Auger cast-in-place (ACIP) piles and drilled displacement piles are being increasingly used as foundation elements for structures, particularly in projects requiring accelerated construction or involving the rehabilitation of foundations of existing, overstressed structures. Auger cast-in-place piles (also referred to as continuous-flight-auger piles) are widely used to construct the foundations of all types of structures. There are many different types of drilled displacement piles, with the installation methods varying according to the equipment used. Depending on the specific rotary piling technology used, responses ranging from those associated with non-displacement to those associated with full-displacement piles are obtained. Conventional pile design methods do not account for how the various construction techniques involved in auger piling change the soil state around the pile during installation and, hence, cannot accurately estimate the pile resistance in a consistent way. Research on this subject, identifying the different variables that must be accounted for in design and linking these variables to installation methods, is lacking. This paper describes the different piling methods available for auger cast-in-place and drilled displacement piles, the equipment used to install them and the quality control processes typically used. It also reviews some of the design methods currently used.

**Introduction**

Deep foundations are extensively used in geotechnical engineering practice. The wide spectrum of piling methods results in a variety of pile types. Each type behaves differently, depending on the installation or construction methods. On one end of the spectrum are non-displacement piles, the classical examples of which are bored piles or drilled shafts. These piles are constructed by removing a cylinder of soil from the ground and replacing it with concrete and reinforcement. On the other end are full-displacement piles, such as closed-ended pipe piles or precast reinforced concrete piles, which are typically driven into the ground. Driven piles preload the materials below the toe of the pile and displace the soil surrounding the pile shaft laterally during the installation process. Therefore, displacement piles are, in general, more likely to have a stiffer response than non-displacement piles. This is true particularly in the case of sandy soils where displacement causes densification.

Other pile types show behavior that is intermediate between non-displacement and full-displacement piles, e.g., open-ended pipe piles (Basu et al., 2005). In general, displacement piles are preferable from a design point of view because they are capable of carrying larger loads than non-displacement piles. However, the driving procedures may cause excessive vibration to neighboring structures or noise that may be unacceptable under certain conditions. Additionally, in some soil profiles (e.g. quick clays), the use of driven piles may not be advisable.

A large number of pile types can be referred to as auger piles if the similarities in the installation methods are considered. A continuous- or partial-flight auger or a helical tool is drilled into the ground to install these piles. A variety of auger pile equipment is available in the market; each is associated with a certain degree of soil displacement during installation. The more commonly used terminology for auger piles is presented in Fig.1. For example, under auger cast-in-place (ACIP), we have augercast piles, which are called continuous-flight-auger (CFA) piles in Europe.

CFA piles are installed by drilling with a hollow-stem, plugged, continuous-flight auger until a competent layer is reached. After the auger tip reaches the desired depth, concrete or grout is pumped through the hollow stem while, at the same time, the auger is withdrawn from the ground. The plug is released by the weight of the concrete as soon as the auger is lifted. The installation of CFA piles causes, at most, small horizontal displacement of the soil around the pile shaft as most of the soil within the pile volume is transported to the ground surface through the auger flights. As augercast or auger pressure-grouted (APG) piles are the USA-equivalent of CFA piles,
they are installed following the same steps described above. In the case of APG piles, high-strength grout, instead of concrete, is injected under pressure as the auger is withdrawn from the ground (Brettmann, 2003; Brown, 2005; Brettmann and NeSmith, 2005).

As result of the advances in piling technology, another class of auger piles was created; these are known as screw piles in Europe and drilled displacement or augered displacement (Brown and Drew, 2000) piles in the USA. Drilled displacement piles are rotary displacement piles installed by inserting a helical, partial-flight auger into the ground with both a vertical force and a torque. The soil is displaced laterally and the void thus created is filled with grout or concrete. The significant advantages of these piles are (i) the ease of construction with minimal vibration or noise and almost no spoil (important for contaminated sites), (ii) the higher load carrying capacity due to partial or full displacement of the soil surrounding the pile, and (iii) the associated savings that result when they are installed in the right soil conditions.

This paper presents a review of the different auger piles available, their installation methods, and the quality control procedures typically used. Some of the design methods available in Europe and the USA for ACIP and drilled displacement piles are presented and discussed.

**ACIP Piles**

The progress in auger piling technology was motivated in part by the development of ACIP piles. These piles have been in use for more than five decades (Brettmann and NeSmith, 2005; Van Impe 2004). Typically, the diameter of ACIP piles ranges from 0.3 to 1.0 m (Brown, 2005) and the lengths reach up to 30-35 m (Brettmann and NeSmith, 2005; Mandolini et al., 2002).

To install an ACIP pile, a plugged hollow-stem, continuous-flight auger is drilled into the ground at a certain rate (Fig. 2). The plug prevents soil from entering the hollow stem of the auger during drilling. The rate of auger penetration during the pile installation is very important as it has an impact on the pile performance. During auger penetration, some soil is removed by the auger flights, and “bulking” of the soil adjacent to the auger occurs. Ideally, the rate of auger penetration should be such that there is minimal release of lateral stress due to soil removal. In reality, there is always some lateral displacement (Van Impe, 2004). Problems may be encountered during ACIP pile installation when there is the need to penetrate a comparatively hard stratum underneath a soft clayey or loose sandy soil layer. If the penetration rate decreases when the auger tip enters the hard stratum, then the supply of soil into the auger flight from the auger tip drops. At the same time, there is more lateral feed of soil into the auger flights from the relatively soft / loose overlying layers. This may cause considerable loss of lateral confinement to adjacent piles and structures. Ground subsidence may also occur (Brown, 2005).

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**Figure 1 – Nomenclature used for Auger Piles in Europe and the USA.**
According to Viggiani (1989), the critical penetration rate \( v_{cr} \) is given by

\[
v_{cr} = n \left( 1 - \frac{d_0^2}{d^2} \right)
\]

where \( n \) is the rate of auger rotation, \( d \) is the diameter of the auger, \( d_0 \) is the outer diameter of the hollow stem of the auger and \( l \) is the pitch of the auger. If, for a given penetration rate \( v \), the rate of auger rotation \( n \) is comparatively high, then \( v < v_{cr} \). Consequently, the horizontal stresses are reduced, and more soil is removed from the region around the auger than from the region below the auger tip.

After the desired depth is reached, concrete or grout is pumped into the hollow stem, and the auger is raised a small distance (about 0.3 m) to release the hollow-stem plug and then lowered back to the original position. A certain amount of concrete or grout is then pumped to form a concrete or grout head on the auger flights. Subsequently, the auger is withdrawn, while concrete or grout (high-strength grout is used in the case of Berkel’s APG piles) is continuously pumped under pressure throughout the auger withdrawal process. Auger withdrawal is accomplished by initially rotating the auger clockwise to fill out with concrete or grout the lower flights of the auger and then by lifting it without rotation (CFA piles); alternatively, the auger is rotated clockwise at low speeds (Berkel’s APG piles) at the same time it is lifted (Brettmann and NeSmith, 2005). After concrete or grout placement is completed, the reinforcement cage is inserted or vibrated down into the fresh concrete or grout mixture and tied off at the surface.

The rate of withdrawal of the auger is important as well; it needs to be synchronized with the concrete or grout pumping rate. The average cross-sectional area of the pile is equal to the ratio of the concrete pumping rate to the auger withdrawal rate. This ratio should be selected based on the pile diameter assumed in design. An erroneous selection of this ratio may lead to a different pile diameter. If the withdrawal rate is too fast compared to the concrete pumping rate, the integrity of the pile is compromised. A smaller diameter will result in lesser capacity, while a larger one will lead to excessive consumption of concrete (Mandolini et al., 2002).

Computer monitoring of the rate of auger penetration, the concrete or grout pumping rate and the rate of auger withdrawal from the ground provides additional confidence on the integrity and performance of these piles. With the currently available equipment, CFA and APG piles can be installed with diameters ranging from 0.3 to 0.9 m and lengths reaching approximately 40 m (Brettmann and NeSmith, 2005).

Another type of ACIP pile is the Starsol pile developed by Soletanche SA. The basic difference in the installation of CFA or APG piles and Starsol piles is that in the case of Starsol piles, the rotation head drives a hollow-stem auger and a tremie pipe simultaneously into the ground. The auger and the tremie pipe are fitted with earth-cutting tools at the base and rotate and drill together. After drilling is
completed, the tremie pipe is clamped in position while the auger is raised slightly to open two holes on the sides of the tip of the tremie pipe. Concrete is then pumped through these holes under pressure as the auger is raised slowly. Typical diameters of the Starsol pile are between 0.4 and 1.0 m, and the maximum length is about 20 m.

**Drilled Displacement Piles**

Modifications in the installation of ACIP piles have led to the development of displacement piles that produce larger lateral soil displacements than ACIP piles. These piles are classified under a broad category as drilled displacement piles. Drilled displacement piles not only include those that are variations of the ACIP piles but also a variety of other piles that have different installation tools. Drilled displacement piles include, for example, those developed by Bauer Maschinen GmbH (Brunner, 2004) and Berkel and Company, Inc. (Brettmann and Nesmith, 2005).

The soil displacement produced during the installation of these piles can vary from that of a partial- to a full-displacement pile. The soil displacement is enhanced by using modified drilling tools that laterally displace the soil and also by providing additional vertical thrust during the augering process. This technology is available due to a remarkable development in piling rig hydraulics in recent years that has produced rigs with torque capacity ranging from 150 to 500 kNm (Van Impe, 2004). Several companies fabricate drilled displacement pile rigs. Accordingly, many drilled displacement pile types - Atlas, Bauer, Auger Pressure-Grouted Displacement (APGD), De Waal, Franki VB, Fundex, Olivier, Omega, Pressodrill, SVB, SVP and Tubex - are available throughout the world.

During the drilling process, the downward thrust is generated not only by the rotation action but also by a vertical force (the crowd) typically applied by hydraulic rams. Different drilling tools are used by each of the different pile types. In general, the drilling tool contains one or more of the following components: a) a soil displacement body, b) a helical, partial-flight auger segment and c) a specially designed sacrificial tip, which is attached to the bottom of the drilling tool. The shape of the displacement body varies significantly from one pile type to another. Broadly, it consists of a cylindrical body that in some cases also contains single or multiple helices that help in the lateral displacement of the soil. A casing (or mandrel) of diameter smaller than or equal to the diameter of the pile is connected to the drilling tool. Once the drilling tool reaches the desired depth, the sacrificial tip (if used) is released from the casing or displacement body. Concrete or grout is then placed through the casing as the drilling tool and casing are extracted from the ground. Reinforcement is inserted either before or after concrete placement. The drilling tool and casing can be withdrawn from the ground without or with rotation (which may be clockwise or counterclockwise). A nearly smooth pile shaft is obtained if the casing is withdrawn with alternating 180° clockwise and counterclockwise rotations (Fundex). A nearly smooth shaft results as well if the drilling tool is rotated clockwise as it is withdrawn from the ground (APGD, De Waal, and Omega). However, if the displacement body is rotated counter-clockwise (Atlas, Olivier) during withdrawal, then a screw-shaped shaft is obtained.

Proper knowledge of the subsurface profile is needed in the selection of the most efficient pile type for a given site. Although drilled displacement piles have been successfully used for various soil conditions, these piles are not recommended in certain situations. According to Bustamante and Gianeselli (1998), in the case of very loose sandy soils or very soft clayey soils (N < 5, qc < 1 MPa), the performance of drilled displacement piles may be compromised because of difficulties that may be encountered during their installation in these conditions. In the case of very dense sandy soils or thick alluvium layers, a drastic drop in the penetration rate may be observed and premature wear of the screw head (drilling tool) may result if it is often used in these soils.

A distinction should be made between concrete/grout cast drilled displacement piles described in this section and those where a single- or multiple-helix steel auger is screwed into the ground to form the pile. These piles are similar to helical ground anchors but installed vertically to function as piles. Their design and installation differ greatly from those of the concrete drilled displacement piles covered in this paper.

Despite the existence of many types of drilled displacement piles, the literature contains limited information on the design and installation of these piles. The installation procedures of the most common drilled displacement piles are described next.
**Atlas Pile**

The Atlas screw pile is a drilled, dual-displacement, cast-in-place concrete pile (De Cock and Imbo, 1994). Lateral displacement of soil occurs both during drilling and extraction of the auger (this is the reason why it is called a dual-displacement pile). The drilling rig has two hydraulic rams that can work independently (one taking over from the other after its full stroke is achieved) to allow a continuous drilling operation. In the case of hard soils, the two hydraulic rams can work simultaneously. The rig can be operated at dual rotational speeds. This helps to control the drilling tool penetration rate in different soil types.

In the Atlas pile installation, a sacrificial tip (a lost pile shoe) is attached to a displacement body, which, in turn, is attached to a steel casing or mandrel (Fig. 3). The displacement body consists of a cast-iron dismountable helical head with an enlarged helical flange. The joint between the displacement body and the sacrificial tip is made watertight. The combined action of the torque and the vertical thrust forces the casing down into the ground with a continuous, clockwise, helical penetrating movement. After the desired depth is reached, the steel shoe is detached from the casing. A steel reinforcing cage is inserted into the casing. High-slump concrete is then poured through a hopper placed on top of the casing to cast the pile shaft. As the casing and the displacement body are extracted by a vertical pulling force and counter-clockwise rotation, concrete completely fills the helical bore formed by the upward-moving displacement screw. This way, a screw-shaped shaft is formed. After concrete placement, it is possible to push into the pile a supplementary reinforcing cage. Typically, the diameter of the displacement body (minimum diameter of the pile shaft) ranges from 0.31 to 0.56 m, and that of the enlarged helical flange, from 0.45 to 0.81 m (Bustamante and Gianeselli, 1998; De Cock and Imbo, 1994). The Atlas pile length can reach up to 22-25 m.

A modified Atlas pile with a thin-walled casing attached to the screw head is used in highly compressible soils, or in soils with large cavities or voids. The casing is left in the ground with the sacrificial tip. This type of pile is characterized by the thick flange of the helical head.

**APGD Pile**

The APGD pile technology, which is patented by the Berkel & Company Contractors, Inc., is a modification of the original APG piling system (Brettmann and NeSmith, 2005). Compared with
Figure 4 – Installation of the Berkel’s APGD pile.

partial soil displacement and 2) auger pressure-grouted with full soil displacement. The partial-displacement pile installation causes less lateral soil displacement around the pile shaft than the full-displacement one. In contrast to APG pile rigs, the APGD pile rigs are capable of producing both a torque and a downward crowd force, which facilitates the drilling operations. Once the desired depth is reached, high-strength grout is pumped under pressure through the drill stem and the drilling tool is withdrawn as it rotates clockwise. The reinforcing cage is inserted into the grout column to complete the pile installation process. Full-displacement piles can be 0.3 to 0.45 m in diameter and up to 24 m in length. These piles are used in loose to medium dense sands ($N_{SPT} < 25$). The partial-displacement APGD piles can be 0.3 to 0.5m in diameter and up to 17 m long. These are used in loose to dense sand with $N_{SPT} < 50$ (Brettmann and NeSmith 2005).

**Bauer Pile**

Bauer Maschinen GmbH fabricates equipment for construction of partial- or full-displacement auger piles (Brunner, 2004). The tool for the partial-displacement pile consists of a lower auger with a small hollow stem with large flights and an upper auger with a large hollow stem with small flights. During drilling, the soil is transported by the bottom auger upwards as the soil moves up, it displaces the surrounding soil laterally because there is less room available in the helical space of the upper auger which has a larger diameter. This pile installation method is effective when a loose stratum is underlain by a dense layer. After the design depth is reached, concrete is pumped through the hollow stem, and the auger is withdrawn. The reinforcing cage is either pushed in or inserted with the help of top vibrator. The Bauer pile can be up to about 30 m in length. Piles with a diameter of up to 0.6 m are possible with this technology.

The tool for the installation of the full displacement pile consists of a lower tip, a middle displacement part and an upper auger section with counter-rotating flights. The installation method is identical to that of the partial-displacement pile. However, the use of a Kelly extension may increase the drilling depth by 6 to 8 m.

**De Waal Pile**

The drilling tool used to install the De Waal pile consists of a sacrificial tip, a partial-flight auger and a displacement body (Fig. 5). The drilling tool is attached to a casing that has additional helices.
welded near the top. The partial-flight auger is closed at the bottom with the sacrificial tip. To install the De Waal pile, the drilling tool is rotated clockwise to the required depth with a torque and a vertical force, the sacrificial tip is released and the reinforcement cage is installed. Concrete is injected into the casing as the casing is extracted with clockwise rotation and a vertical force. Unlike the Atlas piles, installation of the De Wall pile creates a nearly smooth shaft. The helices near the top of the casing produce an enlarged shaft near the pile head.

Franki VB Pile

The Franki VB (Verdrängungsbohr) pile is a term used in Germany for "displacement auger" pile. To install this pile, a large-stem auger is rotated and pushed into the ground. A sacrificial bottom plate is attached to the auger. Once the desired depth is reached, reinforcement, which can be anchored to the bottom plate, is installed. The casing is then filled with concrete. As the casing is withdrawn, more concrete is pumped into the casing to guarantee the quality of the shaft.

Fundex Pile

In the Fundex pile installation, a casing with a conical tip attached to its end is rotated clockwise and pushed down into the soil (Fig. 6). The joint between the casing and the conical tip is made watertight. As the casing is drilled into the ground, soil is displaced laterally. In dense or hard layers, drilling can be combined with grout injection or water jetting through the conical tip. After the desired depth is reached, the sacrificial conical tip, which forms an enlarged pile base, is released. The reinforcement cage is then inserted into the casing and concrete is placed. As the concrete is placed, the casing is extracted in an oscillating upward and downward motion with alternate 180° clockwise and counter-clockwise rotations. The withdrawal of the casing with both clockwise and counter-clockwise rotations produces a nearly smooth shaft. The diameter of the conical tip ranges from 0.45 to 0.67 m, and that of the casing ranges from 0.38 to 0.52 m (American Piledriving, Inc.). The length of the Fundex pile can reach up to 25 to 35 m, depending on the piling rig used.

Olivier Pile

The installation of the Olivier pile is similar to that of the Atlas pile (Fig. 7). A lost tip is attached to a partial-flight auger which, in turn, is attached to a casing. The casing, which is rotated clockwise continuously, penetrates into the ground by action of a torque and a vertical force. At the desired installation depth, the lost tip is released, and the reinforcing cage is inserted into the casing. Concrete is then placed inside the casing through a funnel. The casing and the partial-flight auger are

Figure 5 – Installation of the De Waal pile.
Omega Pile

In the case of the Omega pile, drilling is done by a displacement auger which is closed at the bottom with a sacrificial tip (Fig. 8). A casing is attached to the upper end of the displacement auger. Unlike the other drilled displacement piles, concrete is injected under pressure into the casing even before the desired depth is reached. After reaching the required depth, the sacrificial tip is released, and the auger is slowly rotated clockwise and pulled up. The withdrawal of the auger with a clockwise rotation produces a nearly smooth shaft. The reinforcement cage is then vibrated down into the fresh concrete.
Pressodrill Pile

The installation equipment consists of a crane that supports a leader on which a rotary head slides. A large hollow-stem auger, sealed at the base with a plate, is inserted into the ground by rotation and by a vertical force provided by the weight of the rotary head and the weight of the casing. After the installation depth is reached, reinforcement is lowered into the casing and locked to the bottom plate of the auger. The lower ends of the bars are bent towards the pile center. A hollow-steel mandrel, provided with side holes, is then lowered down through the auger to rest on the auger bottom plate. The mandrel and the auger are then filled with high-slump concrete. The top of the auger is equipped with a device that forces the mandrel to move downward and the auger to move upward. This upward force extracts the auger in successive stages, while the downward movement of the mandrel exerts a reaction force on the bottom plate, preloading the soil under the pile base. After withdrawal of the auger, the mandrel is removed from the ground.

SVB Pile

The SVB pile (Schnecken-Verdrängungsbohrpfahl), which was developed by Jebens GmbH, is a drilled, partial-displacement pile. The drilling is done by a large-stem auger which also acts as a casing. Both a torque and a pull down force are used during drilling. The bottom of the casing is sealed off with a disposable plate (Fig. 9). When installing the casing, some of the soil is transported along the helices to the surface, while a certain amount of soil is displaced laterally. When the desired depth is reached, reinforcement is installed and concrete is pumped into the casing. The casing is extracted by a pull-out force and a torque, leaving the bottom plate in the ground. Since the casing is rotated clockwise during extraction, a nearly smooth shaft is formed. The SVB-pile can have diameters ranging from 0.40 to 0.67 m with a maximum length of 24 m (Geoforum).

SVV Pile

The SVV pile (STRABAG Vollverdrängungsbohrpfahl), which was also developed by Jebens GmbH, is a drilled large-displacement pile (Fig. 10). The pile is installed using a patented casing that has a segment with an enlarged diameter and a drill head. The installation procedure of the SVV pile is similar to that of the SVB pile. The SVV pile typically has a diameter of 0.44 m and a length of up to 20 m (Geoforum).
The Tubex pile, developed by Fundex Verstraeten B.V., is a drilled displacement pile with a permanent casing that is left in the ground. The pile casing is fabricated from a tube by welding a special drill point to its base and helical flanges to its shaft. In order to install this pile, the casing is drilled into the ground until the desired depth is reached. The casing is then cut off at ground level, reinforcement is inserted into the casing and concrete is placed. This type of pile can be used in very unstable ground and is well suited for temporary foundations because it can be drilled out and removed from the ground. This type
of pile can also be installed under limited headroom; in this case it is known as Tirex pile.

**Installation Monitoring**

Depending on the equipment available, some or all of the following quantities can be measured or calculated during the installation of ACIP piles: the rate of auger rotation, the rate of auger penetration, the torque, the concrete pumping rate, and the auger extraction rate (Mandolini et al., 2002). In the past, quality control (QC) of these piles was performed by field inspectors, based mainly on the industry standards published by the DFI in the 1990’s (Brettmann, 2003). Currently, automated systems are attached to many pile rigs throughout the world. Even though these monitoring systems can provide valuable information on the quality of the piles, they are not meant to replace qualified field inspections. Automated QC monitoring techniques are based on measurements of either volume or pressure of the grout/concrete. Typical automated systems measure: i) time, depth and hydraulic pressure during drilling and ii) time, depth, grout/concrete volume or grout/concrete pressure during casting. Continuous, real time graphs of relevant data are available to the operator during the installation (this facilitates any impromptu adjustments that may be needed). These files can also be stored electronically for future reference.

Similar automated monitoring systems are available for the drilled displacement pile rigs as well. These can be used to continuously monitor the depth of penetration, the vertical force, the torque, and the rate of auger/casing penetration and rotation. A specific energy term can be calculated which involves the variables mentioned above and other machine-specific installation parameters. The specific energy profile along the depth of the pile can be correlated with in-situ test results and used to visualize the effects of pile installation and to help predict pile load capacity (De Cock and Imbo, 1994).

**Design Methods**

ACIP and drilled displacement piles are designed based on in-situ test results. The design methods available for these piles follow the same design philosophy of any other pile. The unit base and shaft resistances of the piles can be related to the cone penetration test (CPT) tip resistance $q_c$, the standard penetration test (SPT) blow count $N$ or the pressuremeter test (PMT) limit pressure $p_l$. The ultimate pile capacity $R_u$ can be expressed as

$$R_u = R_b + R_s$$

where $R_b$ and $R_s$ are the ultimate base and shaft capacities calculated as

$$R_b = r_b A_b$$
$$R_s = r_s A_s$$

and $A_b \left(= \frac{\pi D_b^2}{4}\right)$ and $A_s \left(= \pi D_s\right)$ are the representative pile base and shaft areas, with $D_s$ being the representative pile diameter. For ACIP piles $D_s$ is equal to the shaft diameter. For drilled displacement piles that have a smooth shaft, such as the De Waal and Omega piles, $D_s$ is taken equal to the maximum diameter of the screw head (displacement body) $D_h$. In general, for the Atlas piles, $D_s = 0.9 D_f$ but, in the case of thick-flanged Atlas piles with thin-walled casing, $D_s = D_f$ (Bustamante and Gianeselli; 1993, 1998).

**ACIP piles**

According to Moss and Stephenson (2004), several of the design methods available for ACIP piles were developed either for drilled shafts or for displacement piles. Two of the available design methods for ACIP piles are presented in Table 1. The design methodology of ACIP piles described in the German standard uses CPT tip resistance $q_c$ to calculate the unit base and shaft resistances (see Table 1). In the case of clay, the undrained shear strength $s_u$ can be derived from $q_c$ (Table 1) or, alternatively, from unconfined compression tests (O’Neill, 1994). According to Rizkallah (1988), the German standard does not account for the difference between a bored pile and an ACIP pile (or piles that are installed using a continuous-flight auger).

Bustamante and Gianeselli (1982) proposed a design method based on the results of 197 full-scale, static-load tests on different types of piles. It is to be noted that Bustamante and Gianeselli (1982) used the term “cast-screwed piles” to describe ACIP piles. In this method, the equivalent CPT resistance $q_{ca}$ to be used in design is determined from the original $q_c$ profile obtained in the field as follows: 1) the original $q_c$ profile is smoothed out by eliminating peaks, 2) the arithmetic mean $q_{ca}^*$ is calculated over a depth $d$ ($d = 1.5$ times the pile diameter) above and below the pile base, 3) the $q_c$ profile is modified again by eliminating values higher than 1.3 $q_{ca}^*$ and lower
Table 1 Design unit shaft and unit base resistance values for ACIP piles

<table>
<thead>
<tr>
<th>Source</th>
<th>Soil Type</th>
<th>$r_b$ (MPa)</th>
<th>$r_s$ (MPa)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>German Standards</td>
<td>Sand</td>
<td>$0.12 q_c + 0.1$</td>
<td>$0.008 q_c$</td>
<td>$s_u = \frac{q_c - \sigma_{vb}}{N_c}$</td>
</tr>
<tr>
<td>(Moss and Stephenson, 2004;</td>
<td></td>
<td>$(q_c \leq 25$ MPa)</td>
<td></td>
<td>$N_c = 16 – 22$</td>
</tr>
<tr>
<td>based on 5% relative settlement</td>
<td></td>
<td></td>
<td></td>
<td>$\sigma_{vb} =$ total vertical stress at the pile base</td>
</tr>
<tr>
<td>criterion)</td>
<td>Clay</td>
<td>$6 s_u$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(0.02 \leq s_u \leq 0.2$ MPa),</td>
<td>$q_{ca} = \text{equivalent cone resistance at the pile base (in kPa)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\lambda$ and $k_c =$ coefficients that depend on soil type (Table 2)</td>
</tr>
<tr>
<td>Bustamante and Gianselli (1982)</td>
<td></td>
<td>$k_c q_{ca}$</td>
<td>$q_c \lambda$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$q_{ca}$ = equivalent cone resistance at the pile base</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>base (in kPa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\lambda$ and $k_c =$ coefficients that depend on soil type (Table 2)</td>
</tr>
</tbody>
</table>

than 0.7 $q_{ca}^*$, and 4) the arithmetic mean $q_{cb}$ (to be used in design) is calculated from the modified $q_c$ profile (obtained in step 3) over a depth $d$ above and below the pile base. Unlike the German standard, this method takes into account different soil types through the coefficients $k_c$ and $\lambda$ (Table 2).

Table 2 Values of $k_c$ and $\lambda$ to calculate $r_b$ and $r_s$ for ACIP piles (Bustamante and Gianselli, 1982)

<table>
<thead>
<tr>
<th>Nature of soil</th>
<th>$q_c$ (MPa)</th>
<th>$k_c$</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft clay and mud</td>
<td>&lt;1</td>
<td>0.5</td>
<td>30</td>
</tr>
<tr>
<td>Moderately compact clay</td>
<td>1 – 5</td>
<td>0.45</td>
<td>40</td>
</tr>
<tr>
<td>Silt and loose sand</td>
<td>≤ 5</td>
<td>0.5</td>
<td>60</td>
</tr>
<tr>
<td>Compact to stiff clay and</td>
<td>&gt; 5</td>
<td>0.55</td>
<td>60</td>
</tr>
<tr>
<td>compact silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft chalk</td>
<td>≤ 5</td>
<td>0.3</td>
<td>100</td>
</tr>
<tr>
<td>Moderately compact sand and</td>
<td>5 – 12</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered to fragmented chalk</td>
<td>&gt; 5</td>
<td>0.4</td>
<td>60</td>
</tr>
<tr>
<td>Compact to very compact sand</td>
<td>&gt; 12</td>
<td>0.4</td>
<td>150</td>
</tr>
<tr>
<td>and gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Drilled Displacement Piles

Bustamante and Gianselli (1993; 1998) developed a design method for drilled displacement piles based on the results of 24 load tests on Atlas piles. The ultimate load for these tests was selected based on a 10% relative settlement criterion. The ultimate load was reached only for 14 of the load tests performed. For the other 10 load tests, the ultimate load was determined by extrapolating the load test data (Bustamante and Gianselli, 1993). According to this method, the unit base resistance is calculated as

$$r_b = K \alpha$$

where $\alpha$ represents an equivalent average of the in-situ test results spanning over a length $2a$ (a above and below the pile base) (Table 3). Table 4 provides values of the coefficient $K$, which depends on soil type. Based on the guidelines given in Table 5, a design curve is selected ($Q_1$, $Q_2$, $Q_3$, $Q_4$, or $Q_5$). These design curves depend on pile and soil type. Fig. 11 is then used to estimate the unit shaft resistance $r_s$ for the design curve selected. This method was proposed based on correlations developed for the Menard pressuremeter, the SPT, and the mechanical CPT. When using an electric cone, the unit cone resistance $q_c$ needs to be modified according to:

$$q_{cm} = \beta q_{ce}$$

where $q_{cm}$ and $q_{ce}$ are the unit cone resistance for a mechanical and an electrical cone, respectively. The coefficient $\beta$ can be taken equal to 1.4 - 1.7 for clayey soils and 1.3 for saturated sands (Bustamante and Gianselli, 1993).

Table 3 Values of $\alpha$ and $a$ for drilled displacement pile design (Bustamante and Gianselli, 1998)

<table>
<thead>
<tr>
<th>In situ Tests</th>
<th>Description of $\alpha$ (MPa)</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT</td>
<td>$1000 \times \frac{3}{2} N_1 \times N_2 \times N_3$</td>
<td>0.5 m</td>
</tr>
<tr>
<td>CPT</td>
<td>Arithmetic Mean over a length = $2a$</td>
<td>$1.5 D_s$</td>
</tr>
<tr>
<td>PMT</td>
<td>$\frac{3}{2} p_{11} \times p_{12} \times p_{13}$</td>
<td>0.5 m</td>
</tr>
</tbody>
</table>

$N_1$, $N_2$, $N_3$ and $p_{11}$, $p_{12}$, $p_{13}$ are calculated at and 0.5 m above and below pile base level.
NeSmith (2002) developed a design method for APGD piles. It is based on 28 load tests on APGD piles. In this method, $r_b$ is calculated as

$$r_b = 0.4 \cdot q_{cm} + w_b, \quad \text{for } q_c \leq 19 \text{ MPa},$$

or

$$r_b = 0.19 \cdot N_m + w_b, \quad \text{for } N_m \leq 50 \text{ (} r_b \text{ in MPa})$$

where $q_{cm}$ and $N_m$ are representative values of the cone resistance and blow count number in the vicinity of the pile toe, and $w_b$ is a constant that depends on soil gradation and angularity. For rounded materials with up to 40% fines, $w_b$ is equal to zero and the $r_b$ upper limit is 7.2 MPa. For well-graded, angular materials with less than 10% fines, $w_b$ is equal to 1.34 MPa and the $r_b$ upper limit is 8.62 MPa. To determine $q_{cm}$ and $N_m$, NeSmith (2002) suggests the method described by Fleming and Thorburn (1983), but recommends that the influence zone be extended to four times the diameter of the pile above and below the pile base.

The unit shaft resistance is calculated from

$$r_s = 0.01 \cdot q_c + w_s, \quad \text{for } q_c < 19 \text{ MPa},$$

or

$$r_s = 0.005 \cdot N + w_s, \quad \text{for } N < 50 \text{ (} r_s \text{ in MPa})$$

where $w_s$ is a constant similar to $w_b$. For uniform, rounded materials with up to 40% fines, $w_s$ is equal to zero and the limiting value of $r_s$ is 0.16 MPa. For well-graded, angular materials with less than 10% fines, $w_s$ is equal to 0.05 MPa and the limiting value of $r_s$ is 0.21 MPa. Interpolation is suggested for intermediate materials. This relationship is recommended only for sandy soils, where

---

### Table 4: Values of K for drilled displacement piles (Bustamante and Gianeselli, 1998)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>For PMT</th>
<th>For CPT</th>
<th>For SPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>1.6 – 1.8</td>
<td>0.55 – 0.65</td>
<td>0.9 – 1.2</td>
</tr>
<tr>
<td>Sand</td>
<td>3.6 – 4.2</td>
<td>0.50 – 0.75</td>
<td>1.8 – 2.1</td>
</tr>
<tr>
<td>Gravel</td>
<td>≥ 3.6</td>
<td>≥ 0.5</td>
<td>--</td>
</tr>
<tr>
<td>Chalk</td>
<td>≥ 2.6</td>
<td>≥ 0.6</td>
<td>≥ 2.6</td>
</tr>
<tr>
<td>Marl</td>
<td>2.0 – 2.6</td>
<td>≥ 0.7</td>
<td>≥ 1.2</td>
</tr>
</tbody>
</table>

### Table 5: Criteria for selection of a design curve to estimate $r_s$ from Fig. 11 (Bustamante and Gianeselli, 1998)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Limit pressure from PMT (MPa)</th>
<th>Cone Resistance (MPa)</th>
<th>Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay/Clayey Silt/Sandy Clay</td>
<td>&lt; 0.3</td>
<td>&lt; 1.0</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.5</td>
<td>&gt; 1.5</td>
<td>Q3</td>
</tr>
<tr>
<td></td>
<td>≥ 1.0</td>
<td>≥ 3.0</td>
<td>Q4</td>
</tr>
<tr>
<td>Sand/Gravel</td>
<td>&lt; 0.3</td>
<td>&lt; 1.0</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.5</td>
<td>&gt; 1.5</td>
<td>Q3</td>
</tr>
<tr>
<td></td>
<td>≥ 1.2</td>
<td>≥ 3.0</td>
<td>Q4</td>
</tr>
<tr>
<td>Chalk</td>
<td>&gt; 0.5</td>
<td>&gt; 1.5</td>
<td>Q4</td>
</tr>
<tr>
<td></td>
<td>≥ 1.2</td>
<td>≥ 4.5</td>
<td>Q5</td>
</tr>
<tr>
<td>Marl</td>
<td>&lt; 1.2</td>
<td>&lt; 4.0</td>
<td>Q4</td>
</tr>
<tr>
<td></td>
<td>≥ 1.5</td>
<td>≥ 5.0</td>
<td>Q5</td>
</tr>
</tbody>
</table>

C = Cast-in-place screw piles,  
M = Screw pile with casing

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**Figure 11** – Values of unit shaft resistance $r_s$ as a function of $p_b$, $q_c$, or $N_{SPT}$. 
displacement of the surrounding soil due to pile installation results in soil densification.

NeSmith (2003) correlated the installation torque and the drilling tool penetration rate with the capacity of drilled displacement piles. In his approach, the measured fluid pressure of the motor driving tool $I_{fp}$ and the tool penetration rate $P_R$ are normalized with respect to some base values to obtain a torque index $T_I$ and a penetration rate index $P_{RI}$. The product of $T_I$ and $P_{RI}$ is defined as the installation effort $IE$, which can be used to predict the capacity of APGD piles. Although $IE$ could not be correlated well with the base and shaft resistance, a reasonable correlation was reported between $IE$ and the ultimate capacity of the APGD piles tested.

**Discussion on the Design Methods for Drilled Displacement Piles**

A design method should capture as closely as possible the essence of the relationship between pile resistance and both the state and intrinsic characteristics of the soil. As different equipment and procedures are used to install piles, the degree of soil displacement induced on the surrounding soil can differ significantly. There is a pressing need to better understand how the installation of piles changes the state of the soil around them, as these changes reflect directly on the load-carrying capacity of the piles. The effect of pile installation on pile capacity is particularly important for drilled displacement piles because there are many different types of these piles. Vertical and lateral soil displacement and densification occur as the drilling tool (with or without a sacrificial tip) advances into sandy soil, and these changes are a function of the design of the drilling tool and drilling operations. Different drilling tools and different installation procedures also create piles with different shapes. Drilled displacement piles can have either corrugated screw-shaped (Atlas, Olivier) or smooth (Berkel, De Waal, Omega, etc.) shafts. For the same outer pile diameter, a screw-shaped shaft may develop a slightly larger shaft capacity than a smooth shaft on account of passive pressures that might be mobilized in sub-vertical directions, but that has not been quantified or even demonstrated as yet. Empirical methods are directly related to the specific drilling tool employed to install the piles. For example, the method presented by Bustamante and Gianeselli (1993) (Fig. 11) is based on load test results for Atlas piles. However, the shaft and base capacities of other drilled displacement piles will not be the same as those of the Atlas piles, as these quantities depend on the degree of soil displacement and disturbance around the piles caused by installation.

Presently available design methods were all derived from pile load test results performed in a particular area, which means they are only valid for the site conditions for which they were developed. For some types of geologic conditions, the methods are not available. For example, Bustamante and Gianeselli (1998) pointed out that there is a lack of experience with drilled displacement piling technologies in soils like marls, gravels and chalk. There is also a need for design methods to be more discriminating, going beyond just textbook soils (sand and clay). There is realization of this need in practice. For example, NeSmith (2002) proposed a method in which fines content, particle shape and gradation are factors.

Understanding of the fundamental behavior of non-textbook soils (silty sands, clayey sands, and other mixtures of silt, clay and sand between the two extremes of clean sand and pure clay) has been increasing (Carraro et. al., 2003). This knowledge will gradually be incorporated into pile design methods. As an illustration of the benefits to pile design of understanding how the clay content of the soil affects its behavior, consider pile shaft resistance. It is directly related to the large-strain shear strength of soil, which in turn depends on the clay content of the soil. The clay content of the soil determines whether the shaft resistance is related to the residual or critical-state shear strength of the soil. If the clay content of a soil exceeds approximately 50%, the residual strength (the strength at which the clay particles are aligned with the direction of shearing) of the soil is the same as that of pure clay. So shaft resistance depends on the same residual friction angle in both cases. If the clay content is less than approximately 25%, shaft resistance is closely related to the critical-state shear strength (the shear strength at constant effective stresses and constant volume) of the clay-silt-sand soil. This is so because clay particle realignment does not happen for low clay contents. Finally, for clay contents increasing from 25 to 52%, the residual strength of the soil drops towards that of the pure clay (Salgado, 2005).

Another important capability of a pile design method is whether or not it establishes the link between pile capacity, relative settlement, and the pertinent limit states. Ultimately, a pile foundation supports a structure, which must remain serviceable and safe. A design method should allow prediction of ultimate
loads based on such criteria, as opposed to criteria that are arbitrary in nature or ill defined.

Development of a database containing cone penetration test results (performed before and after pile installation) and pile load test results can help improve the prediction capability and consistency of design methods. These load tests should be extended to large pile settlements (certainly in excess of 10% of the pile diameter), and the site must be characterized as fully as possible for the data to be truly useful. Pile instrumentation, which should be at least sufficient for separating base and shaft resistance, is also extremely important. Additional information obtained from installation monitoring would also be helpful.

In summary, future development of pile design methods should (1) account for the particularities of each pile installation method and their impact on the state of the soil around the pile; (2) capture the interaction of the pile and soil in a way that reflects the stress-strain response of the soil, which in turn is a function of the soil state and intrinsic variables; (3) take into account the limit states that must be prevented.

Conclusions

Auger piles, namely auger cast-in-place piles and drilled displacement piles, are used extensively in practice. The advantages of these piles are that their construction is fast, economic and environmentally friendly. These piles, depending on the method of installation, can be classified as partial- or full-displacement piles. Hence, their capacities are greater than that of drilled shafts with comparable length and diameter and, in many cases, approach that of driven piles. The installation methods and the quality control techniques for different types of auger piles were described, and the available design methods based on in-situ test results were presented. Analytical or numerical modeling of the installation of these piles combined with well-designed experiments and systematic monitoring of their installation in construction projects is needed for meaningful advances in analysis and design of these piles.

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References

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