UNCERTAINTIES IN THE PERFORMANCE OF FLIGHT AUGER BORED PILES

F.M.Abdrabbo and M.A. Mahmoud
Structural Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

ABSTRACT

Flight auger bored piles are formed by a continuous flight auger into the ground, and pumping cement/sand grout or concrete down the hollow stem of the auger as its withdrawn. Four loading tests on concrete piles are described. The stability plot method is used to drive the shaft friction and end bearing load components of the pile capacity. This paper outlines features of crucial construction factors that affect the geotechnical capacity of this type of piles. These factors include, vertical speed of auger during boring, grout factor, grout pressure, number of reborings, type of material, and slump of concrete used to form the piles. Two of these factors are highlighted in this paper. It was found that, shaft resistance is independent of grout factor, whilst point resistance increases as grout factor increases. Nevertheless the engineer should decide the safe pile load associated with the most economical grout factor. High vertical speed of auger during boring of piles may cause disaster for the adjacent buildings, due to soil decompression.

INTRODUCTION

The technique of continuous flight auger bored piles has been evolved in the late 1940s, and becomes wide spreed all over the world since 1973.

These piles are formed by boring a continuous flight auger into the ground down to the required depth, followed by pumping down cement / sand grout or concrete through a hollow stem of the auger as it is withdrown. During drilling the auger is advanced, usually, at a steady rate without over loading the power source unless hard soils are encountered. On reaching the required depth, of the pile, the auger is raised up to a certain distance to blown of the stopper in the discharge outlet, this distance is rebored after filling with grout. Sometimes carbide cutting teeth are incorporated to the bottom end of the auger to facilitate the advance of the auger through hard soils. Thus it is clear that the success of auger cast piling method depends, uniquely, on the operator skill. The method has the advantageous of using a compacted, and easy to mobilize machinary, less workers, fast performance and vibrationless. But on the other hand the method has disadvantegeous as it is sensitive to operator control during all different phases of pile construction. Also the auger can not proceed, easily, through filling layers containing boulders of size larger than about a third of the diameter of the auger, so the locations of the piles need to predrilled by percussion, to break off the boulders into small fragments. The method becomes drastic, from economical point of view, if the soil formation contains gallaries, caves, and voids. As an example, it was happend once that the engineer pumped 23 cubic meters of concrete to form a pile of 13 m length and 600 mm in diameter, which confirms, without any, doubt that the auger goes into a gallory or cave such an unanticipated problems which can arise during construction, cause dispute between engineer, contractor, and owner.

The technique for predicting pile capacity has received a great deal of the attention in the past, and with some success, According to this technique, the geotechnical ultimate load of completed pile is usually calculated as the sum of shaft friction and end bearing load components as;

$$P_u = f_s A_s + q_b A_b \quad (1)$$

$$P_u = \sum_{\ell=0}^{\ell=L} \sigma'_{o\ell} A_s k_s \tan k\, \delta + A_b N_q \sigma'_{o\ell} \quad (2)$$

where;

A_s; A_b	are the surface area of shaft and the base area of pile.
$\sigma'_{o\ell}$, $\sigma'_{o\ell}$	are the vertical effective stress at depth l and pile base;
N_q	Bearing capacity factor;
k_s	lateral coefficient of earth pressure,
δ	Angle of wall friction.

The persistent uncertainties in the above equation are in the effect of pile installation on the factor N_q, the value of $k_s \tan \delta$ and the distribution of vertical effective stress $\sigma'_{o\ell}$ along the pile shaft. The factor N_q depends upon the relative density of the soil beneath the pile toe which is affected by the recovery of soil above it. If loosening in soil occurs during pile construction, the end bearing load component may be substentially reduced.

This loosening effect depends on the boring speed and grout factor. Shaft friction is usually calculated by assuming the angle of friction between pile and soil to be less than the angle of friction of soil. Touma and Reese [1] proposed that the shaft friction for piles with length to diameter ratio varies between 13 and 30 may be calculated directly from the effective overburden pressure. Nevertheless, Vesic [2] reported from model tests on long piles that, both base resistance and unit shaft friction reach constant final values at a critical depth of about 15 times pile diameter. Vesic [2] attributed this phenomenon to the arching effect of soil. But it is felt that the arching of soil may be of little effect on the performance of flight auger bored piles, nevertheless the k-value may depends on grout factor, type of grout material and on the slump of used concrete. The effects of grout factor , grout pressure, slump of concrete and type of grout material on adhesion factor along piles installed in clayey soil, are still, also embegous.

Prediction of pile load using sounding test results is not by any way better than using shear strength parameters of soil. The existence of numerous approximate methods, to predict the pile load from sounding test results, may lead to confusion. To investigate the performance of the pile, the two components contributing the pile load, that is to say the shaft friction component and end component resistance must be separated. This can be done either by placing load cells at the pile base while the pile is loaded, or applying the stability plot method proposed by chin [3], using the data obtained from load tests on piles. Roscoe [4] used the latter method, and reported that reboring of pile to full depth, due to blockages in concrete delivery line, affects the pile load in a way that the end bearing load and shaft friction load decrease as the number of rebores increase. The value of $k_s \tan \delta$ reported by Roscoe [4] ranged between 0.31 and 0.68, while the values reported by Neely [5] for cement/sand grout pile decrease from 2.5 as the depth below ground surface increases and approach a constant value of 0.25 at a depth of 26 m (pile diameters ranging from 300 mm to 600 mm). Roscoe [4], also reported that the values of $k_s \tan \delta$ derived from the loading tests on cement/sand grout piles lies between 0.8 and 1.2, while those derived from concrete grout piles lie between 0.31 and 0.68. This is in contradictory with the conclusion reported by Neely [5] in which he found that there is no significant difference between the shaft resistance of cement/sand grout piles and concrete piles. Neely [5] reported also that the volume of grout pumped into the continuous flight bored pile has a marked effect on the performance of the pile. Lee and Poulous [6] carried out loading tests on model instrumented grout piles installed into beds of calcareous sand. From these tests, it was found that the average skin friction decreases with increasing pile diameter, up to pile diameter equal to about 800 mm, but it is felt that the conclusion drawn by Lee and Poulous [6] has a certain limitation with respect to pile diameter. Unfortionatly the installation procdure of model grouted piles is different from that employed in the environment and thus the effects of pile installation on the performance of a pile are still embegous. Thus one can thought that the performance of continuous flight auger pile is affected by different construction factors such as; boring speed, number of reborings, type of grout material, grout pressure , slump of concrete used in grout and grout factor. These factors are not easyly to be modelled, and cosequently need an intensive experimental work to establish their effects, particulary little attention has been given to the auger-cast pile in literature, with the result that there are considerable variation in local practice. Also most of the international codes do not include practical way of design of auger-cast piles, although these piles are wide spreed now all over the world.

The paper is aimed to study the effects of one or two of the above mentioned construction factors on the performance of flight auger piles. This will be carried out using field data collected from two different sites.

SITE NO. 1

SOIL CONDITION

The soil condition at the site was obtained from two sources of geotechnical information, shell and auger borings with standard penetration test and mechanical static cone penetrometer. The site is 17 m by 24 m. Classification of the extracted undisturbed soil samples reveals the following soil strata; a top layer of fill comprising mixture of sand and small pieces, up to 10 mm, of crushed stones, trace silt; the domenant of this formation is calcareous sand. The fill layer, which extends down to a depth of 9 m, overlies layer of sandy silty clay extends down to 12 m. The second layer overlies a bed of medium to coarse calcareous sand and pieces of cemented sand. Figure (1) illustrates a detailed description of soil samples recovered from one of the two shell and auger borings conducted at the site. The soil formation at the two boreholes are relatively identical. Standard penetration test results are presented in Figure (2).

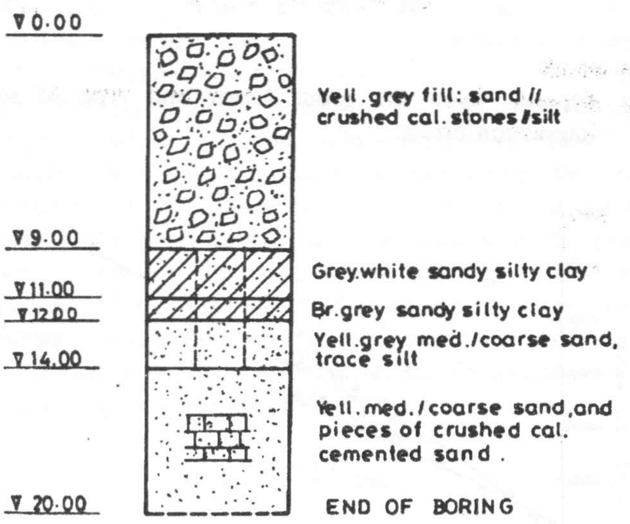

Figure 1. Soil profile.

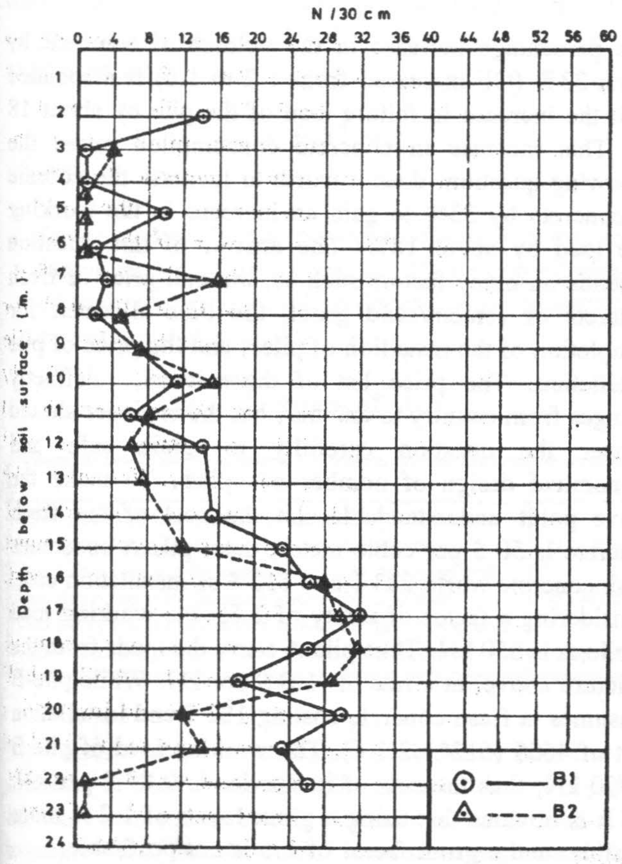

Figure 2. Standard penetration test results.

The scattering in individual test results through the top fill layer may be attributed to the existence of calcareous stone. Figure (3) illustrate a typical results obtained from mechanical dutch cone penetrometer at the site. These tests were conducted at four locations and show approximately similar results. From the above geotecnical informations the length of the pile was decided to be 16 m below ground surface, and the working load of a pile having 500 mm diameter is 700 kN. Flight auger piles using concrete grout, were adopted.

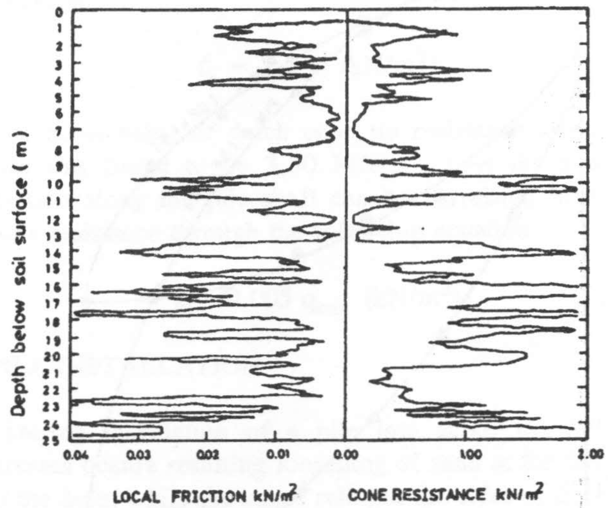

Figure 3. Cone penetration test results.

PILE LOADING TEST

Two pile loading tests were carried out in accordance with ASTM D-1143 reaching a maximum test load of twice the working pile load, in one cycle. One of these tests was conducted on pile deliberately grouted by an amount of concrete equal to 1.6 times its theoretical volume pile-A, while the other test was conducted on a pile grouted by an amount of concrete equal to 1.2 times its theoretical volume, pile-B. These ratios were expressed by Neely [5] as grout factor. The aim of the tests is to investigate the effect of grout factor on the performance of these piles, and to evaluate an economical design procedure of the number of piles in a project. Also to focus the uncertainties in the current empirical design methods implied in calculating the ultimate pile load.

Figure (4) shows the achieved results from the loading tests on the two piles, pile-A and pile-B. The two piles were constructed using the same drilling equipment, drilling speed, grout pressure, and grout equipment with the exception that the volume of concrete pumped down through the hollow stem to form the two piles is different. The large volume of concrete was achieved by cessing withdrawal of auger whilst the concrete is pumping down to the hollow stem. Figure (4) indicates that up to 86 % of the pile working load there is inappreciable effect of the grout factor on the load - displacement relationship of the two piles .

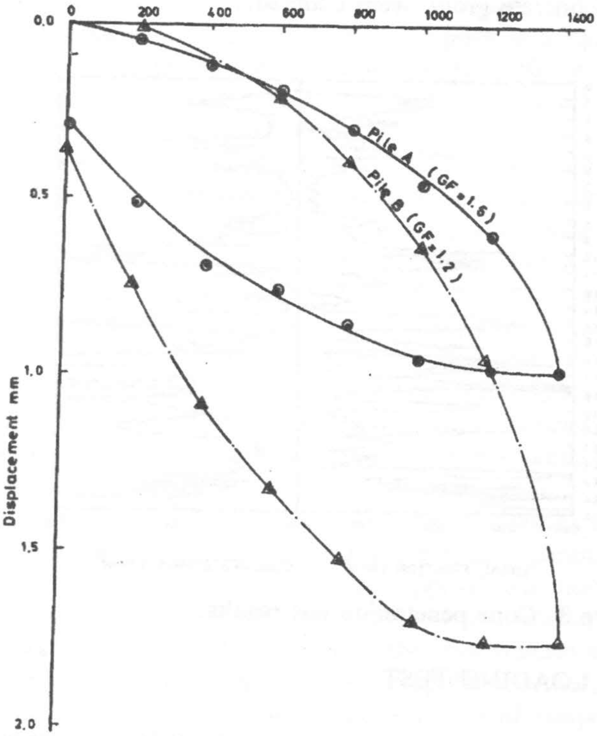

Figure 4. Pile loading test results.

The stability plot method, Chin [3] which is based on the assumptions that the relationship between applied load P and the pile movement Δ is hyperbolic, and a plot of Δ/P versus Δ is linear, was used for predicting the ultimate pile load of the two piles, Figure (5). Figure (5) enabled us to predict , also, unambiguously the shaft and base loads. From the plot, Figure (5), the following was obtained: for pile with grout factor 1.2, pile-B, the shaft load , the base load and the failure load are 0.43 MN, 1.36 MN and 1.79 MN respectively, and for pile with grout factor 1.6, pile-A, these loads are 0.43 MN, 1.69 MN and 2.12 MN respectively. Thus the increase of grout factor from 1.2 to 1.6 (33%) increases only the base load by 24% without any noticeable affect of the shaft load. The percentage increase in failure load is 18 %. Thus one can conclude that the base load Q_b of the pile depends upon the grout factor (GF), this can be expressed as;

$$Q_b = A_b\, N_q\, \sigma'_{ol}\, \mu \quad (2)$$

in which

μ depends upon the grout factor and type of soil interaction effect.

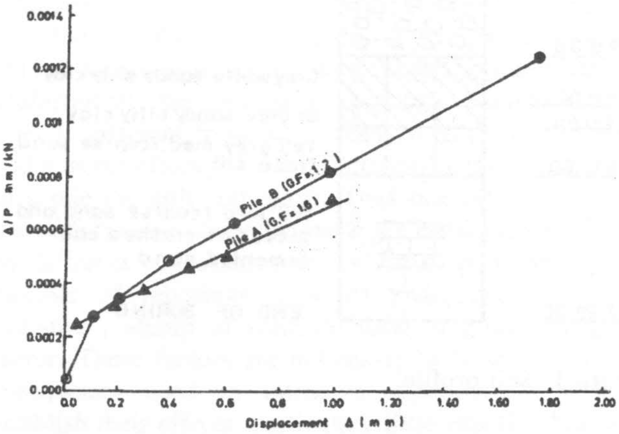

Figure 5. Displacement vs Δ/P.

The percentage increase in the volume of concrete by about 33% (GF increased from 1.2 to 1.6) is associated with the increase in failure load of the pile by about 18 %. This increase in concrete consumption raises the following question; does it worth to increase the volume of concrete by 33% to gain an increase in the working pile load by about 18%. The answer of this question depends on many factors such as, the unit price of fresh concrete or cement/sand grout, the time allocated for completion of the installion of piles, and the price of pile installation. The price list of these items, definetly changes from country to another, but the engineer should answer the question carefully to attain safe and economical design of number of piles. To make the above point understandable, let the cost of the fresh concrete is 50 $ per cubic meter, thus, pile-A consumes fresh concrete worth 243 $ and 612 $ as installation cost. Considering a factor of safety of 2.5, the working load of pile-A is 850 kN. Thus pile-A serve the loads from the structure above, at a rate of 1.0 $ per kN. While pile-B consumes a fresh concrete costing 182 $ and installation cost of 460$ (612*1.2/1.6). The working load of pile-B is 720 kN, thus the cost of its service is 0.89 $ per kN. So, it is obvious that using a grout factor of 1.2 is more sensible, and a grout factor of 1.6 is not profitable.

The ultimate point resistance of pile-A and pile-B is 8.62 kPa and 6.93 kPa respectively. To correlate these values with the dutch cone results, a mean value q_{cm} of the tip cone resistance along a specified distance at the pile base was implied, Table (1). Table (1) illustrates the correlation factor q_b/q_{cm} ,for q_{cm} averaged along different distances at the pile base.

In Table (1) the lower values of q_b/q_{cm} are obtained for pile-B while the higher values for pile-A. Table(1) indicates that the uncertainty in calculating the tip resistance of a continuous flight auger bored piles twofold; the grout factor, and the distance at the pile base, overwhich the mean value of q_{cm} might be calculated. But, if the effect of grout factor on the base resistance is excluded, and by considering a grout factor of 1.2, which is the practical case, the tip resistance of the pile may be correlated to dutch cone tip resistance as;

$$q_b = 0.57\ q_{cm} \qquad (3)$$

Where

q_{cm} is the average cone tip resistance over a distance of four times the pile diameter below the pile base and four times the pile diameter above the pile base. If the effect of grout factor is considered, the tip resistance may be expressed as;

$$q_b = 0.57\ q_{cm}\ \mu \qquad (4)$$

where;

μ factor depends upon the type of soil and the grout factor, equal to 1.4 for pile-A. Thus the performance of flight auger bored pile is dependent on construction procedure that is used.

Table 1. values of q_b/q_{cm}

Distance equal to	q_b/q_{cm}
Four times the pile diameter below the pile base and four times the pile diameter above the pile base.	0.57-0.80
Two times the pile diameter below the pile base and four times the pile diameter above the pile base.	0.57-0.80
Two times the pile diameter below the pile based and eight times the pile diameter above the pile base	1.29-1.7

The mean value of standard penetration test over a distance of four times the pile diameter below the pile base and four times the pile diameter above it is 24. This average value was measured from sounding tests at four locations at the site without any correction. Thus the tip resistance of pile-B can be correlated to N values as,

$$q_b = 288\ N\ (kN/m^2) \qquad (5)$$

and for pile A, with grout factor of 1.6,

$$q_b = 288\ N\mu \quad (kN/m^2) \qquad (6)$$

Where

μ factor defined as above

The average friction along pile-A or pile-B is 17.1 kN/m^2, and the mean value of standard penetration test along the pile is 8. Thus the average friction along the pile may be correlated to N value through the following equation;

$$f_s = 2.0\ N\ (kN/m^2) \qquad (7)$$

The mean value of dutch cone tip resistance along the pile was found to be 3.30 MN/m^2, thus the average friction along the pile shaft can be correlated to dutch cone resistance through the following equation.

$$f_s = 0.005\ q_{cm} \quad (kN/m^2) \qquad (8)$$

PILE INSTALLATION

During installation of a pile into sand, a relief of stresses occurs resulting loosening of sand at the bottom of the hole, while the stress relief at the sides of the hole is less affected since these sides are supported at all times with soil-filled auger. Available literatures have not any measurements in loosening of soil due to boring using continuous flight auger. But accidentally, it was observed that during construction of piles at the mentioned site a tilt of an adjacent reinforced concrete skeleton-type building of 24 m high was occured towards the working area. The building is resting on plain concrete piers of unknown depth. At this instant, it was found that the piling contractor, just construct about twenty piles in the farthest side of the site with respect to the adjacent building, that is to say at about 16 m away from the building. These piles were bored at a speed of 1.6 m/min, and filled with concrete using a grout factor of 1.2 . The tilt of the building was monitored, and the boring speed of the subsequent piles was reduced to 0.6 m/min and filled with a sufficient amount of concrete, the grout factor was found to be 1.6. The installation order of the piles was altered to resume at the nearest side to the building. After construction of few piles, it was found that the tilt of the building was ceased. The tilt of the building indicates, inevitably by a qualetitative manner that loosening of soil takes place during boring of piles, with relatively high speed, and this loosening decreases as the boring speed decreases , and as the grout factor increases. No doubt that this decompression of soil affects the geotechnical ultimate pile load. And in order to determine this load the decompression effect must be evaluated quantitively, which is not feasible up to now.

SITE NO. 2

SOIL CONDITION

Soil samples recovered from two borings conducted at the site using shell and auger, reveal different soil stratigraphy from that reported at site No.1, in a way that the top layer is fill comprising sandy clay, and clayey sand extends down to a depth of 3.0 m overlies a layer of soft clay extending down to a depth of 5.3 m. At that depth a layer of silty sand extending down to a depth of 9.0 m was encountered. This layer overlies a bed of medium to coarse calcareous sand, Figure (6). The sand bed was explored down to a depth of 20 m. A discontinuous layer of very weak cemented sand was encountered at a depth of 11 m and extending down to a depth of 14 m. Standard penetration test results indicated unreliable values, and these results were disregarded. The second source of geotechnical information was obtained using mechanical dutch cone penetrometer. The tests were carried out at two locations at the site and the cone tip resistance and local friction were recorded down to a depth of 22m, Figure(7).

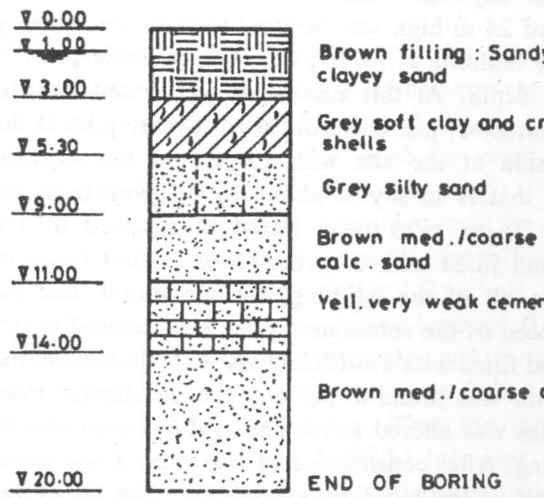

Figure 6. Soil profile.

It was decided to use 500 mm diameter continuous over flight auger bored piles the length of the pile was designed, by mistake, to be 11 m depth and the working load is 750 kN. The concrete were used to form the pile, with a grout factor of 1.2 .

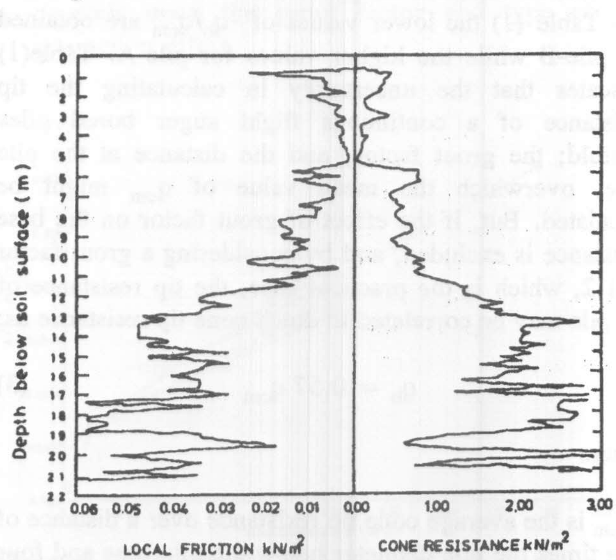

Figure 7. Cone penetration test results.

LOADING TESTS

Two piles were chosen to be tested, one up to 1150 kN and the other up to 950 kN. There is no obvious reason for the difference in pile test load except that the engineer was suspicious about the pile load. Test loading was commenced once the concrete had reached a strength of 2.5 MN/m^2. None of the piles was instrumented with strain gauges and the loading test results revealed only load-movement curve measured at the head of the pile. Test loadings generally followed that given by ASTM D-1143, but in two cycles of loading and unloading, Figure (8). Stability plot method was used to predict the ultimate shaft load, ultimate base load, and failure load, Figure (9). From Figure (9) it can be predicted that the failure load, ultimate shaft load, and ultimate base load are 1.21 MN, 0.57 MN and 0.64 MN respectively. The corresponding mean skin and tip resistance are 0.033 kPa and 3.26 kPa respectively. The average friction along the pile shaft can be correlated to the mean dutch cone tip resistance CPT along the pile as

$$f_s = 0.015\, q_{cm} \ (\text{kN/m}^2) \quad (8)$$

The tip pile resistance, is also, correlated to the mean dutch cone tip resistance q_{cm} averaged along different distances at the pile base, Table (2).

Table 2. Correlation of q_b / q_{cm} .

Distance equal to	q_b/q_{cm}
Four times the pile diameter below the pile base and four times the pile diameter above the pile base.	0.32
Two times the pile diameter below the pile base and four times the pile diameter above the pile base.	0.42
One diameter below the pile based and four times the pile diameter above the pile base	0.47

It is clear, again, that the correlation factor depends upon the distance at the pile base overwhich the mean value of cone tip resistance was averaged. Nevertheless a reasonable correlation may be expressed as;

$$q_b = 0.4\, q_{cm} \qquad (10)$$

Which is corresponding to the case of mean value of q_{cm} over a distance of two times the pile diameter below the pile base and four times the pile diameter above the pile base.

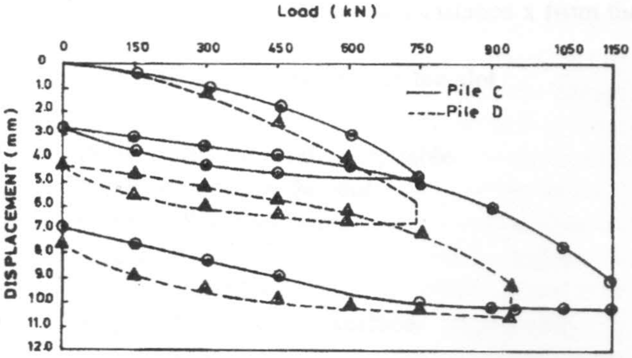

Figure 8. Loading test results.

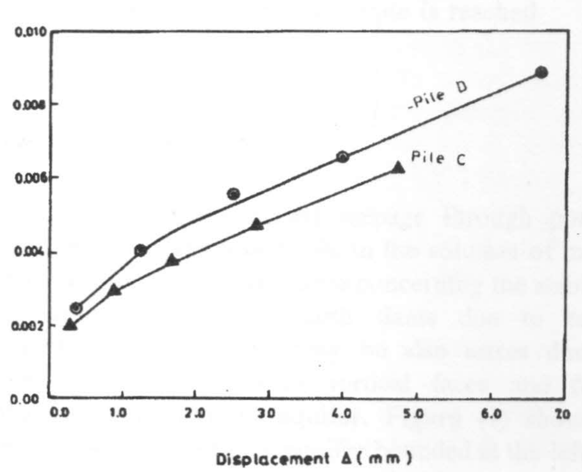

Figure 9. Displacement vs Δ/P.

CONCLUSIONS

1- Fast drilling of a pile using continuous flight auger produces decompression of soil. The side effect of this decompression on the behaviour of an adjacent building was qualitatively evaluated.

2- There are many factors in addition to the geotechnical properties of soil, that affect the performance of flight auger bored piles, some of these are : boring speed, number of reborings, grout material, grout pressure, slump of fresh concrete, and grout factor. The last factor was previousely investigated by Neely [5] and confirmed in this work, But one should select the most proper grout factor. The other factors need an intensive experimental and theoretical work.

3- The grout factor affects the base resistance of flight auger bored pile in a way that this resistance increases as the grout factor increases. The obtained results indicated that the grout factor has inappreciable effect on the shaft resistance of the pile.

4- The tip resistance of flight auger bored pile installed in sand may be correlated to mechanical dutch cone tip resistance as; $q_b = (0.4\text{-}0.6)\, q_{cm}$, while the mean shaft resistance of piles installed in sand can be correlated to mechanical dutch cone tip resistance as; $f_s = 0.005\, q_{cm}$; and for piles installed in clays as; $f_s = 0.015\, q_{cm}$.

5- Using standard penetration test, the tip and shaft resistance of flight auger bored piles installed in sand may be correlated as;
$q_b = 300\ N\ (kN/m^2)$
$f_s = 2.0\ N\ (kN/m^2)$

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