Pile Testing Verification – an Alternative Approach

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ABSTRACT

Dynamic pile testing is undertaken for a number of reasons including: 1. To confirm that the pile meets serviceability and geotechnical capacity requirements; 2. To assess pile integrity, either during installation (driven piles) or after construction (cast-insitu piles) and 3. To verify that the piling hammer delivers the energy required to satisfy the design criteria and that stresses during testing are kept within acceptable limits. In addition, testing allows us to establish and calibrate acceptance criteria - relationships such as resistance vs set curves, and/or correlated pile driving formulas. These relationships are premised on the interrelationship of capacity (C), transferred energy (E) and pile movement (M) which is represented primarily by pile set. These ECM relationships allow capacity to be inferred from measurement of transferred energy and pile movement and are used to infer the capacity of untested piles. However, for a variety of reasons, transferred energy can vary significantly between piles which, being undetected, undermines the reliability of ECM relationships. An alternative approach to using ECM relationships is proposed based on pile set and pile force (F). We demonstrate through parametric studies and review of project data, that these FCM relationships are reliable alternatives which bypass the problems with variable energy transfer. Of course, impact force will also vary with hammer performance, but impact force can generally be accurately determined from the measured impact velocity as a proxy. Pile velocity can be measured by attaching a single accelerometer to the pile, or by using a high frequency displacement monitoring device. FCM-based acceptance criteria have the significant advantage that both the necessary force (F) and displacement (M) inputs can be verified by simple measurements on all untested piles.

Keywords: Pile Testing, Pile Verification, Dynamic Formulae, PDA, Case Study

1 INTRODUCTION

The intent of this paper is to discuss an alternative approach to estimate the resistance of untested driven piles. The traditional methods of pile verification for these piles are almost universally based on Energy-Capacity-Movement relationships. Pile driving formulae are various forms of ECM relationship (Seidel, 2018, 2021). Without these relationships every pile would need to be tested.

An alternative Force-Capacity-Movement (FCM) approach has been developed which relates pile capacity to the pile head force generated by the driving hammer and to pile set. In application, this approach involves measuring pile impact velocity (as a proxy for pile impact force). In all but exceptional cases, pile-top force and pile velocity are related by pile impedance at the time of impact. The benefit of the FCM approach is that pile-top impact force can be inferred from simple measurements for each pile, whereas transferred energy (in ECM relationships) can only be assumed. The FCM approach is therefore intrinsically more reliable than traditional ECM approaches.

This paper will focus on demonstrating the nature of the relationship between pile head force and pile capacity using data generated from both a GRLWEAP (Goble et al., 1988) wave equation parametric study and also from actual piling data.

2 BACKGROUND

Deep foundations are constructed to transfer loads from a superstructure into the ground. There is an inherent uncertainty associated with the interaction between the piles and the ground in which they are installed or constructed. In order to reduce the risk of failure for these foundation elements, design methods take into account this uncertainty. In order to reduce this uncertainty, and benefit from higher capacity reduction factors, driven piles are tested during installation.

Pile testing is undertaken to confirm that the pile meets serviceability and geotechnical capacity requirements. Depending on the type of test, the structural integrity of the pile may also be assessed to ensure that the pile is intact and free of damage. Testing can further provide information on the performance of the driving system. In summary, testing is a quality control process which helps increase confidence that the test pile meets the design intent.

The uncertainty of a particular pile capacity evaluation is related to the intrinsic reliability of the test method used. However, the benefit of any test has indirect benefit to the evaluation of other similarly installed piles. Under AS2159-2009 the applicable geotechnical reduction factor (φg) for untested piles is determined from a risk assessment in conjunction with the proposed type of pile test and percentage of piles being tested. The so-called testing benefit factor increases with the percentage of piles tested.

Static pile testing is the traditional and direct method of pile testing where the movement of the pile is monitored and recorded as the pile is gradually loaded to the desired capacity. Due to practicality, time and cost implications of static pile testing, only a limited number of piles are usually tested (Rausche et al., 2008), which is not ideal for large projects, especially for sites with significant geological variability as there is a significant risk where test piles may not be representative.

The focus of this paper is on driven displacement piles which allow a wider range of testing opportunities, including high strain dynamic testing (commonly referred to as PDA testing). PDA testing has been used in Australia and New Zealand since the early 1980's. PDA testing has substantial cost and time advantages relative to static testing, and this allows more testing to be conducted for the same testing budget. PDA testing therefore allows statistically significant, and widely distributed testing to be conducted – a significant benefit compared to traditional static testing.

Typically, less than 15% of piles on a project are tested, leaving the remaining 85% of piles untested. The verification of the untested piles can be done in several ways. For example, by simply comparing installation data of untested piles to installation data of tested piles and ensuring that the untested piles have been driven to similar or harder conditions. In practice, dynamic formulae, such as the Hiley formula (Hiley, 1930) are often used for this verification. Hiley formula is recognised in AS2159-2009 and is also in the Auckland Structural Group Piling Specification (2002). However, academic debates from as early as 1941 (American Society of Civil Engineers, 1941) and to this date (Allin, 2015) continue to discuss the inaccuracies of the use of dynamic formulae. Allin recommends using wave equation analyses instead of generic dynamic formulae for the assessment of untested piles. Seidel (2015) proposes the use of site-specific dynamic formulae, which are to be calibrated based on test data, which has been further investigated with success (Damen & Denes 2017, Denes & Kroenert 2019). Nevertheless, the use of dynamic formulae in projects may lead to mis-guided results and inaccuracies and should be used with a correct understanding and informed approach.

Regardless of whether a dynamic formula, a modified dynamic formula or a wave equation analysis is used for comparison between tested and untested piles, the capacity of a pile is related to the applied energy (or hammer drop height) and the pile movement (or set). This is discussed further below in detail.

3 PILING RELATIONSHIPS – CURRENT PROCEDURE

There is a requirement for most driven piling projects to provide a driving (or installation) criterion prior to commencement of pile driving to ensure the required pile capacity is achieved. This is usually in the form of graphical correlation between pile capacity, applied hammer energy and measured permanent movement (set) from a single (or a specific number of) hammer stroke(s). This graphical representation is usually referred to as a bearing graph. Bearing graphs can be generated from either the traditional dynamic formula (e.g. Hiley) or Wave Equation Analysis Programs (e.g. GRLWEAP). Dynamic formula use simplified empirical relationships relating to energy transfer between two bodies. Wave Equation Analysis Programs simulate the driving sequence and estimate the energy applied to the pile considering a much wider range of factors including stiffness and dimension of the pile and striking weight, hammer and piling cushions, etc.

Once a bearing relationship has been developed for pre-piling, the first installed piles are tested to confirm the bearing relationship. The bearing graph may be further calibrated based on observed field results taken during end of initial drive or restrike testing. At the end of the test piling process, the aim is to use the pile test results to produce a relationship that reliably predicts resistance of the untested piles to the tested piles.

The result of Wave Equation analysis is a relationship between pile capacity and pile set, which is energy dependent – i.e. a form of ECM relationship. This is traditionally presented as one or more curves relating capacity to blow count (blows/metre) called a bearing graph, as shown in Figure 1.

The problem with this traditional form, is that at very low pile sets (high blow counts), blow counts become excessively high and the relationship below 1.0mm set (1000 blows/m) is difficult to evaluate. Therefore, in the following, the bearing graphs shown will relate capacity to set, as shown in Figure 2 which represents the same data shown in Figure 1.

3.1 Set and Hammer Energy Measurements

In order to use the bearing graph for pile capacity verification, measurements of the pile set and hammer energy are required. Different methods can be used to measure pile set, with various degrees of accuracy. The traditional method used to measure set involves a person (a) standing beside a pile and marking a piece of paper attached to the pile during each hammer strike. Due to safety concerns associated with standing and working beside a hammer, this method has mostly been replaced with one of the following methods: (b) monitoring using surveying equipment; (c) manually marking the pile prior and

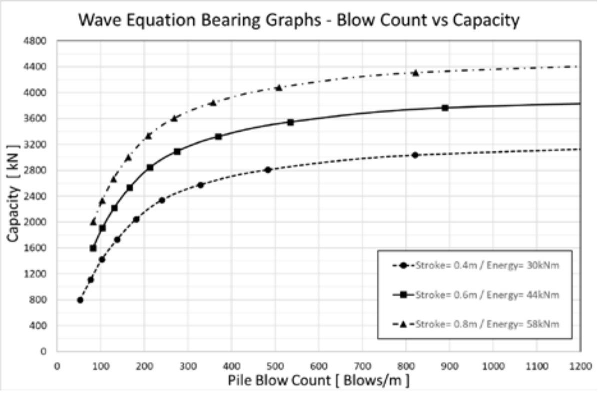

Figure 1. Bearing graph relationship – blow count

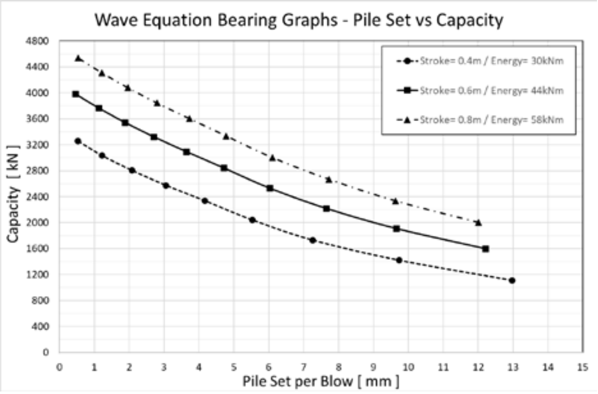

Figure 2. Bearing graph relationship – pile set

subsequent to the final 10 hammer blows; (d) onboard piling hammer instrumentation (such as the iPilier system by Junttan or NDT lazer & computer system); (e) counting the number of hammer strikes for the pile to move a certain distance (blow count); (f) non-contact high frequency displacement monitoring devices, such as the Pile Driving Monitor (PDM) which has sub-0.1mm accuracy.

It can be unreliable to rely on options (a) to (d), especially when pile set is small. Ideally, more focus towards set measurement using digital equipment should be embraced, as anything that involves manual pile marking and/or counting is likely to introduce an element of error.

Set is usually measured over a sequence of 10 blows. It is important that these blows be consistent so that the average set is meaningful. Any 'warm up' blows to reach the specified drop height should be discarded from consideration. In summary, set is a fundamental measurement used in all ECM relationships, so it is important that set measurement is reliable.

It is noted that temporary compression measurement is used in the Hiley Formula. This can only be measured using methods (a) and (f) above. Method (a) is not recommended for safety reasons, as discussed.

Hammer energy for an untested pile can be estimated from the potential energy of the ram which is a function of the weight and drop height. The drop height of a hammer is usually recorded for the full sequence of pile driving (referred to as pile driving record) which can be used to estimate the energy applied to the pile. The actual delivered energy to the top of the pile is often less than the potential energy of the ram due to frictional losses in the hammer, energy losses in the hammer and pile cushion, energy losses during impact, and restrictions on energy transfer that are functions of the pile material, cross-section, length and driving resistance. There have been several papers that document and emphasize the high variability in energy transfer from impact hammers and caution for the sensitivity of driving formulae and wave equation analyses to this parameter (Allin (2015), Seidel (2015b), Flynn & McCabe (2016)). Given the sensitivity of driving formulae to this parameter, a calibration using either measurements of actual energy in the test piles or an energy efficiency factor based on previous performance of the hammer is usually recommended for estimation of hammer energy. However, the performance of a hammer, including the efficiency, can vary from pile to pile and over time. Various factors such as hammer alignment, pile-hammer contact surface and hammer maintenance frequency can also affect the energy transferred to the pile which in turn affect the accuracy of the bearing graph correlation. Further to this, there can be errors in identifying the actual hammer drop if it is undertaken visually when the hammer is in operation.

Seidel (2015) has reported in one comprehensive study for a major project that the measured energy observed from PDA testing on the same pile type (and hammer) varied by +/- 33% about the median energy. The first author's experience has often seen variation in energy ranging between +/- 15 %. This demonstrates the uncertainty associated with estimation of the delivered energy to untested piles.

Using Seidel's observation, and assuming a 5mm set per blow, if we apply a +/- 33% variation to the 44 kNm energy example in Figure 2, the resistance acting on the pile can range between 2200 kN and 3050 kN which is an unacceptably large range.

4 AN ALTERNATIVE APPROACH - FORCE

As noted, an alternative approach to using the standard ECM relationship has been developed using the pile set and the force applied to the top of the pile. This FCM approach was first discussed and presented by Seidel (2018).

In simple terms, the general principle that applies to piling is similar to driving a nail into timber. For a nail to drive into timber, the force applied must overcome the force resisting the nail to move. If the nail does not move under the force of the hammer, one can assume that the force resisting the nail to movement is equal to or greater than the force from the hammer. On the other hand, if the nail moves, then resisting force is expected to be less than the force applied by the hammer. This is often seen with pile testing. If the pile movement is zero under a hammer strike, one can infer that the resistance acting on the pile is equal to or greater than the applied force.

Based on the principles of one-dimensional wave theory pile force and velocity are related by pile impedance for as long as there is only a single wave in the pile. Under those conditions, the following holds true.

$$F = vZ \qquad (1)$$

where F is the pile-top force, v is the pile-top velocity and Z is a constant of proportionality called the pile impedance, and

$$Z = EA/c \qquad (2)$$

where E is the pile modulus, A is the cross-sectional area, and c is the pile wave-speed.

During impact, and generally up to the time of maximum impact force and velocity, this proportionality between F and v can be reliably assumed. Therefore, knowing Z, the peak pile-top impact velocity can be used as a proxy for measurement of peak impact force.

it is important to distinguish between capacity and resistance in relation to pile driving. The resistance to penetration that the pile experiences when struck by the hammer is called the driving resistance. Driving resistance comprises a dynamic component due to the velocity of the pile movement, and a static component, which is the (static) capacity of the pile at the time of impact, and would be the expected capacity if it were possible to undertake an instantaneous static load test.

The parametric study and case studies described relate to the relationship between pile capacity, C, and peak impact force, F. The capacity/force (C/F) ratio is dependent on hammer, soil and pile characteristics, and is also shown to be a function of pile set, being maximum at low set, and progressively decreasing as pile set increases (and dynamic resistance represents a progressively larger proportion of the driving resistance).

Figures 1 and 2 presented the results of a GRLWEAP analysis for a 9t hammer hitting a 400mm square concrete pile from drop heights of 0.4m, 0.6m and 0.8m. The three curves in each Figure relate capacity to blow count or set for each of the three drops/ energies. The parametric study takes this one step further by normalizing the capacities by peak impact force.

The same data presented in Figures 1 and 2 is shown in Figure 3 in normalized form – i.e. the FCM relationship - C/F ratio vs set. What is striking is that all three curves reduce to a single and unique relationship between C/F ratio and set, regardless of drop height.

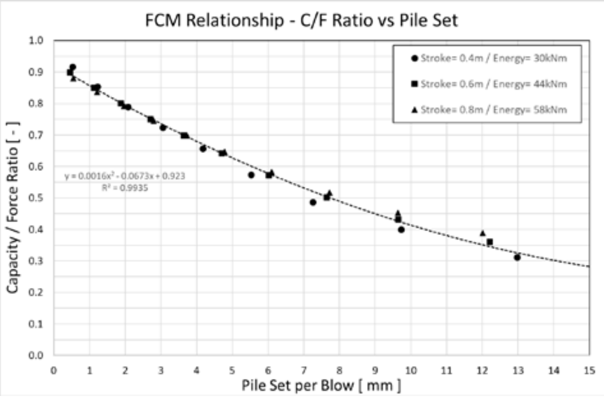

Figure 3. Normalized bearing graph (FCM relationship: C/F ratio vs pile set)

5 CASE STUDY CORRELATIONS

Two case studies will be presented for historical piling projects. PDA testing equipment from Pile Dynamics (PDA-PAX and 8G systems) were used to collect the pile force and velocity data. The data was analysed using CAPWAP to determine pile capacity.

In each case, the CAPWAP results were normalized using the PDA-measured peak impact force and the data presented as data points on a C/F ratio vs set plot.

The FCM relationship has also been computed using GRLWEAP based on the site hammer, pile and soil characteristics using representative resistance distribution, damping and quake values determined in the CAPWAP analyses.

5.1 Case Study One – Open Ended Steel Tube Piles

The project used for case study one is the upgrade of an existing berth. At this project the soil stratigraphy consisted of dense clayey sand and very stiff to hard sandy clay layers. All piles were open ended 610mm steel tubes with 16mm wall thickness each with a total length of 35m and an average penetration of 16m (ranging between 13m to 18m). The end of drive sets were between 5mm and 22mm using 1200mm drop height. The piles were driven with a 9t hammer. All piles were restrike tested between 4 to 18 days after installation using the same hammer with 1.5m drop height. The restrike sets ranged between 0.5mm and 10mm and estimated CAPWAP resistances varied between 3500kN to 6800kN. GRLWEAP analyses were undertaken replicating all relevant characteristics as noted above.

Figure 4 compares the C/F ratio vs set data from PDA tests and the FCM relationship from GRLWEAP analysis. At pile sets less than 1mm per blow, the inferred capacity is approximately equal (96%) to the peak impact force. At sets of 5mm, the achieved capacity is only 70% of the peak impact force; at 10mm the ratio reduces to 55% and at 15mm pile set the ratio drops further to 44%.

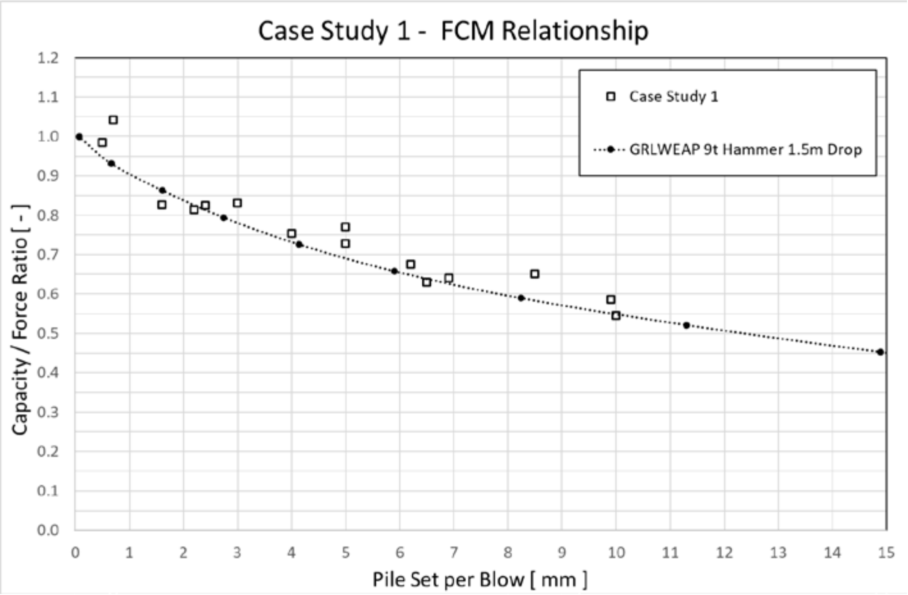

Figure 4. Case study 1 - data comparison to FCM relationship

It is clear that there is very good correlation between the site data and the theoretical prediction. There are two important findings relating to this case study.

1. If the GRLWEAP parameters can be reasonably estimated in advance, then the FCM relationship can be predicted, and initial target sets can be established in advance of piling.
2. The FCM approach offers a piling control and acceptance method which can accommodate large variations in hammer efficiency without impacting reliability. The capacity of all non-PDA tested piles, can be estimated with greatly improved accuracy provided that the set and pile velocity can be measured accurately.

5.2 Case Study Two – Precast Concrete

The project used for case study two is the construction of 13 bridge pier foundations for a river crossing. At this project the soil stratigraphy consisted of very stiff to hard sandy clay layers. All piles were 400mm square simply-reinforced precast concrete with total lengths ranging between 20m to 41m and penetration ranging between 18m to 36m. The end of drive sets were between 1mm and 13mm using 300mm to 500mm drop height. The piles were driven with a 9t hammer. All piles were restrike tested between 1 to 24 days after installation using the same hammer with drop heights between 400mm and 800mm. The restrike sets ranged between 0.3mm and 9mm and estimated CAPWAP resistances varied between 1100kN to 4500kN. Timber ply was used as a pile cushion for all tests.

For the GRLWEAP models, three different drop heights were used for assessment. The reason is related to the practicalities of driving precast piles where different drop height may need to be applied due to varying soil/ground conditions, controlling driving stresses (especially tension stresses) and/or different load requirements.

Figure 5 presents the correlation between the C/F ratio and pile set for PDA/ CAPWAP data compared to the GRLWEAP models with 3 different drop heights. Similar to Case 1, the correlation between the C/F ratio and pile set can be clearly seen from these results. It is also evident that GRLWEAP models can predict the correlation with reasonable accuracy if the necessary parameters for the GRLWEAP models are available.

Nevertheless, there is some increase in scatter evident which may result from minor PDA data issues (proportionality), accuracy of the manual set measurement especially at small sets or variable pile cushion stiffness.

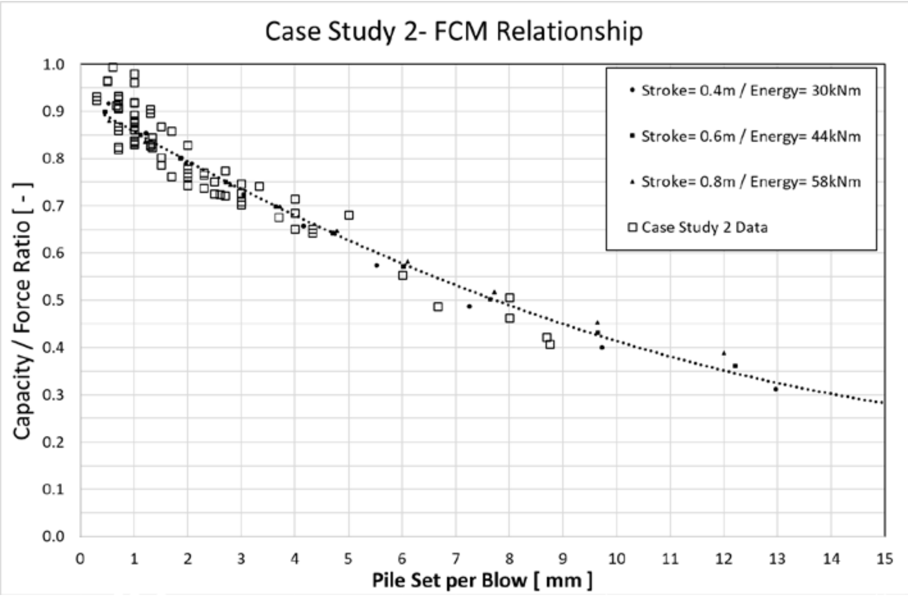

Figure 5. Case study 2 - data comparison to FCM relationship

The general form of the FCM relationship is similar for both Case 1 and Case 2, albeit with different specific values, and again, predictable by theoretical analysis using relevant analysis parameters.

For Case 2, at pile sets less than 1mm per blow, the inferred capacity is slightly less (92%) of the peak impact force. At sets of 5mm, the achieved capacity is only 63% of the peak impact force; at 10mm the ratio reduces to 42% and at 15mm pile set the ratio drops further to 29%.

The results also confirm that the use of different drop heights has little effect on the correlation between C/F ratio and measured set.

6 RECOMMENDED FCM RELATIONSHIP PROCEDURES FOR A PROJECT

The FCM relationship can be developed using the following method:

1A. Undertake a GRLWEAP analysis with estimated driving parameters from site investigation using proposed pile and driving hammer details.
1B. Undertake PDA testing and CAPWAP analysis on the first pile. Analysis to be undertaken at various different pile sets (e.g., 12mm, 6mm and 2mm).
2. Use data from either step 1A, 1B or both, to establish a site correlated FCM relationship.
3. Measure pile velocity and pile set for untested piles.
4. Estimate pile force using the measured velocity and calculated pile impedance
5. Use the site correlated FCM curve to find the C/F ratio for the measured set and then calculate resistance using the force estimated in step 4.

Ongoing pile testing with CAPWAP analysis should also be undertaken on a percentage of piles to check the relationship. Minor adjustments/refinement may be required as more data is collected.

7 FURTHER DISCUSSION

7.1 Measuring Velocity

There are only two known methods currently undertaken to measure the velocity during pile driving. The first is by using accelerometers recording the acceleration of the pile which can then be used to obtain the velocity.

Examples of equipment used are accelerometers from the PDA system (PDI / Allnamics).

The second is by measuring displacement and differentiating with respect to time to calculate velocity. An example is the Pile Driving Monitor (PDM). PDM is a device that records the displacement of the pile with high frequency and can therefore accurately measure pile set and pile velocity, and hence, can be further used to estimate pile resistance for all untested piles from a FCM relationship created from tested piles or GRLWEAP modelling.

7.2 Set Limitation

Similar to dynamic formulae, bearing graphs, PDA testing and CAPWAP analysis, the pile set that is recommended to be used for the FCM correlation has a range and should be between 2 mm and 12 mm. Sets outside this range may provide results that do not have the required level of accuracy.

Small sets (less than 2mm) can be a sign that the full resistance of the pile may have not been mobilized during driving which can lead to under-estimation of the static capacity.

Large sets (greater than 12mm) during driving can generate large dynamic component of resistance which may lead to over-estimation of the static capacity.

7.3 Pile Cushion

As discussed earlier, the calculated pile force is a function of pile impedance and velocity. Hence, the change in cushion stiffness does not affect the relation between velocity and force.

The importance of this is to note that although the pile cushion ‘stiffness’ does not affect the pile head force calculation but it may alter the relationship between the force applied and the pile resistance.

This will be further researched by the authors and presented at a later date.

However, the authors do note that there are cushions available in the market which claim to have a very consistent modulus or ‘stiffness’ form the start to the end of the cushion life. This may have significant benefits to a project as this will provide a higher level of confidence to the FCM relationship.

8 CONCLUSION

An alternative approach to pile verification using a force base relationship with respect to pile set has been generated using GRLWEAP. Two case studies on two very different pile types show very good correlation between the theoretical GRLWEAP results and the field results.

The determination of force and consequently capacity using pile velocity provides more confidence when untested piles are concerned. The use of this velocity correlation removes the reliance on hammer energy and the inaccuracies associated with estimating hammer energy which are the result of variable hammer performance from pile to pile and from time to time.
Recording pile velocity using readily available equipment is quick and easy, with some equipment able to record both the pile set and velocity. Pile set is an important aspect of this force base verification and an accurate measurement of set should always be a strict requirement.

The use of this force relationship for projects should follow the same process used for standard bearing graph relationships. That is to undertake a GRLWEAP analysis prior to piling works to establish an initial correlation. Then once the first pile(s) has(have) been PDA tested, refinement of the relationship is required for application to the remaining piles. Ongoing testing should also be undertaken to identify the need for further refinements as the project progresses.

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