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20 years of automated load testing; key learning points, principals and the role of new technology

20 ans d'essais de chargement automatiques; les expériences, les principes et le rôle des nouvelles technologies

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ABSTRACT: The use of automatic load testing, where a computer processor controls the progress of a maintained load test, was pioneered by Cementation Skanska in the 1990’s and has been in use in the UK for over 20 years. This technique is now widespread throughout the world and is increasingly carried out using either proprietary or commercially available systems. When it was first developed, the technology brought about a step change in both safety and productivity within the industry. 20 years on, standards of safety and quality have continued to improve, however, the application of such loads can still present a hazard. It is therefore essential that newly developed systems include the important safety features that have been established and refined over the past 2 decades. This paper draws upon Cementation’s 20 years of experience in the field and presents the key components of an automated load testing system which ensure that it is able to function safely and correctly. It highlights how these technologies are continuing to develop and provides examples of how they are implemented in current systems. Data is presented from both proprietary and commercially available load testing systems and, although reference is primarily made to UK practice, the principals are widely applicable.

RÉSUMÉ: La méthode des essais de chargement automatiques, selon laquelle un processeur informatique contrôle le déroulement des essais de chargement, fut développée par Cementation Skanska dans les années 1990, et elle est utiliseé au Royaume-Uni depuis plus de 20 ans. A présent la technique est appliquée dans le monde entier, à l’aide des systèmes propriétaires ou disponibles sur le marché. Lors de son développement, la technologie provoqua un changement profond au sein de l’industrie sur le plan de la sécurité et de la productivité. Au cours des 20 années suivantes, la sécurité et la qualité des essais continuèrent à s'améliorer, mais l’application des chargements représente toujours un risque. Il est donc indispensable que les systèmes nouvellement développés contiennent les dispositifs de sécurité établis et affinés pendant les deux dernières décennies. Cette article s’appuie sur les 20 ans d’expérience de Cementation dans ce domaine et présente les constituants essentiels d’un système automatisé d’essais de chargement qui assurent qu’il peut fonctionner correctement et sans risque. Il souligne les développements récents et fournit des exemples de leur utilisation dans des systèmes actuels. Les données sont tirées aussi bien des systèmes propriétaires que des systèmes disponibles sur le marché. Bien que l'on se réfère principalement aux pratiques britanniques, les principes sont largement applicables.

Keywords: Foundation Testing; Instrumentation; Automation;

1 INTRODUCTION

The principal of establishing the performance of a piled foundation by applying a load and measuring the resulting displacement has been widely used for at least 100 years. The photograph presented in figure 1 is of a compression load test carried out in 1936. A simple examination of this photograph identifies the principal components of the test system, the majority of which have not changed significantly in the 80 years since it was taken. The compressive load is applied to the head of the pile using a hydraulic jack which, in the case of figure 1, is manually pressurised by the technician using a hand pump. Measurement of this load is made by recording the hydraulic pressure in the pump. The load applied is transferred into tension anchor piles by a series of reaction beams and the displacement of the pile head is measured, in this case using an optical levelling staff.

Figure 1. A compression load test carried out in Yorkshire, UK. 1936.

Although many of the physical aspects of a load test have remained unchanged since this photo was taken, there have been significant improvements made to both the technology employed and the process. One of the most significant changes came in the 1990s when Cementation Skanska Ltd (CSL) published and patented a system for automating the pile load test (England, 1999).

Instead of relying on manual interventions, this technique used the developments in computer technology to manage the process of applying and maintaining a load as well as measuring the pile head displacements. This approach facilitated a significant improvement in the accuracy of monitoring and control of maintained load tests.

The benefits of this system in terms of both safety and cost were considerable. Additionally, the increased reliability of the test data collected using this method made possible more sophisticated analysis of observed load settlement behaviour. This was important to the work of Fleming who was able to drawing on a large and reliable data set of test results in order to develop and publish the details of a new method for characterisation of pile behaviour, a method which is still in widespread use (Fleming, 1992).

20 years on from these developments, the (CSL) patent on automatic load testing has expired and new systems for carrying out automatic

load testing are becoming available. It is essential, therefore, that any prospective clients for these systems are able to evaluate them for both the quality of data they will produce and the safety of the processes they employ.

The following section on the principals of load testing is not intended to be an exhaustive guide to load testing, excellent published works already exist on this subject, rather it is intended to cover those pertinent points not typically included in project specifications.

Additionally, with the increasing capability of the plant and equipment used to install deep foundations, piles are now being designed for much higher loads. This is presenting new challenges for both the understanding and analysis of pile load test results. Simple back analysis of pile head displacements is often insufficient to describe the behaviour of these foundations and so the use of embedded instrumentation is of increasing importance. This is covered in section 3 which describes the merits of distributed fibre optic sensing (DFOS) along side more traditional instrumentation.

2 PRINCIPALS OF LOAD TESTING

Although many aspects of carrying out a load tests are described in detail by model specifications such as the third edition of the ICE‘s specification for piling and embedded retaining walls (SPERW), (ICE 2017) and the newly published international standard, ISO 22477-1 (ISO, 2018), some aspects of how such a system operates are still determined by the manufacturer and operator. Typically this may be left to the specialist employed to carry out the test.

Three important areas for consideration are the calculation of settlement rate, safety and the use of secondary measurement systems. Standardisation of pile load testing is essential to ensure that comparable results are recorded from one project to the next and it is important that these items are both defined and understood.

2.1 Settlement Rate

As a general rule, a static load test involves applying a load to a pile gradually, certainly when compared to a dynamic load test. This is achieved by applying the load in a series of discreet steps during which the pile head velocity is allowed to stabilise prior to the application of the next load. This creates a pattern of loading more representative of the conditions present in the finished structure and reduces the potential over prediction of capacity associated with rapid load application.

During the development of ISO 22477-1 (ISO, 2018), much of the discussion related to the duration of the hold periods at each load step. There is wide recognition that a minimum duration is required and that these should be the facility to extend the hold period until the velocity of the pile had has reached an acceptable limit, whatever that may be. However, there is still little information provided about how this velocity, commonly referred to as the settlement rate, should be calculated. Whilst it might appear trivial, it is actually an important parameter and needs to be defined and understood in order to achieve effective and consistent load testing.

In the calculation of settlement rate, the accuracy of displacement readings become very important. A criteria common in UK practices is that the settlement rate should reach a value of 0.1mm/hr or less before the load is increased to the next step. If this rate calculated over a five minute period, this represents a movement of less than 0.0085mm which is close too, if not below the working accuracy of most displacement monitoring systems. A robust means of calculation (and measurement) is therefore required if the settlement rate is not to be unduly influenced by measurement accuracy.

To further illustrate this point, Figure 2 presents the difference between the settlement rate values obtained from a linear regression, equation 1, and simple point to point method of calculation, equation 2. These have been calculated for and are presented against pile head displacement measurements from a working test pile in the UK.

$$SR = \left(\frac{\sum(t-\bar{t})(d-\bar{d})}{\sum(t-\bar{t})^2}\right)60 \qquad (1)$$

$$SR = \left(\frac{d-d_{t-5}}{5}\right)60 \qquad (2)$$

Where t = current time in minutes, d = current displacement in mm, d_{t-5} = displacement 5 minutes ago and SR = settlement rate in mm/hr.

The considerable variation observed in the point to point method is a feature of the transient influences in the measurement system such as vibration and temperature effects. As a consequence, the pile would have advanced to the next load step much earlier than if the settlement rate had been calculated by the liner regression approach. The linear regression method has been use by CSL and found to provide a stable measurement of the settlement rate without unduly prolonging the load test.

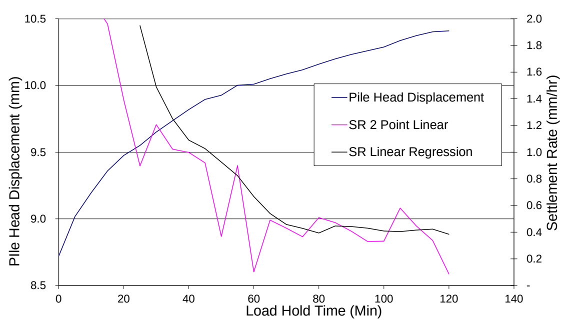

Figure 2. Settlement rates, calculated by equation 1 and equation 2.

Any prospective purchaser of a static load testing system should ensure that they understand the process and implication of the settlement rate criteria and how it is being calculated.

2.2 *Safety*

An automated load test has a number of health and safety benefits when compared to a manual, attended test. Firstly, by no longer requiring the presence of the technician during the course of the test it reduces the risks that they are exposed to. These risks include hydraulic injection from a failure of the hydraulic system or injury as a result of destabilisation of the reaction system. There are also considerable improvement to the health and wellbeing of the technician who is no longer required to be in attendance with the pile test over night, often working by themselves.

Secondly, a computer is able to identify and react much more quickly to destabilising events than a human would. When implemented correctly, an automatic system will greatly reduce the risk of a load test failing due to destabilisation of the reaction system.

A comprehensive set of safety checks to include in an automatic load testing system was published by CSL (England, 1999). These include checks on the both the pile cap and reaction system.

Commercially available systems are now employing new technology and approaches. For example, the Titan 250 pile testing system, manufactured by Atlas Pile Testing Systems employs tilt sensors mounted on the reaction frame to detect any uneven movement. However, one critical element which should be present in any system is the ability to sense sudden changes in the applied load and to respond accordingly.

Any yield in the reaction system or displacement of the pile head will most rapidly be identified from a reduction in the pressure of the hydraulics. The resulting drop in load will be apparent much sooner than any movement registered by other instruments. It is imperative that any system is able to detect this occurrence and pause until an assessment is made of the significance of this event.

This is implemented in the Titan 250 system as a trigger level set to a percentage reduction in load. When triggered, the test will pause and await manual intervention. During this time no further loading will be added or removed, an important part of ensuring the system is left in the safest condition. The original Cementation system considered a value of 10% reduction in load to be significant.

2.3 Secondary measurement

An important principal in the monitoring of a pile test, or indeed any measurement system, is the provision, where appropriate, of a secondary and independent method of measurement. This is not normally required to compensate for any lack of accuracy in the primary method of measurement. It is more generally a means to ensure that there is no ambiguity in the event of unusual results or system failures. This principal should be applied to the key measurement made during a pile test.

The first application of this should be in the measurement of the load itself. Both SPERW and ISO 22477-1 permit measurement of load with a load cell or a pressure gauge, however, in both cases calibration of these devices is essential. SPERW goes further and requires that a secondary method of measurement is also employed.

The original system developed by CSL used load cells alone. However, in response to SPERW, new systems such as the Titan 250 also include an oil pressure transducer as a secondary method of measuring load. This greatly reduces the risk of overloading the reaction system by failure of one of the load measurement devices. This can occur through calibration errors or simply the technician selecting the wrong load cell. It is essential to the safe working of such equipment to include a secondary system of measuring load.

The second area where this principle should be applied is in the measurement of pile head displacement. Both SPERW and ISO 22477-1 require a secondary means of measuring pile head displacement.

In the automated load testing system developed by CSL this was normally achieved by a fifth displacement transducer which monitored the position of the pile head relative to the reaction system. Although not truly independent, this is often deemed to suffice and is rarely called upon. However, with the modern electronic precise levels available to the industry, real time measurement from a secondary system can readily be incorporated into an automated load test without compromising the benefits of automation. Leica, for example, have developed a Geo Serial Interface (GIS) protocol which allows communication and control of their instruments with other devices. This technique has been used by CSL on several recent projects.

3 INSTRUMENTATION

The methods developed by CSL in the 1990‘s have been carried out successfully for over 20 years and, if implemented correctly, with particular reference to the points mentioned in section 2, can provide safe and reliable load testing data.

In most cases the methods of analysis proposed by Fleming, which rely on measurement of pile head displacement alone, will be sufficient to interpret and analyse the pile‘s performance.

However, as piling technology develops, tests are having to be carried out on piles which are both deeper and more highly loaded than those which have been tested before. In these cases, mobilisation of a significant portion of the base capacity is not always possible, making interpretation of the test results by standard means problematic. Table 1 contains examples of recent pile tests in London where it has not been possible to reach the ultimate capacity of the pile. The results from these tests are summarised graphically in figure 3.

There are also a subset of pile tests where the results do not match up with expectations and where more information is required. In these cases, instrumentation is essential for understanding the pile‘s performance.

Traditional pile instrumentation includes extensometers and tell tales which provide measurements of displacement from various depths with the pile. Discreet strain gauges can also be placed with the reinforcement which allow measurement of strain at specific depths. From these, and a knowledge of the sectional properties of the pile, it is possible to determine the distribution of load within the pile (Fellenius 2001).

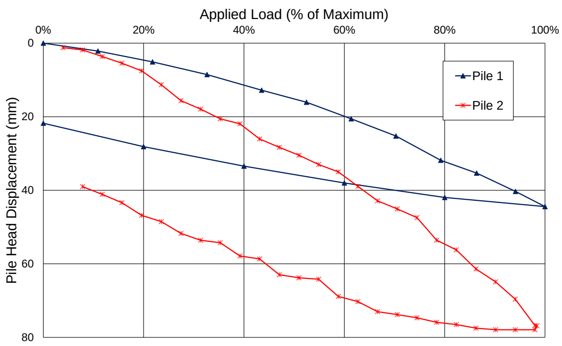

Figure 3.Pile head displacements from load test data presented in Table 1.

Most recently, DFOS has been developed as a means of measuring strain within a pile under test (Ouyang et al, 2015). This technique uses the principals of optical time domain reflectometry to determine the strain and temperature at any point along an optical fibre. The principal benefit of a distributed system is that it provides a continuous profile of strain within a foundation element. This significantly reduces the subjectivity associated with interpolating date from discrete point sources. It is particularly applicable where the likely changes in ground conditions are not know prior to installation which makes the location of traditional instrumentation difficult. From this strain profile, the distribution of load can be calculated and the geotechnical performance understood, (Kechavarzi et al, 2017).

Table 1. Examples of recent pile tests in London where verification of ultimate capacity was not possible.

Heading	Pile 1	Pile 2
Diameter (mm)	1050	1200
Length (m)	60.2	60.3
Founding Strata	London Clay	Thanet Sand Formation
Design Verification Load (DVL) (kN)	11,100	19,500
Settlement at DVL (mm)	12.79	21.92
Settlement at 150% DVL (mm)	20.56	34.37
Settlement at 200% DVL (mm_)	31.85	52.31
Maximum Test Load (kN)	25,500	50,500
Settlement at Maximum Test Load (mm)	44.43	77.93

Figure 4 shows the result of a tension load test carried out with an embedded, distributed fibre optic sensor. 2 levels of vibrating wire strain gauges (VWSGs) were also included in the pile. The pile design was based upon a 3m rock socket and, due to its variability, the resistance of the overburden was discounted. In this case, contribution to the resistance from the overburden was significant and the VWSGs revealed that no load was transferred into the bedrock. However, the precise nature of the piles performance could only be properly determined by examination of the fibre optic strain profiles which identified where the load was being resisted and provided confidence in the measurement made by the VWSGs. The increased strains identified at 4.0m depth were related to the presence of a coupler in the reinforcement.

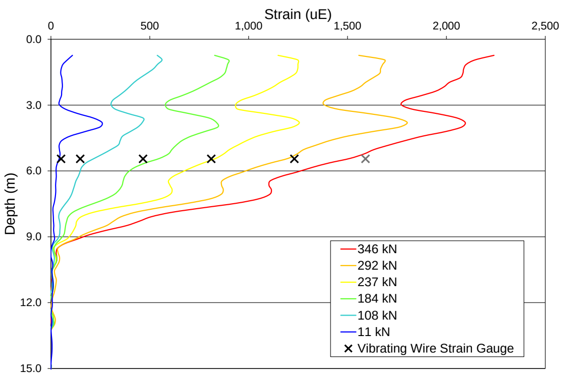

Figure 4. DFOS and VWSG results for a tension test on a micro pile.

4 CONCLUSION

The automation of pile load testing, when carried out safely and effectively produces good quality data for which there are established and reliable methods of interpretation.

Despite the growth in specifications and standards for the pile load test, there are still a number of important considerations which are left to the specialist. These relate both to the safety and the quality of the process. It is of vital importance that effective systems are in place to ensure that the applied load is measured correctly and reliably and that, should the load reduce rapidly, a procedure is in place to ensure that the pile test is made safe.

Additionally, the determination of the settlement rate is important to ensure that testing is carried out consistently and a method of linear regression is preferred over a 2 point linear approach.

The sound principal of employing an independent, secondary method of measurement for the essential data should be adopted and, given the improved equipment available, this should not be seen as a barrier to automation.

Finally, there are many pile tests carried out where the complexity of the result does not lend itself well to standard methods of back analysis. In theses cases, the use of pile instrumentation is essential to successful interpretation of the test. In particular, the recent developments in DFOS systems make them well suited to deployment in pile tests where they can yield valuable results.

With these points in mind, the next 20 years of load testing would appear to hold as much potential for improving our understanding of pile performance as the previous 20 years.

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