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Continous Flight Auger (CFA) Piles – A Review of the Execution Process and Integrity Evaluation by Low Strain Test

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Abstract. Although the Continuous Flight Auger (CFA) pile installation process is monitored by an electronic system, it is known that its structural integrity is still affected by different sources of uncertainties and errors, for example inadequate maintenance and calibration of the monitoring sensors, equipment operation and installation in difficult soils. On the other hand, low strain tests (LST) have been used as a good alternative to evaluate the integrity and length of piles, but due to some limitations its efficiency has become a controversial issue in the geotechnical community. The aim of this paper is to discuss the CFA piles integrity assessment by LST, showing real signals (force-velocity) that reflect typical impedance changes and accounting for the peculiarity of its executive process and associated damages. A brief review on integrity analysis of piles is presented as well.

Keywords. augered cast-in-place piles, continuous flight auger piles, low strain test, pile integrity

1. Introduction

The Pile Integrity Test (PIT) is a non-destructive test also known as Low Strain Test (LST) that has proved to be a good alternative to evaluate integrity and length of piles [1]. PIT has become popular worldwide in the past two decades. Despite the increasing demand, its efficiency has become a controversial issue in the geotechnical community, due to methodology limitations and its applicability to different types of piles. In some cases, the collected force and velocity data has an unusual shape, making it hard or even impossible to be interpreted with adequate reliability. The present paper discusses the application of the PIT test to Continuous Flight Auger (CFA) piles, analyzing the effects of the pile construction process on its integrity and quality of data interpretation.

2. Time Domain Analysis

It is important to state at the outset that for a consistent test interpretation achievement, the pile logs, soil borehole logs and all other available specifications of the pile foundation have to be clearly understanded [2, 3]. Pile installation logs can provide valuable information about the pile condition, such as the volume and injection

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pressure of the concrete and the withdraw auger speed (among other data). Soil borehole logs are important to help the engineer identify the soil resistance influence. The soil effect acts generally in a gradual manner on the signal (low frequency) but can also act locally, as for example on a weak layer overlaying a hard soil layer (resulting in a signal similar to local impedance increase). Pile foundation design and related specifications are essential, since they provide pile characteristics.

2.1. Shaft Integrity Evaluation

The integrity evaluation of piles in the time domain is simply the analysis of the effect of impedance changes on the velocity signal. The impedance of a pile (Z) is related to its cross section (A), and to the elastic modulus (E) and specific weight (ρ) of the concrete according to equation 1. Even considering that (Z) is more sensitive to variations of (A), it is still not possible to attribute an impedance change to only one factor, which is a limitation of the method.

$$Z = A\sqrt{E\rho} \qquad (1)$$

Potential damages locations are evaluated by searching for impedance reductions (pulses in the same direction as the initial velocity peak) along an interval between the initial pulse and the estimated wave time return or the toe reflection. On the other hand, pulses in the opposite direction mean increase in impedance. An impedance cycle (increase–decrease or decrease–increase) needs a relative magnitude analysis, as in the case shown in figure 4a. Gradual velocity changes usually reflect the soil resistance.

Impedance changes are evaluated through a baseline, considering the soil resistance effect. The magnitude of the damage can only be estimated for piles with clear toe reflection. In this case, the toe reflection has to be adjusted so that it has the same amplitude as the initial pulse, so the Beta method can be applied. Briefly, β is the rate of impedance change from Z_2 to Z_1 [4]:

$$\beta = \frac{Z_2}{Z_1} = \left(\frac{1 - \alpha}{1 + \alpha}\right) \qquad (2)$$

where: α is the damage amplitude divided by twice the amplitude of the initial pulse. Beta analysis only allows a crude estimate of the magnitude of the damage due to the simplifications made, as neglecting the soil resistance in equation 2. When better accuracy is needed, damages should be evaluated through High Strain Test.

Impedance change evaluations near the pile top may be difficult, due to the superposition with the initial velocity peak. The use of an instrumented hammer (force measurement at pile top) can be helpful in that case. Integrity assessment is achieved by comparing force and initial velocity peak magnitudes and width. If the force is larger and/or wider, the pile top may have an impedance increase; when smaller or narrower, an impedance reduction may be present.

2.2. Pile Length Evaluation

When the downward compressive wave arrives at the pile toe, the impedance is null (Z_2=0) and the wave is reflected integrally in tension (same direction as the initial pulse). In usual practice, where test is performed with only one accelerometer, the concrete wave speed (c) is unknown and the pile length (L) can only be estimated within a range. The data processing software plots the velocity x time signal with a length scale based on an assumed wave speed value. When the wave speed is varied, the length scale runs along the time axis until the pile toe indication matches the observed pile toe reflection. A concrete wave speed of 4,000 m/s with a ±10% variation is assumed and the pile length has to be evaluated within this range or otherwise, the pile length is questionable [5]. Toe reflections observed for wave speeds lower than 3,600 m/s are indicative of longer piles or poor concrete quality, while reflections obtained for wave speeds greater than 4,400 m/s may indicate shorter or damaged piles.

2.3. Final Pile Evaluation

Rausche and Goble [4] recommended the values given on table 1 to correlate the severity of the damage with the calculated *Beta* value, for piles with clear toe reflections and no major signal anomalies (i.e., only one major impedance change).

Table 1. Classification of pile structural integrity on computed Beta factors [4].

Beta (β)	**Pile condition**
1,0	Uniform pile
0,8 - 1,0	Slight damage
0,6 - 0,8	Damage
< 0,6	Broken

When data quality is not good enough, the records are partially or even not interpreted (inconclusive signals), so the application of table 1 may become difficult or not representative. Webster et al. [6] proposed a general classification for the evaluation of piles based on the obtained data quality (table 2).

Table 2. Recommended Low Strain Test record classification for concrete piles [6].

Class	**Class name**	**Commentary**
AA	Sound shaft integrity indicated	A clear toe reflection can be identified corresponding to the reported length and a wave speed within acceptable range; records in this category may indicate normally accepted variations of size or material quality.
AB	No major defect indicated	The records indicate neither reflections from significant reductions of pile size or material quality nor a clear toe response. Records in this category do not give indications of a significant deficiency; however, neither do they yield positive evidence of the shaft being flawless over its full length.
ABx	No major defect indicated to a depth of x (m)	Because of method limitations, interpretation of the record for the full length is not possible. Examples are long piles/shafts and those with high soil resistance and/or major bulges.
PFx	Indication of a probable flaw at an approx. depth of x (m)	A toe reflection is apparent in addition to at least one reflection corresponding to an unplanned reduction of size or material quality. Additional quantitative analysis may help identify the severity of the apparent flaw.
PDx	Indication of a probable defect at an approx. depth of x (m)	The records show a strong reflection corresponding to a major reduction of size or material quality occurring; a clear toe reflection is not apparent.

IVx	Inconclusive record below depth of x (m) due to spurious vibrations	Data is inconclusive due to vibrations generated by construction machinery or heavy reinforcement extending above the pile top concrete; retesting is advisable under certain circumstances.
IR	Inconclusive record	- Poor pile/shaft top quality/low concrete strength (pile tested too early); retesting after waiting / pile top cleaning is advisable.
		- Planned impedance changes or joints generate signals, which prevent toe signal identification.

3. CFA Piles – Topics on the Execution Process

Relative time-cost efficiency and execution flexibility have made Continuous Flight Auger (CFA) piles widely used nowadays. Furthermore, its installation process is usually monitored by an electronic system, which is an advantage due to the additional control that it allows of its integrity. However, different sources of uncertainties and errors, mainly due to inadequate maintenance and calibration of the monitoring sensors, equipment operation or installation in difficult soils can affect the structural integrity of the piles. CFA piles execution process has already been extensively discussed in the literature. Here, we focus on the withdraw auger/placement of concrete phase, as it is the most influential factor on its integrity.

During the entire execution process, monitoring sensors measure important parameters in real time, and the data is continually checked to verify the pile integrity. Usual sensors used can measure: auger tip depth, verticality, concrete pumping pressure, auger rates (drilling and withdrawing) and applied torque. The volume of the placed concrete is assessed by two possible methods: stroke count or in-line flowmeter. The first and most common method consists of counting pump strokes and using an assumed volume-per-pump stroke to calculate the injected concrete volume, which can be inaccurate due to variations of the volume pumped per stroke (assumed constant) and/or missing or erratic behavior of the counter sensor. Almeida Neto and Kochen [7] pointed out other limiting factors like pumps without calibration/maintenance (loss of efficiency) and damaged sensors/transmission wires. The in-line flowmeter method uses an induced magnetic field around the pumping tube to calculate the velocity of the flown concrete and, after a conversion to pressure, its volume using the tube section area. With the introduction of modern monitoring equipment, the stroke counting is now considered a poor quality control practice [8].

Almeida Neto [9] related real cases where, although the pumped volume of concrete measured by stroke count was satisfactory, piles were found damaged, through evaluation by visual inspection after soil excavation. The non-representative overrated volume of concrete was possibly associated with the concrete that flows up the auger flights (until the ground level) and the other factors mentioned by that author.

There are two others key monitoring parameters in the placement of concrete phase that can indicate the pile integrity in real time: The concrete pumping pressure and the auger-withdrawing rate. The pressure is commonly measured in the line above the swivel on top of the auger string; although its best location is as near to the auger tip as possible. Raising up the withdraw auger speed can simultaneously reduce the pumping pressure. In such cases, the space between the auger tip and soil cannot be completely filled by concrete, resulting in a soil collapse inward and a neck in the pile. To avoid it, the operator has to control the auger withdraw rate, so there is always a positive pressure of about 50 to 100 kPa [9] and a relative consumption ratio (real to theoretical volume) of about 15 to 20% of concrete. Moreover, concrete placement should be continuous from the base to the top, so the whole wall is supported, whether above the auger tip by the soil between the flights or below the tip by the placed concrete.

Pile section changes (bulges or necks) along its shaft are then likely and natural to be expected, because of concrete pumping and soil radial pressure variations [3].

As far as the concrete is concerned, contractors should check and follow its design specifications. An adequate mixture is essential in CFA pile integrity [10]. Poor concrete quality with low workability, low cement consumption or maximum aggregate sizes out of range are the major problems, which can cause difficulties in the cage introduction, segregation, exudation, among other problems.

Installation in difficult soils is also a likely cause of structural damage, as in [8]:

- Soft soils: Necks/section reductions are caused by soil instability. To control it, an overconsumption of concrete is often used, as well as bulge formations, which are commonly undesirable because of soil negative friction effect.
- Loose sands with high water level: Soil mining could be a problem, and the control of drilling and concrete placement is critical.
- Ground with presence of voids, pockets of water, flowing water, lenses of soft soils: Can lead to problems with hole stability and control of auger rates.
- Other particular situations as loose sand or soft soils overlaying hard soil, sand-bearing stratus underlying stiff clay, highly variable ground conditions.

To minimize the uncertainties on the execution process it is strongly recommended to verify the sensor calibrations and maintenance report and an evaluation of the technical capacity of the operating drilling equipment staff in the field.

Day-to-day of integrity testing practice confirms that CFA piles are not exempt from damage occurrences. Klingmüller and Kirsch [11] described a study carried out at the Technical University of Braunschweig, in Germany, on the investigation of 3773 integrity tests of in situ concrete piles. For CFA or screw piles, figure 1 shows that in 18% of the analyzed cases a considerable deficiency was detected. They also concluded that a special knowledge and experience in integrity testing and in pile construction methods (foundation engineering) is required in the interpretation of the results.

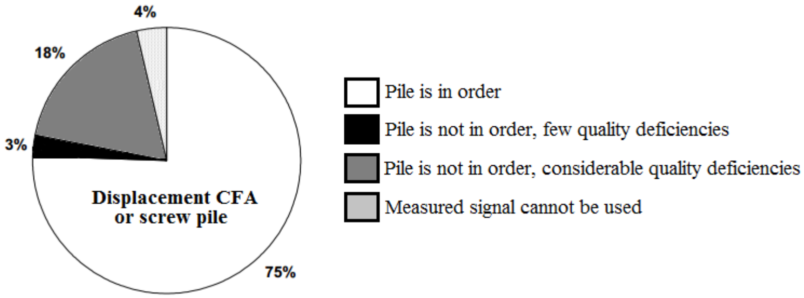


Figure 1. Failure class distribution for CFA or screw piles [11].

4. Characteristic Records from CFA Pile Testing

4.1. Reinforcement Cage Interference

In normal applications, CFA piles are not fully reinforced, because of the difficulty in cage installation procedure after placing the concrete. As a result, the downward compressive wave travels part in reinforced concrete and part in pure concrete, so an impedance reduction is expected to occur at the transition section. However, such reduction does not cause an important reflection on the velocity signal. For example, for a pile (Ø 50cm, 10m long), reinforced by a cage with 6 longitudinal steel bars (Ø 16,0mm, 6m long), the respective found beta value is β ≈ 0, 97.

Another question about cages is its free length above pile top that can cause vibration noise in the velocity signal. Figure 2a shows a noisy signal, from a pile tested without caging cut-off (2m free length above pile top), where interpretation becomes very difficult. A good practice to avoid such noise is to cut-off the exposed cage to a maximum 1m length above pile top. When this procedure is not applicable, noise interference on signal quality needs to be considered or adequately filtered (figure 2b).

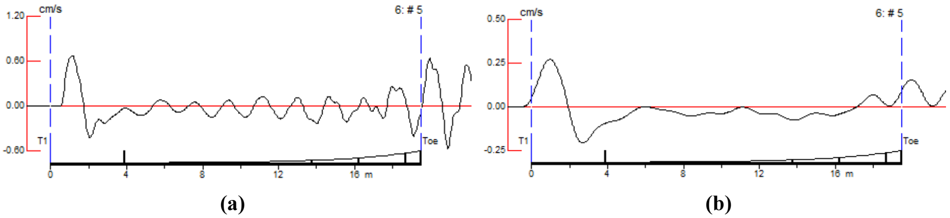


Figure 2. Reinforcement cage interference. (a) Original data; (b) Filtered data.

4.2. Pile Toe Reflections

In most cases, when the L/D (Length to Diameter) ratio is below 30, pile toe reflections are clearly observed (figure 3a). However, due to other factors, such as high resistance soils or vibration noise, the pile toe may not be clearly interpreted (figure 3b).

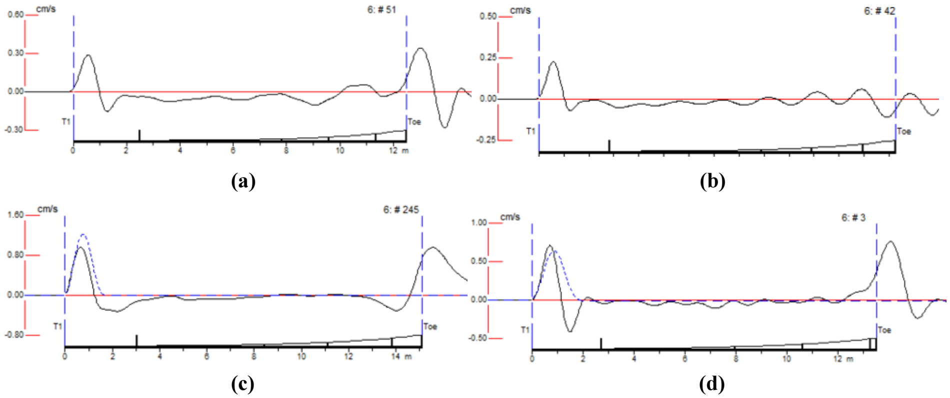


Figure 3. Pile toe reflections. (a) Clear toe reflection; (b) Toe reflection not apparent. (c) Possible bulge formation at the toe; (d) Gradual impedance reduction near toe, from approximately 12m depth.

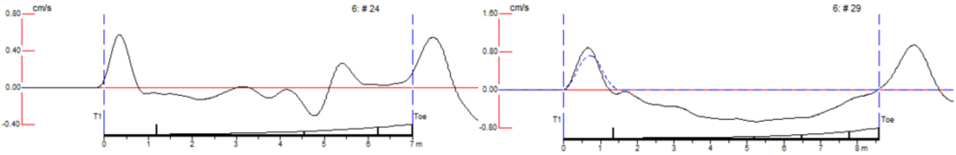
Indications of increasing impedance near the pile toe (figure 3c) probably means a local concrete bulge formation, if the soil around this area is not hard enough. In other cases, the toe reflection can be preceded by a gradual impedance reduction (figure 3d), that might be associated with:

- The auger tip format that may not guarantee a perfect geometry at the base.
- When starting to withdraw the auger, the concrete could not flow out sufficiently to cover the drilled area at the base and/or an excessive lift up distance caused instability of the hole wall, so soil mixed up with the concrete.

For those reasons and also due to the fact that the end bearing resistance could require larger displacements to be mobilized (presence of loose soil at the base), it is advisable not to assume full end bearing resistance for such piles.

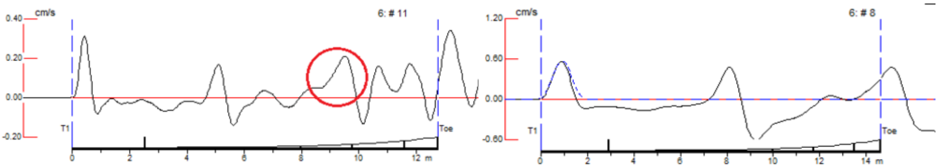
4.3. Typical Impedance Changes

Figure 4 shows good piles, with increasing impedance reflections. In the first case, impedance increases between 4,3m to 5,3m depth followed by a returning to the normal pile impedance value. The second graphic illustrates an example of a progressive impedance increase, reasonably related to the soil resistance. Figure 5 shows examples of shaft impedance reductions. In case (a), a reduction between 4,5m and 5,2m depth, with β=0,6 is observed. It is interesting to note the presence of the secondary reflection of the damage, at approximately 9m depth, and the clear indication of the pile toe. Case (b) shows a reduction near the pile center. As the secondary reflection shows up at two times the location of the first damage appearance, it could be occurring near the pile end, so a toe reflection cannot be ensured (because of the likely superposition effect).



(a) **(b)**

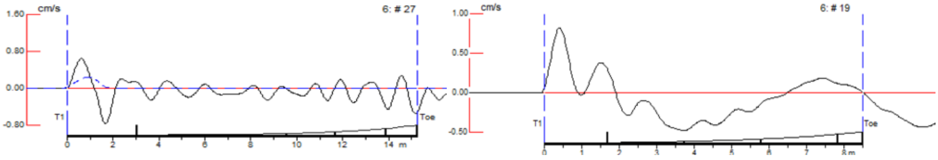
Figure 4. Impedance increase reflections. (a) Local bulge formation; (b) Probable soil friction effect.



(a) **(b)**

Figure 5. Shaft impedance reductions. (a) Damage indication at 4,5m depth and secondary reflection at 9m depth; (b) Damaged at 7m depth, with unclear toe reflection (due to secondary reflection of the damage).

Figure 6 presents two piles tested at its execution level, without cutting the concrete below the ground. The positive reflection in the first case indicates a likely local damage but the secondary reflections and the signal loss at this point do not allow the evaluation of the rest of the pile (partially conclusive test). The second case demonstrates an impedance reduction (dashed blue line – force signal), due to poor quality concrete. It is recommended to test piles at their cut-off level or at least sufficiently trimmed, so a sound concrete is observed. It helps avoiding poor concrete quality at the pile top that is generally injected with low or zero pressure (due to reduced soil confinement), and subjected to soil debris contamination and concrete exudation phenomena.



(a) **(b)**

Figure 6. Impedance reductions near pile top. (a) Indication at 1m depth and secondary reflections; (b) Force signal indicates impedance reduction near pile top due to poor concrete quality.

5. Conclusion

The use of monitored execution process may give a false impression of simplicity and guarantee of integrity of CFA piles. On the other side, although LST has proved to be a good alternative for pile integrity assessment, due to its limitations and, in certain cases, to the subjectivity of the data interpretation, it has been a met with some criticism from the geotechnical community. It is emphasized that the application of PIT to different types of piles, as in the CFA case presented here, has to be discussed and validated by the contractor, the consultant and the testing engineer before going to the field, so the expectations on the resulting data becomes more consistent and realistic to what PIT is able to achieve. In addition, the standardization of the interpretation data is important to reduce test misconceptions and to state out its limitations in a more evident manner.

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