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Appraisal of Innovative Finned-Pile Foundations to Resist Lateral Loads

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Abstract. Multistoried buildings are subjected to a significant amount of lateral forces due to winds and earthquakes in onshore structures and forces due to water currents and heavy winds in offshore structures. Foundations supporting such structures as offshore wind turbines should resist extensive lateral forces and pullout forces. To sustain these loads, innovative types of pile foundations need to have experimented with in place of regular pile foundations for more economic and efficient performance. In this paper, an attempt is made to demonstrate the efficiency of adopting finned-piles concerning previous literature studies. This work highlights some of the Experimental investigations, Model studies, Numerical studies (FEM, FDM) adopted to find the usefulness of finned-piles in resisting the lateral loads. Some of the key-points of adopting such foundations are discussed. Finally, future untapped avenues explored on finned piles are also brought out in the paper.

Keywords: Innovative; Finned-piles; Lateral Loads; Offshore; Foundations.

1 Introduction

In modern developing countries like India, more preference is given to Infrastructure development to enhance the requirement for the corresponding needs, which leads to its contribution towards schemes like Make in India, Digital India Programme, Urban Infrastructure Development, Samudra Setu, etc. These schemes utilize the large capital to achieve the desired goal, which indirectly uses high raised buildings in onshore construction and offshore constructions for utilizing renewable resources like wind turbines, jetties, etc. for its economy.

As these platforms transmit larger loads to the subsoil, pile foundations are generally adopted. These structures have to resist larger lateral loads throughout their lifetime. Though pile foundations resist lateral loads up to an extent, they can't carry larger lateral loads effectively with smaller length and diameter. Hence, primary preference must be given for applying an innovative pile foundation to resist these lateral loads economically with a considerably smaller diameter and length piles.

This paper gives an overview of the previous literature, its outcomes, and recommendations for adopting one such innovative pile foundations, i.e., finned pile foundations.

Regular pile converts to the finned piled foundation when they are stiffened at the pile head employing plates, as shown in Fig.1, which increases the foundation system's lateral load-carrying capacity.

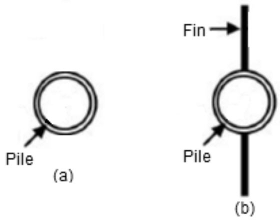

Fig.1. Plan view of (a) Regular Pile and (b) Finned pile.
(Redrawn by authors after Ahmed, 2014)

2 Experimental Studies on Finned Pile Foundations

Reese et al. (1974) attempted to analyze the laterally loaded piles in the sand at the field with two piles of 601mm dia piles for both static and cyclic loadings, and the results were presented in terms of p-y Curves. The lateral load is applied to the full-sized piles that are open driven, and suitable instrumentation was done to record the Pile-head deflection and Pile-heal rotation along with BM, along the length of the pile. The lateral soil resistance was developed, as shown in Fig. 2. A computer program was developed to compare results with measured field values. Finally, it was concluded that a close agreement was found between the results obtained at the program's site developed.

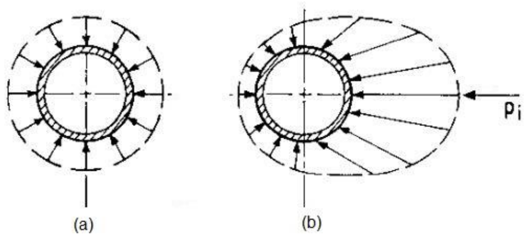

Fig. 2. Lateral soil resistance developed
(a) Before the application of lateral load (b) After applying lateral load.
(Redrawn by authors after Reese et al., 1974)

Christos and Michael (1993) made an experimental investigation over the possible effects of lateral loading over axial pile displacements, stresses, and influence of axial loads on lateral pile responses. The model tests were performed over the closed-ended aluminum piles of outer dia 19mm and 1.5mm thick. They were pushed into the soft clay bed up to 500mm. Both axial and lateral loads were applied at increments, and responses were noted by strain gauges attached along the pile's length. The results were compared with the same set of nonlinear finite-element analysis. Finally, it is concluded that the lateral load increases the axial deformation and is dependent on the magnitude and location of the lateral load on the pile. Also, the applied lateral load reduces the axial pile stress to a smaller extent. The nonlinear finite element analysis successfully studies the interaction between axial and lateral pile response. Still, this interaction cannot be studied by conventional elastic half-space and subgrade reaction methods.

Sastry and Meyerhof (1994) studied the behavior and effect of effective embedment depth of flexible piles in layered soils for Lateral and inclined loads by both model tests and field studies. Layered soils consisting of loose soil overlain by compacted sands, A PVC pile of 1.25m length, 73mm diameter, and 7.6mm thick are pushed into it. They are graduated with minor equipment to measure the Bending moment, Lateral Deflection, and lateral soil resistance at the suitable points all along the length of the pile with the spacing of 145mm. These tests were carried out for Eccentricity to embedment depth ratios (e/D) of 0.13, 0.33, and ∞ load inclinations of 0˚, 15˚, and 30˚ w.r.t vertical. The load is applied to failure in about 10 to 12 increments, and these values are used to validated modal tests. It is seen that the Embedment depth helps in finding out the BM, lateral deflections, and lateral resistance, pile flexibility will not have its influence over axial capacity. Finally, it is concluded that the soil's lateral resistance is dependent on the stiffness of the pile and the variation of horizontal soil modulus along the pile length.

Prasad and Chari (1999) attempted to verify the applicability of the previously available works of literature (Hansen, 1961) (Broms, 1964) (Christos et al., 1993) (Meyerhof et al., 1981) defining the ultimate lateral capacity of the pile which is based on the soil pressure distribution along pile length as shown in Fig.3. Their study attempted to study this for rigid steel model piles of outer diameter, length, and thickness of 102mm, 1135mm, and 5.6mm, respectively. That is driven into well-graded dry sand along with suitable arrangements made to record lateral soil resistance. Finally, a simplified method is proposed to predict soil pressure distribution and ultimate lateral capacity of the rigid piles, and a comparison was made almost the previously published literature.

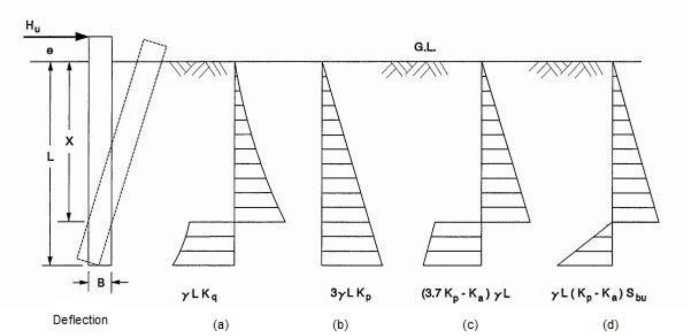

Fig. 3. Lateral soil pressure distribution assumed by
(a) Hensen, (b) Broms, (c) Petrasovits et al., and (d) Meyerhof et al.,
(redrawn by authors after Prasad et al., 1999)

Zhang et al. 2005, attempted to improve the ultimate lateral resistance of piles in sands over the several available previous methods and its distribution are as shown in

Fig. 4, which were difficult in selecting the suitable approximate method for designing laterally loaded piles since each method will yield different resistance values. By conducting model rigid pile tests, this work tried to analyze the distribution of lateral soil resistance all around the pile's c/s. Finally, proposed a method by bifurcating the lateral soil resistance in Frontal soil resistance and side shear resistance, as shown in Fig.5 below, which is also satisfied for flexible piles and proposed formulae for estimating the same are as shown in Table 1.

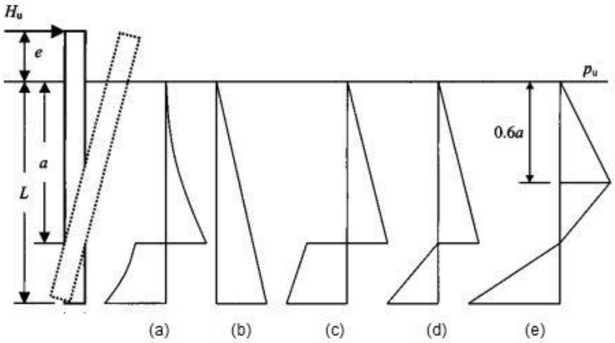

Fig. 4. Lateral soil pressure distribution as per
(a) Hensen, (b) Broms, (c) Petrasovits et al., (d) Meyerhof et al., and (e) Zhang et al., (redrawn by authors after Zhang et al., 1999)

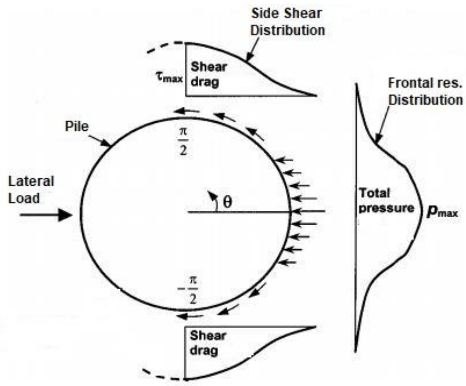

Fig. 5. Frontal Soil resistance and Side shear resistance distribution. (redrawn by authors after Zhang et al., 1999)

Table 1. Proposed Formulae for estimating lateral soil resistance

Resistance developed	Ahead of pile	Behind pile
Frontal Soil Resistance	$\eta BK_p^2\gamma(0.6a)$	$1.7\{\eta BK_p^2\gamma(0.6a)\}$
Side Shear Resistance	$\beta BK\gamma \tan\delta\ (0.6a)$	$1.7\{\beta BK\gamma \tan\delta\ (0.6a)\}$

Where η and β are the shape factors obtained from Fleming et al. (1992) and API (1991).

Peng (2005) made an extraordinary work on laterally loaded finned piles by conducting model tests on scaled-down piles embedded in the sand for both static and cyclic loadings. An effective setup to conduct the cyclic 1D test for laterally loaded piles for varying fin dimensions was developed and tested for varying magnitude, frequency, which were later compared to monopile results to check its effectivity in carrying lateral loads. 3D FEM analysis Software LUSAS was used to depict pile-soil response and soil reaction around fin. The relationship between maximum load and deflections are plotted as p-y curves.

It is stated that the Ultimate lateral Resistance is generally considered at the point on the p-y curve whose slope will be lesser than 0.05. From a serviceability point of view, the load is considered at the lateral deformation of 10% of the pile diameter. An increase in load by finned piles is shown in Fig. 6. Ultimate lateral capacity for both the cases, i.e., ultimate limit state and serviceability limit state, is almost the same.

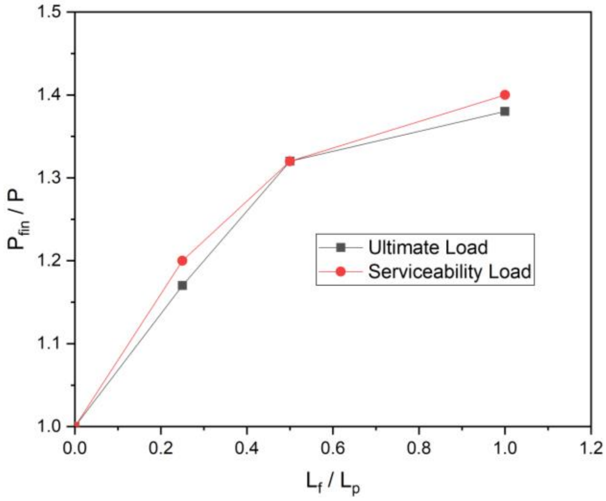

Fig. 6. Increase in lateral load with an increase in fin length for both the cases. (redrawn by authors after Peng., 1999)

Finally, it was found that the pile head deformations are reduced by the provision of fins at the pile head. To achieve efficiency in adoption, recommended optimum fin dimensions as wind width and length nearly equal to the diameter of pile and half the pile length, respectively, that helped future scope over finned pile study in resisting lateral loads.

Peng et al. (2011) studied the increase in piles' resistance subjected to cyclic lateral loads. Tests were done on small-scale finned and monopile piles to evaluate the effect of fin length over displacement for cyclically loaded piles. The tests were conducted for varying magnitude, load direction, and frequency to simulate the actual offshore structure loading for varying types of fin tip and length of fin. It is found that the provision of fins reduces the displacement to piles as an alternative for efficiency. The type of pile tip will not have any deterministic effect on lateral displacement. Hence, it concluded that up to half the piles' length lateral displacement would be reduced by about 50% after ten thousand loadings monopiles if the fins were provided.

Rudolph and Grabe (2013) attempted to study the cyclic loading effect from varying directions over laterally loaded piles with wings, i.e., Finned piles. A series of large-scale in-situ tests were carried out on two tubular steel pipes (each for monopile and wingedpile testing) equipped with two wings, i.e., finned piles to economize the real offshore condition. The cyclic loading is applied by hydraulic cylinders such that loading direction will vary by 90˚ after each loading, which is load controlled. Piles were equipped with sensors to note the deflection all along the pile length.

It is concluded that on proving wings to the piles below the sea bed, the loading will activate the wings with an enlarged diameter than the pile, hence reducing pile drifting. Since the soil resistance developed will be greater than the pile alone, it will increase the activated soil cross-section from circular to star-shaped. The lateral deformation of the pile gets reduced by adopting winged piles. The varying cyclic loading directions will not have any influence on lateral soil resistance.

Ahmed (2014) attempted to study the numerical study using the FEM software PLAXIS 3D package and validate the same using small-scale modal tests in evaluating the response of laterally loaded finned piles embedded in the sand. Modal tests were carried out for two different sand densities corresponding to the loose and medium dense case. Investigations were performed for varying fin dimensions (length and width) L_f/L_p values of 0.1 to 0.5 and W_f/D_p values of 0.5 to 2.0 for varying fin shapes, i.e., Rectangular and triangular fins as shown in fig.7 below.

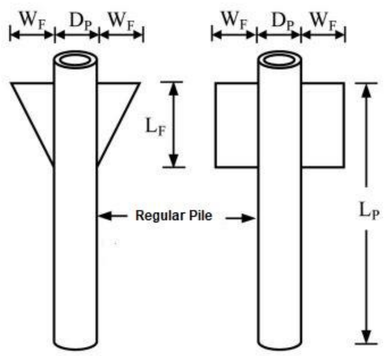

Fig. 7. Finned pile description. (redrawn by authors after Ahmed., 1999)

It was concluded from both experimental and numerical analyses that the finned piles provide higher lateral resistance along with reduced lateral displacement than regular piles. Fin length affects the resistance developed than that of fin-width. From an economical point of view, optimum fin dimensions were L_f/L_p=0.4 and W_f/D_p=1.0. Whereas, Rectangular fins as the effective fin shape.

Murphy et al. (2016) conducted a series of field tests to investigate winged-monopile behavior. Tests were performed at two sites with sand deposits whose soil properties were estimated with CPT and MASW tests. It was noted that the groundwater table was lower below the pile tip; hence, it didn't influence pile testing. The piles installed were displacement concrete piles over which static loads are applied in increments using a hydraulic jack. The results were demonstrated as p-y curves, from which it

was found that the Ultimate lateral Resistance was found to increase by 16% and 36% at two sites, respectively, compared to the reference pile. Even peak loads were also mobilized within lateral displacement of 10% of pile dia or lesser. The higher resistance in the second site is due to the higher initial stiffness of the sand. The ultimate serviceability load (for a displacement of 1.2% pile dia, as per Lloyd, 2005) for both sites was found to be increased by 111% and 117%, respectively. Also, the lateral displacement was reduced by about 45% and 60%. The wing efficiency was greater at lower loads and decreases as the pile proceeds towards failure.
Bariker et al. (2020) conducted series of small-scale model test to investigate the effectiveness of varying fin parameters like the number of fins (two and four finned), fin location along pile length (pile head, mid-length, and pile tip), fin orientation for loading (90º and 45º fin orientation), for long-flexible, intermediate and short-rigid piles, embedded in the dry sand of relative density corresponding to loose and medium-dense case, in sustaining the static-lateral loads and also an attempt is made to study the optimum fin dimension, i.e., fin-length (L_f) and fin-width (W_f) in resisting load effectively.

The results of lateral load response were recorded as p-y curves, increase in load-carrying capacity was denoted by fin efficiency as stated by (Peng et al., 2011) stating that the fin will effectively help in reducing the lateral deformation and increasing the load-carrying capacity, pile head fin location was found to be optimum with fin-length relative to pile length (L_f /L_p) of 0.4 and fin-width relative to pile dia (W_f/D_p) of 1.0.

3 Numerical Studies on Finned Pile Foundations

Many researchers like (Peng, 2005), (Zhang et al., 2011), (Marcelo and Jose, 2013), (Hussien et al., 2014), (Zhi et al., 2017), (Wenjun and Ga, 2020) made it possible to use available software packages in modeling and recommended the key points for the regular pile problems subjected to lateral loading. It isn't easy to model finned piles in software because fewer efforts were made on the same. Few people made it possible to effectively build a finned pile problem in software packages, taking the previous literature (as specified above) as a platform to use it effectively.

Peng et al. (2010) attempted to improve his work in fin piles on two-dimensional numerical analysis software LUSAS (Peng, 2005), which had the problem of explaining the difficulty to explain soil-pile theory because of complicated fin geometry in the system, by Three-dimensional analysis of laterally loaded fin piles using PLAXIS-3D program to study the effectiveness of the small-scale model and full-scale studies using the pile material as steel for varying fin location on the pile, varying loading directions, length, and diameter of pile later the same results are validated with the experimental results. A close agreement was found between the results obtained also an attempt was made to check the mesh sensitivity on the laterally loaded fin piles as shown in Fig. 8, which explains that with an increase in the number of elements thereby increasing the mesh numbers or decreasing the mesh size, the results get finer and accurate.

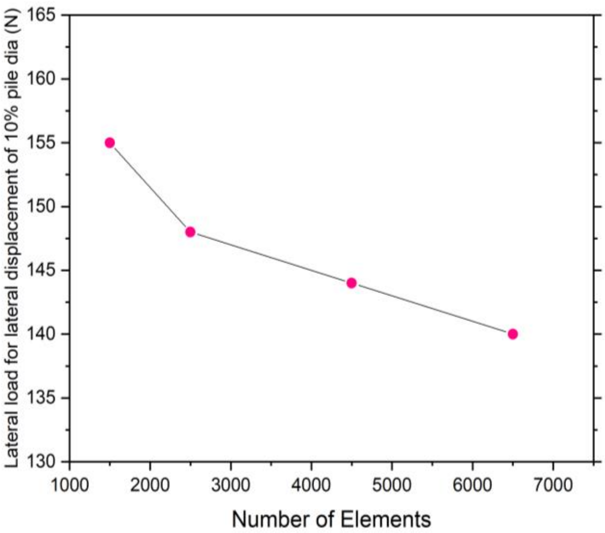

Fig. 8. Mesh sensitivity map. (redrawn by authors after Peng et al., 1999)

Babu and Viswanadham (2018) attempted to study the effect of fins over resisting the lateral loads effectively by performing the numerical analysis in ABAQUS software, performing three-dimensional analysis. Investigations were performed for varying fins (straight, diagonal, and star fins), location of fins (top, middle, and bottom), the direction of loading, and fin dimensions (Length and width of fins) embedded in medium-dense sand.

It was concluded that the fins placed at top resist larger lateral loads than the other two positions, increase in the number of wings in fin geometry resist larger loads, the fin is found to be significant when fin length is 0.5 of pile length. It also concluded that the fin piles exhibit lesser bending moment than the regular piles.

Mohammad et al. (2019) attempted to investigate the effectiveness of fin in enhancing the pile's lateral load-carrying capacity by conducting the numerical analysis in ABAQUS software, which were later validated from small-scale model tests. A series of investigations were made to study the effect of pile dia, fins, and aspect ratio of fins in resisting lateral loads. The results found that the aspect ratio of fin had largely influenced the fin efficiency in resisting loads. But, on comparing the influence of the length and width of fins alone, the fin's length was found to influence the design than the width of the fin because that provides higher lateral soil resistance.

An attempt was also made to study the optimum fin dimension. It was found that the fin pile of 40mm diameter was found to resist 29% more load than the 40mm diameter regular pile. When results of different fin diameters were made, it was found that the fin pile of 40mm diameter to carry the same load as by 50mm regular pile. Since fin-length had influenced the design than fin-width, it was concluded that the material usage reduced by 19% resulting in the same resistance.

4 Conclusions

This paper reviewed the works of finned piles in resisting the lateral loads. It is found that the involvement of fin with pile is a tedious task to analyze either by basic soil-pile theory or two-dimensional analysis complicated fin geometry and its influence over resisting lateral loads. It has various parameters controlling the design of theory for finned piles like fin-type (two finned, four-straight finned, four-diagonal finned), Fin location (pile-head, mid-length, and pile-tip), fin-length and fin-width, the direction of loading along with pile material, pile length, the soil surrounding the pile, and nature of the load. Also, it isn't easy to analyze these influencing factors by conducting small-scale experimental tests. Full-scale in-situ tests as human-made losses like experimental errors will largely influence the obtained results, which is one reason for not developing the recommendations and design methods for finned piles testing.

It is necessary to predict the same by conducting the numerical analysis by various software packages available in the market validated by experimental results, which gives better results compared to experimental results, i.e., they don't include experimental errors. But, they fail if mistakes are made while defining the model and boundary conditions, leading to a false result. To boycott these failures, it is required to develop an advanced method to solve these influencing factors without faults to overcome experimental errors and analyze errors. This can only be tackled by modern methods like Artificial Neural Networks (ANN) that can consider each of the influencing factors defined above.

Developing new methods can either be Convolutional Neural Network (CNN), which generates somewhat close results, considering only the important or highly influencing factors. If accurate results are expected, Recurrent Neural Network (RNN) must be developed considering all the influencing factors defined above and all the recommendations provided by the above-discussed literature, providing the strong basement for developing the modern methods.

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