Offshore Piles under Combined Pullout Loading

Mohamed I. Ramadan

Civil Engineering Department, Faculty of Engineering-Rabigh, King Abdulaziz University, KSA
Corresponding Author Email: *maramadan[at]kau.edu.sa*

Abstract: ***Offshore piles are being used at harsh environment. These piles could be monopiles for supporting offshore wind turbines, or anchor piles to moor floating structures. These piles are usually subjected to a wide range of monotonic and cyclic lateral-to-inclined pullout forces. There is no design methods recommended for offshore piles subjected to inclined pullout loads. Most of the research done in this area was for lateral or tension loads on the piles. The effect of horizontal and vertical components of applied load has been assumed to be uncoupled. The present study aims mainly to provide design recommendations for offshore piles in dense sand subjected to monotonic inclined pullout loading. Three-dimensional finite element method was used to simulate the problem under study. Soil was modeled using plasticity constitutive model obeying hardening-softening rule. Soil-pile interaction was considered in the study using contact elements between pile and soil. The effect of pile installation was considered. It was found that there is a significant interaction between both tension and lateral loading. This interaction should not be neglected in the design of offshore piles*.**

Keywords: offshore, piles, pullout; combined, sand

1. Introduction

Offshore piles are usually subjected to a wide range of monotonic and cyclic lateral-to-inclined pullout forces. These piles could be mono-piles for supporting offshore wind turbines (Abdel-Rahman and Achmus, 2006), or anchor piles to moor floating structures (Bhattacharya et al., 2006, Ramadan et al., 2013a, and Ramadan et al., 2013b). Due to the complexity of the response mechanism of an inclined pullout loaded pile, this problem has received little attention. The analyses proposed have made very crude assumptions that may invalidate their applicability to full scale. Most of the research done in this area was for lateral or tension loads on the piles. The effect of horizontal and vertical components of applied load has been assumed to be uncoupled, Yoshimi (1964), Broms (1965), Chattopadhyay and Pise (1986), and Jamnejad and Hesar (1995).

The pile resists the inclined pullout loading by a combination of bending plus passive resistance and skin friction shear. Bhattacharya et al. (2006) reported that the geotechnical analysis of a pile subjected to inclined pullout loading can be de-coupled, in the sense that the axial and lateral capacities can be considered independently. Their assumption is considered valid based on the understanding that the axial tension capacity is provided by the soil around the lower part of the pile, whereas lateral resistance is provided mainly by the soil around the upper part of the pile, typically to a depth of 3 to 6 times the diameter of the pile. In addition, the lateral load component loads the soil passively whereas the axial tension load component loads the soil in shear. Therefore, they suggested no significant interaction is expected for long piles. However, for short/rigid piles both lateral and axial pullout load components will interact. Most of offshore mono-piles and anchor pile can not be considered as long piles. Also, it should be noted that the assumption of de-coupling of lateral and axial pullout components for long piles may not be valid for offshore driven pipe piles as concluded by Ramadan et al., (2013a).

Ramadan et al., (2013a) performed a series of centrifuge tests to study the behavior of offshore anchor piles under inclined pullout loading. The study was extended to a parametric study using Finite Element Modeling (FEM), Ramadan et al., (2013b). FEM was calibrated using the centrifuge tests results. They concluded that when a pile is subjected to inclined pullout loading, the tension load component will cause elastic “Poisson” radial contractions of the pile cross section, which is more significant with pipe piles as reported by Jardine et al. (2005) (ICP method). This radial contraction of the pile section will cause both an increase of pile flexural stiffness and a decrease of soil confining pressure around the pile. Two design methods were proposed to predict the ultimate total capacity and the maximum bending moment of the pile. It should be noted that their simulation was successful for the case of pure lateral loading. However, maximum pile bending moment and soil pressure were over-predicted for the case of inclined pullout loading. This could be due to modeling the soil using elastic perfect plastic Mohr Coulomb model. That model does not allow for hardening – softening behavior which is the case of dense sand.

Three-dimensional finite element method was established to simulate the problem under study. Soil was modeled using plasticity constitutive model obeying hardening-softening rule. This soil model will overcome the shortcomings of using elastic perfect-plastic Mohr Coulomb model for soil. The soil model followed soil parameters recommended by Daiyan et al. (2011). The presented study aims at identifying the behavior and capacity of offshore rigid piles in dry dense sand subjected to monotonic inclined pullout loading.

2. Finite Element Model

A 3-D FEM was established to study the behavior of offshore piles subjected to inclined pullout loading. The commercial finite element analysis program ABAQUS 6.10 (Hibbitt et al. 2010) was used in the analysis. The first step in this analysis was the geostatic step for the soil, to apply soil gravity. In the next step, the pile and the contact elements were activated, and a prescribed displacement was applied at the top of the pile. The prescribed displacement had been applied with different angles (θ) to horizontal at the ground surface (no eccentricity; e = 0). A sketch of the problem under study is shown in Fig. (1). In this section the FEM geometry, meshing, constitutive models of the pile and the soil, and soil-pile interaction will be discussed.

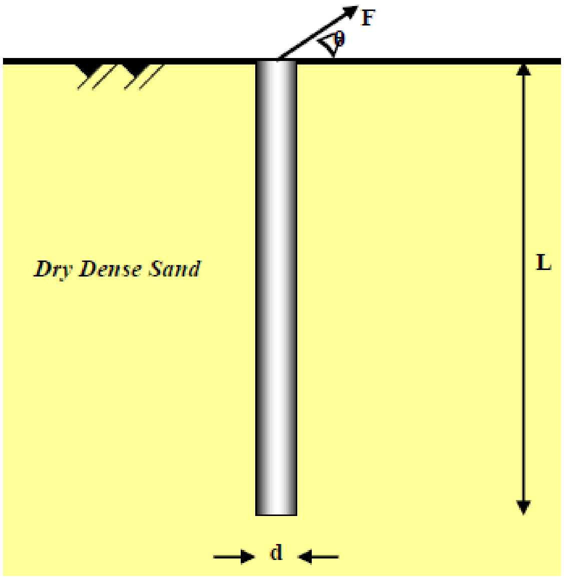


Figure 1: Problem under study

2.1. Model Geometry and Meshing

Figure 2 shows the geometry of the FEM. Due to the symmetric loading condition only a half-cylinder representing the soil and the pile was considered. The boundaries of soil domain were selected to minimize boundary effects on pile behavior. The soil boundaries extend horizontally 20 times the pile diameter, while below the pile tip the soil extends 7 times the pile diameter. The model boundary at the bottom is restrained from displacement in all directions. The side boundary is restrained from horizontal displacement. At the symmetry plane, the boundary is restrained from displacement in the perpendicular direction. The top of the model is free to move.

The finite element mesh used in the analysis is shown in Fig. 2. Eight-node continuum brick elements with reduced integration (C3D8R) were used for soil domain. The elements are biased towards the pile to have finer mesh close to the pile where the stresses are expected to be higher. The mesh is coarser farther from the pile to reduce the analysis processing time. Four node shell elements with reduced integration (S4R) were used for pile. The pile was modeled as a pipe pile of 2 m diameter, d and 8 m length, L. To have different pile flexural stiffness (EpIp) for the same axial stiffness (EpAp), pile wall thickness, t was changed.

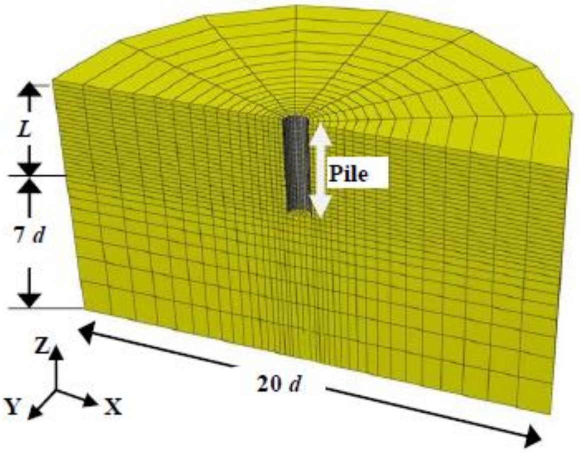


Figure 2: Finite element model meshing and geometry

2.2. Constitutive Models

The pile material is assumed to be linear elastic. The linear elastic material is defined by the elastic Young's modulus of the pile material (Ep) and Poisson's ratio (νp). Offshore piles are usually made of steel. The Young's modulus of steel is 2.1 × 108 kN/m2 and the Poisson's ratio(νp) of steel is about 0.3. However, to simulate different pile flexural stiffness for the same axial stiffness in the current analysis, different Ep values were used as shown in Table 1. All piles have an axial stiffness (EpAp) of 3.9 x 107 kN.

Mohr Coulomb plasticity constitutive model was used to model dense sand behavior. Non-linear elastic behavior was simulated by the constitutive model prior to reaching the yield surface. Soil elastic modulus (Es) was defined simulate its dependence on soil stress.

Hardening/softening behavior of dense sand have been expressed in terms of friction angle (ϕ) and dilation angle (ψ) as a function of plastic strain magnitude (ε_{pl}), Nobahar et al. (2001).

2.3. Soil-Pile Interaction

A basic Coulomb frictional model was used to govern the interaction between the pile and sand surfaces. The contact surface approach, in ABAQUS, allowed for separation and sliding of finite amplitude and arbitrary rotation of the contact surface. When surfaces are in contact, they usually transmit shear as well as normal forces across their interface. It was assumed that the soil and pile are both deformable bodies and can undergo finite relative sliding. In the FEM analysis a value of 0.6 was assumed for μ along the soil-pile interface.

2.4. Modeling Pile Installation Effect

Pile installation method has a major effect on the pile loading behavior. For offshore driven piles, the lateral stresses will increase in the soil in a limited zone adjacent to the pile. In the current analysis, the lateral earth pressure coefficient (K) after pile installation was calculated based on the Imperial College pile (ICP) 2005 method (Jardine et al. 2005). The soil was divided into horizontal layers. The lateral earth pressure coefficient (K) values were assigned to each layer. Although the increase in the lateral stress should be limited to a specified zone around the pile, it has been found, to simplify the model and due to the numerical convergence, that increasing the lateral stress along the full width of the soil model has small effect on the results.

3. FEM Results

The current study was carried out by changing pile flexural stiffness and keeping pile axial stiffness constant. In all cases the pile was loaded at the ground surface (no eccentricity; e = 0) at loading inclination angles θ = 0˚, 15˚,30˚, 60˚, and 90˚ to horizontal. Although offshore anchor piles are usually subjected to mooring forces with maximum loading angles of about 30°, as reported by Randolph et al. (2005), higher loading angles were examined in the present study to understand the effect of the interaction between vertical and horizontal pullout loading on offshore anchor pile behavior. The analysis was carried out for piles of a range of (L/T) less than 3.0 which was not considered by Ramadan et al. (2013b). Soil-pile rigidity was calculated as the ratio of pile length (L) to the elastic length (T). The elastic length was calculated using the equation suggested by API (2000), as follows:

$$T = \sqrt[5]{\frac{E_p I_p}{n_h}}$$

where n_h is the constant of horizontal subgrade reaction (FL−3 dimensions). It was assumed to be 40 MN/m3 as recommended by API (2000) for dense sand.

Figure (3) shows vertical load (V) - vertical displacement (v) relationship at pile head for all cases. It can be observed that the behavior of all piles are almost identical under tension loading (θ = 90˚). This is because all piles have the same axial stiffness (EpAp). The selected range of (L/T) of all cases is small. This is clear from Fig. (5) where the change in the initial stiffness of horizontal load (H) – horizontal displacement (u) relationship at (θ = 0˚) is small. As (L/T) increases the initial stiffness slightly increases.

Figure (6) shows the horizontal load (H) versus horizontal deflection (u) relationship, vertical load (V) versus vertical displacement (v) relationship, and total load (F) versus total displacement (w) relationship for case (3) at (θ = 30˚). There is a significant interaction between lateral and vertical pullout loading conditions. The lateral load component is affected by the vertical pullout loading. Due to tension load component the lateral capacity of pile increases significantly by increasing (L/T).

The ultimate tension capacity (Vmax) increases by increasing (θ). This increase in (Vmax) is almost constant for all (L/T) values, as shown in Fig. (7); where (Vo) is the ultimate tension capacity at (θ = 90˚). By increasing (u) at the pile head, the increasing rate of (H) starts to decrease at a specified point. However, this deviation from the initial stiffness of the lateral load component happens when the pile starts to fail in tension. This is observed for all piles regardless of the soil-pile rigidity (L/T).

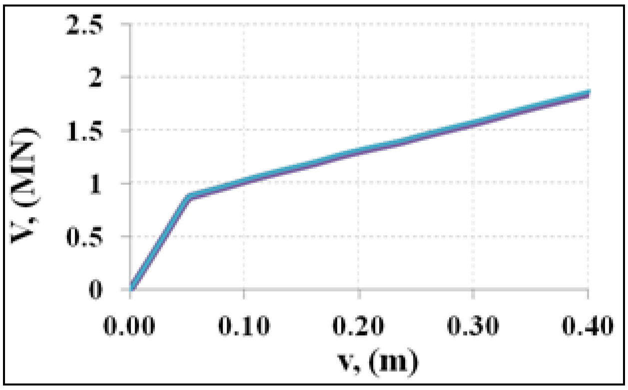


Figure 3: Vertical load (V) - vertical displacement (v) of all piles.

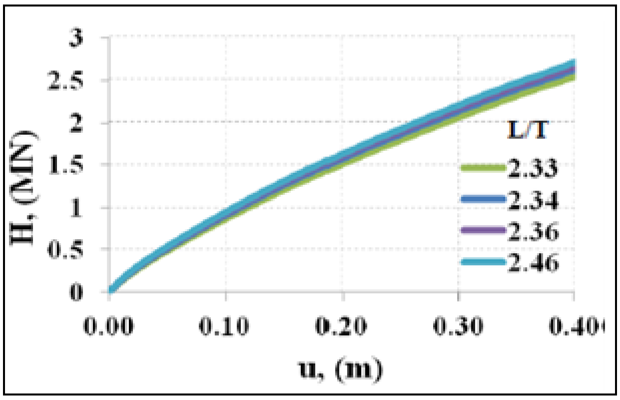
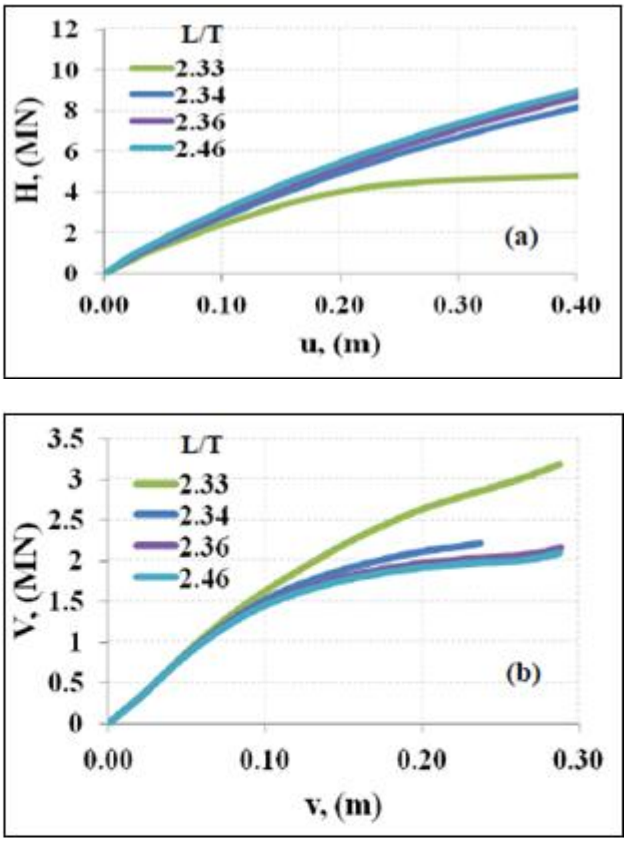


Figure 4: Horizontal load (H) - horizontal displacement (u) of all piles



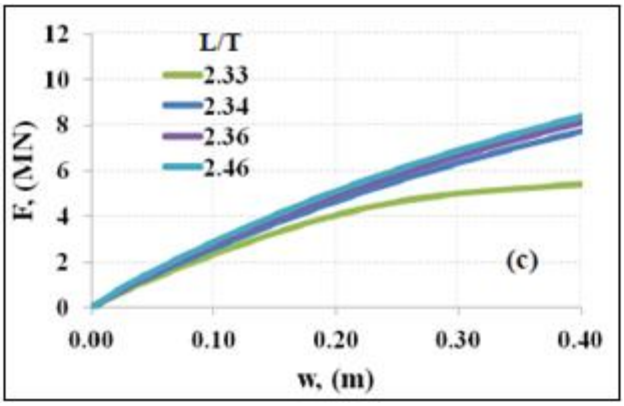


Figure 5: Load – displacement relationships at pile head. (θ = 30˚): (a) horizontal component, (b) vertical component, (c) total load

4. Results Analysis

From the previous results, it can be seen that the behavior of rigid offshore piles that have the same axial stiffness (EpAp) will be affected by the change of pile flexural stiffness (EpIp) or pile-soil rigidity (L/T) under inclined pullout loading. Although the change of (L/T) is small, it has a significant effect on the behavior of rigid offshore piles. Before tension failure, by increasing (L/T) pile elongation (Δv) increases. This increase in pile elongation from the case (θ = 90˚) is due to pile bending. The increase in (Δv) will cause contraction in pile section and a decrease in pile rotation.

The ultimate capacity of a rigid offshore pile subjected to inclined pullout load was obtained when the pile failed in tension. The ultimate tension pile capacity for different (θ) values was determined by plotting the vertical load–displacement curves on log–log scale and picking the point of maximum curvature to bethe failure load. Figure (6) show the change of the normalized pile ultimate capacity (Fmax / Vmax) with loading angle (θ); where (Fmax) is the total ultimate capacity of pile. It can be observed that (Fmax / Vmax) decreases by increasing (θ) for all cases. The rate of the decrease increases by increasing (L/T).

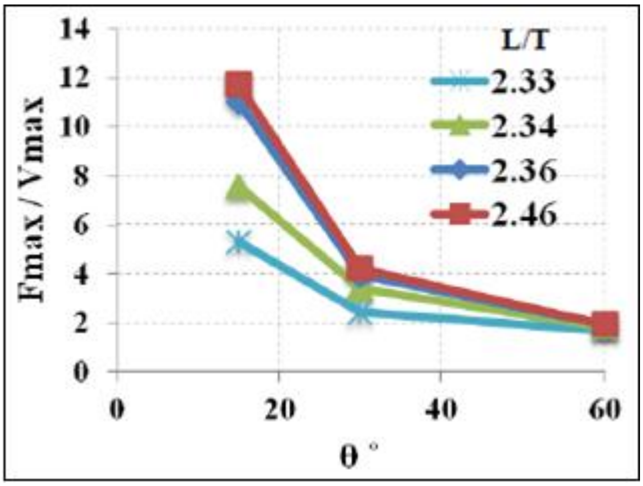


Figure 6: Normalized total capacity (Fmax/Vmax) versus loading angle (θ).

5. Conclusion

In this paper, FEM was used to study the behavior of offshore rigid piles under inclined pullout loading. It can be concluded that there is a significant interaction between lateral and vertical load components. The maximum tension capacity of a pile subjected to inclined pullout increases by increasing (θ) for all cases regardless of (L/T) value. This means that the lateral load component contributes in increasing the tension capacity. As the rigid pile rotates, bending of pile causes additional elongation and increase of soil shear stresses along pile surface especially close to pile tip as observed by Ramadan et al. (2013a & b) as well.

Also, the vertical load component increases the lateral capacity of rigid pile. The vertical load component cause elastic “Poisson” radial contractions of the pile cross section, which is more significant with pipe piles. This radial contraction of the pile section will cause an increase of pile flexural stiffness. This is observed as a reduction of pile bending moment and pile rotation.

Over a small range of (L/T), the effect of pile flexural stiffness is significant. By increasing (L/T), total ultimate capacity of a rigid pile increases and bending moment decreases. This means that the effect of the presence of vertical load component becomes more significant as pile flexibility increases. By increasing (L/T) under inclined pullout loading, offshore rigid pile behaves stiffer.

References

[1] Abdel-Rahman, K., and Achmus, M. (2006) Numerical Modeling of the Combined Axial and Lateral Loading of Vertical Piles, *Proceedings of the Sixth European Conference on Geotechnical Engineering*, Graz, Austria.

[2] API (2000) *Recommended practice for planning, designing and constructing fixed offshore platforms working stress design*. RP2A-WSD 21st ed. American Petroleum Institute.

[3] Bhattacharya, S., Carrington, T.M., and Aldridge, T.R. (2006) Design of FPSO piles against storm loading. *Offshore Technology Conference*, OTC 17861.

[4] Broms, B.B. (1965) Piles in Cohesionless Soil Subject to Oblique Pull, Discussion, *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 9, p. 199-205.

[5] Chattopadhyay, B.C., and Pise, P.J. (1986) Ultimate Resistance of Vertical Piles to Oblique Pulling Load, *In Structural Engineering and Construction: Advances and Practice in East Asia and The Pacific, Proceedings of The First East Asian Conference on Structural Engineering and Construction*, Bangkok, Thailand. Vol. 1, p. 1632-1641.

[6] Daiyan, N., Kenny, S., Phillips, R., and Popescu, R., (2011) Investigating pipeline-soil interaction under axial-lateral relative movements in sand, *Canadian Geotechnical Journal*, Vol. 48, p. 1683- 1695.

[7] Hibbitt D., Karlsson B., and Sorensen P. 2010. ABAQUS User’s Manual. Version 6.10 [computer program]. ABAQUS, Inc., Providence, R.I.

[8] Jamnejad, G.H., and Hesar, M.H. (1995) Stability of Pile Anchors in the Offshore Environment, *Transactions of the Institue of Marine Engineers*, Vol. 107, p. 119-134.

[9] Jardine, R.J., Chow, F.C., Overy, R.F., and Standing, J.R. (2005) *ICP Design Methods for Driven Piles in Sands and Clays*, Thomas Telford, London.

[10] Nobahar, A., Popescu, R., and Konuk, I. (2000) Estimating Progressive Mobilization of Soil Strength, *Proceedings of the 53rd Canadian Geotechnical Conference*, Montréal, Que., Edited by D. Leboeuf. BiTech Publishers Ltd., Richmond, B.C.

[11] Ramadan, M. I., Butt, S. D. and Popescu, R., (2013a) Offshore Anchor Piles under Mooring Forces: Centrifuge Modeling, *Canadian Geotechnical Journal*, Vol. 50, p. 373- 381.

[12] Ramadan, M. I., Butt, S. D. and Popescu, R., (2013b) Offshore Anchor Piles under Mooring Forces: Numerical Modeling, *Canadian Geotechnical Journal*, Vol. 50, p. 189-199.

[13] Randolph, M.F., Cassidy, M.J., Gourvenec, S., and Erbrich, C.J. (2005) Challenges of Offshore Geotechnical Engineering: state of the art paper. *Proceedings of International Conference on Soil Mechanics and Foundation Engineering*, Osaka, Japan.

[14] Yoshimi, Y. (1964) Piles in Cohesionless Soil Subjected to Oblique Pull, *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 90, p. 11-24.