81:27–41. doi:10.1016/j.soildyn.2015.11.006.

[41] Prendergast LJ, Gavin K, Doherty P. An investigation into the effect of scour on the natural frequency of an offshore wind turbine. Ocean Eng 2015;101:1–11. doi:10.1016/j.oceaneng.2015.04.017.

[42] Qi WG, Gao FP. Physical modeling of local scour development around a large-diameter monopile in combined waves and current. Coast Eng 2014;83:72–81. doi:10.1016/j.coastaleng.2013.10.007.

[43] Rani S, Prashant A. Estimation of the Linear Spring Constant for a Laterally Loaded Monopile Embedded in Nonlinear Soil. Int J Geomech 2015;15:4014090. doi:10.1061/(ASCE)GM.1943-5622.0000441.

[44] Sánchez M, Roesset JM. Evaluation of models for laterally loaded piles. Comput Geotech 2013;48:316–20. doi:10.1016/j.compgeo.2012.07.011.

[45] Shadlou M, Bhattacharya S. Dynamic stiffness of monopiles supporting offshore wind turbine generators. Soil Dyn Earthq Eng 2016;88:15–32. doi:10.1016/j.soildyn.2016.04.002.

[46] Sharma A, Reddy GR, Eligehausen R, Genesio G, Pampanin S. Seismic response of reinforced concrete frames with haunch retrofit solution. ACI Struct J 2014;111:673–84. doi:10.14359/51686625.

[47] Troldborg N, Sørensen J. A simple atmospheric boundary layer model applied to large eddy simulations of wind turbine wakes. Wind Energy 2014;17:657–69. doi:10.1002/we.

[48] Wan L, Gao Z, Moan T, Lugni C. Comparative experimental study of the survivability of a combined wind and wave energy converter in two testing facilities. Ocean Eng 2016;111:82–94. doi:10.1016/j.oceaneng.2015.10.045.

[49] Zania V. Natural vibration frequency and damping of slender structures founded on monopiles. Soil Dyn Earthq Eng 2014;59:8–20. doi:10.1016/j.soildyn.2014.01.007.

[50] Zhan YG, Wang H, Liu FC. Modeling vertical bearing capacity of pile foundation by using ABAQUS. Electron J Geotech Eng 2012;17 M:1855–65.

[51] Zhang L. Nonlinear analysis of laterally loaded rigid piles in cohesionless soil. Comput Geotech 2009;36:718–24. doi:10.1016/j.compgeo.2008.12.001.

[52] Zheng XY, Li H, Rong W, Li W. Joint earthquake and wave action on the monopile wind turbine foundation: An experimental study. Mar Struct 2015;44:125–41. doi:10.1016/j.marstruc.2015.08.003.