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Comparative Study between Suction Bucket and Monopole for Supporting Wind Turbines

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ABSTRACT

With the present worldwide direction for increasing the commitment of sustainable energy, the construction rate of wind farms is high, to achieve significant amount of the entire energy production. Energy production and consumption efficiency are the two main factors, that the location of a wind farm is dependent on them. There are many controlling parameters during selection a wind farm location such as; wind speed, possibility of connecting to the existing electrical networks, local population, and available construction site. Moreover, the choice of the optimal foundation system is an important aspect in the design of wind turbines. Suction buckets and monopiles are promising foundation options for offshore wind turbines, which are subjected to complex loading conditions resulted from both of self-weight of turbine and environmental loads including; wind, wave, and current. This paper aims to investigate the behavior of a monopile and a suction bucket as foundation proposals for offshore wind turbines. Comparative study are carried out between the two options under the same loading conditions using a three-dimensional finite element model by Plaxis3D software. The interaction between each foundation system and the subsoil is taken consideration during numerical analysis. The responses of a suction bucket and a monopile were analyzed and discussed. Therefore, interactions diagrams relating moment with lateral load (M-H) at different values of vertical loads (V) were presented. Also, the research was focused on initial lateral stiffness and initial rotational stiffness of the studied substructures. The effects of the related parameters on the response of the substructures in the two cases were discussed. Useful recommendations were revealed based on the obtained results.

Keywords: *monopile, suction bucket, lateral, moment, wind turbine, stiffness*

INTRODUCTION

The choice of the foundation system is considered a key aspect of any structural design, because it can seriously impact on total cost and execution time. Therefore, the selection of a suitable foundation is an essential factor in determining the economic feasibility of the design. Meanwhile, the selection depends on the nature of applied loads, in addition to detailed soil characteristics. In the case of relatively small loads or strong supporting soils, a shallow foundation would represent the most economical solution, so reinforced concrete raft is the typical foundation system, which will be installed directly over a bed rock or over a soil with good geotechnical properties. This type of foundation is optimal proposal for onshore wind turbines and it is not suitable for offshore wind turbines. Due to vast increasing popularity of alternative energy production, it is becoming common to challenge with poor geotechnical conditions at the sites in which wind turbine structures are planned to be installed. Thus, the use of spread foundations on unreinforced soil is either uneconomical or unsuitable. However, as loads increase or as bearing soil becomes weaker, it is essential to use larger and thicker footings. The classical foundation type in poor geotechnical conditions is the use of a monopile, but now the suction bucket foundation is a relatively novel design concept for offshore wind energy convertors which seems to be its advantages regarding environmental issues, Achmus et al. [1].

To investigate the behavior of suction buckets, field tests were carried out by many authors such as, Bang & Karnoski [2], Tran et al. [3], Ibsen et al. [4], Cho et al. [5], and Mausi et al. [6]. They conducted these field tests to investigate the feasibility and cost effectiveness of the installation. Jara et al. [7] pointed out that the performance of caissons depends on the method of installation. Therefore, installation process is a key factor in studying the long-term performance of caisson. Wang et al. [8], Houlsby et al. [9], and Houlsby & Bryne [10] carried out field tests of buckets foundations under cyclic loading. Gao et al. [11], Eid [12], Elwakil [13], and Vaillalobos et al. [14] performed experiments on small scale model buckets with different dimensions (L/D ratios) in different types of soil to investigate the effect of bucket dimension on its bearing capacity. Houlsby and Byrne [9] developed a design procedure for using skirted foundation in sand. Houlsby et al. [10] carried out field tests on bucket installed in both sand and clay and the bucket was subjected to pull-out loads. Additionally the author emphasized that, skirted foundation is attractive foundation alternative for wind turbine structures.

Numerical simulation using finite element models were carried out to investigate the bearing capacity of suction buckets by Rahman & Achmus [15], and Achmus et al. [1]. Meanwhile, Yingchen [16], Supachawarote et al. [17], and Bang & Cho [18] conducted numerical analysis to investigate the effect of bucket dimensions on the bearing capacity under monotonic loads. Liu et al. [19] carried out large-scale tests to study the bearing behavior of wide-shallow buckets. Yang et al. [20] simulated buckets of different dimensions installed in different types of soil, through finite element analysis, and compared the numerical results with results obtained from centrifuge models. The authors provided modified method of lateral load-moment capacity of buckets for preliminary design.

The research work on lateral load-moment conditions on large diameter piles is scarce. However, the most widely used current design method for monopiles is the *p–y* curve technique. Since the anticipated loads on offshore wind turbines supported on monopiles include a large moment as well as large horizontal load, the design of these large diameter monopiles based on the *p–y* curve method may be questionable.

Hald et al. [21] measured vertical and horizontal loads of a monopile installed in sand in an offshore wind farms. The test results were used to verify and to develop design method for offshore wind farm foundations. The tests revealed that the measured response was 30%-50% from the response predicated by the p-y curve technique. Doherty et al. [22] performed field tests by installing an instrumented monopile in dense sand. The tests showed that the conventional design method (p-y curve) overestimated the lateral capacity of the monopiles.

Numerical simulation through finite element analysis carried out by Rahman & Achmus [15], Lesny & Wiemann [23], Jeanjean [24], Pardham [25], Wolf et al. [26], and Jung et al. [27] pointed out that the (p-y) method for the computation of the deformation of large diameter monopiles is not recommended.

Klinkvort et al. [28] conducted laboratory series of tests on laterally loaded piles and they reported that, the pile diameter is the main effective parameters in the capacity of monopiles. Their results agreed well with Lada et al. [29], who performed a numerical analysis and obtained the same results. UnCouglu & Laman [30], and Nicolai & Ibsen [31] studied the effect of the elasticity modulus of sandy soil and the relative density on the performance of monopiles. Le Blanc et al. [32], Christiansen & Moller [33], and Klinkvort et al. [28] performed a series of cyclic loading tests on monopiles and they showed that with the increasing of the number of cycle the soil stiffness increased.

3- Installation procedure of bucket and monopile

The bucket can be manufactured onshore and transported to the construction site by towing. Then it can be installed under its own weight with suction if needed. This process is a simple way, short construction period and cost effective. The soil inside the bucket is used to resist loading, which may reduce the material cost. While, installation of monopiles needs special and huge construction rigs to be transported to the construction site. Also, steel pipe piles have to be transported, hard soil driving may require special soil treatment or special tools. Also, overdriving may damage the piles.

4- Aim Of Research

The choice of the foundation of the wind turbines and the superstructures is a complex task. Therefore, the research is aimed to compare between the behavior of monopiles with buckets under the effect of complex loading (V, H, and M). Meanwhile, the research was focused on the interaction diagrams of ultimate lateral load-ultimate moment (H_U-M_U) developed at different applied vertical loads (V), for both monopiles and buckets.

5- Limitations of research

Monotonic lateral load, instead of cyclic load, was considered. The effects of different wind speeds, and different water waves on lateral load (H) and magnitude of moment (M) were considered by varying lateral load (H) and the point of load application (h) above mud line. Presumed soil stratification was considered. Each layer of soil is considered to be isotropic and homogenous. The effects of installation process of the bucket or the monopile on soil properties are out the scope of this present research.

6-CASE STUDIES

Two case studies are presented in the current research. Firstly, a monopile supporting the superstructure of wind turbine (WT), while in the second, a bucket is used instead of the monopile. The bucket consists of heavy steel lid of thickness equal to 100 mm, provided with a skirt of thickness equal to 30 mm attached to the steel lid. The caisson is completely filled with soil. Fig. (1) presents a schematic drawing of a wind turbine and its foundation. The length of the skirt is equal to 9.00 m and the diameter of the bucket is12.00 m. The length of the monopile is equal to 30.00 m with a diameter of 5.00 m. The wall thickness of monopile is 50 mm. A plate is attached to the pile head of thickness 100 mm to support the superstructure of the wind turbine. The substructures, bucket or monopile, are subjected to different monotonic lateral loads (H) acting at different load eccentricity (h). The geometric parameters of a suction bucket and a monopile are shown in tables (1, and 2). Soil constitutive parameters used in the model are given in fig. (3).

7- STUDIED PARAMETERS

Usually, wind turbines are subjected to environmental lateral loads (H) of different magnitudes, where the vertical load (V) is of a small value compared to the applied lateral load. Therefore, the main dominant load is the moment (M) resulted from lateral load (H) acting on the wind turbine and its superstructure. Accordingly, the considered parameters are lateral load (H), height of the load eccentricity (h). Additionally, the wind turbine may be replaced by another one of smaller or bigger vertical load (V) on the same substructure system, therefore different values of vertical loads (V) were considered in the analysis. Furthermore, length (L) and diameter (D) of substructure are the main concern as studied variables. Due to limitation space of this paper, the effects of the studied parameters are not presented here, the interesting reader can refer to Saad [34].

8- GEOMETRIC AND MODEL DISCRIBTUION

Bucket is simulated as a hollow steel cylinder of diameter (D) equal to 12.0 m provided with a heavily stiffened steel lid of thickness equal to 100 mm. While, steel skirt of length (L) equal to 9.00 m and a thickness of 30 mm was considered in the analysis. To perform finite element simulation, the geometry of the bucket has to be discretized into small elements. The bucket was discretized using 15-nodes triangle elements including soil and bucket. These elements are non-rigid quantic displacement models. So, the walls and the lid can be deformed by shearing, bending and axial deformations. To ensure the results with a sufficient accuracy, the mesh is refined in a volume of soil close to the bucket itself. The soil domain in case of bucket has a diameter equal to 6.67 times the bucket diameter, and of depth equal to twice the skirt length under the tip of the skirt. This means that the total height of soil is about 2.25 times the bucket width.

Monopile is simulated as, a hollow cylinder tube of 5.00 m diameter, and pile penetration depth equal to 30.0 m. The wall thickness of monopile is 50 mm. Monopile was modeled using 15-nodes triangle element including soil element and pile element. Therefore, the wall can deform by shearing, bending, and axial deformations. The plates forming the pile are assigned in order to model the stiffness of the pile. The soil domain in the case of monopile has a diameter equal to 16 times the monopile diameter and with depth equal to twice the monopile length below the mud level. Yang et al. [20] consider a soil domain of diameter 10 times the substructure diameter and a depth of 4 times the substructure length from mud level. The size of soil domain was obtained from sensitivity study carried out by Saad [34]. The vertical load (V) was applied as concentrated load at the center of substructures lid. The lateral load was acted at the same node. While the moment is replaced by two equivalent loads (push& pull) acting at two nods on a line passing through the center node and in the same plan of the applied moment. The distance between the two loads is taken as the diameter of the substructure.

9-Soil stratification

Usually subsoil formation at a construction site may be comprised from different deposits of different properties. Fig.(3) presents the presumed succession of soil layers used in the current study, this succession was considered by Jung et al. [28]. The top 6.0 m of soil formation comprising medium clay, with different shear strength profiles. The top 2.0 m of a constant shear strength, which equal to 44 KN/m^2. The underlying layer, which of a thickness 2.0 m, has a shear strength profile (44+3Z) KN/m^2 , where Z in meter measured from the top surface of the layer. At level 4.0 m, a third clay layer of thickness 2.0 m, has soil strength profile of (50+2.5Z) is considered. The clay layers overlie a bed of sand. The bottom boundary level is (-27.0 m) in case of bucket and (-90.0 m) in case of monopile. The constitutive stiffness (E_S) of the different clay layers was assumed 400 time the undrained shear strength, and having the same profile as (S_U). While (E_S) of sand layer is of a constant value equal to 47MPa, as shown in fig.(3). Poisson´s ratio of clay (v) of 0.495, while for sand (v_S) of 0.35 is considered. The assumption of E_S profile are valid in clay, but inherent approximation in sand bed.

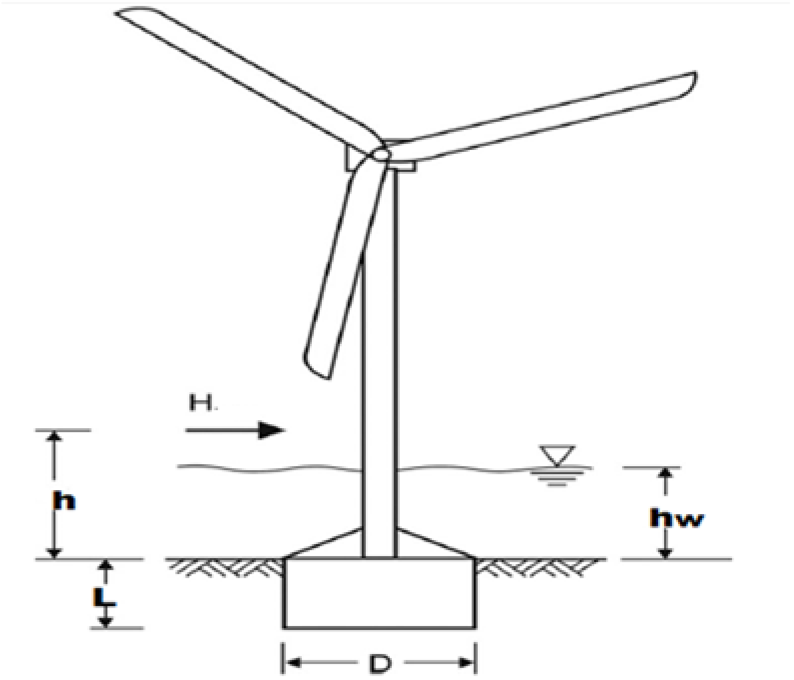

Figure.1: Sketch of a bucket supporting a wind turbine structure [1].

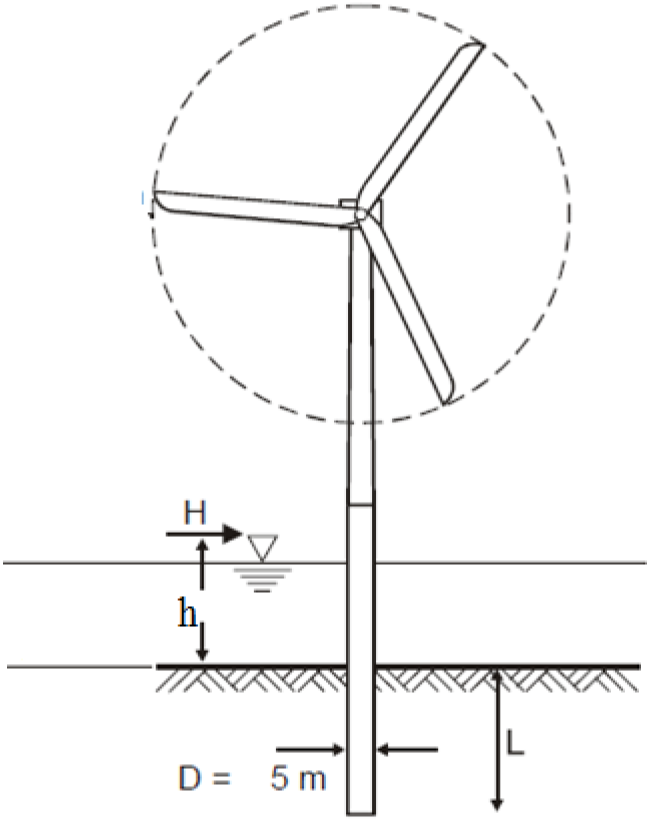

Figure.2: Sketch of a monopile supporting a wind turbine structure [15]

10- BOUNDARY CONDITIONS

The boundaries of the soil domain are chosen so that the failure surface of the substructure has enough space to fully develop without being influenced by traction stress that may be developed along these boundaries. The displacements along the vertical boundaries of the soil domain are restrained horizontally out of the plane direction. The displacements along the bottom boundary of soil domain are restrained in all directions. The top surface of the soil domain including top surface of the substructure was kept free in all directions.

Table.1:Suction Bucket Parameters, Achmus et al. [1]

Parameter	Value
Bucket diameter (m)	12
Skirt length (m)	9
Skirt thickness (t_s) (mm)	30
Young´s modulus of elasticity of bucket material(E_p) (KN/m^2)	2.1E8
Poisson´s ratio of bucket material(ν)	0.3
Buoyant unit weight(γ') (KN/m³)	68
Lid thickness(t_L) (mm)	100

11-LOADS AND SOLUTION STEPS

The analysis is carried out stepwise. Firstly, initial geostatic stress state was modeled by the application of gravity stresses, the coefficient of earth pressure at rest (K_0) was considered as; (K_0= 1 - sinϕ). In the second step, the predefined elements contained within the substructure geometry were replaced by steel elements modeling. In the following loading steps; the vertical load (V) was applied on the substructure lid, which simulating the own weight of the superstructure of the wind turbine (WT) and kept of a constant value. Then, lateral monotonic load (H) and bending moment (M=H.h) were applied in increasing steps until reached the failure of the bucket/ monopile soil system. Each step of loading was started from the initial conditions. The lateral displacement at failure load is considered as 8.3% of the bucket diameter, while it is considered as 20% of the monopile diameter.

. **Table.2: Monopile Parameters, Rahman & Achmus [15]**

Parameter	**Value**
Pile outer diameter (m)	5.00
Pile length (m)	30
Wall thickness (t_s) (mm)	50
Young´s modulus of elasticity(E_p) (KN/m^2)	2.1E8
Poisson´s ratio(ν)	0.3
Buoyant unit weight(γ')(KN/m^3)	68

12-FAILURE LOAD CRETERIA

Lateral ultimate load(H_U) corresponding to horizontal displacement of 1.0m was denoted as; the failure load, Achmus et al.[1]. Different failure load criteria are reported by Saad [34].
The ultimate moment M_U is calculated as;

$$M_{U}= H_{U}.h \tag{2}$$

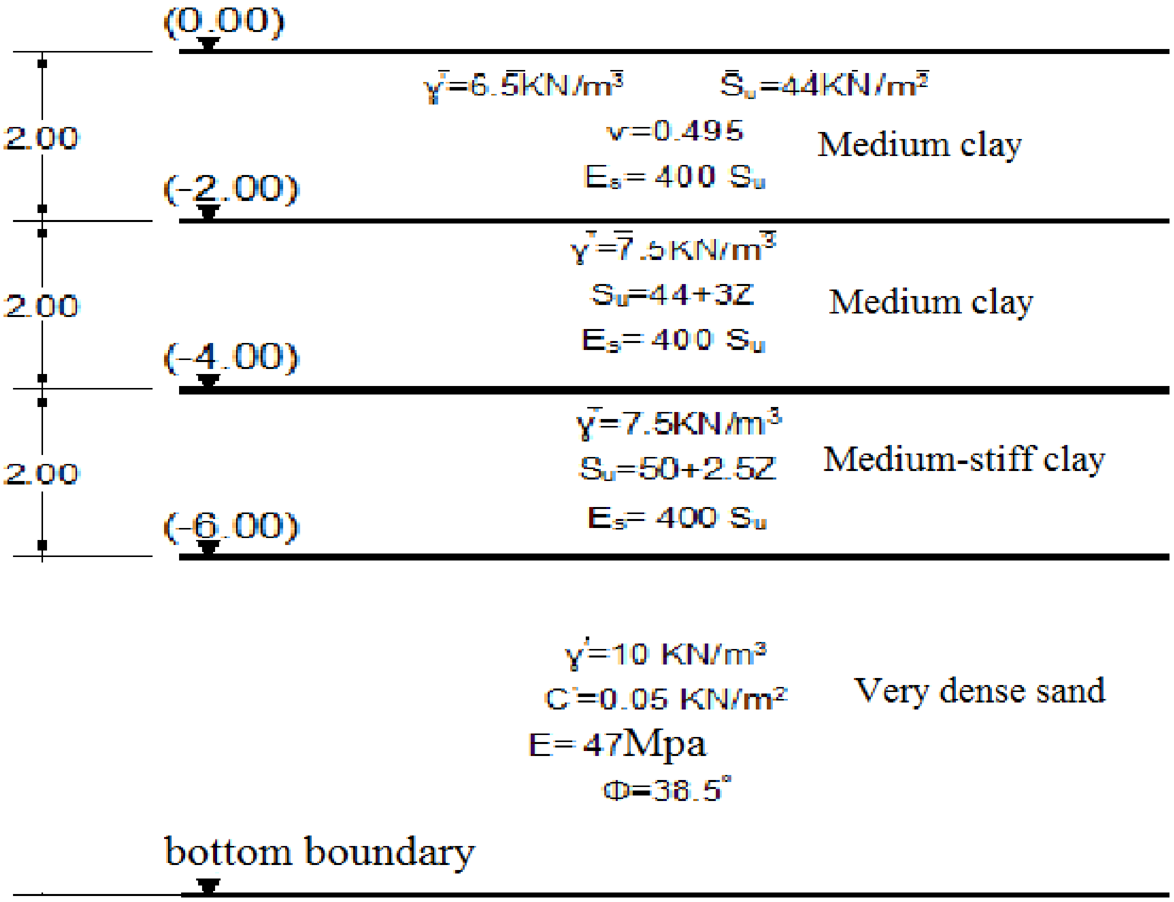

Figure.3: Sketch of soil layer stratification [28].

13-SENSITIVITY STUDY

The refinement of mesh in finite element modeling is a key factor in the precession of results. Therefore, different models with different refinement were built for suction bucket with diameter equal to 12.00 m and skirt length equal to 9.00 m, to investigate the sensitivity of this parameter in the model. The number of elements and nodes are shown in table (3). The obtained results presented in fig.(4). It is obvious that, the mesh refinement has a weak impact on (H-Y) relationships. Results of Achmus et al. [1], lies between fine mesh and medium mesh models. Furthermore, (H-Y) relationships obtained using medium and coarse meshes are identical. Therefore, coarse mesh was adopted in the present study, in order to cut down the computation time without appreciable lack in accuracy.

Table 3.: Number Of Nodes and Element in Considered Meshes.

Mesh description	Nodes number	Elements number
Coarse	5240	1680
Medium	9320	3120
Fine	19101	6560

14-VALIDATION OF THE NUMERICAL MODEL

In order to validate the numerical simulation of the suction bucket, the results of numerical analysis by PLAXIS3D software were compared with the published results by Achmus et al. [1]. The achieved results along with that published by Achmus et al. [1], were compared in fig.(5) at different load eccentricities (h). It is clear that the lateral load- lateral head displacement (H-Y) of the considered suction bucket had a good agreement with Achmus et al. [1], and the tendencies of the relationships are almost similar.

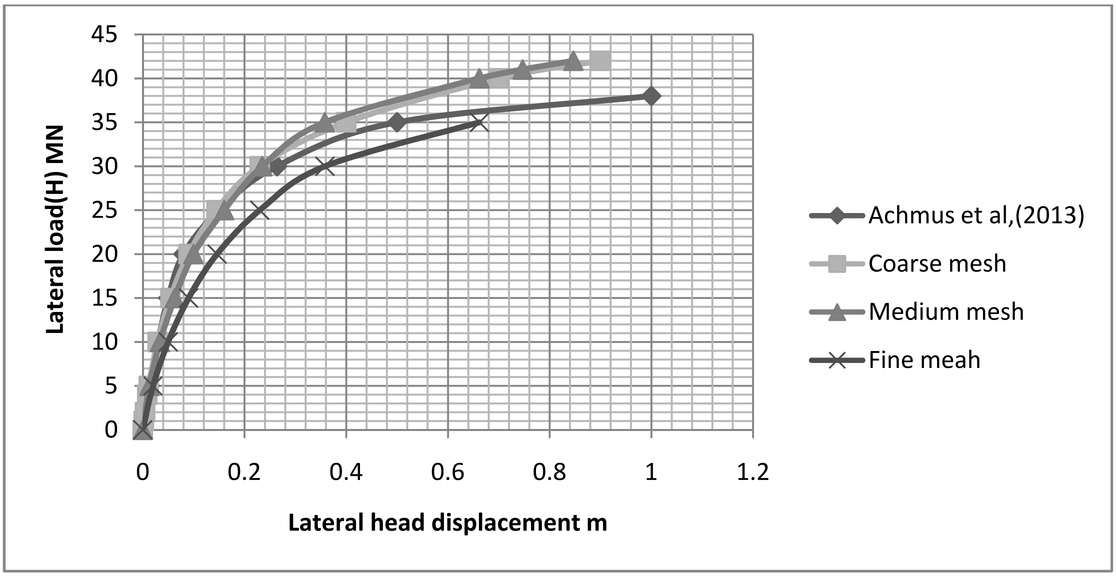

Figure .4: Effect of meshing on H-Y relationship of bucket

Figure (6), presents applied lateral load versus lateral pile head displacement relationships (H-Y) at different load eccentricities (h), along with that published by results Rahman & Achmus [15]. The figure revealed that the obtained results from current study conform well with Rahman & Achmus 's results [15]. Figs.(5) and (6) provided information that the developed numerical model can be used, with reasonable satisfaction, to carry out a parametric study to explore the effects of the relevant parameters.

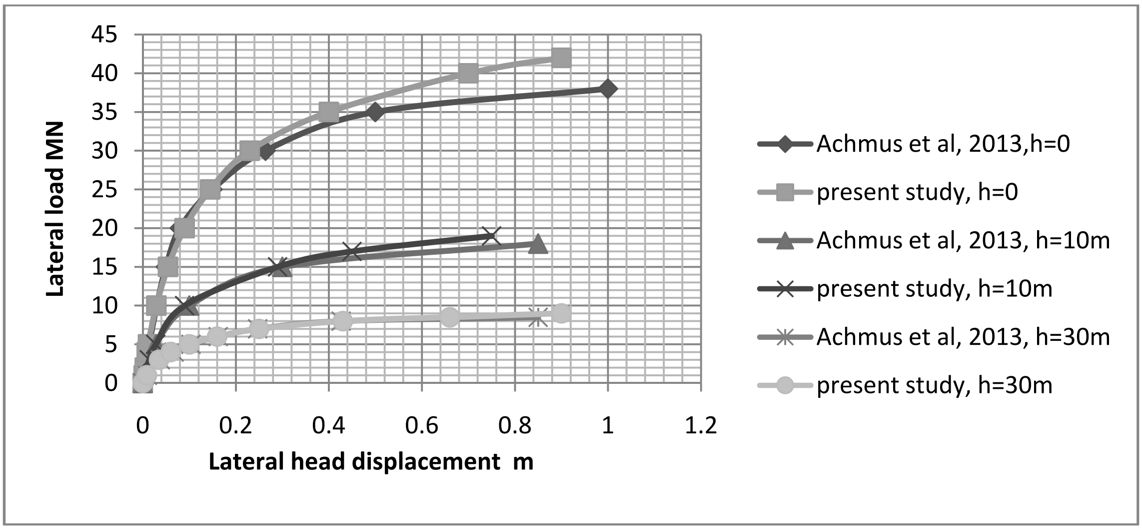

Figure .5: Comparison of present study results for suction bucket with Achmus et al. [1]

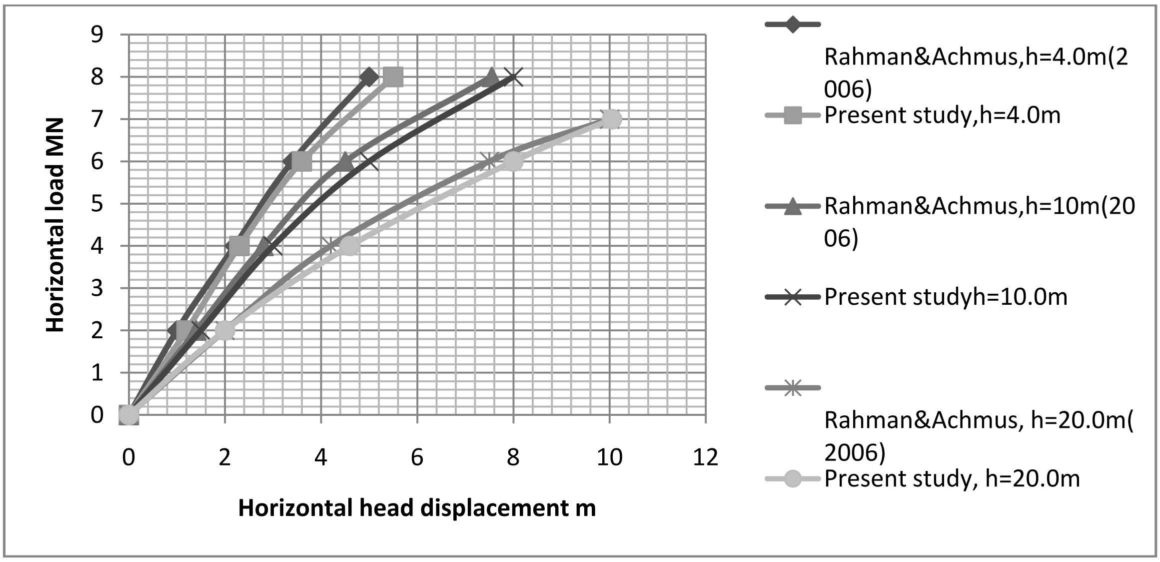

Figure.6 :Comparison of present study results for monopile with Rahman & Achmus [15]

15. PARAMETRIC STUDY

The substructure is normally designed to carry the vertical load (V) in addition to large lateral load (H) and the corresponding moment (M). Vertical load (V) was kept a constant during the application of lateral load (H) and the resulting bending moment (M). The lateral load (H) was applied in increasing steps. The geostatic stress is the initial conditions for each lateral loading step. The resulting moment (M) shall be increased stepwise. The loading continue up to a lateral displacement equal to 1.00 m at the bucket head, which an equivalent to 8.3% of the bucket diameter. In the same manner, monopile was loaded up to lateral displacement equal to 1.00 m, which an equivalent to 20% of the pile diameter. Various loading combinations such as (V, H, and M) were applied on a wind turbine substructure to get different lateral loading conditions. Lateral head load-lateral head displacement (H-Y), moment-rotation (M-ɵ), and lateral load-rotation (H-ɵ) relationships are recorded and drawn. Lateral ultimate load-ultimate corresponding moment (H_U-M_U) interaction diagrams at different load eccentricities (h) were presented. In numerical analyses, different load eccentricities (h) were considered. The load eccentricities (h) were considered as; zero, 5.0, 10.0, and 30.0 m above ground surface.

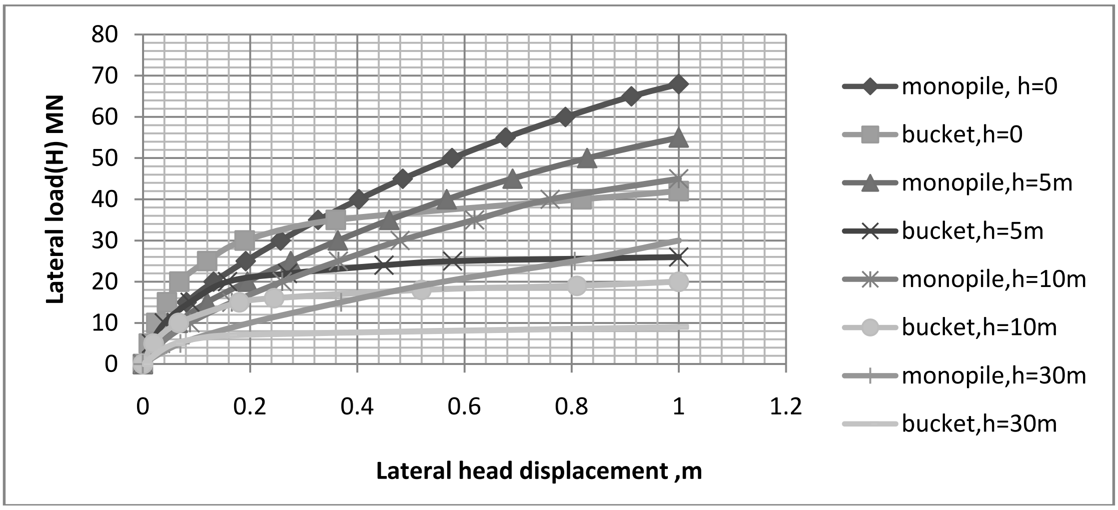

Figure .7: Lateral load- lateral head displacement

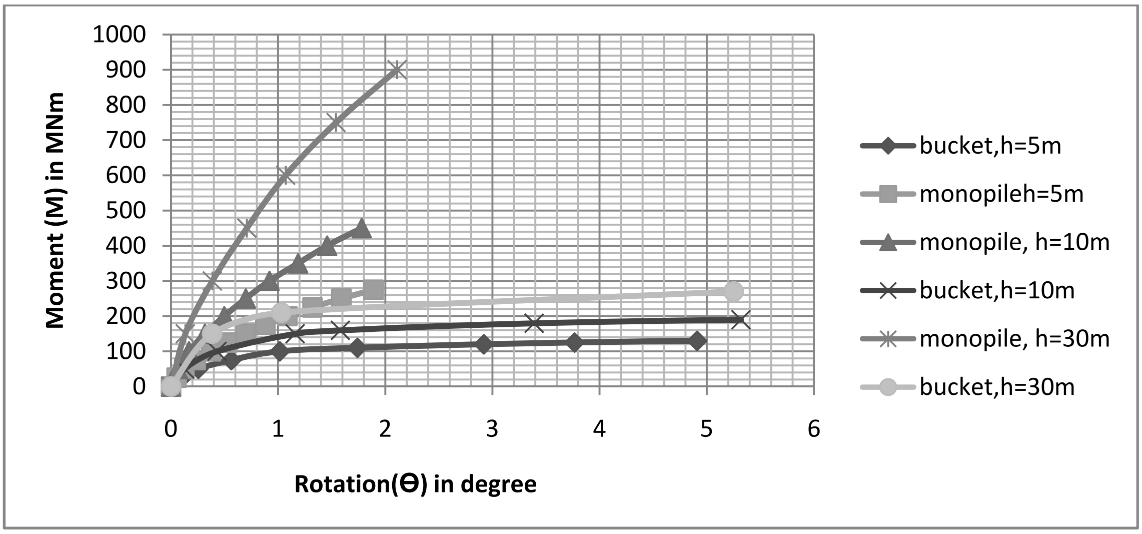

Figure .8: Moment versus rotation of suction bucket and monopile

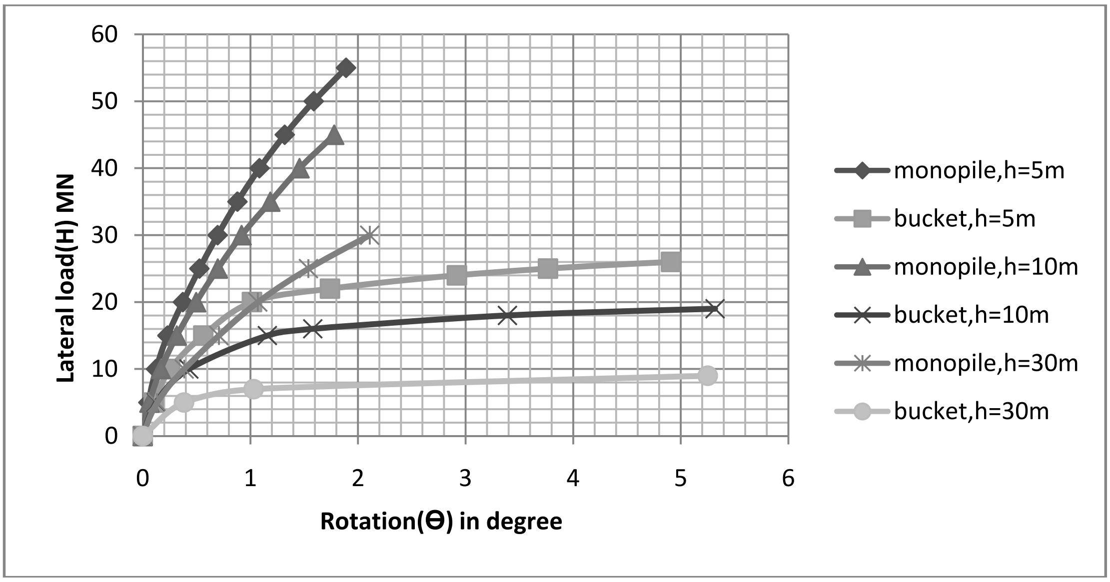

Figure .9 : Lateral load versus rotation of suction bucket and monopile

15.1. EFFECT OF LOAD ECCENTRICITY

Numerical simulation were performed on a bucket with skirt length (L) of 9.00 m, and diameter (D) of 12.0 m (L/D = 0.75). While they were conducted on a monopile of length (L) of 30.00 m and diameter (D) of 5.00 m (L/D = 6). The substructure is considered to be installed in soil stratification shown in fig.(3). Analyses were conducted under vertical load of 10 MN, and horizontal load (H) acting at different load eccentricities (h) of 0, 5.0, 10.0, and 30.0 m above ground surface. The results of the analyses in terms of lateral load-lateral head displacement (H-y), moment-vertical rotation at substructure head (M-ɵ) and lateral load-rotation (H-ɵ), were obtained and drawn through fig.(7) to (9). Load eccentricity (h) significantly affects the lateral loading capacity of the foundation substructure. The finding agrees well with Achmus et al. [1]. The lateral load (H) decreased with the increasing of load eccentricity (h), meanwhile the corresponding moment (M) increased. The figures revealed that, the failure lateral load (H_U) of a monopile of length 30.0 m and diameter 5.0 m is much bigger than that of a bucket of 9.0 m skirt length and 12.0 m diameter. Also, the monopile can resist imposed moment bigger than that resisted by bucket. Figure (9) depicted that, with the increase of load eccentricity (h), the lateral load (H) producing specified rotation decreased due to the increase of moment.

The lateral load-lateral displacement relationship (H-Y) was characterized by initial lateral stiffness (K_W) and ultimate lateral load (H_U), fig (10). At the same time, moment-rotation relationship (M-ɵ) was characterized by initial rotational stiffness ($K_ɵ$), and ultimate moment (M_U), fig(11). The initial lateral stiffness (K_W) and initial rotational stiffness **(**$K_ɵ$) are of main concern in the studying of the response of a bucket and a monopile under combined loads (H, V, and M).

The comparison is evident that, a suction bucket behaves as stiff or even stiffer than a monopile under smaller loads levels, fig.(10).This finding agree qualitatively with Rahman & Achmus [15]. The figure revealed that the initial lateral stiffness of a monopile is much less than the initial lateral stiffness of a bucket. The difference decreased as the load eccentricity (h) increased. While under higher load eccentricities (h), the lateral deformations of the monopile increase strongly compared to the lateral deformations of the bucket, fig.(7). The initial rotational stiffness of the monopile is bigger than that of the bucket, fig.(11).

The ultimate moment (M_U) versus ultimate lateral load (H_U) predicated at different vertical loads (V) is presented in figures (12), and (13) for both of a suction bucket and a monopile. Therefore any combination of loads and moment in region (A) is admissible, while it is unacceptable in region (B). Region (A) expand with the increase of the vertical load (V). The figure revealed that the ultimate lateral-moment loading conditions of the monopile is much higher than that of the bucket. Additionally, the monopile can sustain ultimate moment bigger than that resisted by bucket at the same lateral ultimate loads. This means a monopile of a diameter less than 5.00 m may be equivalent to a bucket of 12.00 m diameter and provided by a skirt of 9.00 m length.

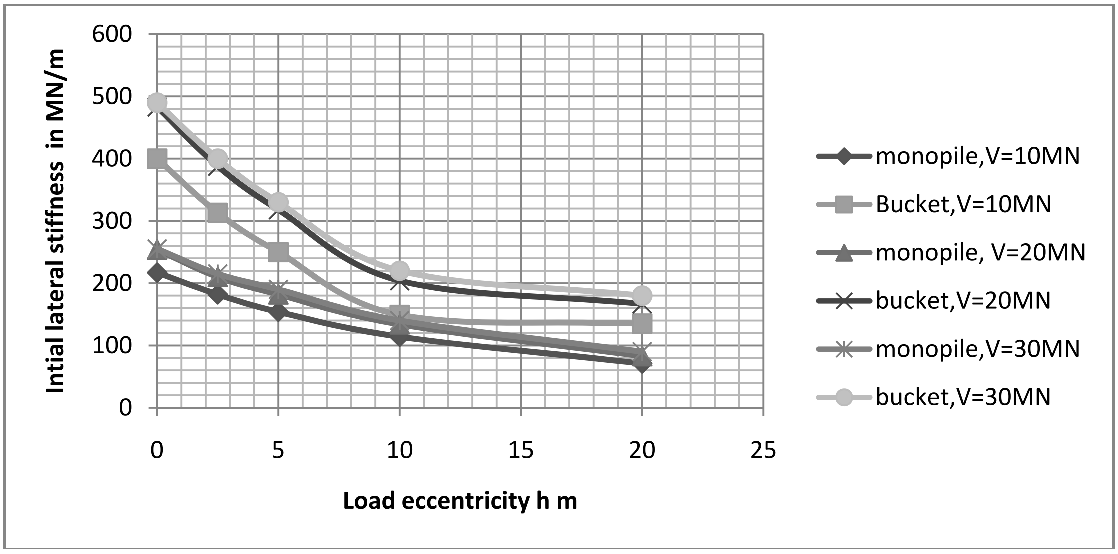

Figure 10.: Initial lateral stiffness (K_W) versus load eccentricity of suction bucket and monopile

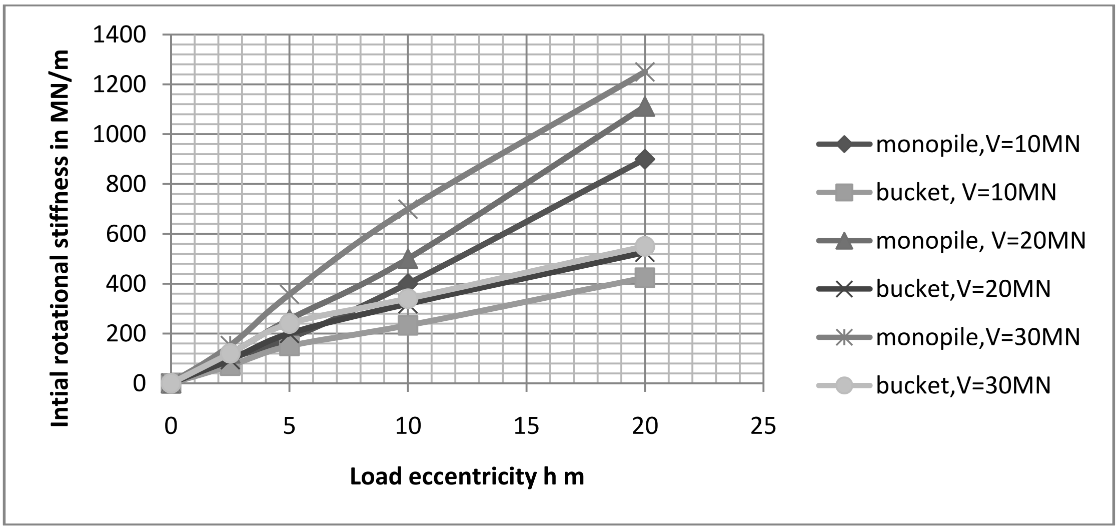

Figure .11 : Initial rotational stiffness (K_θ) versus load eccentricity of suction bucket and monopile

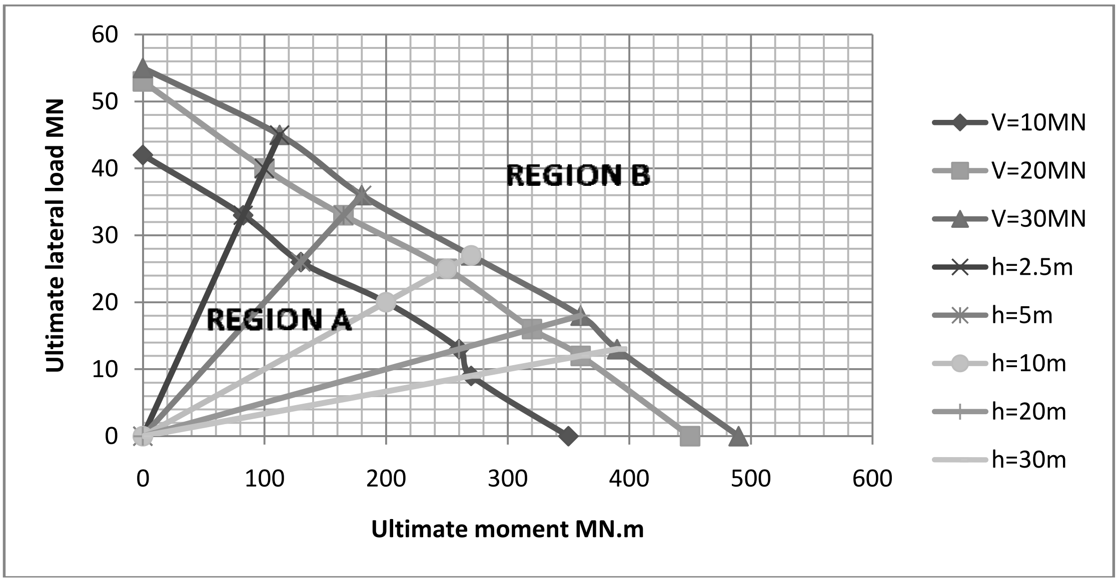

Figure. 12:Interaction diagrams for a suction bucket

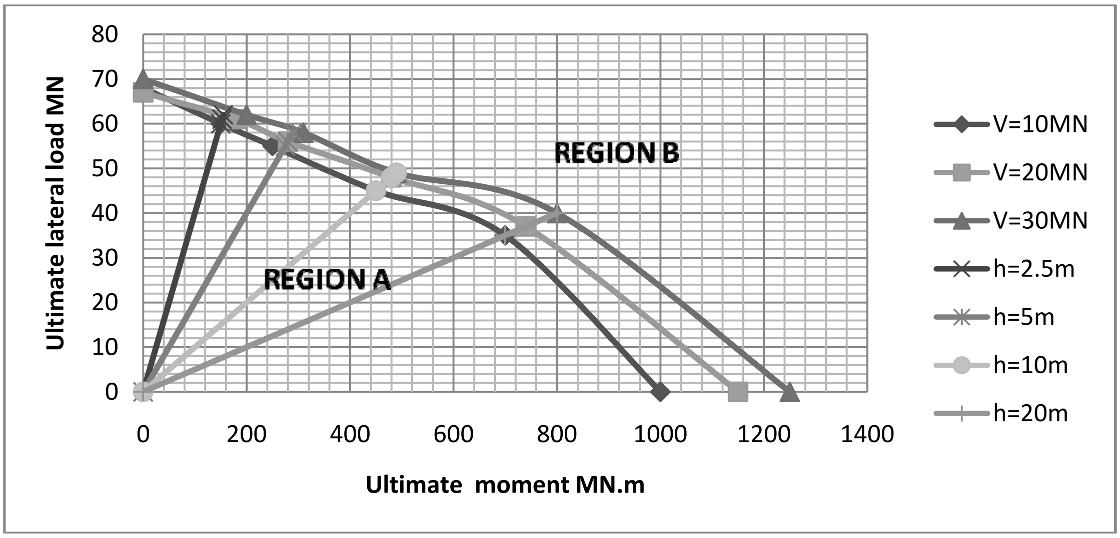

Figure .13.: Interaction diagrams for a monopile

16. CONCLUSIONS

Buckets and monopiles as wind turbine substructures installed in stratified soil, have been simulated by a three-dimensional finite element model using Plaxis 3D software. Numerical simulations were performed on a bucket of a diameter 12.00 m provided by a skirt of 9.00 m length, while they were conducted on a monopile of a length of 30.00 m and a diameter of 5.00 m. A parametric study was carried out to investigate the effects of the related variables on the response of each foundation proposal. From the obtained results, the following conclusions were revealed;

1. The relationships between lateral load-lateral displacement (H-Y), moment-rotation (M-ɵ) and lateral load-rotation (H-ɵ) showed that with an increase of the load eccentricity (h) the resisted lateral load of both proposals decreased, because the corresponding moment increased.
2. With an increase of load eccentricity (h), the rotation of a substructure due to the applied moment (M) decreased, due to the decrease of lateral load (H).
3. With an increase of load eccentricity (h), the rotation of a substructure, due to lateral load (H) increased, due to the increase of moment (M) imposed on a substructure head.
4. With an increase of load eccentricity (h), the ultimate lateral load decreased, meanwhile the ultimate moment increased.
5. The initial lateral stiffness and the initial rotational stiffness of a wind turbine substructure are dependent on both of load eccentricity (h), and vertical load (V).
6. The initial lateral stiffness of a bucket is much higher than that of a monopile while, the initial rotational stiffness of the monopile is higher than that of the bucket.

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