A NEW APPLICATION OF RADAR IN IMPROVING PILE DYNAMIC FORMULAE USED IN THE QUALITY CONTROL OF PILE FOUNDATIONS

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ABSTRACT

Installing piles into the ground is a very complex if not uncertain activity. This is particularly true from the point of view of proofing piled foundations. One of the methods currently available is the Dynamic or Energy Formulae that are the oldest and frequently used formulae in determining the bearing capacity of piles. The more recent methods are based on the Wave Equation Analysis and different formulations such as Case Method, TNOWave, CAPWAP® and TEPWAP were developed for pre-driving analysis and post-driving measurement applications. The energy or dynamic formulae, which were developed based on the Newtonian Impact theory, have been regarded as being unreliable and less accurate than the more analytical Wave Equation Analysis methods. The two main reasons for the poor performance of the dynamic formulae are that the hammer energy is assumed and that they do not take the dynamic resistance into account. The advent of new technologies in the construction industry has produced gradual improvements that have resulted in the dynamic method to be used on many projects with greater reliability. In this paper, a new application of radar called IBIS-S is proposed as well as site test results are presented using the Hiley, Gates and MnDOT formulae. The comparison of the results with the more rigorous PDA, CAPWAP® and the GRLWEAP™ analysis show that with the application of new and precise testing equipments, the dynamic formula can be used with greater accuracy than the Case method. It is also shown that the IBIS-S unit may also be used to estimate and evaluate the empirical parameters used in the CAPWAP® and GRLWEAP™ analysis. This approach enables evaluation of the pile capacity to be made more accurately using the dynamic equations.

Keyword: foundation design

1 INTRODUCTION

1.1 DYNAMIC FORMULA

Since piles were first used by humans they searched for ways to estimate the loading capacity of the pile once it is in the ground in the most efficient and economic manner. One of the oldest methods is the Dynamic Formula that is still in common use amongst the piling practitioners and consultants according to research surveys by Fleming *et al.* (2008) and Abelsalam *et al.* (2009).

The early users of the pile driving formula applied the idea of driving a stake to driving of a pile and have made the assumption that the effort required to drive the stake is directly related to the resistance provided by the ground (Whitaker, 1970). As a result many empirical formulae termed 'dynamic formulae' have been derived to establish the relationship between the driving resistance or penetration when hammering piles and ultimate working load from a structure.

Pile Dynamic formula is a term used to describe a range of formulae of which Engineering News (ENR), Danish, Gates, Janbu, Hiley, FHWA and WSDOT are well known among many others. Countries with a strong tradition of using the Hiley Formula are particularly Hong Kong, UK and Australia while Gates, Janbu, FHWA and WSDOT are commonly used in the US.

These dynamic equations are generally categorised into theoretical, empirical and those consisting of the combination of the two. The theoretical basis for the derivation of the pile driving formulae is based on the Newtonian principles of impact between two rigid bodies, for example the driving hammer and the pile. As a consequence, the problem with applying the Newtonian impact principles in the derivation of the theoretical driving formulae, unlike the wave equation, is that it assumes the energy transfer from the hammer to pile is instantaneous. Thus driving formulae are simple idealisation of complex interactions between hammer, pile and the ground.

The elementary form of the dynamic formula is based on the energy equilibrium equation that relates the total resistance of the pile to the energy of falling hammer and pile displacement, namely:

$$R_u = \frac{W_h h}{(s)} \tag{1}$$

Where: R_u – total resistance or ultimate pile capacity, W_h – weight of the hammer, h – hammer drop height or 'stroke'and s – permanent pile displacement or 'set'.

Of course, this type of formula ignores energy losses and assumes the entire energy is transferred at impact. It also assumes that the ground resistance, as a result of the impact, remains constant for the duration of the impact.

The theoretical dynamic formula, such as the Hiley formula, takes into account the energy losses in the driving system (hammer, cap and cushion) as well as the losses in the pile due to elastic compression. It also assumes that the soil response is elasto-plastic, as is presented in Figure 1(b).

Thus the Hiley formula (Hiley, 1925) can be expressed as:

$$R_u = \frac{e_h W_h h}{s + \frac{1}{2}\left(C_1 + C_2 + C_3\right)} \times \frac{W_h + e^2 W_p}{W_h + W_p} \tag{2}$$

Where: R_u – total resistance or ultimate pile capacity, e_h – efficiency of hammer, W_h – weight of the hammer, h – stroke, e – coefficient of restitution (COR), material property, defined as ratio of initial and final velocities after impact, W_p – weight of the pile, s – set, C_1 – elastic compression (recoverable movement) of the pile cushion, C_2 – elastic compression (recoverable movement) of the pile and C_3 – elastic compression (recoverable movement) of the soil.

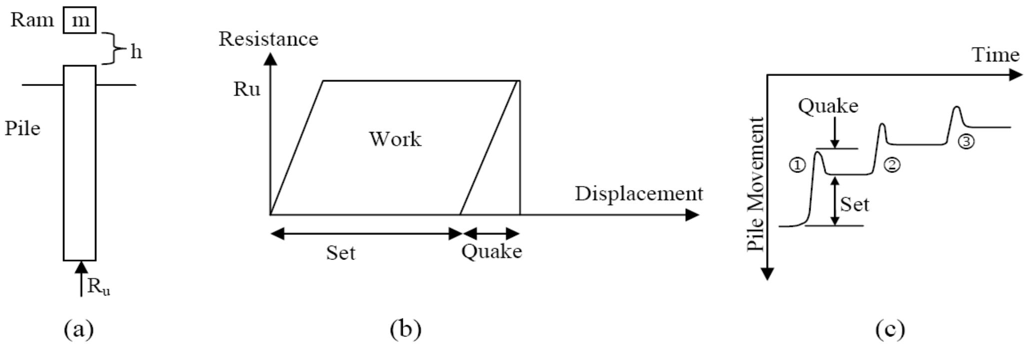

Figure 1: Dynamic equation principle: (a) hammer, pile and soil model, (b) assumed elastic-plastic soil response under an impact and (c) pile top movement under continuous hammer impacts (Paikowsky, 2009).

A more field-usable form of the above Hiley formula is expressed as:

$$R_u = \frac{E_{max}}{S + C/2} \tag{3}$$

Where E_{max} is maximum transferred energy, S is set and C is total elastic compression.

Paikowsky (1994, 2004) and Broms (1988) proposed the above equation based on the actual energy evaluation by Pile Driving Analyser (PDA).

In Equation 3, E_{max} can be evaluated by PDA in the field. The set and the temporary compression parameters can be determined directly by attaching paper to pile and fixing a horizontal reference beam close to the pile and using a pen to mark pile movement on the paper which is attached to the pile. This pile top movement is illustrated in Fig. 1 (c). This method of measurement is known as taking 'set-card'. Obviously this method of taking set measurement is not very accurate and large errors in resistance capacity can result due to the sensitivity of the formula to the set and temporary compression. Moreover, the transferred hammer energy to pile is rather assumed which is a major source of inaccuracy in the application of the dynamic formula. Therefore, a more precise method of measurement is needed. Now with the IBIS-S radar, it is possible to record the set (S) and temporary compression (C) much more accurately and greatly improve the results from the dynamic formulae. The transferred hammer energy to pile can be evaluated from the impact velocity, which can simultaneously be recorded by the IBIS-S radar.

Experience and pile test data over the years have shown that the dynamic formula in general and the Hiley formula in particular consistently over predict pile capacity compared to the reference static tests. The reason for this over-prediction of capacity evaluation by the Hiley formula is that the formula does not take into account the dynamic component of the capacity. Hence a correction factor, f, can be used to adjust for this dynamic component similar to the damping parameter used in the Wave Equation Analysis methods as briefly outlined below. This factor 'f' is assumed to be function of pile velocity and displacement and the expression for the Hiley formula can be modified as:

$$R_u = \frac{1}{f} \cdot \left(\frac{E_{\max}}{(s + c/2)} \right) \quad (4)$$

Lowery and Hirsch *et al.* (1968) were probably the first to propose such factor to 'bring the formulas into agreement with the wave equation'.

Fung (2005) used 'bias factor' and named it HKCA 2004 formula. Fung (2005) evaluated the bias factor by expressing it as a ratio Hiley capacity to CAPWAP or static load capacity and assumed it to be constant. However, based on a comprehensive parametric study by the author and the field testing carried out, it has been shown that the factor proposed here is not constant and will vary depending on the pile velocity and displacement records.

Hussein *et al.* (2004), Rausche *et al.* (1997), Hannigan *et al.* (1998) and Svinkin (2002) provide detailed discussion of the deficiencies of the dynamic formula and its comparison with the dynamic and static testings. Rausche *et al.* (1997) in a research project supported by FHWA compiled a database of static analysis method, refined wave equations and PDA measurement method coupled with CAPWAP pile capacity analysis. A reliability analysis of the various capacity prediction methods was compared with the results of static testing. The results of the dynamic formula evaluation showed that, overall, the performance of the dynamic formula was comparable to the wave equation analysis methods. The results presented shows that the mean value of the capacity prediction ratio to static by Gates formula were 0.96 (c.o.v=0.41) for end-of-drive and 1.33 (c.o.v.=0.48) for restrike compared to CAPWAP with a mean value of 0.92 (c.o.v=0.22) for restrike condition.

Chellis (1951, 1961) suggests that if it can be determined that the dynamic formula results are in reasonable agreement with the wave equation analysis results, then it is permissible to use such simple formula to be quickly applied in the field.

Lowery and Hirsch *et al.* (1968) presented the results of a study in which it was demonstrated that it was possible to find a range between the Wave Equation Analysis and the Gates formula in which they can be in close agreement.

Tavenas *et al*. (1972) presented statistical analysis drawn from approximately 478 driving records. Observation made on a very large foundation built in a homogenous sand deposit showed that the poor quality of the pile driving formulae originates essentially in the estimate of the driving energy. Tavenas *et al.* (1977) concluded that if the energy estimation is erroneous, then in fact the dynamic formula will also be erroneous.

Paikowsky *et al.* (1994, 2004) showed that the reliability of the dynamic formulas can be improved and in fact are comparable to the stress wave theory calculation. Paikowsky (2004) studied the relationship between the pile resistances to pile penetration with comparison to the pile capacity measured from the static load tests. Based on a large database of tests, the mean values of the ratio of static test capacity to the energy based method at the end of driving (EOD) varied between 1.1 and 1.31.

The need for the continued usage of the dynamic formula is that in any given project only a very limited percentage (0.5 % to 1.0 %) of piles are tested by static load testing and 5 % to 10 % of piles are dynamically tested by PDA measurement and signal matching analysis based on the wave equation. The remaining 90% to 95% of the piles remain untested. Therefore, there is a need to fill the gap and the conventional pile dynamic formulas can fill and satisfy the project quality control requirements.

Current research in the area includes probabilistic method applied to the dynamic formula approach. Sakai *et al.* (1996) and Uto *et al.* (1981, 1992) derived an approximate dynamic formula based on the stress-wave theory. Triantafyllidis (2001) modified Hiley formula, also based on the stress-wave theory, to be used for very long piles driven into weathered mudstone. The interesting aspect of the results is that when viscosity or damping parameter was allowed for, the comparison between Hiley and the static loading result using H-pile matched very well. This is precisely the main focus of the current research by the author.

1.2 WAVE EQUATION ANALYSIS

The theory of wave propagation provides the proper theory of pile driving. Wave equation was proposed nearly 150 years ago in 1866 by Saint Venant and Boussinesq for longitudinal impact of bars (Timoshenko and Goodier, 1951). Isaacs (1931), an Australian, was the first to point out the application of wave propagation theory to piles and developed a set of graphical charts and formulas to analyse the stresses and displacements in piles. In 1938, E.N. Fox published a solution of the wave equation and because of the physical and numerical complexities it never took off the ground until 1960 when Smith (1960) presented the mathematical method which, with some modifications, could be applied to pile driving problems and solved numerically by computers. Smith modelled the pile, hammer and cushion as a series of springs and the actions were analysed in 1/40,000sec time steps. Smith compared the process of the numerical pile calculation to that of an animation artist trying to compute the picture motion based on the 1/24 frames per second so that the final motion is smooth and uniform. Smith also used a simple analogy to explain the basic method for obtaining the numerical solution of the pile driving problem: he used the analogy of water wave travelling in one direction and trying to capture the shape of the wave by small ‘rigid floats’ connected together by flexible links. For the ground resistance, Smith (1960) used Chellis (1951) concept of the elasto-plastic response at pile toe and suggested using soil quake and soil damping or ‘viscous damping’ to model soil behaviour subject to impact loading. The reason for introducing the additional damping factor, according to Smith, was to consider the time dependent of pile penetration, as is evidently used in vibration problems.

The stress propagation in a pile during a pile driving is given by the following governing hyperbolical differential equation:

$$\frac{\partial^2 w}{\partial t^2} - c^2 \frac{\partial^2 w}{\partial z^2} = 0 \tag{5}$$

Where $c = (E_p / \rho)^{0.5}$, w(z,t) is the axial displacement of cross section at distance z and time t.

Equation 5 is easily solvable by the various mathematical methods such as Laplace, Separation of Variables and Method of Characteristics. Timoshenko (1951) and Verruijt (2005) provide details of the solution and propagation of stress wave in elastic solid media for simple boundary conditions that give an excellent insight into the behaviour of stress wave induced in solid media as result of hammer impact energy.

When friction resistances are introduced into the partial differential equation, as in equation 6, then the solution is neither simple nor practical, except for very simple cases where the friction can be expressed as a function.

$$E_p A_p \frac{\partial^2 w}{\partial z^2} - P_p f_s = \rho A_p \frac{\partial^2 w}{\partial t^2} \tag{6}$$

Where, A_p is pile cross section area, E_p is modulus of elasticity, ρ is density of pile material, P_p is pile perimeter and f_s is frictional force acting on perimeter by soil.

In the true physical world where ground shear resistance is present, the solution for the above differential equation is carried out by numerical finite difference method and in fact the Smith’s approximation in itself turns out to be essentially a finite difference technique.

The Case method described in Section 2.6 uses a closed-form method of superposition to evaluate pile capacity from the strain and acceleration measurement taken at the pile head by the PDA. The CAPWAP® or Signal Matching method also described below tries to match this strain and acceleration measurement taken at the pile head by PDA and produces pile capacity based on the finite difference solution of the hyperbolic.

2 TESTING METHODS

2.1 TEST SITE

A site located at the north-western fringe of Melbourne CBD was chosen to conduct a trial test of radar IBIS-S. The IBIS-S testing was carried out in parallel with the PDA testing using 350 mm square section precast concrete pile. The IBIS (Figure 5) was set up at an offset distance of approximately 20 m from the pile.

PDA and IBIS-S testings were carried out at the end-of-driving (EOD) under low driving resistance (easy-driving) and high driving resistance (hard-driving) conditions. The pile was driven by a 6 tonne single-acting hydraulic (Banut) hammer with strokes of 300 mm for easy and 700 mm for hard driving conditions. The pile embedded lengths were approximately 15 m and 18 m for the two pile driving conditions respectively.

2.2 SITE CONDITIONS

According to the site geotechnical report, the subsurface condition generally comprised 0.5m thick of borrowed sedimentary rock materials (siltstone), followed by underlaying Coode Island Silt (CIS) of 10.5m thickness. The consistency of the CIS material was predominantly soft. Fishermens Bend Silt (FBS) typically 4m in thickness, generally occur below CIS and was of stiff to very stiff consistency. A sedimentary formation deposit called Moray Street Gravels (MSG) that mainly comprise fine grain sandy materials, underlay the FBS formation. The MSG was approximately 2.5m thick. The Melbourne Formation (Silurian age siltstone) underlay the MSG and forms the bedrock. A generalised ground condition at the site is shown in Figure 2 below.

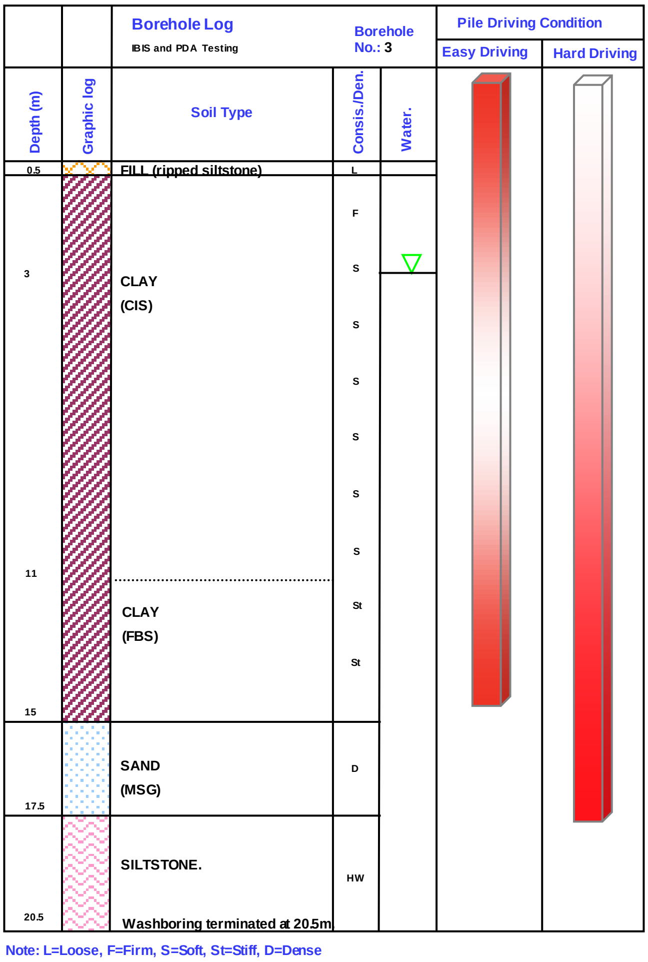

Figure 2: Generalised subsurface profile at the test site and the driving conditions analysed.

2.3 IBIS RADAR

The IBIS radar system is a recently developed non-contact displacement and vibration monitoring device for civil engineering applications. It comes in two configurations such as IBIS-L and IBIS-S. The IBIS-L configuration is used for static terrain deformation monitoring and is mainly used in mining and slope stability applications. The IBIS-S configuration is used for dynamic and static monitoring by remote sensing of structures such as buildings, bridges and telecommunication towers.

The IBIS-S radar unit can simultaneously monitor several points, providing real-time displacement response for each point. The unit operates at frequency of 200Hz giving displacement accuracy of 0.01mm up to range of 1 km (IDS, 2008; IDS Australia, 2009). Bernardini *et al.* (2007) conducted a laboratory test and it showed an excellent quality of the displacement measurements and a good operational stability. IDS Australia (2009) performed some real validation tests with accelerometers and LVDTs and the results showed an excellent match with the accelerometers and LVDTs tests.

The main advantage of IBIS-S, apart from the accuracy, range and resolution, is the fact that it can be operated in all weather conditions over very long distances without the need of accessing the target to install sensor or optical targets. However, if required, one or several specific points on a target could be measured by a simple passive radar reflector that can be easily fixed. All the measured quantities are displayed in real time via a computer. Other quantities such as velocity and acceleration records can also be displayed.

It should be emphasised that the IBIS-S unit has never been used in piling application and its use was first suggested by the author who recommended a trial site test. Therefore, the purpose built software used for the test was not well suited for the pile testing to calculate the required parameters.

As a precautionary measure, it was decided to use a passive reflector. Subsequently a V-shape passive reflector was made at RMIT's laboratory and it was bolted to the pile at approximate same vertical distance as the transducers, as shown in Figure 3. Continuous readings of all the blows during easy and hard driving test conditions were measured by the IBIS-S radar.

Figure 3: Passive reflector target made at RMIT laboratory and PDA transducers.

The radar unit operates on a 12V battery and comes with a hard case. It also comes with an adjustable tripod for easy and quick set up as shown in Figure 4.

Figure 4: IBIS-S radar set-up and real-time monitoring of deformation.

2.4 GRLWEAP ANALYSIS

GRLWEAP™ software is a pre-driving computational analysis tool for simulating pile response based on the solution (Smith, 1950) of one-dimensional wave equation. Smith first developed the numerical solution to the wave equation by discrete element idealisation of the hammer-pile-soil system as a series of mass, springs and dashpots. One of the first programs was developed by Goble and Rausche in 1976 was named Wave Equation Analysis Program (WEAP) and later it was updated to WEAP87. Amongst the many available programs, currently GRLWEAP is the most widely used program and improvements such as residual analysis, pile-soil modelling and driveability analysis were incorporated in the later versions (Rausche, 1988; Hussein *et al.*, 2004).

The main input data in GRLWEAP™ program are hammer, cushion and pile details as well as soil parameters. It outputs driving stresses, hammer performance and the pile bearing capacity both graphically and in tabular format. Since 2002, the GRLWEAP™ has included the Residual Stress Analysis (RSA), which is a concept relating to the fact that the pile shaft is elastically compressed during hammer strokes and the resistance distribution between shaft and base varies. RSA analysis is not undertaken for end bearing piles where the toe capacity is significantly larger than the skin friction.

Two GRLWEAP™ analyses were carried out for the easy driving and hard driving conditions based on the soil profile at the site. The standard GRLWEAP™ parameters were input for hammer, cushion and the pile. The soil parameters were input based on the *in situ* testing results. These cushion, pile and soil parameters were changed till a good match between the GRLWEAP™ program and the PDA results were achieved.

2.5 CAPWAP ANALYSIS

CAPWAP® (**Ca**se **P**ile **W**ave **A**nalysis) is a signal matching or reverse analysis program for piles using the wave equation theory, in which the PDA measured forces and velocities are matched with the calculated forces and velocities based on the Smith model of mass, springs and dashpots. It models the ground reactions (both skin and toe) as elasto-plastic spring and a linear dashpot. In the radiation damping model, an additional dashpot is inserted for the toe to take into account the movement of the surrounding soil. Therefore, the soil model can be described by ultimate resistance, quake and viscous damping factor. The total resistance is the sum of the displacement (quake) dependant static resistance and the viscous velocity dependent dynamic resistance.

Smith quake and damping factor are assumed to be soil type dependent and can be estimated by load tests or perform CAPWAP® analysis by using the PDA monitoring data. However, Paikowsky (2004) showed in a large database of load testing that no correlation existed. CAPWAP® analysis is a linear process to determine the best-fit solution and the parameters it produces are not unique. As a result, there have been numerous studies undertaken to understand the correlations of the Smith model parameters (McVay, 1999) and there is still lack of understanding about the factors attributed to these parameters. McVay (1999) provides a comprehensive literature review of the many methods. Liang and Sheng (1992) derived a theoretical expression by using the spherical expansion and punching theory to express the toe/skin quakes and damping.

Normal CAPWAP® analysis procedure involves selecting a blow record and matching the measured and computed force-velocity trace by changing a number of variables, which under a normal case, would be 11 plus the number of shaft resistances that are dependent on the depth of pile or soil. In cases where additional options are required, such RSA, radiation damping, toe gap and unloading, the variables would, of course, add up even more.

For the CAPWAP® analysis of the PDA results, the author selected and performed two CAPWAP analyses for each driving conditions. Good CAPWAP Match Quality (MQ) of approximately 3.5 were obtained for the records analysed.

2.6 THE CASE METHOD

Pile Driving Analyser (PDA) is a field tool to measure the acceleration and strain with the aid of strain transducers and accelerometers at approximate depth of two pile diameter below the pile head. This method of field measurement was developed by George Goble of Case Western Reserve University in 1964 as a result of a research project funded by Ohio Department of Transportation and FHWA.

Pile driving resistance and static capacity can be performed by PDA in-built routine from these measurements by simplified closed method solution. This method is known as the Case Method and there are several procedures that were developed for different driving conditions and the measured force velocity traces.

The QULT procedure is the dynamic formula equivalent. It uses the measured maximum energy (EMX) and the maximum displacement (DMX) to calculate the ultimate capacity. This value is not reliable and is only used for reference purposes.

Automatic Resistance procedure is employed in cases where the pile skin friction is very low (RAU) or moderate shaft resistance (RA2). This procedure is best suited for hard driving cases and is independent of the damping parameter.

The Maximum Resistance (RMX) is generally most appropriate when large quakes are observed. This ensures full capacity is mobilised. This method is preferred when velocity doesn’t become negative prior to the time at which the travelling wave returns.

The RSP is original procedure that uses the peak forces and a soil (grain size) based empirical damping factor is applied to calculate ultimate capacity. It is very sensitive to the damping factor.

3 FIELD TEST RESULTS & ANALYSIS

A tabular summary of the results for the PDA and IBIS-S field testings as well as the CAPWAP signal matching are presented in Table 1. Capacity comparison results calculated by the Case, Hiley, Gates and MnDOT methods are also presented in Table 1.

The real-time IBIS-S monitoring of the pile head movement is give in Figure 5 and Figure 6 for the two driving conditions. For the easy-driving condition, the first three blows recorded seem to be invalid and the reasons may be attributed to perhaps target interferences by the hammer hoses and chain used to hold and position the pile.

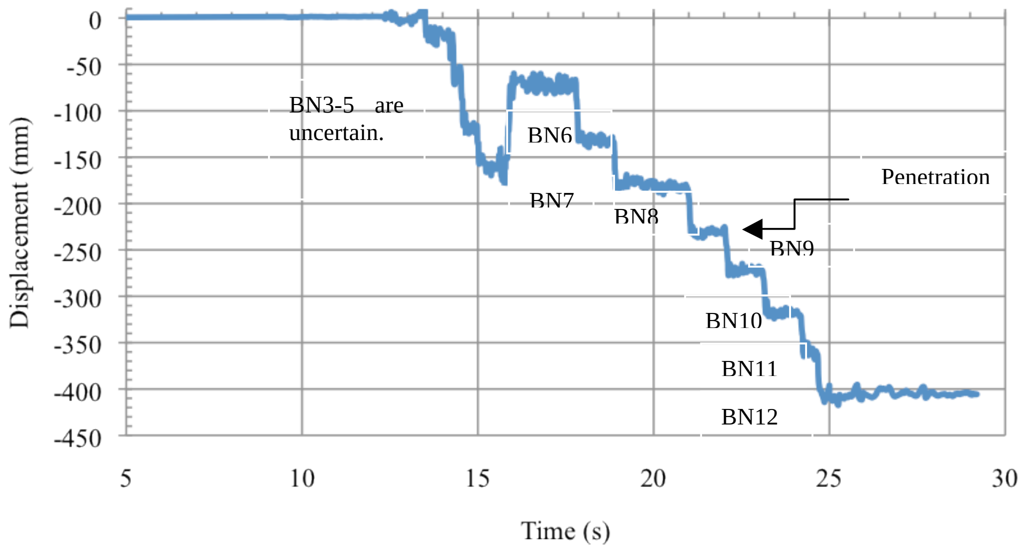

Figure 5: IBIS-S Set Measurements for Easy-Driving Condition.

For the hard-driving condition, all the seven blows were captured and are presented in Figure 6. The pile head velocity and acceleration records can also be obtained from the Ibis-S software or can be calculated from the raw data by other suitable programs by simple differentiation technique. The transferred energy to the pile can be calculated from the impact velocity records because the transferred energy to the pile is directly dependant on the hammer impact velocity.

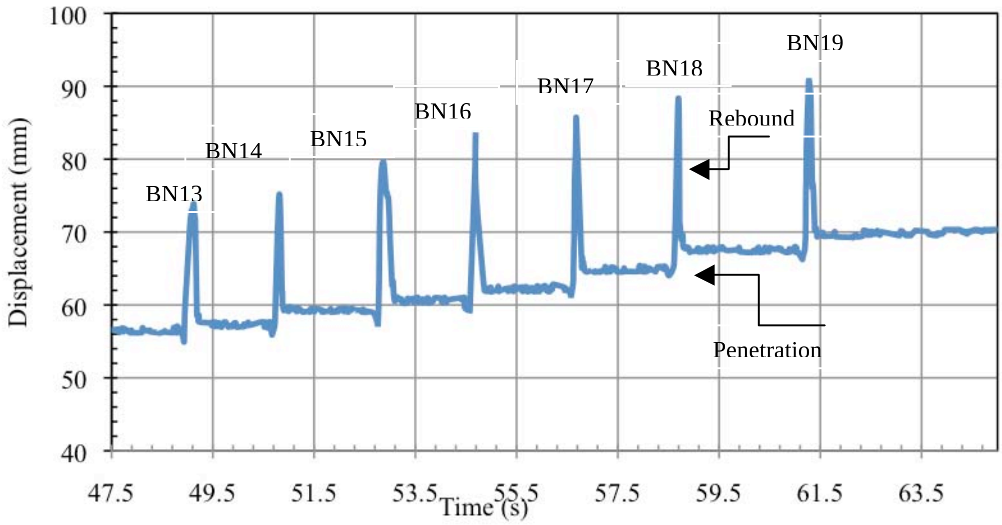

Figure 6: IBIS-S Set Measurements for Hard-Driving Condition.

Table 1: Results of field testing.

Blow No. (BN)	Depth	Stroke	Observed set		IBIS-S Measurement			PDA		Max. Energy (EMX)	Max. Force (FMX)	Max. Velocity (VMX)	Case Resistance (RMX)	(RAU)	Capacities: QUT	Hiley (set card)	Hiley (Ibis)	Gates	MnDOT	GRLWEAP	CAPWAP
	(m)	(m)	Set (mm)	TC (mm)	Set (mm)	TC (mm)	VMX (m/s)	DMX (mm)	DFN(mm)	(kN-m)	(kN)	(m/s)	(kN)	(kN)	(kN)	(kN)	(kN)	(kN)	(kN)	(kN)	(kN)
3	15	0.3	38.2	0	-	-	-	41.00	38.9	17.016	1852	1.93	283	-	426	445	-	-	-	-	300
4	15	0.3	38.2	0	-	-	-	41.50	40.7	17.115	1876	1.94	295	-	417	448	-	-	-	-	-
5	15	0.3	38.2	0	-	-	-	47.50	45	20.081	2029	2.13	250	-	433	526	-	-	-	-	-
6	15	0.3	38.2	0	43.58	0	1.594	44.70	41.8	19.186	1995	2.09	290	-	444	502	440	471	583	262	-
7	15	0.3	38.2	0	40.3	0	1.842	45.80	44.3	19.131	1969	2.06	281	-	425	501	475	491	609	285	345
8	15	0.3	38.2	0	47.55	0	1.835	43.90	42.8	18.761	1991	2.06	314	-	433	491	395	443	554	235	-
9	15	0.3	38.2	0	38.49	0	1.732	42.70	42.3	18.48	1971	2.02	327	-	435	484	480	495	624	299	-
10	15	0.3	38.2	0	40.75	0	1.633	41.70	41.7	18.247	1947	2.01	337	-	437	478	448	477	605	282	-
11	15	0.3	38.2	0	37.74	0	1.862	40.30	39.7	17.861	1901	1.99	348	-	447	468	473	491	631	305	-
12	15	0.3	38.2	0	46.79	0	1.741	39.70	36.9	17.815	1958	1.99	353	-	465	466	381	435	560	240	-
13	18	0.7	2.4	16	1.82	16.02	2.866	18.70	0.5	36.445	3431	2.58	3387	2615	3806	3504	3708	1818	2496	3276	-
14	18	0.7	2.4	16	2.24	17.8	2.642	19.30	3.3	38.529	3507	2.67	3400	2637	3409	3705	3459	1791	2391	3059	3038
15	18	0.7	2.4	16	1.54	18.43	2.617	18.90	4.2	37.066	3468	2.63	3397	2584	3202	3564	3446	1896	2580	3450	-
16	18	0.7	2.4	16	1.47	20.84	2.576	18.70	3.3	36.5	3418	2.57	3393	2614	3324	3510	3070	1898	2603	3498	-
17	18	0.7	2.4	16	2.31	20.51	2.613	18.70	2.5	36.742	3459	2.60	3423	2653	3469	3533	2924	1737	2375	3027	-
18	18	0.7	2.4	16	2.3	20.73	2.597	18.70	1.8	36.715	3445	2.59	3432	2643	3581	3530	2899	1738	2377	3031	3200
19	18	0.7	2.4	16	2.3	20.73	2.571	18.70	2.9	36.375	3395	2.55	3380	2657	3367	3498	2872	1730	2377	3031	-

The author performed the CAPWAP testing on two of the PDA records for the easy driving and two for the hard driving conditions. The records from the blows were selected on the basis of energy, set and the overall quality of the records. The results together with the damping and quake parameters computed by the CAPWAP are given in Table 2. The signal matching quality results are shown in Figure 7 and Figure 8.

Table 2: Soil parameters derived from signal matching CAPWAP.

BN	Depth (m)	Stroke (m)	Computed Set (mm)	Computed EMX (kNm)	Shaft Damping (-)	Shaft Quake (mm)	Shaft Resist. (kN)	Toe Damping (-)	Toe Quake (mm)	Toe Resist. (kN)	Total Resist. (kN)
3	15	0.3	42.4	16.94	0.42	2.5	161.6	0.15	40.2	138.4	300.00
7	15	0.3	40.69	18.66	0.661	1.62	139.5	0.279	26.25	205.5	345.00
14	18	0.7	2.92	38.38	0.168	6.21	1788	0.229	9.78	1250	3038.0
18	18	0.7	2.833	36.84	0.085	4.84	1037.8	0.455	5.55	2162.2	3200.0

Figure 8: Match Quality of CAPWAP Analysis Results for Hard Driving Condition.

GRLWEAP analyses were also performed for the easy and hard driving conditions and the Bearing Graph showing the ultimate capacity versus set is presented in Figure 9.

Figure 9: GRLWEAP Bearing Graph for Banut6T hammer

The ratios of the Hiley, GRLWEAP and the CAPWAP capacities are also plotted in Figure 10 and Figure 11. From Figure 10 it can be seen that the capacity ratio of GRLWEAP and the CAPWAP for the easy-driving condition is about 0.9, which indicates that, although the test results are consistent, GRLWEAP slightly under predicts capacities in easy-driving conditions. However, in hard driving conditions the ratios are nearly one, indicating the results are consistent and in good agreement.

Figure 10: GRLWEAP Analysis for easy-driving condition. Hiley Correction Factor vs. Set for Banut6T hammer, 350mm precast pile – Easy driving condition.

Similarly, the ratio of Hiley to GRLWEAP (or CAPWAP) is approximately 1.35, which indicates that, irrespective of the driving conditions, the Hiley formula over predicts the capacity by this factor and that this over estimation is consistent.

Figure 11: GRLWEAP Analysis for hard-driving condition. Hiley Correction Factor vs. Set for Banut6T hammer, 350 precast pile – Hard driving condition.

The capacities calculated by the various methods such as the CAPWAP, Gates, GRLWEAP, Hiley and MnDOT methods are plotted and shown in Figure 12. The results show that the Hiley formula pile capacity predictions are very good compared to the CAPWAP and consistent throughout the blow records. On the other hand, Gates and MnDOT perform poorly for the easy driving condition, but compare reasonably well in hard driving conditions. It should be mentioned that the Hiley capacities in Figure 12 are not factored.

Figure 12: Overall Comparisons of Capacities by CAPWAP, Hiley, Gates, GRLWEAP and MnDOT Methods for the Easy and Hard Driving Conditions.

The performance of the Banut hammer for the two driving conditions is shown in Figure 13. It can be seen that the hammer is very efficient and that the efficiency decreases slightly with increasing velocity.

Figure 13: GRLWEAP Analysis. Hammer performance and efficiency for Banut 6T.

The Hiley Correction Factor shown Table 3 are calculated from the field measurements. The factors are based on the GRLWEAP and Hiley capacity predictions for the set measured by IBIS-S. It shows that it slightly under predicts capacity compared to the CAPWAP capacity in easy-driving condition. It is interesting to note that the Hiley factor of about 1.35 is consistent in all conditions compared to both the CAPWAP and GRLWEAP capacities, with the exception of hard driving where the correction factor is about one which indicates that the Hiley capacity is same as the CAPWAP capacity prediction.

Table 3: Correction factor calculations based on the field set measurement by IBIS-S.

	Hiley Correction Factor (HCF)		
	GRLWEAP Analysis	IBIS-S	
	(GRLWEAP/CAPWAP)	(Hiley/CAPWAP)	(Hiley/GRLWEAP)
Easy Driving	0.83	1.38	1.32-1.33
Hard Driving	0.95-1.01	0.91-1.14	1.31

4 EXTENDED APPLICATION OF IBIS-S

As mentioned earlier, the CAPWAP signal matching program does not produce a unique solution due to the many unknown empirical parameters. Some of the parameters are damping factors, quakes, toe gap and radiation damping. Therefore, due to the high resolution and accuracy of the IBIS-S unit, it is possible that some of these empirical parameters could be directly evaluated. Additionally, it is possible to evaluate the integrity of driven piles from the velocity and acceleration records, especially if a defect has been detected and the need to proof test the untested piles.

Another very useful application of the IBIS-S radar, due to its multi-target measurement capability, is in the assessment of pile mechanical joints. The current VicRoads standard only requires visual inspection under many repetitive hammer blows. In some situations PDA dynamic testing is done concurrently and the results are checked with CAPWAP analysis to ensure the movement complies with a given standard.

5 CONCLUSION

The field test data gathered during trial test of IBIS-S radar provide an excellent basis for the evaluation of the Hiley formula in prediction of pile capacity for all driving conditions. A comparison of the predictions obtained from the pile driving formulae with the higher order methods such the CAPWAP and GRLWEAP wave-equation analysis showed that the results are very consistent and accurate.

The present investigation thus demonstrates that the pile capacity predictions by the Hiley formula are very reliable provided that the variation in the energy input can be accurately measured and allowed for in the calculations. Since under normal pile driving conditions, variability in the driving system and the energies delivered to the pile exists, it is important to account for this variability so that the driving formula can be used with greater confidence.

In the past the poor quality of the results obtained by pile driving formula was partly related to the erroneous estimate of the driving energy. It is now possible, with the aid of new technology, to measure with high accuracy not only the energy delivered to the pile by each blow, but also the full pile displacement records.

A correction factor to allow for the dynamic effects, similar to the Case damping factor, was back-calculated from the CAPWAP and GRLWEAP analysis. It showed that the correction factor is quite consistent and can be developed for a variety of ground conditions, hammers and pile types. This will allow for the dynamic formulae, particularly the Hiley formula to be used with greater accuracy comparable to the wave equation analysis.

More general conclusions of the study in this paper can be as follows:

- The wave-equation analysis only describes the energy transfer mechanism from the hammer to the pile toe in a systematic and accurate fashion and if the dynamic formulae are modified to account for the energy losses, then the dynamic formulae should technically fulfil the same function.
- The dynamic formulae, which ignore the dynamic effects, need to be accounted for in the formulae.
- The energy delivered to the pile and its set measurements need to be accurately determined in order to render the dynamic formulae reliable.
- Create a comprehensive database with driving records for various soil conditions, driving systems as well as different piles and establish driving formula correction factors against the database.
- The correction factors can be established from GRLWEAP and CAPWAP analysis as well as static testing results.

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