Çakma Kazıkların %100’e Uygunluk Verilmesi Konusuna Giriş

AN INTRODUCTION TO 100% DRIVEN PILE VERIFICATION

Seidel,J.P.[1],Ahmadi,H.[2], Süer,B.[3]

ÖZET

Kazık tasarımı ve doğrulaması zor ve riskli bir iştir. Konferanslarda sunulan kazık taşıma kapasitesi tahminlerinin çeşitliliği genellikle şaşırtıcı ve ürkütücüdür. Bu durum, çakma kazıkların tasarımının yalnızca tasarım mühendisinin masasında sona ermediğini, inşaat sürecinde devam ettiğini ve imalat süreci boyunca sağlanan değerli bilgilere dayandığını vurgular. Her bir çakım darbesi bir testtir-kazığa uygulanan çekiç darbesinin zemine olan tepkisinin testidir. Geleneksel olarak, kazık kapasitesi, çeşitli kazık çakma formülleri aracılığıyla çakım ve çakıma bağlı tepki ilişkisi üzerinden yorumlanmıştır. Elli yıl önce, kazıklarda çekiç darbelerinin etkisi ve zeminden yansıyan gerilim dalgalarını ölçmek ve yorumlamak için ölçüm sistemleri ilk kez kullanılmış ve bu sistemler, taşıma kapasitesini dalga mekaniği ilkelerine dayanarak daha gelişmiş ve güvenilir bir şekilde elde etmeyi sağlamıştır. Bugün, PDA testi ve dalga eşleştirme rutin olarak kabul edilen uygulamalardır. Ancak, her PDA testi sadece test edilen belirli kazık için doğrudan bir anlam taşır. Bu makale, tasarımcılar ve danışmanlar olarak temel görevimizin, PDA test sonuçlarının lokal olarak kanıtlanmış ve hedeflenmiş dinamik bir formülünü sentezleyerek temel yapısının durumunun belirlemek olduğunu savunacaktır. Bu nedenle, yalnızca düzgün bir şekilde modifiye edilmiş ve ilişkilendirilmiş dinamik formüller, yerel gerçek durumun sağlanması ve nihayetinde onay için temel olması gereken araç olmalıdır. Bir yapı temeli bazında, PDA testlerinin rolü kritik olmakla kalmayıp, prensip olarak, ilgili dinamik formülün geliştirilmesine dayanak sağlayan da bir işlev görmektedir. Temelin son kabulü ve kazık taşıma kapasitesi azaltma faktörlerinin belirlenmesi için önerilen yeni yaklaşımın doğuracağı sonuçlar da tartışılacaktır.

Anahtar Kelimler: Kazık çakma formülleri, Kazık Kabulü, PDA Testi, Kapasite azaltma faktörleri, Dalga denklem analizleri

ABSTRACT

Piling design and verification is a fraught and risky business. The spread of pile capacity estimates submitted to conference predictions exercises is often staggering and sobering. This underlines why design of driven piles does not stop at the design engineer’s desk but continues through construction, and relies on the valuable information provided by the installation process. Each installation blow is a test - a test of the ground response to hammer input delivered into the pile. Traditionally, pile capacity has been interpreted from this input-response relationship through various and many pile driving formulae.Five decades ago, measurement systems were first used to measure and interpret the stress waves in piles generated from the hammer inputs and reflected from the ground response to infer capacity in a more sophisticated and reliable way using wave mechanics principles. Today, PDA testing and wave matching are routinely accepted practice. However, each PDA test has direct relevance only to the individual pile which is tested. This paper will argue that our fundamental task as designers and supervisors is to establish ground truth, by synthesizing the results of PDA tests into a locally-evidenced and locally-targeted dynamic formula. Therefore, only dynamic formulae, properly modified and correlated, must be the vehicle for delivering local ground truth and ultimately being the basis for sign-off. On a foundation-wide basis, the role of PDA tests is critical but subservient, and principally to provide the evidence on which a correlated dynamic formula is developed. Consequent implications for the foundation sign-off process, and for a proposed new approach to establishing capacity reduction factors for driven piles will also be discussed.

Key Words: Pile driving formulas, Pile acceptance, PDA testing, Capacity reduction factors, Wave equation analysis

Managing Director, Construction QA, j.seidel@construction-qa.com(Resp. Author)[1]
Managing Director, Pile QA Turkey İnş ve Dan. LTD STI, hossein@pileqa.com[2]
Europe – Asia Regional Director, Pile QA Turkey İnş. Ve Dan. LTD STI, b.suer@pileqa.com (Contact Author)[3]

1. INTRODUCTION

Piling design is a fraught and risky business. The spread of pile capacity estimates submitted to conference predictions exercises is often staggering and sobering. Figure 1 shows the results of such a prediction exercise undertaken by the Institution of Engineers, Singapore (IES). A pile was driven and subsequently statically load tested. Prior to load testing, 34 participants were invited to predict the capacity of the pile using their preferred design method and using any of the comprehensive site investigation data that was provided at the location of the test pile.

The failure load was 1806 kN, but the range of predictions varied from 667kN to 3195kN – ie between 37% and 177% of the actual test load. Assuming for argument's sake that the designers would use a factor of safety of 2 in their designs, the working loads would range from 18.5% to 88.5% of the ultimate capacity – either excessively conservative or dangerously close to failure.

For driven piles there is another opportunity to evaluate capacity for individual piles based on monitoring of key installation characteristics. The potential uncertainty of geotechnical design underlines why design of driven piles does not stop at the design engineer's desk but continues through construction, and relies on the valuable information provided by the installation process.

For pile driving, each installation blow is a test. A test of the ground response to hammer input delivered into the pile. Traditionally, pile capacity has been interpreted from this input-response relationship through various and many pile driving formulae. A particularly good summary of many of these traditional formulas can be found in (Groom, 2019).

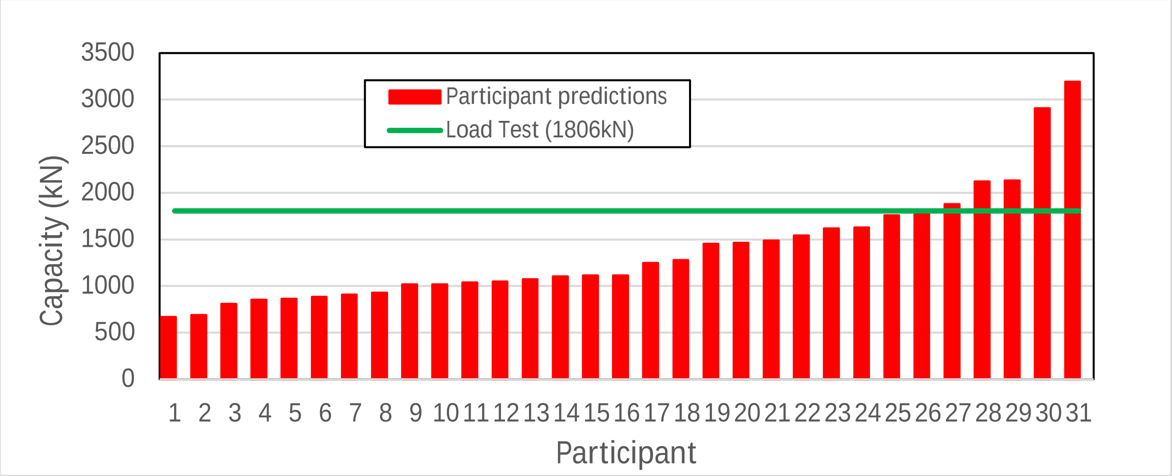

Figure 1. IES pile load test prediction exercise results

The underlying assumption of any pile driving formula is that it should be applicable across the whole site and reflect a local ‘ground truth’ and by application of this formula, pile capacity can be inferred by measurement or assumption of some key parameters.

In reality, the many studies which have assessed the comparative merits of different formulae by comparison with static load tests all indicated large scatter and poor reliability which resulted in recommended factors of safety of up to 6 (for the Engineering News Record formula).

However, it should be considered that at the time of many of these comparison studies, the effect of pile setup could not be assessed, and the true energy delivered by pile driving hammers could also not be measured. These are critical factors which the authors of early studies did not have at their disposal and would undoubtedly have influenced their findings.

Fifty years ago, electronic systems were first used to measure and interpret the stress waves in piles generated from the hammer inputs and reflected from the ground response to infer capacity in a more sophisticated and reliable way using wave mechanics principles (Rausche et al., 1972; Goble et al., 1975). Today, PDA testing and wave matching are routinely accepted practice (Hannigan, et al., 2016). But prior to 1985, pile driving acceptance was based only on static load testing and pile driving formulae.

Our fundamental task as designers and supervisors is to ensure that capacity and integrity of every pile installed meets the demands of the structure that it supports. To do this we need to establish a ‘ground truth’, albeit a locally-evidenced and locally-targeted ground truth capable of application to all piles in a foundation system.

PDA testing is well established internationally as a reference method for evaluating pile capacities by measurement, interpretation and Wave Equation analysis (CAPWAP). Even though PDA testing is far less costly and far more convenient than static pile load testing, in practice typically only 3% to 10% of project piles are PDA tested.

Specifications typically require that the other 90 to 97% of piles are accepted on the basis of a specified pile driving formula, which is necessarily less reliable than PDA testing. Thus there exists a 2-class system in which PDA tested piles have a higher reliability and lower risk, and conversely all untested piles have a lower reliability and higher risk.

Actually, the primary purpose of PDA testing should be to evaluate the local ground truth, so that the chosen dynamic formula approach can be correlated to the PDA tests. In this way, the PDA-correlated and modified dynamic formula extends the value and reliability of PDA testing to every pile on the project.

On a foundation-wide basis, the role of PDA tests is critical, but its principal role is not to confirm the capacity of individual piles, but to provide the evidence of ground truth on which a correlated dynamic formula is founded. Random PDA testing throughout the project provides the basis of confirming or adjusting the ground truth if needed.

Consequent implications for the foundation sign-off process, and for a new approach to establishing capacity reduction factors for driven piles will also be discussed.

2. DYNAMIC FORMULAE AND PILE ACCEPTANCE

The term 'ground truth' is shorthand for the effect of the ground at a particular site on the relationship between the input from the pile driving hammer and the response of the pile to estimate pile capacity. This will be different at every site because of variations in ground conditions, different hammers and varying hammer and driving system performance, and variations in both the pile type, size and length.

In a PDA test, the pile-top force and velocity in the pile are measured, and through simple application of one-dimensional wave mechanics, these measurements can be converted to the 'downward-travelling wave' (which is the input wave from the hammer) and the 'upward-travelling wave' (which is the response of the pile). In this case, the ground truth, i.e. the capacity can be determined approximately using the Case Method equation, or more reliably and in details using CAPWAP analysis which is an iterative wave-matching technique.

The PDA/CAPWAP input and response are relevant to the particular hammer, ground conditions and pile at the project site, and can therefore be used as a reference for any other simple method of capacity evaluation, ie pile driving formulas, at that site.
The many pile driving formulas referred to previously all have their basis in some simplified or simplistic theoretical model of the actual pile driving process. But for each of these formulas, the hammer input is represented by either a hammer energy or hammer force term, and the pile response is represented by the pile movement – generally pile set, or pile temporary compression.

In this paper we will only examine two of these formulas – the energy-based Hiley Formula, which is used as a pile acceptance method in the UK and many of the former British colonies (eg in much of south-east Asia, Australia and New Zealand) and the Kümmel Method which is used in Türkiye and elsewhere (Kümmel, 1984).

Like a number of other dynamic formulae, the Hiley Formula (Hiley, 1930) is based on Newton's Theory of Impact for two (concentrated) inelastic bodies. The original form of this equation is as follows :

$$R_u = \frac{e_h W_H H}{s+0.5(c_1+c_2+c_3)}\left(\frac{W_H+e^2 W_p}{W_H+W_p}\right) \tag{1}$$

Where R_u is the ultimate capacity, e_h is the (assumed) hammer efficiency, W_H and W_p are the weight of the hammer and pile respectively, s is the pile set for a single impact, and c_1, c_2 and c_3 are the temporary compression of the pile, the ground and the hammer cushion, and e is the coefficient of restitution to represent energy loss.

There are many problems with application of this equation to pile driving. First, the pile does not act as a concentrated mass – it is a distributed mass whose response is characterised by wave transmission.

Second, without reference PDA testing, the hammer efficiency can only be assumed. Even then, longitudinal studies of PDA testing have shown that hammer efficiency is not constant, but varies considerably over the course of a typical project (see Figure 2). Furthermore, the hammer stroke is not accurately known.

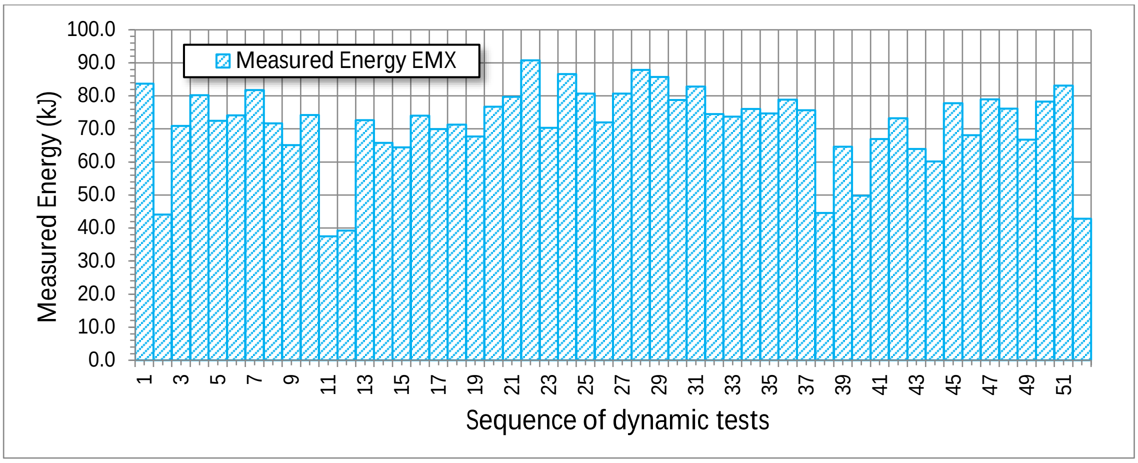

Figure 2. Longitudinal Study of hammer energy transfer (Seidel, 2018a)

Third, the accurate measurement of set and temporary compression is difficult (especially in marine conditions) and is not always reliable. The measurement of the ground and pile temporary compression requires a worker to make marks on the pile during driving, which is a critical safety issue, and even less reliable than measurement of pile set. In marine conditions, temporary compression is not possible. The measurement of temporary compression in the helmet can only be at best estimated but more probably, guessed.

Fourth, the coefficient of restitution, which affects the computed net energy transmitted to the pile is chosen from published tables which are more than likely not to be relevant.

Energy transfer is highly affected by the nature and condition of the hammer and pile cushions, and these are not taken into account in the equation.

The above is a condensed summary of problems with the Hiley Formula, which is considered one of the more advanced pile driving formulas.

However, one of the most critical problems with the Hiley Formula is that the capacity estimate R_u is not the ultimate pile capacity, but is actually the Driving Resistance which is the sum of the ultimate pile capacity and the additional resistance caused by the motion of the pile into the ground. The Driving Resistance is greater than the ultimate pile capacity, and is increasingly greater the higher the pile velocity (and pile set).

It is clear from the above summary that the Hiley formula (as a representative of pile driving formulas generally) are not reliable if used in isolation. However, if a correlation can be established between the driving formula and the reference PDA/CAPWAP results so that an evidence-based correction factor can be applied to the pile driving formula, then the pile corrected and site-correlated pile driving formula can be used to apply the ground truth, established by PDA/CAPWAP to the 95 to 97% of untested piles.

Current practice is to avoid some of the problems in the original formula, by substitution of the PDA measured energy (EMX) for the original energy terms, as well as removing the helmet temporary compression and using a combined pile and ground temporary compression, (c) so that the modified Hiley equation reduces to:

$$R_u = \frac{EMX}{(s+c/2)} \tag{2}$$

This modified Hiley formula is certainly simpler, and has the benefit of using site evidence of actual energy transfer to the pile, but the issues of energy variability, set and temporary compression measurement reliability, and the overestimation of ultimate capacity due to dynamic effects still remain.

Seidel (2018b) proposed a set-dependent correction function to this modified Hiley Formula. The Dynamic Reduction Function (DRF) is of the following form:

$$DRF(s) = DRF_1 + DRF_2 . s \tag{3}$$

The derivation of the constant DRF_1 and the pile set coefficient DRF_2 are shown in Figure 3.

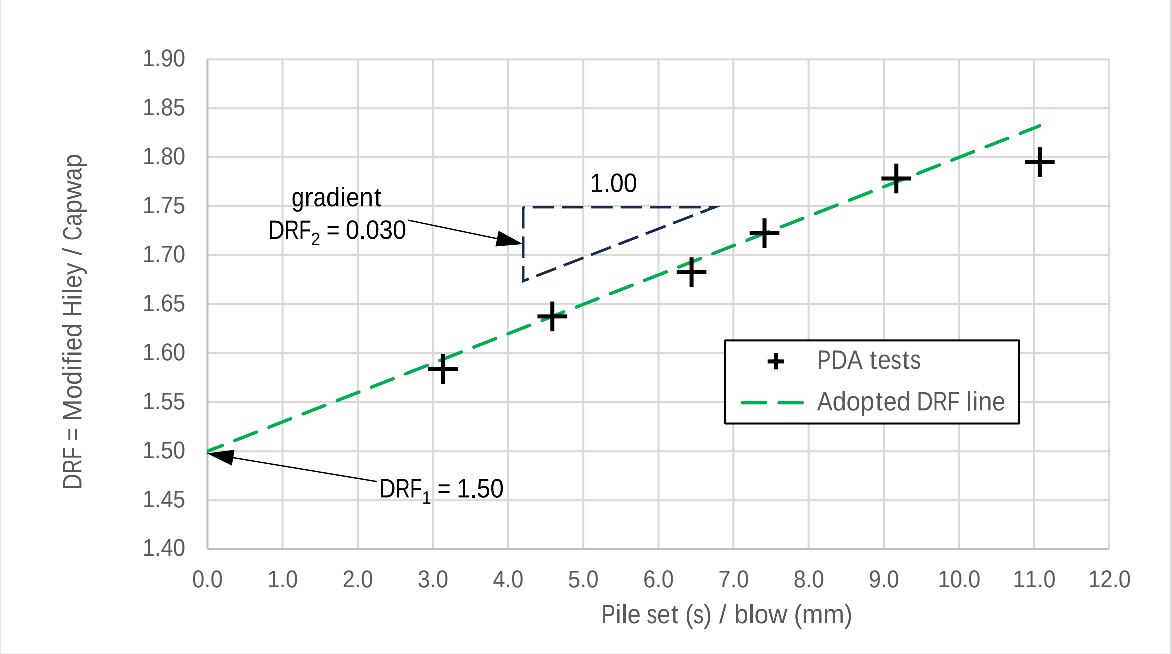

Figure 3. Derivation of Dynamic Reduction Formula constants

As previously noted, this data shows that as the pile set increases (and there are consequent larger pile velocities) the dynamic resistance component of the Driving Resistance increases, and the Hiley Formula overpredicts the CAPWAP capacity by an increasing amount.

Equation (4) shows the DRF-corrected modified Hiley Formula, in which the ultimate capacity estimate, R_u, is correlated against the reference PDA/CAPWAP results and corrects for the dynamic component of Dynamic Resistance.

$$R_u = \frac{EMX}{DRF\ (s+c/2)} \tag{4}$$

This equation extends the benefit of the PDA/CAPWAP tests to all the piles on the site, directly and based on site evidence.

The other method of evaluation of pile capacity considered here is the Kümmel Method. This method is said to predict the driving resistance by analyzing the force field and the subsequent elastic compression of the pile, and relates the driving resistance to the value of penetration per blow (ie. pile set).

Interestingly the method clearly states that what is predicted is driving resistance, which as noted previously in regard to the Hiley Formula, is not the same as ultimate capacity, and indeed overpredicts the ultimate pile capacity. Accordingly, this method should potentially be subject to the same Dynamic Reduction Function as previously described.

The Kümmel Method does not reduce to a simple equation such as that shown for the Hiley Formula, but is rather conveniently solved by spreadsheet analysis. Regardless, the final set is computed using the following equation:

$$s = \Delta L * (P_{max} - W)^3 / (2.P_{max}^2 W) \tag{5}$$

where s is the pile set , ΔL is the total pile compression, P_{max} is the maximum impact force, and W is the target ultimate capacity (the required pile capacity x factor of safety). These parameters are derived from a series of tables and equations.

Kümmel notes that the maximum impact force can either be measured directly from strain gauge measurements (eg PDA testing) or can be derived based on hammer characteristics, including fuel pump setting and a given cushion reduction factor, R_f which varies from 1.0 to 4.0 for a range of hammer cushion configurations varying from no cushion ($R_f = 1.0$) to timber hammer and pile cushions ($R_f = 4.0$). It appears that for local practice driving steel pipe piles, an R_f value of 1.22 is commonly adopted.

The Hiley and Kümmel methods are applied to the case of a diesel hammer driving a steel pipe pile in near-shore marine conditions. The pile was PDA-tested on restrike and at the same time was remotely monitored using a Model PDM3 Pile Driving Monitor device. A 100mm wide tape with isolated 10mm reflective strips at 200mm spacing was attached along the piles axis, and the PDM3 tracked the pile restrike at 5267Hz and to high accuracy.

The PDA/CAPWAP results for the restrike test are summarized in Table 1. Also shown for comparison and based on the PDA measurements, are the uncorrected modified Hiley and Kümmel Method capacity estimates. These pile driving formula approaches overestimate capacity by 96% and 109% respectively.

Table 1. PDA/CAPWAP results and Pile Driving Formula capacity estimates

PDA measured peak pile force, FMX (kN)	10996
PDA measured input energy, EMX (kNm)	117.5
PDA measured peak pile velocity (m/s)	3.84
PDA measured peak pile movement, DMX (mm)	16.3
Survey measured set, s (mm)	0.8
Equivalent blow count (blows/10cm)	125
CAPWAP computed capacity, R_u (kN)	7000
Modified Hiley capacity (uncorrected) (kN)	13743
Modified Hiley capacity overestimation ratio	1.96
Kümmel Method capacity (for measured blow count)	14636
Kümmel Method overestimation ratio	2.09

It is clear from this example that the pile driving formulas are unreliable unless correlated to the reference PDA/ CAPWAP results. The appropriate DRF equation (which evaluates the variation of the reduction factor with set) can be established with further CAPWAP analyses at different pile sets. Alternatively, the DRF equation can be found by matching the CAPWAP result in GRLWEAP (Rausche et al, 2004) and extrapolating to a range of pile sets, as shown in Figure 4.

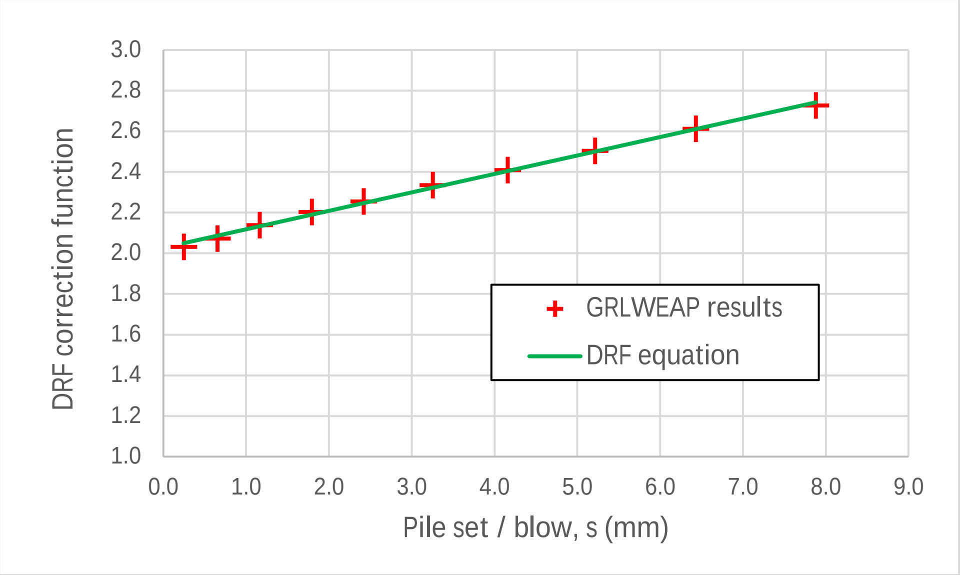

Figure 4. Derivation of DRF Parameters from GRLWEAP analysis

3. IMPLEMENTATION OF 100% DRIVEN PILE VERIFICATION

In order to implement this approach to every project pile, it is necessary to easily and reliably measure the key parameters for the verification method for each pile. For instance, for the Hiley Formula, it is necessary to measure energy, pile set and temporary compression. For the Kümmel Method, peak force and maximum pile compression must be measured. The PDM3 allows these parameters to be simply measured

The following data set was collected by the PDM3 monitoring a pile from 24m offset distance.

Table 2. PDM3 Pile Driving Monitoring results

Blow	Max Velocity, VMX (m/s)	Max Force, FMX (kN)	Set/blow, s (mm)	Rebound, c (mm)	Blow Rate (blows/min)
1	3.85	10560	3.7	15.7	35.5
2	3.85	10560	4.0	15.7	35.5
3	3.89	10670	4.4	14.9	35.1
4	3.84	10533	4.1	15.4	35.9
5	3.84	10533	4.9	14.4	35.5
6	3.63	9957	3.9	15.0	35.7
7	3.63	9957	4.3	15.0	35.5
8	3.97	10890	4.5	14.3	35.7
9	3.80	10423	4.9	14.7	35.5
10	3.90	10698	4.3	14.3	35.9
average	3.80	10423	4.3	14.9	35.5

For the Hiley Formula, energy (for the diesel hammer) can be derived from the blow rate, and the set and rebound are measured directly.

For the Kümmel Method, the maximum velocity is measured, which when multiplied by the known pile impedance, Z , provides the maximum impact force P_{max}.

4. CONCLUSIONS

Pile driving formulas, are inherently flawed. Specifically, limitations of the Hiley Formula and Kümmel Method have been discussed, and prediction errors of these methods have been shown by example.

On the other hand, pile driving formulas are a necessary and convenient way of evaluating pile capacities for untested piles. However, if all piles on a project are to be driven to the same level of reliability and risk, then it is necessary to correlate these pile driving formulas to reference PDA/CAPWAP results. The concept of a dynamic reduction factor has been introduced and demonstrated.

In order to implement effective, reliable and efficient verification of 100% of piles, the PDM3 Pile Driving Monitor provides necessary and accurate measurement of key parameters for both the Hiley Formula and Kümmel Methods.

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