CONTINUOUS FLIGHT AUGER (CFA) PILE RETAINING WALLS BOUNDARY SETTLEMENTS DURING PILE INSTALLATION

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ABSTRACT

It is incumbent on developers, designers and contractors to ensure the safety of buildings and occupants on adjacent sites during construction. The critical period on most sites is prior to and during the excavation of the site. This is particularly true on sites where the strata are mainly sands. The use of contiguous and secant pile walls using the continuous flight auger (CFA) method is commonly adopted to provide support to the excavation on such sites. This method can be an economical and, in most cases, effective method. However, there seems to be little cognisance given to the damage caused during installation of the piles by the process sometimes known as "sand mining". There have been several instances of severe damage to adjacent buildings due to this process not being recognized during the investigation, design and early construction phases. This paper discusses the main causes of settlement during construction and proposes a method to estimate them during the investigation so that the structural engineer can assess their effect on adjacent buildings and services.

1 INTRODUCTION

Most structural and geotechnical engineers, some building and civil contractors and all piling contractors are aware of the problems and effects of excavating for basements adjacent to contiguous and secant pile retaining walls in sand strata. Advanced design software can predict lateral and vertical deflections of the walls and supported soils with a reliable degree of accuracy provided that the geotechnical investigation is sufficient to determine design parameters for the strata. Procedures are commonly in place for the general contractors to observe for and rectify groundwater leakage and loss of soil through gaps between piles, repair damaged and improperly constructed piles and monitor deflections during excavation of the site.

The main advantages of the CFA system over other piling methods in urban areas are relatively low noise and low vibration. The advertising literature produced by most piling companies also promote the system as being safe because the soil filling the auger flights provides sufficient lateral support to prevent collapse of the bore. Nevertheless serious problems due to settlement around the bore occur more frequently than is generally realised, particularly on sites with significant depths of loose to very loose sands. Visual evidence includes the following:-

- Engineers experienced in the supervision of CFA piling in loose sand will have observed the formation of a depression close to the auger which increases in depth and diameter as drilling proceeds. The zone of disturbance can be several times the diameter of the auger depending on the depth of loose sand. It is also apparent that the soil close to the auger rotates at an angular speed similar to the auger and reduces to stationary close to the edge of the depression. In many respects it is similar to the formation of a vortex in fluids. The depth of settlement around a single pile is usually only a few millimetres and is often obscured by sand flighting up the augers when the pile is drilled into underlying dense sand.
- However, experienced piling contractors and supervisors will have observed settlements of one to two hundred millimetres, sometimes more, at pile groups. This indicates that settlements are cumulative. As these movements are usually at column locations within the site boundaries, they are often just casually observed as being of little consequence. However, if they can occur at pile groups why would anyone think they cannot occur at CFA pile walls, which are effectively linear groups?
- It is common practice to reset and relevel CFA piling equipment while drilling through loose sands. This can only be necessary because of significant ground movement to at least the one and a half metres or more from the auger to the track of the crane base on which the equipment is mounted.
- Personnel working close to CFA piling equipment have been "sucked into the ground" when the soil movements have suddenly expanded out to where they were standing. Fortunately, training of the drivers of the equipment

includes observation of the people around the machine so they have been able to stop drilling before serious injury occurred.
- Severe damage of buildings on adjacent properties has occurred on projects in the Sydney Region before bulk excavation of the site has commenced.

2 SOME PREVIOUS DISCUSSIONS OF SETTLEMENT.

The causes of settlement and ground disturbance during the installation of CFA piles have been recognized and discussed in the literature since no later than 1991. In that year Esrig and his coworkers presented measurements of building displacements on a project in New York involving the installation of CFA piles.

Leznicki et al. (1992) further discussed the measurements of the New York project. The foundations required the installation of 400mm diameter CFA piles to depths of about 27 metres to support loads of 700kN. The underlying strata comprised loose to medium dense, fine to coarse sand overlying mica schist bedrock at a depth of 36m. The groundwater table was 3m below working level. Two buildings, one of which was designated as historic, were located adjacent to parts of the boundaries. Settlements of up to 38mm were observed at the historic structure after installing only 19 piles at distances of 1,2m to 4.6m from it. At the time the settlements were attributed mainly to equipment problems which caused excess soil to be removed during the drilling operation. Some particular observations were:-

- The estimated volume of spoil was between $6.1m^3$ and $9.2m^3$ per pile compared to a theoretical pile volume of $3.8m^3$.
- The grout factor (ratio of actual grout usage to theoretical volume) ranged from 1.8 to 2.4. The specification required a minimum factor of 1.4.
- The typical time to drill down to the founding depth was 7 to 8 minutes. The contractor used a high rotation speed to achieve a high rate of production.

The work was stopped while the effects of procedural changes were observed. After a period of trial and error, changes were made to the grouting procedure and to the drilling speed. The slow rotation drilling mode was adopted and the drilling time increased to 12 to 15 minutes. This reduced the volume of spoil to $3.8m^3$ to $4.6m^3$. Settlements of adjacent structures reduce to 13mm. "*A significant portion of this movement was believed to be caused by ground loss during augering." Other observations suggested that minor settlements could occur to a radius of about 6 pile diameters but that ,if loss of ground occurred, the influence zone could increase to up to 15 diameters."*

Andrews (1998) wrote that "*when continuous flight auger (CFA) piles are drilled through loose filling, sand or gravel and then socketed into rock, the continual rotation of the auger while slowly penetrating the rock can cause the loose material to compact in an ever widening zone around the auger. This alone can cause settlement, but if the compact soil then feeds up the auger more soil is drawn into the cavity and the problem can be increased considerably. This has been known to cause severe damage to buildings on adjacent properties in Sydney. It can also be a danger to the piling equipment and personnel".*

Brown (2005) discussed the advantages and disadvantages of installing of CFA piles in different soil conditions. These discussions were later incorporated into the Federal Highway Administration's report on the "Design and Construction of Continuous Flight Auger Piles", (Brown et al., 2007), of which he was a Principal Author. These reports state that the following are among the soil types considered to be unsuitable for CFA piles.

'Very soft soils
In these soils, the installation of CFA piles can present problems concerning ground stability due to soft-ground conditions, which can produce necks or structural defects in the pile……..'
'Loose sands or very clean uniformly graded sands under groundwater.
Clean, loose sands with shallow groundwater are unfavourable because the potential for soil mining is high….."
Hard soil or rock overlain by soft soil or loose, granular soil.
The installation of CFA piles is typically difficult in a soil profile in which it is necessary to drill into a hard bearing stratum overlain by soft soil or loose granular soil ….. The problem occurs when the hard stratum is

encountered and the rate of penetration is slowed because of the difficult drilling; the overburden soils are then flighted by side loading of the auger above the hard stratum….."

The concern for "sand mining" and the resultant effects on the capacity of the pile and ground settlement are evident.

Carrier (2007), described a project where CFA piles were installed on a site with a groundwater table at or within 50mm of the surface. The strata comprised 15m of fine sand and silty sand overlying hard clay. A layer of loose to very loose sand occurred between 3.5m to 7.0m, with SPT blow counts averaging 5 and about one third of the values equal to 1 or 2. Piles were founded "at refusal" in the hard clay. During the work "*clear water was observed percolating from the tops of piles and from the surrounding ground. This transient event, typically lasting less than an hour, occurred in approximately 40% of nearly 700 piles."* It was further recorded that the grout in many of the piles subsided soon after they had been installed, requiring constant topping up. The contractor noted that topping up was necessary until the percolation ceased. The added grout volume averaged 1.1 m^3 per pile; the average grout factor was 2.10 compared to an expected factor of 1.15.

The liquefaction was attributed to constant shearing of the very loose and loose sand layer by the auger, exacerbated by the need to drill to refusal at the toe of the pile. The excess pore pressures dissipate at the surface of the ground water, causing densification of the stratum and hence the need for the additional grout. The author considered that this phenomenon probably occurs on many other projects but is not observed because the groundwater level is well below the working level.

The above is not intended to be an exhaustive review of the literature. But it is sufficient to demonstrate that densification of loose sand can and does occur during the installation of CFA piles and that it occurs both above and below the water table.

3 CAUSES OF SURFACE SETTLEMENT DURING CONSTRUCTION

The conventional wisdom of drilling CFA piles, as described by Brown (2005) and Brown et al. (2007), is to balance the speed of penetration to the rotation of the auger so as to keep the auger flights filled with soil and hence maintain the stability of the bore. If the augers rotate too quickly the auger acts as an "Archimedes pump" and conveys soil to the surface, leaving the auger partially full.

Figure 1, attributed to Fleming (1995) illustrates the concept. In the upper diagram the auger penetrates rapidly so that it remains filled with soil from the cutting bit at the base of the auger without lateral feed. There must be a small amount of soil feeding to the surface to balance bulking of the soil as it is cut plus the volume of the auger itself.

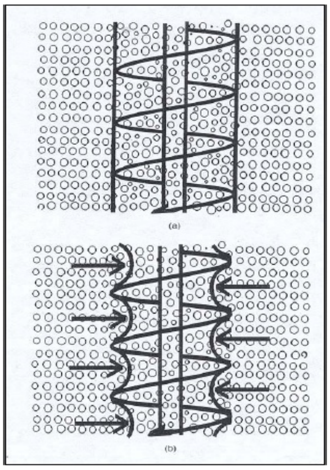


Figure 1: Effect of Over-excavation with CFA Piles. (After Fleming, 1995)

The lower part of the diagram illustrates the effect of drilling with fast rotation or slow penetration. There is insufficient feed from the base cutting bit to keep the auger full and too much soil is fed up the auger to the surface. This can cause a reduction of the horizontal stress around the pile with consequent lateral movement of soil towards the auger and ground subsidence at the surface.

The relationship between rotation and penetration is sometimes expressed as the penetration ratio, PR, as:

$$PR = L/(N.p) \qquad (1)$$

where, L is the depth of penetration, N is the number of turns of the auger and p denotes the pitch of auger.

A PR of 1 means the auger would screw itself into the ground, similar to a self-tapping screw into wood. A value of 0 would mean no penetration while the auger rotates.

To achieve the balance of rotation and penetration it is necessary to have equipment with enough torque capacity and down force. It is impractical to build equipment of drilling at a high PR and a typical value of about 0.5 or less would be used in practice.

However, while the above factors are important and can affect the degree of settlement, the author of this paper does not consider that incorrect drilling techniques are the main cause of surface settlement.

Many text books on soil mechanics and geotechnical engineering (e.g. Leznicki, 1997) describe the concept of the “critical density” or “critical void ratio” of cohesionless soils. The concept is that a soil at the critical density will not undergo volume change regardless of any deformation that it may be subjected to. A soil at less than the critical density will compact until its density approaches the critical value if it is continually disturbed. Similarly, a soil at a density greater than the critical value will dilate when it is disturbed. The critical void ratio decreases with confining pressure, so that there is a potential for greater compaction of the lower levels of a uniformly loose sand and less potential for dilation of deeper levels of dense sands.

In the context of CFA piling, loose sands will compact and settle during drilling and, except for some stirring and mixing, not feed up the auger to the surface. Dense sand will dilate and the additional volume will flight up the auger to mound around it at the surface.

If the piles are drilled through a loose stratum and into a dense one, it is likely that compaction of the upper layer will continue while sand is flighted up from the deeper layer, visually masking much of the settlement. The flighted sand does not mix into the loose sand and does not reduce its compaction. Thus, if CFA piles are drilled close to an existing building, compaction of the upper stratum may cause damage to a building on high level footings, while dilation of the deep stratum will reduce the capacity of a pile foundation. (This latter effect has been well documented and is not discussed here.)

If the upper sand is medium dense or denser and underlain by a loose stratum, the volume of the loose layer is still likely to reduce. However, there may not be visible settlement at the surface unless the upper layer collapses, slowly or quickly, into the lower. At the very least these conditions demand comprehensive monitoring of grout demand along the pile to check for cavitation in and above the loose layer. Although settlement may not be immediately visible, the possible movement of the upper layer into the lower may affect the bearing capacity of nearby high level footings.

4 FACTORS AFFECTING SETTLEMENT OF LOOSE SAND STRATA

When drilling with CFA equipment in loose sands the rotation of the auger causes the sand adjacent to it to turn around in the direction of rotation. This movement causes the sand near to the auger to compact. The next annular area rotates and moves in to fill the void and is then compacted, etc. The effect reduces with distance from the side of the hole and the process continues out to a radius where there is no movement and no settlement. The zone of influence has been described by others as conical, however, the author’s observations are that the surface is curved, steep adjacent to the auger and near horizontal at the perimeter.

The major factors affecting total settlement may be summarised as:

- Soil type –Properties such as grain size and angularity will affect the critical density.
- Relative density – the lower the relative density of the soil the greater the potential for settlement.

- Thickness and location of the loose layer(s) – If the loose layers are close to the surface the densification will be evident as settlement but may not be immediately visible if they are bridged by denser layers.
- Depth of pile – Some previous reports (e.g. Kenny et al., 1997; Thorburn et al., 1993) indicate that the settlement zone is proportional to the depth of the pile. This may be true if the soils are relatively similar over the length of the pile but is unlikely in mixed loose to dense layers.
- Diameter of pile – Most reports describe the settlement zone as multiples of pile diameter. It is likely to be a more significant factor than depth in mixed soil conditions
- Time of drilling – There is little doubt that the duration of the drilling is a major factor in causing densification of loose sands. Time will be affected by all the other factors.
- Groundwater – The critical density concept is not affected by the presence of groundwater. However, it can affect drilling times as well as the duration of the densification process. A report by Carrier (2007) describing the effects of liquefaction has been summarised above
- Presence of piles already installed – If piles have already been installed in a group or along a wall their presence will shield some parts of the zone of influence from further settlement when drilling for other piles.
- Equipment – The equipment must have sufficient torque and down force capacity to drill to the required depth with a high PR and in minimum time. The equipment should be in good condition and properly braced so that it does not shake or shudder or create unwanted vibrations that would increase the rate of compaction of the soil. In particular, the auger string should be effectively held in place by guides attached to the leaders and the auger string should be straight to prevent it wandering and causing excessive movement and vibrations.
- Drilling techniques – Drilling techniques outlined previously can assist in the reduction of settlement by reducing the disturbance and drilling time, however, they cannot eliminate it. Other techniques, such as the injection of compressed air or water through the hollow auger stem while drilling have been used on occasion, sometimes successfully, sometimes not.

It is apparent that with this diversity of factors it will not be possible to estimate the settlement of ground surfaces if only a conventional geotechnical investigation is carried out. Where there is a potential for damage to existing buildings it is recommended that a trial drilling programme be carried out.

5 TRIAL DRILLING PROGRAM

It is possible to hire CFA piling equipment without the grouting equipment and accessories. The cost is moderate compared to the cost of damage to adjacent structures. The minimum hire period will be sufficient to carry out several trial bores in most conditions likely to be encountered in the sand regions of Sydney.

The locations of the tests should be remote from the boundaries to eliminate risk of damage to other properties. The diameter of the auger should be the same as the piles proposed by the structural engineer. Preferably, the length of the auger string should be enough to drill to the design depth of the piles but, if full depth equipment is not available must be able to drill into dense soils below the loose layers of concern. The effects of drilling full depth can be simulated by continuing to rotate the auger at one level in the dense soil for an appropriate time

A section of the area around the pile should be smoothed and leveled out to at least 5 auger diameters from the edge of the auger to enable visual examinations and measurements as the test bore is drilled. Any spoil flighting up the auger should be carefully removed so as to maintain the prepared surface and not affect measurements. Settlement measurements should be taken radially from the side of the auger at distances of 0, ¼d, ½d, ¾d, d, 1½d, 2d and then as required at ½d interval out past the limit of the disturbance, (where d is the diameter of the pile.) Measurements should be taken at regular time intervals, say 1 minute, and or at regular penetration spacing of 1 metre to record the development of the settlement zone with respect to time and or penetration. Photographs should be taken of the surface at each stage of measurement to record visual effects such as rotary and radial movements of the surface.

The measurements may then be analysed to find a suitable equation of the surface profile and enable further analysis of group effects. A suggested method is outlined below

6 SETTLEMENTS AROUND A SINGLE PILE

If we consider a 1 metre thick layer of loose sand with an in situ void ratio of 0.65 and a critical void ratio of 0.4, the total potential settlement of the layer would be about 160mm. Such settlements would be rarely experienced when drilling a single pile, even adjacent to the auger. Evidently the full potential settlement is unlikely to occur and it is not possible to accurately estimate the proportion that is likely to happen without the trial drilling programme. However, there still remains the likelihood that some of the remaining potential settlement will be caused by drilling another pile nearby, as in a group or wall.

To continue this discussion it will be necessary use an example and to make some assumptions. Experienced piling contractors and engineers will recognize that the following assumptions would not be the worst they have seen.

A pile diameter of 600mm is adopted, this being a common size used in contiguous and secant CFA pile walls. The zone of influence is taken to be 2 pile diameters (1200mm) from the side of the auger; the diameter of the zone is thus 3.0m. A parabolic surface profile will be adopted as this is the profile of a vortex in a liquid. The maximum settlement (S) adjacent to the auger, is taken to be 40mm

The generalized profile is shown on Figure 2.

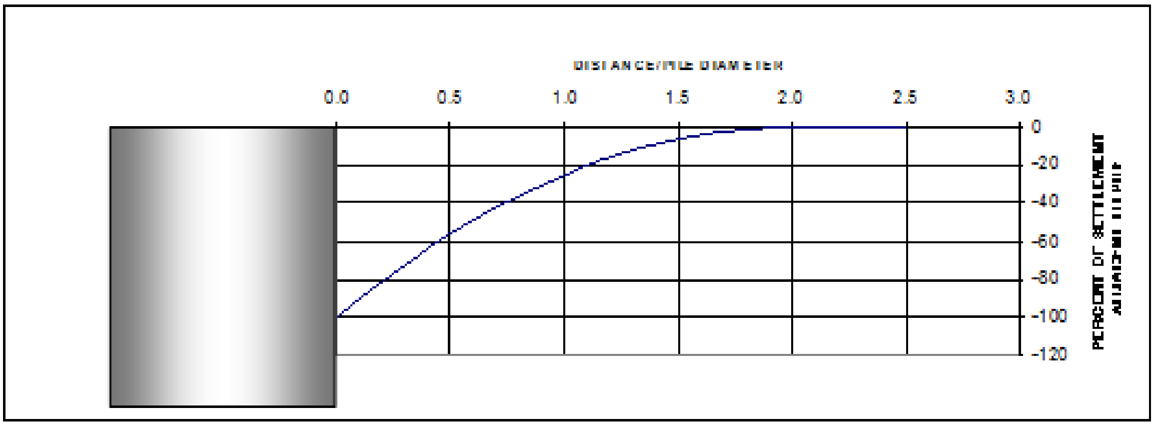


Figure 2: Generalised settlement profile around a single CFA pile

The general equation for a parabolic surface profile is:

$$-s = ar^2 + br + c \qquad (2)$$

where s is the settlement at a distance r from the side of the pile and a,b and c are constants. The constants are evaluated from the boundary conditions, i.e.:

when r = 0, s = S	i.e. the settlement adjacent to the pile
when r = 2d, s = 0	i.e. no settlement at a distance of 2 pile diameters
when r = 2d, ds/dr = 0	i.e. horizontal surface at a distance of 2 pile diameters.

and Equation (2) becomes:

$$s = -Sr^2/(4d^2) + sr/d - S \qquad (3)$$

The settlement around the example 600mm diameter pile is shown in Figure 3. It should be noted that the settlement 600mm away from the pile is only 10mm. This would be noticed during drilling only by a most diligent observer.

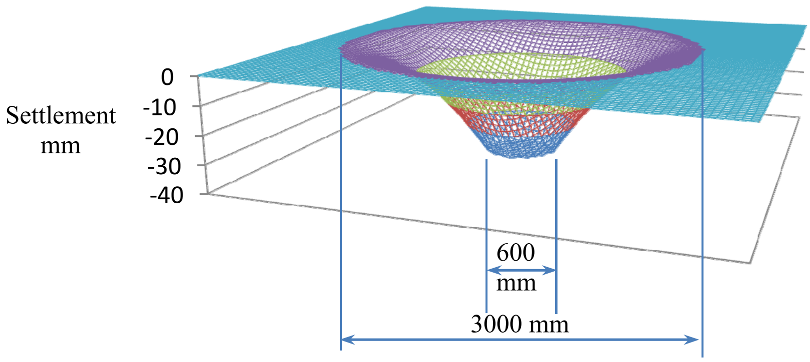


Figure 3: Settlement around the example CFA pile

7. Group Effects and CFA Pile Walls.

When considering the settlements in proximity to a group of piles, it seems reasonable to assume that the sands have the potential to densify cumulatively during the installation of all the piles.

However, the presence of already completed piles close to the pile being installed must affect the amount and distribution of the additional settlement. The overlapping effects of the zones of influence of piles installed at wide spacing are shown on Figure 4. In this case the existing piles, representing the first phase of a contiguous pile wall, lie outside the zone of influence of each other and do not affect the accumulation of settlement in the overlapping zones between piles.

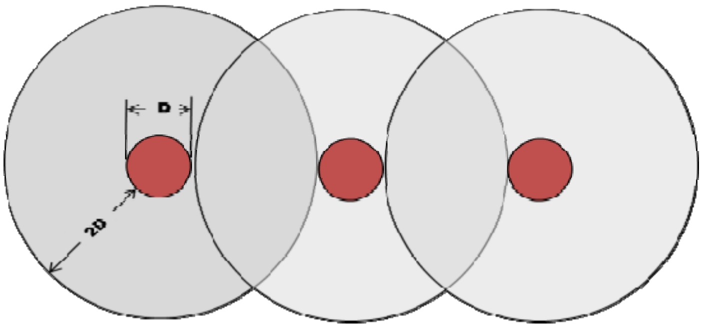


Figure 4: Effect of Overlapping zones of Influence of First Phase of Piling in a Contiguous Pile Wall

There are two additional effects when drilling for the second phase of piles in the wall due to interference or shadowing from the first phase piles. Firstly, there can be neither settlement at the installed piles nor in the shadowed areas behind them. Secondly, it is likely that the average additional settlement at the new pile will be reduced due to the smaller affected area. A case can be made that there is no reduction in the unshadowed areas but the lower bound case is adopted here. The shadowing for the second phase of piling is shown on Figure 5 and the settlement reduction factor is 0.804.

A similar diagram for the final, third, phase of the piling would show that the settlement reduction factor is 0.667

Calculations have been carried out using a 50mm square grid for an example contiguous pile wall comprising 600mm piles at 600mm spacing with the single pile settlement profile described above. The settlement profiles for the example wall after the completion of the three phases are shown in Figure 6.

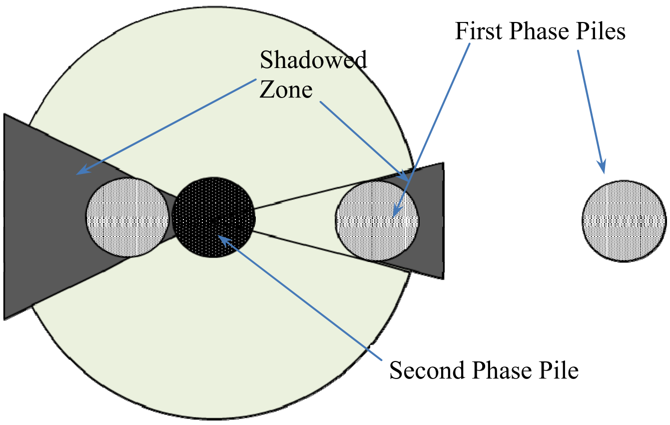
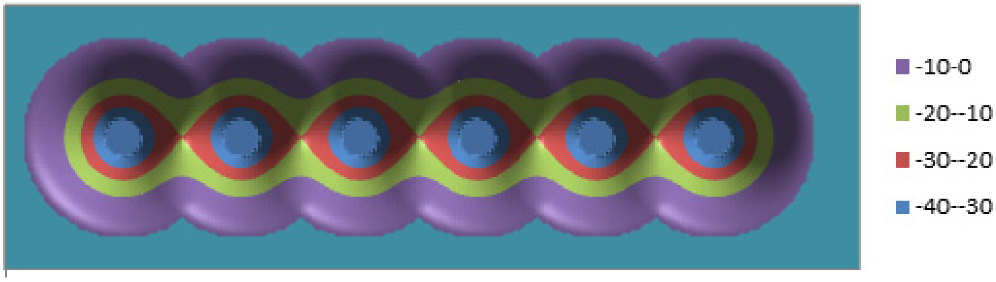
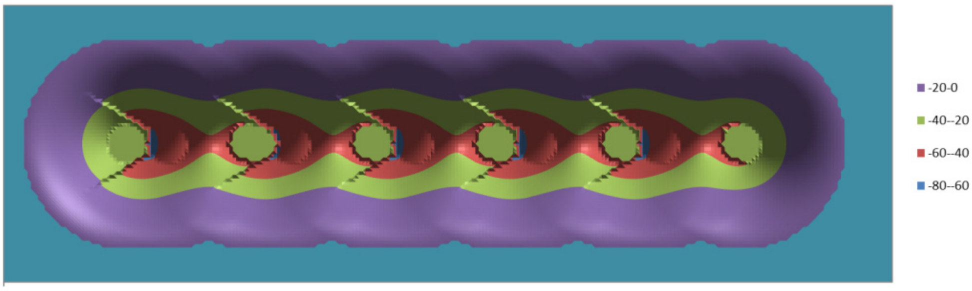


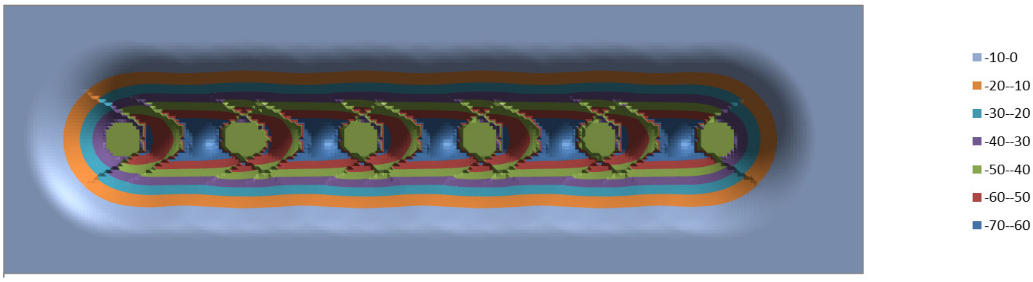
Figure 5: Effect of Shadowing when drilling Second Phase Piles in a Contiguous Pile Wall



a. Estimated Settlement Profile after First Phase of Piling of Example Wall



b. Estimated Settlement Profile after Second Phase of Piling of Example Wall



c. Estimated Settlement Profile after Third Phase of Piling of Example Wall

Figure 6: Estimated settlement profile of piling of the example wall

The maximum estimated settlement close to the face of the wall is 61mm and the average is 54mm. Of more interest to the present discussion is the settlement at a footing on an adjacent site. A typical clearance from the centre of the CFA wall to the face of a building is 600mm. The maximum estimated settlement at this distance is 42mm and the average is 38mm. This would be enough to cause moderate to severe damage to the building unless it was on piles or underpinned.

Secant CFA pile walls are usually constructed with alternate hard and soft piles, sometimes with hard and hard piles. The pile spacing is less than the diameter. The soft piles are installed first and the hard piles, which are the main structural units, are then drilled to intersect both adjacent soft piles with the aim of building a waterproof wall without gaps between piles. The procedure described above has been used to estimate the settlement caused by installing 600mm diameter piles at 500mm spacing. The settlements after installing the soft piles and after installing all piles are shown in Figures 7 and 8.

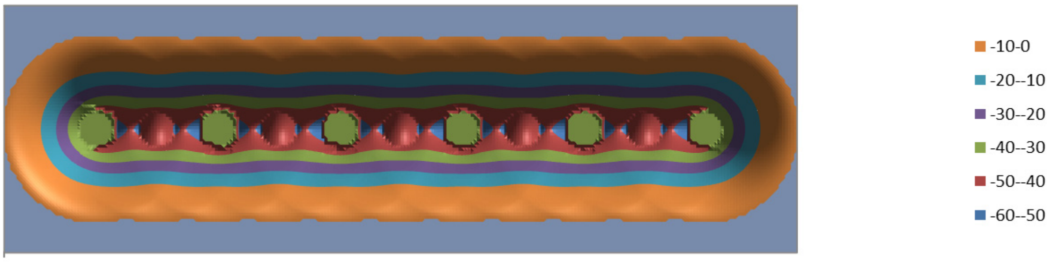


Figure 7: Estimated Settlement Profile after "Soft" Piling of Example wall

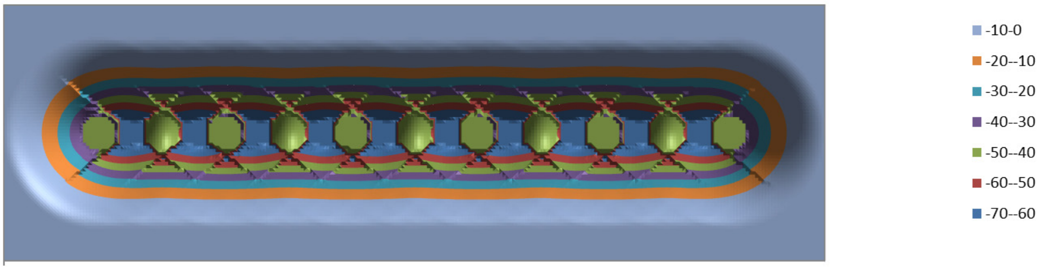


Figure 8: Estimated Total Settlement Profile of Example wall

The average estimated settlement adjacent to the wall is 59mm and the maximum is 63mm. The average estimated settlement 600mm from the face of the wall is 41mm and the maximum is 45mm. These are slightly higher than the contiguous pile wall, which can be expected in view of the additional work.

8 CONCLUSIONS

CFA piles have been successfully used on many projects to construct contiguous and secant pile retaining walls close to site boundaries. However, settlement can occur due to densification of loose to very loose sand soils when installing the piles, which can, and in some cases has, caused damage to buildings close to the walls. These settlements are in addition to those which occur due to deformation of the wall when the site is excavated and should be considered when decisions are made regarding the need to protect nearby buildings and their residents.

It is not possible to reliably estimate these settlements during normal geotechnical investigations. This paper has outlined a simple field test which can be used to provide these estimates. The author recommends that geotechnical engineers suggest in their reports the test be carried out whenever they recognize that loose sand is present and that CFA pile walls may create a hazard.

Further research is needed into the cumulative effects of drilling closely spaced piles. This work cannot be carried out so easily due to interference to survey stations when maintaining safe and clean site conditions. However, it would be possible with the good will and cooperation of all parties on the site. The author hopes that this will happen sooner rather than later.

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