Forensic investigation of laterally loaded screw pile using finite element analysis

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ABSTRACT

Recent studies on the screw piles indicate that it has huge potential to resist the lateral loads. Large diameter screw piles may be useful to support wind turbines where it could be subjected to a significant amount of lateral loads due to wind. In this paper, a forensic investigation is conducted to determine the failure behaviour of a laterally loaded screw pile installed in sand using three dimensional finite element analysis. Lateral behaviour of screw piles (single and double helix) are backpredicted in terms of lateral load-deflection curves and the results are compared with the measured field tests data. In the analysis, the soil is modelled using Mohr-Coulomb criteria and the shaft and helix are modelled as a linear elastic material. The interface between the shaft, soil and the helix is modelled using the master-slave approach available in ABAQUS. The numerical results for the single-helix pile are found to be in good agreement with that of the field tests data. However, for double helix pile, the backpredicted lateral load-deflection behaviour deviates from the field tests. This deviation may be due to the soil disturbance caused during installation which is not considered in the present study. The ultimate lateral capacity of the screw pile is also backpredicted using the finite element analysis and the available empirical and analytical relationship. The results are finally compared with that of the field tests data. Forensic study shows that the available empirical and analytical relationships highly overpredicts the ultimate lateral capacity and is valid only for rigid/short screw piles. Therefore, future study should focus to develop improved relationships involving flexible/long screw piles.

Keywords: Forensic investigation, screw pile; field tests; finite element analysis; lateral load capacity

1 INTRODUCTION

Screw piles generally consist of a central hollow steel shaft with helical plates attached to it and are installed into the ground by applying torque and axial force (Al-Baghdadi et al. 2017). These are gaining popularity as they can be installed quickly with a minimum soil disturbance and can be loaded immediately (Wang et al. 2013). Screw piles are used in different applications (residential and commercial buildings, light poles, solar farms, and wind turbines, etc.) to resist the axial compressive, uplift and lateral loading (Elsherbiny and El Naggar 2013). The typical sources which contribute to the lateral load include wind load, earthquake load, load eccentricity, and unbalanced earth pressures (Sakr 2010). The past studies show that there is significant progress made in terms of the installation and in increasing the axial capacities of the screw pile (Sakr 2010). However, limited information is available on the lateral behaviour of screw piles at failure. The failure of piles can be assessed based on various criteria. According to IS 2911, Part 4, the ultimate lateral load capacity is the load corresponding to 12 mm lateral deflection (this is similar to the ultimate axial capacity of pile. The tolerable lateral deflection of pile typically ranges from 5-50 mm (Salgado 2008). Reddy and Ayothiraman (2016) defined that the ultimate lateral pile capacity is the load beyond which the load-deflection curve becomes linear or the load estimated using double tangent method.

Forensic study which in general is a back analysis based on the actual failure observations (Rao 2016) could play an important role to understand the lateral behaviour of screw piles at failure. Muthukkumaran et al. (2016) conducted a forensic investigation on a series of field piles to assess the failure behavior of piles subjected to axial load. The study revealed that the failure of the piles occurred due to the lack of proper soil investigation and improper installation of the pile. Madhabhushi (2016) conducted a series of centrifuge tests (Madhabhushi 2016) to study the failure mechanisms (buckling and excessive settlement) of piles subjected to earthquake-induced liquefaction and lateral spreading. However, the past studies are limited to normal piles and till now no forensic study has been reported to assess the failure of laterally loaded screw piles. In this regard, the finite element modelling could be a useful tool to carry out the forensic studies of laterally loaded piles (Kumar et al. 2019).

In the present paper, the forensic investigation of laterally loaded screw piles installed in the sand is conducted using three-dimensional (3-D) finite element analysis. The load-deflection behaviour of the piles is backpredicted using the field tests data (Sakr 2010). The ultimate lateral capacity of screw piles are also backpredicted using the finite element analysis and available empirical and analytical formula and the results are then compared with that of the measured values from the field test.

2 FIELD TESTING

Field tests are carried out by Sakr (2010) to determine the ultimate lateral resistance of single and double-helix piles installed in dense to very dense sand. The site soil conditions reported up to a depth of 18 m are shown in Table 1. Two pile types 3A (1-helix) and 6A (2-helix) with an embedment depth of 5.6 m and 6.5 m respectively were installed at the test site and their properties are shown in Table 2. Loads were applied to the screw pile at a height of 200 mm above the ground level using a hydraulic jack. Pile types 3A and 6A were loaded to its ultimate lateral capacity producing a lateral deflection of 80 mm (24% of shaft diameter) and 78 mm (19% of shaft diameter) respectively. Figure 1 shows the typical installation set-up of the helical pile in the field (Sakr 2010).

3 FINITE ELEMENT ANALYSIS

The lateral load-deflection behaviour of the field pile (Sakr 2010) is backpredicted using a three-dimensional finite element analysis (ABAQUS CAE 2018). The soil, shaft and the plate are modelled using 8-noded, linear brick (C3D8R) element with hexahedral element shape. Interaction is provided between the soil-shaft and soil-helix with the help of the penalty method available in the ABAQUS. The coefficient of friction for the screw pile and soil is chosen to be 0.7 (Al-Baghdadi et al. 2017). Figure 2 shows the finite element model along with the boundary and loading conditions. Mesh convergence study has been done for both the pile types (3A and 6A) before performing the analysis and the meshing is shown in Figure 3. The boundary conditions provided include: bottom surface of the soil is fully fixed and the vertical boundaries were restrained in the horizontal direction. The soil is modelled assuming the Mohr-coulomb criteria and the shaft and helix were modelled as a linear elastic material.

In order to minimize numerical instability, a small amount of cohesion (1 kPa) is provided to the soil. To determine the ultimate lateral capacity of the screw pile, initially gravity load is applied to generate the in-situ stresses in the soil and lateral loads are applied later. The screw pile installation is neglected and is considered to be wished-in-place. For simplicity in modelling, the helical plates as modelled as flat plates.

Table 1. Soil properties

Depth (m)	Soil	SPT Number	Total unit weight (kN/m^3)	Angle of internal friction, ϕ (°)
0 – 10	Sand (dense)	23 – 37	18	36
10 – 18	Sand (dense to very dense)	41 – 63	20	40

Table 2. Pile properties

Pile type	Shaft		Helixes		Number of helixes
	Diameter, D (mm)	Thickness, t (mm)	Diameter, D_h (mm)	Thickness, t_h (mm)	
3A	324	9.5	610	25.4	1
6A	406	9.5	762	25.4	2

Fig. 1. Installation of the screw pile (Sakr 2010)

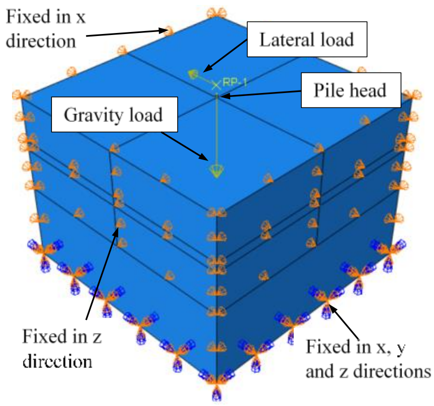

Fig. 2. Finite element model with partition and boundary conditions

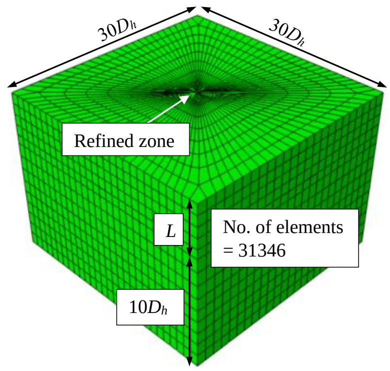

Fig. 3. Finite element mesh with boundary extents

4 RESULTS AND DISCUSSION

Finite element analysis is carried out for the single and double-helix piles to backpredict the ultimate lateral load and are validated with the field test results. The load-deflection profile of the single helix pile from the field test and numerical analysis is shown in Figure 4 and shows a good agreement with the field test data. The initial slight increase in the deflection of the numerical result is observed as the installation effect is not considered in the analysis. Figure 4 also shows the result of Al-Baghdadi et al. (2017) studied using PLAXIS 3D. Compared to PLAXIS 3D, ABAQUS CAE shows conservative result close to the field tests. Figure 5 shows the deflection profile of the pile 3A and the soil. From Figure 5(a) it can be observed that the pile behaves as a flexible pile where the top portion of the pile is deflected but the bottom portion is un-deformed. This is observed as the pile rotates, soil offers bearing resistance on the helical plate resisting the rotation of the bottom portion of the pile.

Figure 5(b) shows the radial extent of the deflection of soil extending up to a maximum of 4.2*D*. Figure 6 shows the load-deflection graph for the pile type 6A. The result shows that the maximum deflection obtained from the numerical study is around 23% less than that of the field test result. This is due to the fact that the installation of the double-helix screw pile causes significant soil disturbance around the pile thereby increasing the deflection. Figure 7 shows the deflection profiles of the screw pile and the soil. The helices provide sufficient resistance to deflection due to which only the upper portion of the pile gets deformed (Figure 7(a)). The radial distance of the deflection in the soil is observed to be 3D (Figure 7(b)). Compared to pile 3A, pile 6A provides higher lateral resistance due to its larger shaft and helix diameter reducing the radial distance of the deflection profile of soil.

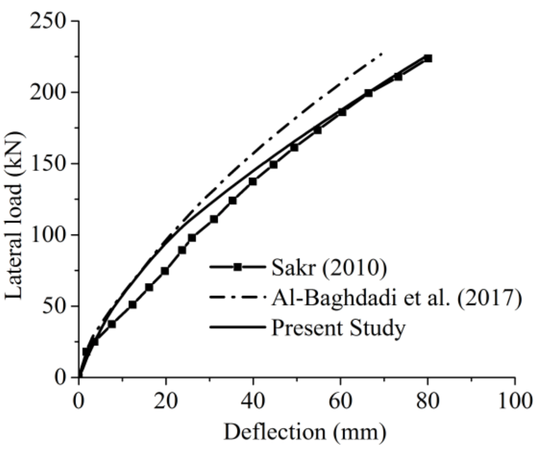

Fig. 4. Measured versus backpredicted lateral load-deflection curve for pile type 3A

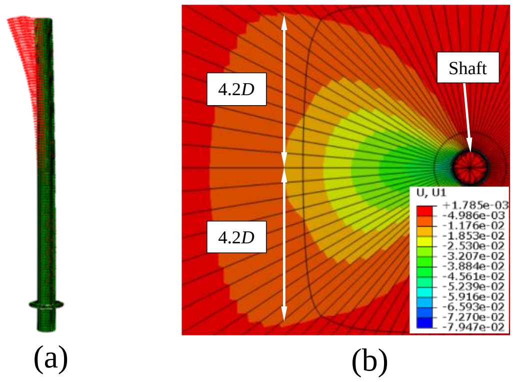

Fig. 5. Backprediction of lateral deflection profiles (a) pile 3A (b) soil (plan view)

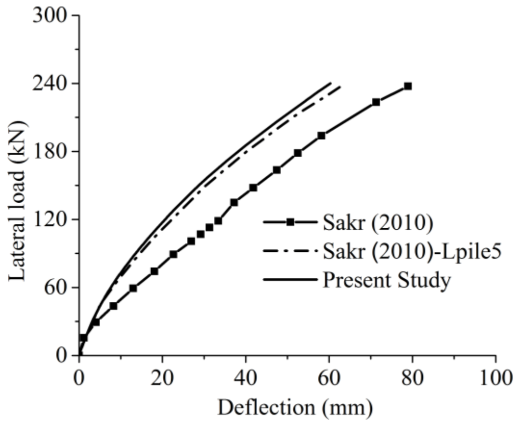

Fig. 6. Measured versus backpredicted lateral load-deflection curve for pile type 6A

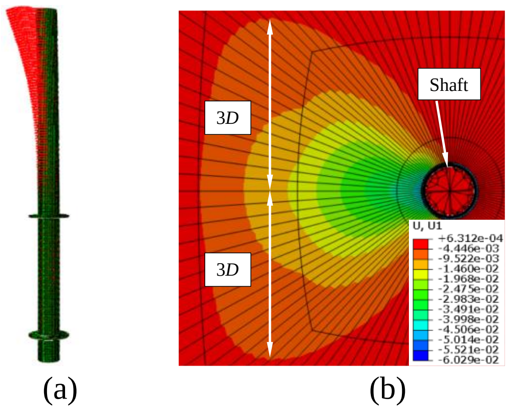

Fig. 7. Backprediction of lateral deflection profiles (a) pile 6A (b) soil (plan view)

4.1 Backprediction of ultimate lateral capacity

The forensic investigation has been also conducted to determine the ultimate lateral capacity based on finite element analysis and existing empirical and analytical relationship (Mittal et al. 2010), using the field test data (Sakr 2010). The ultimate lateral capacity is badckpredicted corresponding to 50 mm lateral deflection (Salgado 2008). Table 3 shows the measured and backpredicted values of ultimate lateral capacity at

50 mm deflection for two different pile types 3A and 6A (Sakr 2010).

The empirical relationship gives much higher values of ultimate lateral capacity as compared to the measured values and the present analysis (Table. 3). This is mainly due to the fact that the empirical relationship did not consider the soil properties and was developed for rigid/short piles. Since the present forensic investigation suggests that the existing empirical relationship and analytical formula highly overpredict its lateral capacity, the pile so designed may fail in practice. This is particularly true for long/flexible screw piles in sand and therefore, the future study should focus on developing any such relationships.

Table 3. Comparison of measured versus backpredicted ultimate lateral capacity of screw piles

Pile type[1]	Measured[1]	Empirical[2]	Analytical[2]	FEM[3]
3A	162	6300	1600	166
6A	171	14408	2736	213

[1]Sakr (2010); [2]Mittal et al. (2010); [3]present analysis

Mittal et al. (2010) proposed an analytical method using modified Brom's (1964) method (where Brom's constant 3 is modified to 3^{α} following Ganjoo (2008) to account the increase in flexural rigidity of the pile due to helix) for estimation of the ultimate lateral capacity of screw pile in the sand. However, this formula is only valid for short/rigid pile (Length to stiffness factor ratio $L/T<3.5$) thus overpredicts the ultimate lateral capacity (Table 3) of field tests data ($L/T > 24$, Sakr 2010). Hence, suitable modifications should be incorporated in the formulation proposed by Mittal et al. (2010) before applying for long/flexible piles. However, the finite element analysis gives better results compared to the available empirical and analytical relationship.

5 CONCLUSION

In the present paper, forensic investigation is conducted to investigate the behaviour of a laterally loaded field pile at failure using a finite element analysis. The load-deflection response backpredicted by the finite element analysis shows a good agreement with the field test data for the single-helix pile. However, for the double-helix pile, the backpredicted lateral resistance is greater as compared to the measured values and the load-deflection behaviour shows a slight deviation from the field test data. This behaviour is observed since the installation of screw piles in the field causes sufficient disturbance to the surrounding soil thus reduces its lateral resistance. The ultimate lateral capacity of screw pile is backpredicted using the finite element analysis and the results are found to be in good agreement with the field tests data. The existing empirical and analytical relationships are also employed for the backpredition. However, the forensic investigation shows that the existing relationships highly overpredicts the ultimate lateral capacity of the screw pile. Because these relationships are mostly developed based on the assumption of the short/ rigid pile. The effect of appropriate soil parameters is also not considered in its formulation. The present study also suggests that there is a greater need for the forensic study to understand the lateral behaviour of the screw pile at failure. In addition, the future study should focus on the development of improved relationships to estimate the ultimate lateral capacity of screw piles.

REFERENCES

Al-Baghdadi, T. A., Brown, M. J., Knappett, J. A., and Al-Defae, A. H. (2017). Effects of vertical loading on lateral screw pile performance. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 170(3), 259-272.

Broms, B. B. (1964). Lateral resistance of piles in cohesionless soils. Journal of the Soil Mechanics and Foundations Division, 90(3), 123-158.

Elkasabgy, M. A. and El Naggar, M. H. (2015). Lateral performance of large-capacity helical piles. In IFCEE 2015, Geotechnical Special Publication 256, ASCE, VA, USA, 868-877.

Elsherbiny, Z. H. and El Naggar, M. H. (2013). Axial compressive capacity of helical piles from field tests and numerical study. Canadian Geotechnical Journal, 50(12), 1191-1203.

Ganjoo B (2008) Behaviour of helical screw anchor piles under lateral loads, M. Tech. Dissertation, Indian Institute of Technology Roorkee, Roorkee, India.

Kumar, P.V.P., Patra S., Haldar, S. (2019). A critical review on design aspects of screw piles for renewable energy devices. Proceedings of the 1st international screw pile symposium on screw piles for energy application, Dundee, Scotland, 59-66.

Madabhushi, G. S. (2016). Forensics of Pile Foundations Subjected to Earthquake Induced Liquefaction and Lateral Spreading. In Forensic Geotechnical Engineering, 403-431, Springer, New Delhi.

Mittal, S., Ganjoo, B., and Shekhar, S. (2010). Static equilibrium of screw anchor pile under lateral load in sands. Geotechnical and Geological Engineering, 28(5), 717-725.

Muthukkumaran, K., Raaj, S. K., and Kumar, M. V. (2016). Assessment of pile failures due to excessive settlement during pile load test. Japanese Geotechnical Society Special Publication, 2(73), 2520-2524.

Rao, V. V. S. (2016). Guidelines for Forensic Investigation of Geotechnical Failures. In Forensic Geotechnical Engineering, 39-44, Springer, New Delhi.

Reddy, M. K., and Ayothiraman, R. (2015). Experimental studies on behavior of single pile under combined uplift and lateral loading. Journal of Geotechnical and Geoenvironmental Engineering, *141*(7), 04015030.

Sakr, M. (2010). Lateral resistance of high capacity helical piles–case study. In Proceedings of the 63rd Canadian Geotechnical and 6th Canadian Permafrost Conference. Calgary, Alberta, 402-412.

Salgado, R. (2008). The engineering of foundations. McGraw-Hill, Europe.

Wang, D., Merifield, R. S., and Gaudin, C. (2013). Uplift behaviour of helical anchors in clay. Canadian Geotechnical Journal, 50(6), 575-584.