The Load Capacity of Driven Cast In-Situ Piles Derived from Installation Parameters

D. Egan
Chief Engineer, Keller Foundations

ABSTRACT: The theoretical estimation of the ultimate capacity and serviceability performance of common displacement foundation systems such driven cast in-situ (DCIS) piles is difficult due to the huge disruption in soil structure and insitu stress regime caused by the installation process. Even though much research effort is expended on complex numerical modeling and reduced scale laboratory or centrifuge modeling there remains the difficulty of translating the knowledge gained into practical prediction tools appropriate for routine design and installation of the full size product in the field. So to advance and validate the conclusions drawn from numerical and small scale research the third strand of measuring and analysing full size field behaviour must be added. This paper will summarise recent advances made in the field measurement and analysis of installation parameters to predict the load capacity of driven cast in-situ piles. The results from installation and testing of a DCIS pile is used to illustrate the methodology now being routinely by Keller Foundations in the UK. The conclusions drawn from this paper are already raising the standard of reliability, efficiency and sustainability of DCIS piles on routine projects.

1 INTRODUCTION

The driven cast in-situ (DCIS) piling method has been in use for many decades and has over this period demonstrated its effectiveness and efficiency. Examples of more recently completed large structures supported on DCIS piles installed by Keller in the UK include the O2 Arena (constructed within the Millennium Dome – itself supported in DCIS piles) and the London 2012 Olympic stadium.

The body of published literature relating to the design of DCIS piling is not large. Neely (1991) created a database of load tests on DCIS piles with expanded bases and developed correlations for design. Evers et al (2003) provided a useful study for the performance of DCIS piles compared to CFA piles at a site in France and Flynn et al (2012) present a case study for the performance of a DCIS test pile at a site in London.

Development of a complete theoretical model for the design of DCIS piles is complicated by the very significant disruption in soil structure and insitu stress regime caused by the installation process. Even the selection of appropriate soil parameters for use in design equations from ground investigation tests is problematic due to the state changes occurring during pile installation.

Even though much research effort is expended on complex numerical modeling and reduced scale laboratory or centrifuge modeling there remains the difficulty of translating the knowledge gained into practical prediction tools appropriate for routine design and installation of the full size product in the field. This paper considers a method to estimate DCIS geotechnical capacity based on installation parameters measured during the installation of a pile by modern instrumented piling rigs.

2 MODERN DCIS PILING EXECUTION

In recent times advances in piling rig instrumentation and telecommunications have enabled a new level of sophistication in the recording of installation parameters and this opens up the potential of assessing pile capacity in real time.

DCIS design using a static design approach, based on ground parameters derived from boreholes and laboratory testing has for many years been the approach used to estimate ultimate pile capacity, but, as noted above, this approach has its difficulties. At the start of execution of piling, trial drives, are undertaken to validate the ground conditions are as envisaged in the initial design. (Historically with manual counting of the number of hammer blows to achieve a given penetration.) The control criteria can then be set for installation of the production piles. Where required this can be supplemented with project specific static load testing to support and validate the achieved pile load capacity. While this approach has been used satisfactorily for the installation of hundreds of thousands of piles over many decades, modern instrumentation now allows both robust and detailed control and feedback of the pile driving process, in real time, for every pile installed.

On modern instrumented DCIS piling rigs the energy delivered to each pile can now be measured and used to validate that pile's ultimate load capacity. As the pile is driven the driving parameters (drive energy, drive tube depth and rate of advancement) are displayed to the rig driver giving a high degree of control to the installation process. Additional benefits of an automated electronic data capture system include a reduction of manual recording and on-site paperwork (which requires a finite manpower resource), robust archiving of records and real time access to installation data remote from the work site.

From the experience of developing a large database of systematically acquired pile installation data it has been possible to map the process required to allow real time assessment of pile capacity. Initially focused on piles founded in granular soils an empirical approach has been developed which has been used to validate, in near real time, the adequacy of DCIS piles as they are driven. Of course these advances should be seen in the context of dynamic pile driving formulae which have been used on preformed piles for many decades. Not withstanding widespread the use of set calculations for pre-formed piles, their applicability (and reliability) for driven cast in-situ piling, where the drive tube is firstly driven into the ground and then removed and replaced by cast in place concrete, is highly questionable.

The development of real time assessment of DCIS pile capacity for piles driven into coarse grained soils is presented in detail below. This method has been developed over a period of time and is based on drive data and load test data carried out on a series of sites. However to better illustrate the process reference to a single test pile (TP3) installed at a site in Erith, London is made.

3 DESCRIPTION OF TEST SITE

The test site was located within the Thames basin to the south of the river at Erith, London. The ground conditions comprised a mantle of Made Ground, overlying soft and very soft clay and peat Alluvium. The piles were founded in coarse grained River Terrace Deposits (RTD) comprising medium dense to very dense gravelly sand. Thanet Sand was found beneath the RTD. Figure 1 shows a typical bore hole for the site. The Made Ground and Alluvium were not considered as contributing to the pile geotechnical capacity, but rather a source of potential negative skin friction, they are ignored in the assessment of ultimate pile capacity for design purposes.

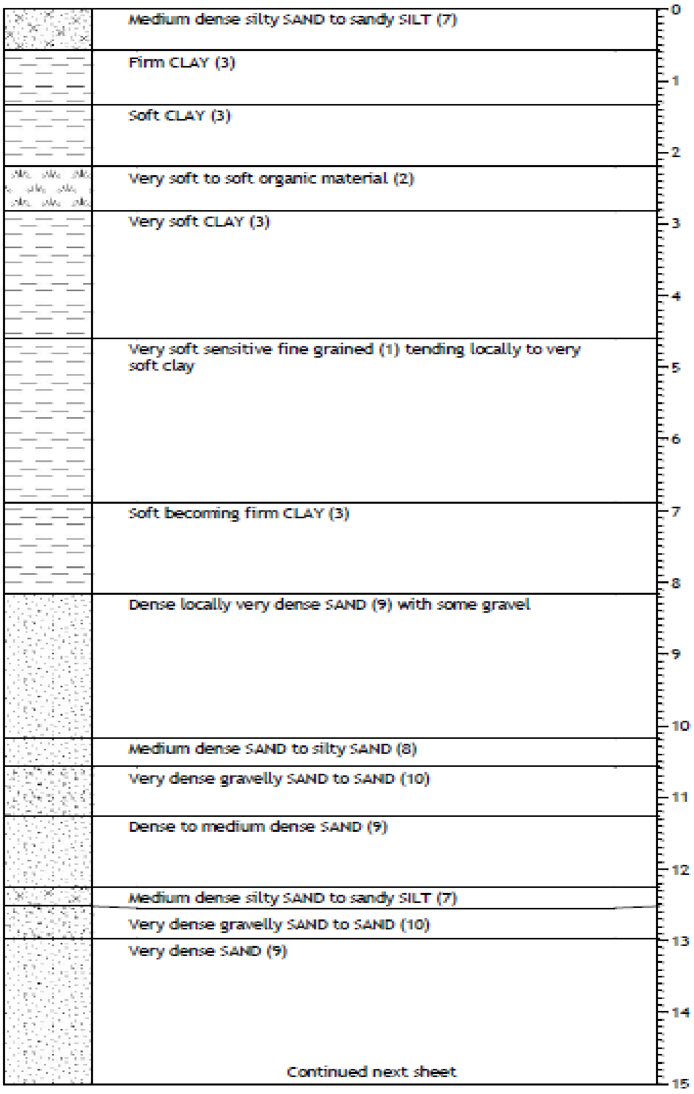

Figure 1 Typical Borehole from the test site.

4 DRIVEN CAST INSITU PILE INSTALLATION

Figure 2 illustrates the pertinent features of the DCIS system. A steel drive tube, closed at the base by a sacrificial base plate, is top driven to the required depth. The steel tube is then charged with a free flowing concrete and withdrawn from the ground. Steel reinforcement can be inserted in the pile bore before or after the concrete is placed. The requirements for the execution of DCIS piles are set out in EN 12699 'Execution of special geotechnical works – Displacement piles'. In addition Keller monitor all aspects of the installation process by on-board computer, with the key parameters for capacity assessment being the hammer energy imparted for each blow, the rate of advancement of the tube per blow and the tube and base plate geometry. The recorded data are instantly fed back to the design office by modem enabling secure backup of the information as well as providing the facility for the design engineer to see feedback on the ground conditions encountered immediately the pile is completed.

5 RECORDED INSTALLATION PARAMETERS

From the recorded parameters the tube drive resistance with depth is calculated, where Ru is the drive resistance, N is the hammer energy, s is the rate of tube advancement per hammer blow and c is the elastic compression of the tube.

$$R_u = \frac{f_1 f_2 N}{\left(s - \frac{c}{2}\right)}$$

The factors f_1 and f_2 are hammer and energy transfer efficiency factors. The elastic compression of the drive tube is calculated using the following equation, which is based on the Danish pile driving formula, and where N is the hammer energy, L is the tube length, A is the cross sectional area of the tube and E the elastic modulus.

$$c = \sqrt{\frac{2 f_1 f_2 N L}{AE}}$$

Figure 3 shows the drive resistance, Ru, plotted with depth for TP3 and the four associated anchor piles used for reaction in the subsequent maintained load test. The piles were DCIS piles of nominal diameter, d, of 340mm with a base plate diameter, d_b, of 380mm. TP 3 was driven fractionally over 11.0m (11.01m) and the anchor piles to 15m.

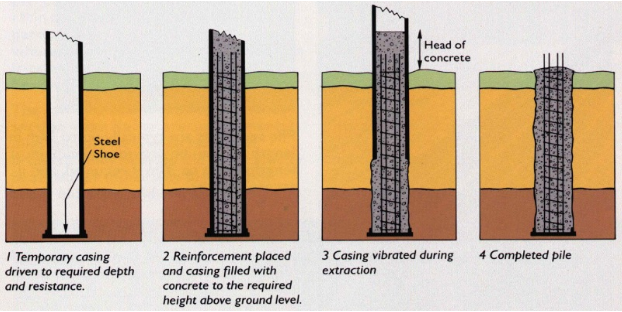

Figure 2 The DCIS installation process.

The Made Ground and Alluvium proved to be of very low strength which drive tube easily penetrated with little energy required. The RTD was encountered at around 8.25m depth as indicated by a sharp increase in drive resistance to between 500kN and 700kN as shown in Figure 3. This corresponds to medium dense to dense gravelly RTD. Below 12m the anchor piles encountered a further sharp increase in drive resistance to around 2300kN at 15m, which is thought to coincide with the top of the Thanet Sand at this location. The test pile was intentionally stopped within the medium dense zone so as to ensure geotechnical failure during the maintained load test.

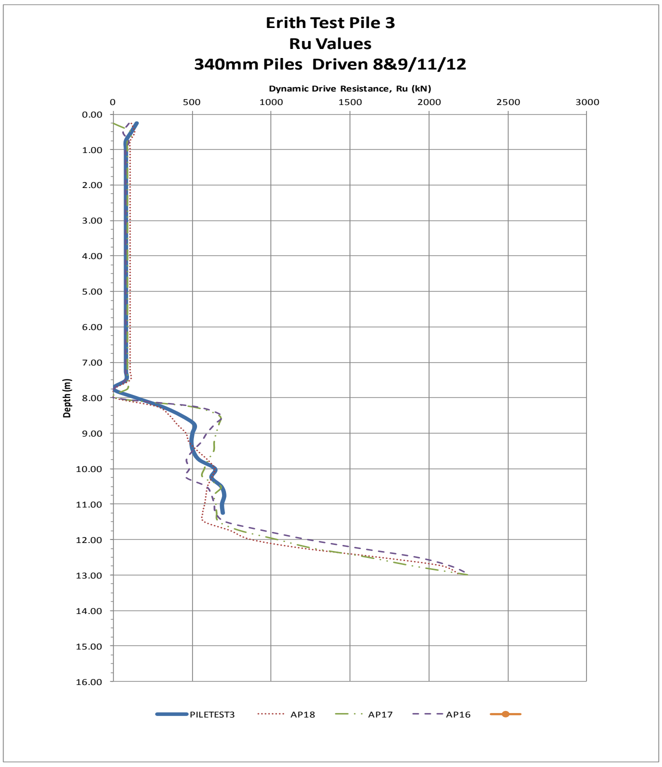

Figure 3 Dynamic drive resistance, Run, plotted with depth.

6 CORRELATION OF PILE INSTALLATION PARAMETERS WITH SOIL PARAMETERS

The installation of each pile where state of the art instrumentation is used can be considered as a form of large scale ground investigation test from which ground parameters may be derived. Dividing the drive resistance by the area of the base plate, A_b, gives the bearing pressure, q_{pc}, at the pile toe.

$$q_{pc} = \frac{R_u}{A_b}$$

Taking q_{pc} to be analogous to the cone resistance, q_c, obtained by a static cone penetration test a ready and quick evaluation of the nature of the ground into which the pile is being driven can be obtained. In developing the analogy between q_{pc} and CPT q_c factors leading to energy losses within the drive/tube system such as frictional losses along the drive tube shaft, rate effects and size effects have all to be considered.

Field tests using dynamic pile driving analysis have been undertaken to assess the loss in energy between the point of impact of the hammer at the top of the drive tube and the pile base plate.

The ratio of the area of the base plates of different sizes of DCIS pile and a standard CPT range between 26 and 6, and taken in the round this is considered beneficial. One of the characteristics of the CPT, especially in coarse soils, is the propensity for the tip resistance to be influenced by larger soil particles (or localised weaker or softer layers) in the soil. In contrast the larger diameter of the DCIS base plates stresses a greater depth of soil leading to somewhat of lower bound (and safe) smoothing effect when compared to the CPT q_c. Indeed the zone of soil stressed beneath the pile toe at the end of driving is exactly that which will be stressed by the finished pile in the working condition. (This is in the context of a single pile, where piles are grouped such that they interact suitable consideration of group effect must be made in the design.)

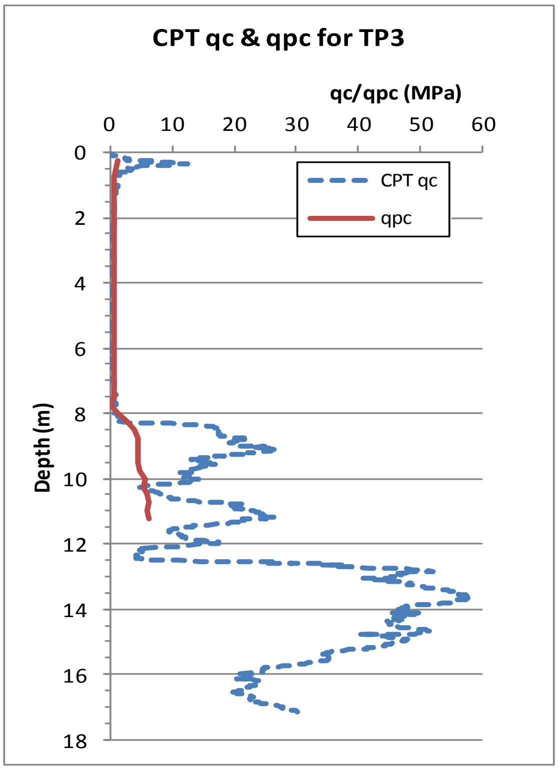

Figure 4 Comparison of q_c and q_{pc} for TP3.

Figure 4 compares q_c from a CPT test undertaken about 4m from TP3, and pile toe bearing pressure, q_{pc}, and illustrates the lower bound averaging effect of q_{pc} compared to the CPT q_c values.

Once q_{pc} is derived a correlation with effective angle of friction, ϕ', may be made, for example using the method shown in Lunne et al (1997).

From the measured drive resistance, R_u, the dynamic bearing pressure, q_{pc}, is derived and correlated to in-situ angle of friction for the gravelly sand founding stratum. Figure 5 shows the derived angle of friction over the socket length of TP3 driven into the RTD.

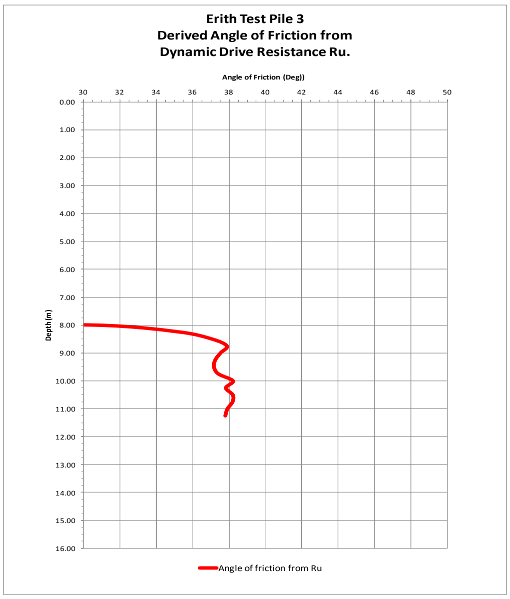

Figure 5 Angle of friction, ϕ', from drive resistance R_u.

7 ESTIMATE OF PILE CAPACITY FROM INSTALLATION PARAMETERS

The ultimate pile socket capacity, Q_{ult}, comprising a shaft component, $Q_{s,ult}$, and base component, $Q_{b,ult}$, may now be derived using standard soil mechanics principles, where:-

$$Q_{ult} = Q_{s,ult} + Q_{b,ult}$$

$$Q_{ult} = \beta.\sigma'_v.\pi.d.l + N_{q.}\sigma'_v.A_b$$

The above equation is readily implemented in commercially available software or spreadsheets. The program Oasys Pile, using the angles of friction shown in Figure 5 and the Berezantzev formulation for the bearing capacity factor, N_q, (Oasys Pile user manual, 2012) was used to give:-

$$Q_{ult,socket} = 217\text{kN} + 1763\text{k} = 1980\text{kN}$$

Test Pile 3 was subjected to a maintained extended proof load test to failure following the procedure outlined in the ICE Specification for Piling and Embedded Retaining Walls (2007). Figure 6 shows the load settlement response. A plunging failure of the pile under an applied load, Qf, of 1947kN and at a displacement of 45mm was observed.

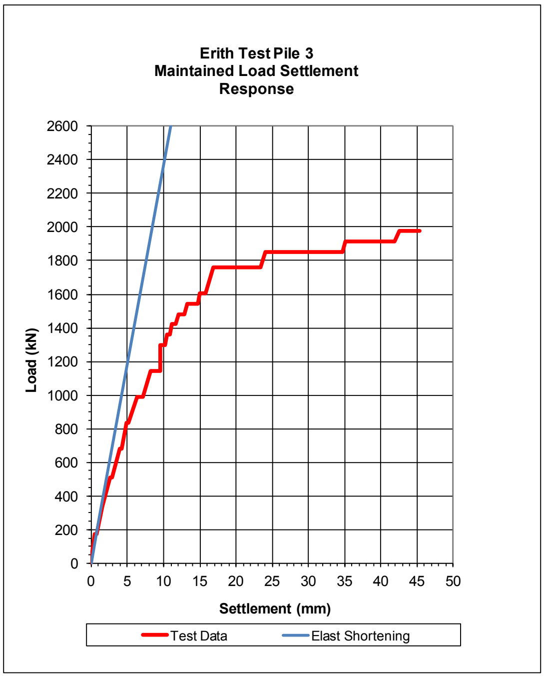

Figure 6 Load settlement response of Test Pile 3.

In the analysis of the pile test results the temporary hold up resistance generated over the pile shaft passing through the made ground and alluvium was estimated at 80kN, which must be added to $Q_{ult,socket}$ as calculated in Oasys Pile to give the true anticipated theoretical pile capacity of 2060kN.

Thus the pile under test achieved 94% of its theoretical capacity which is considered an excellent correlation between the calculated capacity and that shown by the static load test.

The results of the illustration of the installation and load testing of pile TP3 show that a rational procedure to assess the ultimate capacity of DCIS piles located in coarse grained soils based in pile installation data is available.

8 CONCLUSIONS

Driven cast in-situ piling has proved a popular and efficient piling method over many decades, which, in suitable ground conditions, produces piles of high capacity and efficiency. Recent developments in rig instrumentation have enabled the routine and systematic acquisition of high quality installation records. The benefits of an automated electronic data capture system include a reduction of manual recording and on-site paperwork (which requires a finite manpower resource), robust archiving of records and real time access to installation data remote from the work site. In addition Keller has demonstrated the development of a real time validation method for DCIS piles is viable. A rational link between the installation parameters, fundamental soil parameters relevant after pile installation, the physical mechanisms of load generation and observed load capacity has been established.

These developments in the driven cast in-situ piling process have lead to improved efficiency (and hence sustainability) of the DCIS method.

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