Study of fin shape on the behaviour of finned piles under combined loading conditions

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Abstract. Several types of structures, such as bridge abutments, retaining walls, transmission line towers and other structures exposed to wind and earthquake loads, supported by pile foundation are being subjected to large lateral loads. Finned pile is an emerging form of pile foundation that is capable of resisting large lateral displacements. Here, it is attempted to assess the effect of the shape of fins on the lateral carrying capacity of a pile with fins subjected to combined loading conditions. Small-scale laboratory model tests were performed on normal piles (without fins) and also with finned piles. These piles were embedded in sand. The studies were carried out by varying the geometric factors such as length, width and shape of the fins. Results show that there is a substantial increase in lateral resistance capacity of the piles after fitting the fins close to the pile head. The increase in lateral resistance capacity gained by placing fins on a pile varies with dimension of the fins. On the basis of the laboratory model test results, optimum dimension of the fin for maximum improvement are recommended for combined loading conditions. The trend showed in the results were comparable with those reported in the literature as on studies with lateral load alone.

Keywords: finned piles; combined loading; lateral load capacity.

1. Introduction

Pile foundations are resorted to in situations where shallow foundations are not suitable. Large diameter monopiles or smaller diameter group piles are being widely used as foundations for high rise structures. In the case of structures like transmission line towers, tall buildings and fixed arch structures, foundations are required to resist large lateral forces. When deep foundations are adopted for such structures, the size and number of piles are dictated by the magnitude of lateral forces rather than the vertical loads. Provision of structural fins near the pile top has found to enhance its lateral load carrying capacity. The dimensions of the straight shaft portion or the number of piles can be reduced leading to economy of construction. These foundations are usually subjected to large environmental loads like wind loads and earthquake loads, which could exceed 30% of its gravity loads.
load. Ramakrishna and Rao [1] established that the environmental loads like strong winds result in a reduction in the lateral resistance pile foundations. Thus, the lateral load carrying capacity of pile foundations gain considerable significance.

Finned piles have found to improve the lateral capacity of piles [2-6]. Finned piles are found to be a better solution than other conventional approaches like strengthening of shallow ground or increasing the dimensions of the piles [2, 3, 6, 7]. Based on the studies under lateral load alone, fin efficiency was found to increase with the fin length [2, 3, &6], fin width [2 & 3] position of fins [2, 3] and shape of fins [2, 6]. Thus, it can be established that the surface area of the fins influences their behaviour. Rectangular fins were found to be more effective [6].

However, the studies on the finned piles have been limited to the effect on lateral capacity on lateral loading only. The response of piles is more critical when they are subjected to a combination of lateral and vertical loading [8-14]. Information on behaviour of finned piles under the combined loading effect needs attention.

Rekha et. al. [16] investigated the effect of fin length on the load deformation behaviour of piles under combined loading and observed that the lateral load carrying capacity increases with increase in fin length. Experimental investigations were conducted in the laboratory environment for the purpose. In the investigation reported herein, the effect of fin shape was considered.

2. Experimental programme
The tests were conducted inside a steel tank of dimensions 1.00 m x 1.00 m x 1.00 m fitted with a loading frame as shown in Figure 1. The tank dimensions were fixed considering the fact that the failure wedge below the model piles did not prolong up to walls of the tank. Lateral displacement and load at the pile head were measured by transducers which were recorded by a data logger system. Experimental studies were conducted under two sets of loading systems namely lateral as well as combined lateral and axial loading. Both mono piles and finned piles were load tested. Various configurations of the fin system were obtained by varying the shape of fins. The experiments were carried out on dry sand with physical properties summarized in Table 1. Sand bed was prepared by placing sand in layers of 100mm thickness using rainfall technique. The model piles were of diameter 45.5 mm and 2 mm thickness and were fabricated from smooth steel pipe. Thickness of the fins was fixed as equal to the thickness of the pipe. For all the model piles, two fins were positioned near the head of the pile just below the soil surface and welded at right angles to the direction of lateral loading. Pile cap was provided as a solid element of outer diameter same as the pipe diameter. The dimensions of the model piles used in the present study are listed in Table 2.

![Figure 1 Schematic diagram of experimental setup](image-url)
Table 1. Physical properties of sand

| Property                     | Value |
|------------------------------|-------|
| Effective grain size, D10 (mm) | 0.32  |
| Uniformity coefficient, Cu   | 1.98  |
| Coefficient of curvature, Cc  | 1.18  |
| Maximum dry unit weight (kN/m3) | 18.3  |
| Minimum dry unit weight (kN/m3) | 16.8  |
| Relative density (%)         | 35    |
| Specific gravity             | 2.61  |

Table 2. Dimensions of piles and fins

| Type of pile | Dimensions of piles (mm) | Dimensions of fins (mm) |
|--------------|--------------------------|-------------------------|
|              | Length | Diameter | Thickness | Length | Width |
| Mono pile    | 400    | 44.5     | 2         | -      | -     |
| Finned Pile  | 80     | 22.25    |           | 160    | 44.5  |
|              | 160    | 44.5     |           | 200    | 66.75 |
|              | 200    | 66.75    |           | 240    | 89    |

Three sets of loads were applied on each pile. At first, in Series I experiments, the vertical load carrying capacity of each pile was determined and vertical displacements were recorded at the top of the pile cap. A 4 mm diameter steel wire was connected to the pile cap to apply the lateral loads in increments in Series II experiments. The wire was wound over a smooth adjustable pulley at the other end. Transducers were fixed to the pile head to note the lateral deflection of the pile. In Series III experiments, the finned piles were tested for combined loading i.e., both vertical and lateral load. The vertical load was provided as a dead load on the top of pile cap. This load was taken as 1/3rd of the maximum vertical load got from the tests in Series I.

3. Results and discussion

From the observations of the experimental work, lateral load vs. lateral displacement (P–y) curves were plotted and the effects of loading and geometric properties of fins were analysed. In the present study, the lateral load corresponding to a lateral displacement equal to 10% of the pile diameter at the pile head was defined as the ultimate lateral load capacity [4,15]. Peng et al. [15] have established that the lateral resistance reduces as the starting position of fins move down the pile. The authors also proved that performance of the piles will be maximum when the fins are placed perpendicular to the loading direction. Hence, in all the experimental investigations on finned piles in this study, the fins were positioned at the top of the piles and perpendicular to the load direction. A non-dimensional term efficiency factor was used to represent the increase in the pile resistance. This factor is expressed as a ratio of the ultimate lateral load of a finned pile to ultimate lateral load of a pile without fins.

3.1 Effect of combined loading on finned piles

Figure 2 shows a typical load – deflection graph (P – y curve) obtained from the experiment on finned piles and mono piles subjected to lateral loading as well as combined loading. It can be noticed that the lateral load carrying capacity of both mono piles and finned piles increases significantly under
combined loading in comparison to lateral loading alone. Comparing the P-y curves of monopiles and finned piles under lateral and combined loading conditions, it can be inferred that the provision of fins is considerably more beneficial under combined loading conditions.

3.2 Effect of fin length on the behavior of finned piles
To investigate the effect of fin length on the behavior of finned piles under combined load, experiments were conducted by varying the length factors. The fin length is normalized with respect to length of pile as the ratio of fin length to pile length (L_f/L_p) and is termed as length factor. The experiments were performed for various normalized length factors of 0.2, 0.4, 0.5 and 0.6 by keeping the width factor (if W_f is the width of fin and D_p is the diameter of pile, width factor = W_f/D_p) constant under lateral and combined loading conditions. The experiments were conducted on finned piles (short rigid pile) embedded in loose sand. The changes in ultimate lateral load (P_u) with length factors are shown in Figure 3. The finned piles offered a significantly greater resistance as well as a stiffer reaction when compared to the monopile. Further to this, provision of fins resulted in a decrease of lateral displacement at a given lateral load. As the length factor increases, maximum lateral load carrying capacity also increases under lateral loading alone and combined loading.

A similar observation in the case of lateral loading alone was also made by Peng [4] and Nasr [6] The variation is found to be linear. Under lateral loading alone, increase in lateral load carrying capacity up to 57% was obtained within the normalized fin length which was varied from 0.2 to 0.6. Under combined loading, the corresponding increase in the lateral load carrying capacity was 100%. In these experiments, normalized fin width W_f/D_p was kept at unity. Thus, it can be concluded that the provision of fins is more advantageous in resisting lateral loads when the pile is under combined loading. The pattern of variation of lateral load carrying capacity obtained for pile under lateral loading alone is similar to the result obtained by [6].

![Figure 2. Typical load vs lateral deflection plots for lateral and combined loading conditions](image-url)
3.3 Effect of fin width on the behavior of finned piles

To analyse the effect of fin width, a series of tests was performed by varying fin widths. A dimensionless term called width factor is defined as \( Wf/Dp \) where \( Wf \) is the fin width and \( Dp \) is the diameter of pile. Experiments were performed on finned piles with various width factors of 0.5, 1.0, 1.5, and 2.0, by keeping the length factor constant. The relative density of sand bed was kept constant at 35%. The variations of fin efficiency with width factor are shown in Figure 4. The results show that the efficiency of fins increases with increasing width factors (at constant fin length). Under lateral loading alone, the variation of lateral load capacity with the width factor seems to be almost linear. A similar trend was reported by Nasr [6]. Increasing the fin width will provide greater soil resistance as well as a stiffer response. This is because of an increase of the area resisting passive earth pressure in comparison to monopiles. This leads to a hike in the lateral load capacity of finned piles. In the experiments, the pattern of soil movement around the piles indicated a marked difference in the behaviour of finned and normal piles. While the monopile moved forward under lateral loading, the experiments with finned piles depicted the formation of a passive wedge in front of the pile.

![Figure 3. Effect of fin length on the response of finned piles](image1)

![Figure 4. Effect of fin width on the response of finned piles](image2)
3.4 Effect of aspect ratio of fins

The lateral load capacity is found to increase linearly with the Lf/Wf (length of fin by width of fin) ratio termed as the aspect ratio. The effect is more pronounced in the case of combined loading, as depicted in Figure 5. The efficiency factor – aspect ratio relation shows a steeper slope for wider fins. At large fin widths, even a slight increase in the aspect ratio has a pronounced effect on maximum lateral capacity. This may be because of the resulting substantial increase in surface area of the wider fins with aspect ratio. It can be noticed that for attaining the same maximum lateral load, a smaller fin width (Wf/Df) with the required aspect ratio is more advantageous. The width factor equal to 1 is found to be the most optimum in this figure also.

![Figure 5: Effect of aspect ratio of fins](image)

### Figure 5. Effect of aspect ratio of fins

![Figure 6: Effect of shape of fins on the response of finned piles](image)

### Figure 6. Effect of shape of fins on the response of finned piles

3.5 Effect of fin shape on the behavior of finned piles

In the present study, to analyse the effect of fin shape and fin area on the lateral displacement, tests were carried out on triangular and rectangular fins with different width factors. Nasr [6], made the comparison between triangular and rectangular fins of unequal area, but same width. Surface area is an important factor which affects the resistance offered by the fins. Hence in the present study, experiments were conducted on rectangular and triangular fins both having the same surface area as detailed in Table 3. The results are presented in Figure 5 in terms of variation of efficiency factor with area factor. Area factor is termed as the ratio of surface area of fins to the cross-sectional area of the pile. In Figure 6, steeper curves are obtained for lesser fin width factor indicating that even a slight increase in surface area (obtained by increasing the length of the fin) has much effect on lateral load capacity. The rectangular fins were found to be performing in a better way. However, in the experiments with width factor 1.0, the performance of triangular fins and rectangular fins were comparable. The triangular fins offer more area near the ground surface, where confinement is minimum. The rectangular fins offer larger area for resistance at deeper depths. The earth pressure increases with depth. A wider width at deeper depths will be able to provide higher passive resistance.
In comparison, the triangular fins, due to their tapering shape has limited area to offer passive resistance at comparable deeper depths. Deflection of a pile is maximum at the top and decreases with increase in depth. Nasr [6] based on his experiments with lateral loading alone reported that rectangular fin is better in resisting lateral loads in comparison to triangular fin, though the comparison was made without parity in the fin areas.

3.6 Effect of surface area of fins on the behavior of finned piles
From Figure 6, it is quite evident that the surface area of fins is an important factor affecting the performance of finned piles. As discussed earlier, the fins show improved efficiency under combined loading conditions. Figure 7 shows the plot of the variation of efficiency factor with area factor for all the piles analysed in the present study. The efficiency is seen to vary almost linearly with the surface area of fins in the case of lateral loading. However, in the case of combined loading, the variation is seen to be logarithmic. For the same efficiency, the surface area of fins required is lesser for combined loading conditions.

Table 3. Details of surface area and shape of fins used in the study

| Sl. No. | Surface area of fins (mm²) | Dimensions of rectangular fins (mm) | Dimensions of triangular fins (mm) |
|---------|---------------------------|------------------------------------|-----------------------------------|
|         |                           | Length    | Width   | Length    | Width   |
| 1       | 1780                      | 22.25     | 80.00   | 44.50     | 80.00   |
| 2       | 3560                      | 22.25     | 160.00  | 44.50     | 160.00  |
| 3       | 4450                      | 22.25     | 200.00  | 44.50     | 200.00  |
| 4       | 5340                      | 22.25     | 240.00  | 44.50     | 240.00  |
| 5       | 3560                      | 44.50     | 80.00   | 89.00     | 80.00   |
| 6       | 7120                      | 44.50     | 160.00  | 89.00     | 160.00  |
| 7       | 8900                      | 44.50     | 200.00  | 89.00     | 200.00  |
| 8       | 10680                     | 44.50     | 240.00  | 89.00     | 240.00  |

Figure 7. Relation showing the effect of loading conditions on the efficiency factor

4. Conclusions
The following conclusions could be drawn from the present study:
   i. Finned piles offer significantly higher lateral resistance under combined loading in comparison to the case with lateral loading alone.
ii. As the fin width increases, the lateral load carrying capacity increases up to a width factor of 1 and decreases thereafter.

iii. Under combined loading, rectangular shaped fins are found to perform better in comparison to triangular fins having the same surface area.

iv. The efficiency of finned piles under combined loading follows a logarithmic relation with the surface area of fins. The relationship is linear for piles under lateral loading alone.

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