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Numerical Investigation of Triangular Shape Fin Pile under Lateral Loading.

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Abstract— *Monopiles have been widely used as a foundation for offshore as well as onshore structures. These foundation are generally subjected to environmental loads such as wind load. To improve the lateral resistance of monopiles, a spin fin pile has been proposed. A spin fin pile is a newly developed type of pile foundation that is capable of supporting large lateral loads. Finned piles consist of two or more fins welded at top or bottom of a regular pile around its circumferential area. In this study, a nonlinear 3D analysis with an elastic plastic soil model (Mohr-Coulomb), an elastic pile material (steel)and interface elements are used to model the pile–soil interaction using MIDAS GTS-NX finite element software. Analyses were performed in sand with different relative densities, namely 40% and 55%. Influence of sand on single and group of spin fin pile, relative density and slenderness ratio (L/D) on lateral response of fin piles is highilighted. Analysis shows that the existence of fin pile provides higher lateral resistance. Further, it was also observed that relative density of sand influences the lateral load carrying capacity of spin fin piles.*

Keywords— Spin fin pile, lateral loading, MIDAS GTS NX, resistance, circular pile, slenderness ratio

I. INTRODUCTION

Many transmission towers, high-rise buildings, and bridges are supported by piles. These structures may be subjected to large lateral loads such as violent winds and earthquakes. Under these loads, the lateral resistances of piles will be small and thus need improvement. Current offshore engineering strategies for the foundations, such as piles, may not be suitable for these structures to be cost effective. New techniques of design and analysis must be developed. (B. W. Byrne et al. 2003). Lutenegger (2012) performed field tests on plain piles and piles with fins placed at top and bottom of piles located in sandy silty soils. Application of these piles was to support solar panels. From the field tests, it was reported that piles with fins provide higher lateral load capacity compared to plain piles.

A Spin Fin pile is described as a pile that has four plates welded along the length of traditional monopile at 90° to each other. Peng et al. (2004) stated that the lateral load capacity of model tests on a monopile increased significantly if fins were introduced. Spin Fin pile is new pile-modification strategy of these conventional piles, which increases pile capacity by providing an affirmative anchorage close to the pile tip. Thus, Spin Fin pile is a modification of a pipe pile, introduced by PND Engineers in 1983. The name for the spin fin pile is derived from the fact that the pile actually rotates while being driven due to the angled fins, much like a screw. (Steven Halcomb et al. 2018).

This paper presents 3D computer simulations of laterally loaded triangular shape fin piles to explore the effect of slenderness ratio, relative density on their load bearing capacity in sand. It should be noted that the numerical analyses were carried out using the standard Mohr–Coulomb model in order to assess the potential of fin piles to reduce foundation costs.

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II.MATERIALS AND METHODS

Material Properties

A three-dimensional (3D) finite element model was established in order to analyse the behaviour of spin fin pile. The computations were carried out using the finite element program system MIDAS GTS-NX. The sand was assumed to be a linear elastic perfectly plastic material. A non-associated Mohr–Coulomb constitutive model was assumed to govern the soil behaviour for which the material parameters are well established in geotechnical engineering practice. An elasto-plastic analysis under drained conditions was used to model piles with the yield of the sand, defined by the Mohr–Coulomb model. Soil properties used in finite element analysis are given in Table 1. Hollow portion finned pile were filled with sand having properties same as given in table 1 for loose sand and medium dense sand respectively. Fin and pile properties used in finite element analysis are given in Table 2.

Table 1: Properties assigned to soil used in finite element analysis

Parameter	**Symbol**	**Loose Sand**	**Medium Dense Sand**
Relative Density of soil	Dr (%)	40	55
Unit Weight of soil	Υ(kN/m^3)	16.33	16.5
Young's modulus	E (MPa)	20000	27000
Poission's ratio	μ	0.3	0.3
Angle of internal friction	φ (^{0})	34	37.88
Cohesion	c (kN/m^2)	1	2

Table 2: Properties of pile used in finite element analysis

Parameter	**Symbol**	**Value**
Pile outer diameter	D (m)	1.2
Pile wall thickness	T_p (m)	0.075
Fin wall thickness	T_f (m)	0.075
Length of pile	L_p (m)	18, 24, 30
Length of fin to length of pile	L_f / L_p	0.5
Width of fin	B_f (m)	0.6
Slenderness ratio	L/D	15, 20, 25
Type of material		Mild steel
Poisson's ratio	μ	0.3
Modulus of elasticity	E (GPa)	200

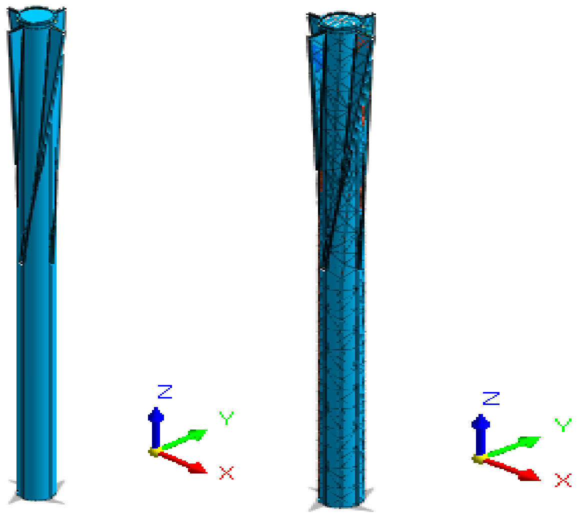
It was assumed that the pile was installed in a normally consolidated sand with Ko= 0.42. It should be noted that interface elements were applied between the sand filling and the pile in order to model the sand filling – pile interaction. Along the pile the strength reduction factor of the interface is set to 0.65 which is typical of sand -steel interfaces.This factor relates the interface properties to the strength properties of a soil layer as follows:

$\tan\phi^i = R_{int} \tan \phi^{'}$

$C_i = R_{int} C^{'}$

$\Psi_i = 0$ if $R_{int} < 1$ otherwise $\Psi_i = \Psi$

Where ϕ^i, C_i and Ψ are the friction angle, cohesion and dilatancy angle of the interface, respectively. The piles and the fins, shown in Fig. 1, were assumed to be linear elastic mild steel material which has typical properties of Young's modulus, Ep = 200 GPa, Poisson's ratio ν_p = 0.3, and unit weight, Υp = 78 kN/m^3. The yield of steel was not considered in this study.



(a) (b)

Fig. 1: a) Three dimensional view of geometric modelling and b) meshing of spin fin pile

The 3D Geometry of the Embedded Pile and the Soil Mesh

The three-dimensional finite element program, MIDAS GTS-NX was chosen to model the finned pile and the sand. Three dimensional view of pile and fins are show in Fig. 1. The boundary is a cube with sides of 22.5 times the diameter of the pile and a depth 2.5 times the length of pile (J. R.Peng, 2010). The geometry of a three-dimensional model of group of four spin finned pile embedded in soil is shown in Fig. 2. The bottom boundary was fixed against movements in all directions, whereas the 'ground surface' was free to move in all directions. The vertical boundaries were fixed against movements in the direction normal to them. This geometry approximated was used by Peng et al. in their 1G laboratory tests on model piles.

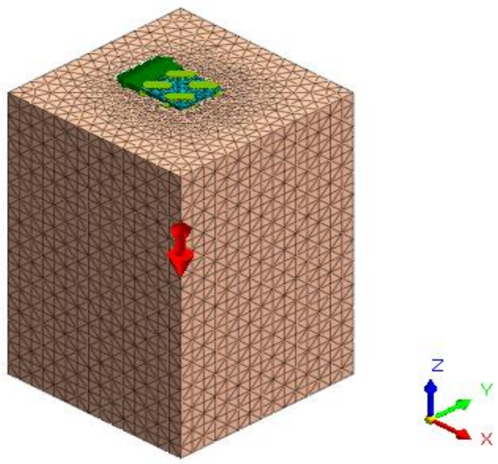


Fig.2: Three Dimensional View of Group of Four Spin Finned Pile Embedded in Soil.

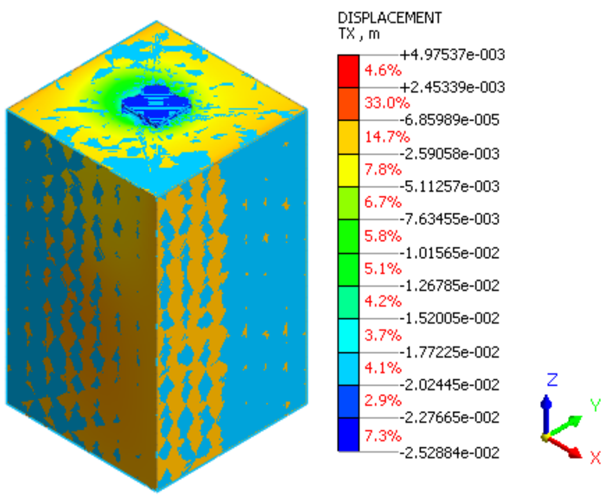


Fig. 3: Displacement Contour around Spin Fin Pile.

III. RESULTS AND DISCUSSION

Pile head P–Y curves

The analyses were conducted on triangular shape spin fin pile for loose and medium dense condition. The load -displacement curves for these pile subjected to lateral load in loose and medium dense sand for L/D ratio = 15, 20, 25 are plotted. The ultimate load capacity taken as the load corresponding to the settlement equal to 10 percent of the diameter of pile base as per provisions of IS 2911 (Part 4): 2013. The displacement contour obtained after analysis is shown in fig. 3. Lateral load and pile head displacement (P–Y) curves for numerical analyses of finned pile for loose and medium dense sand are shown in Fig. 4 – 8.

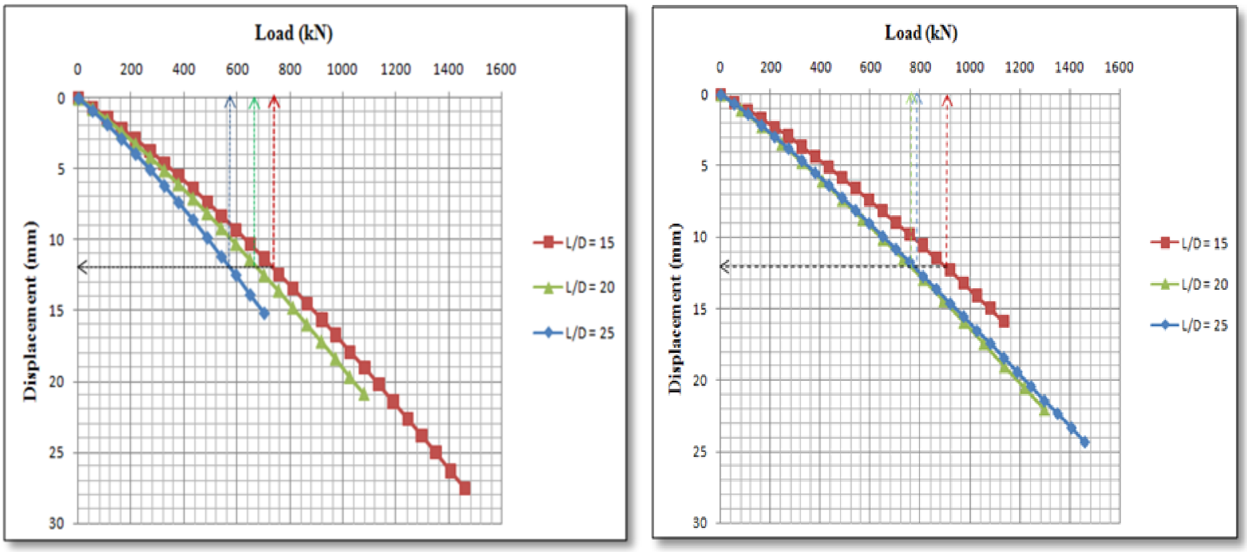


Fig. 4: P-Y curves for single spin fin pile for loose and medium dense sand, showing the effect slenderness ratio upon the lateral resistance.

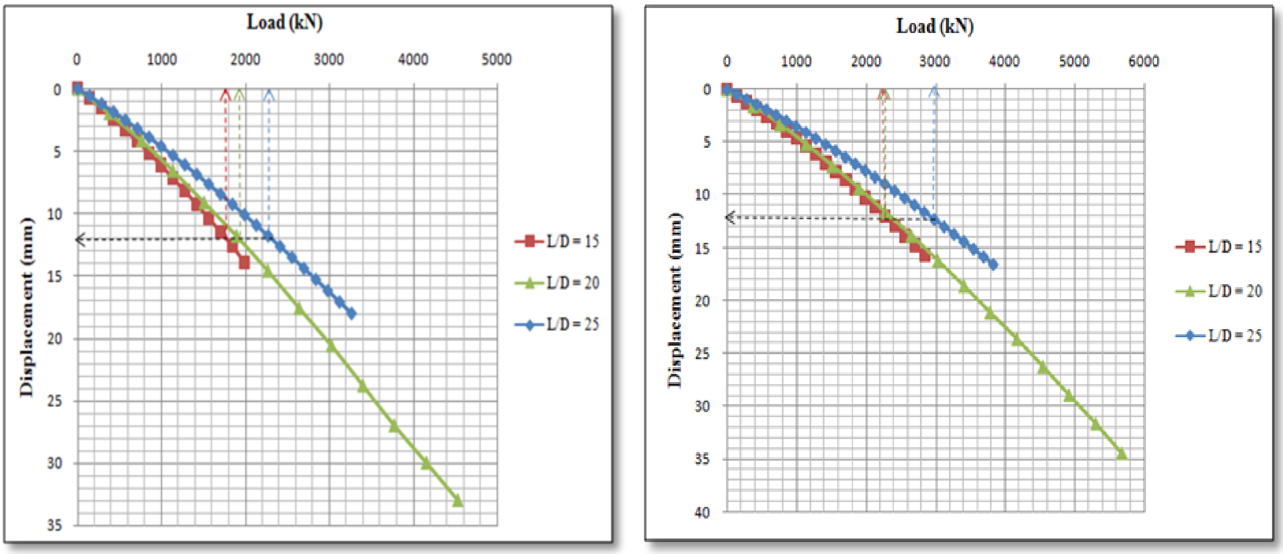


Fig. 5: P-Y curves for group of three spin fin pile for loose and medium dense sand, showing the effect slenderness ratio upon the lateral resistance.

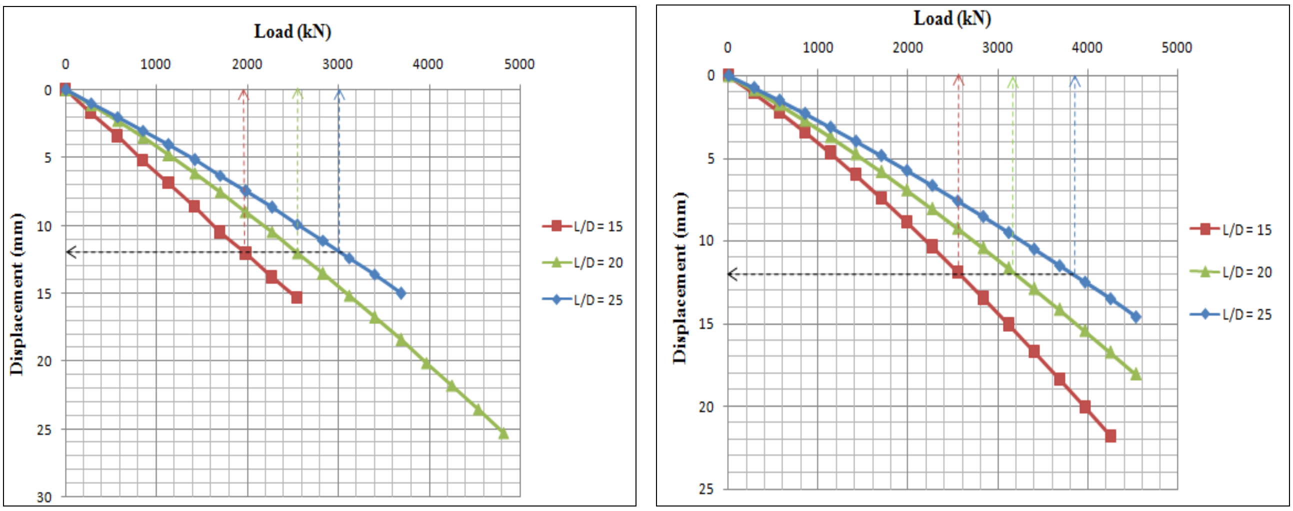


Fig. 6: P-Y curves for group of four spin fin pile for loose and medium dense sand, showing the effect slenderness ratio upon the lateral resistance.

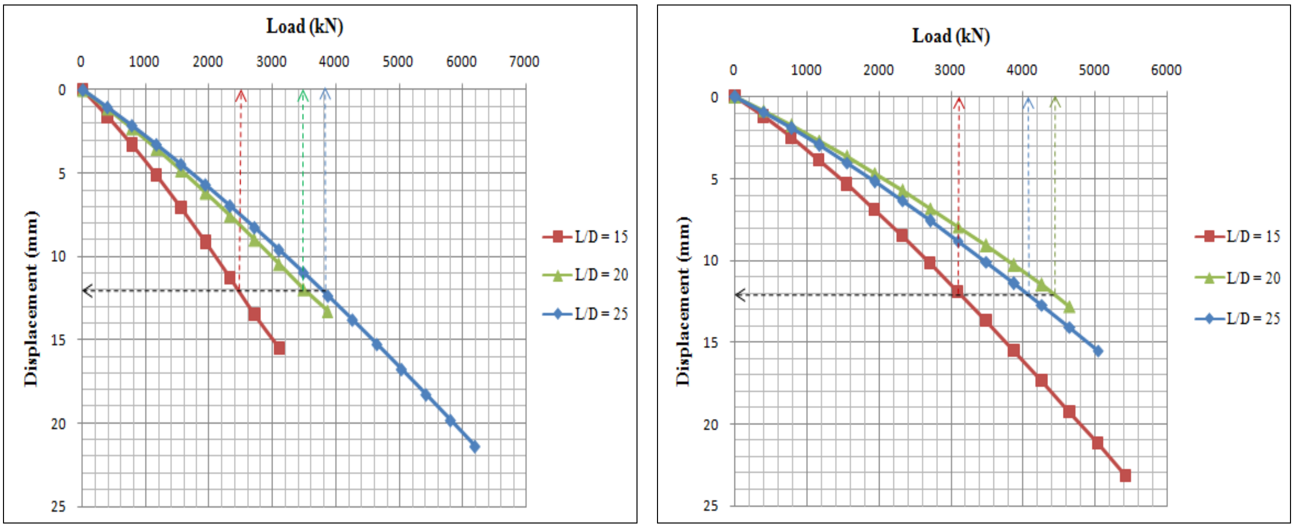


Fig. 7: P-Y curves for group of five spin fin pile for loose and medium dense sand, showing the effect slenderness ratio upon the lateral resistance.

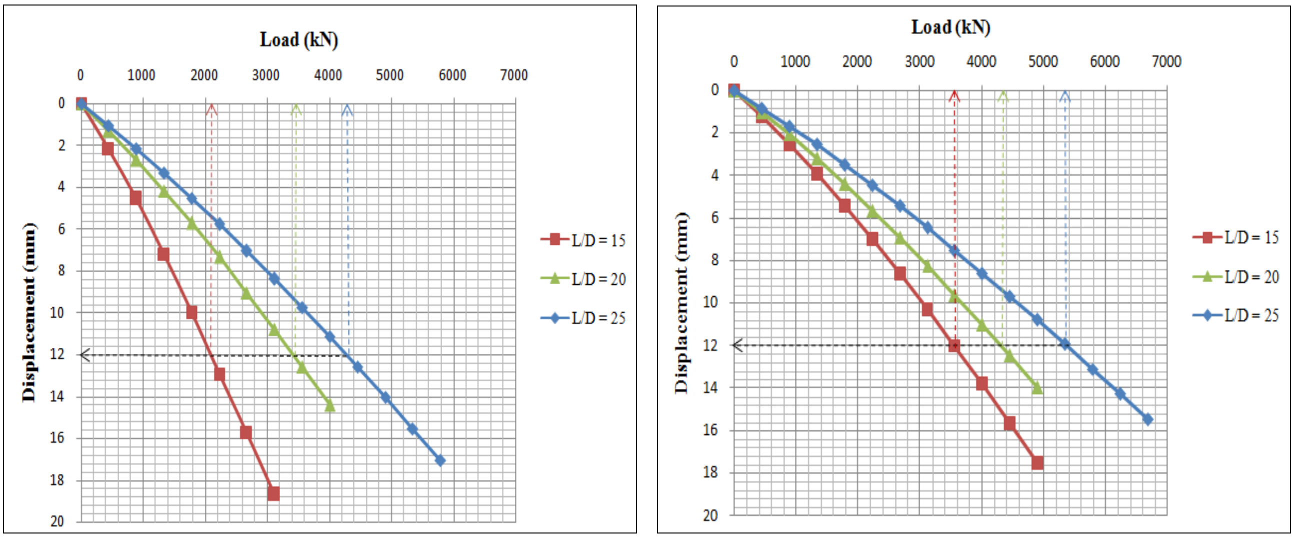


Fig. 8: P-Y curves for group of six spin fin pile for loose and medium dense sand, showing the effect slenderness ratio upon the lateral resistance.

Influence of Slenderness Ratio

In the current study, the fin efficiency was observed by varying the length of the pile. The length of the pile varied from L/D =15 to 25, so that performance of long-pile and short-pile could be analyzed. The variations of load – displacement with different L/D ratio for relative density (Dr = 40% and 55%) are shown in Fig. 4-13. The results obviously showed that load effectiveness depends on pile stiffness. It can be seen that any increase in pile length leads to a gradual increase in load. Fig. 14 and 15 show the % change (increase) in pile capacity compared with single pile of fin piles in loose and medium dense sand for various slenderness ratio. It can be noticed from the figures that spin fin piles in group carry more than 150% of the load compared to single spin fin pile irrespective of its slenderness ratio. It is obvious that, at L/D =15 the improvement in the load capacity is relatively small.

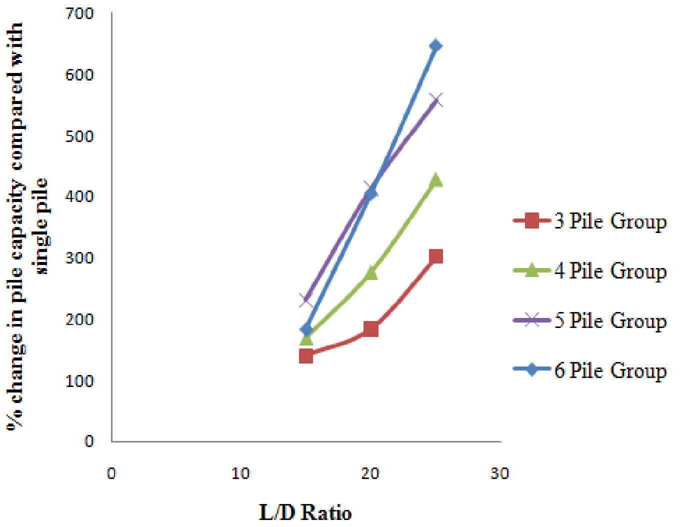


Fig.14: Variation of slenderness ratio versus % change in pile capacity for loose sand.

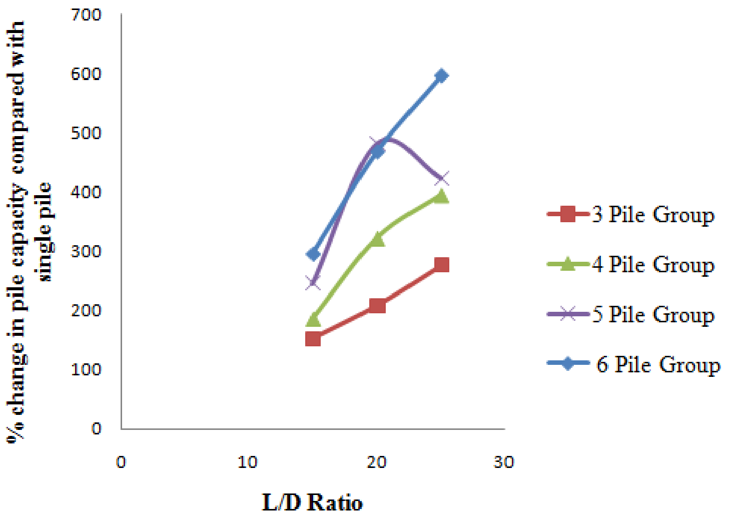


Fig.15: Variation of slenderness ratio versus % change in pile capacity for medium dense sand.

Influence of Sand Relative Density

In cohesionless soils, one of the main factors influencing the lateral resistance of pile is its relative density. In the present study, to evaluate the influence of relative density on lateral resistance of fin piles with different, two density indices are considered ranging from loose (40%) and medium dense (55%) conditions. The ultimate lateral load capacities of the single and group of spin fin pile are tabulated in table 3 and 4.

Table 3: Ultimate lateral load capacities of spin fin pile for loose sand.

Type of pile	Ultimate Lateral Load (kN)			% change in pile capacity compared with single pile		
	L/D ratio			L/D ratio		
	15	20	25	15	20	25
Single Pile	737	677	573	-	-	-
3 Pile Group	1768	1920	2303	140	184	301
4 Pile Group	1984	2553	3031	169	277	429
5 Pile Group	2447	3483	3770	232	414	558
6 Pile Group	2086	3422	4277	183	405	646

Table 4: Ultimate Lateral Load Capacities of Spin Fin Pile for Medium Dense Sand.

Type of pile	Ultimate Lateral Load (kN)			% change in pile capacity compared with single pile		
	L/D ratio			L/D ratio		
	15	20	25	15	20	25
Single Pile	898	758	772	-	-	-
3 Pile Group	2268	2336	2910	152	208	276
4 Pile Group	2577	3202	3827	186	322	395
5 Pile Group	3111	4408	4040	246	481	423
6 Pile Group	3564	4310	5373	296	468	596

It can be observed that lateral load carrying capacity of triangular shape spin fin pile in dense sand is more than piles in loose sand. Increase in lateral load in the case of spin fin piles in dense sand was mainly due to development of high confining stresses around the fins and piles. Results verify that the ultimate lateral load increases with an increase in relative density.

IV. CONCLUSIONS

The behavior of finned piles subjected to a lateral load in sand deposits of different densities was investigated through three-dimensional nonlinear FE analyses. The results obtained from numerical analyses were compared. Based on the investigations the following main conclusions can be drawn:

- Piles with trangular fins provide considerably higher ultimate lateral loads and lateral resistance behavior compared with a regular reference circular pile.
- The lateral resistance increases with the increase in slenderness ratio of finned pile for both loose and medium dense sand.
- The ultimate lateral load capacities of triangular shape spin fin pile increases with increase in number of piles.
- Spin fin piles in group carry more than 150% of the load compared to single spin fin pile irrespective of its slenderness ratio.
- Ultimate lateral load capacities of spin fin pile in dense sand is more than piles in loose sand.

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