Enhancement of lateral load carrying capacity of a pile incorporating fins – a parametric study

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Abstract. Infra-structure plays a vital role in the development of the country. Such growth directly or indirectly forces the engineers to construct the structures like high rise buildings, bridges, underground utilities, dams, etc. effectively focussing the sustainability and effective utilization of time and money. To design such structures, it is much needed to have an effective plan of design and selection of suitable techniques to execute. The load from the super structure will be transferred through the structural element called foundation. The load from the superstructure is high or the subsoil having a low bearing capacity, pile foundation is generally recommended. During the process of execution, there will be a chance of occurrence of defects in the pile such as necking or bulging. The defect in the pile may affect the load transferring mechanism and load carrying capacity. Occurrence of defects in the cast-in-situ concrete pile can be accessed through non-destructive field testing. As there are no established guidelines available to consider such defective piles, engineers go for construction of new piles instead of taking risk. From the extensive literature review, it was observed that the top one-third portion of the pile has more impact on reduction in capacity due to the existence of defects. This research focused to study the behaviour of the laterally loaded defective (necking) pile incorporating the fins around the pile using the finite element analysis software PLAXIS 3D V20 Connect Edition. The results confirm the enhancement of lateral load carrying capacity of defective pile encased with fins up to the top one-third portion. The outcome of this study helps the engineers to utilize the defective pile with the recommended incorporation of pile casing with fins.

1 Introduction

The foundation is the substructure element to transfer the loads from the superstructure to the ground safely satisfying the shear failure and permissible settlement condition. The foundation is classified into two types broadly as shallow and deep foundation. Shallow foundation is usually recommended to transfer the light loads from residential buildings or industrial buildings. The pile foundation is one of the types of deep foundation in which load is transferred to the soil by means of end bearing or friction or by both mechanisms. The structures like transmission towers, high rise buildings, bridges, onshore structures, offshore

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structures, etc are constructed with pile foundations to transfer load to the ground having different soil profile. Such piles are designed to resist vertical loads, horizontal loads and bending moments acting on it.

The construction of pile foundations need more care to achieve the designed target requirements. The quality of the pile depends on a number of factors such as quality of concrete used, grade of corrosion free reinforcement, density of concrete, curing period of concrete, denseness and stiffness of surrounding soil, achievement of desired pile dimension etc. The poor quality construction leads to the formation of defective piles. The pile containing the necking, bulging and segregation is generally coined as defective pile.in construction industry. The engineers generally construct a new pile by terminating / abandoning the defective pile to avoid future risks related to performance. In fact, all the defective piles never show poor performance and the performance purely depends on the characteristics of the defects in it. Understanding the behavior of the pile containing the defects under any type of loading is a challenging task. Few researchers studied the behavior of such defective piles under different loading and suggested solutions to overcome the issue.[1-6] However less attention has been paid to develop the solution to utilize the defective pile based on the intensity of the defect formation in the pile. The characteristics of the pile defects can be accessed through the advanced Non-destructive testing methods after the construction.

The behavior of the pile with necking defect under lateral loading studied by researchers through experimental and by numerical investigation. The reduction in lateral load capacity was observed higher when the necking defect situated at top one third of the pile.[7-9] This research focussed on the enhancement of lateral capacity of the necked pile by incorporating casing alone and casing with fins around the defective pile up to one third portion of the pile under the lateral loading in the cohesionless soil. There are different methods available to study the behavior of the pile such as 1 g laboratory investigation through scale down pile element, centrifuge modelling investigation and numerical investigation.[10-12] This study carried through numerical analysis using the finite element analysis software PLAXIS 3D Connect V20.

2 Numerical Investigation

PLAXIS 3D Connect V20 is a finite element analysis software used globally to arrive at the behavior of the soil under different loading conditions from the structural elements such as soil deformation and stress acting on it. Also, PLAXIS 3D software facilitates to observe the shear force and bending moment mobilised on structural elements due to soil-structure interaction under static and dynamic loading. The pile is configured in software using the linear elastic model incorporating the characteristics of concrete material. The behavior of the surrounding soil is modeled with the Mohr-Coulomb model. In this study, the zone of 20 m x 20 m is considered and the homogeneous soil profile created through the borehole option up to the depth of 20 m. The boundary conditions for the created model are updated as the bottom surface is restricted to move in both the vertical and horizontal direction and side faces are restricted to move in horizontal direction and permitted to move in vertical direction. The boundary of the model is fixed in such a way that the influence of lateral load on the pile does not reach the boundaries in both X and Y direction. The lateral load applied on the pile head through the option “prescribed settlement”. The lateral load will be applied on the pile with a number of increments during the calculation stage till the lateral displacement of the pile reaches the prescribed value given in the software. Then the created model processed with the mesh generation stage with the medium sized mesh. The whole model is discrete into the number of finite elements. PLAXIS 3D incorporates each element as a quadratic tetrahedral 10 noded element. Each element in the model is linked with another element by sharing common nodes. The calculation stage of this model comprises two stages such as “Initial stage” and “Loading stage”. In the initial stage, the software analyzes the initial stress and displacement in each node of the model. In the loading stage, the pile element and the lateral loading is activated and the calculation triggered with incremental lateral loading till reaches the prescribed value. Through the output window, the results such as ultimate lateral load for the prescribed displacement, soil displacement pattern, stress variation in soil around the pile, pile deformation pattern, shear force and bending moment on the pile element can be retrieved.

3 Parametric Study

The enhancement of the lateral capacity of the defective pile depends on the different factors such as casing thickness, number of fins, width of the fins, thickness of the fins, profile of the fins, soil properties around the pile, etc. To understand the effectiveness of the enhancement, a detailed parametric study is executed. Figure 1 shows the pictorial representation of the intact pile and the necking defect pile. The intact pile is created with a diameter and embedment length of 1 m and 10 m respectively as shown in Figure 1 (a). The necking defect in the pile was introduced as the uniform throated section with for a particular length. The necking diameter and necking length considered in this study is 0.5 m and 1.0 m positioned 1 m from top of the pile as shown in Figure 1 (b). The defective pile performance is enhanced by incorporating steel casing with various thicknesses as shown in Figure 2 (a). Likewise, Figure 2 (b) shows the pile incorporating casing with fins up to the one-third length of the pile from surface. Figure 3 shows the pictorial representation of the pile cross section having two, three and four fins around it. The thickness, width and profile of the fins influence the performance of the pile capacity. Figure 4 shows the different profile of the fins such as rectangular, triangular with zero at top, triangular with zero at bottom, triangular with minimum at top - maximum at bottom and triangular with maximum at top - minimum at bottom.

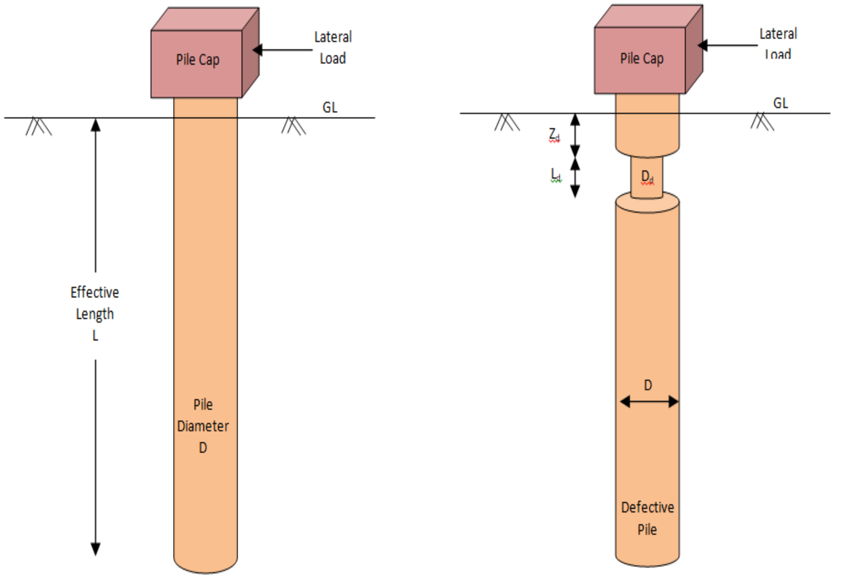

Fig. 1. Configuration of pile under lateral load a) intact pile b) necking defect pile

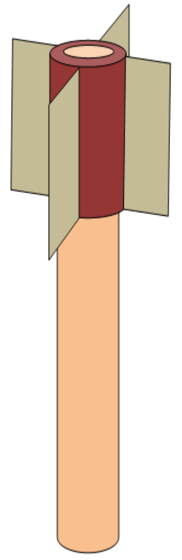

Fig. 2. a) Defective pile with steel casing b) Defective pile with casing and fins

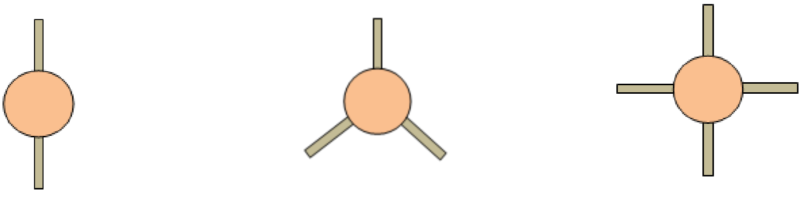

Fig. 3. Pictorial view of orientation of fins a) two fin b) three fin c) four fin

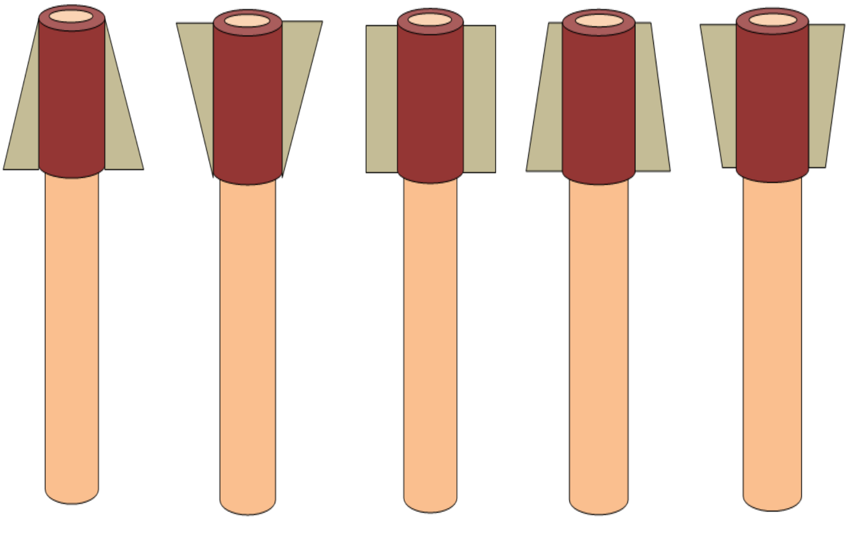

Fig. 4. Different configuration of fins

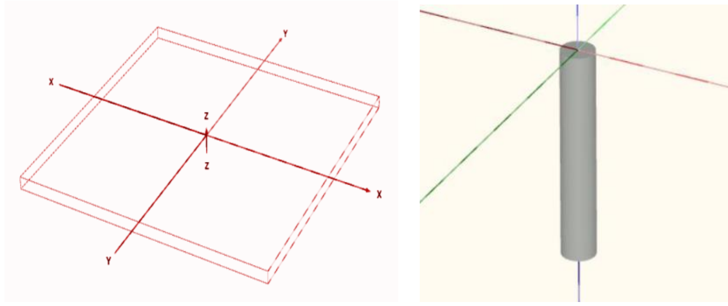

Fig. 5. Creation of model boundary and pile element in PLAXIS 3D

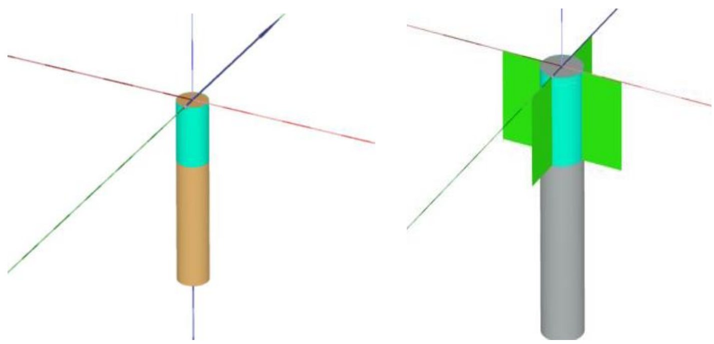

Fig. 6. Creation of defective pile encased by casing alone and casing with fins

In the present study, the lateral load corresponding to the lateral displacement of 10% of the pile diameter (10 cm) is considered as the ultimate lateral load capacity of the pile.[13] The numerical investigation executed through PLAXIS 3D by developing the model containing the homogeneous soil and concrete pile incorporating lateral load on it. Figure 5 and 6 shows the model created through PLAXIS 3D software. The Mohr-Columb model simulates the behavior of the soil and demands properties such as unit weight, angle of internal friction, cohesion, young's modulus and poisson ratio of the soil. The pile element is simulated using the linear elastic model and it demands unit weight, young's modulus and poisson ratio value as the input parameter. Table 1 and 2 describes the input parameters for soil and pile element. The interface between the soil and pile is simulated by proving R_{inter} value of 0.67.

Table 1. Properties of sand incorporated in PLAXIS 3D

Description	Properties of Sand
Type of Homogeneous Soil	Medium Dense Sand
Model Adopted	Mohr-Columb Model
Unit Weight of Soil	20 kN/m^3
Young's Modulus	20000 kN/m^2
Poisson Ratio	0.30
Angle of Internal Friction	34 Degree

Table 2. Properties of pile incorporated in PLAXIS 3D

Description	Properties of Pile
Type of Material	Concrete (M25 Grade)
Model Adopted	Linear Elastic Model
Unit Weight	25 kN/m^3
Young's Modulus	25 x 10^6 kN/m^2
Poisson Ratio	0.15

4 Result and Discussion

The parametric study was executed to assess the influence of each factor over the enhancement of lateral load carrying capacity of a defective pile. The soil model was created using the PLAXIS software. As this study focussed to investigate the enhancement of defective pile preliminarily, the observation and discussion carried only based on ultimate lateral capacity of the pile for the prescribed lateral displacement of 10% of pile diameter. This study can be further extended by considering pile deflection. soil deformation, shear force and bending moment along the pile with different configuration of fins under lateral loading.

4.1 Influence of thickness of casing

Initially, the ultimate lateral capacity of an intact pile having 1 m diameter and 10 m length is observed as 905 kN for the soil and pile properties mentioned in Table 1 and Table 2. The necking defect pile is created by incorporating a necking defect having 0.5 m diameter and 1 m length positioned at 1 m from top of the pile and its capacity is observed as 754 kN. The percentage reduction in lateral capacity arrived as 16.69% with respect to the intact pile. To understand the influence of the thickness of the casing around the pile, the casing for a top one-third portion (3.33 m) was modeled with different thickness of 3, 5, 8 and 10 mm by keeping other parameters constant. Table 3 illustrates the observed results for the different cases. It clearly shows that the increase in the casing thickness enhances the lateral capacity with respect to the intact pile and defective pile without casing. Enhancement in pile capacity is proportional to the casing thickness. Considering the drivability of the casing around the existing defective pile, the thickness of casing can be recommended from 5 to 8 mm for the effective enhancement.

4.2 Influence of number of fins around the casing

The study further extended by incorporating fins around the pile. The influence of the number of fins in the casing around the defective pile is studied by introducing fins (2, 3, 4 and 6 numbers) by keeping the casing thickness of 8 mm, fin width of 1 m, fin thickness of 5 mm, rectangular fin profile and the properties of pile and soil as constant. Table 4 illustrates the influence of the number of fins on pile lateral capacity with respect to intact and defective piles without casing. In the cross sectional view of the pile with casing and fins, the angle between the nearer fins is 180° for two fin pile, 120° for three fin pile, 90° for 4 fin and 60° for 6 fin pile. The increase in the number of fins around the casing increases the lateral capacity of the pile. The difference in percentage of enhancement for 4 fins pile and 6 fins pile was observed less. Considering the material expenses involved in the fins, 4 fin pile can be treated as the optimum for the enhancement of pile lateral capacity.

Table 3. Influence of thickness of casing on lateral capacity of defective pile

Description		Ultimate Lateral Load (kN)	Percentage Increase in Ultimate Lateral Load (%) with respect to	
			Intact Pile	Defective Pile
Intact Pile		905	-	-
Necking Defect Pile		754	-16.69%	-
Defective Pile incorporated by Casing alone with different thickness keeping other parameters constant	**3 mm**	910	+00.55%	+20.69%
	5 mm	944	+04.31%	+25.20%
	8 mm	959	+05.97%	+27.18%
	10 mm	989	+09.28%	+31.17%

Table 4. Influence of thickness of casing on lateral capacity of defective pile

Description		Ultimate Lateral Load (kN)	Percentage Increase in Ultimate Lateral Load (%) with respect to	
			Intact Pile	Defective Pile
Intact Pile		905	-	-
Necking Defect Pile		754	-16.69%	-
Defective Pile with Casing alone		959	+05.97%	+27.18%
Defective Pile incorporated by Casing with different number of fins keeping other parameters constant	**2 Fins**	1105	+22.09%	+46.55%
	3 Fins	1132	+25.08%	+50.13%
	4 Fins	1340	+48.07%	+77.72%
	6 Fins	1359	+50.17%	+80.24%

4.3 Influence of width of the fins

The dimension of the fin from the casing (projected length) is considered as one of the important factors which influences the enhancement of lateral capacity of the pile. This is studied by modeling the defective pile encased with fins of different widths keeping the other parameters constant. Table 5 illustrates the observed results for the defective pile encased with different width of the fins keeping other parameters constant. The casing thickness of 8 mm, the fin thickness of 5 mm, fin profile of rectangular, fins of two numbers, soil and pile properties are kept constant while observing the lateral capacity for the various fin widths of 0.50, 0.75, 1.00, 1.25 and 1.50 m respectively. The observed results show that the increase in width of the fins increases the pile lateral capacity. Meanwhile, the zone of soil disturbance also increases. Considering the percentage of enhancement and soil disturbance around the pile, the optimum width of the fins can be taken as 1 m (One times the diameter of the pile).

Table 5. Influence of width of fins around casing on lateral capacity of defective pile

Description		Ultimate Lateral Load (kN)	Percentage Increase in Ultimate Lateral Load (%) with respect to	
			Intact Pile	Defective Pile
Intact Pile		905	-	-
Necking Defect Pile		754	-16.69%	-
Defective Pile with Casing alone		959	+05.97%	+27.18%
Defective Pile incorporated by Casing with fins having various width keeping other parameters constant	**500 mm**	980	+08.29%	+29.97%
	750 mm	1011	+11.71%	+34.08%
	1000 mm	1105	+22.10%	+46.55%
	1250 mm	1145	+26.52%	+51.86%
	1500 mm	1195	+32.04%	+58.49%

4.4 Influence of thickness of fins

The influence of thickness of each fin is studied by modelling a pile encased with two fins varying the thickness of fins such as 2, 3, 4, 5 and 6 mm keeping other parameters constant such as rectangular fin profile, fin width of 1 m and casing thickness of 8 mm. Table 6 illustrates the variation in ultimate lateral capacity of the pile for different thickness of fin. The drivability of the pile with casing and fin plays an important role. Higher the thickness of fin increases the self-weight of the pile system. Based on the percentage of enhancement for different fin thickness, thickness of 5 mm can be treated as optimum value for effective enhancement of the defective pile.

Table 6. Influence of width of fins around casing on lateral capacity of defective pile

Description		Ultimate Lateral Load (kN)	Percentage Increase in Ultimate Lateral Load (%) with respect to	
			Intact Pile	Defective Pile
Intact Pile		905	-	-
Necking Defect Pile		754	-16.69%	-
Defective Pile with Casing alone		959	+05.97%	+27.18%
Defective Pile incorporated by Casing with fins having various thickness keeping other parameters constant	**2 mm**	975	+07.73%	+29.31%
	3 mm	996	+10.06%	+32.09%
	4 mm	1065	+17.68%	+41.25%
	5 mm	1105	+22.10%	+46.55%
	6 mm	1112	+22.87%	+47.48%

Table 7. Influence of width of fins around casing on lateral capacity of defective pile

Description		Ultimate Lateral Load (kN)	Percentage Increase in Ultimate Lateral Load (%) with respect to	
			Intact Pile	Defective Pile
Intact Pile		905	-	-
Necking Defect Pile		754	-16.69%	-
Defective Pile with Casing alone		959	+05.97%	+27.18%
Defective Pile incorporated by Casing with 2 fins having various profile keeping other parameters constant	**Rectangular**	1105	+22.10%	+46.55%
	Triangular (Zero at Top)	985	+08.83%	+30.64%
	Triangular (Zero at Bottom)	1046	+15.58%	+38.73%
	Triangular (Minimum at Top)	1003	+10.83%	+33.02%
	Triangular (Minimum at Bottom)	1078	+19.12%	+42.97%

4.5 Influence of profile of fins

The profile of fin around the pile has a major impact on the ultimate lateral capacity of the pile. Its influence is studied by modelling the different profile of the fin as described in Table 7. In general, higher the area of the fin, higher will be the soil resistance. As the lateral load is applied on top of the pile, the resistance offered by the soil will be maximum at the top and linearly reduce towards the pile tip. Meanwhile, shear force and bending moment exert on the pile system under lateral loading. Hence, the profile of the fin greatly impacts the percentage of enhancement. Table 7 illustrates the lateral capacity of the pile for different profiles of the fin. From the results, it can be observed that the rectangular profile shows a higher percentage of enhancements. But, the percentage variation among the other profiles are not much differed as the casing and fins provided only in the top one-third length of pile.

5 Conclusion

This study presents the influence of casing and casing with fins around the necking defect pile under lateral loading in the cohesionless soil deposits. The various factors considered for the study such as thickness of casing, number of fins, width of fin, thickness of fin and profile of the fin. The lateral load corresponding to the lateral displacement of 10% of the pile diameter is considered as the ultimate lateral load capacity of the pile. The ultimate lateral capacity of the pile for all the cases were compared with the intact pile condition and the following conclusions are drawn from the detailed parametric study:

1. The defect pile encased with casing alone shows the increase in the lateral load carrying capacity of the pile. The thickness of the casing plays a significant role in the percentage of lateral load enhancement. Considering the drivability of casing and expenses involved to retrofit the defective pile, the thickness of the casing recommended to be 5 to 8 mm with a length of one-third of pile embedment length.
2. The pile casing with fins around the defective zone enhances the lateral capacity of the pile significantly with respect to the intact pile and defective pile. The percentage of enhancement of lateral capacity depends on the configuration of the fin.
3. Increasing the number of fins around the pile shaft enhances the lateral load carrying capacity of the intact pile and defective pile efficiently. The percentage of increases is minimal after four fins around the pile shaft.
4. The profile of the fin plays the major role in the aspect of achieving the higher lateral capacity with minimum volume of steel involved in fin. Rectangular profile consumes higher volume compared with the triangular profile. As the fins provided only in the top one third portion of the pile, this effect is observed as minimal impact in the lateral load carrying capacity of the pile. Meanwhile, the characteristics of necking defects play a vital role in soil structure interaction.
5. The increase in the width of the fin influences the zone of soil disturbance around the pile significantly with an increase in lateral capacity of the pile. The increase in width of fin has minimal effect on lateral capacity of pile after a certain range and the width of fin is optimised as the diameter of the pile for the effective enhancement.

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