Enhanced Use of Dynamic Pile Testing in Foundation Engineering

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ABSTRACT

Over the past 30 years, dynamic pile testing (PDA) has become a generally accepted technique for verification of driven pile capacities in many western countries, Australia and New Zealand included. In the vast majority of projects, the technique is specified as a quick, inexpensive and generally reliable method for proof load testing for contractual reasons. PDA testing can also be used to measure and monitor piling hammer performance, measure and allow control of driving stresses, and provide the basis for rational pile acceptance criteria. However, its abilities as a quality control tool are often insufficiently utilized. A risk associated with PDA testing is interpretation which is not geotechnically credible due to insufficient consideration of geotechnical base information by practitioners and the automatic wave matching optimization routines they may employ. The outcome may be disinformation and confusion. The effective use of PDA testing should always be guided by a sound geotechnical understanding. In this case, PDA testing can be used not only for quality assurance and control but also for design verification and guidance, and for providing insights into the dynamic interaction of hammers, piles and soils. This paper highlights the risks of injudicious use of PDA testing, and will demonstrate by example the importance of a systems approach, and the potential benefits of careful geotechnically-referenced interpretation.

Keywords: dynamic pile testing, PDA, Capwap, foundation verification

1 INTRODUCTION

Dynamic pile testing has a primary function in the implementation of quality assurance and quality control processes on most infrastructure and commercial building projects founded on driven piles since the introduction of this testing method in Australia in the early 1980s. Although the technique was specifically developed for use on preformed driven piles, the technique continues to be used on some cast-in-situ piling projects as a quality control tool although such use requires additional information and carries an implied lower certainty. The use of dynamic testing for both driven and cast-in-situ piles is codified in the Australian Standard AS2159-2009.

The particular role, importance, limitation and reliability of dynamic pile testing in driven piling projects is described in principle in a companion paper to this conference (Seidel, 2015). The same principles broadly apply for its implementation in cast-in-situ piling projects. In the significant majority of projects, the predominant use of dynamic pile testing is to infer the axial compression capacity of piles, and this paper will focus on this use. These capacity estimates are most reliably determined for dynamic testing using one of a number of proprietary wave-matching algorithms in which the static and dynamic pile-soil interaction to a hammer impact are modelled. Progressive adjustment of the models to achieve the best correlation between measured and predicted responses to the impact are assumed to define the most appropriate static and dynamic soil models and hence the most likely static capacity mobilized during the dynamic event.

Wave matching is not a unique process (Rausche et al., 2008), and therefore it is incumbent on the analyst to apply sound principles and due care during the matching process. If this is not applied, the value of the analysis, and the fundamental intent of the analysis in the QA/QC process is degraded, with a range of negative consequences. This paper outlines some important principles which should be considered in the implementation of the wave matching process on all projects.

This paper is based on the premise that dynamic pile testing and its associated wave matching analysis, when undertaken appropriately and in conjunction with reduction factors such as those in AS2159-2009 provides a factored capacity estimate which will be conservative in all but a small number of cases, as discussed in Seidel (2015).

2 INFERENCE OF CAPACITY FROM INPUT AND RESPONSE

Pile capacity is inferred from all tests by the interplay between input energy and pile response. For a static load test, the input energy is derived from the applied pile head force, and the response is the measured deflection of the pile-soil system. The capacity is determined from the load-movement response (Fellenius, 1980). For dynamic tests, the input energy is the downward travelling wave from the hammer, and the pile response is the reflected upward travelling wave, which is the reference for the wave matching process. For the majority untested piles, the input energy is assumed or pre-calculated as in the Hiley Formula (1925), predicted as in Wave Equation studies or referenced to available dynamic tests. The pile response is the measured set, blow count or in some instances also the temporary compression.

3 THE NEXUS BETWEEN ENERGY, CAPACITY AND PILE MOVEMENT

In order that piles can be installed and accepted without testing, there is always an implied Energy-Capacity-Movement relationship that underlies the acceptance process. Without such a relationship, it would not be possible to install driven pile foundations without testing each and every pile. This Energy-Capacity-Movement relationship is expressed in dynamic formulas, bearing graphs or target sets. For any given (measured or assumed) energy, there is a relationship between capacity and pile movement. Any change in energy transferred to the pile correspondingly affects the capacity-movement relationship. Measurement of pile movement, such as set or blow count is therefore an incomplete acceptance criterion unless energy is also measured or assumed.

Just as static load testing is the golden reference for the evaluation of a single pile capacity, the Energy-Capacity-Movement relationship which is intrinsic to the particular combination of piling hammer, driving system, pile and stratigraphy should be considered the golden reference for the determination of the capacity of the hammer-pile-foundation system. Naturally, if the stratigraphy changes and piles are significantly longer or shorter, or founded in different strata, the reference relationship will change accordingly.

Just as dynamic testing is subservient to properly performed static load testing for correlation purposes, so dynamic testing is also subservient to the Energy-Capacity-Movement relationship for evaluation of the capacity of the foundation system as a whole. Each dynamic test and analysis provides an estimate of this underlying relationship, and the relationship is discovered by undertaking a holistic assessment of the set of dynamic test results. The individual dynamic test results must form a credible suite of results from which the relationship can be established to inform further piling.

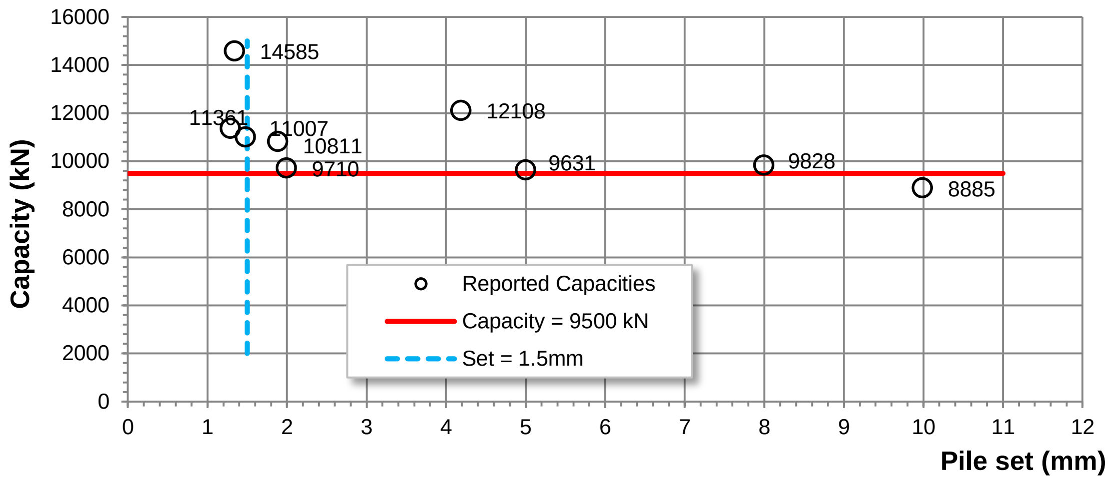

Figure 1. Unsystematic suite of dynamic test analyses

By undertaking dynamic pile tests in isolation and without undertaking a holistic assessment, the risk is that the tests will be disparate and incoherent. They will not provide clear guidance to the project on an appropriate acceptance criterion. The consequence may be a higher rate of testing, and even 100% pile testing because of the resulting confusion. Figure 1 shows an example of a suite of such incoherent tests. The piles were all of one size and driven into similar ground conditions. The delivered energies also varied less than 10%. These tests suggest that a pile capacity of 9,500 kN may be achieved at pile sets of between 2 and 10 mm, or that capacity is effectively independent of pile set. Conversely it could be interpreted that at sets of between 1.3 and 2.0 mm, the achieved capacity could be between 9700 and 14600 kN, suggesting extreme variability and sensitivity to pile set. Neither proposition is reasonable or helpful to the assessment and acceptance of untested piles.

Figure 2 shows the corresponding wave equation capacity-set relationships which were presented for each pile. The inconsistency of the results is highlighted by the diversity of these curves which suggest that at an 8 mm set, the capacity would be any value between 3800 kN and 9800 kN.

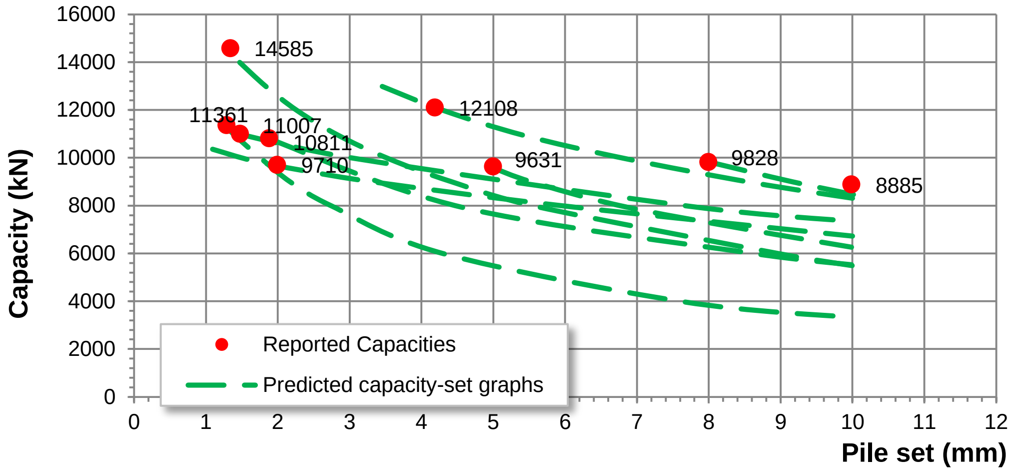

Figure 2. Inconsistent capacity-set relationships

The diversity and inconsistency of these results could arise from a combination of (a) poor data acquisition (b) poor quality analysis (c) inconsistent modelling of data in cases where the range of potential solutions is wide. It is very unlikely that the diversity is due to actual differences in the underlying hammer-pile-ground response. If this were true, then the consequence would naturally be a requirement for testing of 100% of piles, but this is much less likely than inconsistent or incorrect analysis.

4 RELIABILITY THROUGH SOLUTION CONSISTENCY

As noted, wave match analysis does not provide a unique solution to the interpretation of dynamic pile testing results. The more appropriately the static and dynamic soil models capture the true pile-soil interaction, the lower the range of possible solutions and the narrower the range of credible soil parameters. In ideal cases, the capacity range may be as low as ±5%, but less commonly the range may be as much as ±25% for a single analysis. However, if a consistent set of dynamic and static soil parameters can be applied generally across a suite of tests, that modelling solution gains greater credibility through the universality of its application.

This is not to say that parameters must be identical from pile to pile, as clearly ground conditions are variable, however, a consistent set of analyses will display tight ranges of parameters and modelling solutions. A database approach to summarizing all dynamic testing data including analysis parameters, and resistance distributions is paramount to ensuring that analyses form a consistent and credible suite of solutions.

5 GEOTECHNICALLY CREDIBLE SOLUTIONS

Wave matching analysis is an iterative process in which static and dynamic soil models are progressively modified with the objective of producing the optimum correspondence between the measured soil response (upward wave-time) and the computed response from the wave equation algorithm using the hammer input (downward wave-time) as the boundary condition. Each match, and the differences between the measured and computed responses allows the model to be refined. The analysis can be performed both manually and automatically. The automatic routines are based on numerical optimization techniques, and utilize inbuilt match quality assessment routines which allow the calculation engine to determine whether or not speculative model changes are beneficial.

As noted by Rausche et al (2008) there are two schools of thought in relation to the approach to the matching analysis process. The first school of thought is that automatic analysis removes subjective operator bias from the solution, and is therefore justified and preferable because of its independence. This is not completely correct, because the automatic process is only allowed to commence after manual analysis has generated a match of minimum acceptable quality. Initiating the automatic matching process from different manual seed solutions does not result in a unique final solution.

The alternative school of thought is that ceding control of the matching process to a mathematical algorithm, which is not informed by any knowledge of the geotechnical conditions or what constitutes a physically credible solution is fundamentally risky. It also excludes from consideration key reference information which may allow the range of credible solutions to be narrowed and invalid solutions to be excluded.

As will be discussed further, there are significant pressures and therefore great temptations for analysis to be done using the automatic analysis approach. It is the author's experience that this path leads to inconsistent solutions and resistance distributions which could only be described as geotechnical nonsense. For instance, solutions with layers of no shaft resistance for several metres sandwiched between competent layers have been attributed to "underground rivers". Solutions with shaft resistances above the toe equivalent to loose sand frictions, but paired with end bearings in excess of 20MPa are not credible and even result in such high end bearings being considered as orthodoxy, when they actually result from an optimized mathematical process.

The difference between solutions generated by an automatic matching process and one in which the geotechnical conditions are considered are shown in Figure 3. The 6 piles were installed through a suction cutter dredged berth pocket into underlying variably weathered rock. Testing appeared to indicate that the rock below the dredged bed was significantly disturbed by the dredging process. Figure 4 compares the mobilized shaft and end bearing resistances reported in the automatic and manual wave match analyses.

These figures show that the automatic analysis approach generated resistance distributions which were both grossly inconsistent and not geotechnically credible in the prevailing subsurface conditions. The automatic analysis for P19, for instance suggests zero shaft resistance for the element of shaft immediately above the pile toe, and 19m below rock head. The same analysis indicated an end bearing of 5647 kN. Not only is the resistance distribution not credible, but the analysis is internally inconsistent. Generally the shaft resistance distributions show no discernible pattern, and the shaft resistances, which were critical for assessment of tension capacity, range from 3030 to 11313 kN – a range of +53%/-59% about the mean of 7375 kN.

The resulting interpretation was that the ground conditions were so variable, that the critical tension capacity of these projects piles could not be inferred without increasing the testing rate to 100% of all piles. The credibility of the solutions was apparently not questioned by any of the project team.

The manual distributions shown in Figure 3 also vary, but show generally increasing shaft resistance with depth, which seems more geotechnically credible. Figure 4 also indicates that the total shaft resistances were more consistent, with shaft resistances ranging from 8150 to 11313 kN – a range of +21%/-22% about the mean of 10387 kN.

Subsequent testing and analysis for a further stage of the project was undertaken using a manual approach to analysis, and based on the development of geotechnical models and acceptance criteria derived from the testing so that the testing rate resumed at the original 20% of piles.

Another example of the difference between automatic and geotechnically referenced analyses can be seen in Table 1. The table shows the unit shaft and toe resistances for the lower sections of a 56 m long 800 mm diameter closed-ended steel tube pile. The lower section of the pile is in dense sands with SPT N>50. The automatically generated shaft resistance of only 10.3 kPa in the lowest shaft element (at 56 m) is difficult to reconcile with both the high SPT value, and the computed end bearing of 14.9 MPa (which is a ratio of 1452). By contrast, the manual analysis, which infers a final element shaft resistance of 134.5 kPa and an end bearing of 12.8 MPa shows a ratio of 95, which is consistent with typical design recommendations.

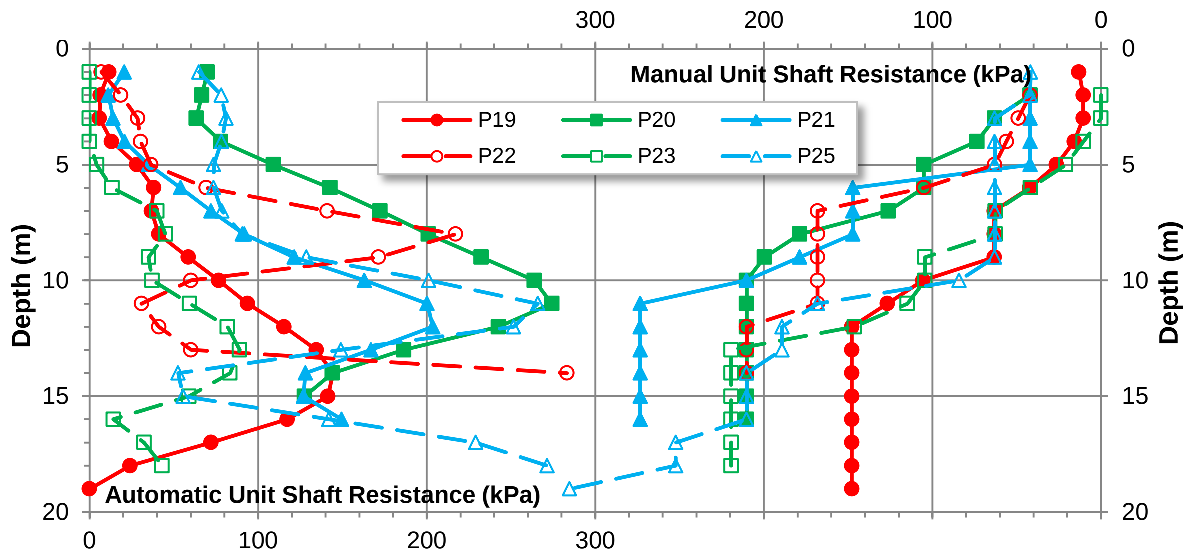

Figure 3. Resistance Distributions for 6 piles using automatic wave matching (LHS) and manual analysis (RHS)

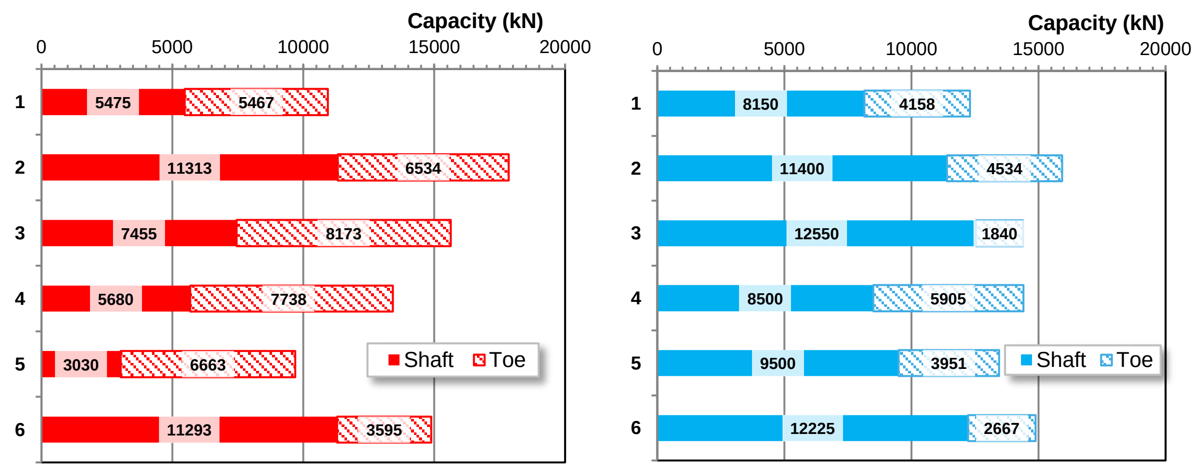

Figure 4. Comparative Shaft Resistance and End Bearing for 6 piles using automatic wave matching (LHS) and manual analysis (RHS)

Table 1: Comparative Unit Shaft and End Bearing for automatic and manual wave matching

Depth (m)	50.0	51.0	52.0	53.0	54.0	55.0	56.0	Toe	Ratio
Auto Shaft/Toe (kPa)	48.6	73.0	79.2	77.0	59.4	60.8	10.3	14900	1452
Manual Shaft/Toe (kPa)	67.3	67.3	67.3	89.7	112.1	112.1	134.5	12800	95

It should be emphasized that although automatic analysis may result in similar estimates of total pile compression capacity as a manual analysis, the distributions of resistance computed by a numerical optimization analysis cannot be assumed to lead to a credible geotechnical model. From the perspective of design review, where the tests are only required to evaluate compression capacity, the consequence may be no more than a reduced confidence in the reliability of the analysis – which ultimately reflects negatively on the method itself.

However, for projects in which the testing is undertaken not only for compression capacity assessment, but also tension capacity evaluation and even assessment of lateral stability, development of a geotechnically credible and consistent pile resistance model is paramount. With such an approach, a rational methodology can be developed in regard to pile sign off based on a global or system approach to the foundations.

6 THE ISOLATED TEST APPROACH AND QUICK TURNAROUND ANALYSIS

In the project discussed in relation to Figures 3 and 4, there was a requirement in the specification that wave matching analyses was required to be completed in a specific timeframe with the understandable intention that such quick turnaround would minimize delays to the project. For tested piles (ultimately all piles on the project) sign-off was only possible after the data had been downloaded and analysed, and then independently reviewed. This requirement placed both the tester/analyst and the independent reviewer who had to sign off each pile under extreme time pressure, as the contractor could not commence pile cut-off and barge relocation until final approval was given. Despite good intentions, such stipulations are based on and encourage a blinkered vision approach.

A tester/analyst, under such time pressure is not encouraged to evaluate the dynamic testing data in a broader sense or to reference geotechnical borelogs, to review the internal consistency of analyses, or to consider upper or lower bound solutions – i.e. to apply sound quality assurance processes and engineering judgement and review to the analysis process. The expedient solution is automatic analysis which can generate solutions faster and with less effort than a considered manual approach. Automatic analysis does not provide this sound engineering approach which leads to consistent and credible models. The diverse and significant results and the consequences to construction and design risk have been described.

This approach is effectively premised on the assumption that each pile test is an independent, unique and unrelated 'event' which will be designated here as the 'isolated test' (IT) approach. In general, this is not true - as in a consistent or gradually transitioning stratigraphy, individual pile tests are related by the commonality of the pile-ground interaction process, and should rather be considered a set of diverse but connected expressions of the underlying 'global' Energy-Capacity-Movement (ECM) relationship.

The implication of the IT approach, which is encouraged by the requirements for fast turnaround analysis, is that a set of unconnected ECM relationships can result – as shown in the widely different bearing graphs in Figure 2. Each ECM relationship is assumed to be relevant for the pile installations subsequent to each test – at least until the next test is performed and a new ECM relationship is computed. Although the motivation for this IT approach is to generate least delays to the contract, the result is a poor technical outcome, and a foundation installed to potentially very inconsistent standards. As noted in relation to Figure 2, a set of 8mm could generate a capacity of anywhere between 3800 and 9800kN, depending on the particular bearing graph or ECM adopted. All things be equal, especially the delivered hammer energy, this proposition is clearly nonsense.

7 A SYSTEM APPROACH USING A UNIFYING ENERGY-CAPACITY-MOVEMENT RELATIONSHIP

A system approach is necessary – and it happens that a system approach not only results in a technically superior foundation delivered to a consistent standard, but it also results in less, if any, delay to the piling process. In a system approach it is first necessary to establish or determine a unifying ECM relationship. Normally this would be developed over the first 5 or 6 piles tested, or over a smaller number of piles, but tested at different stages of driving which encompass a range of hammer energies and pile capacities. Given that wave matching of any dynamic test does not provide a unique solution, the initial wave matching solutions should be considered draft, for subsequent review during the development of the unifying ECM relationship.

The aim then is to develop a set of wave matching analyses which are geotechnically credible, internally consistent, and which together define this unifying ECM relationship. Perfection cannot be expected, so a variability of 5 to 10% about the solution must be expected. As noted before, the ECM relationship may be expressed in several ways – for instance as a correlated dynamic formula, a suite of bearing graphs for different hammer energies, or in general any numerical or graphical solution which encapsulates the nexus between energy, capacity and movement for the hammer, pile and ground combination.

Having established this unifying ECM relationship, thereafter, all piles – both tested and untested should be installed and accepted according to this standard. This is no different to normal practice for untested piles, except that the ECM relationship to which they are installed is rather constant, and is only modified on an 'as needs' basis as determined by subsequent testing.

The significant difference is that the tested piles are also accepted using the same ECM relationship determined in advance of the test, not based on the specific wave matching results for that pile. The underlying philosophy is that piles are not tested to provide contractual verification of isolated piles, but rather to provide an opportunity to review and if necessary amend the predetermined ECM relationship which underlies the whole foundation system.

It is important to understand this philosophy in the context of the following principles:

1. From a foundation system perspective, there is no particular significance of tested piles, as all piles should be installed with the same level of quality and risk to support the designated loads
2. The approval of piles should be on the basis of an integrated assessment in which the installation of untested piles is informed by the suite of test results, not segregated into piles which are approved according to different, unrelated and uncorrelated groups of piles separately verified by static testing, dynamic testing and dynamic formula approaches. Such an uncoordinated approach would result in piles being installed to different standards.
3. The vast majority of piles will be untested (typically 90 to 95%), and hence tested piles represent a relatively minor portion of the foundation system.
4. The highest priority should be given to establishing the unifying ECM relationship, and then ensuring that untested piles can be effectively monitored to ensure compliance of the whole foundation system.

Wave matching is still performed on the tested pile, but the analysis is undertaken in a timely manner, conducive to proper assessment of the data and with proper engineering judgement. As noted, the expectation is that the analysis will support the continuation of the ECM relationship being used to install piles generally, however, if the data indicates a distinct change in pile-soil interaction because of stratigraphic changes, the ECM relationship is revised accordingly. This approach results in a measured and holistic approach to the foundation system verification, and provides more consistent, stable and reliable pile acceptance criteria.

8 IMPLEMENTATION OF A SYSTEM APPROACH

Having established the unifying Energy-Capacity-Movement relationship, it is necessary to implement this rigorously to determine capacity. That requires accurate assessment of pile movements (set and rebound as necessary depending on the relationship being used), and accurate measurement of energies being transferred to the pile.

Traditional pile driving formulae such as the Hiley Formula assume constant energy is delivered, based on a flawed model of the hammer-pile impact event. Dynamic pile testing is able to compute energy delivered to the pile (generally designated EMX) based on strain and acceleration measurements. Dynamic formulae can be modified to include energy measured by PDA in place of the traditional assumptions of transferred energy. However, longitudinal studies of piling projects with dynamic testing measurements generally show that energy delivery varies considerably and unsystematically.

Figures 5 and 6 show measurements of transferred energy from well-controlled projects with hydraulic hammers, and uniform hammer stroke requirement. Even in these ideal conditions, energy transfers varied by -16%/+20% about the average for the steel piles, and -37%/+27% for the concrete piles. Under less controlled conditions and with other hammers, even greater variations are possible. The capacity estimate for untested piles will vary by the same percentages. The importance of verifying the energy delivered to each individual pile is demonstrated to be a necessary part of an effective QA system for driven pile foundations. Non-contact monitoring of piles using the Pile Driving Monitor (Seidel 2015) is an ideal way to measure both hammer performance and pile movements for implementation into the Energy-Capacity-Movement relationship.

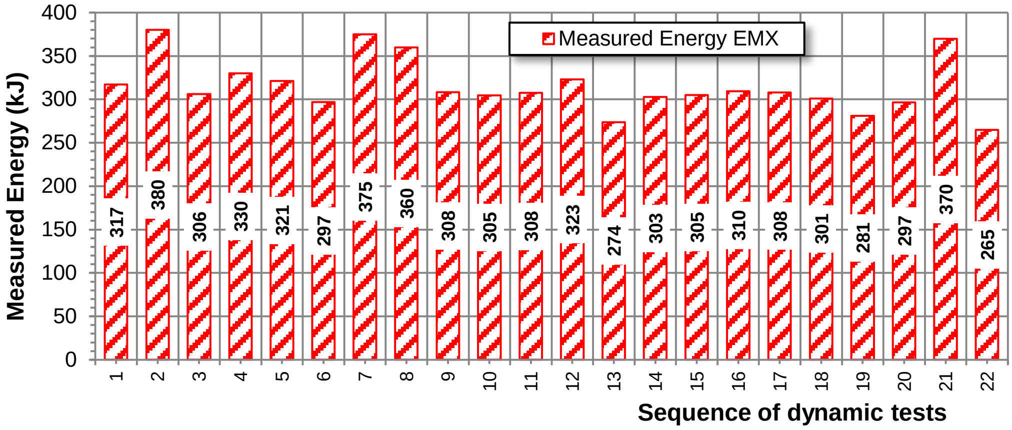

Figure 5. Measured Energy transfers for hydraulic hammer and steel piles

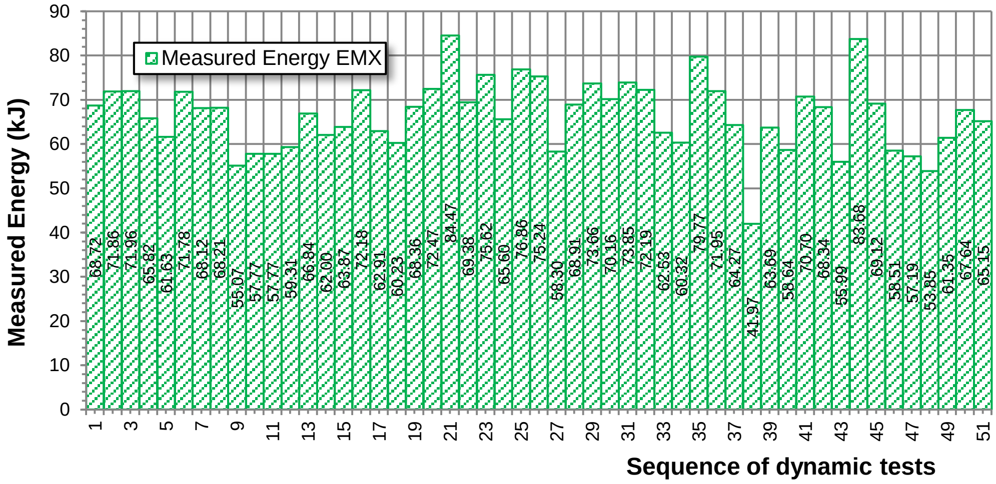

Figure 6. Measured Energy transfers for hydraulic hammer and concrete piles

9 CONCLUSIONS

For driven pile foundations, a system approach is needed to ensure that piles are driven to a consistent and reliable standard. The matter of primary importance is to establish a unified Energy-Capacity-Movement relationship, which can be used to reliably install the 90 to 95% of piles which will not be tested. This relationship must be calibrated against and developed from dynamic pile testing, which provides the reference assessment of the dynamic pile driving event. Sound and geotechnically informed analysis techniques are required. The dynamic pile testing may be referenced with care to static load testing, which provides the ultimate reference of single pile capacity. The importance of monitoring the energy delivered to each pile, and accurately measuring pile movements is critical to effective implementation of driven foundation quality assurance.

REFERENCES

AS 2159-2009 (2009). Piling – Design and Installation. Standards Australia.

Fellenius, B.H. (1980). The analysis of results from routine pile loading tests. Ground Engineering, London, Vol. 13, No. 6, 19-31.

Hiley, A. (1925). A rational pile-driving formula and its application in piling practice explained. Engineering, 119 (3100) : 657-658.

Rausche, F., Nagy,M. and Likins, G. (2008). Mastering the Art of Pile Testing. Proc. of the 8th Int'l Conf. on the Application of Stresswave Theory to Piles. Lisbon. J.A.Santos (ed) : 19-32

Seidel, J.P. (2015) Overview of The Role of Testing and Monitoring in the Verification of Driven Pile Foundations. 12th Australia New Zealand Conference on Geomechanics, Wellington, New Zealand. Accepted for publication.