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Overview of the role of testing and monitoring in the verification of driven pile foundations

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ABSTRACT

Static pile load tests have traditionally been considered the gold standard test, and if well executed provide the reference load-movement response of the pile. Setting aside any difficulties with proper execution of static pile load tests, their primary deficiency is in the statistically insignificant rates at which they are undertaken — typically 0.5 to 2.0%. Furthermore, static pile load tests cannot be directly related to installation parameters and are therefore not well suited to development of driven pile acceptance criteria. If well executed, dynamic pile tests provide a rapid and generally reasonable estimate of pile load-movement response. The primary issue is that the static response is inferred from a dynamic response using simplistic models of complex dynamic pile-soil behaviour. However the advantages of dynamic testing are that it is generally performed on a statistically meaningful sample size - 5 to 15% in many cases - and it is concurrent with installation, which allows dynamic testing to be the basis for construction control and development of pile acceptance criteria. The remaining 85% to 95% of piles are necessarily installed using simple set criteria, or dynamic formula approaches which of themselves have significant deficiencies and represent project risk. Given that the foundation system will only be as good as the pile installed with the least confidence, improvements in foundation quality will be most effectively achieved by improvements in the monitoring and assessment of untested piles. This paper discusses a state-of-the art approach to reduction of overall foundation risk.

Keywords: Foundations, Driven piles, Static testing, Dynamic testing, Dynamic Formulas

1 INTRODUCTION

The design of deep foundations is a complex soil-structure interaction problem. Common to most geotechnical design problems, predicting pile capacity is highly dependent on the site variability and the intensity and quality of the site investigation including the insitu and laboratory testing which is undertaken. Overlaid on these general issues of the quality of information, are the issues of the uncertainty of insitu horizontal stress conditions, and the effect of pile installation itself on the virgin stress state. Ground stresses will be relieved by removal of soils in drilled piles to varying degrees depending on the particulars of the drilling process and the temporary soil support mechanism. Conversely ground stresses will increase to varying degrees due to installation of displacement pile systems such as open steel pipe or full-section prestressed concrete piles. Further complications arise at the interface due to disturbance of the insitu pore pressure regime, smearing due to the installation process, pile plugging, and effects such as friction fatigue, setup and relaxation.

The risk and uncertainty associated with pile design is reflected time and again in various pile capacity prediction exercises which have been arranged at previous conferences. Fellenius (2013) summarizes the results of such a prediction exercise for a continuous flight auger (CFA) pile installed in clay till with sand and gravel lenses. The predicted load-movement responses from 41 invited foundation engineers are shown in Figure 1 with the actual load test results. The test had to be terminated prematurely for safety reasons, nevertheless, the diversity of both capacity and stiffness predictions is starkly indicated. The average capacity prediction was 1920kN, with the range of predictions between 830 and 3600kN. A pile capacity prediction exercise associated with the 2nd International Conference on Site Characterization (ICS2) in Lisbon in 2004 was also reported by Fellenius and others (Fellenius et al. 2007). Amongst the piles tested was a precast concrete pile driven into the residual clay soils at the test site. Figure 2 compares the ultimate capacity predictions of 32 participants. Again, there is a wide range of predictions – from 500kN to 2700kN, although in this case, some participants based their estimates on the results of dynamic pile testing rather than the site investigation results. Failure with large plastic displacements occurred at 1500kN.

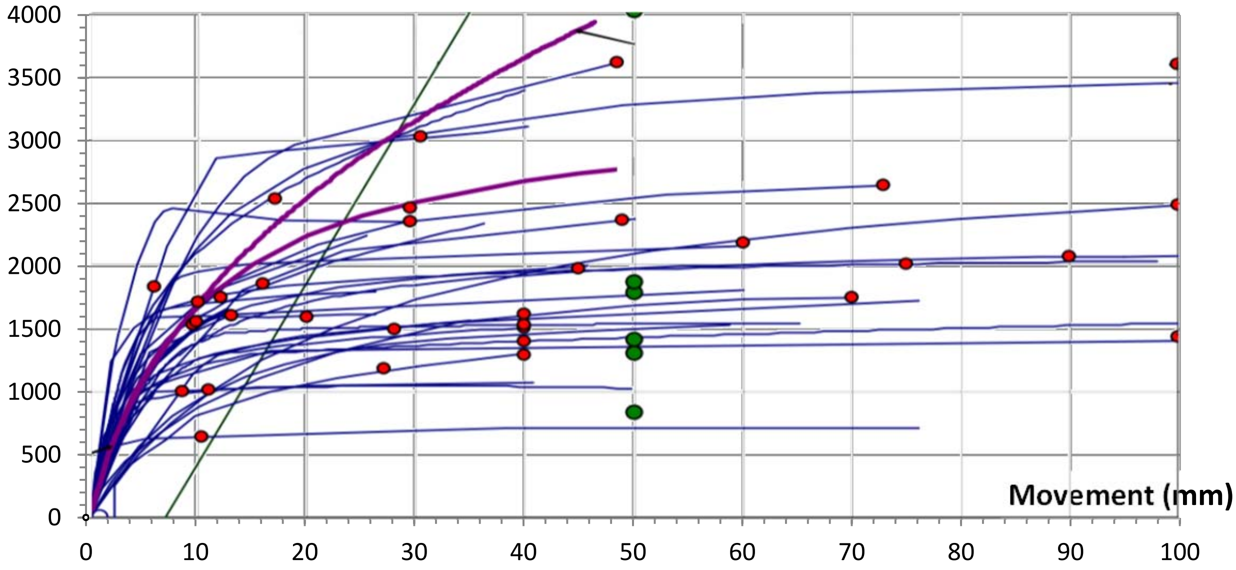

Figure 1. Load-movement predictions from Fellenius (2013)

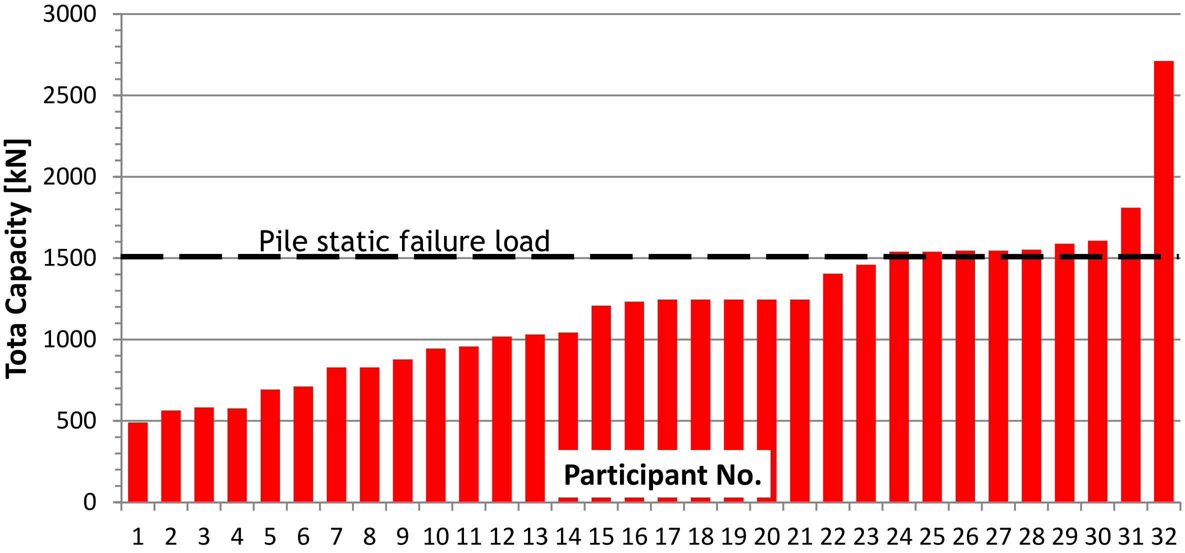

Figure 2. Load-movement curve and capacity predictions from Fellenius (2007)

It is clear from these two examples (which are typical of other similar prediction exercises) that there is significant uncertainty associated with pile design. It should be particularly noted that these predictions were based on site investigation information (boreholes and CPTs) in the direct vicinity of the tested piles. The uncertainty in capacity prediction will be multiplied in engineering projects where ground information from the site investigation must be interpolated or extrapolated from often distant site investigation information.

To put some context to the extrapolation process inherent in design, it is worth noting that a site investigation with 100mm diameter boreholes on a 20m x 20m grid and SPTs at depth intervals of 1.5m samples only 0.0006% of the foundation materials.

2 PILE TESTING

Given the evident risks in pile capacity prediction based on design, there are compelling reasons to use either installation records, pile monitoring or pile tests to provide pile-specific information to better assess the installed capacity of piles.

Driven piles are the foundation type which provides the widest range of monitoring and testing opportunities. Apart from static load testing, dynamic load testing and rapid load testing have been developed, as practical alternatives to static load testing In addition, the installation process itself provides the opportunity to assess pile capacity based on the pile response to the energy delivered by the driving hammer. This paper will review the testing and assessment of driven pile foundations.

2.1 Static Load Testing

The prediction examples shown in the Introduction section use static load testing as the reference test for the load-movement response of the piles. It is self-evident that static load testing, correctly undertaken, should be considered to provide the most reliable assessment of individual pile performance.

2.1.1 Load Measurement

Fellenius, who has been an important contributor to the literature on pile testing and performance, has written a number of key papers on the reliability and assessment of static load tests (e.g. Fellenius, 1980). Fellenius found that the interpretation of applied load from the hydraulic pressure in the test jacks can be in error by 25% or more, as shown in Figure 3. Fellenius concluded that based on many similar measurement results, that a load cell must be used if one wants to ensure an imprecision of load measurement of less than 20% - a requirement also in Australian Standard AS2159-2009 Piling – Design and Installation.

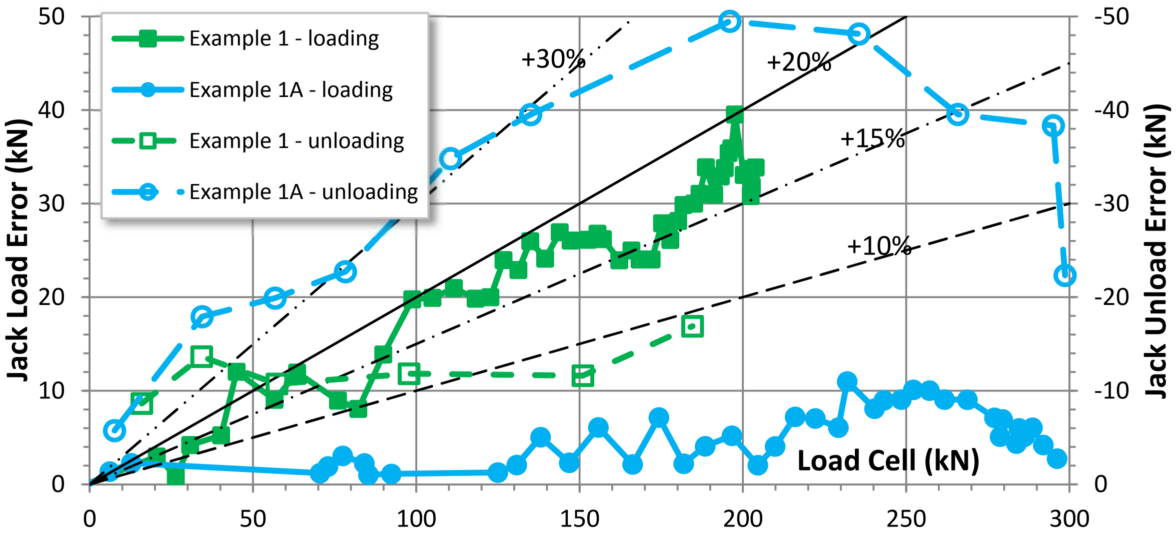

Figure 3. Errors in Jack Loads from Fellenius (1980)

2.1.2 Capacity Interpretation

In many cases static load tests may not be loaded to geotechnical failure. Various graphical interpretations have been proposed to infer ultimate pile capacity. Fellenius highlighted the significant variations in predicted ultimate pile capacity which result from these different methods (see Figure 4). Depending on the selected definition, static pile capacity for this data set could be reported as between 1610 and 2090 kN, a range of 470 kN or 25% of the average value.

In some cases, the interpretation of ultimate capacity will be unequivocal, however, without access to the load-movement curve, and an understanding of the interpretation method adopted, a single reported value of static ultimate pile capacity may lie anywhere within a range of possible values.

2.1.3 Capacity Mobilization and Proof Tests

As noted in the previous section, static load tests are not always loaded to geotechnical failure, despite the technical benefits of such a test. The reality of many projects is that static load tests are only undertaken to a proof load nominated in the specification which satisfy contractual capacity obligations. It is noted that proof load tests will also provide the important benefit of establishing pile movements at service loads.

If the proof test is reasonably close to full mobilization, then the various interpretations (as shown in Figure 3) may be applied to estimate the ultimate capacity, albeit that a wide range may still result. However, if the test terminates before substantial mobilization has occurred, then it is unlikely that the failure load can be interpreted with any reliability. This devalues the use of static load tests to establish credible criteria for control of driven pile installations.

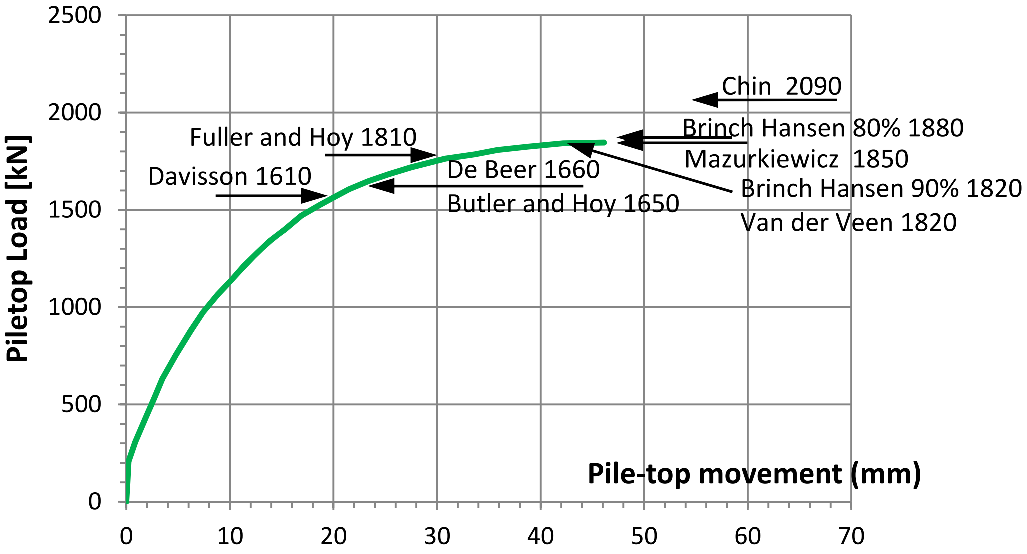

Figure 4. Range of interpretations of ultimate pile capacity from Fellenius (1980)

The ultimate capacity of piles subjected to proof tests should be extrapolated with caution. There are various methods in the literature available to infer ultimate capacity by various assumptions – but the success of these methods depends on the degree to which the full capacity has been mobilized. The value of static load testing is diminished as a reference test for other methods if the ultimate capacity must be estimated by extrapolation.

2.1.4 Low statistical representation

Due to cost and time factors, even for land-based piling, static load tests are typically conducted at a rate of only 0.5% to 1.0% or 1 pile for every 100 to 200 piles, if undertaken at all. Figure 5 summarizes the capacities for 16 piles on a single pile cap on a large bridge project. Capacities were determined from dynamic formula correlated to dynamic pile tests. The cap measures 5m x 12.6m in plan. Figure 5 shows that there is in excess of 30% variation of interpreted capacity in the installed piles at this pier, despite a maximum variation in toe level of less than 0.3m or 1% of pile length. The piles are installed in an alluvial flood plain and resistance is predominantly frictional.

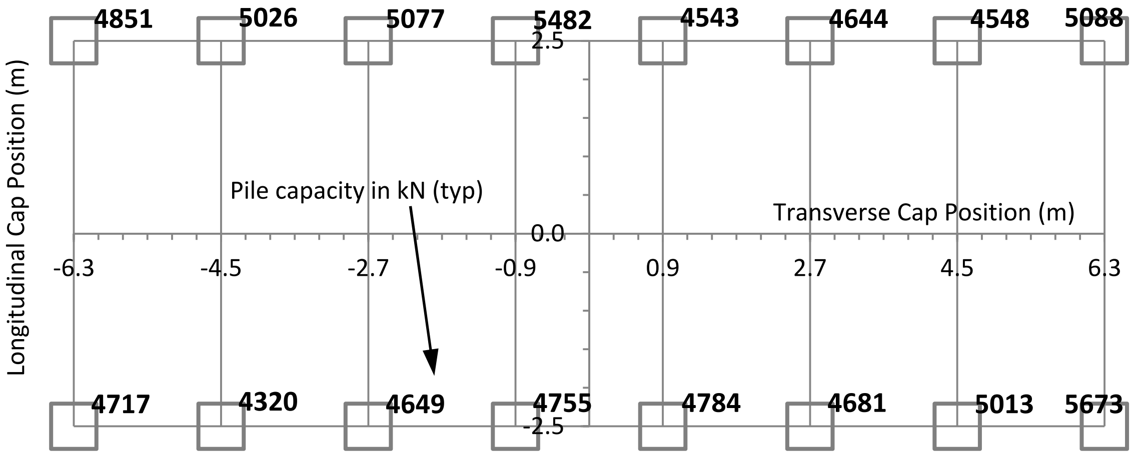

Figure 5. Individual pile capacities in a single pile cap

The bridge site is some 1500m in length, and testing at a rate of 0.5% to 1% implies a static test every 6 to 12 piers or at 150m to 300m centres. Given the demonstrated 31% variation in capacity over a distance of only 10m, to extrapolate the results of even a static test to failure to the intervening piles would be subject to considerable uncertainty.

2.1.5 Time-dependent capacity changes

Control of a driven pile project requires the development of clear acceptance criteria which reduce to a nominated pile movements for each blow under a given impact energy. This may be implemented in a blow count criterion based on Wave Equation analysis, or it may be by application of one of a number of available pile driving formulas.

Because static load testing, is an involved process, it can only realistically be performed days (say 3 to 30 days) after driving of a pile is completed. As previously discussed, pile installation causes ground disturbance that can result in transient changes in pore pressure conditions, or other short-term effects. After installation, pile capacities commonly increase (set-up) or decrease (relax) due to any number of possible mechanisms. Therefore testing after a delay period provides a progressively better estimate of long term capacity.

However, despite the benefits of post-installation testing, practical pile driving requires some clear termination criteria (eg energy and set) that relate to the installation phase and therefore the installation capacity. Static testing does not measure the capacity at the end of driving, and hence cannot be directly related to installation termination criteria.

The particular risk of relating static load testing to installation parameters is an underlying assumption that post-installation changes in capacity are consistent and reliable. In reality these changes will vary considerably depending on very localized stratigraphic variations, pile lengths and layering. The only way to reliably incorporate setup effects into the determination of target installation capacities is by a series of tests both at the moment of driving and subsequent to driving. Such test pairs must be undertaken across the site, and must be capable of evaluating the distribution of resistance, as setup effects will be both material-dependent and layer-dependent.

2.2 High Strain Dynamic Pile Testing

High strain dynamic pile testing is an alternative pile testing method which has been in use in Australia and New Zealand since the 1980s. It is a technique which has been codified in two Australian Piling Standards (AS 2159, 1995; AS2159, 2009), and has become a standard technique on many driven piling projects either independent of or in collaboration with static load testing. From a commercial perspective, dynamic testing is attractive because it is rapid and significantly less expensive than static load testing. This provides the opportunity to undertake many dynamic tests for the cost of a single static load test.

This cost advantage provides a unique opportunity to conduct comprehensive testing programs across the site and over the duration of the works, incorporating different stratigraphic zones, pile types and sizes, and piling hammers. Dynamic testing therefore allows testing to be performed at a statistically significant rate, which can provide distributed and meaningful pile capacity assessments, if undertaken and analysed appropriately.

In respect of capacity assessment it is significant that dynamic tests can be performed both during the installation phase and subsequent to driving (restrike).

Driving tests allow a direct relationship to be established between pile capacity, hammer energy and pile movements (i.e. pile set and temporary compression). These relationships may be used for correlation of wave equation driveability analyses, or dynamic formulas so that the installation and acceptance of untested piles can have a sound engineering basis.

On the other hand, restrike tests provide better assessments of long term pile capacities. A detailed comparison between driving and restrike tests allow changes in the distribution of capacity over time (setup or relaxation) to be evaluated.

2.2.1 Reliability of Dynamic Pile Tests

It is important to understand that dynamic pile tests do not measure the pile static capacity, but infer the static capacity from an analysis of a single dynamic impact event. The quality of that inference is fundamentally based on the suitability of the static and dynamic soil models in the analysis program, but also to an extent on the quality of the individual wave matching analysis.

There are broadly 3 possible outcomes of the analyses.

- Type A. The wave match is clear and there are tight bounds to the possible solutions. The quality of the match and the tightness of the bounding solutions suggest that the models are appropriate and the evaluation is relatively reliable. This represents the majority of cases.
- Type B. The wave match is clear, but there are wide bounds to the possible credible solutions. In this case, there is a risk of an incorrect assessment of capacity. Either the lower bound solution should be adopted, or clarification of the appropriate modelling is required – for instance by correlation with static load testing. This represents a minority of cases.
- Type C. The wave match is poor. In this case, the pile-soil interaction is more complex than the analytical models, and the reliability of the dynamic analysis is compromised. It may still be possible to be confident of a lower bound solution, but again, reference to static load testing may be required. This case is relatively infrequent.

AS 2159-2009 recognizes that the reliability of dynamic testing of a single pile is lower than static load testing by virtue of the lower capacity reduction factor range which is applied to dynamic pile testing. The intrinsic factors, ϕ_{tf}, which have been assigned to static load testing and dynamic load testing on preformed piles are 0.90 and 0.80 respectively, which reflects the suggested relative reliability of the two tests on a single pile. A factor of 0.80 implies that a capacity estimate by dynamic testing should not be more than 125% (or 1.0/0.8) of the true pile capacity. These intrinsic factors were adopted on the basis of historical practice. A testing benefit factor, K, modifies the intrinsic factor to establish a project-wide factor based on the percentage of piles tested. For 5%, 10% and 15% of piles dynamically tested, and a moderate to high project average risk rating the computed geotechnical reduction factors are 0.69, 0.75 and 0.77 respectively.

Figure 6 shows the cumulative distribution functions for the ratio of dynamic to static load tests from two studies (Likins and Rausche, 2008 and Chambers and Lehane, 2011) in which the tests were compared for 197 and 92 piles respectively. The study by Likins and Rausche suggest only 1.1% of tests overpredicted static capacity by more than 25%, whereas Chambers and Lehane found as much as 15.3% of tests were overpredicted by 25% or more. In practice, assuming that testing is undertaken on 5% of project piles, a capacity reduction factor of 0.69 is applied to estimated capacities, which implies that the actual capacity will still exceed the ultimate load if there is less than a 45% overprediction. According to the two sets of analyses, this could occur with a 0% or 7% probability.

These are significant differences between the two sets of analyses, but without detailed evaluation of each case in each study, the reasons for the differences could arise from any of the following :

- whether the static load was measured by manometer or load cell (see 2.1.1)
- the definition of static capacity adopted for each data set (see 2.1.2)
- whether the static load test was a proof or ultimate capacity test (see 2.1.3)
- the relative timing of the static and dynamic tests (see 2.1.5)
- the quality of execution of the dynamic pile testing and wave matching
- whether the pile-soil interaction was amenable to analysis and therefore whether the wave matching was a Type A, B or C analysis

Given the potential sources of error, such statistical evaluations should be accepted with caution. Rigorous individual case studies which are extensive in their details provide a more significant basis for comparison of static and dynamic test methods.

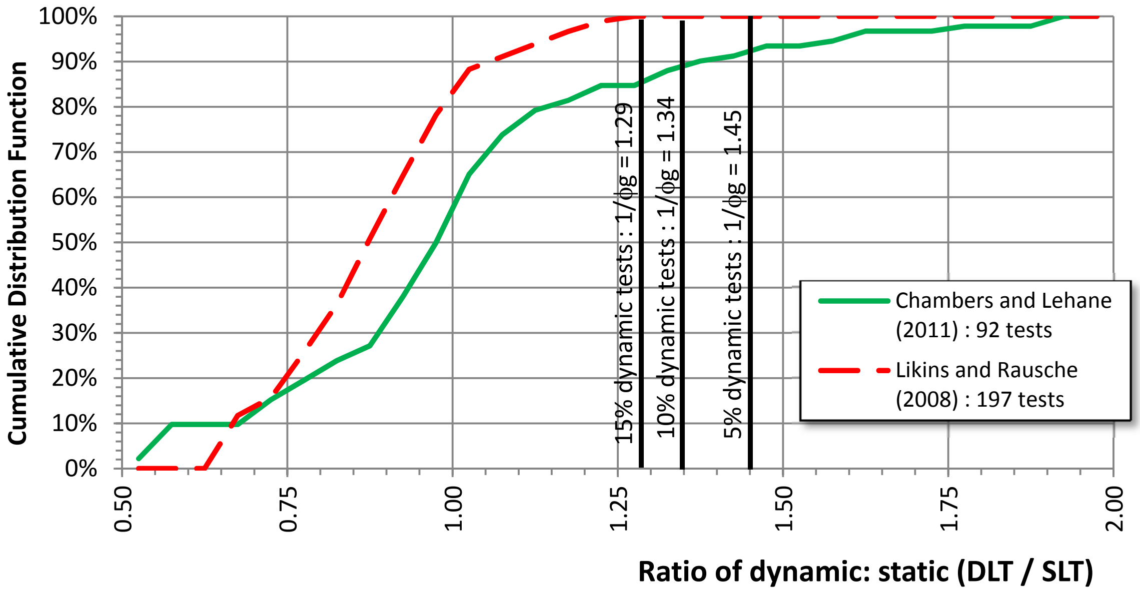

Figure 6. Cumulative Distribution Functions for the ratio of dynamic to static testing after Likins and Rausche (2008) and Chambers and Lehane (2011)

Nevertheless, both studies suggest that in the significant majority of cases, a program of dynamic pile tests will provide capacity estimates which, in combination with specified capacity reduction factors will still lead to safe estimates of pile capacity.

It is also noted that testing programs may be targeted rather than random, so that the piles likely to have the least capacity based on installation characteristics are assessed – resulting in yet higher confidence.

3 PILE MONITORING

It remains that even with dynamic testing being applied at 5% to 15% of project piles, 85% to 95% of piles are untested. Despite being untested, the structural importance of these piles is no less than the tested piles. Therefore, it is necessary that methods for their approval be informed by and correlated with the specific testing undertaken. As these untested piles will be approved based on driving parameters, they must of necessity be correlated against a driving test – the dynamic pile test.

Evaluation of the capacity of every pile on the project must be necessarily simple and provide real-time confirmation. Normal approaches used include bearing graphs and dynamic formulae, however these approaches are simplistic, and can only provide valid capacity estimates if they are correlated to load tests. Furthermore, all capacity estimates rely directly and critically on a knowledge of the energy transmitted to the pile.

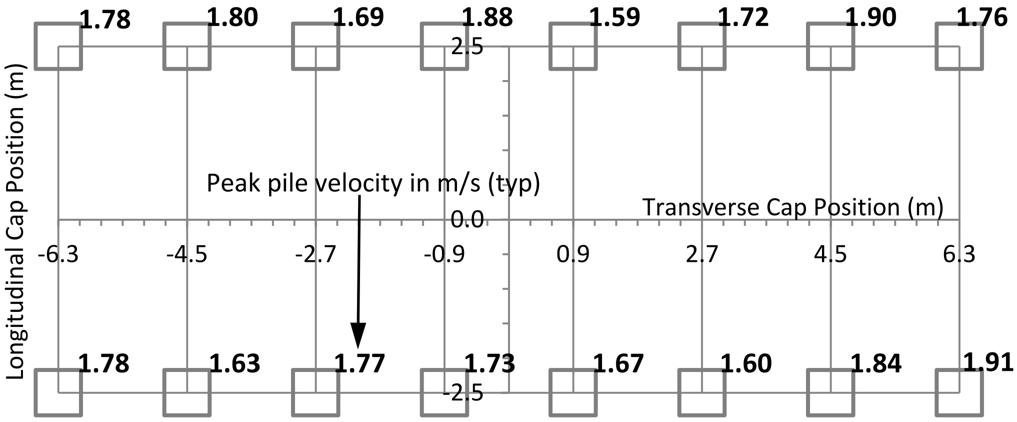

Figure 7. Individual peak pile velocities in a single pile cap

On the project described previously, and for which the individual pile capacities were shown in Figure 5, a longitudinal study of delivered energy varied from 42 to 84kJ for the same hammer, with a constant hammer stroke. This is a ±33% variation about the median energy. The variable performance of the hammer is highlighted in Figure 7 which summarizes the variations in peak pile velocity recorded across only a single pier. These were recorded using a Pile Driving Monitor (PDM) which makes non-contact measurements of pile movements and velocities. There is a measured range of 18% in peak pile velocities, which translates to a 39% variation in delivered energy to piles on this one pier alone. Energy variations are random and unsystematic. The capacities shown in Figure 5 are derived from a correlated dynamic formula which incorporates the variations in energy.

Longitudinal studies of dynamic testing on other projects demonstrate that these large variations in energy, although not universal, are the rule rather than the exception. Unless these variations in hammer energy are captured and incorporated in the acceptance criteria, pile capacity estimates for untested piles will be in error by the same amount as the error in energy.

In order to achieve effective quality control on driven pile projects, the PDA testing program should be supplemented with PDM monitoring of every pile so that the substantial variations in energy delivered to piles can be captured and properly incorporated in the pile capacity assessments.

4 SUMMARY

Prediction of pile capacity is a significantly uncertain process, due to variability of ground conditions and the effects of pile installation on pile-soil or pile-rock interaction. Although piling codes such as AS2159-2009 allow in some cases that foundations may be installed without testing, pile testing is recognized as a desirable way of reducing foundation risk, and encouraged by assigning meaningfully higher capacity reduction factors for tested foundations.

Static load testing, when conducted to geotechnical failure and when accurately measured provides a reference capacity estimate. The primary use of this test for driven pile projects is to provide a correlation for dynamic load tests, which have particular benefit when conducted across a site over the duration of a project.

Dynamic tests infer rather than measure static capacity, and can be correlated against static tests, but statistical studies indicate that in the significant majority of cases, even standalone estimates will in combination with codified capacity reduction factors, provide safe estimates of ultimate pile capacity.

The acceptance of untested piles requires simple real-time approaches which must in turn be correlated against dynamic pile tests. The proper implementation of such acceptance methods requires measurement of not only pile response (set and temporary compression) but also hammer performance, which often varies significantly and unsystematically.. Transferred energies can be inferred from monitoring pile velocities.

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