Design, installation and verification of CFA piles and common challenges in the Melbourne region

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ABSTRACT

Continuous Flight Auger (CFA) piling is a common foundation type for building and infrastructure projects in and around Melbourne, as well as nationally. The Australian piling market has significant expertise and capability in their design and construction, which has been developed over the past two decades or more, primarily in the building industry. Most of this expertise and experience is held by specialist piling subcontractors. In the building industry, CFA piling projects have been delivered primarily using a design and construct contracting model, where the specialist piling contractor has responsibility for designing, installing and certifying the foundation system. More recently, CFA piling has become popular on infrastructure projects, where responsibility for design, construction and verification involves a broader range of parties, including geotechnical and structural consultants, main contractors and specialist piling contractors. Successful project delivery in this environment requires good understanding and alignment between all parties, and sound design, construction and verification processes. Deficiencies in these processes can lead to conflicts and practical difficulties during the piling works. Further, they can expose designers, contractors and project owners to risks with respect to cost, quality and program outcomes. The geology of Melbourne also presents some challenges in relation to CFA pile design and installation, including a predominance of low strength soils in the Yarra Delta area, deep siltstone bedrock and variable and unpredictable basalt flows. This paper discusses important aspects of CFA piling projects in the building and infrastructure sectors, as well as some commonly encountered challenges in and around central Melbourne. The author endeavours to provide an overview of important aspects of this pile type to assist in broadening the understanding of industry practitioners who are involved in planning and executing CFA piling projects.

Keywords: Deep Foundations, Continuous Flight Auger Piles, High Strain Dynamic Pile Testing, CFA Pile Constructability, Coode Island Silt.

1 INTRODUCTION

Continuous Flight Auger (CFA) piling has become a common foundation type across both the infrastructure and building sectors in Victoria and nationally. Industry capability and practice in design and construction of this pile type have developed significantly over the past 20 years. While many specialist practitioners are highly skilled and experienced in CFA piling, this expertise is often not readily accessible to the broader profession.

In Australia, the use of CFA piling methodology developed initially in the commercial building sector, where it is typically used under a 'design and construct' contracting arrangement, where the contractor is responsible for the design, installation and certification of the foundation system. Design, construction monitoring, inspection, testing and verification processes have evolved in the building sector to suit this commercial environment.

More recently, CFA piling has become prevalent on infrastructure projects where, in contrast to the building sector, the design is generally carried out by the engineering consultants and the piles are often installed under a 'construct only' contract. As construction equipment, methodology and practices significantly influence CFA pile performance, it is important that appropriate construction monitoring, inspection, testing and verification processes are incorporated in the project documentation and are properly implemented.
Considerable published literature is available in relation to CFA pile design and construction. One notable publication is Brown et al. (2007), which is a comprehensive reference prepared for the U.S. Federal Highway Administration. However, CFA piling practice is often heavily influenced by local factors associated with geology, plant, design and delivery methods, specifications and standards.

The author's experience in the Melbourne piling market, and Australia more generally, suggests that important issues associated with the use of CFA piles are not broadly understood by many practitioners, outside of the specialist piling contractors. This paper discusses important considerations for the use of CFA piles in both the building and infrastructure sectors, highlighting some key technical, practical and commercial considerations.

It is important to note that CFA pile construction is a dynamic process that unfolds in real time and is critically dependent on the skill and experience of the specialist piling subcontractor and, particularly, their site personnel. This paper does not advocate that geotechnical practitioners (or other project personnel), other than piling subcontractor personnel, should seek to involve themselves in the real time construction process; except for the purpose of collecting any information they may require to carry out their responsibilities (e.g. geotechnical inspections and pile sign-off) and communicating any important feedback. However, when design and verification responsibilities rest with consultants (as opposed to a design and construct subcontractor delivery model), it is essential that all parties understand the requirements and constraints of other project participants.

It is the author's experience that concerns and discrepancies can be very difficult to resolve if design, construction and verification processes are not well understood and executed, and this can cause unnecessary delays, and technical and commercial disputes that can affect all parties. This paper seeks to provide geotechnical practitioners, as well as the broader industry, with an understanding of key issues that require consideration, communication and alignment between the parties for consistently successful project outcomes.

1.1 CFA Piling in the Geology of Melbourne

The engineering geology of Melbourne presents some particular issues in relation to the design and installation of CFA piles. In the author's experience, the most prevalent and challenging issues include the following:

- *Determination of achievable geotechnical axial capacity* – Piles installed across Melbourne's variable geology may encounter rock of a broad range of strength and weathering, and soils which are often interbedded and present a risk of inconsistent founding conditions.
- *Drilling to refusal in rock* – CFA piles are often found in weathered siltstone which can usually be penetrated to some depth to form a socket, and basalt which can be highly variable in quality and strength and can present challenging conditions for formation of a consistent base.
- *Discontinuous basalt flows or layers of limited thickness* – Sites where basalt is discontinuous or of limited strength require the designer to consider whether piles can be safely founded on the basalt flow, or whether it is necessary for piles to penetrate past the basalt to a deeper founding layer.
- *Ground displacement in soft soils* – CFA piles are a common foundation solution for building developments around the Yarra Delta, where the thickness of Coode Island Silt (typically soft to firm in consistency) can be significant. Concreting pressures can cause lateral ground displacements, which can impact adjacent structures as well as previously installed piles.
- *Dynamic load testing requirements* – High-capacity CFA piles installed to found in rock can require very large test loads to be demonstrated to meet the requirements of AS2159-2009. On infrastructure projects, as compared to building projects, program, pile layout and access considerations make load testing more challenging, and rationalisation of the testing program is often preferred.

The above items, which are particularly relevant to practitioners in the Melbourne area, are discussed in this paper.

1.2 Advantages and Limitations of CFA Piles

CFA piles have steadily increased in use in Melbourne, and Australia more broadly, primarily for economic and constructability reasons. This has coincided with the ongoing development of piling plant globally, which has allowed some of the initial challenges to implementation in the Melbourne market (such as limitations on drilling depth and pile diameter, and reliable installation monitoring) to be overcome. Some of the key advantages offered by CFA piles in the Melbourne market are as follows:

- They are relatively fast and cost effective to install, compared to bored piles, particularly in urban areas where high-quality concrete supply is available, and delivery is generally timely and reliable.
- Ground support in potentially unstable soils is inherent in the construction methodology, as soil retained on the auger prevents collapse, provided the penetration rate is appropriate. CFA piles can therefore be installed through potentially collapsible soils without the need for secondary ground support, such as steel casings or drilling slurry, which can significantly add to the cost of bored piles.
- Full computer instrumentation, when properly used, calibrated and operational, provides a relatively high level of construction quality control.
- When installed to a high standard of quality, they can achieve good end bearing in sands below the water table, which is difficult to achieve in bored piles.
- High geotechnical capacities can be achieved by founding piles in rock and the typical properties of Melbourne Formation siltstone are conducive to achieving a socket into rock, if appropriate high-capacity plant and equipment are used.
- They are often preferred over driven piles on environmental grounds because they generate less noise and vibration. It should be noted that, while not traditionally considered a displacement pile type, CFA piles can generate significant lateral and vertical ground movements in some soil conditions.

Figure 1. CFA pile drilling.

As with all pile types and construction methodologies, selecting the appropriate foundation system must be undertaken on a case-by-case basis and CFA piles have some important limitations, which must be considered. Some key limitations are as follows:

- The construction process, and its outcomes, is heavily reliant on concrete quality, which is critical to both concrete placement and cage installation. Concrete supply service levels can govern productivity and pile completion risk.
- The ultimate pile capacity and load-settlement performance is heavily influenced by “installation effects”. There are a range of factors involved in both drilling and concreting that contribute to installation effects, including plant capability, auger design and condition, operator skill, contractor construction procedures, and drilling criteria.
- The reinforcing cage is inserted into the fluid concrete after extraction of the auger and cage length is limited to that which can be practically installed. This often necessitates partial length reinforcement. While it is the author’s experience that cage lengths of up to around 30m can be used in favourable ground conditions with carefully controlled special purpose concrete mixes, reinforcing length is generally limited to around 20m length (at most). As cage length increases, there is a higher risk of premature cage refusal during installation. Centralised bars can be installed beyond the main reinforcing cage and can generally be inserted to full depth – these are often used to provide tension capacity, where necessary. Contractor experience in specific ground conditions and localities is the best guide to what can be practicably achieved on a consistent basis.
- Pile diameter is generally governed by drilling rig capability, both with respect to drilling processes and auger extraction. In the Melbourne market, diameter is typically limited to up to 1,200mm and pile length at large diameters can be limited by extraction winch capacity and consideration of the risk of losing an auger that cannot be extracted.
- CFA piles generate spoil, which must be disposed of in accordance with regulatory requirements, and this can be undesirable where contaminated material or potential acid sulphate soils are present. In cases where this is a significant factor, driven piles may be preferred.

As with all pile types, the advantages and limitations of CFA piles can only be properly considered in the context of specific project conditions and requirements. These include plant and material availability, ground conditions, pile loads, expected founding depths, installation risks, environmental considerations and the requirements of applicable codes and standards.

1.3 Important Differences between Building Industry Projects and Infrastructure Projects

Design, construction monitoring, inspection, testing and verification processes for CFA piles evolved primarily in the building sector to suit the design and construct delivery model, where the contractor will often take responsibility for delivering a fully certified foundation system.

More recently, CFA piling has become prevalent on infrastructure projects, where the design is generally carried out by the engineering consultants and the piles are often installed under a ‘construct only’ contract. As construction equipment, methodology and practices significantly influence CFA pile performance, it is critical that the allocation of responsibility is properly understood and appropriately incorporated in the design and construction phase of infrastructure projects.

Table 1 summarizes some key differences between private building sector projects and infrastructure projects. There are important differences in the allocation of responsibility between industry sectors and this is summarised in Table 2.

Infrastructure projects involve design processes with a range of participants, and it is important that the designers understand the construction procedures and verification methodologies that will be used to confirm that the as-built works meet the design requirements. It is the author’s experience that successful delivery of CFA piling on infrastructure projects requires understanding and alignment between the designers, specialist geotechnical consultant, piling contractor, main contractor and client representatives to avoid unnecessary difficulties.

The available Australian Standards (AS2159-2009 and AS5100.3-2017) offer limited guidance in relation to CFA piles, specifically, and are less prescriptive than some project owners (e.g. public authorities) would prefer. In response, various authorities have produced their own specifications for CFA piles (see References). While these include relatively consistent requirements in relation to some elements of pile construction (such as materials, plant and monitoring requirements, and record keeping), it is evident that a variety of approaches have been adopted in relation to key geotechnical considerations.

A detailed discussion of these authority specifications is beyond the scope of this paper. However, it is apparent that there is inconsistency across the infrastructure sector in relation to geotechnical requirements for CFA piling projects. Further, in some cases, requirements are included in authority specifications which are impractical to implement and regularly result in non-conformances or departures.

Table 1 - Key differences between foundation systems for building projects and infrastructure projects.

Building Projects	INFRASTRUCTURE PROJECTS
• Typically large, concentrated loads - axial load generally governs pile design. • Geotechnical investigation scope and quality of information is quite variable. • Builders typically rely on specialist piling contractors to design and construct a suitable foundation solution. • Foundation systems are often contractor-driven alternative designs. • AS2159-2009 is the governing standard. • Current industry practice evolved largely in building to suit design and construct environment.	• Greater variety of loading conditions. Axial loading is often more moderate (compared to buildings) and lateral loading can significantly impact pile design. • Geotechnical investigation requirements are more prescriptive, typically based on the requirements of AS5100.3. Sites are often more linear, and piling locations are more spatially distributed. • Design responsibility usually lies with multiple project consultants. Design and approval processes involve multiple parties and are typically much more involved. • Specialist piling contractors are often consulted, but generally do not design and document the foundation solution (other than some temporary works). • AS5100.3-2017, AS2159-2009, Project and Authority Specifications are applicable.

Table 2 - Typical allocation of responsibilities on building and infrastructure projects

<table>
<tr><th>Activity</th><th>Building Projects</th><th>Infrastructure Projects</th></tr>
<tr><td>Design and Specification</td><td rowspan="4">Piling Contractor</td><td>Geotechnical and Structural Consultants, Statutory Authorities, Proof Engineer, Independent Verifier</td></tr>
<tr><td>Construction</td><td>Piling Contractor</td></tr>
<tr><td>Construction Monitoring and Implementation of Verification Processes</td><td>Piling Contractor, Structural Consultant, Geotechnical Consultant, Independent Verifier</td></tr>
<tr><td>Verification of As-Built Piles (Certification)</td><td>Structural Consultant, Geotechnical Consultant, Independent Verifier</td></tr>
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In the author's opinion, the industry would benefit from a broad practical understanding of critical elements of CFA pile construction and verification processes and, eventually, more consistent and practical authority technical specifications.

1.4 Critical Stages of CFA Piling for Geotechnical Engineers

The Melbourne piling market, and Australia more broadly, is fortunate to have highly capable and experienced practitioners and access to state-of-the-art plant and equipment for construction of CFA piles. Quality outcomes in pile construction are critically dependent on a broad range of factors that are well beyond the scope of this paper, and these will necessarily be under the control of the engineers and construction personnel who design and execute the works on a day-to-day basis, primarily the specialist piling contractors.

For geotechnical engineering consultants, who may be responsible for designing, inspecting and/or signing-off on CFA piles, it is important to understand the key stages and elements of pile construction that are relevant to this process. Figure 2 illustrates the process of pile installation, highlighting the following key stages at which geotechnical outcomes can be most affected:

- *Design and Planning (Prior to Stage 1)* – It is critical that the pile design and any associated design parameters consider what is practically and reliably achievable using available plant. This may require interaction with potential piling contractors to confirm plant and equipment capability. Drill depth and pile diameter should be achievable using best-practice drilling methodology (i.e. single pass without de-densifying granular soil), with consideration of potential site variability. In some geologies, consideration of hard layers overlying softer layers, and the viability of drilling through these layers to founding depth may be a key consideration. End bearing parameters adopted in the design must be reliably achievable within the intended founding strata, with the plant and equipment that is available.
- *End of Drilling (Stage 2a) – Termination Criteria* – It is important that each pile is drilled to a predetermined termination criteria that can be consistently applied across all piles of a particular type. For piles terminating in soils where drilling refusal is unlikely to occur (with appropriately sized plant), the termination criteria is typically the design founding level. For piles installed in layered in soils, it is critical to ensure that the founding material is consistent with the design assumptions, e.g. sand rather than clay, if required. Generally, targeting granular layers that may be inconsistent in presence and thickness is not advisable. In persistent layers of significant thickness, this may be reasonable. For piles drilled into rock, the termination criteria may be effective drilling refusal and/or a required penetration into a certain material type, as indicated by torque and crowd readings approaching termination depth. As discussed in subsequent sections, drilling to a predetermined socket length may not always be appropriate, particularly if high end-bearing resistance is required. The drilling termination criteria is an important element of the geotechnical verification process and departures from predetermined criteria or expected conditions should trigger a review of the suitability of the achieved founding level.

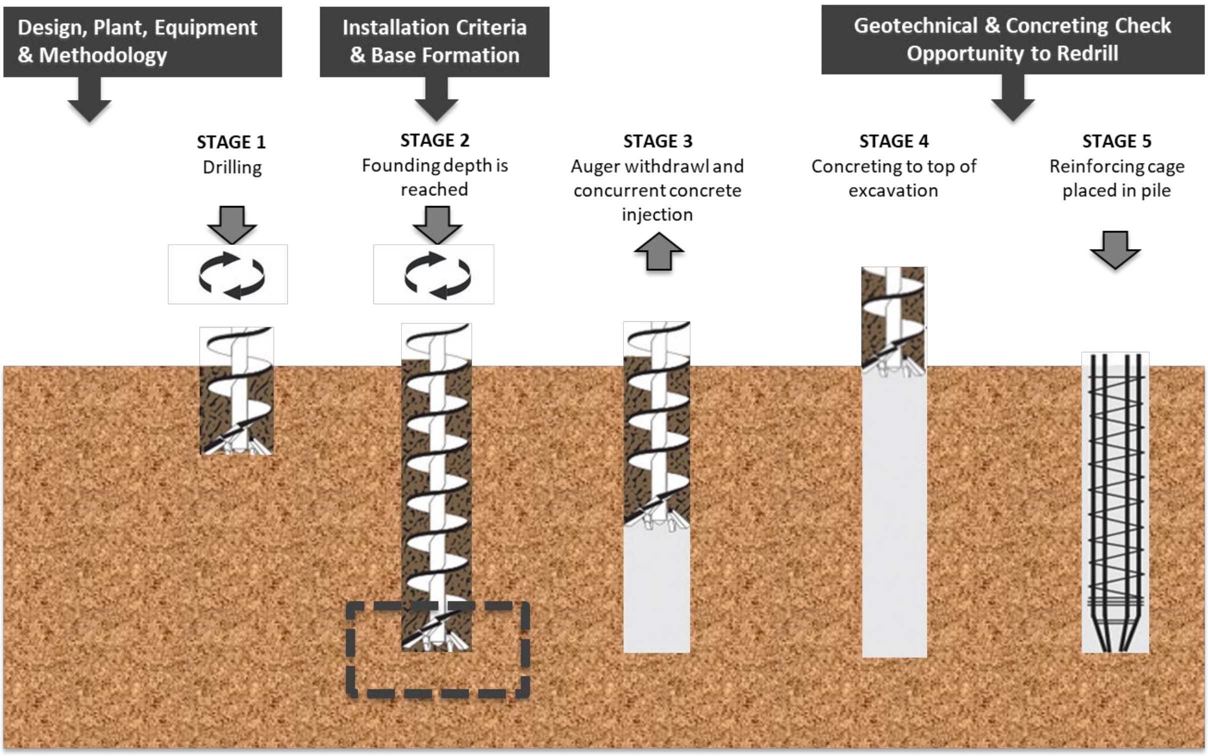

Figure 2. CFA pile installation process.

- *Commencement of Concreting (Stage 2b)- Base Formation* – The process adopted for base formation can significantly impact the end bearing response of the pile. For piles that rely on a high-end bearing component, it is critically important that the base formation technique is both appropriate for the founding strata and consistent across all piles. The specifics of the base formation process are controlled by the piling rig operator in real time but can be reviewed by inspection of the pile installation records.
- *Auger Inspection (end of Stage 4)* – The soil and rock that is retrieved at the ground surface and on the flights of the auger upon extraction is heavily disturbed and, to some extent, transported vertically from its original level. However, with an understanding of the drilling process, important geotechnical observations can be made to assist in verifying that the design founding conditions have been achieved. This is particularly relevant to the material at the tip of the auger, which can be inspected to confirm the type of material at the pile base, in the same way that observations can be made of disturbed material retrieved by bored pile drilling tools. As is the case for bored pile inspections, it is essential that geotechnical engineers carrying out inspections have the understanding and experience to infer in-situ conditions from observation of the disturbed materials.
- *Opportunity to Redrill (prior to Stage 5)* – Immediately following completion of concreting, prior to reinforcing cage placement, there is an opportunity to redrill the pile if any significant concerns exist in relation to its suitability. This is an undesirable and expensive exercise due to the time and material wastage involved; however, it is an opportunity to rectify potential construction defects and adjust the founding depth if conditions do not align with design requirements. Any review of installation records can only be carried out by inspection of the monitoring data on-screen in the piling rig or another real-time display if available. Experienced piling rig operators will carry out progressive reviews of monitoring data as they build the pile. It is not usually practical or necessary for any engineering involvement, provided the operator is properly aware of, and attentive to, key installation requirements, so that they can respond in real-time as required.

The above elements apply to installation of each pile and the records generated, along with pile testing results, represent the key information that is used to verify that design requirements have been met. Therefore, consideration must be given to consistency across similar pile types and between tested and untested piles on the project.

2 DRILLING EQUIPMENT AND METHODOLOGY

As the method of temporary ground support during pile construction is inherent in the CFA methodology, the process of drilling a pile can significantly affect its shaft and end bearing resistance, particularly in unstable and/or granular ground conditions.

CFA augers are essentially a soil conveyor (also known as an Archimedes Screw). To avoid reducing support to the surrounding soil, theoretically, the volume of soil removed from the pile during drilling should equal the volume of the auger introduced, with the balance of the volume of the pile represented by the soil retained on the auger. Industry experience indicates that, typically, a target penetration rate in the order of 50% of auger pitch (flight angle) results in a low risk of loss of soil support.

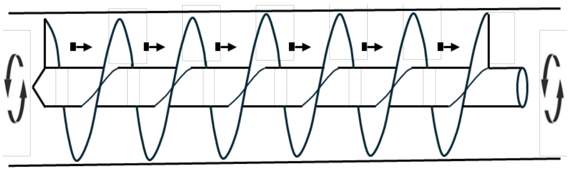

Figure 3. Schematic of Archimedes Screw.

Slow penetration rates, which may be caused by unsuitable plant or equipment or strata that are difficult to penetrate, can cause ‘flighting’ in sands. Flighting is the term given to the removal of a greater than optimal volume of soil due to excessive rotation of the auger for any given penetration. The most obvious sign of significant flighting is surface coning; however, this may not necessarily be evident when flighting occurs. Slower penetration rates are generally not problematic in clay and rock as these materials are not usually susceptible to flighting.

An example of installation effects is illustrated in Figure 4, which shows Cone Penetrometer Test (CPT) data before and after installation of a pile in granular soil that appears to have experienced some flighting during installation. This case illustrates a fairly moderate reduction in soil density. Significantly more pronounced reductions have been reported by a number of researchers, such as Van Weele (1988).

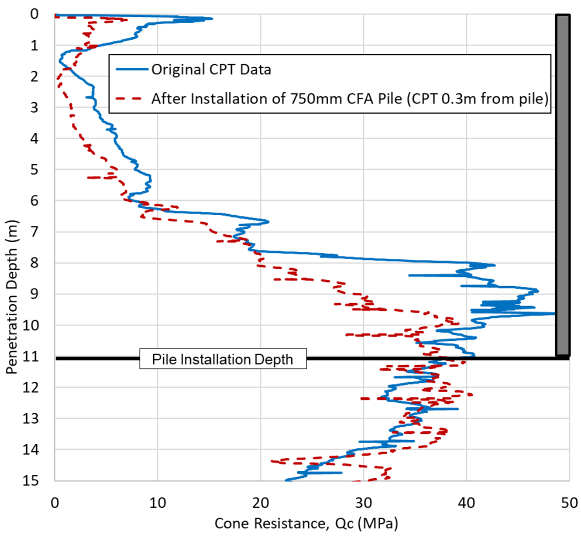

Figure 4. Example of CPT cone resistance before and after installation of a CFA pile.

To ensure adequate penetration rate and to avoid flighting, sufficient rotary torque and crowd (downward force) are necessary. Typically, for deep CFA piles in Melbourne, the preferred minimum drilling torque is around 20tm, while industry leading equipment has up to around 47tm drilling torque, and this is regularly increasing as piling plant is further developed. To minimise the need to break augers during drilling, mast lengths of up to around 40m are generally preferred. Using industry leading equipment and utilising auger extensions, CFA piles up to around 54m in depth have been installed in Melbourne.

2.1.1 Installation Monitoring

There are a variety of proprietary systems available for installation monitoring for CFA, which record a range of drilling, extraction and concreting parameters and display them in real time in the piling rig. The various systems use a range of instrumentation and measurement techniques, and each has its own proprietary software to process, interpret and display the results. Examples of installation monitoring data are shown in Figure 5.

During drilling penetration rate, rotational speed, torque and crowd (downward force) are recorded. These parameters can generally be used to identify distinct strata, but their sensitivity to changes in ground conditions is dependent on a range of factors, including the capacity of the drilling rig and the operator’s drilling method. For these reasons, correlations between drilling parameters and ground conditions, and interpretation of this data generally, should be by direct comparison between the installation data and site investigation data.

The use of torque readings to estimate or verify founding conditions and pile capacity, as is sometimes attempted, is not in itself a technically robust method. Whilst useful and appropriate in some circumstances, inference of founding conditions from torque data should be used with caution.

Placed concrete volume is a critical aspect of quality control for CFA piles and installation monitoring systems generate an estimated pile geometry with depth. It is important to note that concrete volume is inferred rather than measured, generally by recording pump strokes and assuming a pumping efficiency with respect to volume. For concrete volumes indicated in monitoring data to be reliable, the concrete pump must be properly calibrated and pump efficiency must be monitored progressively over the course of the works by comparing delivered and pumped volumes. It should be noted also that monitoring data interpretations cannot account for vertical movement of concrete within a pile, e.g. concrete migrating up the auger flights.

For a range of reasons, there are limitations to the accuracy of pile geometry inferred from installation monitoring and generally only obvious features or consistent trends should be given significance in review and interpretation. Figure 6 shows two examples of apparent features:

a) A rapid auger lift accompanied by low concreting pressure, which presents a high risk of necking in the pile, particularly in soft or unstable soils. Another incidence of low pressure is shown in the installation log, slightly higher in the pile, but this occurs at a reduced lifting speed and therefore presents far lower risk.
b) An auger lift off the bottom of the pile with no concrete pressure, which presents a high risk of generating a soft toe in some ground conditions, e.g. sands.

It is evident that the graphical representation of pile geometry does not always align with the installation data. Installation records should be reviewed by a practitioner experienced in CFA pile monitoring to avoid misinterpretation.

Figure 5. Installation monitoring control and display panels (Top) and concrete truck unloading into concrete pump (Bottom).

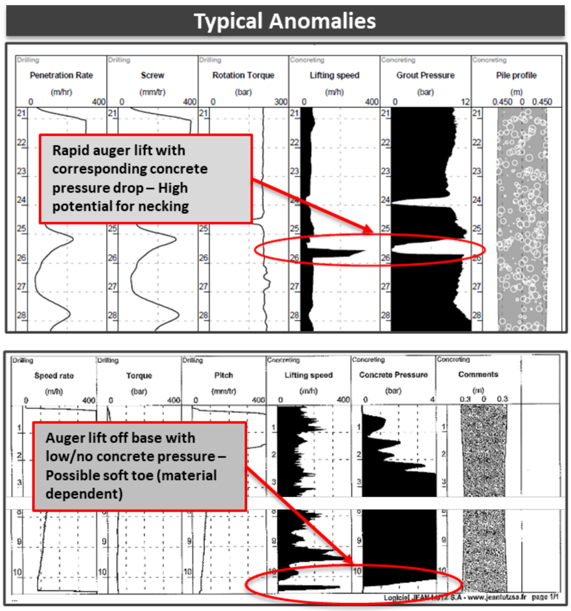

Figure 6. Example of Installation Monitoring Records.

2.1.2 Drilling Termination Criterion

To ensure that founding conditions are consistent with design requirements, every pile should have a clearly defined termination criterion, involving some, or all, of:

a) a design toe level;
b) a defined founding material;
c) bounds on installation parameters such as torque, crowd, and penetration rate; and
d) a drilling refusal criterion.

The appropriate method of defining drilling termination criteria will depend on a range of factors, including drilling rig capacity and founding strata - particularly whether founding in soil or rock.

High-capacity CFA piles are often installed to what is termed ‘effective drilling refusal’ on rock, which is the depth at which the auger can no longer penetrate effectively. However, it is necessary to define what constitutes refusal for any combination of relevant factors, including drill rig capacity, auger configuration, and rock type and strength. Considerations in relation to refusal criteria include the following:

- It is generally best practice to calibrate effective refusal with reference to site investigation information, typically a borehole in close proximity, to determine appropriate values of parameters such as penetration rate, torque and crowd, which indicate the required founding material has been reached and/or a sufficient penetration into an appropriate stratum has been achieved (e.g. socket into rock).
- The conditions which will lead to effective refusal will vary with plant and drilling tools, so it is important that a refusal criterion is reviewed and revised, as necessary, if plant or equipment changes.
- Where end bearing resistance is a critical element of achieving the design requirements, the resistance that can be achieved should be demonstrated by load testing results, and the refusal criterion calibrated accordingly.
- It is important that a consistent drilling methodology and refusal criterion is adopted across all piles, to achieve consistent and reliable outcomes with respect to load-settlement performance. The criterion should be clearly defined and communicated to site personnel.

In determining a drilling termination criterion, consideration should be given to the risk of flighting due to excessive rotation as penetration rate reduces towards the termination depth. In some ground conditions, it is necessary to balance the need to achieve high end bearing with the potential to de-densify the overlying strata. In some cases, the shaft resistance in overlying soils may not be critical to pile performance, but excessive flighting can cause undermining of the working platform. These considerations should be considered at design stage to avoid producing a design that is difficult to construct without complications.

2.2 Base Formation

Base formation technique is a critical element of pile construction, which can significantly impact the end bearing resistance response of a pile. Various techniques and preferences are implemented by different piling contractors, and it is necessary that the methodology used is compatible with the equipment and ground conditions.

A consistent base formation approach and concreting commencement process is essential to achieve optimal end bearing, particularly in soils that are susceptible to disturbance. The timing of concrete flow and auger lifting at the commencement of concreting is critical and equipment also plays a significant role.

It is important to recognize that the configuration of the auger head and the location of the concrete outlet can have an important effect on the characteristics of the as-built pile toe. Figure 7 shows two alternative auger head configurations, illustrating the following:

a) Tooth arrangement to cut a flat pile base and concrete outlet centralized at end of auger stem (top). This places the point of concrete discharge as close as possible to the un-cut soil or rock at the toe of the pile and is generally conducive to minimizing the disturbed zone at the toe of the pile.
b) Staggered tooth arrangement with large pilot bit to penetrate hard material and side-mounted concrete outlet on auger stem. The outlet, in this case, is located some distance above the un-cut soil or rock at the toe of pile and its location is less conducive to achieving good contact between the concrete and the undisturbed material at the toe of the pile. It is likely that more disturbed material will be present at the toe of the pile, which is less conducive to optimal end-bearing response, unless measures are taken to address this.

It is necessary for equipment designers to balance the auger tip design with drilling requirements, which sometimes necessitate less optimal tool and concrete outlet arrangements, in order to drill hard material. In such cases, it may be possible to achieve high-capacity end bearing with a compatible base formation technique. For example, some contractors may lift the auger slightly while injecting concrete before lowering it again to the initial drill depth while rotating the auger, with the intent of mixing any disturbed material with the concrete and/or lifting disturbed material off the pile base. This may help improve the end bearing response.

Approaches vary within industry, generally based on past experience with the contractor's specific plant and equipment.

It is important for designers to note that base resistance outcomes, even in the same materials, can vary significantly. Achieving typical, let alone optimal, end bearing should not be assumed without attention to base formation, local experience in similar ground conditions, where available, and appropriate verification of end bearing outcomes by load testing.

Pile diameter can also be a limiting factor for end bearing in some ground conditions, for geometric and practical reasons. When the auger is initially raised, concrete must flow to the perimeter of the base very rapidly to fill the space created but, if the rate of delivery is insufficient, the integrity of the base can be compromised if the ground is not self-supporting. This can be a limiting factor in sand below the water table, for example, where it is more difficult to achieve high end-bearing as pile diameter increases. This effect is not as likely to be limiting in rock and competent clays. Examples of the outcomes of base formation methodology are shown in Figure 8, which illustrates a high-quality pile toe and a soft toe. The implications with respect to end-bearing response are self-evident for these examples.

Figure 7. Alternative auger head configurations, showing flat tooth arrangement and centralised concrete outlet (top) and staggered tooth arrangement with side concrete outlet (bottom).

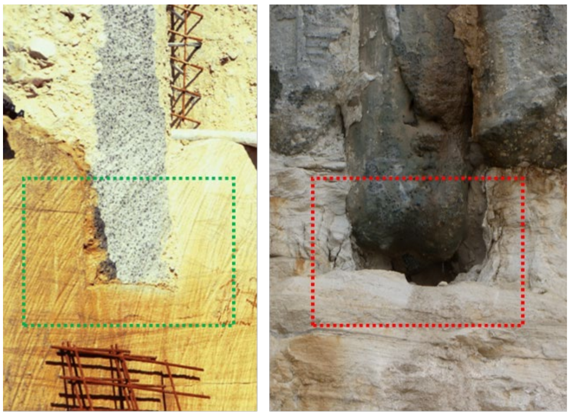

Figure 8. Good base formation outcome (L) and soft toe (R).

2.3 Geotechnical Observations

Geotechnical inspections can provide valuable information to assist in quality control and capacity verification if carried out effectively. The spoil that can be observed during geotechnical inspections is heavily disturbed and, in some elements, significantly transported, so it is essential that inspections are carried out with an understanding of the drilling process. Soil zones and associated considerations can be summarised as follows (refer *Figure 9*):

- *Upper soil layers* – Highly disturbed and transported and may be expelled at surface level. Generally, uppermost soil layers have limited impact on design (with respect to axial capacity), and it is generally sufficient to identify the relevant material type.
- *Middle soil layers* – Heavily disturbed and transported. Generally, removed by the auger cleaner upon extraction. Only broad interpretation of material types is possible, but it is possible to identify major differences from the expected conditions.
- *Lower flights* **–** Heavily disturbed with some transportation up the auger. Spoil may remain on auger flights below auger cleaner depending on its location. It is generally possible to identify the predominant material near the pile toe, which can often be more relevant to design assumptions.
- *Tip of Auger* **–** Heavily disturbed but limited transportation. Generally, spoil remains in place on tip of auger and may need to be exposed/investigated using a shover or pick (where safe to do so). It is generally possible to confirm the type of founding material at pile toe.

An associated element of geotechnical inspections during construction is the base formation process. As noted previously, there are a range of approaches that may be used, but it is essential that the base formation process is consistent across all piles.

2.4 Testing Considerations

The minimum testing requirements for CFA piles are based on AS2159-2009, with additional requirements being specified in statutory authority specifications where applicable. Load testing is typically carried out using the dynamic testing method, due to the relative cost and program penalties associated with static testing. Key considerations in relation to pile load testing are as follows:

- Load testing of piles is intended to demonstrate construction methodology, as well as load bearing performance. It is important that the load testing program is tailored to project requirements, with specific attention to the selection of representative pile types and founding conditions.
- Installation methodology for test piles must be representative of that used for production piles that they represent. Drilling termination criteria and base formation methodology should be consistent across tested and untested piles within each pile type.
- The frequency of testing must be consistent with design assumptions (with reference to the geotechnical reduction factor, ϕ_g, adopted from AS2159-2009) and the testing program must be designed to verify key design assumptions, such as achievable end-bearing in specific founding material.
- Untested piles must be correlated to test piles by an appropriately rigorous method, which should consider: a) site investigation information and the range of conditions that are present; b) installation parameters and drilling termination criteria; c) toe levels in conjunction with any expected or inferred variability in ground conditions between piles; and d) geotechnical observations, particularly material at the auger tip, where end bearing is significant.

Load testing at a frequency of around 3% to 5% of piles is common for building projects, with testing frequencies for infrastructure projects, where piles are more distributed and ground conditions may vary more due to the often-linear nature of the project sites, more variable and determined to suit the project requirements and constraints.

Dynamic load testing is a time consuming and relatively expensive element of the work, which requires access for large testing equipment and cranage. It is sometimes impractical to test a significant quantity of working piles on infrastructure projects and it is often necessary to rationalize testing requirements for practical reasons. In such circumstances, a program of dedicated test piles at accessible locations can provide a practical alternative to testing working piles. In the author's opinion, it is reasonable to seek dispensation from authority specifications to rationalize testing requirements where project constraints make testing genuinely impractical.

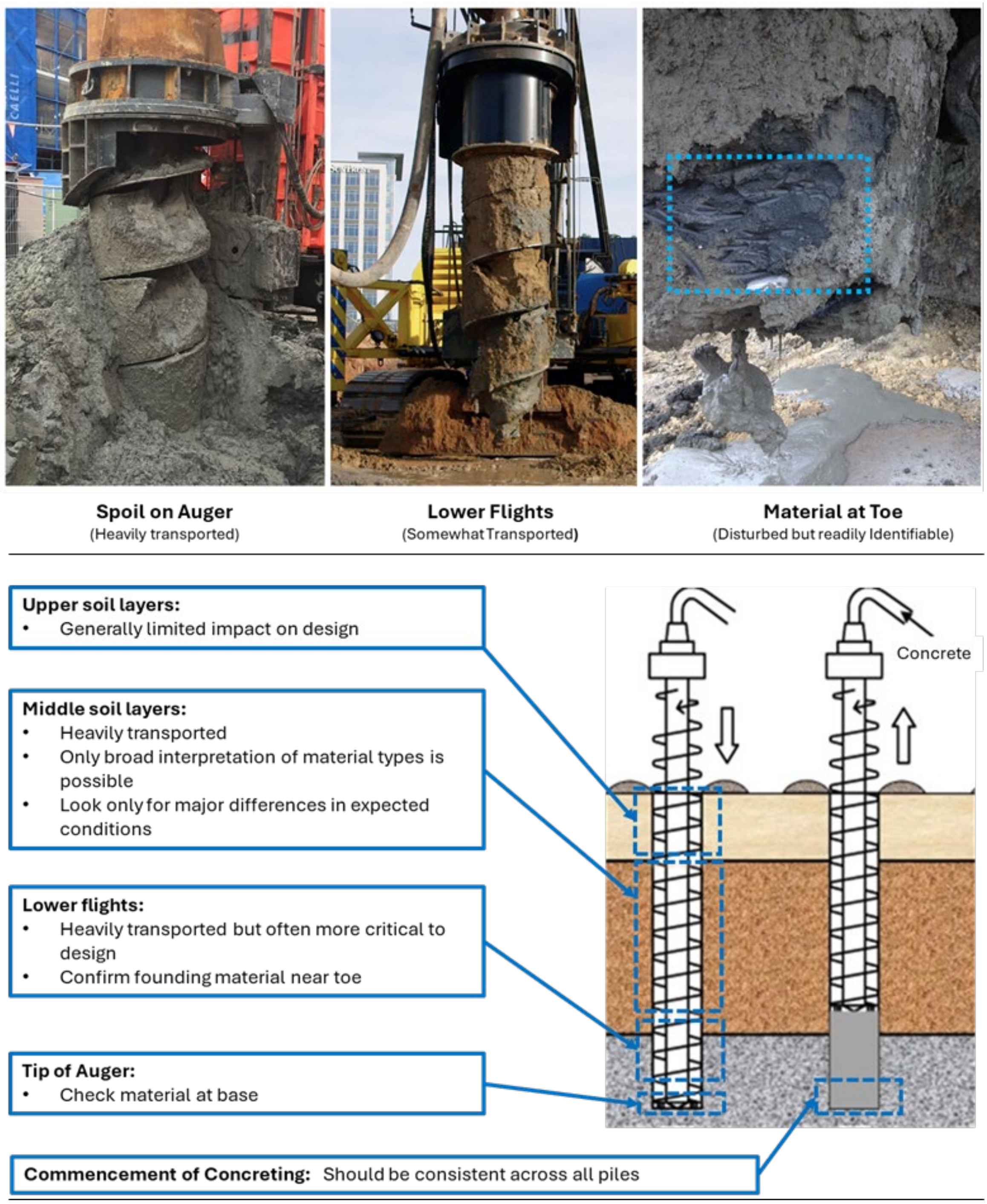

Figure 9. Examples of stages of drilling observations and zones of material as relevant to geotechnical inspections.

However, given the critical relationship between construction methodology and pile integrity and performance, some load testing is almost always necessary to confirm that the construction methodology is producing satisfactory outcomes, and the project requirements have been achieved.

Integrity testing is also a necessary requirement and should be aligned with the frequencies given in AS2159-2009. The predominant integrity testing method used for CFA piles is low strain sonic testing (PIT), which has limitations in its effectiveness. Cross-hole Sonic Logging (CSL) and Thermal Integrity Profiling (TIP) can be used in some circumstances, but the implementation of these methods for CFA piles is more difficult due to the need to fix CSL tubes or TIP wires to the reinforcing cage before it is inserted, which presents a risk of installation difficulties and damage. Dynamic load testing with PDA and CAPWAP analysis, when executed to a high standard, provides a high-quality form of integrity testing to complement other low strain methods.

Figure 10. Example of a large drop hammer used to dynamically test a built-up CFA pile.

3 COMMON ISSUES IN CFA PILING PRACTICE IN MELBOURNE

The geological conditions and project requirements in and around Melbourne present some particular issues and challenges for the design and construction of CFA piles. Some of the key issues most commonly encountered by the author are discussed in the following sections.

3.1 Design for Axial Capacity for Piles Founding in Melbourne Formation Siltstone

CFA piles carrying large loads are a common foundation solution for building projects around Melbourne's Southbank and Docklands. They are often founded Melbourne Formation siltstone, which can be encountered at depths of up to 40m to 50m around the Melbourne inner city area.

Piles founding within highly or less weathered siltstone can carry large compression loads and a significant socket length is often achievable with large state-of-the-art drilling equipment. The adopted geotechnical design strength of CFA piles will, in part, depend on the depth of penetration that can be achieved into the weathered rock. However, the stiffness of the base response that can be achieved is also a critical factor, particularly with respect to settlement at serviceability loads.

To ensure consistent founding conditions for highly loaded piles, rather than drilling to designated toe levels or penetrations, it is preferable to drill to a consistent termination criterion based on effective refusal. As noted previously, this must be defined appropriately for the drilling rig, pile size and drilling tools that are in use.

Adopting a design socket length and drilling to obtain this inferred socket length based on rates of penetration, torque, or some other measure can be problematic and is not always appropriate. It can be very difficult to assess the actual socket length from drilling data and, due to the variable nature of Melbourne Formation siltstone, it is unlikely that consistent base material will be present at pile toes, including the potential to terminate the pile in weathered dyke material. Increased depths of penetration may be warranted should variations in the weathering profile be present such that a significant thickness of more deeply weathered lower strength rock is encountered. Generally, it is not advisable to adopt a criterion based on achieving a small nominal socket length into siltstone due to the inconsistent and variably weathered characteristics of the top zone of this material.

A key element of pile design for highly loaded CFA piles in Melbourne Formation is the specialist subcontractor's prior experience in installing and testing piles to the required loads. While it is a conventional practice for the pile designer to assess a theoretical design resistance based on shaft and end bearing correlations, for high-capacity CFA piles, the details of the plant, equipment, construction methodology and the expertise of piling personnel are particularly critical to achieving consistent load-settlement performance.

Based on a range of projects in the Melbourne building sector within the past decade, executed with state-of-the-art piling plant and high-level expertise, CFA piles drilled to refusal in highly or less weathered siltstone (or basalt at similar depths) are often designed to loads limited by the design structural capacity of the unreinforced pile section below the reinforcing cage. They must then be installed and tested to demonstrate the required ultimate geotechnical resistance required by the design, which can present some challenges.

With large drop hammers (typically up to around 20t in ram weight and able to achieve energies of up to around 500kNm), demonstrated test loads in the 15MN to 20MN range are common. Significant variability has been observed in the resistance that can be mobilised, often as a result of inconsistent end-bearing response. This reinforces the critical importance of using a consistent pile termination criterion and sound base formation technique across both tested and untested piles.

While load and integrity testing requirements are governed by AS2159-2009, the frequency of testing should consider the design parameters adopted and the level of experience with equivalent piles in similar ground conditions.

Pile diameters have typically been limited to up to 900mm diameter due to piling rig limitations, but larger diameter (1,050 mm or 1,200 mm diameter) CFA piles have become more common in recent years with plant development.

3.2 Encountering Basalt Rock

The presence of newer and older volcanics basalt across parts of Melbourne can be problematic with respect to the construction of CFA piles. The presence of this material can often (although not always) cause drilling refusal and it is commonly found in flows which overlie soils, creating the potential for consolidation settlements over time if large loads are supported on piles founding in the basalt rock.

The thickness and quality of basalt is highly variable over short distances, particularly towards the edge of flows (Peck et al., 1992). This can be particularly problematic when heavily loaded structural elements are located near the edge or straddling the edge of the flow. Figure 11 shows an example of a high-rise building core located over the edge of a basalt flow. In addition to the technical challenge of estimating potential settlements for piles founding on the basalt, it is often difficult to accurately define the location of the edge of the flow and the locations at which the basalt can be penetrated by a CFA pile. Where the basalt rock mass is reasonably competent (predominantly highly or less weathered) it is likely to be difficult for CFA rigs to penetrate any significant depth into this unit. Even large CFA pile rigs may encounter practical refusal where relatively thin layers of more competent basalt are encountered, noting that the strength and thickness that can be penetrated will vary considerably with piling rig capability, overburden materials and drilling tools.

It is potentially problematic for heavily loaded structural elements, such as building cores or outrigger columns, to be founded on relatively thin basalt layers (due to the risk of consolidation settlement) or partially on and partially off a basalt flow. In some cases, it can be satisfactorily demonstrated that the load settlement response of piles founding on basalt will be satisfactory and, where relevant, compatible with piles founding deeper in siltstone; particularly if there is competent material or a limited thickness of soil between the basalt and siltstone rock. However, often, predrilling the basalt is necessary to ensure all piles are founded in siltstone.

Given the difficulty of accurately assessing which piles will refuse in basalt near the edge of a flow based on site investigation data, it is usually necessary to predetermine which piles will be predrilled based on a prudently conservative assessment.

Another challenging aspect of CFA piling where basalt is present is base formation to provide for high end-bearing resistance. Slightly weathered and/or high strength basalt can be difficult to penetrate without purpose designed drilling tools and a high-capacity drilling rig. The presence of high strength basalt therefore presents the opportunity to generate very large end bearing resistance, but this requires sufficient drilling penetration into the rock to achieve full effective base area. This can be particularly challenging if overburden soils are prone to 'flighting' when the drilling penetration rate slows when hard rock is encountered. A lack of penetration into an uneven or variably weathered rock surface can result in a partially effective base, sometimes only engaging a small proportion of the base area.

For these reasons, it is critical that the pile designer adopts an end bearing value that can be reliably achieved by the piling subcontractor with the plant and equipment that is proposed. This issue can be readily managed by the subcontractor in a design and construct contracting environment but can be more challenging where procurement is by construct-only contract.

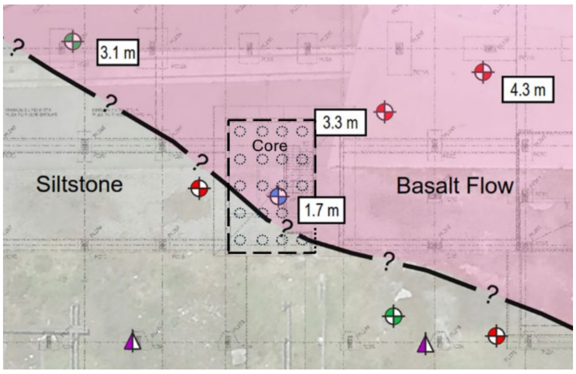

Figure 11. Building core straddling edge of basalt flow.

3.3 Ground Displacement in Soft Soils

CFA piles are a common foundation solution in Melbourne's Docklands and Southbank areas, which are characterised by a deep Yarra Delta soil profile. This soil profile has been described in many publications, including Peck et al. (1992), and is characterised by a layer of Coode Island Silt, typically a normally or lightly consolidated silty clay, which can be present to depths of up to around 25m.

CFA piles should not be considered to be non-displacement piles in low strength soils such as Coode Island Silt. However, the amount of ground displacement is governed by concrete oversupply volumes (i.e. the concrete volume placed in the pile above the theoretical pile volume). Oversupply volumes depend on a range of factors, but primarily ground stiffness, pile diameter, concreting pressure and extraction rate. Concrete oversupply on projects in sites with deep Coode Island Silt have been found to be typically in the range of 40% to 60%, on average for complete piles, but oversupply of up to around 100% has been observed in the Coode Island Silt layer itself. It has been found that initial oversupply volumes are often able to be reduced after experience at a site and with careful attention from piling subcontractor field personnel. However, it should be noted that reduced concreting pressures can significantly increase the risk of necking in piles and should not be pursued to the extent that structural integrity may be compromised.

Where warranted by the proximity to and sensitivity of adjacent assets, assessment of likely lateral ground movements and associated effects should be carried out at the preliminary design stage to inform foundation system selection and planning. Where warranted, detailed modelling of ground movements and associated effects should be carried out.

Fetherston et al. (2019) presented lateral ground movements due to CFA pile installation in Coode Island Silt, for both single piles and a large pile group, measured by inclinometers at various offset distances from the piles. Ground movements were found to vary with pile diameter, concrete oversupply and offset distance, with the characteristic displacement profile variable with depth and distance from the source pile. The sequence and program of installation was also noted as having an effect. The authors conducted finite element modelling in *PLAXIS 2D* to simulate pile installation and generated estimates of soil displacement with depth for a range of pile diameters and distances from the source pile.

It is the author's experience, based on a number of projects in Melbourne's Docklands, that ground displacements at particular locations and site features are significantly affected by a range of factors, including:

- Pile layout and the density of piles in nearby areas of the site.
- Ground surface geometry and the presence of any slopes.
- The presence of existing piles and the sequence of installation of new piles.
- The presence of retaining walls and the characteristics and stiffness of the walls.
- The proximity of piles and piling plant (which generate concurrent surcharge and concreting pressure) to sensitive site features, particularly retaining walls.

It is difficult to incorporate specific site details, such as the above, in ground movement estimates without a detailed modelling approach. To properly incorporate important site features, piling layout and existing structures, modelling has been undertaken using *PLAXIS 2D* and *PLAXIS 3D*. After establishing the geotechnical conditions and structural elements in the model, pile installation can be simulated by introducing volume elements corresponding to the desired concrete over-supply volumes. For volume displacement simulation, fine-grained soils have typically been modelled using undrained parameters and switched to drained (effective) parameters only to simulate long-term conditions, while coarse-grained soils have all been modelled using effective parameters.

A key element of this modelling has been estimating the lateral movement of retaining walls, often adjacent to the Yarra River. The properties of the retaining wall, particularly whether it is cantilevered or tied back or propped in any way, significantly impacts wall movements. This is particularly the case for simulation of piles installed in close proximity to the wall, and this effect has been observed in the field in both trial piling program and production piling works.

A detailed discussion of ground displacement modelling is beyond the scope of this paper; however, the approach summarised has been found to produce reasonable estimates of ground movements, although the *PLAXIS* outputs have been found to typically over-estimate movements. Actual movements have been found to be usually in the order 60% to 80% of modelled movements, depending on site characteristics and piling details. Factors such as sequencing and potential shadowing effects (as outlined below), partial drainage of fine-grained soils over the duration of a piling project and limitations associated with modelling the construction process are considered to be important.

Piles installed in close proximity to retaining walls can generate significant movements if the walls are not propped or tied back. Figure 12 illustrates the arrangement of a trial piling program where two CFA piles were installed at offsets of around 4.6m and 8.2m from an existing retaining wall adjacent to the Yarra River, with a modest retained height of around 4m. Pile installation generated lateral movements of around 30mm and 7mm respectively due to installation of these piles. In this case, the retaining wall was not tied back to a buried anchor or restrained in any way, other than the frame action of the wharf structure that it formed part of. While the wall was not fully cantilevered in this case, it had limited lateral stiffness.

Lateral displacements can be reduced by the use of tiebacks to buried anchors or raking piles to provide propping resistance. In the case of the former option, displacements can still be significant as it is difficult to resist high anchor loads in a shallow buried anchor in fill and/or Coode Island Silt. For both options, estimated lateral loads generated by pile installation in finite element models are large. A study of a tied back wall with load measurement would be of value to better understand how this type of arrangement can be most efficiently designed.

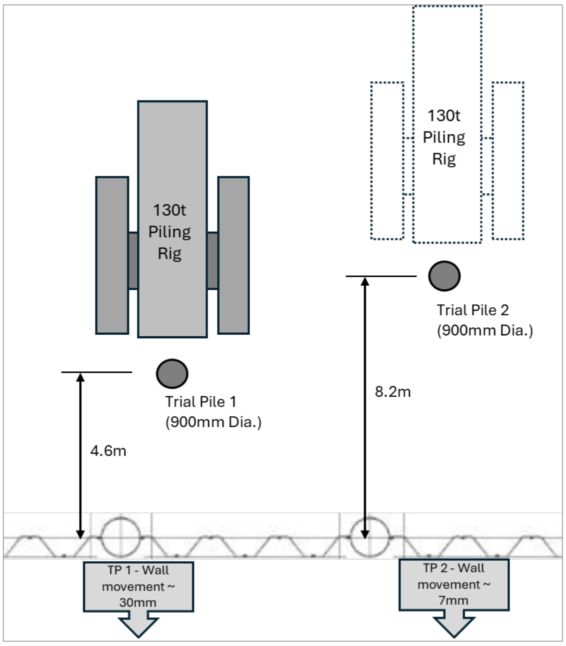

Figure 12. Arrangement of CFA trial piles installed through Coode Island Silt adjacent to retaining wall.

In the author's experience, the use of a cantilevered retaining wall that can displace freely is a viable alternative to a propped or anchored wall in some circumstances. Movements of up to around 350mm during piling works have been observed in sea-walls adjacent to the Yarra River, with little or no ongoing movement after the completion of piling. In these cases, ground movements have been caused by volume displacement from pile installation, and when the piling is completed, the movement ceases. The suitability of this approach requires that the geometry of the site and the nature of the displacements do not create a failure that becomes unstable and/or allows ongoing movements.

It has been found that the sequence of pile installation plays a critical role in project outcomes with respect to ground movements and their impacts. Important aspects of pile installation sequence include the following:

- Piles installed in areas of the site that are subject to subsequent lateral displacement are likely to be displaced from their original location. This effect tends to be more significant for slender piles (smaller pile sizes) than for larger pile sizes. Pile displacements of up to around 200mm have been observed on some projects, which can be problematic with respect to structural eccentricity and bending moments generated in the piles due to lateral movement. Generally, it is best to install piles in a direction of increasing anticipated overall ground movement, so that piles in areas of the site that are expected to move the most are installed towards the end of the piling program. While this approach tends to result in larger overall ground movements, the risk of structural damage to piles and/or redesign of the structure due to pile eccentricity is minimised.
- In contrast, a 'shielding' effect appears to occur where previously installed piles can reduce movements at sensitive locations as piles further away are installed. There is some evidence that this is particularly significant in cases when piles are installed in groups or clusters. Where the pile arrangement is not sensitive to eccentricity (e.g. large cores and pile groups) and/or overall movements are not expected to be excessive, local sequencing of pile installation can be planned to mitigate lateral movement effects by installing groups of piles in a sequence moving away from sensitive locations.
- The process of installing piles progressively reinforces and improves the ground generally and 'stiffens' the response of the site as the works proceed.

In planning a CFA piling project in soft soils, the sequencing of the piling works should be carefully considered, based on an understanding of objectives with respect to movement control at key receptors around the site, including newly installed piles. The following should be considered for projects at sites with deep Coode Island Silt or similar low strength cohesive material:

- Limits on displacement at critical locations should be established in the preliminary design phase and considered throughout the design and procurement process, to ensure that the adopted scheme is compatible with all project requirements and risk management considerations are understood by all parties.
- Foundation systems (incorporating piles, pile groups and overlying structural elements such as pile caps, slabs and ground beams) which provide greater robustness with respect to pile positional tolerances should be preferred, as this offers more flexibility in relation to installation sequencing. Piles and pile groups should be designed to accommodate positional tolerances with consideration of expected ground movements during the works. It is noted that piles installed first have the greatest potential for movement, and this progressively reduces for piles installed later in the works. Piles should also be designed structurally to accommodate expected lateral displacements and associated bending moments.
- New structures, such as wharves and retaining walls, should be designed to be compatible with potential lateral movements from subsequent piling work and expected temporary and permanent surcharge loads.
- Where sensitive structures are present or where it is necessary to monitor and control lateral movements, inclinometers should be installed at critical locations prior to the commencement of piling works. Movements at critical locations should be closely monitored during the works. Where warranted, a detailed monitoring and reporting regime should be implemented. The extent and frequency of the monitoring should be tailored to the specific project considerations and requirements in response to the sensitivity of adjacent structures and project stakeholders.
- The sequencing of the works should be planned with due consideration to likely ground displacements. During the works, sequencing should be reviewed regularly on the basis of the monitoring results and adjusted where necessary to manage the risk of exceeding displacement limits.

Wherever possible, commercial and practical arrangements should recognise the need for all relevant parties to jointly manage risks with respect to lateral ground movements. Sequencing of the works and optimisation of concrete oversupply plays an important role in achieving the desired outcomes.

3.4 Testing to Large Loads

For economic and practical reasons, CFA piles in Melbourne are generally dynamically load tested. For piles tested dynamically using pile driving analyser (PDA) and associated CAPWAP analyses, the acceptance criteria set out in Table 8.5.2 of AS 2159-2009 should be adopted unless other project specific criteria are provided.

The process of dynamic testing requires a large drop hammer and usually involves the use of a number of blows with progressively increasing drop heights. This approach enables the response and condition of the pile to be assessed for each blow as the energy is increased, to mitigate the risk of causing structural damage in the process of testing. Each hammer blow generates both temporary and permanent components of displacement.

It is important that the permanent deflection (set) generated by each blow delivered to the pile during the test is accurately recorded, as each blow contributes to the overall displacement of the pile. Test blows should be apportioned so that the serviceability test load (working load) is mobilised early in the testing sequence wherever possible. Later blows with increased energy can then be used to check acceptance criteria for the ultimate pile geotechnical resistance.

To rigorously assess the load bearing response of the pile, it is necessary to combine the load-displacement data from each blow to evaluate a consolidated load-settlement response. An example of this approach is shown in Figure 13. In most circumstances, this level of analysis is not warranted, but it may be necessary where settlements at serviceability load are critical or where test pile performance requires a detailed assessment.

In the example shown in Figure 13 the pile response is relatively consistent across the three test blows. A composite load-settlement response is relevant where large sets and modest resistances are measured for initial blows, before further resistance is mobilised on later blows. This can be an indication that the end-bearing response is initially less stiff and then improves as overall displacement increases, which may indicate improvements can be made to base formation methodology.

For testing of CFA piles to be considered representative of all piles installed on a site, the method of pile installation must be consistent across all piles, especially with respect to achieving refusal in rock and effective base formation.

Where CFA piles are installed in closely spaced groups or clusters, it is only practical to undertake testing of an individual pile. If a pile is part of a cluster, the assessment of the results of pile testing must take into account group effects and the settlement and ultimate resistance of the cluster must be assessed. The method of applying the results of testing of an individual pile in verifying the adequacy of a cluster of piles should be considered in the testing and verification methodology.

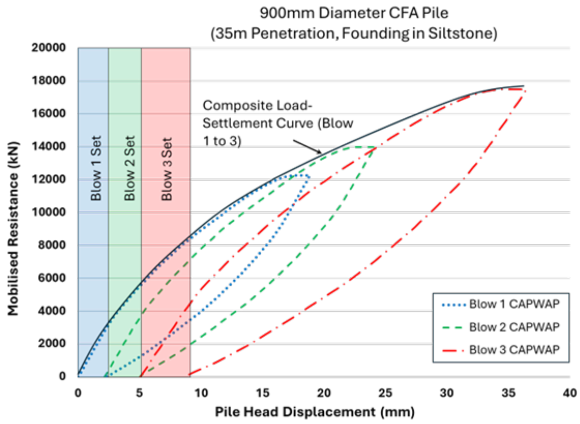

Figure 13. Example of composite load-settlement plot for CFA pile dynamically tested.

4 CONCLUSION

CFA piles have become a widely used and effective foundation solution at sites where potentially unstable soil conditions exist. They offer some significant advantages over bored piles in certain circumstances, with respect to construction risk, productivity and cost. The Australian piling market is relatively advanced in relation to expertise and capability in CFA pile design and installation. However, most of this expertise is held by specialist piling contractors, and the extent of practical knowledge across the broader industry is limited.

The geology of Melbourne offers good opportunities for beneficial implementation of CFA piles, but also presents some challenges. The significant depths to which piles often need to be installed, the high loads that they are now designed and installed to carry, and the prevalence of deep quaternary sediments typical of the Yarra Delta require particular expertise and attention to achieve good project outcomes on a reliable basis.

Some of the more common issues that arise in Melbourne have been discussed in this paper, representing the consolidated experience of the author over many projects in the past two decades.

With the increasing popularity of CFA piles on infrastructure projects, there is a need for greater collaboration and alignment between specialist piling contractors, design consultants and other project participants. It is the author’s hope that providing a consolidated summary of matters of importance in this paper will assist industry in understanding and appreciating critical aspects of CFA pile design and construction, important aspects of verification process, and common challenges at a project level.

In the author’s opinion, further development of industry standards and authority specifications is warranted to provide a more consistent, complete practical and effective industry operating environment which, if done well, can benefit all parties.

5 ACKNOWLEDGEMENTS

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REFERENCES

Brown, D, Dapp, S, Thompson, R, and Lazarte, C, (2007). *Geotechnical Engineering Circular (GEC) No. 8. Design and Construction of Continuous Flight Auger (CFA) Piles (Final)*, Report No. FHWA-HIF-07-03. Federal Highway Administration, U.S. Department of Transportation, Washington D.C. 293 pp.

Department for Infrastructure and Transportation, South Australia (2019). *Master Specification - ST-PI-C3 Continuous Flight Auger (CFA) Piles.* K Net Number: 13523415, Version: 2, 19/09/2019.

Department of Transport, Victoria (2015). *Vicroads Standard Specification - Section 607 - Continuous Flight Auger Piles*. March 2015.

Fetherston, J, Flynn, R & Chong, W (2019). *Lateral soil displacement resulting from the installation of CFA piles in soft marine clays.* 13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.) Australian Geomechanics Society, Sydney, Australia, 427-432. ISBN 978-0-9946261-0-3.

Main Roads, Western Australia (2020). *Specification 814 - Continuous Flight Auger Piles*. 11/349 Issued 22/10/2020.

Peck, W, Neilson, J, Olds, R, Seddon, K [ed.] (1992). *Engineering Geology of Melbourne*. CRC Press. London. 426 pp. ISBN 9780203757413.

Standards Australia (2009). *AS2159-2009 Piling - Design and installation*. Sydney, NSW, Australia. ISBN 0-7337-9286.

Standards Australia (2017). *AS 5100.3-2017 - Bridge design, Part 3: Foundation and soil-supporting structures*. Sydney, NSW, Australia. ISBN 978-1-76035-716-0.

Transport for NSW (2020). *TS 01732.1- QA Specification B63 - Continuous Flight Auger (CFA) Piles*. Edition 2, Revision 2, 22 June 2020.

Van Weele, A.F. (1988) *Cast-in-situ piles – Installation methods, soil disturbance and resulting pile behaviour.* Deep Foundations on Bored and Auger Piles, Balkema, Rotterdam, 219-228.