RECENT DEVELOPMENTS IN CONTINUOUS FLIGHT AUGER (CFA) AND CAST-*IN-SITU* DISPLACEMENT SCREW PILING IN MELBOURNE

J Slatter
Managing Director, Vibro-pile (Aust.)

ABSTRACT

This paper addresses the significant advances which have been made in the fields of CFA and cast-*in-situ* displacement screw piling over the past ten years. Whilst the majority of these advancements are ubiquitous, this paper deals with the effect of such advances with respect to their application in the Melbourne metropolitan area.

1 BACKGROUND

CFA piles are a non-displacement form of cast-*in-situ* piling. The theoretical aim of such a system is for the volume of material to be excavated during construction to be equal to the volume of the auger inserted into the ground, thus resulting in no net change to the surrounding soil during pile installation. Displacement screw piles on the other hand, seek to laterally displace the soil during installation and hence produce little or no spoil and improve the condition of the soil around the pile shaft (see Figure 1).

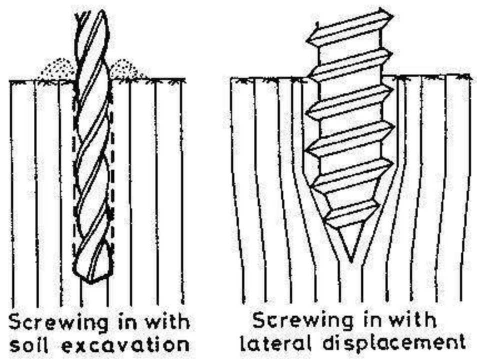

Figure 1: Wood drill vs wood Screw analogy for displacement versus non-displacement augers (after Van Impe, 1988).

CFA piles are formed by drilling a continuously flighted auger with a hollow central stem into the ground (see Figure 2). Once the target depth is reached, rotation of the auger is ceased and concrete or grout is injected under pressure through the hollow stem of the auger. The auger is then extracted at a steady rate and positive injection pressure is maintained at all times to ensure shaft integrity. Once concreting is complete, the top of the pile is cleaned of any debris/spoil and a reinforcing cage is lowered into the fluid concrete or grout.

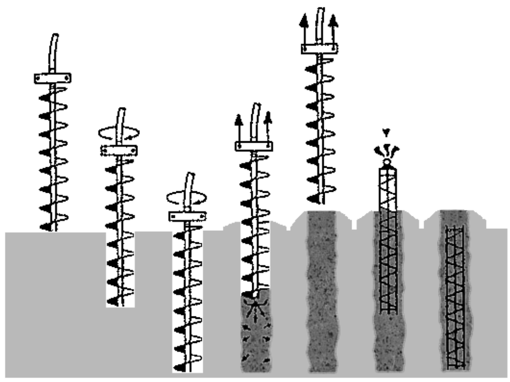

Figure 2: CFA pile installation processes (after Peiffer *et al.*, 1993)

In contrast to the CFA process, which is effectively uniform worldwide there iis a wide variety of proprietary cast-*in-situ* displacement screw piling systems. Whilst each of these systems has an auger head with a different configuration, the general principles are relatively constant. Displacement augers are generally only flighted over a discrete length and they have a central stem which expands in diameter up to the point where it equals, or approaches, the diameter of the pile shaft. The installation processes of most displacement screw piles are also generally similar, with the majority being installed in much the same way as CFA piles but with forward rotation being maintained during extraction (see Figure 3).

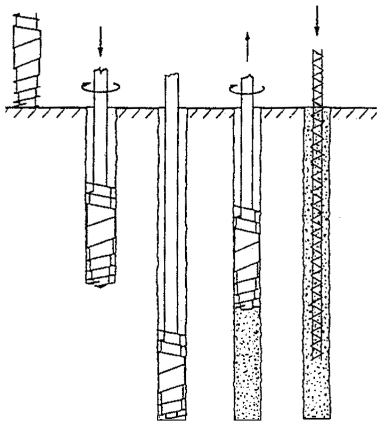

Figure 3: Cast-*in-situ* displacement screw pile installation procedure (after Van Impe, 1994).

2 CFA PILES

Possibly the most significant development in CFA piling has been the improvement in the performance specifications of the drilling rigs which are used to install such piles. In the late 80's and early 90's, typical CFA rigs would have weighed somewhere in the vicinity of 30 t to 40 t, had a mast 10 m to 15 m tall and had a rotary torque capacity of 10 tm to 15 tm. In today's piling market there is a far wider variety of CFA drilling rigs, which vary from the relatively modest 10 tm to 15 tm rigs up to large, high torque drilling rigs weighing almost 80 t and with a rotary torque capacity in the order of 35 tm. Essentially, modern high torque drilling rigs are able to install CFA piles with larger diameters, to greater depths and at faster production rates than has previously been possible.

The increased depth and diameter capability of the CFA system has opened up a number of geographical areas in the Melbourne metropolitan area in which it was previously uneconomical to construct CFA piles (much of South Melbourne and Docklands for example). Over the last 5 years, several thousand CFA piles have been constructed in Melbourne's Docklands Precinct to depths approaching 50 m. Higher torque rigs are also able to socket piles into the underlying rock which, along with increased pile length, has resulted in a significant increase in the ultimate geotechnical strength of such piles.

Clearly the ultimate geotechnical strength of any pile must be assessed on a case by case basis. However for CFA piles constructed with a high torque drilling rig and drilled to "effective refusal" in the underlying Silurian aged Melbourne Mudstones (MMS) or Older Volcanics (OV) formation, it is not uncommon for such piles to work to the safe structural capacity of the pile shaft. However, due to the construction methodology of CFA piles which requires the reinforcing cage to be installed after concreting/grouting, deep CFA piles cannot be reinforced over the full length of the pile shaft in the traditional sense. Reinforcing of a deep CFA pile generally consists of a traditional circular reinforcing cage over the top 12 m or so of the shaft. In addition, central reinforcing bars may be installed over the full length of the pile to carry tension loads as required. The unreinforced portion of the pile shaft (or portion containing only central bars), must be designed as a partially reinforced pile in accordance with AS2159 and stresses are limited to 0.3 x f'c. Hence for a 750 mm diameter CFA pile constructed using 50 MPa concrete, this would equate to a maximum SWL of approximately 4,900 kN (see Table 1).

Table 1: Approx. safe structural strength of partially reinforced piles using 50MPa concrete (ref. Clause 5.3.5 AS2159-1995).

Dia (m)	f'c (MPa)	SWL (kN)
0.9	50	~ 7000
0.75	50	~ 4900
0.6	50	~ 3100
0.5	50	~ 2180
0.4	50	~ 1300

Figure 4 shows comparative load test results of two CFA piles which were tested both dynamically and using a Statnamic™ device at the Eureka Tower site in Melbourne. The tests were carried out on two 750 mm CFA piles founded in high strength basalt (Older Volcanics formation) at a depth of approximately 25 m. In both cases piles were tested using the Statnamic™ device first, followed by dynamic testing. Pile number 6 remained in service and was therefore not tested to a level where there was a significant risk of damage to the shaft. Pile number 5, however, was not a production pile and was tested with an increased energy level. The maximum mobilised end bearing stress during testing of Pile number 5 was approximately 36 MPa.

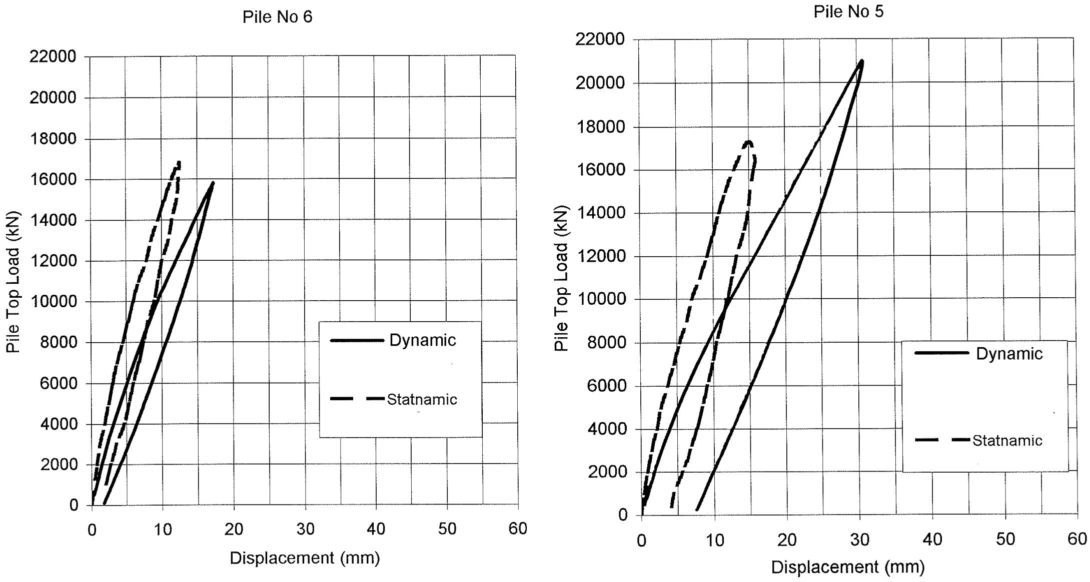

Figure 4: Dynamic and Statnamic™ tests of 750 mm diameter CFA piles at Eureka Tower site.

The detailed discussion of these test results is outside the scope of this paper, however it is interesting to note that neither pile could be described as reaching failure despite over 20 MN capacity being predicted by the CAPWAP analysis carried out on Pile 5. The difference in the predicted load settlement behaviour using the Statnamic™ device and dynamic testing with CAPWAP analysis is also interesting, with the Statnamic™ method predicting a significantly stiffer pile response (possibly due to the treatment of dynamic effects by the two theoretical models or the cyclic loading during testing). The tests presented from the Eureka project, which are also supported by a large number of dynamic tests conducted on in-service piles during the course of the contract, indicated that the pile shafts were stressed to in excess of 45 MPa with no distress to the integrity of the piles.

The load settlement performance of longer CFA piles constructed in the weaker Melbourne Mudstone (MMS) is, not surprisingly, generally “softer” than the performance exhibited at the Eureka Tower site. Table 2 presents the results of dynamic load testing of nine, 600 mm diameter CFA piles founded in relatively poor quality MMS at depths of 40 m to 45 m at a site in Docklands.

Table 2: Summary of dynamic load test results of 600mm diameter CFA piles in Docklands,

Pile No	Pile Length (m)	TC (mm)	Set (mm)	Blow Energy (kJ)	CAPWAP total (kN)
TP21	42.6	21.1	3	237	12,000
TP35A	39.1	20.9	2.7	204	11,800
216	43.3	20.4	2.6	208	12,200
601B	39.5	22.6	3.1	240	12,800
118	40	18.1	0.5	240	11,500
120	41.8	22.2	1.7	225	10,200
123	40.2	20.2	0.5	210	10,900
TP27A	44.7	23	1.5	220	13,800
TP34B	42	18.4	2.6	217	11,500

The maximum mobilised end bearing stress during testing was 25 MPa, with no geotechnical failures being inferred or approached. Predicted settlements for single piles under working loads were generally in the order of 16 mm to 25 mm, and to up to 35 mm when group effects were considered. Subsequent monitoring of pile groups under serviceability load indicated group settlements to be less than 20 mm across the structure, however this could be expected to increase as the long term effects of down drag in the Coode Island Silt become more apparent.

3 DISPLACEMENT SCREW PILES

In a similar fashion to CFA piles, the improvement in drilling rig capacity has led to an increase in the depth and capacity to which displacement screw piles can be installed. The major disadvantage with displacement screw piles is the high torque levels required to install them and this has to date limited the maximum diameter of such piles. To the author's knowledge, the maximum diameter of displacement screw piles is currently in the vicinity of 650 mm, however by far the most common size for such piles is 400 mm diameter. As with CFA piles, because of the need to install reinforcement after concreting of the pile shaft, deep screw piles cannot be fully reinforced. Accordingly, the maximum SWL of a 400 mm diameter deep screw pile is generally limited by the safe structural capacity of the shaft which would be approximately 1,400 kN using 50 MPa concrete.

Figure 5 shows the predicted load settlement performance (generated by CAPWAP) of a number of 400 mm diameter displacement screw piles installed to depths of 34 m to 37 m in Port Melbourne. Piles were founded in the Moray Street Gravel formation and ultimate end bearing values of 14 MPa to 15 MPa were mobilised during dynamic testing, again without realising geotechnical failure.

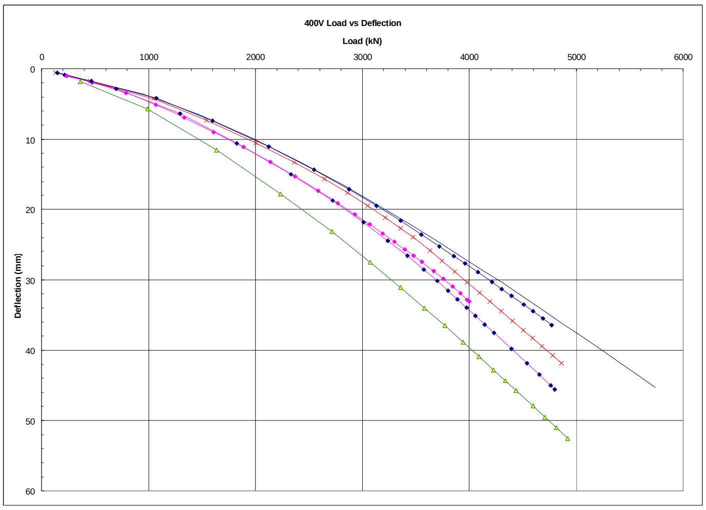

Figure 5: Dynamic load tests results of displacement screw piles founded in Moray Street Gravels.

As with CFA piles, displacement screw piles can be founded in rock, however the configuration of the augers generally precludes sockets of more than 500 mm length being formed in such materials.

4 COMPUTER INSTRUMENTATION

In addition to significant advances in construction plant, computer monitoring equipment has also undergone substantial development over the past 10 years. There are many different proprietary systems available, however most good quality computer monitor systems measure and record relevant construction parameters such as penetration rate, rotational speed, depth, extraction rate and concrete pressure.

The latest generation of computer instrumentation systems, are more sophisticated and display all of the above information in real time into the cabin of the drilling rig in order to assist the operator through the construction process. Additional information such as drilling energy, concrete flow rate, inferred shaft profile and overall drilling and concreting times are also available on the more advanced systems (see Figure 6). All of this data is presented in graphical format, generally on an LCD screen during pile construction. Limits can also be set on many of the construction parameters, for example concrete pressure, and both audible and visual alarms (via pop-up windows) are triggered if pre-set limits are exceeded. Such systems therefore allow non-conformances to be rectified immediately, generally by re-drilling a portion, or sometimes all, of the pile shaft and re-concreting. The latest generation of computer instrumentation systems also have GSM capability which allows engineers or supervisors to dial up the drilling rig at any time and view the construction records from the office. Construction records can also be downloaded directly from the rig, back to a remote computer at any time. To the author's knowledge at least one of the latest generation systems also has the ability to remotely control several aspects of the construction process (such as extraction rate). Whilst on face value this would appear to offer several advantages over human operators, the highly variable nature of in-ground works have to date precluded this facility from being utilised in Australia.

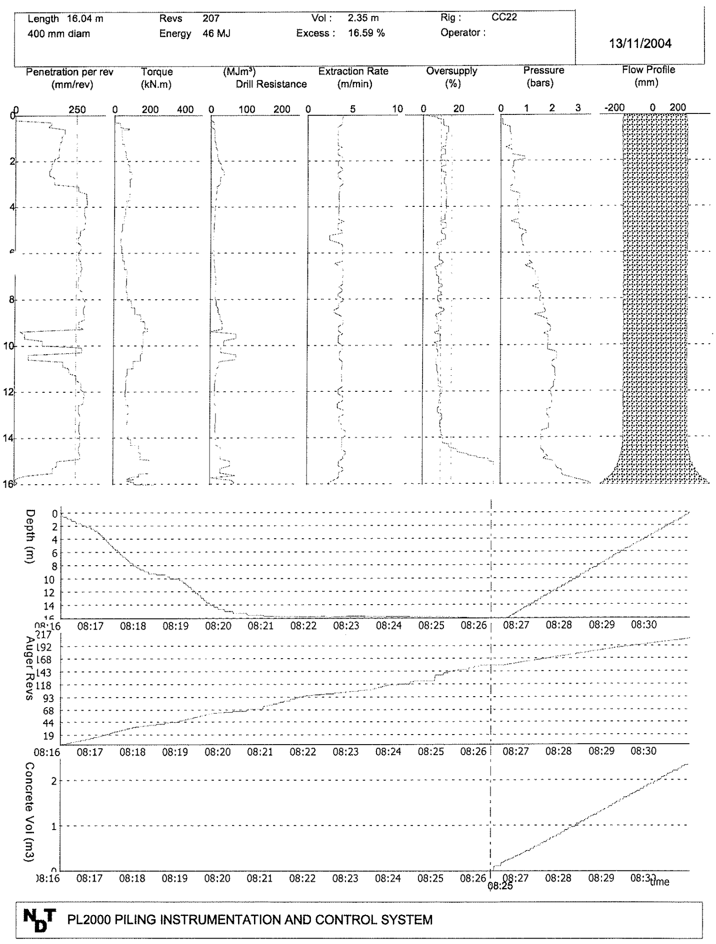

Figure 6: Graphical output from latest generation computer instrumentation.

Note: Figure 6 is a construction record for a displacement screw pile and hence has forward rotation during both installation and extraction. Rotation of the auger was steady throughout the process as evidenced by the relatively consistent gradient of the line on the rotation vs time graph. Rotation in itself is not considered to be a key aspect of pile construction, however when combined with penetration rate it can be a useful diagnostic tool from time to time.

In the author's opinion computer instrumentation for CFA and displacement screw piles is an essential quality assurance tool. However it does have a number of limitations of which potential users should be aware. Firstly, and most importantly, due to current technical difficulties with mounting pressure sensors on auger strings, concrete pressure sensors must be mounted directly above the auger string on the drive head of the drilling rig (on what is generally referred to as the goose neck). However, with highly workable concrete and grout mixes this is almost certainly a conservative measure of concrete pressure at the tip of the auger as it does not account for the hydrostatic pressure of concrete or grout in the auger stem.

Most computer instrumentation systems calculate concrete volumes delivered into the pile by counting individual pump strokes and multiplying this by a known volume per stroke and a pump efficiency factor (generally in the order of 90%). This system is relatively simple and generally effective. However, poorly maintained pumps become inefficient and this can lead to volume errors. Similarly, poor (stiff) concrete mixes with low workability can also have a negative effect on pump efficiencies and concrete volume. This can however be managed relatively simply with regular maintenance of the equipment and by periodically checking the theoretical injected volume against the physical volume delivered to site.

Figure 7: Concrete pressure sensor location.

As with any form of integrity testing/verification system, which computer instrumentation essentially is, the output does require some degree of expertise and experience to interpret. The following are some of the key aspects which one should consider when reviewing computer instrumentation records:

Identification of founding strata - During installation penetration rate, torque and drilling energy (which is a function of the first two parameters) often enable target foundation layers to be identified. Whilst this is not always the case, generally a significantly harder, or denser layer will result in an increased drilling resistance (increased torque and possible reduced penetration rate). An example of this can be seen at approximately 15 m depth in Figure 6.

Side Loading - Prolonged periods of slow penetration during installation of CFA should be reviewed when combined with consistently high rotational speeds as this can lead to "side loading" or collapse of material onto the auger and loosening of the surrounding soil. This is generally only a concern in susceptible (non-cohesive) soils as cohesive materials will remain stable and not collapse onto the auger. As can be seen from the depth vs time graph in Figure 6, the slow penetration rate between ~ 9.5 m depth and 10.5 m depth would not be of particular concern as this occurred over a time period of less than one minute. Furthermore, the overall time to drill the 16 m pile was also only 5 minutes which is more than acceptable.

Extraction rate - Extraction rate, particularly when combined with injection pressure is an important aspect of the construction record. Attention should be paid to the extraction rate during concreting of cast-*in-situ* piles with particular attention paid to significant increases. Large and/or sudden increases in extraction rate combined with a commensurate loss of concrete pressure is an indication that a structural defect may have occurred at this level. Once a potential problem is identified, a degree of engineering judgement is required to determine the likelihood of a serious defect. If the event occurs in a zone where soils are likely to collapse into the shaft, a reduction in section or "necking" is likely. However, should the event occur in a self supporting material such as a stiff clay, necking is relatively unlikely. It is also extremely important to consider both pressure and extraction rate whenever assessing a potential defect. Rig operators must increase the extraction rate of the auger if concrete/grout injection pressures are getting unacceptably high. A relatively rapid increase in extraction rate is not a cause for concern if positive pressure is maintained throughout.

Injection Pressure – Concrete or grout injection pressure is generally considered to be the most important parameter in the formation of a structurally sound pile shaft. It is fair to say that any point along the pile shaft where zero or negative injection pressure has occurred warrants further investigation. In non-cohesive soils, a significant loss of concrete pressure, or negative pressure, particularly when combined with a rapid increase in the extraction rate, is likely to result in a shaft defect. There are however a number of circumstances where very low concrete pressure is unavoidable. The most common case occurs when injecting concrete/grout in very soft soils. In this situation it is often impossible to generate significant positive pressure. In such cases it is not unreasonable to base the concreting process on concrete flow rate or volume (generally referred to as oversupply). Generally the oversupply rate would be set at approximately 15% – 20% above the theoretical volume of the pile shaft and the auger extracted at a constant rate.

Concrete volume (oversupply) - Computers which calculate a theoretical shaft profile rely heavily on the volume of concrete delivered (or oversupply). When the computer shows a concrete shaft with a significant reduction in section there is a tendency to conclude immediately that there must be a defect. Whilst this may very well be the case, there are exceptions to the rule and further investigation of other relevant parameters is necessary before a conclusion is reached. For example, as the tip of the auger moves through material of variable consistency (e.g. from soft to stiff) the concrete oversupply rate may change from 130% or more, to as little as 105% - this will appear on the computer output as a reduction in section. What appears on first inspection to be a "neck" in the pile is simply a change from an enlarged pile section back to a nominal section. Another less common source of error is the failure of the concrete stroke counter to register a stroke. In this case the computer incorrectly registers a very low, or zero concrete flow rate. This generally occurs at high injection pressures where the ambient pressure in the line stays at such a high level that the stroke counter cannot detect the pulse associated with each individual stroke. In such cases the pile may appear to have a severe reduction in section, however the fact that injection pressures are high indicates that this is not likely to be a defect.

5 CONCLUSION

Recent advances in both the construction plant and computer monitoring equipment used to construct CFA and displacement screw piles has lead to a significant increase in the application of these systems. Such piles have now been installed to depths approaching 50 m through Melbourne's Yarra Delta formation and are now considered to be a viable foundation system in areas previously only considered suitable for bored piles and preformed driven systems. The latest generation in computer monitoring systems, when correctly used, allows such piles to be constructed with a high degree of confidence in the structural integrity of the shaft.

6 REFERENCES

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