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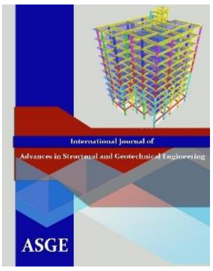

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Numerical Modeling of Unfavorable CFA Pile Drilling

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ABSTRACT

The Egyptian dense urban cities around the Nile and in the Delta region are famous for the high rise buildings due to the lack of land for development. Due to the low bearing capacity of soil encountered in these regions, deep foundations are usually utilized for high to medium rise buildings. Continuous Flight Augers (CFA) piling technique by far the most used technique in those regions due to its minimal vibration, low noise and low cost, beside its quick installation compared to other drilled shaft techniques. Despite all this advantages drilling of these piles can cause settlement and distresses to the adjacent structures especially if the drilling in close vicinity to the adjacent structures. In this paper three-dimensional (3-D) finite element analyses were conducted to understand the factors affect the magnitude of surface settlement due to CFA drilling. The influence of the drilling depth, pile location and soil parameters are systematically studied. The analysis shows that the settlement during the unfavorable CFA drilling is similar to an inverted cone with maximum settlement at the pile location and decreases with distance. The surface settlement profile is extended to a distance of about 0.7 of the depth at which over-flighting occurred. It is also observed that sand relative density has a significant effect on the magnitude of settlement in the vicinity of CFA drilling. Finally, pile group drilling was investigated to gain insight into the effect of pile group on the adjacent structures.

Keywords: *CFA, Unfavorable Drilling, Over-Flighting, Surface settlement.*

INTRODUCTION

The development of Continuous flight auger (CFA) piles, (also known as augured cast-in-place (ACIP) or auger cast piles especially in the United States) started more than 40 years ago on hydraulic drilling rigs [1]. It is a deep foundation technique which has experienced a significant increase in use in recent years. This type of construction can provide many advantages to engineers for many types of projects and ground conditions because of its speed and economy compared to drilled shaft piles [2]. CFA piling technique is preferable especially in residential and commercial multi story building in inner urban areas because of its minimal vibration installation. CFA piles are installed by means of a continuous hollow stem auger having an inner diameter of 100-200 mm and an outer diameter of 400-1000 mm and extended to a depth up to 35 m with a temporarily closure plate at the bottom and it is similar to Archimedes screw. After the auger reached the desired depth by the action of torque and axial thrust, the auger is withdrawn at controlled rate while the concrete or grout is being pumped. Then, a shaft of concrete extended from the desired depth of the pile to the ground surface while the auger withdrawal and removing the soil retained between its flights. The pile pit never becomes unsupported during excavation of CFA piles. The flights of the CFA piling auger is filled with soil theoretically while the auger is advanced in the ground supporting the surrounding soil and maintaining the stability of the hole. This may lead to the wrong believe that CFA piles construction has a minimal surface subsidence and a minimal effect on the adjacent structures. Many researchers have reported cases of settlement in adjacent structures or soil subsidence due to CFA pile construction [2-9].

INSTALLATION OF CFA PILES

To install a CFA pile, a plugged hollow-stem continuous-flight auger is inserted into the soil in a certain rate. During drilling, the plug prevents the soil from entering the auger. The rate of penetration is very sensitive as it has a big effect on CFA pile quality. Ideally, during excavation process, the flights should be full of soil all the time with minimal decrease of lateral stresses around drilling pit and minimal soil being transported to the ground surface. However, some lateral displacement and stresses reduction occur during construction even in soil favorable conditions [5]. Then, the soil in the flights works as a support to the bore-hole during the excavation process and before the auger is being pulled during wet concrete boring. This theoretically may occur only when the penetration rate, v (m/min) is balanced with the rotational auger velocity, n (revs/min) as shown in Fig. 1(a). This balance may not happen when there is a need to penetrate a hard stratum underneath loose sandy soil or soft clay. The supply of soil into the auger flight from the auger tip drops if the rate of penetration, n decreases when the tip of the auger enter an obstruction (hard stratum) on its way as illustrated in Fig. 1(b). So, more lateral feed of soil from the relatively loose sandy soil or soft clay overlying layers into the auger flights. So, loss of lateral confinement to adjacent structures and ground subsidence will occur [2].

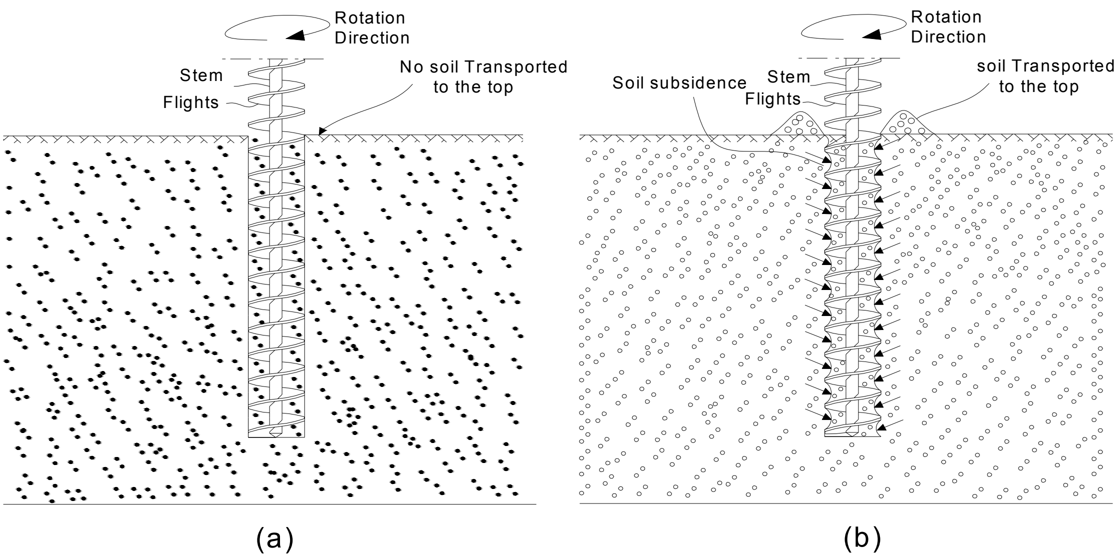


Fig. 1: (a) Ideal conditions, flights full of soil, (b) Over-flighting

Kenny et al. [10] performed an experimental test program to understand the effect of unfavorable CFA drilling using laboratory physical model. The test was performed using a model auger to simulate the field condition of the auger excavating a sand layer from the ground surface with an obstruction placed at a specific depth in the path of the auger. The auger started to rotate and penetrate while monitoring the volume of sand transported to the soil surface by the auger, the ground surface settlement, the variation of sand density around the auger and disturbance zone extension of sand around the auger. The results from the experimental test revealed that the maximum settlement happened in the vicinity of the auger and decreases gradually away from the auger. The surface settlement and ground disturbance reduces significantly at a distance of about 50% of the auger depth. More importantly, the effect of the unfavorable drilling conditions increases with decrease in relative density.

THREE DIMENSIONAL NUMERIAL ANALYSIS

In this study, three dimensional analysis Finite Element Analysis (FEA) was conducted to investigate the settlement and potential effect on adjacent structures, during CFA drilling. In order to investigate the effect of pile drilling, a numerical simulation of single pile drilling was conducted. The pile was assumed with the diameter of 600 mm. The pile was assumed to be 16 m in length. Moreover, the installation of a group of 25 piles effect on the adjacent structures were investigated. Geometry selected for this study is shown in Fig.2. The sequence of the pile installation was assumed to be as shown in the figure from 1 to 25. ABAQUS 6.13 3D commercially available software package was used in this study.

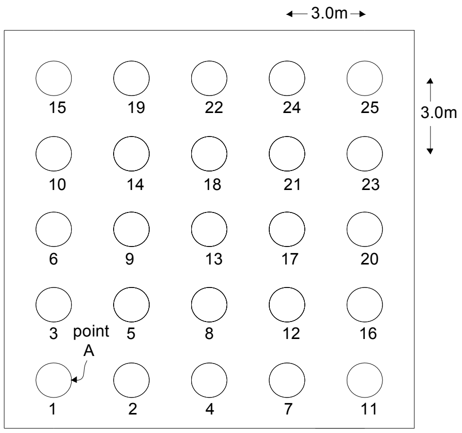


Fig. 2: Plan view of the pile geometry of the pile group selected in this study.

Finite element mesh and boundary conditions for single pile model

The three-dimensional Finite Element (FE) models mesh and boundary conditions conducted in this study shown in Fig. 3 for single pile. In this study, the mesh size 80 m (length along Y-axis), 80 m (width along X-axis), and 30m (depth along Z-axis). Soil was modeled using 8-node hexahedral elements. The model dimensions were large enough to capture the influence zone of settlement and deformations induced by CFA pile excavation. The mesh consisted of 40,573 soil elements and 47,291 number of nodes was conducted. The relative element size factor was 0.2 and the element size was 0.6m in the soil mesh surrounding the pile single pile model and become coarser further away from the edge of the pile to have relative element size factor of 1 and average element size of 2.0 m. Fig. 3 shows the boundary conditions used in this study. The model base were restricted in all directions by using pin support and all the vertical sides were prevented from lateral movement only by providing roller support. The top of the model was allowed to move in any direction.

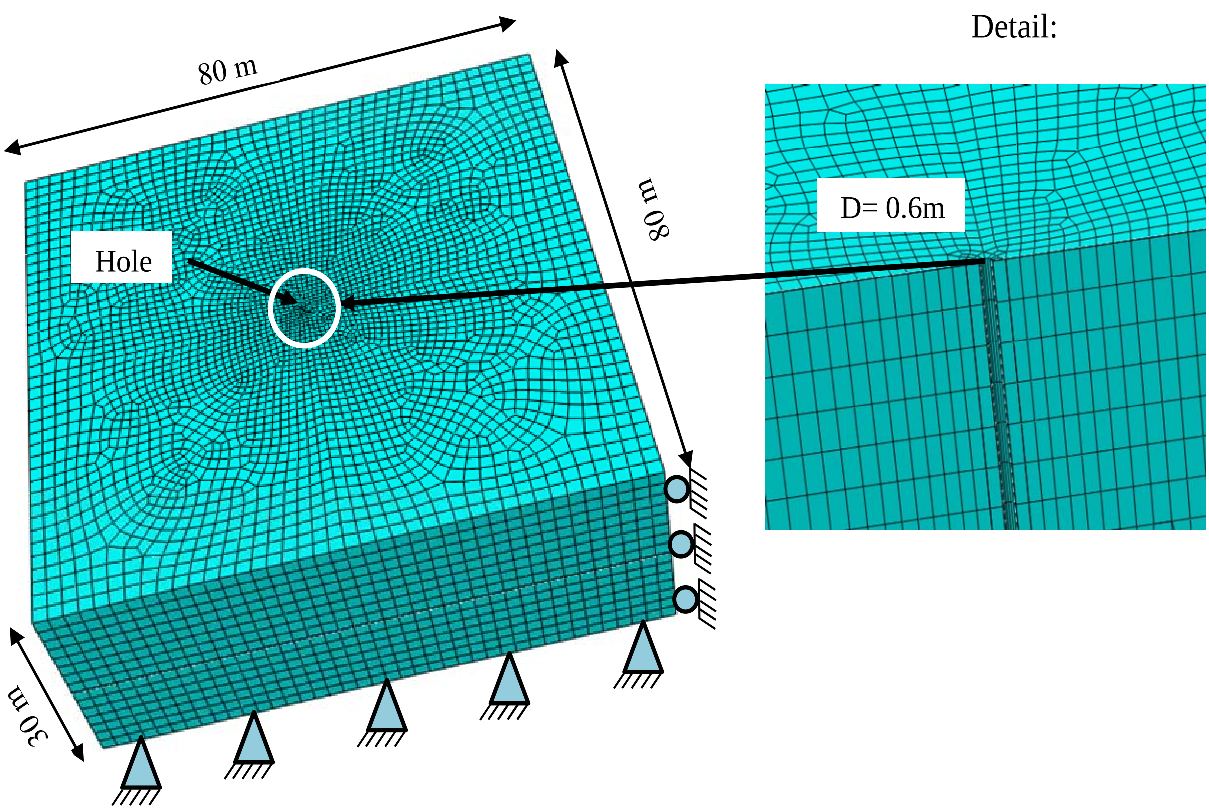


Fig. 3: Finite element mesh and boundary conditions adopted in this study for single pile

Finite element mesh and boundary conditions for pile group numerical model

The pile group model consisted of 25 pile 3 m apart and the soil used in this numerical model was modeled using 8-node hexahedral elements. The mesh size 80 m (length along Y-axis), 80 m (width along X-axis), and 30 m (depth along Z-axis). The mesh consists of 37,363 number of nodes and 31,075 soil elements. In this study, the element size in the soil mesh surrounding the piles was 0.6 m and become coarser further away from the piles edge. As shown in Fig. 4, the model base was prevented from movement in all directions by using pin support and all vertical sides were allowed to move vertically only by providing roller support. The model top was allowed to move in all directions.

Modeling of unfavorable drilling conditions

It is complicated to simulate the process of CFA piles drilling numerically. In order to simplify this process a numerical model was developed to simulate the unfavorable drilling conditions. Only the drilling down phase of the CFA pile installation was modeled. In order to numerically simulate the drilling down process, a borehole with diameter and length similar to the CFA pile intended to be drilled was assumed. In the initial step, the inner wall of the borehole was fixed horizontally by roller support simulating the borehole has not been drilled yet in this step. In the first step, the inner wall of the borehole was allowed to move horizontally with applying a hydrostatic pressure to support the open excavation simulating the auger flights full of soil in favorable drilling conditions. The applied hydrostatic pressure assumed to be the same as the geostatic pressure along the borehole multiplied by the at rest earth pressure coefficient (Ko). In unfavorable soil conditions (in case of overflighting) a loss of horizontal support was assumed to simulate the process of excessive drilling and loss of support.

Hydraulically, the water table was assumed at the ground surface at the initial step which produced a hydrostatic initial pore water pressure profile. No change in pore water pressure was assumed throughout the analysis (water flow is not allowed) at the all vertical sides, the base of the models, and the ground surface. The water was allowed to flow towards the pile in the case in case of over-flighting will happen by simulating the hydrostatic water pressure inside the wall of the borehole having zero water pressure in the assumed portion in which over-flighting happened. In unfavorable drilling conditions, when penetration rate of the auger became slower than the rotation rate due to an obstacle in the auger way, over-flighting occur.

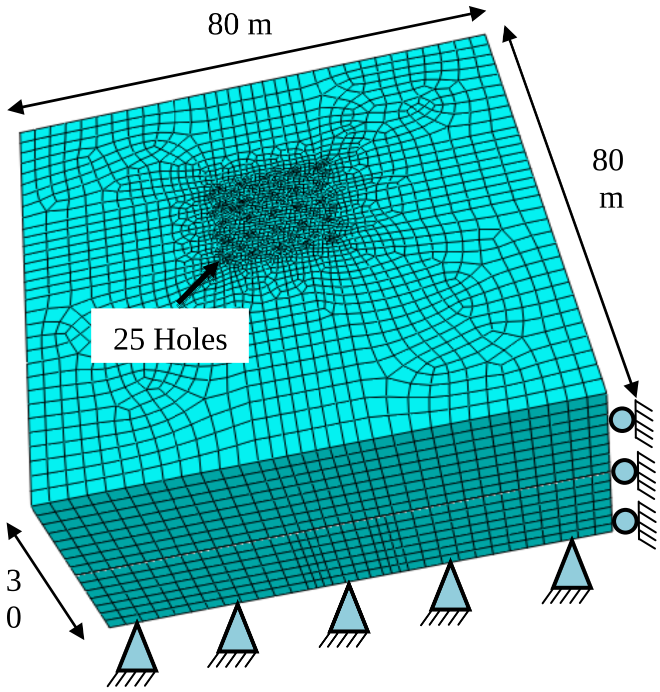


Fig. 4: Finite element mesh and boundary conditions adopted in this study for multiple piles

Soil constitutive model

In this paper the constitutive model used to simulate the soil is Mohr-Coulomb available in ABAQUS 6.13. The Mohr-Coulomb criterion assumes that yield occurs when the shear stress on any point in a material reaches a value that depends linearly on the normal stress in the same plane. The Mohr-Coulomb criterion used can be represented by the equation:

$$F = R_{mc}q - ptan\emptyset - c \qquad (1)$$

$$R_{mc}(\theta,\emptyset) = \frac{1}{\sqrt{3}cos\emptyset}\sin\left(\theta+\frac{\pi}{3}\right)+\frac{1}{3}\cos\left(\theta+\frac{\pi}{3}\right)tan\emptyset \qquad (2)$$

Where q is the Mises equivalent stress, p is the equivalent pressure stress, c is the cohesion of the material used, Φ is the slope of the Mohr-Coulomb yield surface in the p–R_{mc}q stress plane which is commonly referred to as the friction angle of the material and θ is the deviatoric polar angle. The soils used in this study modeled as Mohr-Coulomb with soil properties chosen from the Egyptian Code as shown in Table1.

Table 1: Soil properties used in the parametric study

Soil	Loose sand	Dense sand	Medium sand
Unit Weight (kN/m^3)	16	21	19
Internal Friction Angle (Φ)	30^o	40^o	35
Young's Modulus (kN/m^2)	20000	60000	30000
Poisson's Ratio	0.25	0.35	0.30
Cohesion (c) (kN/m^2)	1.0	1.0	1.0
Void Ratio (e)	0.8	0.7	0.75
Coefficient of At Rest Earth Pressure (K_o)	0.5	0.357	0.426

Model 1: single pile

Depth of over-flighting

The problem of over-flighting may happen in one layer of soil if the auger hits an obstacle in its way which may result in a decrease in penetration rate to be slower than rotation rate. As shown earlier a pile with a diameter of 0.6 m was modeled with a length of 16 m. In order to see the effect of the unfavorable drilling conditions a pile was divided into 4 layers as shown in Fig. 5, The first segment extended from ground surface to 4m depth, second segment extended from 4m to 8m, third segment extended from 8m to 12m, forth segment extended from 12m to 16m. An obstacle was assumed to be at the end of each segment to simulate the over-flighting condition. A hydrostatic pressure with a value as same as the geostatic stress along the borehole multiplied by the at rest earth pressure coefficient (K_o) was assumed to be applied inside the borehole and this pressure works as a support to the inside wall of the borehole. Loss of lateral support is used to simulate the unfavorable soil drilling. The hydrostatic pressure was assumed to be nullified (the lateral support was assumed to be zero) to allow the lateral movement of soil towards the segment in which the problem of over-flighting. The water was allowed also to flow towards the segment in which the lateral movement was allowed by having zero water pressure.

Effect of depth of unfavorable drilling

In order to investigate the effect of the unfavorable soil drilling, the loss of lateral support was assumed to occur over a segment of 4 m of the pile length. The segment of unfavorable soil drilling was assumed at four depths to investigate the effect of loss of support with depth. In this numerical model the soil was assumed to be loose sand soil with properties shown in Table 1. Fig. 6 shows the surface deformation after pile drilling. In this figure the effect of increasing the depth of the unfavorable drilling is illustrated. The deeper the segment where the loss of lateral support occurred the wider the lateral extent of the surface deformation. Also, it can be seen from the figure that surface settlement in case of unfavorable soil drilling has a shape of inverted cone with most of the settlement occur at the vicinity of the pile and decrease moving away from the pile. Fig. 7 shows the contours of the soil deformation after soil drilling for three case of unfavorable soil CFA pile drilling.

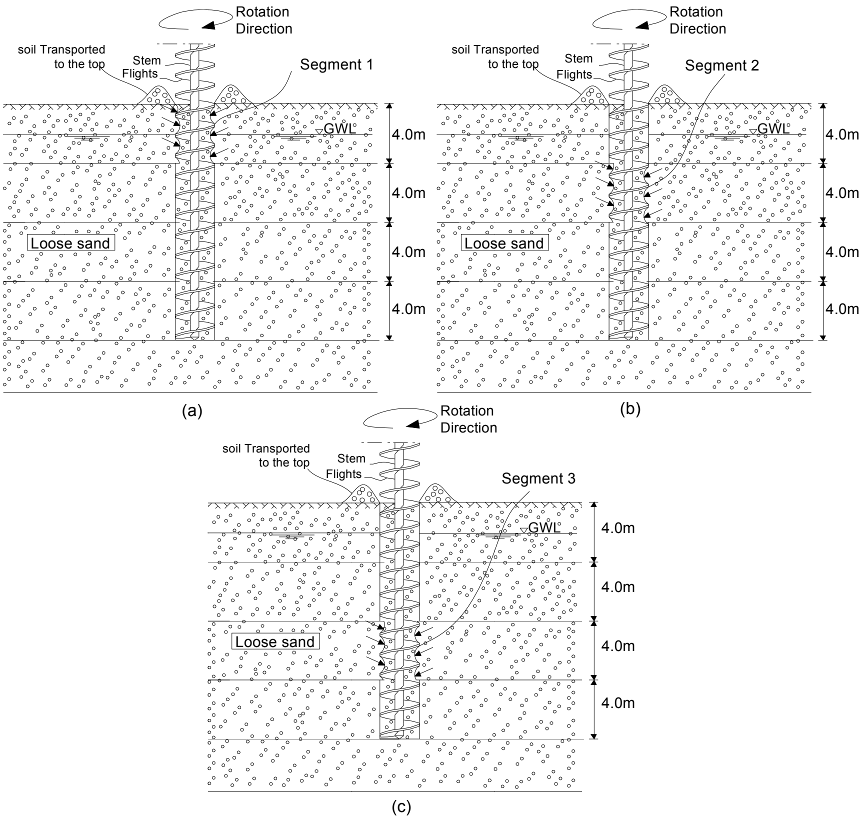


Fig. 5: Arrangement of the four segments for single pile

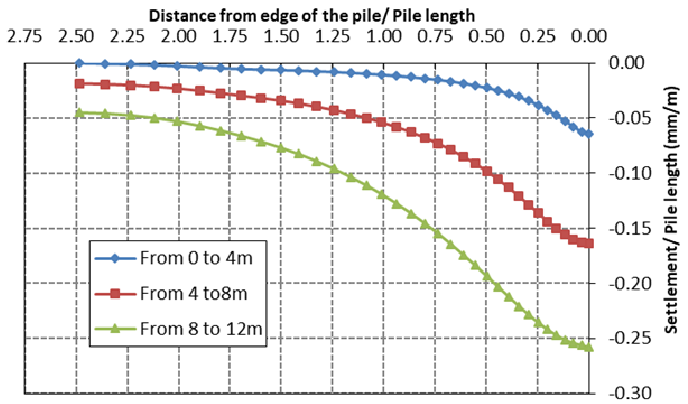
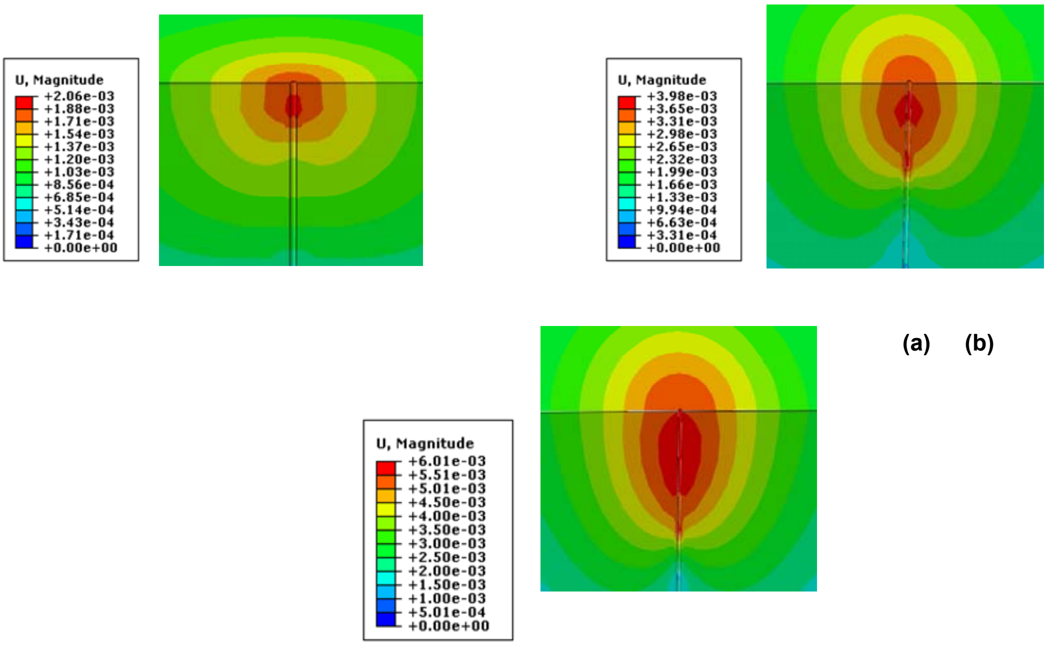


Fig. 6: Settlement induced due to lateral stress decrease in the first three segments



(c)

Fig. 7: Settlement contour calculated due to loss of lateral support at three segments, (a) segment 1, (b) segment 2, and (c) segment 3

Effect of sand relative density

In order to understand the effect of sand relative density on the surface settlement in case of favorable CFA pile drilling a parametric study was performed changing the relative density of sand. Three models with borehole depth of 16 m and diameter of 0.6 m were conducted to with different sand parameters (dense sand, medium sand, and loose sand) as detailed in Table1. An over-flighting condition assumed to occur at the segment extended from 8 m to 12 m. Using a technique similar to the described earlier, lateral movement and water flow were allowed in the segment in which over-flighting was assumed to be happened. Fig. 8 shows the surface settlement calculated in the three cases, higher settlement was calculated in case of loose sand compared to medium and dense soils. The maximum value of ground surface subsidence induced was in loose sand state and the minimum was in dense sand state. This means that, the loose sand is the most critical soil compared to medium and dense sand. This emphasis the importance of higher quality control measures during drilling of CFA piling in loose soil deposits.

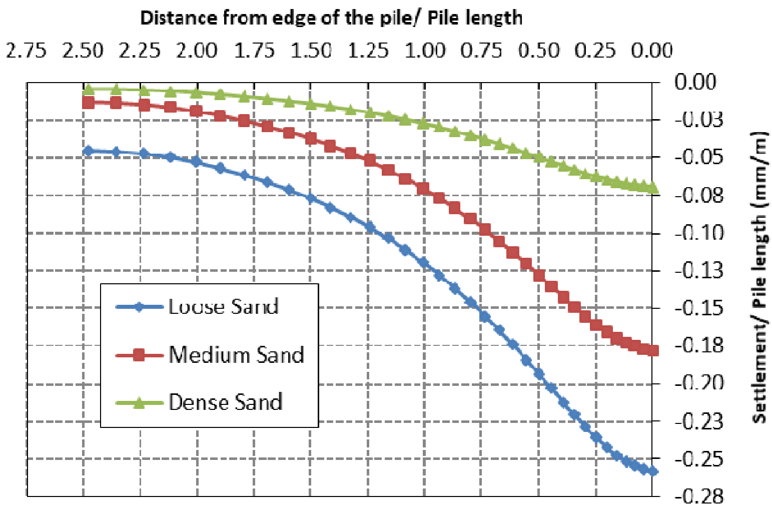


Fig. 8: Settlement calculated for unfavorable CFA pile drilling with change in sand relative density

Model 2: Pile Group

25 boreholes (piles) were simulated to be drilled with spacing of 3.0 m, depth of 16 m, and diameter of 0.6 m to simulate the drilling process for a group of CFA piles. In case of over-flighting condition and to investigate the distance from the excavated CFA piles in which more CFA piles can be excavated with minimal effect on adjacent structures, the following model was conducted. The over-flighting condition was assumed to occure at depth of the pile from 8 m to 12 m. Fig. 2 shows the assumed sequence of CFA pile construction. In initial step, all the piles were prevented from lateral movement by preventing lateral movelemnt. In the first step, for pile 1, the lateral movement was allowed for all the borehole depth with applying a hydrostatic pressure with a value as described earlier except the segment from 8 m to 12 m in which over-flighting assumed to occur. The water flow towards this segment was allowed also. In the second step, the lateral movement and pore water pressure were assumed to be fixed at their current magnitude for borehole1 assuming the poured concrete which able to maintain the borehole in its current position and prevent more water to flow towards the pile. In the same step, lateral movement and water flow were assumed to be allowed in the same potion for pile 2 simulating over-flighting. This operation was repeated for all 25 boreholes (25 steps) respectively according to the sequence in Fig. 2.
Point (A) at the edge of pile 1 was selected to be a reference for settlement calculated after drilling of each pile. Fig. 9 shows the relation between the increase in settlement happened due to each CFA excavated pile individual and the pile distance measured from point A. The results showed that at a distance of about 0.7 of pile length, more CFA piles can be excavated with minimal effect on adjacent structures.

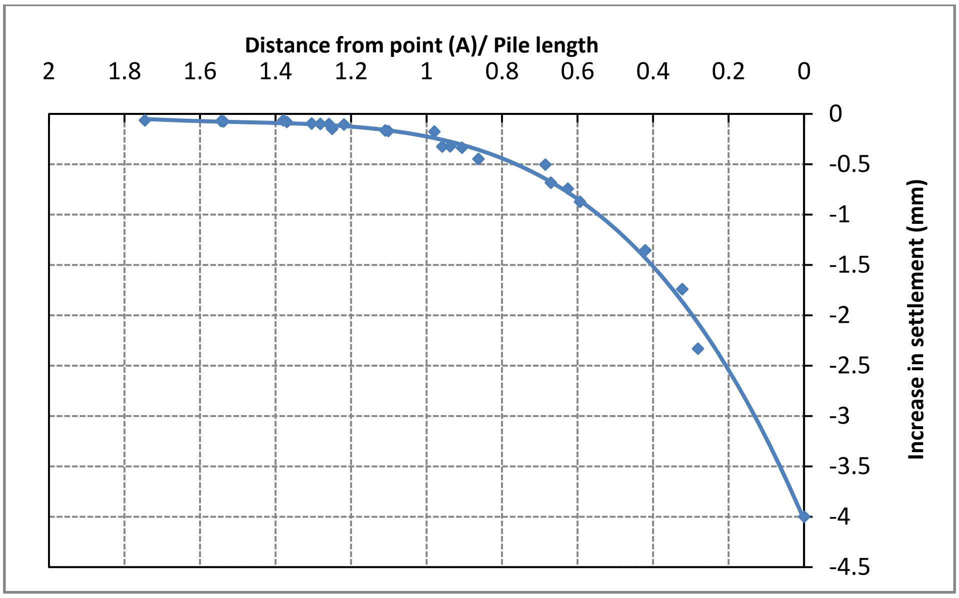


Fig. 9: Increase in settlement happened due to over-flighting during CFA piles drilling with distance

CONCLUSION

Based on the numerical analysis conducted in this paper the following conclusions can be driven:

1- A procedure has been proposed to simulate the overflighting in CFA pile drilling.
2- Pore pressure generated due to CFA drilling may cause settlement during drilling and this settlement.
3- The increase in the depth of the segment over which the overflighting occur increase the extent of the surface settlement and the magnitude of surface settlement. .

4- The effect of unfavorable pile drilling extend to a distance of about 0.70 of the pile length.
5- The maximum value of surface settlement induced is at the pile vicinity and reduces gradually away from it.
6- The subsidence settlement magnitude increases in the case of loose sandy soils compared to dense sandy soils.

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