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Research Article

Experimental and Theoretical Research on the Bearing Mechanism of Group Anchors in Sand

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To investigate the bearing mechanism and efficiency of group anchors in sand, upward pulling tests of model group anchors were carried out for different conditions of the sand density, anchor burial depth ratio, and anchor spacing. The results show that the load-displacement relationships for group anchors is similar to that for single anchors, both being nonlinear for the same relative density and embedment ratio. The load-carrying capacity of group anchors is not a simple superposition of the capacities of two single anchors, but has a clear superposition effect, depending on the relative density, embedment ratio, and anchor spacing. The load carrying capacity increases with the anchor spacing up to a limiting critical value. The bearing mechanism of group anchors was qualitatively analyzed and quantitatively characterized using the strain field and shear stress field obtained through the digital image correlation. Adopting the test data and theoretical derivation, a critical anchor spacing equation is proposed and the relationship between critical anchor spacing, embedment ratio, and relative density is quantitatively characterized. Theory is proposed for predicting the group efficiency of group anchors with different configurations. Comparisons between the results of the developed model and experimental results reported in the literature show good agreement.

1. Introduction

Anchors have been widely used as foundations of electrical transmission towers, utility poles, and earth retaining walls. In recent years, large-scale structures such as suspension bridges, transmission lines, aircraft mooring platforms, and offshore suspension platforms have been continually developed. These structures also need footings that provide considerable uplift bearing capacity. Compared with a single anchor, group anchors are a more effective option for supporting such structures as well as offshore floating structures and other marine constructions.

After Poulos's discovery of the group pile effect in 1968 [1], the group anchor effect has gradually received more and more attention and research. The stress superposition of the group anchor effect is more pronounced in anchors in sand than in rock anchors [2]. During the past several decades, considerable efforts have been made to analyze the uplifting mechanism of group anchors under different conditions [3–6]. Ghaly and Hanna [7] found from anchor pull-out tests conducted in sands of different density that the pull-out resistance depended on the anchor diameter, installation depth, anchor spacing, sand strength properties, installation process, and configuration. Ozturk [8] successfully predicted the tensile capacity of single and group anchors using an artificial neural network training algorithm based on a large volume of single and group anchor test data, providing a new idea for the study of group anchors. Hanna [9] found that the group anchor effect coefficient and ultimate load carrying capacity were affected by the anchor spacing in a study of the group anchor effect of ground anchor groups. Adopting the geotechnical plastic limit equilibrium theory, Zhuang and Zhao [10] obtained an equation for the ultimate pull-out bearing capacity of group anchors.

Table 1: Physical properties of sand.

Parameters	Value
Uniformity coefficient, C_u	1.4
Coefficient of curvature, C_c	1.06
Effective grain size, d_{10} (mm)	0.55
Maximum dry density, $\rho_{d\ \max}$ (g/cm^3)	1.70
Minimum dry density, $\rho_{d\ \min}$ (g/cm^3)	1.41

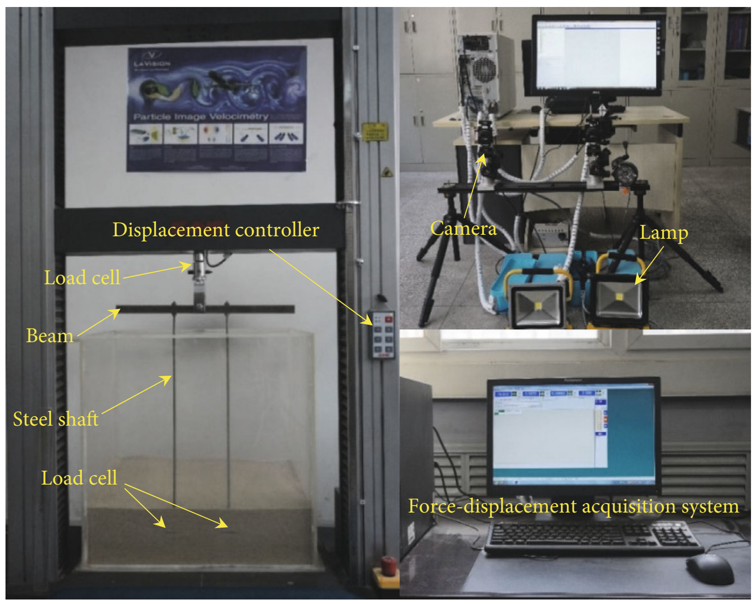


Figure 1: Experimental set-up.

The pull-out characteristics of group anchors are more complex than those of a single anchor [11–15]. However, most of researches have been performed through numerical modelling. Kim et al. [16] analyzed the effects of the anchor spacing and embedding ratio on the group anchor effect by developing a centrifugal model of group anchors in chalk sands. Li et al. [17] used the numerical analysis software FINAL to simulate the development and anchoring of flood relief slopes for three-dimensional analysis of excavation and reinforcement. Numerous experimental and numerical simulation studies have identified anchorage spacing, burial depth ratio, and geotechnical properties as important factors governing the effect of group anchors [18].

Although some of the mechanical properties and pull-out behaviour of the various group anchor anchors have been revealed in the above literature, little has been done to address the deformation mechanism between the group anchors and surrounding soil. In this study, digital image correlation was used to analyze the deformation field of a group anchor foundation. Based on soil deformation analysis around the uplifting group anchors, a possible means of predicting the effect of interaction on the uplift capacity of group anchors is suggested. The analytical results have been substantiated by comparing them with experimental results published by other researchers.

2. Experimental Scheme

2.1. Soil Properties. The silica sand used in the tests had a particle size range of 0.1-1.05 mm. Three conditions of relative density were tested: loose (average dry density $\rho_d = 1.47$ g/cm^3, corresponding relative density D_r=25%), medium (ρ_d=1.54 g/cm^3, D_r=50%), and dense ($\rho_d = 1.61$ g/cm^3, $D_r = 73\%$). The angles of friction corresponding to the three density conditions were 30°, 34°, and 38°, respectively. The physical properties of the sand are given in Table 1.

2.2. Sample Preparation. The soil density was controlled by rainfall and tamping. First, a 50 mm thick sand bed was prepared at the bottom of a mold tank. Second, two semicircular plate anchors with scheduled center-to-center spacing were attached to a beam with slot hole by screws. Third, the semicircular anchors were placed on a sand bed and aligned horizontally against the front surface of the mold tank. Fourth, sand was prepared to an anticipated height using the rainfall method for loose sand. As for medium and dense samples, the same steps were followed except for the fourth step, where sand was instead compacted by tamping each successive layer until the anticipated height was reached.

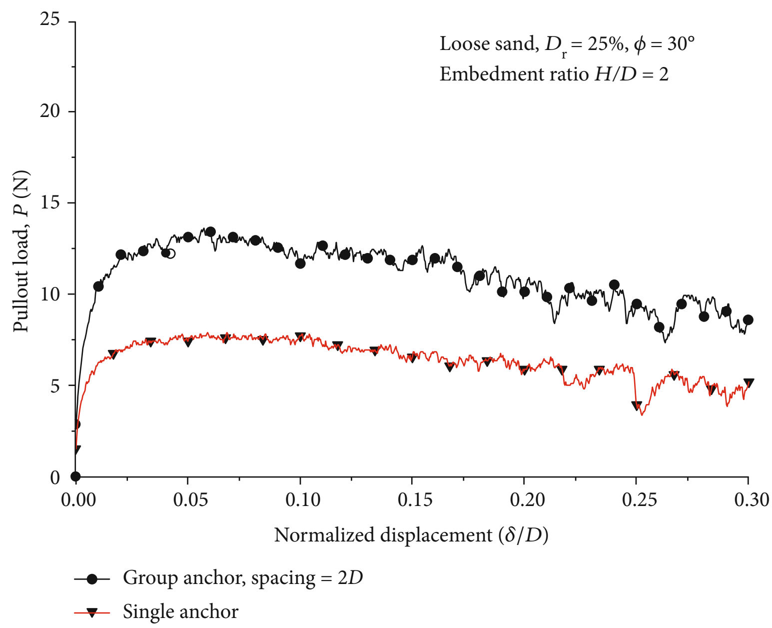


FIGURE 2: Pullout load–displacement curves for two-plate group anchors with $H/D = 2$ in loose sand.

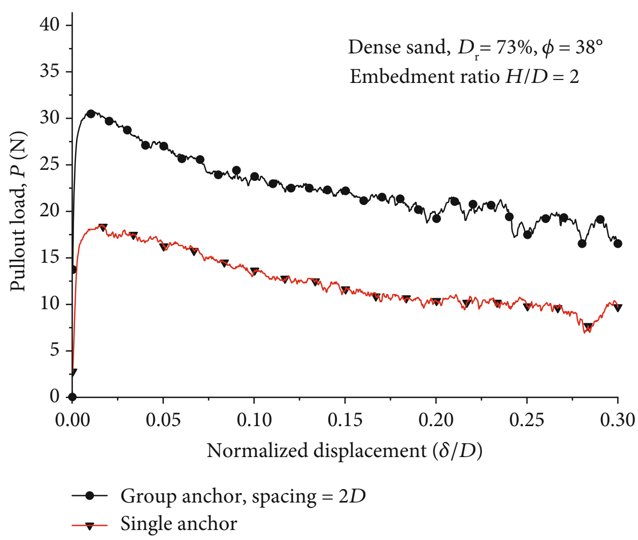


FIGURE 3: Pullout load–displacement curves for two-plate group anchors with $H/D = 2$ in dense sand.

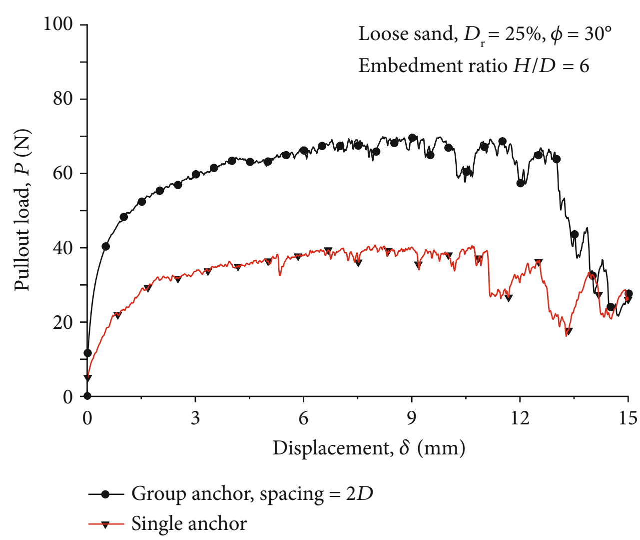
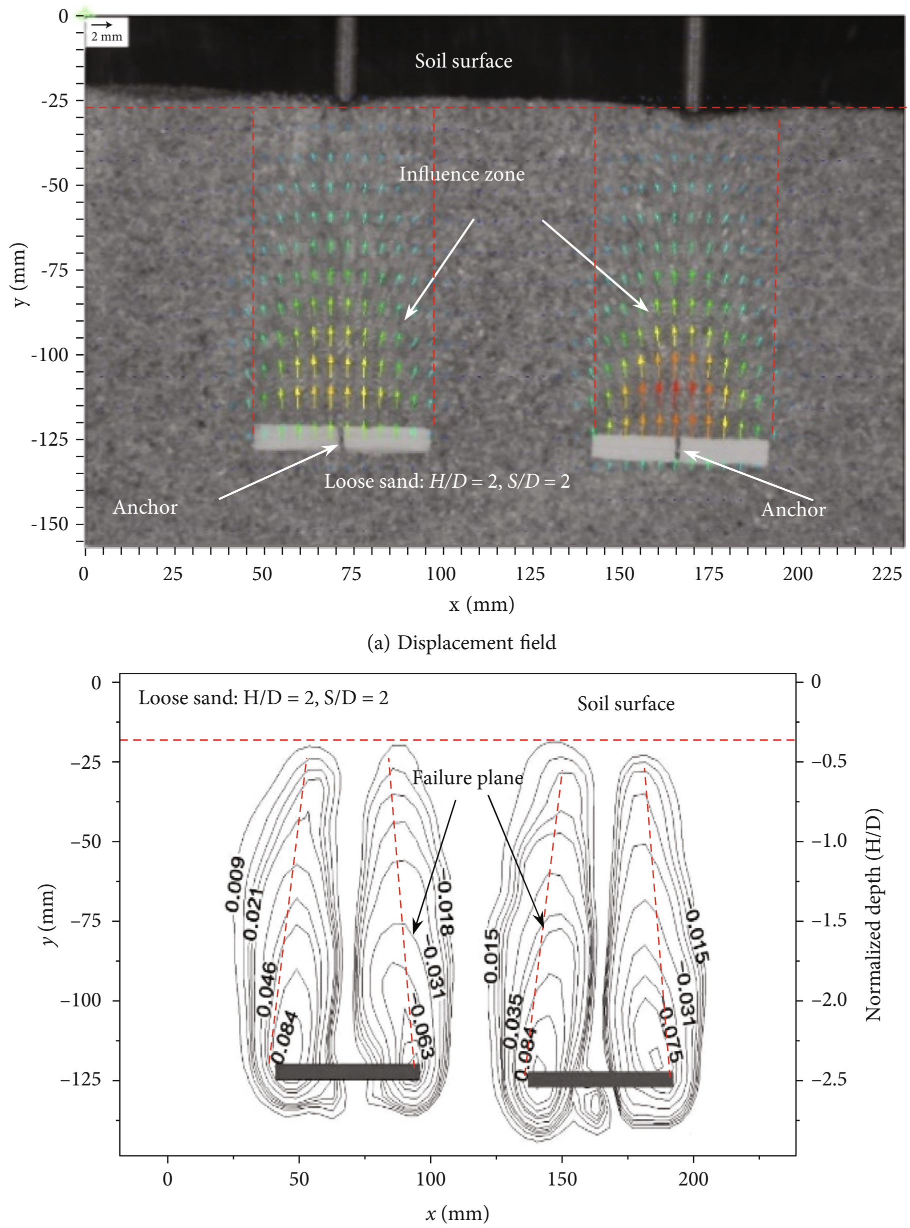


FIGURE 4: Pullout load–displacement curves for group anchors with $H/D = 6$ in loose sand.

2.3. Test Setup and Test Procedure. A Marerial Test System was used in uplifting tests to apply the pullout force and measure the displacement of anchors as shown in Figure 1. The displacement-controlled loading was performed by the data acquisition software. The displacement rate was controlled at 3 mm/min. The load–displacement responses of two group anchors were obtained from load cells and displacement dial gauge readings attached to the MTS. A strainMaster, a noncontact optical measurement system, consists of one Imager E-lite 5 M camera with a resolution of 2, 456 × 2,058 pixels and embedded digital image correlation (DIC) software, was used to analyze the relative movement between images.

The mold tank with dimensions of 900 mm × 800 mm × 800 mm (length × width × depth) was made of poly (methyl methacrylate) to allow observation of soil movement during the pullout tests. All model anchors were semicircular with a 50 mm-diameter and connected to a 6 mm-diameter and 800 mm-long steel rod. The ratio of the tank size to anchor diameter was considered large enough to prevent soil-model-container incompatibilities in model tests. The ratio of anchor size to mean particle size d_{50} (0.75 mm) was about 66 to minimize scaling effects. The model anchors were also placed at a distance of at least 3D from the side walls of the test container to minimize interaction. The beam was predrilled with holes to control the anchor spacing. The test program included test



(a) Displacement field

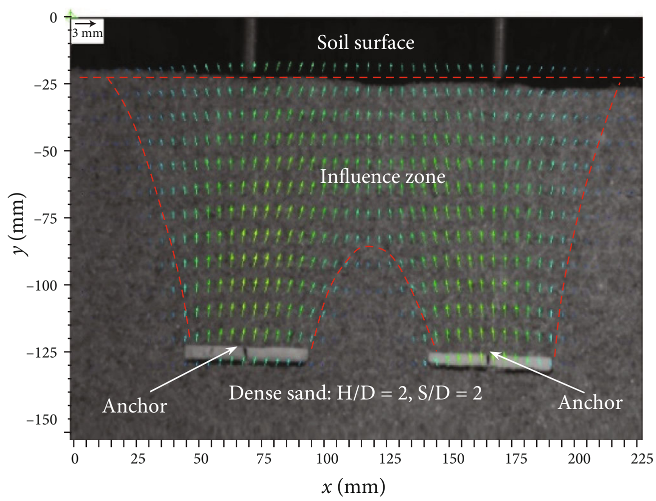
(b) Shear strain field

Figure 5: Soil displacement and shear strain fields for shallow group anchors in loose sand.

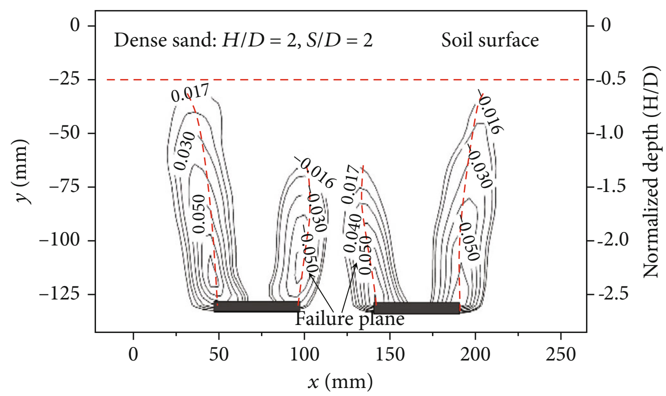
parameters of the sand density (loose, medium, and dense), anchor depth (an embedment ratio H/D varying from 1 to 6 with an increment of 1, where H is the embedment depth and D is the diameter of the anchor), and anchor spacing (a spacing ratio S/D ranging from 1.5 to 6.5 increments of 0.5, where S is the spacing between anchors).

3. Results and Discussion

3.1. Load versus Displacement Response. The uplift bearing capacity of the anchor plate is the sum of the soil gravity in the upper area of influence and the resistance generated by the shear of the soil around the anchor plate [3]. Typical pullout load versus upward displacement relationships for single anchors and the two-plate group anchors with shallow embedment depth are shown in Figures 2 and 3. The load–displacement relationship of group anchors was approximately the same as that of a single anchor. The mechanical characteristics of the sand appreciably affected on the load–displacement relationship. A higher relative density or shearing resistance angle was associated with a higher ultimate pullout load and smaller upward displacement. Figures 2 and 3 show that the ultimate load of the group anchors was approximately 2 and 1.6 times that of the corresponding single anchor in loose and dense sand, respectively. There was thus no interaction between the two anchor plates in loose sand, whereas with increasing relative density, there was an increasing mutual interaction in



(a) Displacement field



(b) Shear strain field

Figure 6: Soil displacement and shear strain fields for a shallow group anchor in dense sand.

dense sand. Therefore, the ultimate load was not the sum of the uplift forces of the two anchor plates.

In the case of a deep anchor (Figure 4), the load again increased with the displacement, but a larger displacement of 7.9 mm was required to reach the ultimate load compared with the displacement of 3.1 mm for the shallow anchor in dense sand in Figure 2. For $H/D = 6$, the ultimate uplift of group anchors was about 1.7 times that of a single anchor in loose sand. With an increasing embedment ratio, interaction between the anchor plates occurred. This is mainly because as the embedment ratio increases, the displacement as the ultimate load is reached also greatly increases, and the sand around the anchor plate experiences considerable compression deformation, which increases the compactness of the sand around the anchor plate, and thus affects the mechanical interaction between the anchor plates.

The above results indicate that the uplift bearing capacity of the two group anchors was not exact the double bearing capacity of a single anchor under the same test condition, but had a clear superposition effect, depending on the sand density and embedment ratio.

3.2. Analysis of the Group Anchor Effect Based on the Displacement Field. Analysis of the above test results indicates that the traditional model test method based on load–displacement analysis can yield a general rule for group anchor interaction. Otherwise, it is difficult to determine accurate critical isolation spacing, which affects the precise determination of the variation of group efficiency. DIC was introduced to analyze the displacement field and thus determine the efficiency more accurately and deduce the internal law of the interaction. This method can be used to visualize the displacement field, which is beneficial for predicting the ultimate uplift capacity of the group anchors.

Figure 5 shows the displacement field and shear strain field at the ultimate uplift load in loose sand for $H/D = 2$ and $S/D = 2$. The soil displacement gradually decreased from the anchor plate to the soil surface. Most displacements were vertical, and there was no interaction between the anchors; i.e., each anchor acted independently.

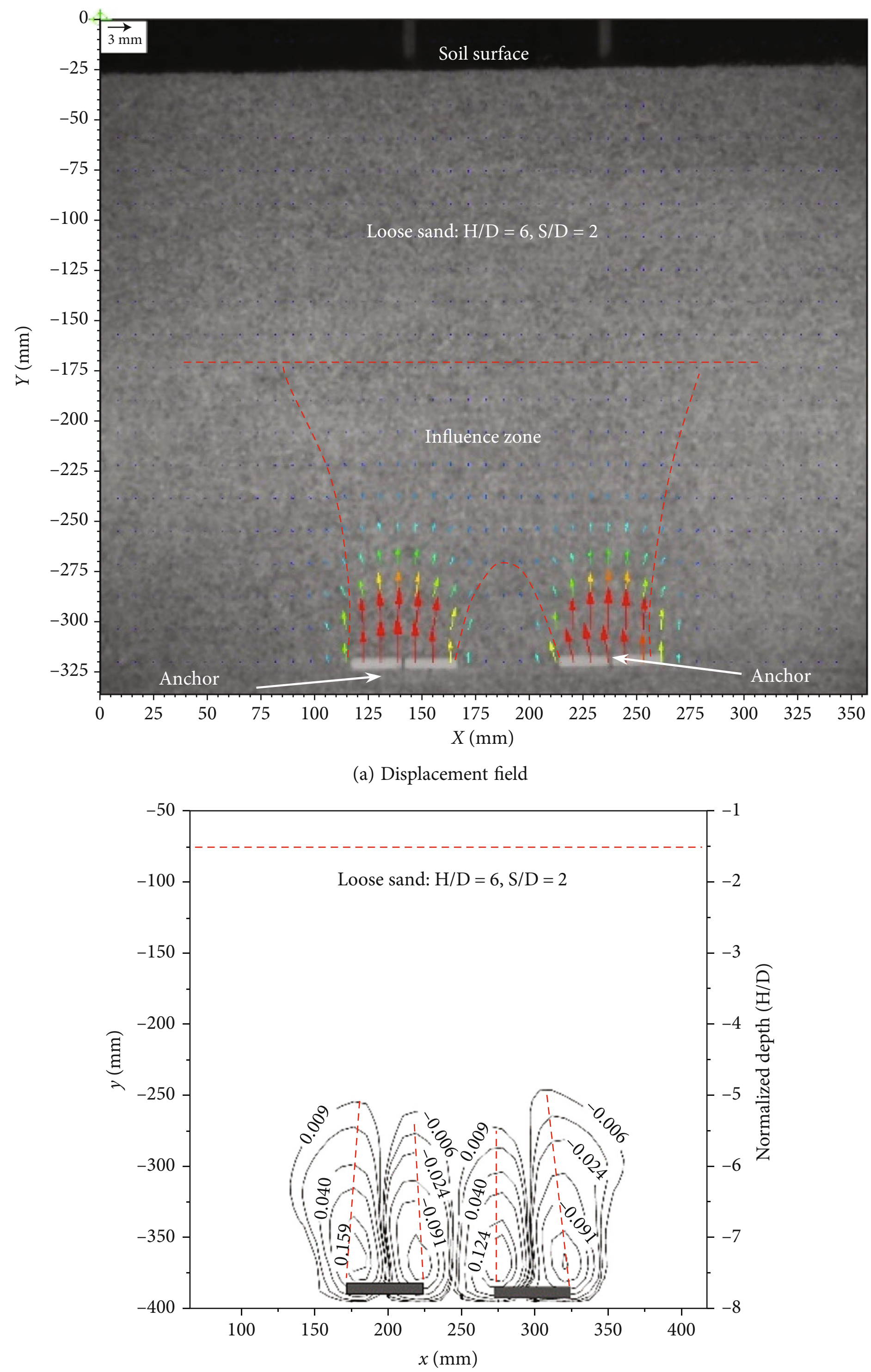
The shear bands of the two anchors were approximately vertical and penetrated into the soil surface. The shear bands on the inner sides of the two anchors had no effect on each other and acted independently (Figure 5(b)).

As shown in Figure 5, the displacement field and shear strain field around two plate anchors have no interaction each other, which two plate anchors play the role independently; therefore, the uplift capacity of the group anchors was twice that of a single anchor. This result is consistent with the load–displacement analysis results shown in Figure 2.

The displacement field and corresponding shear strain field for group anchors in dense sand are shown in Figure 6. The area of influence of the soil displacement was notably expanded. The displacement field among the group anchors reflects superposition at approximately $1D$ above the anchor plate, which indicates that the obvious interaction of the pair of plates.

Figure 6(b) shows the shear strain field for $H/D = 2$ and $S/D = 2$ in dense sand. The outer shear zone of the group anchors had a gradually inclined curved surface and extended to the soil surface. This was mainly due to the shear expansion of the sand during the shear process. However, the inner shear band of the group anchors extended only to approximately $1D$ above the anchor plate and not to the soil surface. The superposition of the inner shear zone reduced the contribution of the shearing resistance to the uplift force, which is consistent with the load analysis results shown in Figure 4.

It is also interesting to examine the results of the displacement field and shear strain field of the group anchors in deep embedment, as shown in Figure 7. Compared with that of the shallow group anchors in loose sand (Figure 5), this displacement field did not extend to the soil surface but was limited to the $3D$ area above the anchor plate. There was superposition of the displacement field among the group anchors, and the superposition area was $1D$ above the



(a) Displacement field

(b) Shear strain field

Figure 7: Soil displacement and shear strain fields for shallow group anchors in loose sand.

anchor plate. In contrast with the shear strain field in Figure 6(b), the shear band for deep group anchors was limited below the soil top surface. The inner shear band was small and almost vertical because of the obvious group anchor effect.

The main reason for the phenomenon mentioned above was that when the embedment ratio increased, the displacement required to reach ultimate capacity also increased, and the soil around the group anchor produced considerable compressive deformation, resulting in the interaction

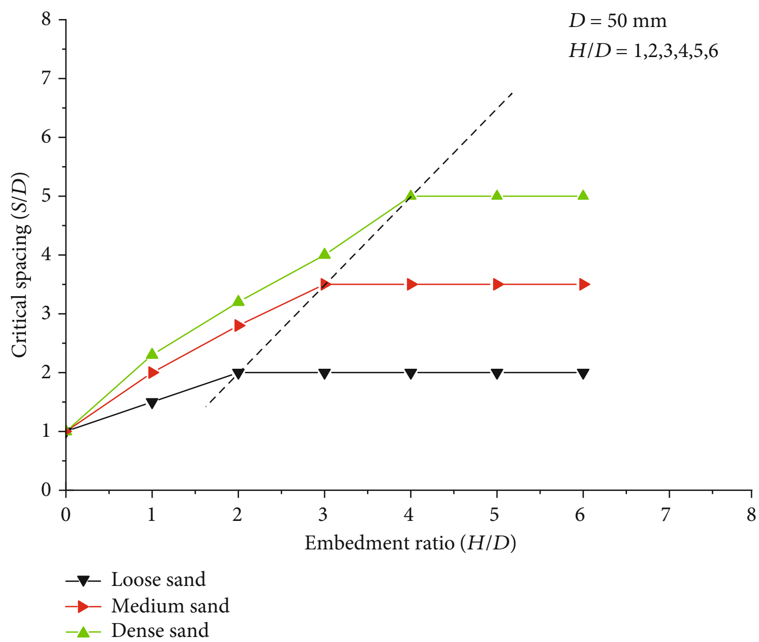


Figure 8: Relationship between critical spacing and the embedment ratio in sand.

between the displacement field and shear strain field among the group anchors.

It is worth noting that the group anchor interaction is related to the relative density, the embedment ratio, and the spacing of the anchor plates. The uplift mechanism of group anchors is not a simple quantitative superposition relationship but depends on the geometry of the failure mechanism indicated by the displacement field and shear strain field.

3.3. Analysis of Group Anchor Efficiency. The uplift capacity efficiency of group anchors is generally obtained by dividing the group capacity by the number of group anchors multiplied by a single anchor's capacity [16].

$$E_g = Q_g / m Q_s, \tag{1}$$

where E_g is the group efficiency, Q_g is the uplift capacity of the group anchors, Q_s is the uplift capacity of a single anchor, and m is the number of group anchors.

The uplift capacity of the group anchors comprises the weight of the sand involved in the failure surface, the vertical component of the shearing resistance along the failure surface, and the surcharge pressure acting on the upper surface of the failed mass of sand. For shallow group anchors, the surcharge pressure is negligible. The group efficiency is mainly attributed to the interaction of the anchor plates, resulting in the area of displacement superposition with the gravity of the soil in the superposition area being shared by the two anchors at the same time. In addition, the arching effect produced by the superposition shifts the entire soil body in the superimposed area, such that the inner shear zone is smaller than the outer shear zone, and the shear strength is partially lost. If the displacement field and shear strain field of the anchor plate do not overlap, the group anchors show the sum of the individual actions of individual anchors, and the group anchor efficiency reaches 100%. The spacing at which group anchors act individually is the critical spacing of the group anchors. The critical spacing can be determined through analysis of the uplift load and displacement field. Figure 8 shows that the critical spacing has a linear relationship with embedment ratio under specified sand density until it arrived at a certain change point. It is worth mentioning that the load-displacement relationships of the experimental results in Figure 8 is shown in Figure 9.

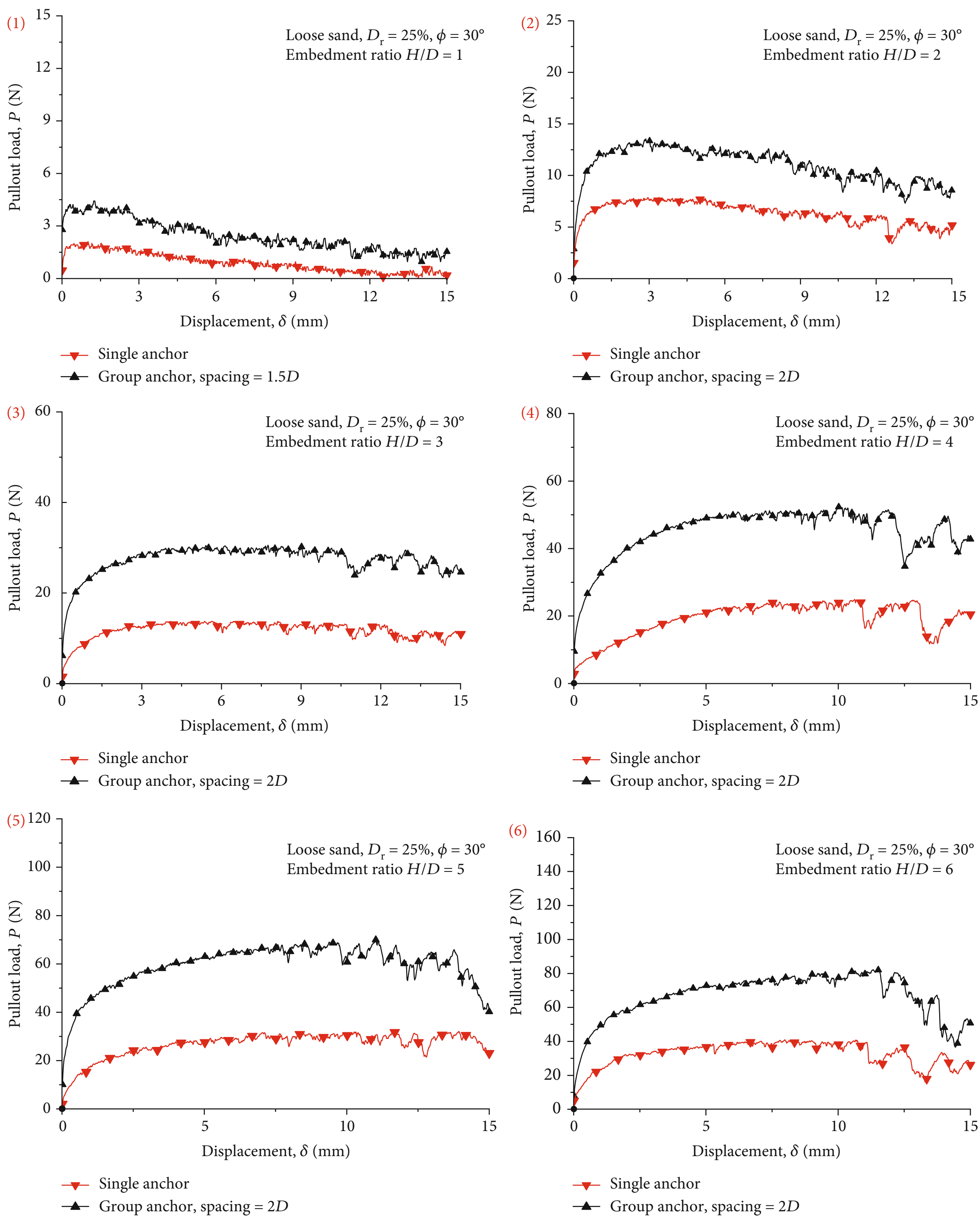
According to the curve fitting results, the critical spacing maybe expressed as

$$\begin{cases} S_L = 1 + (0.3 + D_r)(H/D)\ 1 \le S_L \le S_C, & H/D \le (H/D)_c, \\ S_L = S_C, & S_L > S_C, \end{cases} \tag{2}$$

where S_L is the critical spacing, D_r is the relative density, H/D is the embedment ratio, and S_C is the ultimate critical spacing defined as the critical spacing there is no longer affected by the embedment ratio. $(H/D)_c$ is the critical embedment ratio which define the limitation of H/D. This relationship can be expressed as

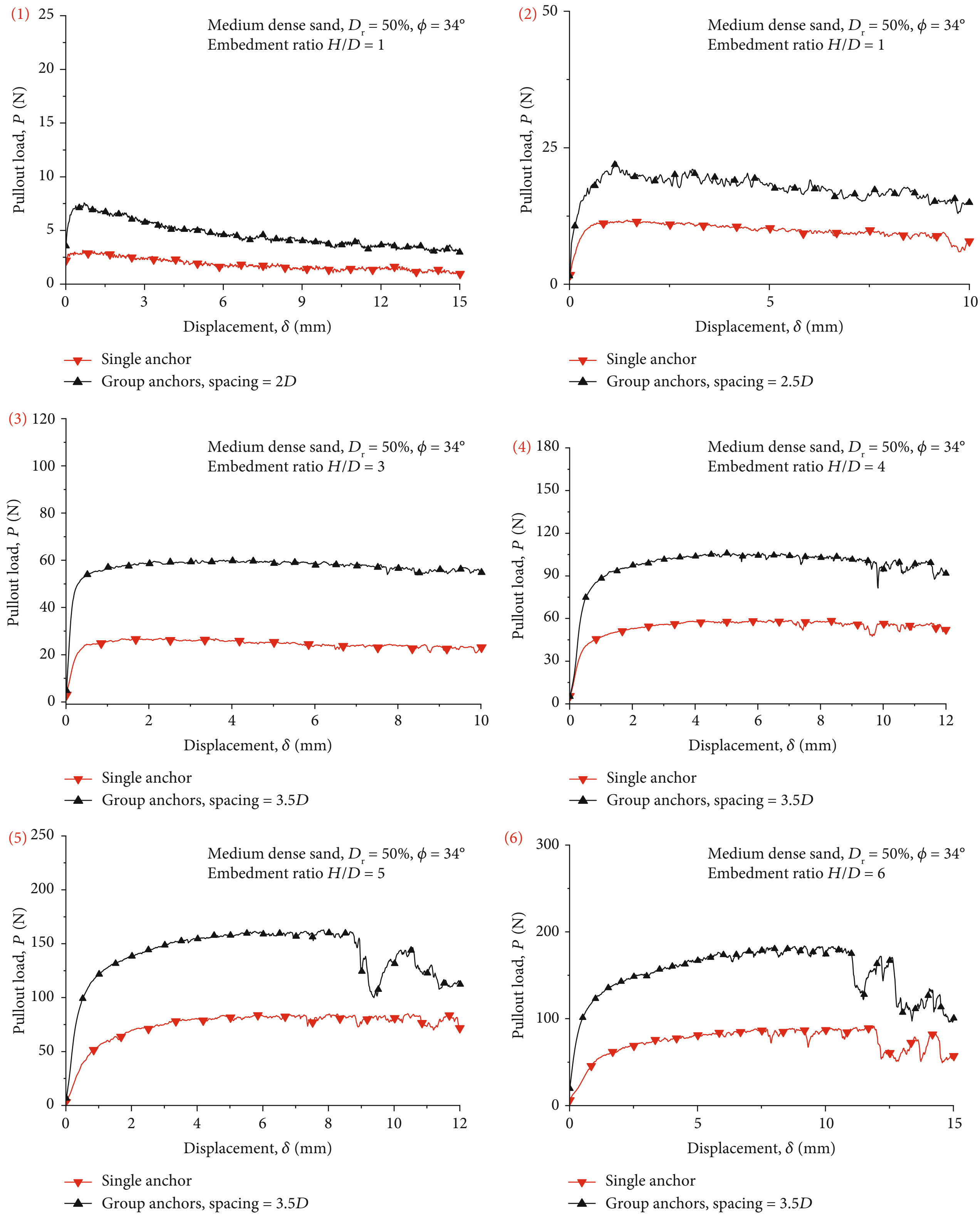
$$\begin{gathered} (H/D)_C = 4D_r + 1, \\ S_C = 6D_r + 0.5, \\ 0 \le D_r \le 100\%. \end{gathered} \tag{3}$$

The relationship of the critical spacing, embedment ratio, and relative density can also be directly obtained as shown in Figure 10.



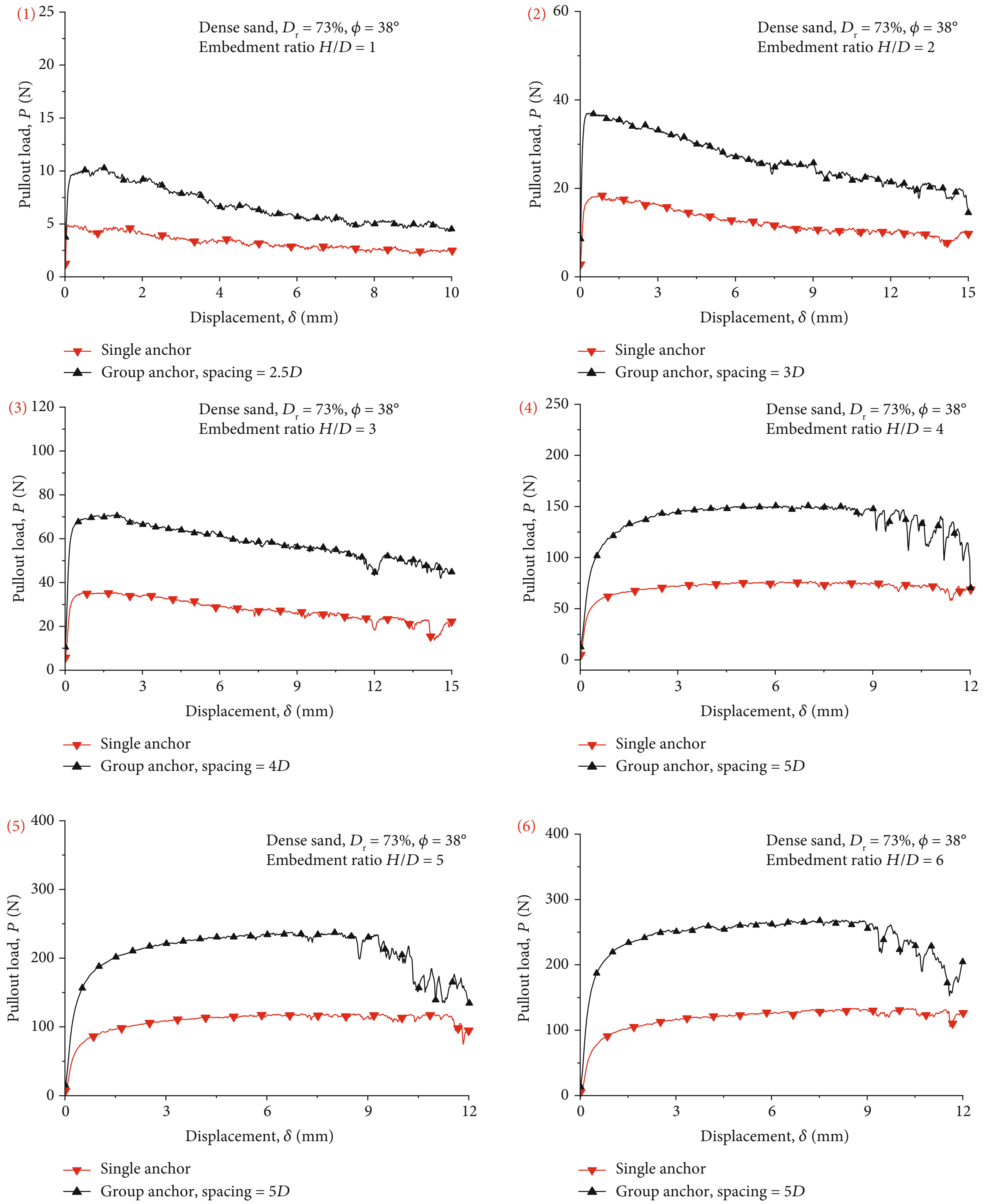
(a) Loose sand

FIGURE 9: Continued.



(b) Medium dense sand

Figure 9: Continued.



(c) Dense sand

Figure 9: The load-displacement relationships of the experimental results at critical spacing.

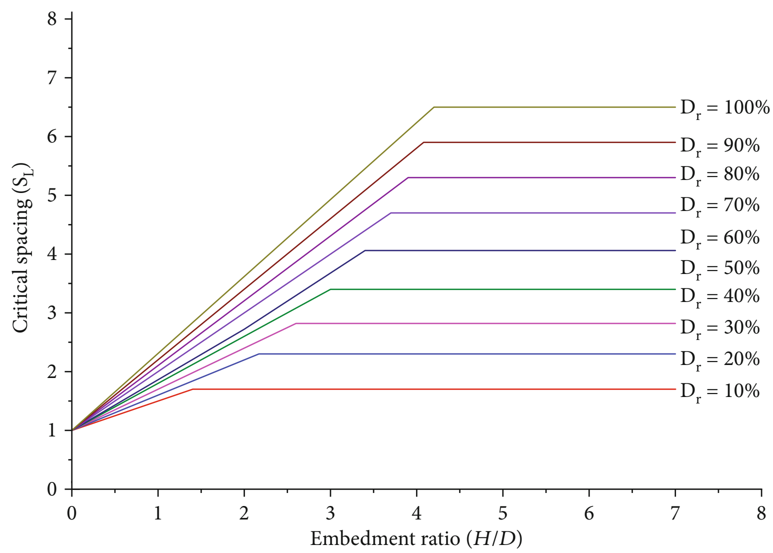


Figure 10: Fitting relationships between the critical spacing and embedment ratio.

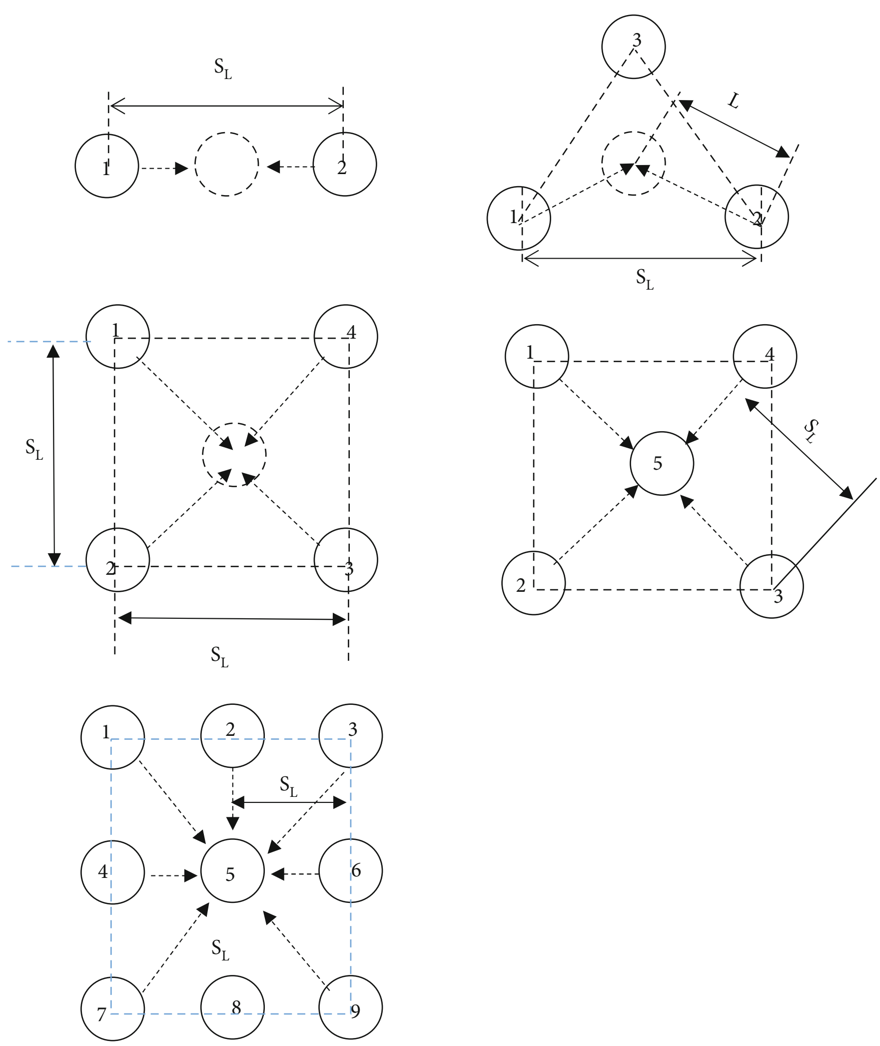


Figure 11: Configurations of group anchors.

Table 2: Sand properties for group anchor tests.

Authors	Sand density (kN/m^3)	Relative density (%)	Frictional angle(°)
Das and Jin	15.4	68	36

Table 3: Group anchor configurations.

Authors	Configuration	Embedment depth ratio	Spacing
Das and Jin	2×1	4	1, 2, 3, 4, 6
	2×2	4	1, 2, 3, 4, 5, 6
	3×3	4	1, 1, 5, 2, 3, 4, 6

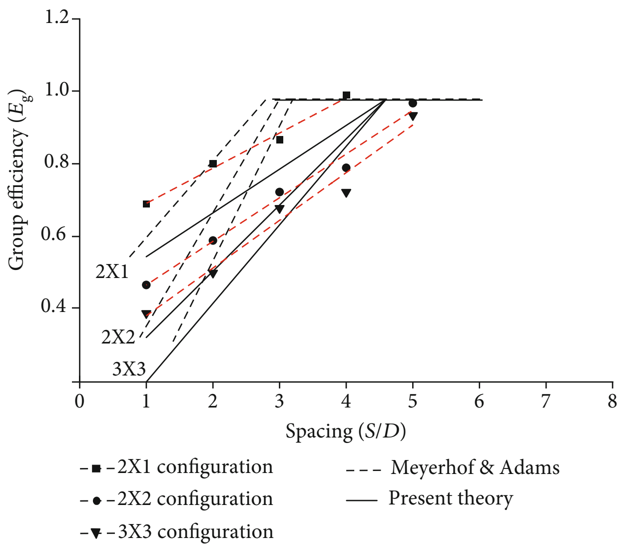


Figure 12: Comparison of the theoretical and experimental variation of group efficiency.

Table 4: Sand properties for group anchor tests.

Authors	Sand density (kN/m^3)	Relative density (%)	Frictional angle (°)
Geddes and Murray	16.5	85.9	43

3.4. Determination of Group Efficiency. Figure 11 shows the critical spacing for different group configurations. For the 2 × 1 configuration, the efficiency ranges from 50% to 100%. When two anchor plates overlap, as shown by the dotted circle in Figure 10, the action is equivalent to that of a single anchor, and the group efficiency is 50%. With an increase in the anchor plate spacing, the group efficiency increases until reaching 100% at the critical spacing. Similarly, the linear relationship can be deduced for other group configurations (Figure 11), and the group efficiency is expressed as

Table 5: Group anchor configurations.

Authors	Configuration	Embedment depth ratio	Spacing
Geddes and Murray	2×1	4	1,1.5,2,2.5,3
	2×2	4	1,1.5,2.5,3,3.5

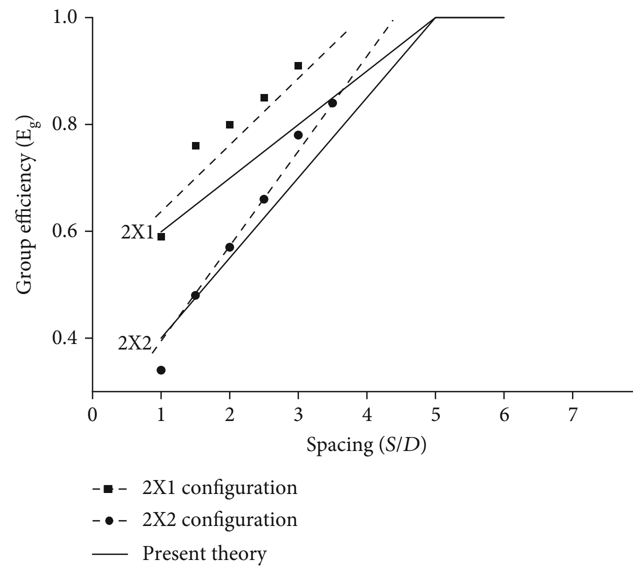


Figure 13: Comparison of the theoretical and experimental variation of group efficiency.

$$E_g = \begin{cases} 0.50 + 0.50S/S_L, & 2\text{ anchors},\ 0 \le S \le S_L, \\ 0.33 + 0.67S/S_L, & 3\text{ anchors},\ 0 \le S \le S_L, \\ 0.25 + 0.75S/S_L, & 4\text{ anchors},\ 0 \le S \le S_L, \\ 0.20 + 0.80S/S_L, & 5\text{ anchors},\ 0 \le S \le S_L, \\ 0.11 + 0.89S/S_L, & 9\text{ anchors},\ 0 \le S \le S_L, \\ 1, & S \ge S_L, \end{cases} \tag{4}$$

where S is the spacing of the anchor plate, and S_L is the critical spacing, as indicated by Figure 9.

4. Comparison of Results

The group efficiency computed in the present analysis is compared with the experimental results of other scholars. Tables 2 and 3 give the soil properties and configurations of the group anchor tests conducted in medium dense sand by Das and Jin [19].

The experimentally observed efficiency values of Das and Jin and the theoretical values of Meyerhof and Adams [20] are shown in Figure 12, along with the data of the present theory study. Although the results of the present theory study are lower than those obtained by Meyerhof and Adams [20], they compare favorably with other results, such as those of Das and Jin. For the 2×1 configuration, the group efficiency reported in this paper is in good agreement with the results of Das and Jin, but the test results of Das and Jin are approximately 15% higher than the theoretical results. For the 2×2 and 3×3 configurations, the theoretical calculations of efficiency are more consistent with the test results of Das and Jin; the maximum difference observed is 10%.

Tables 4 and 5 show the soil properties and configurations of the group anchor tests in dense sand conducted by Geddes and Murray [6].

The comparison of the experimental efficiency values by Geddes and Murry to the present theory study is shown in Figure 13.For the 2×1 configuration tests, the present theory is about 13% less than the experimental results. For the 2×2 configuration tests, the present theory shows a good agreement with the experimental results which only 5% less than the experimental results is observed. Figure 13 indicates good agreement (average 10% accuracy) between the experimental results of Geddes [6] and the present theory for dense sand.

5. Conclusion and Discussion

A noncontact measurement technique adopting DIC was used to study the deformation mechanism of group anchors. The following conclusions are drawn from the tests conducted.

(1) The load-displacement relationship for group anchors is similar to that for single anchors, both being nonlinear at the same relative density and embedment ratio. The load-carrying capacity of group anchors is not a simple superposition of the capacities of two single anchors, but has a clear superposition effect, depending on the relative density, embedment ratio, and anchor spacing

(2) Analysis of the deformation field of the group anchors, revealed that the group efficiency mainly relates to the interaction between anchors, resulting in an area of displacement superposition with the gravity of the soil in the superposition area bing shared by the two anchors at the same time. In addition, the arching effect produced shifts the superposition made the entire soil body in the superimposed area, such that the inner shear zone is smaller than the outer shear zone, and the shear strength is partially lost

(3) The load-carrying capacity of group anchors increases with the anchor spacing up to a limiting critical value. Adopting test data and theoretical derivation, an equation for the critical anchor spacing was proposed and the relationship between the critical anchor spacing, embedment ratio, and relative density quantitatively characterized

(4) An empirical equation was proposed to predict the group efficiency of group anchors, accounting for parameters such as the embedment ratio, relative density, spacing, and configuration. The predicted values of group efficiency were in good agreement with the results of other studies

The proposed test method was based on 1 g small scale model. Although scaling effects are considered in this test study, the results from this type of test are known to be subject to scaling effect more or less and may differ from full-scale test results. Moreover, assumption has been made on the linearity of the relationship between group efficiency and horizontal anchor spacing (Equation (4)), and some differences are observed when comparing the theory and the experimental results. Further studies are required to provide more comprehensive and conclusive observations.

Data Availability

The experiment data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare they have no financial interests.

Authors' Contributions

Xuejiu Wang was assigned in investigation, methodology, and data curation. Xin Zhang was tasked in writing and editing. All authors have agreed to the listing of authors.

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