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ORIGINAL PAPER

Interaction Effect of Group of Helical Anchors in Cohesive Soil Using Finite Element Analysis

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Abstract In this paper, the interaction effect of a group of two and four symmetrical as well as asymmetrical helical anchors resting in homogeneous cohesive soil deposit with different helix configurations is determined using finite element analysis. The anchors were pulled to its ultimate failure controlling the displacement. Eight different types of anchor configuration were considered in the analysis, where mainly the number of helical plates, the depth of upper- and lower-most helical plates and the ratio of spacing between the helical plates to the diameter of the plate were varied. The variation of load–displacement curve for each anchor in the group was obtained and subsequently, the ultimate uplift capacity of each anchor was determined. The soil was assumed to follow Mohr–Coulomb failure criteria. The present theoretical observations are generally found in good agreement with those theoretical and experimental results available in the literature for single isolated helical anchor.

Keywords Finite element analysis · Helical anchor · Homogeneous soil · Interaction effect · Plasticity · Pullout capacity

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1 Introduction

The anchor is a foundation system generally designed and constructed to transmit any uplift force and over turning moment coming from the super-structure to the underlying soil. Anchors are important for many engineering applications such as transmission towers, suspension bridges, tall chimneys, high rise structures which experience lateral load like wind load, buried pipe lines under water, offshore structures as well as tunnel construction. As compared to the installation process of conventional plate anchor, helical anchor is found to be quite easy to install and is pretty cost effective, which may be used both in tensile as well as compressive loading condition. Basically, helical anchors are geotechnical foundations consisting of central steel shaft and number of helical plates welded along the shaft (Fig. 1). These helical plates are generally made up of steel and are formed with a definite pitch. The anchor shaft is used to transmit the torque during installation and to transfer the loads to the helical plates. From the reported investigations, it can be clearly understood that the ultimate uplift capacity of helical anchor depends upon the number of helical plates, the depth of upper- and lower-most helical plates, the ratio of spacing between the helical plates to the diameter of the plate and the embedment depth. A number of investigations were performed by several researchers (Meyerhof and Adams 1968; Rowe and Davis 1982; Murray and Geddes 1987; Basudhar and Singh 1994; Subba Rao and Kumar

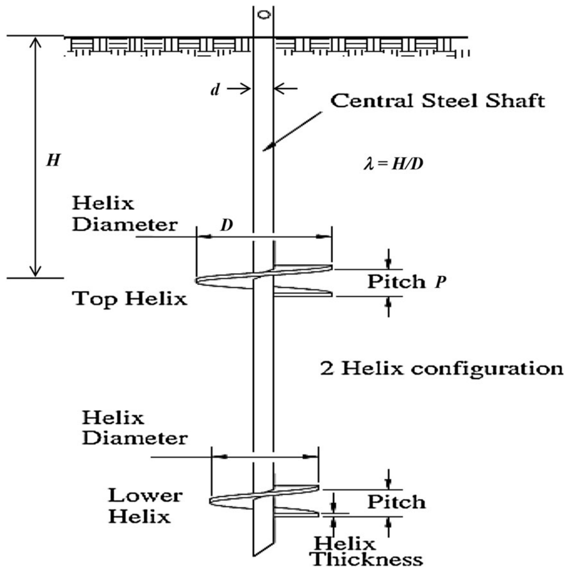


Fig. 1 Schematic diagram of helical anchor

1994; Kumar and Kouzer 2008a) to predict the uplift resistance of the plate anchor with the help of different numerical as well as experimental techniques. However, the work on a helical anchor is still scarce. From the literature it can be seen that few studies (Ghaly and Hanna 1992; Rao and Prasad 1993; Ghaly and Clemence 1998; Hanna et al. 2007; Mittal and Mukherjee 2013, 2014, 2015; Nazir et al. 2013; Wang et al. 2013; Demir and Ok 2015) were carried out to determine the ultimate uplift capacity of single isolated helical anchor theoretically as well as experimentally. However, in a number of occasions such as transmission towers, tall chimneys etc., anchors may be placed in a group to generate the necessary pullout resistance. It is evident from the literature that not much attention was paid by the researchers to determine the response of a group of helical anchors. The effect of interaction on the uplift capacity of a group of plate anchors was studied by various researchers (Geddes and Murray 1996; Kumar and Kouzer 2008b; Kouzer and Kumar 2009; Ghosh and Kumar 2015; Ghosh and Santhoshkumar 2015). However, till date virtually no work is available on the interaction effect of closely spaced helical anchors and therefore, the investigation on the interaction of the group of closely spaced helical anchors demands some attention.

In this investigation, a numerical study on the pullout capacity of closely spaced group of symmetrical as well as asymmetrical helical anchors embedded in homogeneous soil layer was carried out using finite element method developed in the framework of three dimensional failure domain in ABAQUS 6.13. The soil was assumed to obey the Mohr–Coulomb failure criterion. In this paper, the load–displacement response as well as the variation of efficiency factor (ξ_u) of the interacting anchors at different clear spacing are reported, where ξ_u is defined later in this paper.

2 Definition of the Problem

A group of two and four closely spaced symmetrical and asymmetrical helical anchors with multiple helical plates of diameter, D is embedded in a homogeneous cohesive soil layer with an embedment ratio, $\lambda = H/D$, where H is the embedment depth of the upper-most helical plate (Figs. 1, 2). The helical anchor was considered as an elastic member and the surface of the anchor was assumed to be partially rough. The soil was assumed to obey Mohr–Coulomb failure criteria. The objective is to determine the magnitude of the ultimate uplift capacity of closely spaced interacting helical anchors, where the anchors are pulled with an incremental velocity in the upward direction for calculating the uplift loading capacity. Full failure domain was considered for the analysis as the helical anchor was not truly axisymmetric member.

3 Material and Geometry

3.1 Materials

To determine the uplift capacity of the helical anchor, a single layer homogeneous cohesive soil deposit was considered. The properties of the soil deposit were taken from Wang et al. (2013) and were mentioned in Table 1, whereas the properties of the steel anchor used in the analysis were collected from Ghosh and Kumari (2012) and were given in Table 2.

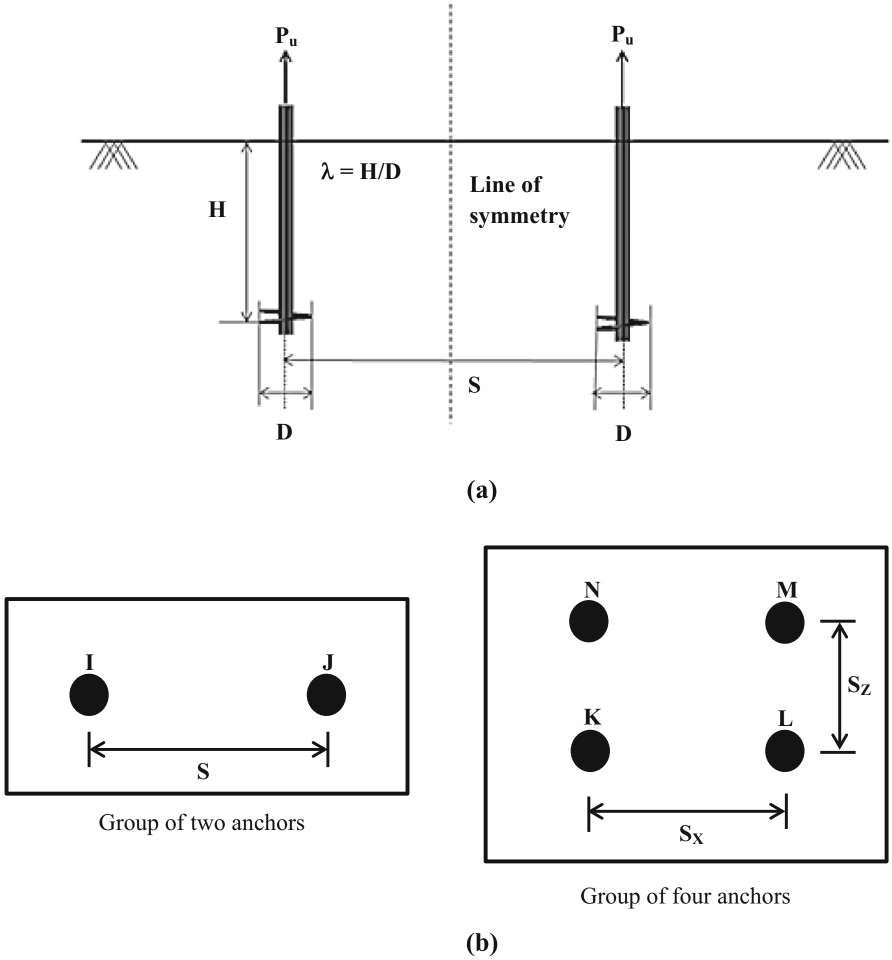


Fig. 2 Configuration of interacting helical anchors **a** cross-sectional view, **b** plan view

Table 1 Properties of soil deposit (Wang et al. 2013)

Young's modulus (E) (kN/m^2)	Undrained cohesion (c_u) (kN/m^2)	Unit weight (γ) (kN/m^3)	Poisson's ratio (υ)	Angle of internal friction (ϕ^0)
12.75×10^3	12.75	16	0.4	0

Table 2 Properties of steel anchor

Young's modulus (E) (kN/m^2)	Density (ρ) (kg/m^3)	Poisson's ratio (υ)
2.1×10^8	7800	0.25

3.2 Anchor Configuration

Eight different anchor configurations were considered for the analysis (Fig. 3) whose geometric specifications were reported in Table 3 (Wang et al. 2013). It can be seen from Fig. 3 that C1–C3 consist of three helical plates, C4–C6 consist of two helical plates and C7–C8 comprise of single helical plate.

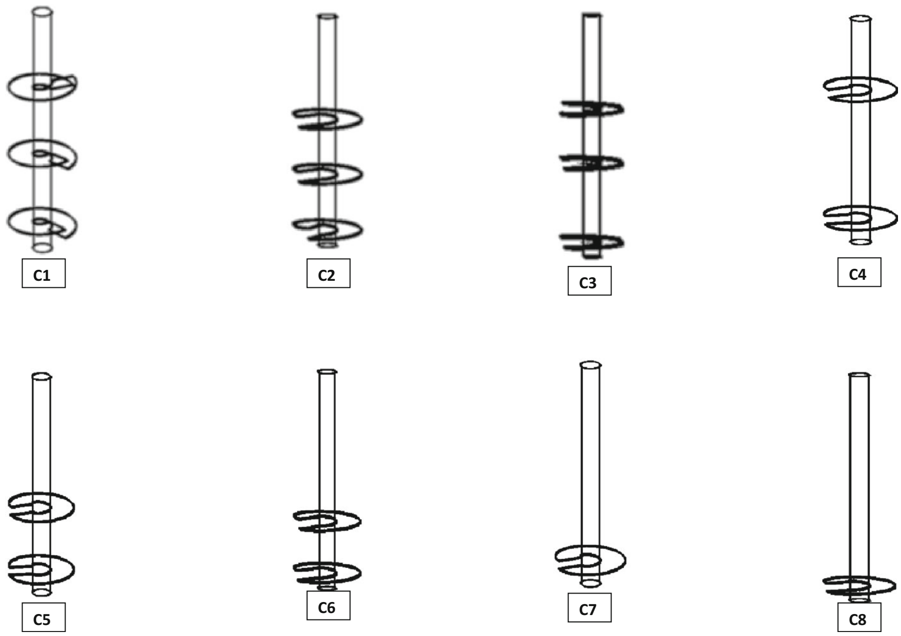


Fig. 3 Configuration of helical anchors

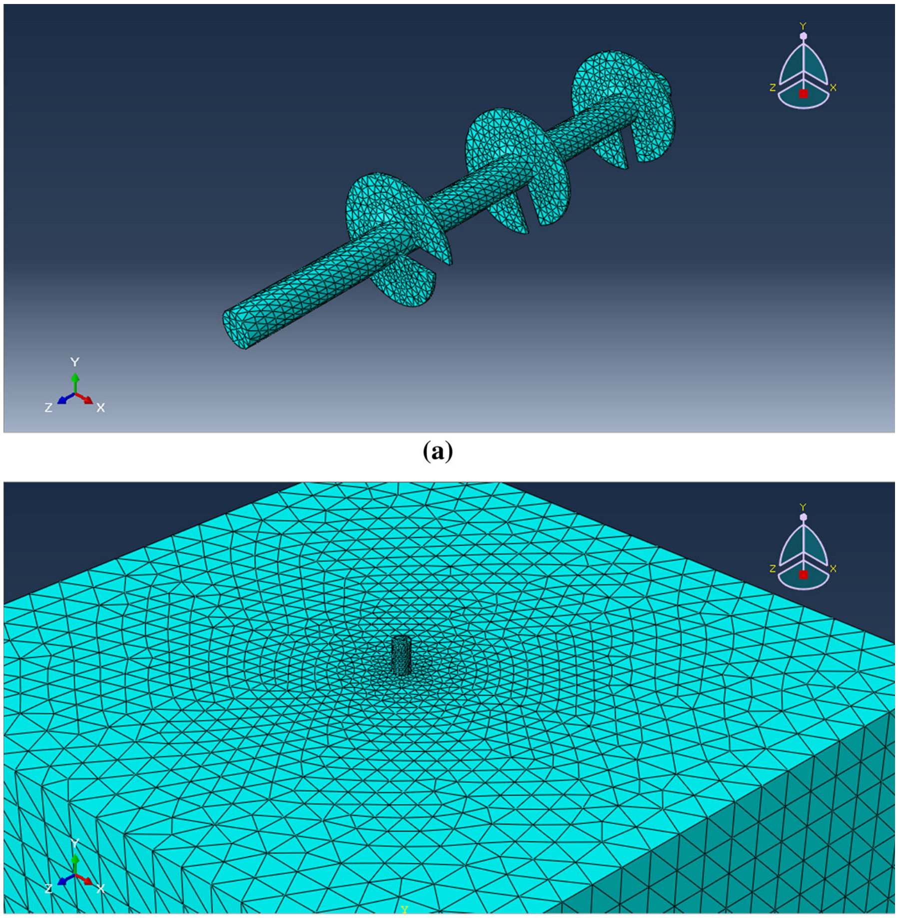
Table 3 Geometric details of different anchor configuration (Wang et al. 2013)

Configuration	Number of helical plates	Depth of uppermost plate, H (m)	Depth of lowermost plate (m)	Spacing between plates, S_p (m)	S_p/D
C1	3	2.65	9.85	3.6	1.5
C2	3	2.65	7.45	2.4	1.0
C3	3	2.65	8.65	2.4, 3.6	1, 1.5
C4	2	2.65	9.85	7.2	3
C5	2	6.25	9.85	3.6	1.5
C6	2	5.05	7.45	2.4	1
C7	1	6.25	6.25	–	–
C8	1	9.85	9.85	–	–

For any particular anchor, the spacing between two plates (S_p) was kept constant except C3, where the spacing was unequal between two successive plates. The diameter of the helical plate and the central shaft were considered as 2.4 and 0.4 m respectively, whereas the pitch of the helix (*P*) was taken as 0.46 m (Wang et al. 2013). The thickness of the helical plate was assumed as 0.1 m, which was considered to be negligible as compared to the diameter of the helical plate.

4 Analysis

The present finite element analysis was performed with 3D modeling using commercially available software ABAQUS 6.13. The whole soil domain was assumed to be at undrained condition. The soil deposit was assumed to follow Mohr–Coulomb failure criteria. The main challenge lying with the numerical analysis was to design the helical anchor in the finite element framework. In the numerical analysis



(a)

(b)

Fig. 4 Overview of **a** AutoCAD drawing and finite element meshing of C1 anchor, **b** finite element meshing of soil domain for single isolated anchor

proposed by Wang et al. (2013), the helical anchor was simplified as plates at different depths, which might not be the true representation of a helical anchor. Therefore, due to complicated geometry, the helical anchor was first designed in AutoCAD and then was imported to ABAQUS. The finite element meshing was done using four nodded tetrahedral elements. The AutoCAD drawing of the helical anchor and the details of finite element meshing are shown in Fig. 4. In the analysis, general contact properties were used to simulate the interaction among all the surfaces. All the interacting surfaces were considered as penalty for tangential behavior and hard for normal behavior. The penalty behavior denotes that there is a finite coefficient of friction value between the surfaces and no slip occurs. In this analysis the penalty value was taken as 0.1 as the soil was a cohesive in nature (Table 1). The following boundary conditions were considered in this analysis (Fig. 5).

- Displacements along X-axis, u_X were set to zero on the vertical boundaries parallel to ZY plane.
- Displacements along Z-axis, u_Z were set to zero on the vertical boundaries parallel to XY plane.
- All displacements were set to zero on the bottom boundary i.e. $u_X = u_Y = u_Z = 0$.

Sensitivity analysis was performed in order to determine the optimum domain size. For finding out the optimum domain size, anchor C1 and C8 were chosen. The main reason behind choosing these two configurations was that, C1 anchor configuration was having three helical plates with uniform spacing between the successive plates and the lower plate embedded at a depth of 9.85 m which was the

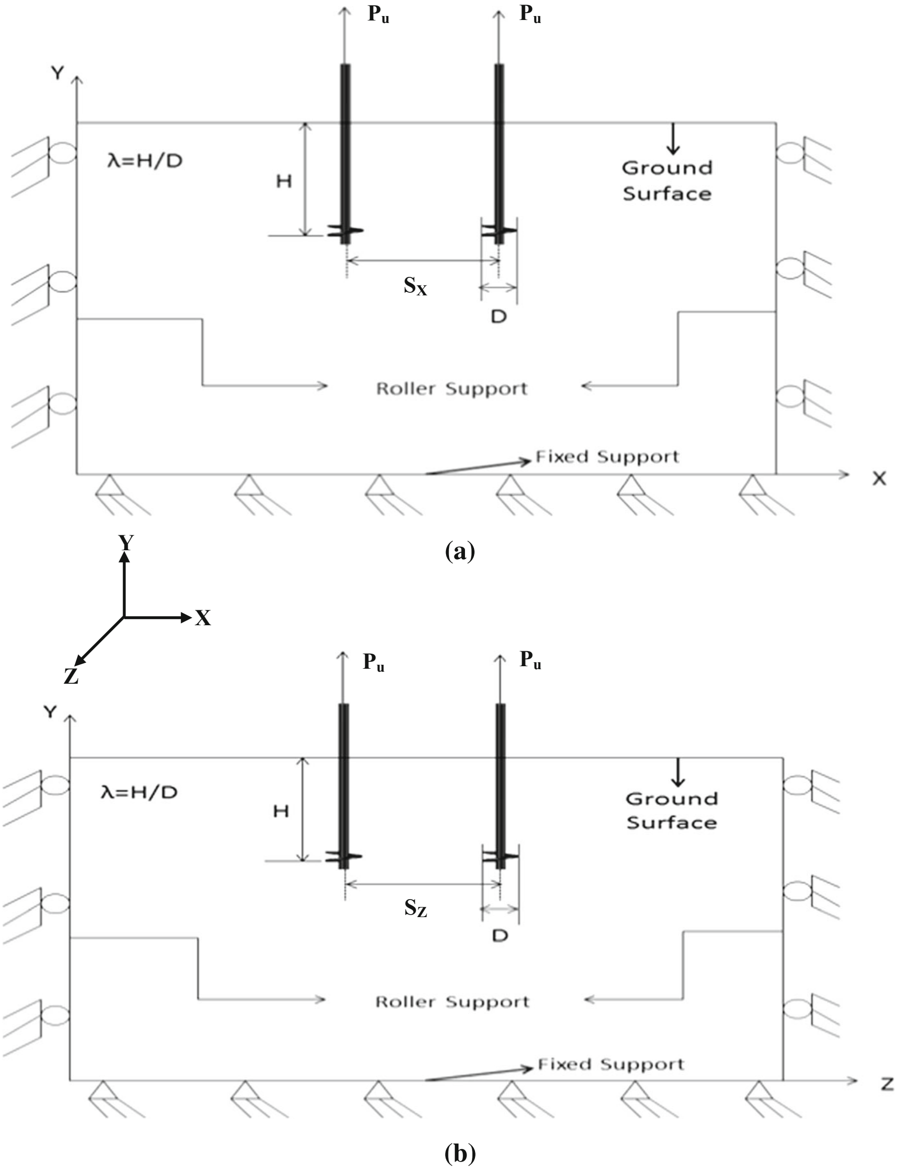


Fig. 5 Boundary conditions along XY and ZY plane for a group of four anchors

maximum embedment depth considered in this analysis, whereas C8 configuration was having single helical plate with $H = 9.85$ m. In this study the depth of the soil deposit was fixed at $12.5D$, which was found to be sufficient enough without any boundary effect. For the group of two anchors, no significant change in the ultimate uplift capacity got observed beyond $7D$ distance from the center of the anchor in the horizontal direction and hence, the optimum domain size in the horizontal direction (horizontal boundary) was selected as $7D$ from the center of the anchor. However, for the group of four anchors, no significant change in the ultimate uplift capacity got observed beyond $9D$ distance from the center of the anchor in X and Z directions and hence, the optimum domain size in the horizontal direction (X and Z) was selected as $9D$ from the center of the anchor.

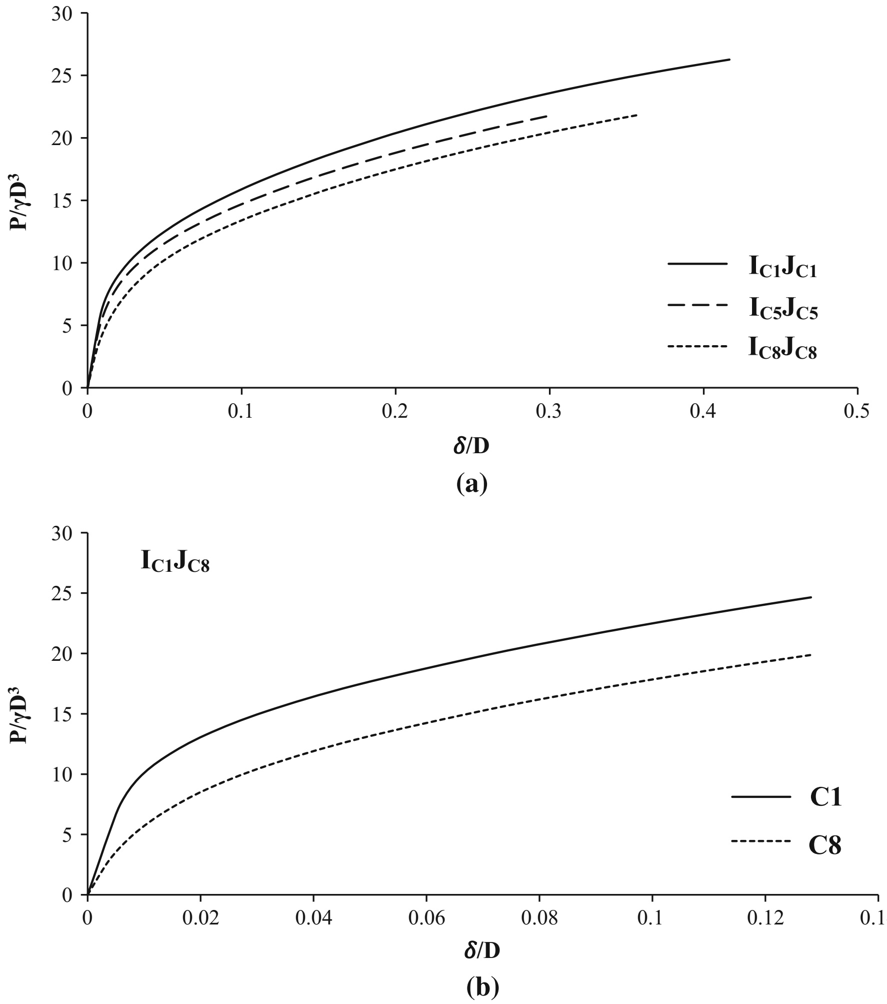


Fig. 6 Normalized load–displacement curve for two interacting **a** symmetric and **b** asymmetric type of helical anchors at S/D = 1

5 Results and Discussion

To understand the interaction phenomenon of the anchors in a group (two or four), each anchor was given a specific name such as I, J, K, L, M and N (Fig. 2). Therefore, $I_{C1}J_{C1}$ represents the interaction between two C1 anchors in a group of two anchors. Similarly, in a group of four anchors, $K_{C1}L_{C1}M_{C1}N_{C1}$ represents the interaction among four C1 anchors. Following the same argument the interaction among the asymmetrical anchors can be represented as $I_{C1}J_{C3}$ in a group of two C1 and C3 anchors or as $K_{C1}L_{C5}M_{C1}N_{C5}$ in a group of two C1 and two C5 anchors.

5.1 Two-Anchor System

In Fig. 6, the typical normalized load–displacement curves for two closely spaced symmetrical and asymmetrical anchors placed in single layer homogeneous soil deposit are shown for different combinations at $S/D = 1$, where P is the uplift capacity and δ is the vertical displacement of the anchor. The ultimate uplift capacity (P_u) of the anchor was then obtained by considering the double-tangent method. It can be seen from Fig. 6a that for the same embedment depth of the lowermost helical plate, the anchor with more number of helical plates provides

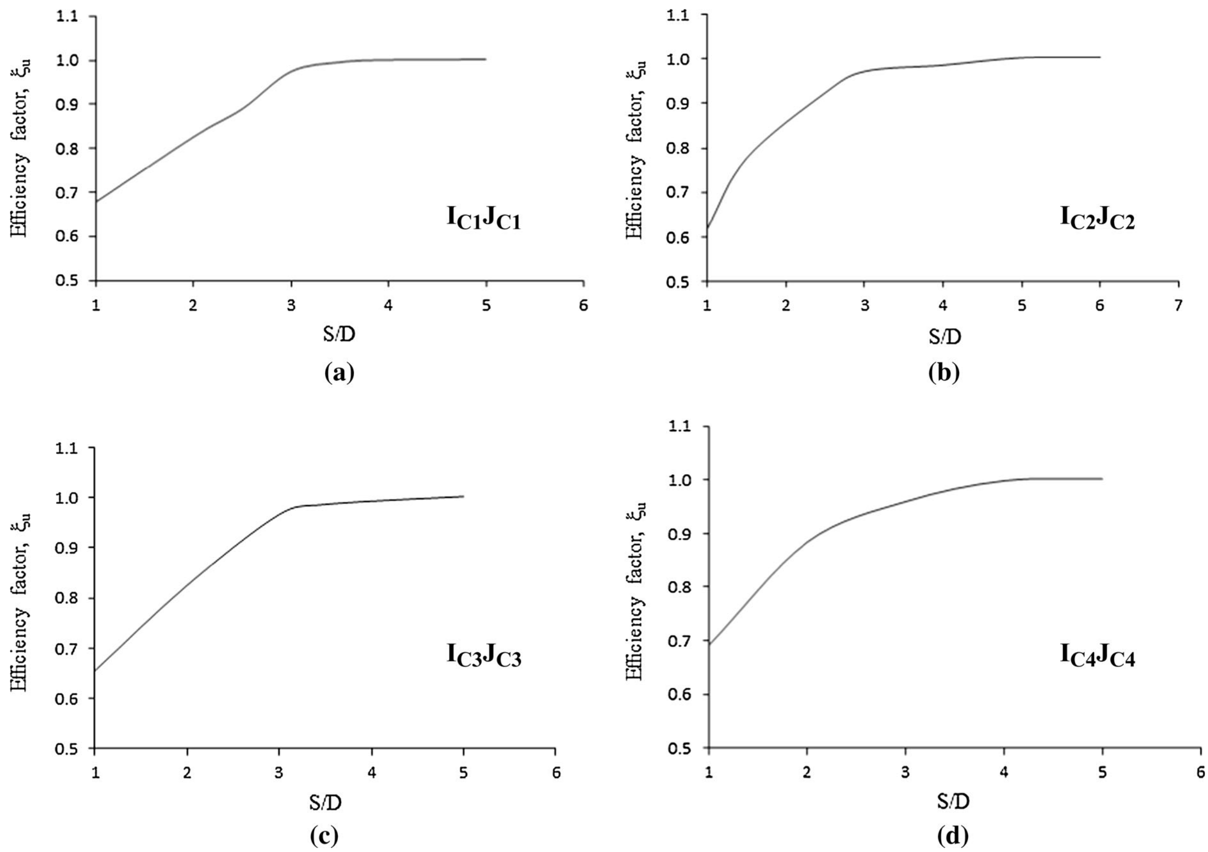


Fig. 7 Variation of ξ_u with S/D for the group of two symmetrical anchors **a** $I_{C1}J_{C1}$, **b** $I_{C2}J_{C2}$, **c** $I_{C3}J_{C3}$ and **d** $I_{C4}J_{C4}$

higher uplift capacity. Similar observation can be made from Fig. 6b even for the asymmetrical group, where being in the group of two-anchor system the anchor with more number of helical plates (C1) depicts higher uplift capacity. This may be attributed to the development of progressive influence zone developed around the helical plates i.e. as the number of helical plates increases, the size of the mobilized shear zone around the helical plates also increases, which eventually enhances the pullout resistance of the anchor. A parameter, efficiency factor (ξ_u) with respect to the ultimate pullout capacity is introduced to compare the uplift resistance of an interacting anchor with that of an isolated anchor, which can be defined as the ratio of the ultimate pullout capacity of an interacting helical anchor of a given type to that of an isolated helical anchor of the same type. The variation of ξ_u with *S/D* ratio for two interacting symmetrical anchors for different combinations is shown in Figs. 7 and 8. The study indicates that the magnitude of ξ_u increases with increase in *S/D* ratio and eventually becomes equal to 1.0 at some maximum spacing, S_{max}. It is worth noting here that the condition $\xi_u = 1.0$ indicates the behavior of single isolated anchor without any interaction. For different combinations of interacting anchors with same number of helical plates, the magnitude of S_{max} is generally found to increase with increase in embedment depth of the lowermost helical plate. This indicates that the size of the influence zone

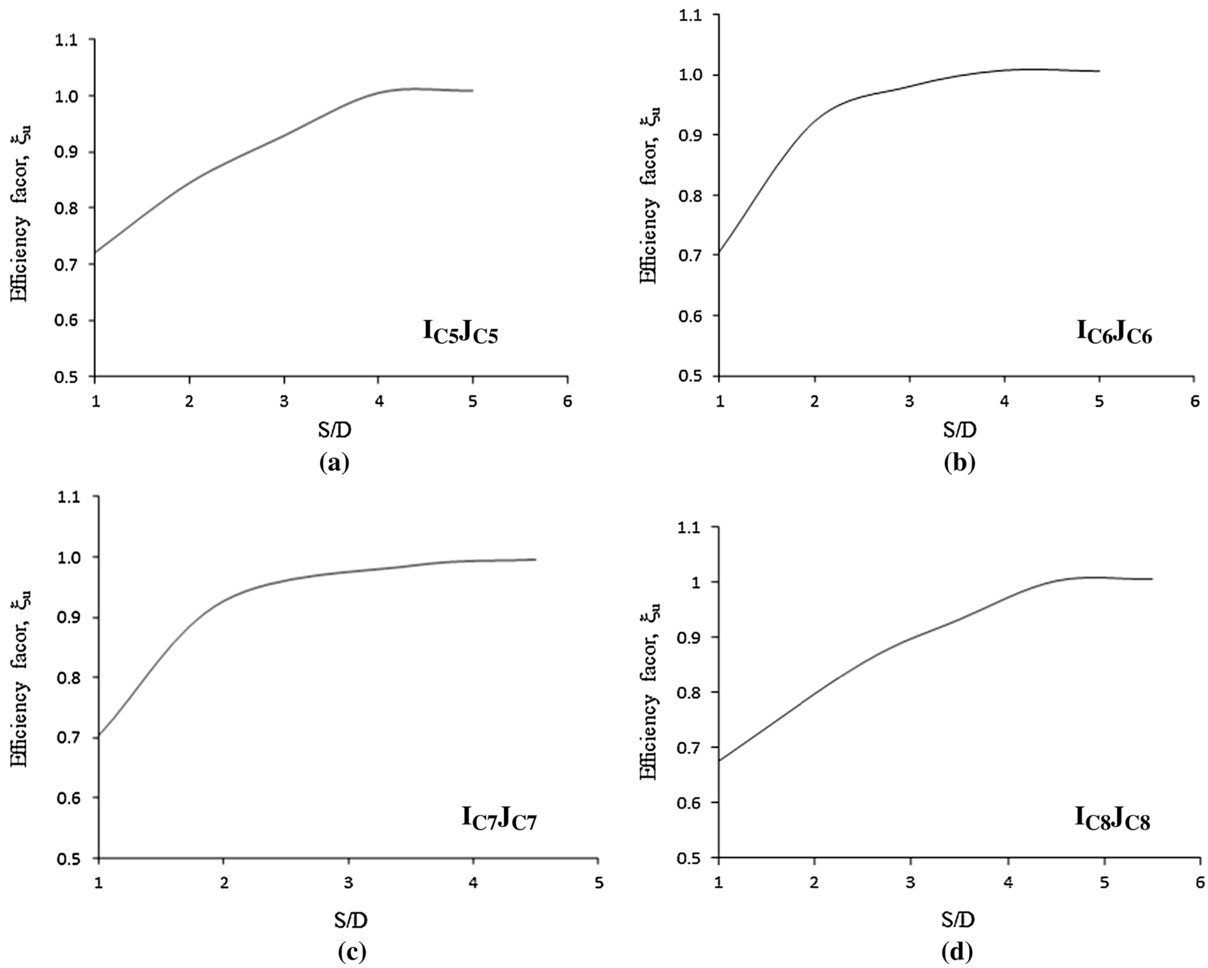


Fig. 8 Variation of ξ_u with S/D for the group of two symmetrical anchors **a** $I_{C5}J_{C5}$, **b** $I_{C6}J_{C6}$, **c** $I_{C7}J_{C7}$ and **d** $I_{C8}J_{C8}$

around an interacting helical anchor becomes larger with increase in embedment depth of the lowermost helical plate. It can be also observed that the magnitude of efficiency factor is found to be lower than unity at closer spacing e.g., ξ_u becomes approximately equal to 0.6–0.7 at $S/D = 1$, which indicates significant reduction in the pullout resistance at lower spacing. This observation is very much unlike to that made by different researchers for interacting foundations under compressive load. Figure 9 shows the variation of ξ_u with *S/D* ratio for two interacting asymmetrical anchors for different combinations. The trend is found to be pretty similar to that observed for the interacting symmetrical anchors. From Fig. 9a, b, the variation of ξ_u with *S/D* ratio is found to be quite similar for two different anchors but with same number of helical plates. However, the magnitude of ξ_u at a particular *S/D* ratio is found to be higher for the anchors with higher number of helical plates (Fig. 9c–f). It can be seen that the variation of ξ_u for the interacting asymmetrical anchors is profoundly influenced by the number of helical plates.

5.2 Four-Anchor System

In Fig. 10, the normalized typical load–displacement curves for four closely spaced symmetrical and

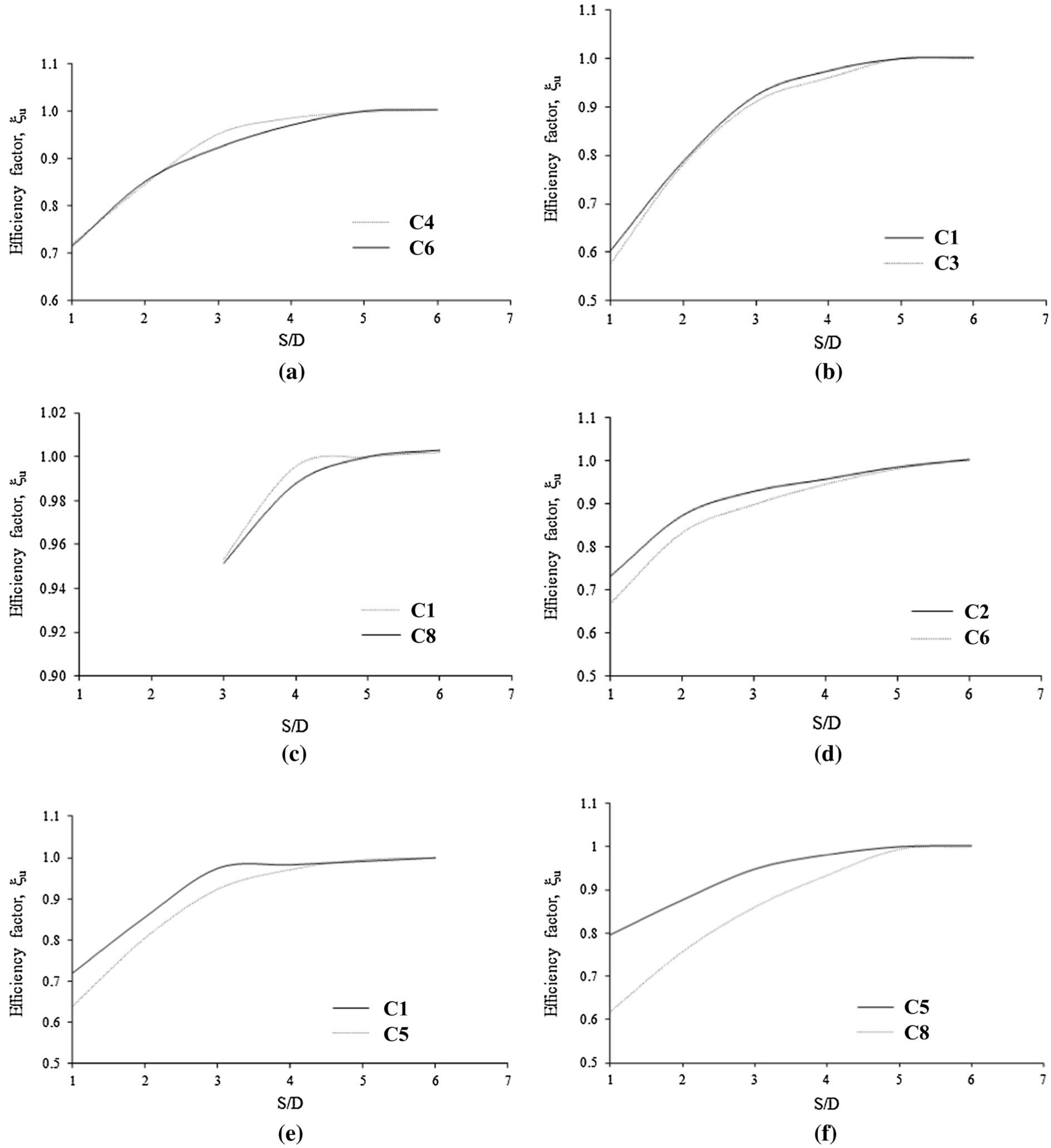


Fig. 9 Variation of ξ_u with S/D for the group of two asymmetrical anchors **a** $I_{C4}J_{C6}$, **b** $I_{C1}J_{C3}$, **c** $I_{C1}J_{C8}$, **d** $I_{C2}J_{C6}$, **e** $I_{C1}J_{C5}$ and **f** $I_{C5}J_{C8}$

asymmetrical anchors placed in single layer homogeneous soil deposit are shown for different combinations at $S_X/D = 2$, $S_Z/D = 2$. It can be seen from Fig. 10a that for the same embedment depth of the lowermost helical plate, the group of anchors with more number of helical plates provides higher uplift

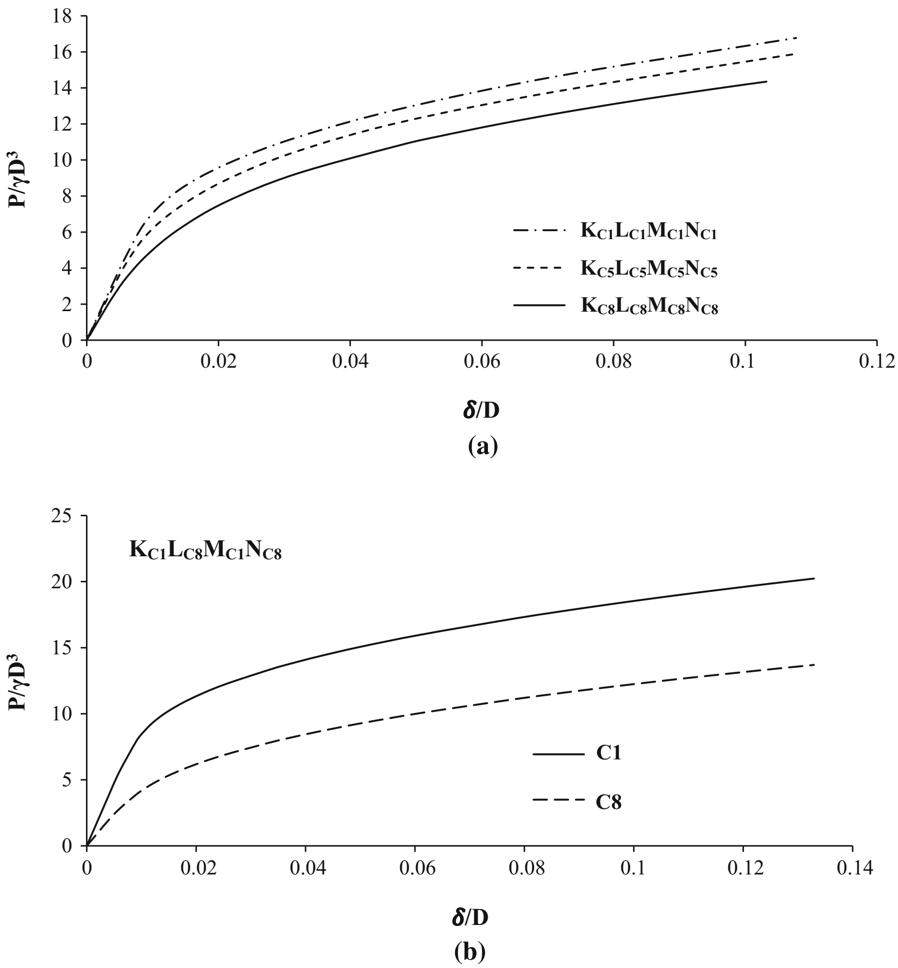
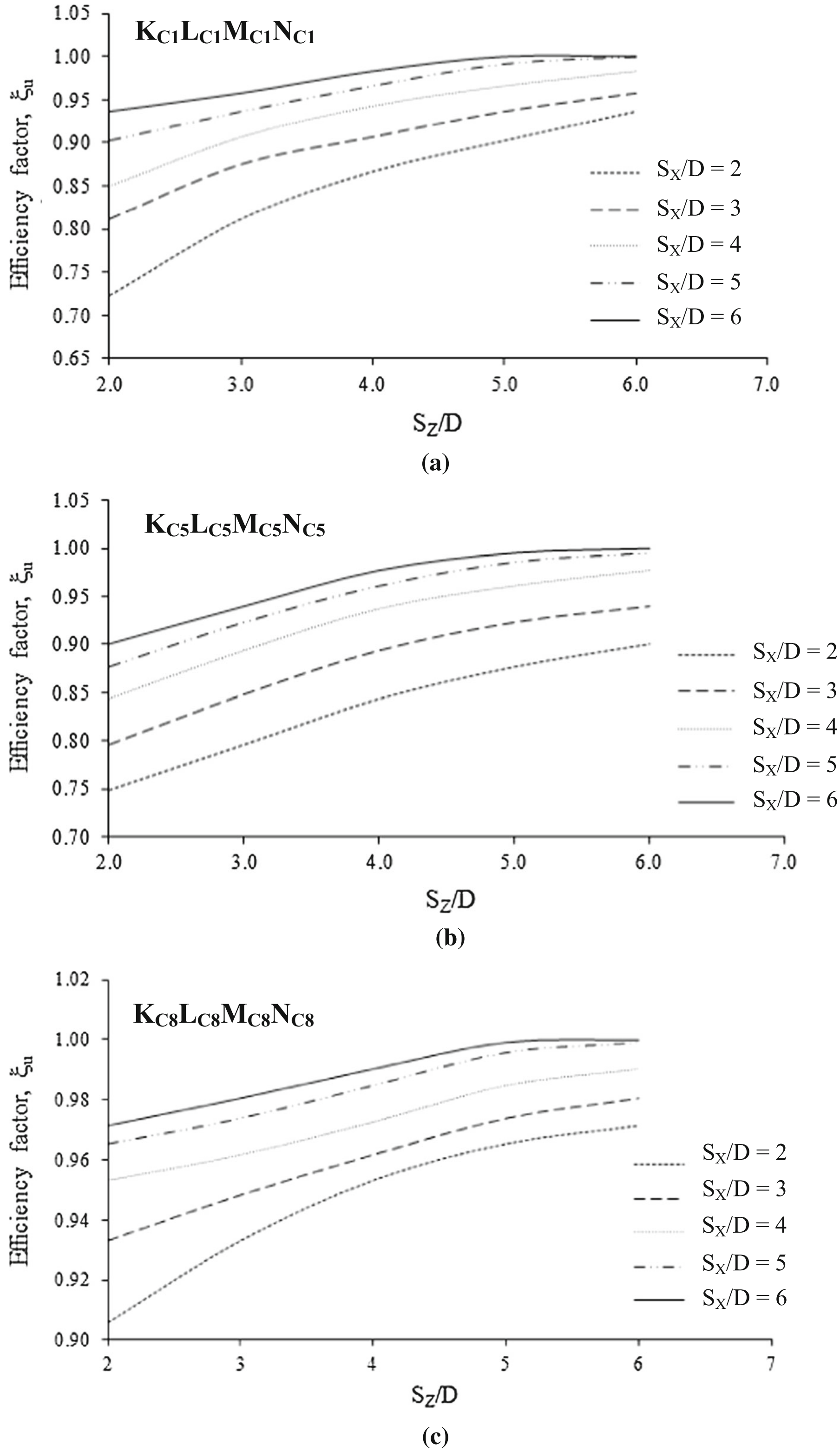
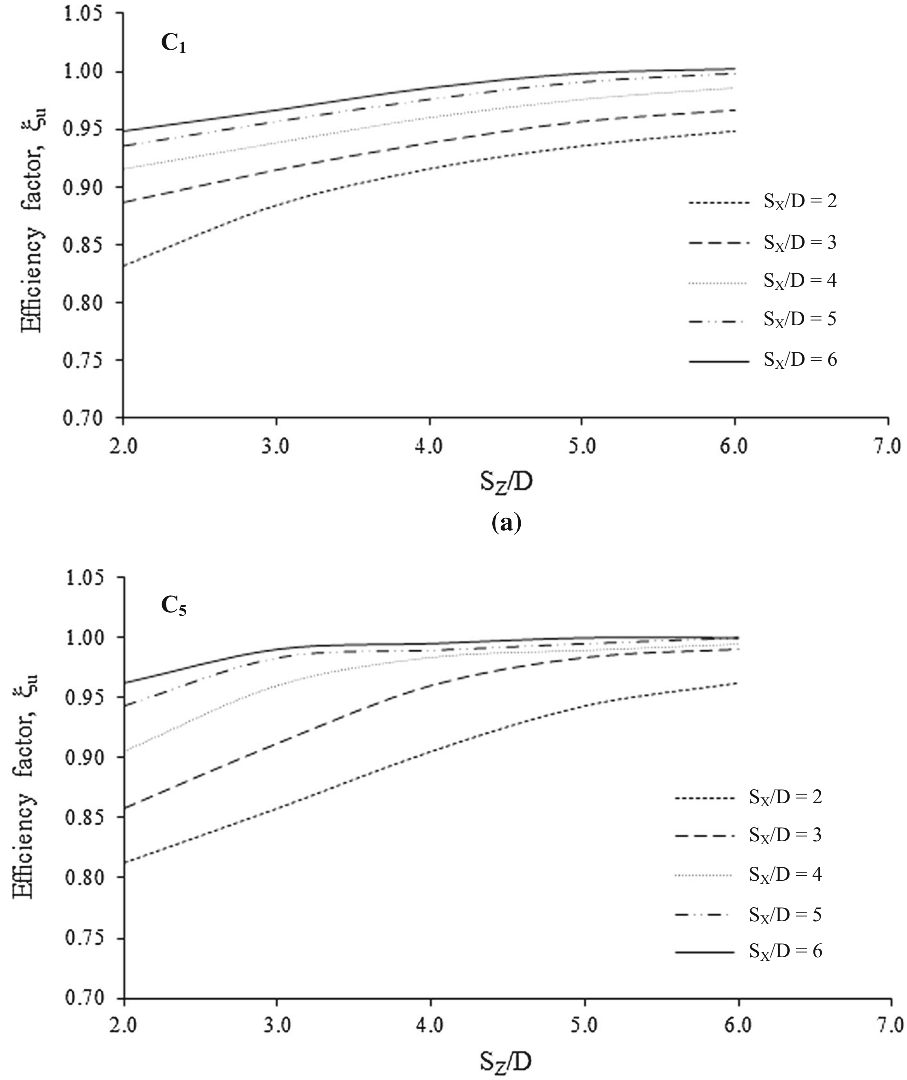


Fig. 10 Normalized load–displacement curve for four interacting **a** symmetric and **b** asymmetric type of helical anchors at $S_X/D = 2$, $S_Z/D = 2$

capacity, which may be due to the same reason as described in the previous section for a group of two-anchor system. Similar observation can also be made from Fig. 10b even for the asymmetrical group, where being in the group of four-anchor system the anchor with more number of helical plates (C1) depicts higher uplift capacity. The variation of ξ_u with S_X/D and S_Z/D ratios for four interacting symmetrical anchors for different combinations is shown in Fig. 11. The study indicates that the magnitude of ξ_u increases with increase in S_X/D and S_Z/D ratios and eventually becomes equal to 1.0 at some maximum value of S_X/D and S_Z/D ratios. It is worth noting here that the condition $\xi_u = 1.0$ indicates the behavior of single isolated anchor free from any interaction, which happens only at the maximum value of both S_X/D and S_Z/D ratios. Therefore, the maximum value of S_X/D or S_Z/D ratio alone does not ensure the fading of interaction among the anchors. The magnitude of efficiency factor is found to be lower than unity at closer spacing, which indicates significant reduction in the pullout resistance at lower spacing. Figures 12, 13

Fig. 11 Variation of ξ_u with S_Z/D ratio for the group of four symmetrical anchors **a** $K_{C1}L_{C1}M_{C1}N_{C1}$, **b** $K_{C5}L_{C5}M_{C5}N_{C5}$ and **c** $K_{C8}L_{C8}M_{C8}N_{C8}$ with different S_X/D ratio





(a)

(b)

Fig. 12 Variation of ξ_u with S_Z/D ratio for **a** C1 and **b** C5 in the group of four asymmetrical anchors ($K_{C1}L_{C5}M_{C1}N_{C5}$) with different S_X/D ratio

and 14 show the variation of ξ_u with S_X/D and S_Z/D ratios for four interacting asymmetrical anchors for different combinations. The trend is found to be pretty similar to that observed for four interacting symmetrical anchors.

6 Comparison

A number of investigations on the single isolated helical anchor are available in the literature; whereas the study on closely spaced group of symmetrical and

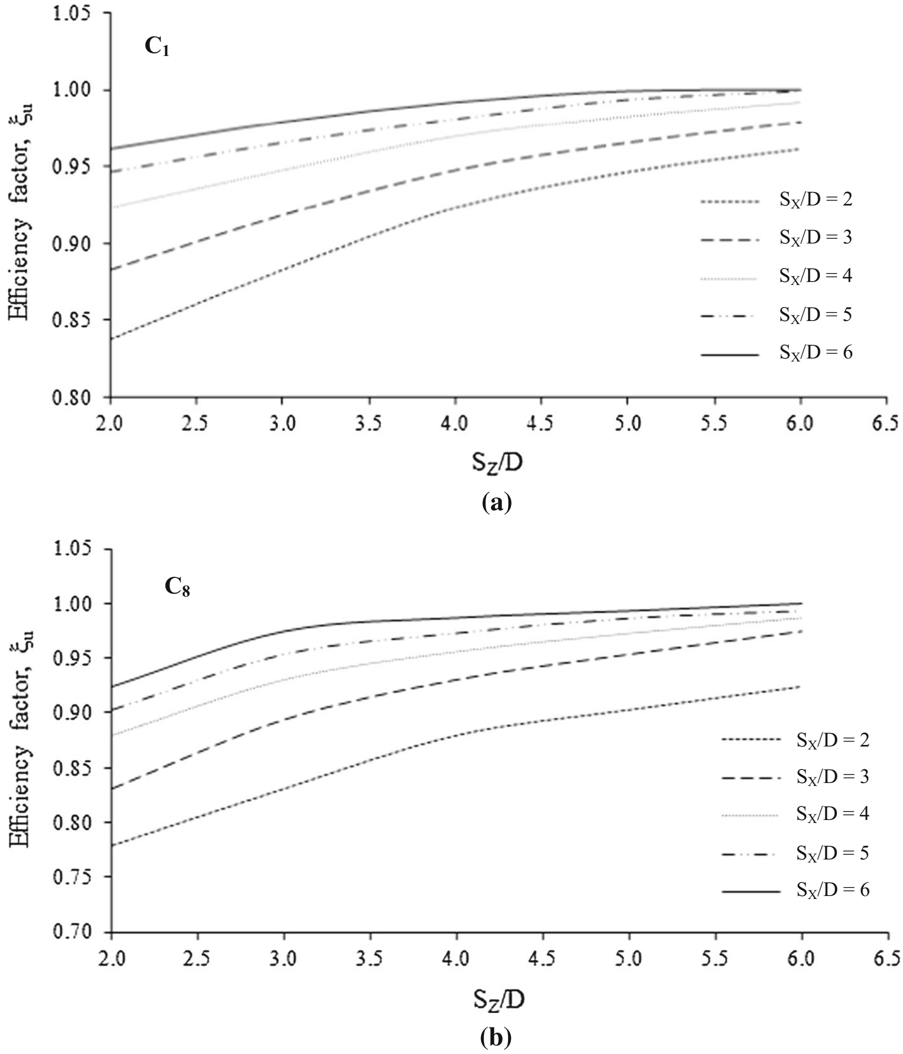


Fig. 13 Variation of ξ_u with S_Z/D ratio for **a** C1 and **b** C8 in the group of four asymmetrical anchors ($K_{C1}L_{C8}M_{C1}N_{C8}$) with different S_X/D ratio

asymmetrical helical anchors is virtually unavailable. Hence, the present results for interacting helical anchors could not be compared with any of the research works due to lack of availability of studies in the literature. However, for the comparison purpose, separate analysis was carried out with isolated helical anchor of different configurations and in Table 4, the magnitudes of P_u for different isolated anchor configurations obtained from the present finite element analysis are compared with the values reported by Wang et al. (2013). It can be seen that the present values compare reasonably well with the experimental and numerical results proposed by Wang et al. (2013).

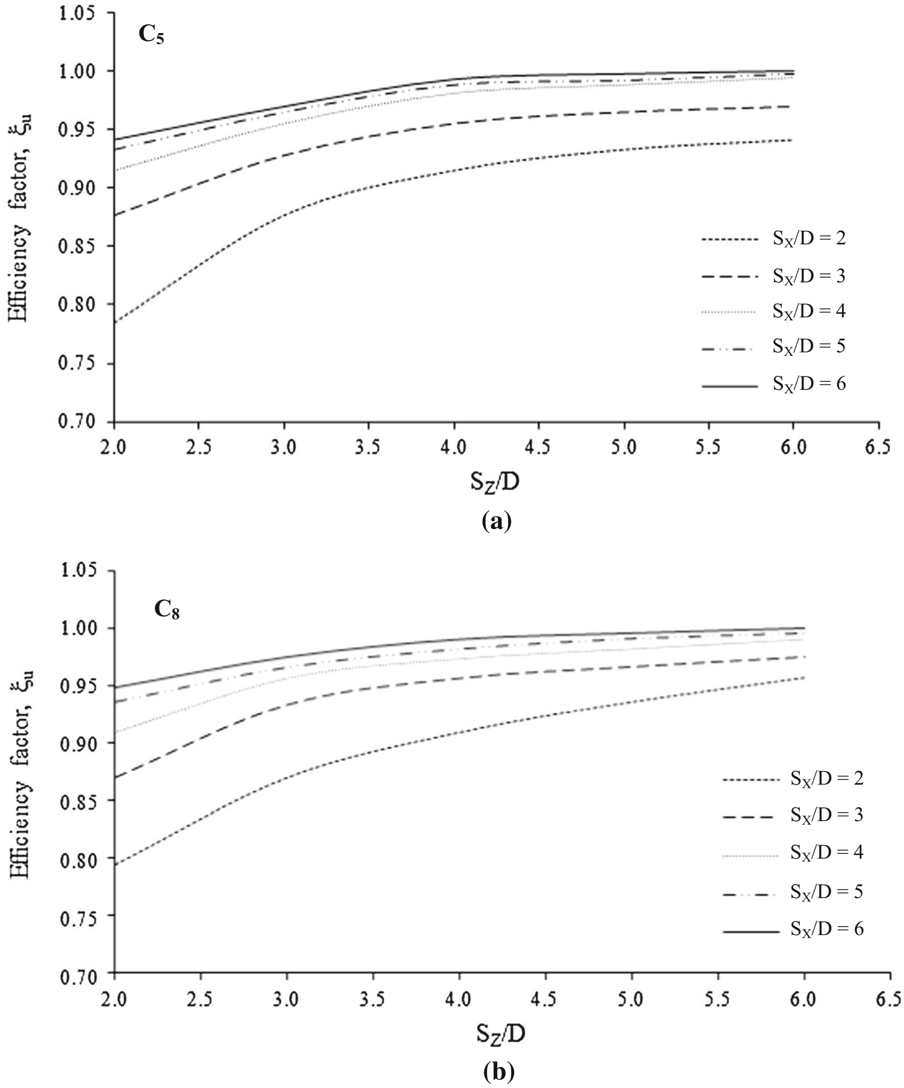


Fig. 14 Variation of ξ_u with S_Z/D ratio for **a** C5 and **b** C8 in the group of four asymmetrical anchors ($K_{C5}L_{C8}M_{C5}N_{C8}$) with different S_X/D ratio

Table 4 Comparison of P_u for different isolated helical anchors

Configuration	P_u (kN)		
	Present analysis	Wang et al. (2013)	
		Experimental analysis	Numerical analysis
C1	2320	1987	2381
C2	1775	1780	1755
C3	2100	2003	2068
C4	2310	1971	2343
C5	2110	1930	2166
C6	1660	1513	1666
C7	1200	1351	1171
C8	1520	1715	1504

7 Conclusions

The static interaction effect of closely spaced two and four symmetrical as well as asymmetrical helical anchors placed in homogeneous cohesive soil medium was determined numerically. The number of helical plates strongly governs the uplift capacity of anchors, which increases considerably with increase in number of helical plates. The magnitude of the efficiency factor, ξ_u is found to increase with increase in spacing among the anchors and eventually becomes equal to 1.0 at some maximum spacing i.e. the magnitude of the ultimate uplift capacity of interacting anchors reduces quite extensively with decrease in spacing among the anchors. For two interacting symmetrical anchors, the magnitude of ξ_u becomes approximately equal to 0.6–0.7 at $S/D = 1$ and the magnitude of S_{max} is found to increase with increase in embedment depth of the lowermost helical plate. In a group of two asymmetrical anchors, the variation of ξ_u with S/D is found to be higher for the anchors with higher number of helical plates. For four-anchor system, the anchors become free from any interaction at the maximum value of both S_X/D and S_Z/D ratios, not just at the maximum value of S_X/D or S_Z/D ratio alone.

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