

# Impact of ACIP Pile Drilling Technique on Subsurface Soil Density

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**Abstract.** For the foundation of an industrial complex, auger-cast-in-place piles (ACIP-Piles) have been installed on behalf of the recommendation of a local geotechnical consultant. With respect to the poorly graded sand deposits and the high ground water table, the installation was critically reviewed with respect to the European Code DIN EN 1536. In the course of the installation process of a couple of working piles, extensive soil was drilled by the auger, which led to a loss of soil mass in the vicinity of the pile shafts. A detailed engineering analysis came to the conclusion, that the reasons of the damage can be attributed to a concurrence of the subsurface soil conditions, the chosen drilling technique, the choice of the contractor as well as the workmanship. However, a distinct soil loosening could also be measured by a plenty of cone penetration tests in the vicinity of those working piles, which have apparently been installed properly. Surprisingly, the compact sand layers were much more affected by the installation process than the loose deposits. These findings lead to the conclusion, that the installation process of ACIP piles has to be critically evaluated during the construction process and may become a decisive design influence in the case of a pile design by empirical pile capacity magnitudes.

**Keywords:** Auger-cast-in-place (ACIP) piles, continuous flight auger (CFA) piles, impact of drilling process on soil density, Archimedean Screw effect, consequences of pile drilling technique on pile design.

**Conference topic:** Geotechnical art and historical experience.

## Introduction

The installation process of drilled piles may affect the subsurface soil conditions. Especially the temporary support of the borehole has a basic impact on the pile quality and capacity, because an insufficient support leads to a soil softening in the vicinity of the pile shaft resulting in a capacity decrease. Generally different installation techniques exist: a) using a casing as temporary support of the borehole, b) using bentonite slurry and c) using a so-called “endless auger” for the drilling of the pile. These piles are called *Continuous Flight Auger Piles* (CFA) or *Auger Cast in Place Piles* (ACIP).

In case of CFA or ACIP piles, the use of a temporary casing is not necessary, because the temporary support of the borehole is ensured by the drilled soil on the auger flights. The key component is the control of the drilling process because the auger has to be drilled to the final pile depth without a distinct soil removal. Subsequently, the auger is withdrawn and the borehole is filled with pressured grout via the auger core. Finally, the reinforcement cage is pushed or vibrated into the freshly poured pile shaft. In order to prevent a softening of the ground, the auger drill must be advanced at the optimum rate, that means the heading and the rotational speed of the auger have to be adapted. In case of a too high rotational speed in conjunction with a too low heading speed (so called “overdrilling”), soil will be drilled and the auger is not kept charged full of soil, which is required to ensure the stability of the hole in case of low-stability soil, e.g. fine grained sand below the ground water table. Moreover, a loosening effect of

the soil in the vicinity of the pile shaft will be inevitable in this case, because an excessive auger rotation without an advance will convey the soil upwards and the lateral effective stress in the ground is reduced (van Weel 1988). A similar effect is also shown by Grabe *et al.* (2012) in the case of CFA piles. However, the auger must not penetrate too quickly, because it would cork-screw into the soil and the torque required to continue the drilling would possibly exceed the available torque of the drilling rig. An overview of installation effects by ACIP piles is given by Brown (2005, 2012), Brown *et al.* (2007), Siegel (2012) and Esrig *et al.* (1994).

With reference to DIN EN 1536 and the Recommendations on Piling (EAP) (German Geotechnical Society 2012), CFA piles should not be installed without a prior pile testing, if any of the subsequent criteria is fulfilled:

- Poorly graded sand with an unconformity of  $C_u = d_{60}/d_{10} < 1.5 - 3.0$  below ground water table;
- Non-cohesive soils with a loose density  $D < 0.3$ ;
- Cohesive soils with a distinct sensitivity;
- Soft cohesive soils with undrained shear strength of  $c_u < 15$  kPa.

## Project

For an industrial project in the USA, *Auger-Cast-in-Place Piles* have been recommended as foundation structure by the local geotechnical consultant. The installation process of the ACIP is basically comparable to those one of the CFA pile, but differs with respect to the

drilling process itself: CFA piles are drilled with powerful fixed mast hydraulic-powered rig whereas ACIP piles are installed by free-drilling. In this case, the auger is attached to a crane with a top-drive gearbox (see Fig. 1) and it is drilled only by the use of the auger's self-weight. This pile type was favoured for the project on behalf of the local experience and the availability of the drilling rigs.



Fig. 1. Installation of ACIP Piles by fly-drilling technique

However, the subsurface soil conditions have been evaluated as critical with respect to the aforementioned criteria of DIN EN 1536. The soil is characterised by an alternating layering of thick non-cohesive soils with interbedded sandy clayey silts and high plasticity clay deposits. Especially the sand layers are suspected to be sensitive to the installation process of the ACIP piles due to the poorly-graded characteristic (soil group SE according to DIN 18 196 and SP according to ASTM D 2487 respectively), the partly loose to medium dense compactness and the high ground water table. However, the density of the sand deposits increases versus depth, so even dense to very dense sand layers have also been encountered during the field investigation and have to be drilled in the course of pile installation.

In order to ensure the basic feasibility of the ACIP pile system, extensive pile test loadings have been previously performed (axial and lateral loading) on piles with diameters of 40.6 cm and 51 cm and pile lengths of 18.3 m and 24.4 m respectively. However, the tests have not been run until the ultimate limit state but to a load-level of 3 times the working load. The test results show that even in this critical soil conditions ACIPs can be properly installed and moderate pile capacities can be

achieved. Generally, this approach corresponds to the requirements of DIN EN 1536, which demands the performance of pile testing in case of critical soil conditions like described above.

### Case of damage

#### Site event

During the installation of the working piles of a plant unit with dimensions of 2800 m<sup>2</sup> (totally 600 piles required), damages occurred in October 2013. In the northern part of the excavation pit, the heading speed of the auger stagnated at a drilling depth of appr. 18 m while the rotational auger speed was not simultaneously choked. As a consequence, overdrilling took place and an appreciable soil mass was drilled to the surface ground level leading to settlements in the vicinity of the pile shaft, see Figure 2.



Fig. 2. Drilled soil mass by the auger and settlement trough in the vicinity of the boring location

Subsequently, the drilling work was immediately stopped in order to evaluate the causes of the overdrilling, the impact on the density of the soil adjacent to the pile and the consequences on the pile capacity and pile design in general. Unfortunately it was not possible with respect to the general time schedule of the site, to perform additional pile test loadings taking into account the extensive installation effects on the soil. Instead of this additional CPT tests were performed directly besides the damaged pile shaft in order to review the depth down to which the soil was loosened by the drilling process. The comparison of the CPT results with those

ones driven at greater distance from the pile showed a distinct loosening of the sand layers down to a depth of at least 12 m below the surface ground level. This corresponds to appr. 50% of the final pile length.

Hereupon the question arose, if this loosening may also have taken place during the installation of the already finished ACIP piles and if the pile capacities resulting from the pile test loadings are still valid for all of the working piles. This question finally led to the basic discussion if ACIP piles should be installed furthermore on site or if displacement auger piles should be used instead as foundation structure of the highly-loaded and settlement-sensitive plant units.

#### Failure analysis

In case of auger-cast piles, the support of the drilling hole is ensured by the auger itself and the drilled soil on the auger flight. It is of basic meaning, that the auger drilling and the auger heading speed are synchronized in a way that the auger is drilled like a “corkscrew” into the ground. Nevertheless, a slight overdrilling is inevitable in order to prevent a sticking of the auger and to ensure a withdrawing of the auger during the pouring process of the pile.

However, the auger becomes an *Archimedean Screw*, see Figure 3, if the drilling speed is too high and/or the heading speed is too low, that means the drilling process is not synchronized and overdrilling takes place. In this case, soil is drilled by the auger and is conveyed by the auger flight to the surface ground. This effect leads to a distinct ground loss in the vicinity of the pile shaft and consequently to a loosening of the soil resulting in a decreasing pile capacity. Moreover, surface settlements take place which may affect nearby buildings and structures. In case of the pile shown in Figure 2, the heading of the auger totally came to a standstill while the auger rotational speed was not reduced at all.

The failure analysis came to at least three causes of the overdrilling: the subsurface soil conditions, the choice of the contractor and the drilling technique.

- Subsurface Soil Conditions: The re-evaluation of an exploratory drilling log in the vicinity of the area of interest showed a 3 m thick layer of Fat Clay with a stiff to firm consistency at a depth of appr. 18 m below surface ground level. However, this depth correlates more or less with the drilling depth in which the auger stuck. Actually, this layer showed a much higher drilling resistance in comparison to the overlaying non-cohesive soil layers, which led to a stagnant auger heading. However, the Archimedean Screw effect resulted from both the stagnant auger heading in conjunction with an unchoked auger rotation.
- Choice of contractor: As mentioned above, test piles have been successfully installed and tested prior to building activities on site. However, the client commissioned another pile-contractor to install the working piles due to a more economic

offer. Unfortunately, the experience of the new contractor in the field of ACIP drilling technique was not questioned anymore, as the test piles already showed the basic feasibility of the pile type in these soil layers. This approach contradicts to the requirements of DIN EN 1536, which demands the verification of experience of the executing contractor.

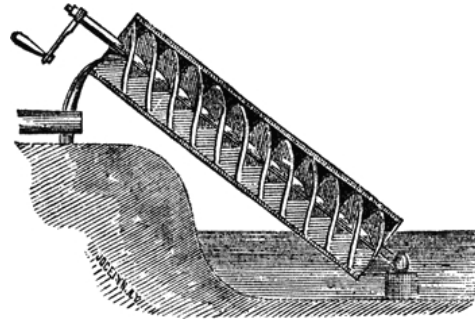


Fig. 3. Principle (Wikipedia 2016) and model of an Archimedean Screw

- Drilling Technique: Finally, the chosen drilling technique benefit the damage. The ACIP have been installed according to the *fly drilling technique*. In this case, the auger is not attached to a frame leader but is drilled by its self-weight into the ground. As a consequence an active pushing of the auger during the drilling process, which may compensate a scattering drillability of the ground, is totally prevented.

#### Additional soil investigation

The site event led to a further evaluation of the drilling impact of the piles on the subsurface soil conditions. Especially it should be reviewed, if a soil loosening also took place in the vicinity of obviously properly installed working piles. Therefore, additional cone penetration tests (CPT) were driven besides the foundation piles of a large pipeline bridge. For each working pile of the bridge, one CPT was driven within the direct vicinity at

a distance of 0.45 m (18"): location A, possibly affected by the drilling process) measured from the pile axis and one additional at a distance of 9.1 m (30': location B, undisturbed area) for comparison. All of the working piles of the bridge have a length of 24.4 m (80') and a diameter of 0.51 m (20").

Figure 4a) and b) exemplarily show the results of two CPTs. Both diagrams contain the cone tip resistance versus depth at location A (disturbed area – red dotted line) and location B (undisturbed area – blue continuous line). Obviously, the tip resistance has distinctly decreased in the vicinity of the pile shaft in comparison to the undisturbed area. This means, that the pile drilling process has led to a considerable loosening of the soil. However, the higher the density of the undisturbed soil, the more pronounced is the loosening effect.

For example at depth from app. 20' to 40' (app. 6–12 m) the cone tip resistance decreased from a maximum magnitude of  $q_c = 30$  MPa prior to a magnitude of minimum  $q_c = 5 - 9$  MPa subsequent to the pile installation. This corresponds to a decreasing density of the soil from *very dense* in the at-rest state to a *loose* density at the end of the pile installation. The averaged tip resistance decrease versus pile length yields app.  $q_c = 18$  MPa to  $q_c = 5$  MPa. This reduction is especially pronounced for the non-cohesive soils layers, whereas

the thin-layered cohesive deposits (e.g. depth 24.4' to 26.3' and 51.8' to 53.8', Fig. 4a)) are obviously less sensitive to the installation process. Moreover, the softening effect is less pronounced in case of already loose to medium dense non-cohesive soils.

The distinct loosening of density in the vicinity of the pile shaft can be drawn to at least two possible causes in conjunction with the chosen *fly-drilling* installation technique of the piles:

- The higher the density of the non-cohesive soil layers at-rest, the more pronounced is the installation effect of the pile drilling. These results can be attributed to the higher drilling resistance of dense to very dense soil deposits. Obviously, the high soil density prevents an auger penetration without a distinct soil excavation, so an overdrilling is quite necessary in order to ensure an auger penetration at all. With respect to the *fly-drilling* technique, an active pushing of the auger is not possible, so the overdrilling is the only possibility to proceed the pile drilling. In comparison, a fixed mast hydraulic-powered rig would be advantageous, as the contact pressure of the auger can be partly adapted to the drilling resistance and the rotation speed in order to prevent an *Archimedean Effect*.

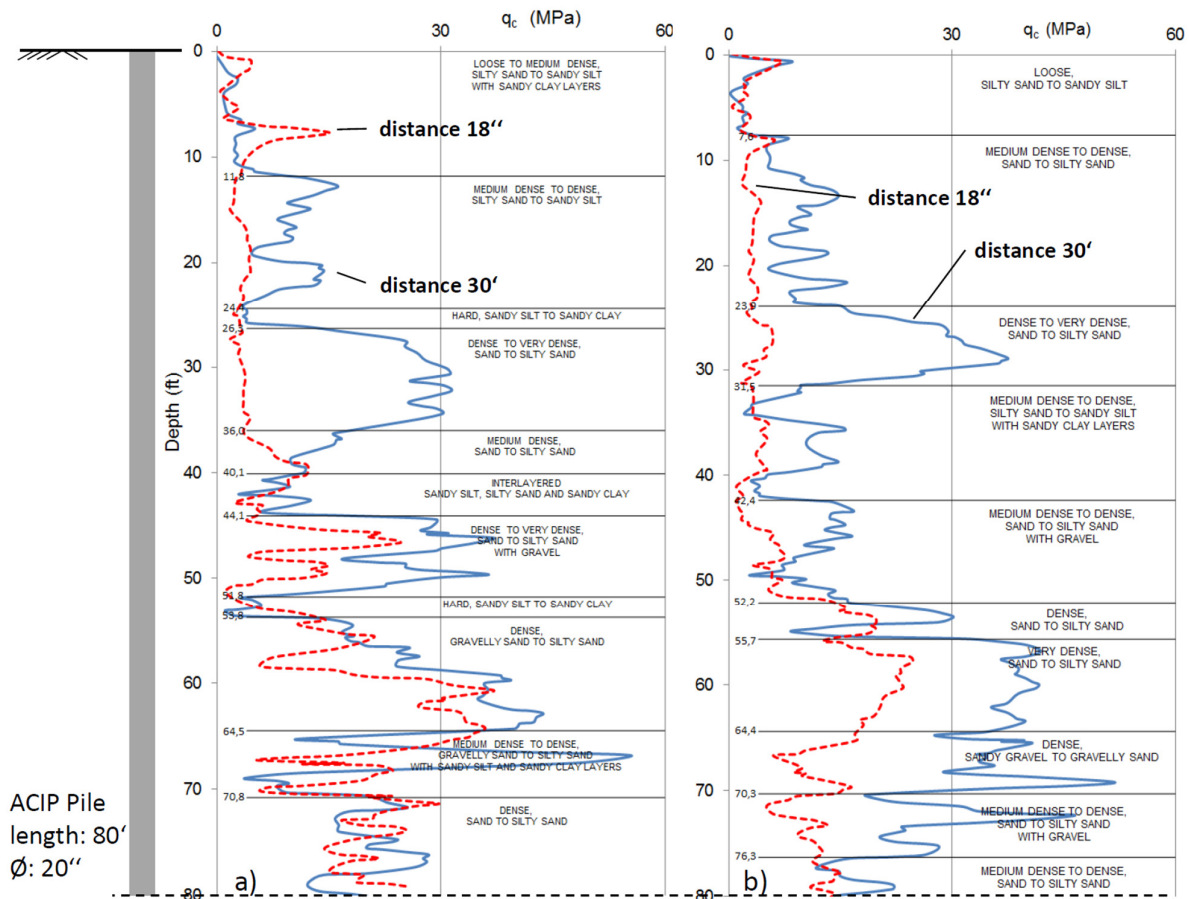


Fig. 4. Example of results of additional CPTs at a distance of 18" (0.45 m, A) and 30' (9.10 m, B) from the pile axis

- Moreover, the interlayered clay layer at depths of app. 40' – 45' below surface ground level additionally affects the softening effect of the drilling process. In Figure 4 it can be seen, that below the non-cohesive soil deposit, which shows the greatest impact of density decrease, the very stiff to hard clay layer directly follows. Obviously, this clay exhibits a much higher drilling resistance which leads to a sticking heading speed of the auger (Brown 2005, 2012).

The two diagrams shown in Figure 4 are representative examples for a couple of cone penetration tests, which have been driven subsequently to the observed case of damage (Schäfer, Belmann 2015). All of them more or less show the same results of installations effects by drilling the ACIP piles. Within the former dense to very dense non-cohesive soil deposits a cone tip resistance decrease of 60–70% could be evaluated.

### Conclusions

The experiences of the project illustrate, that the performance of ACIP piles have to be very carefully evaluated in dependence of the subsurface soil conditions, the chosen drilling technique as well as the contractor's experience. Actually the test piling showed sufficient pile capacities but, however, a review of the installation effect of the test piles on the soil density was not evaluated at all. Unfortunately it was not possible to perform those tests later on during the construction process. A comparison of such results with those ones of cone penetration tests in the vicinity of working piles (like shown in Fig. 4) would have facilitated an evaluation of a capacity decrease of the working piles. Instead of this, the design capacity of the piles with distinct installation effects was reduced and additional piles have been drilled. However, for highly loaded construction units the concept of ACIP piles was abandoned in favour of full-displacement bored piles, which are much less sensitive to a softening of the adjacent soil.

It has to be summarized, that the chosen drilling technique as well as the workman-ship have not been appropriate to the geotechnical subsurface conditions. Due to the installation technique, the soil's density was distinctly disturbed which inevitably leads to decreasing axial pile capacities (Mandolini *et al.* 2002).

In general, the measurements show the liability of the ACIP (and maybe also CFA) concept in case of layered soil conditions with varying drilling resistances. Although these piles systems are normally well-priced, an inexperienced installation may lead to a distinct deterioration of the subsurface soil conditions. This effect may become a problem in case of a pile design which is based on empirical capacity magnitudes.

For example the Recommendations on Piling (EA Pfaehle) propose pile skin friction magnitudes  $q_{s,k}$  which are correlated with the tip resistance  $q_c$  of cone penetration tests. These correlations are based on the evaluation

of numerous of test pile loadings. Actually this design approach uses the results of cone penetration tests which are driven prior to the foundation works, that means the undisturbed soil density is used for the estimate of the pile skin and pile tip resistance and thus for the design of the pile length. But if the soil density is affected by the installation process of the piles, the correlated pile capacity magnitudes may not be valid anymore and the application may lead to a non-conservative pile design, e.g. too low safety factors. However, the Recommendations on Piling explicitly points out the risk of a soil softening in case of ACIP- and CFA piles.

But how to proceed with the design of ACIP- and CFA piles? The actual project experiences as well as the literature review lead to at least three recommendations:

- Actually, the performance of test piles and test loadings is the most favourable approach. From the author's point of view, additionally an evaluation of the installation impact of the test piles on the subsurface soil conditions (e.g. CPTs within the pile axis prior and directly adjacent to the pile shaft subsequent to the drilling) is necessary in order to review the sensitivity of the drilling technique and the workmanship on the soil conditions and to correlate the test pile capacity with the actual soil density. If an over-drilling takes place during the installation of the working piles later, the extend of soil loosening and the impact on the pile capacity can be at least qualitatively evaluated by additional CPTs whose results should be compared with those ones driven adjacent to the test pile. Moreover, the results of the CPTs should be used to define upper bound limits for the impact of the drilling process on the soil conditions.
- If a test pile loading is not performed in general and the pile design is done empirically, at least test piles should be installed prior to the working piles itself in order to review the installation effects and the workmanship. These findings can subsequently be used for the pile design by empirical pile capacity magnitudes, e.g. pile skin friction generally correlated with CPT results should be reduced if considerable installation effects are observed.
- In the course of the quality management on site, the installation effects of working piles on the subsurface soil conditions should be evaluated exemplarily during the construction sequence. For this, cone penetration tests or dynamic soundings have to be driven in the vicinity of completely installed piles. The results of those tests can be compared with those ones of the test pile prior to the execution of the working piles and may be used as basis of valuation, if the installation impacts are still within the tolerance limit.

### Disclosure statement

The author declares not to have any competing financial, professional, or personal interests from other parties.

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