REAL TIME VALIDATION OF DRIVEN CAST IN-SITU PILES

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Abstract Construction clients want their foundation solutions to be right first time, every time; but it is often the geotechnical contractor who carries the most risk in achieving this. Robust validation to ensure that the installed geotechnical product is appropriate for the encountered ground conditions, will perform as required and be correctly measured for payment and record purposes is very important to minimise the contractor's and the client's risk. This paper outlines the development and operation of a robust real-time installation monitoring system which controls and validates the installation of driven cast in-situ (DCIS) piling. Using state of the art information technology the system allows the design engineer to interrogate the data acquired from the piling rig via his computer as the piles are completed. The use of the validation process, where data acquired during the driving of DCIS piles can be processed to estimate the finished pile performance, will be explained with reference to a new case study on large diameter DCIS piles. Examples of the routine use of the system will be presented to illustrate how automated monitoring of installation parameters can be used to raise the standard of reliability, efficiency and sustainability on piling projects. The conclusions to the paper will cover the key features and operational challenges characterising real-time monitoring of the execution of geotechnical works as developed from a number of years of experience of using a rig based data acquisition instrumentation system.

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INTRODUCTION

Driven Cast In-Situ (DCIS) piles have a long and successful history of use worldwide. The process, where a temporary steel drive tube, sealed at the bottom with a sacrificial base plate, is driven into the ground and filled with concrete before the tube is withdrawn, is well known (BS EN 12699, 2001 and Egan, 2013). Examples of large structures supported on DCIS piles installed by Keller UK include the Millennium Dome (now the O2 Arena) and the 2012 Olympic stadium in London.

In recent times advances in piling rig instrumentation and telecommunications have enabled a new level of sophistication in the recording of installation parameters and the validation of pile performance. It is now possible to embed these features into the DCIS design and installation process which has improved the quality and efficiency of DCIS piling.

This paper summarises the development and operation of a real time data acquisition and processing system for DCIS piling, but which is equally applicable to other forms of driven piling (for example concrete precast piling).

The Drivers for Development

The drivers for the development of an automated data acquisition and processing system include:-

- Utilization of existing technology to modernize and increase efficiency and reliability of the recording of pile installation parameters such as driven length, set, number of hammer blows, hammer drop height and details of the pile section size. Historically these data were recorded in site notebooks or in similar paper format, which in inclement weather was a challenge in itself. Certain aspects of the manual recording approach suffer from an inherent error budget, for example measurement (or estimation) of hammer drop height and set, due to a variety of reasons including the environment, the weather and the individual taking the reading. Repeatable parameter measurement using electronic instrumentation improves considerably the consistency and reliability of the data acquired.

- Reducing the time period between the completion of a pile and availability of the installation data to interested stakeholders (project managers, designers etc.).

- Development, with time, of an historic data base of easily accessible installation information acquired from numerous projects in different locations which can be used for reference when designing future schemes.

Of course the advances described in this paper should be seen in the context of the use of dynamic pile driving formulae that have been used on pre-formed piles for many decades. However widespread the use of set calculations their applicability (and reliability) for driven cast in situ piling, where the drive tube driven into the ground is removed and replaced by cast in place concrete, has received little attention in the literature.

DESCRIPTION OF THE SYSTEM

Monitored Parameters

The key parameters required for complete description of an installed DCIS pile are:-
- Pile location, geometrical dimensions (drive tube and shoe diameter and length) etc.
- hammer impact energy (historically defined by hammer mass, drop height with an allowance for energy losses);
- penetration resistance (historically described as the set and measured in blows per unit of penetration).

The system described here records the pile reference number and geometry, hammer mass, number of hammer blows and the hammer velocity for each blow, the depth of penetration of the pile, the penetration per hammer blow, and time.

Data Processing

The monitored parameters must be processed to give them a real-world meaning. The key parameters of interest are time, pile length, pile diameter, and drive resistance. From knowledge of the prevailing ground conditions the performance of the completed pile can then be predicted and validated against the contractual requirements.

From the above list the calculation of the dynamic drive resistance, $R_{u,}$ and correlation to the load settlement performance of the completed pile is the most valuable aspect of the system described here.

Calculation of Dynamic Drive Resistance

Dynamic drive resistance, R_u, is the correct term that should be used to describe the resisting force the pile must overcome to be able to penetrate into the ground.

The term *set*, although routinely used, should be avoided. Fellenius (1999) describes *set* as the penetration for one blow, sometimes a series of blows. On its own the *set* tells us nothing of the ground resistance until the energy imparted to the pile, from the hammer, minus any losses, is known, and hence, because it is incomplete, the term *set* will be not be used further.

The term dynamic drive desistance R_u, defined as the energy required to advance the pile a unit length into the ground, (measured in kN) provides a much more satisfactory parameter to work with.

From the recorded installation parameters the tube drive resistance with depth is calculated, where R_u is the dynamic 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.

$$R_u = \frac{f_1 f_2 N}{\left(s - \frac{c}{2}\right)} \qquad \text{Eq. 1}$$

The factors f1 and f2 are hammer and energy transfer efficiency factors. In practice it is difficult to separate these two factors out. Extensive dynamic testing during drive tube installation has enabled the energy losses when driving DCIS piles to be quantified.

The elastic compression of the drive tube is calculated using equation 2 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.

$$c = \sqrt{\frac{2 f_1 f_2 N L}{AE}} \qquad \text{Eq. 2}$$

As a pile is driven these data are recorded by the rig computer, processed and displayed on a screen as a profile of drive resistance, R_u, with depth. The rig operator then controls the installation of the pile to achieve the predefined installation criteria which are set to ensure the required pile performance under load is achieved for the prevailing ground conditions.

The method to define the installation criteria has been refined over a number of years on the back of extensive site testing using instrumented and non-instrumented piles (Flynn et al., 2012, Flynn et al., 2013, and Egan, 2013)

Data Transfer

Once acquired the data for the installation of a given pile it is transferred through to the Keller computer servers as shown in Fig. 1. Not only is a systematic, robustly archived, database of piling records established, but the data are instantly available to the engineer in their office via their computer. The acquired data may be summarised graphically or interrogated within a spreadsheet.

USE OF INSTALLATION DATA TO VALIDATE PILE PERFORMANCE

Introduction

The driving of a pile in many ways resembles the cone penetration test (CPT) and/or the standard penetration test (SPT), both which allow correlation to soil properties. Therefore it is reasonable to suppose that, with reliable and repeatable data acquisition of pile driving data, a similar approach to the assessment of soil properties and hence pile performance could be undertaken following the driving of a pile.

Egan (2013) discusses how this approach can be adopted and presents a case study on an 11.0m long DCIS pile of nominal 340mm diameter at a site in Erith, Kent subject to a load test to failure. In the load test a plunging failure of the pile under an applied load, $Q_{ult,test}$ of 1947kN at a displacement of 45mm was observed.

The ultimate pile capacity, $Q_{ult,cal}$, calculated from the drive record was 2060kN, demonstrating the observed and calculated pile capacities were within 6%, and well within the confidence level expected for a geotechnical pile design.

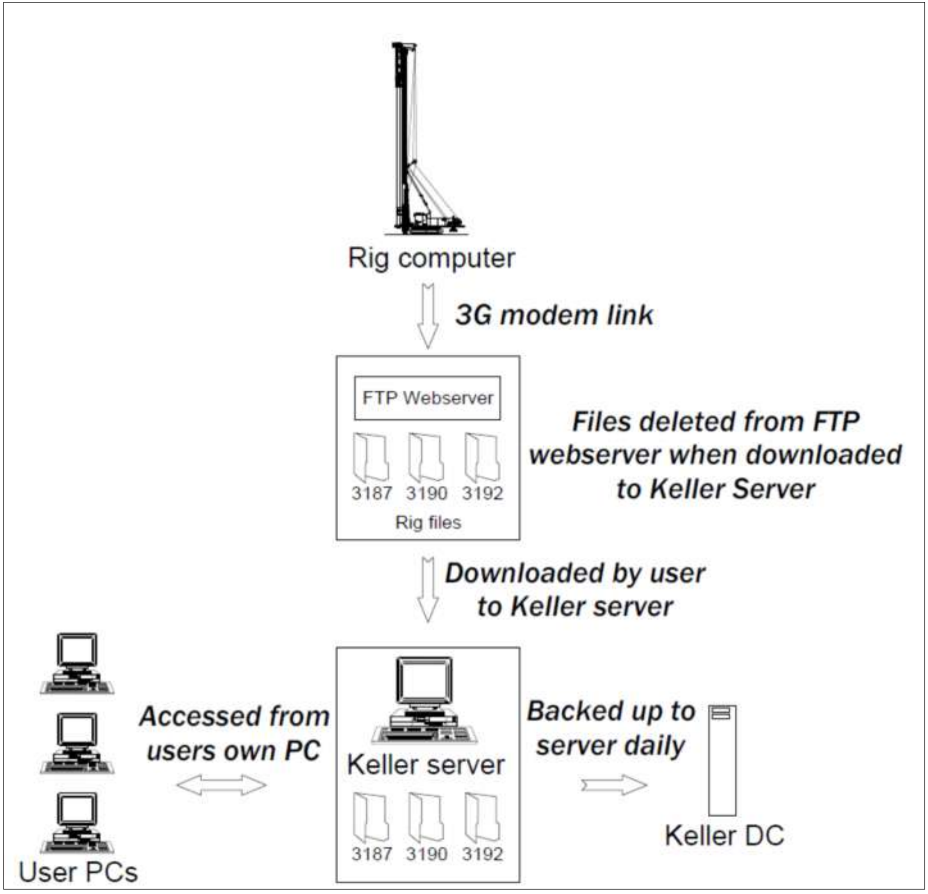

Figure 1. Automated data acquisition system

LARGE DIAMETER DCIS CASE STUDY

Introduction

The following new case study demonstrates the use of the real time validation process for large diameter (610/630mm) DCIS Piles.

Project Details

The project comprised the installation of one-hundred and thirty, 610mm diameter DCIS piles with a 630mm diameter base to support two abutments and a central pier for a new road-over-rail bridge. The site was adjacent to the Thames Estuary in Essex, and Fig. 2a shows the ground profile at the location of a preliminary non-working test pile, which comprised of a 1.75m thickness of granular made ground forming upfilling to the required bridge abutment level overlying soft becoming firm alluvium. The alluvium contained a band of peat from approximately 8.2m to 9.6m depth which was picked up during pile driving as is indicated by a local peak in R_u in Fig.2b. At 12.8m depth medium dense gravel River Terrace Deposits (RTD) with SPT N values in the range 19 to 24, were encountered and were typically 6m thickness.

The DCIS piles were designed to have a nominal penetration into the RTD of around 2.0m, but dependent on achieved, R_u. The standing ground water level was assessed as at approximately 4m below the piling platform level.

The piles were design to provide a nominal specified working load (SWL) of 1650kN plus an allowance of 510kN negative skin friction generated from the compression of the soft alluvium under the surcharge weight of the 1.75m of upfilling.

The test pile was installed using a Junttan PM26 piling rig with a 5 ton HHK5AS hydraulic hammer. Fig. 2b shows the dynamic driving resistance, R_u, recorded during installation of the test pile. The dense platform material is identified down to around 1.75m depth at which point the R_u value of around 400kN indicates the top of the alluvium, which then shows a broadly linear increase in resistance to give an R_u value of around 1300kN at the top of the RTD. From Fig2b.the top of the RTD is defined at 12.8m depth; the pile was driven to a toe depth of 14.9mOD, giving a socket length of 2.1m into the RTD, with an average Ru value of 4200kN.

Estimate of Pile Capacity from Drive Record

From the drive record and using the methodology proposed by Egan (2013) the effective angle of friction of the founding stratum was estimated as shown in Fig. 2C. From this using the standard pile design equation (Eq. 3) the anticipated geotechnical capacity of the pile socket within the RTD was calculated using the Oasys Pile design software.

$$Q_{ult} = \beta.\sigma'_v.\pi.d.l + N_{q.}\sigma'_v.A_b \qquad \text{Eq. 3}$$

A total capacity of the socket embedded into the RTD, $Q_{ult,soc}$, of 11,349kN was calculated.

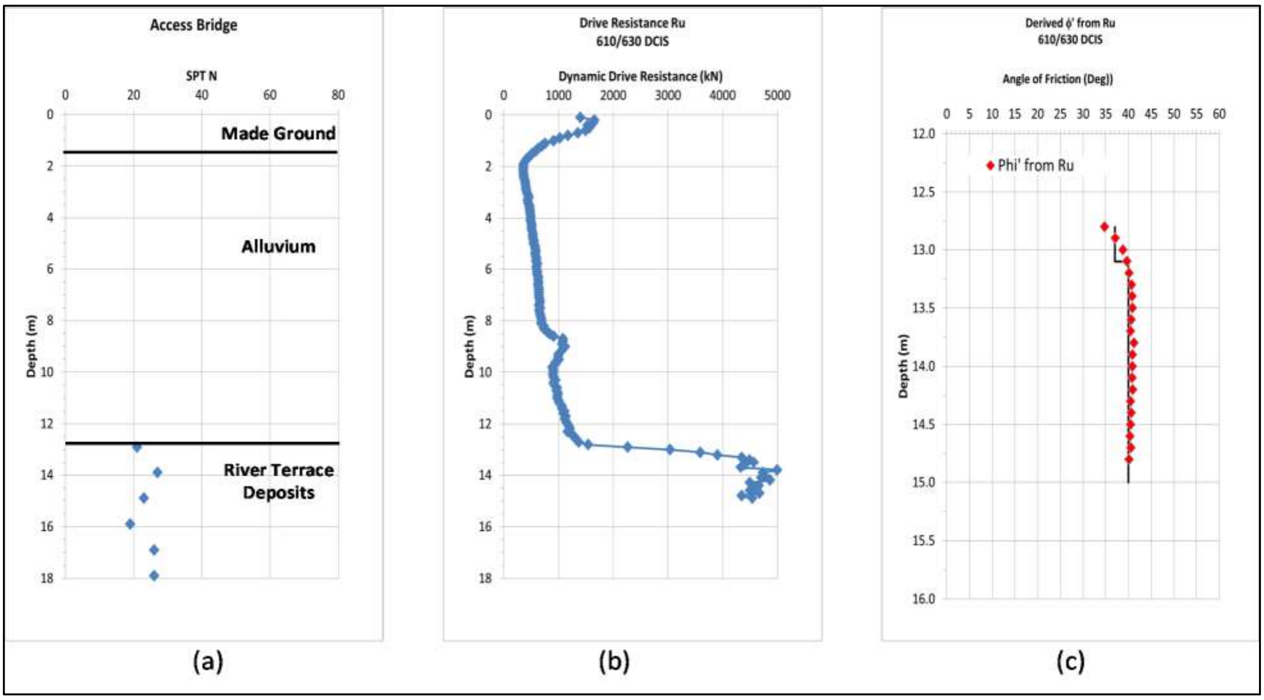

Figure 2. Data relating to 610/630mm DCIS Case Study

It is noted that no limit to the maximum admissible base stress, $qb,_{max}$, was applied, which in the calculation yielded a value of $qb,_{max}$=33,000kPa, this is considered a high value that might have the potential to cause particle crushing or concrete failure should this stress be mobilised. However in practice this situation would not occur as usually a factor of safety of no less than 2.0 is applied on the ultimate pile capacity bringing the mobilised base stress to within acceptable values, and additionally load testing would normally be undertaken to demonstrate the site specific pile performance.

For the pile under test a temporary hold up load, Q_{thu} = 510kN, must be added to the socket capacity to account for the resistance generated through the made ground and alluvium lying above the RTD during the test.

Pile Load Test

The test pile was subjected to a maintained extended proof load test in three cycles to an ultimate load, T_{ult}, of 6,794kN following the procedure outlined in the ICE Specification for Piling and Embedded Retaining Walls (2007). At the maximum test load, T_{ult}, the pile head had settled 51.5mm and the test had to be curtailed as the maximum capacity of the reaction anchor piles had been reached.

Fig.3 shows the test pile load settlement response along with the simulated results derived from a back analysis using the method proposed by Fleming (1992). The Fleming analysis input parameters are shown in Table 1.

At plunging failure an ultimate capacity of, $Q_{ult,Flem}$ of 12,002kN is estimated from the Fleming analysis.

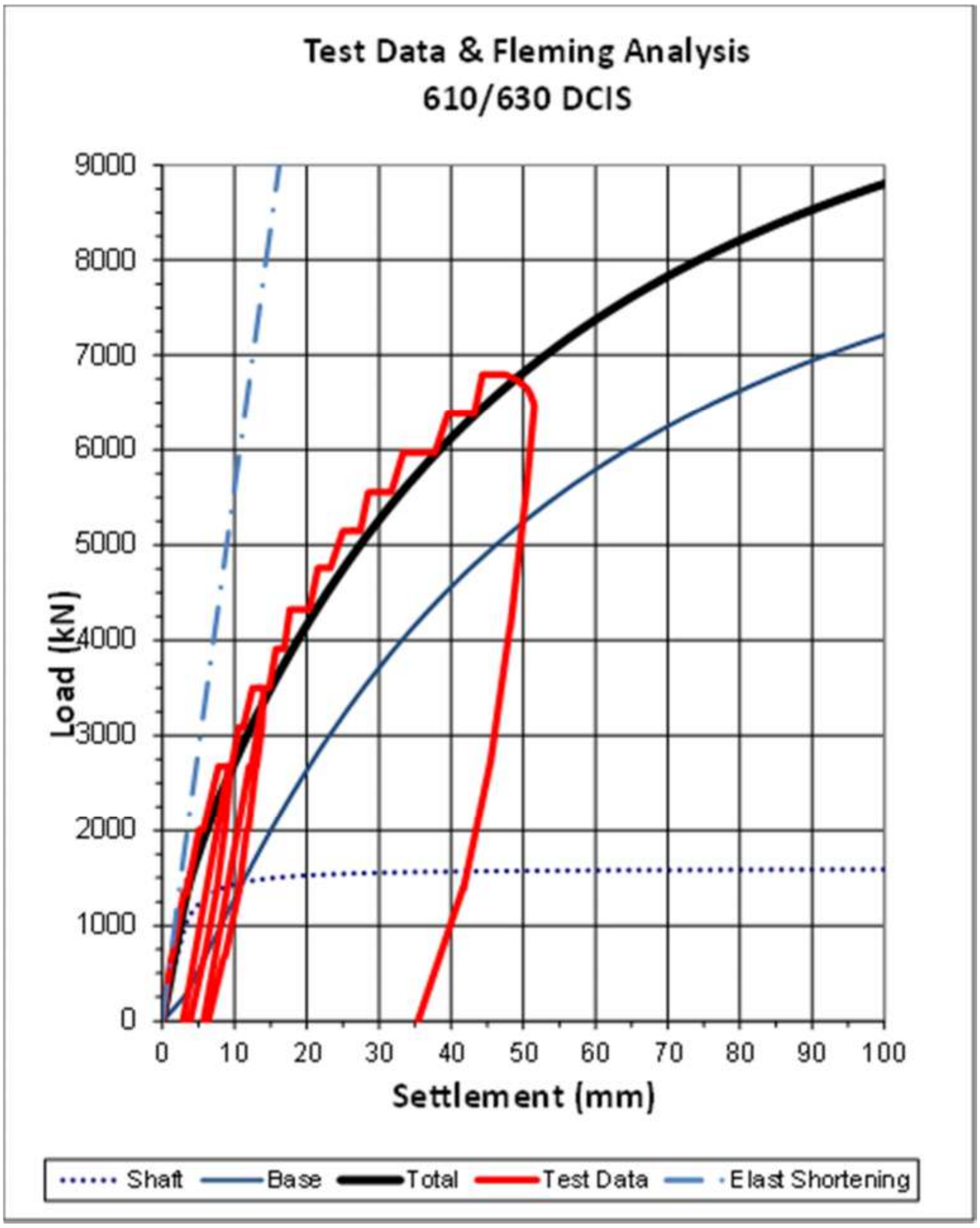

Figure 3 Test pile data & Fleming analysis.

Table 1. Fleming analysis parameters.

Pile details	Value	Modeling Parameter	Value
Shaft diameter (m)	0.610	Base Modulus, Eb (GPa)	275
Base diameter (m)	0.630	Centroid of load transfer, Ke	0.5
Socket length in RTD (m)	2.1	Shaft response factor, Ms	0.001
Low friction length (m)	12.8		
Pile Modulus (GPa)	28		

Conclusions from Test Pile Analysis

The ultimate pile capacity determined from the static load test of, $Q_{ult,Flem} = 12,002$kN, compares with a difference of less than 2% with the calculated capacity which is based on ground parameters derived from the pile installation records, $Q_{ult,cal} = 11,859$kN.

Installation of Working Piles

Based on an assessment of the ground conditions and supported by the pile test results, simple installation criteria were set for the rig operators to follow for the construction of the working piles. As piling proceeded the installation records were able to be easily reviewed by Keller's client and Engineer.

REVIEW OF THE OPERATIONAL CHALLENGES & ADVANTAGES OF REAL TIME DCIS VALIDATION

Operational Challenges

No review of the use of an automated data acquisition system used to control piling operations can ignore the organizational and procedural aspects that a company wishing to maximize the benefit of such a system must consider and embed into its way of working. In common with most geotechnical processes the design, construction and validation of DCIS piles is a very linear process as illustrated by the chain of events in Fig 4.

The process starts with definition of the pile requirements and the prevailing ground conditions which correspondingly leads to the design, scheduling, pile installation (with concurrent data acquisition), validation and creation of as built records.

Each link in the chain may contain its own sub-chain of events. For example the 'Pile Installation & Record' link in Fig.4 contains the sub-links of correct input by rig operator, correct functioning of the data acquisition hardware, software and data processing algorithms, correct control of the pile installation process by the rig operator, and robust data transfer and storage. Typically there is very little redundancy in the overall system, such that if one link in the chain breaks the whole process fails (or is severely impaired). For example incorrect ground assessment leads to incorrect design: malfunction of an instrumentation sensor leads to failure of the data acquisition system etc.

Within Keller the operation of the instrumentation is seen, from the highest level of management, as integral to the control and recording of the DCIS piling process and not simply an add on to it. Measures have been put into place via training, deployment of adequate resources and development of operating procedures to mandate that piling only proceeds when installation can be correctly recorded.

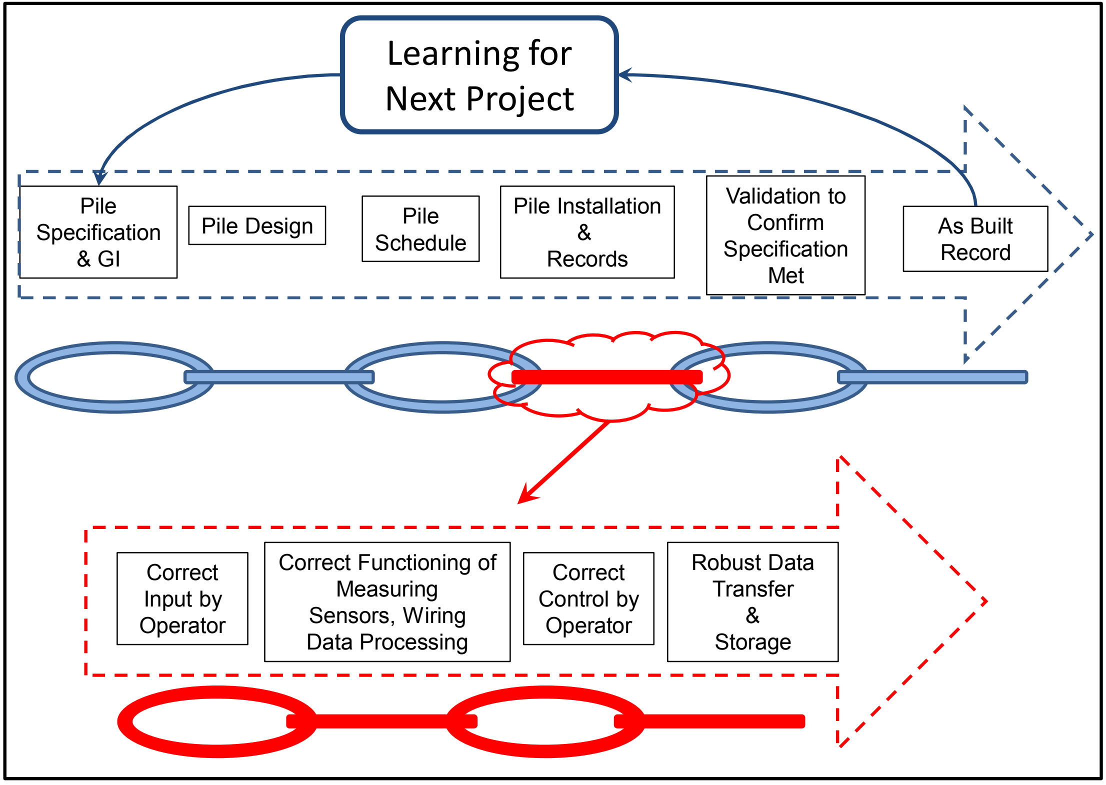

Figure 4. Piling process chain.

Experience shows that high level of support for the strategy of relying on the instrumentation is necessary to ensure continued use and ongoing development of a robust instrumentation system. The challenges that must be overcome to ensure the operation of a practical and robust system include:-

- development of robust hardware that remains operational in the harsh vibration and climatic environment of a typical site;
- provision of training to the rig operators and site operatives to foster knowledge and ownership of the components and operation of the system and engender a culture that sees the instrumentation as a benefit to them (for example by reducing paperwork), and providing them, with additional level of technical support.
- rapid response to system failures (which inevitably occur, but experience shows diminish with use and system development). System failures can usually be categorized into one of three types (i) data flow/modem issues (ii) hardware failure (iii) software errors (most prevalent during the development of the system).

Operational Benefits

Many operational benefits can be leveraged from the integration of real time monitoring of driven piling parameters into the wider piling process. These include:-

- automated repeatable and reliable record keeping that does not tie up site operatives and generates a better quality of piling record;
- enabling an efficient and automatic validation of the anticipated performance of every pile constructed, highlighting, at the time of driving, anomalies such as unforeseen variation in ground conditions;
- providing the rig operator with the control needed to ensure piles are not over driven or under driven, thus maximizing installation efficiency;

- the creation of a large and growing database of consistently acquired and systematically archived data of past projects undertaken in a range of ground conditions, providing a unique knowledge base that can be applied to new projects. (shown in Fig. 4 as learning for the next project);

- provision of electronic records that can be directly imported in to Building Information Management (BIM) models.

CONCLUSIONS

Experience has shown the integration of a real time monitoring system in the driven piling process can improve efficiency and reduce ground risk. This has been achieved by developing a robust yet transparent data acquisition and monitoring system. The system utilizes up to date technology and telecommunications, supported by research work to develop algorithms to predict pile performance based on measured installation parameters.

A new case study showing the implementation of the system for a high capacity large diameter DCIS piling project is presented. The predicted and measure ultimate pile capacity for a 610/630mm diameter DCIS pile shows excellent agreement, providing support for the robustness of the approach.

Experience also shows that full integration of the real time monitoring system into the piling process (as opposed to simply using it as a nice-to-have add on) requires full management support to engender a supportive culture at site level and through the wider project management activities.

Significant business benefits have been realized through the implementation of the real time monitoring process which include:-

- better control of the driven piling process with improved feedback from prevailing ground conditions through systematic measurement of piling parameters, therefore reducing ground related risk for DCIS projects;

- automated record keeping reducing the administrative burden at site level;

- creation of digital data facilitating creation of as built records and provision of data in a format compatible for incorporation into Building Information Management (BIM) models;

- the development of an historic data base of information that can be referred to when considering future projects.

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