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CAPWAP AND REFINED WAVE EQUATION ANALYSES FOR DRIVEABILITY PREDICTIONS AND CAPACITY ASSESSMENT OF OFFSHORE PILE INSTALLATIONS

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ABSTRACT
Open ended pipe piles have to be driven in the offshore environment primarily as platform support piles or as conductor pipes. In either case, deep penetrations have to be achieved. In preparation of these potentially difficult installations, equipment selection and stress control is done by a predictive wave equation analysis. During pile driving, dynamic monitoring combined with CAPWAP signal matching analysis is a preferred method for bearing capacity assessment. After the fact, if dynamic measurements were not provided during pile driving, a wave equation analysis can again help perform a post-installation analysis for bearing capacity assessment, assuming a variety of parameters.

Wave equation analyses require a variety of input parameters describing hammer and driving system performance and the pseudo-static and dynamic behavior of the soil. Measurements taken during the installation yield immediate results about hammer and pile performance. Soil resistance parameters can be extracted by careful signal matching analysis. Unfortunately, the measurement and associated analysis results cannot be used without further modification in the wave equation analysis, because the wave equation approach requires simplifications in hammer, driving system and soil models. Thus, a final step is the so-call Refined Wave Equation Analysis which combines all results obtained and produces a best possible match between measurements and analyses.

This paper describes the process of the three analysis phases utilizing typical offshore pile installation records. The paper also gives guide lines for this analysis process as well as a summary of limitations. An important part of the paper includes recommendations for and discussion of the modeling of the soil resistance near the open ended pipe bottom. Finally, the paper discusses how the results should be used for greatest benefit of the deep foundation industry.

1 INTRODUCTION
The wave equation analysis was originally developed by E.A.L. Smith, 1960 and further developed by many researchers. Today the most frequently used software, for both offshore and on-land projects, is the GRLWEAP program (PDI, 2005). The following will describe procedures for and present examples of calculations done by this program, however, similar results may be expected with similar software of other developers.

The wave equation approach requires the modeling of impact hammer, driving system (helmet and either hammer cushion, if present, pile cushion, if present, or both types of cushions), pile and soil and simulates the pile penetration of the pile during a hammer blow. The basic result is a bearing graph which relates bearing capacity to pile penetration per blow or blow count. The method requires assuming parameters for the hammer performance, driving system and soil. The bearing graph can be used for bearing capacity determination given a measured blow count. It can also provide a prediction of blow count at a certain pile penetration, given an accurate assessment of the static and dynamic soil resistance. Thus, after calculating bearing capacity vs. depth, performing successive wave equation analyses for various pile penetrations, this so-called driveability analysis leads to the prediction of blow count and pile stresses as a function of depth (Rausche et al., 2004).

While wave equation analysis is primarily useful for the preparation of pile driving projects**,** i**.**e**.** for the selection of pile driving equipment**,** for the determination of bearing capacity**,** dynamic measurements by means of a Pile Driving Analyzer (PDA) and signal matching analysis **(**e.g., by CAPWAP; see PDI, 2006**)** is preferred; this combination of measurements and wave equation analysis will be referred to in the following as PDA-CW. The measurements eliminate the need for hammer and driving system modeling which greatly reduces the number of unknowns and for that reason has enjoyed increasing popularity for offshore pile acceptance **(**Webster et al., 2008**).** Of course**,** in the offshore environment where static testing is not practical for reason of cost and time savings**,** the PDA-CW system is particularly valuable and has become the pile testing method of choice**.**

2 BACKGROUND INFORMATION

2.1 Bearing Graph Analysis

The basic result of a wave equation analysis is the bearing graph which relates bearing capacity to blow count for a particular pile depth. Unknown soil resistance parameters are typically reduced to a single shaft damping (range between 0.1 and 1.4 s/m) and toe quake value (dependent on the pile toe diameter and ranging between 1 and 50 mm), while shaft quake and toe damping are fixed at respectively 2.5 mm and 0.5 s/m. Also, the resistance distribution along the shaft and the percentage of shaft resistance are unknown.

In the analysis, the energy transferred to the pile and the pile stresses are a function of the hammer efficiency, $\eta_{H,}$ i.e. the ratio of energy getting into the driving system (hammer cushion, helmet and pile cushion, if present) relative to the available energy. Modern hydraulic hammers often measure the kinetic energy just before impact, however, even in that case it is unknown how much energy is lost during the impact event, e.g. due to hammer-pile misalignment, inaccurate kinetic energy measurement or other unaccountable effects.

Driving system stiffness, k_D, and coefficient of restitution, c_r, are uncertain when cushion materials are employed or when the helmet plate is flexible. Both parameters affect energy transfer and pile top stresses. Even when cushion and helmet materials are well known, their energy dissipation due to bending, poorly matching surfaces, pile top plastification, damaged components etc. is not well understood. For concrete piles, the soft pile top cushion governs the driving system performance and hammer cushion properties are of secondary importance.

2.2 Driveability Analysis

The driveability analysis calculates for a certain capacity at a particular depth, the blow count and the pile stresses. Thus, for each depth analyzed, the soil resistance distribution in the form of a unit shaft resistance and end bearing must be input. Static geotechnical analysis of the soils surrounding the pile determines the long term bearing capacity R_U. Additionally, for the driveability analysis, an estimate has to be made of the static resistance to driving (SRD) which is thought to be the sum of a setup factor reduced shaft resistance, f_{si} R_{SUi}, plus a long term end bearing, R_{BUi}. Thus for each soil layer, i:

$$SRD_i = R_{SUi} / f_{si} + R_{BUi} \qquad (1)$$

Also, for each soil layer i, the shaft soil damping factor, j_{si}, and the toe quake, q_{ti}, are additionally unknown. The number of major unknowns of a driveability analysis is, therefore, at least 3 for the driving equipment plus 5 times the number of soil layers. For a 10 layer soil profile, the resulting number of unknowns is 53. Obviously, it is not a simple task to determine these unknowns. Calculating variable setup, i.e. for a driving interruption during which partial soil setup occurs, requires that the capacity gain with time is furthermore specified and this leads to another unknown as described in the following.

2.3 Variable Soil Setup

Soil setup has been studied by a number of different researchers. Generally accepted is the formulation of Skov and Denver (1988), which describes the gain of pile bearing as a function of the log of time leading to the equation:

$$R(t_w) = R_0[1 + A \log_{10}(t_w / t_0)] \qquad (2)$$

Where A is the capacity gain occurring for every ten fold increase in waiting time, t_w, measured since an appropriately chosen reference time t_0 at which the reference capacity R_0 occurs. Skov and Denver recommended, R_0 to be determined by a restrike test with $t_w = t_0 = 1$ day. In the GRLWEAP program a somewhat modified approach assumes that R_0 is the SRD occurring during driving and that in every soil layer, i, the long term capacity R_{ui} is reached after a setup time, t_{si} (Rausche et al., 1994). With a specified soil setup factor, f_{si}, the long term capacity is

$$R_{Ui} = f_{si}\, SRD_i \qquad (3)$$

and after a waiting time t_w, which is less than the full setup time, the capacity in layer i is

$$SRD_i(t_w) = R_{\underline{U}i}\, [1/f_{si} + A^*_i \log_{10}(t_w/t_0)] \qquad (4)$$

The reference time, t_0, in the GRLWEAP code has been rather liberally chosen as 0.01 hours which implies that the capacity 36 seconds after the end of driving is still equal to SRD and only then begins to increase logarithmically. For a setup time, t_{si}, the parameter A^*_i is calculated from

$$A^*_i = (1 - 1/f_{si})/\log_{10}(t_{si}/t_0) \qquad (5)$$

For example, if for a clay layer the setup factor is 3 and the setup time is 2 weeks or 336 hours then $A^*_i = 0.147$; thus 1 hour after the end of driving (i.e., 100 times t_0) $SRD_i(1hour) = R_{Ui}(1/3 + 0.147\log_{10}100) = 0.628R_{Ui}$ or the capacity has then increased from 33% to 63% of its long term value.

In summary, when driving interruptions have to be modeled, then the wave equation analyst must assume for each soil layer a setup time, t_{si}.

2.4 Plugging Effects

Open ended pipe piles are most commonly installed in offshore construction and questions as to the anticipated end bearing or the meaning of PDA-CW determined end bearing often arise. The piles may experience (a) coring or no plugging, (b) have a fully plugged end bearing (the end bearing is then transferred in full magnitude to the inside of the pipe) or (c) have a slipping plug, i.e., partial end bearing which is causing inside pipe friction. During driving, inertia of the soil mass inside piles of more than 600 mm diameter often prevents full plugging. However, in very dense soils, at least partial plugging is common and, in the static situation, plugging can be expected in very dense soils when there is enough side resistance to transfer the end bearing force to the inside of the pipe wall.

PDA-CW determines by signal matching an end bearing along with a shaft resistance distribution. If full or partial plugging occurs, the solution will frequently include an inertia resistance from soil mass or so-called pile impedance (the product of cross sectional area and the square root of the product of elastic modulus and mass density). Near the pile toe the calculated shaft resistance may include internal pipe friction, if partial plugging occurred. The magnitude of the calculated end bearing and the soil mass or impedance model indicate whether or not some form of plugging occurred.

For wave equation analyses, if a PDA-CW solution exists, then the end bearing for the wave equation analyses can be modeled accordingly. If no measurements were taken during driving, a hind cast matching process will either require assumption of the presence of internal friction or a statically calculated unit end bearing applied to a cross sectional area which can vary between the steel area and the fully plugged one. For driveability analyses prior to pile driving both an optimistic (unplugged) and a pessimistic (fully plugged) assumption is often tried for the prediction of a range of possible blow counts.

3 PROBLEM STATEMENT

The following two problems often must be solved.

(a) After PDA-CW measurement and analysis of an end of driving record, capacity evaluation of other non-tested piles is best done by wave equation approach using their observed blow counts in a bearing graph. Also the driving of other piles, possibly with different hammers and/or energy levels, require reformulation of a driving criterion and this can be best done by wave equation analysis. The wave equation model, therefore, has to be calibrated to the measured PDA-CW results resulting in the so-called “Refined Wave Equation Analysis” (REWE).

(b) Reanalysis of driving logs from pile installations, often conducted without dynamic measurements, require a prediction of the long term pile capacity. Simple analysis of the final blow count would not take advantage of the total driving record including information about soil setup provided by driving resistance (blow count) changes before and after driving interruptions. In order to take advantage of that information, it is necessary to match the complete driving record by “Blow Count Depth Matching” (BCDM).

3.1 Recommendations for Refined Wave Equation Analysis (REWE)

After a PDA-CW analysis has been performed, ultimate capacity, damping and quake values have been calculated. Also, the measurements indicate maximum stresses at the pile top and the transferred energy while calculations provide maximum tension and compression stresses at points other than the pile top.

Since the blow count is an average value over several hammer blows, and since this average is used for construction control, it is recommended to establish an average over several blows for transferred energy and maximum stress values (keeping in mind that the maximum stress does not necessarily occur at the pile top). Obviously the wave equation analysis calculates corresponding values and ideally, standard hammer/driving system parameters plus the PDA-CW calculated dynamic soil resistance values, would immediately yield a good match of stresses, transferred energy and blow count. There are several reasons why these results do not immediately match.

(a) The measured pile force and velocity do not match the calculated curves at all points in time although the single peak points of transferred energy and stress match. Reasons include hammer-pile alignment problems and non-linearly behaving hammer and driving system components.

(b) PDA-CW uses a pile model consisting of continuous sections while the GRLWEAP code works with a lumped mass model.

(c) The GRLWEAP software normally uses the Smith soil model with few exceptions. In order to achieve a good quality signal match, PDA-CW, on the other hand, works with many extensions to the basic Smith model such as viscous damping, variable unloading quakes, variable negative shaft resistance levels and other extensions of the basic Smith soil model. PDA-CW has to use a more detailed model in order to achieve a reliable capacity result.

The flow chart in Figure 1 outlines a basic procedure although modifications maybe necessary. A few remarks are appropriate:

1. Hammer efficiency and the stiffness and coefficient of restitution (CoR) of the driving system affect both transferred energy and pile stresses. Attempt to maintain adjustments within reasonable limits, e.g. to keep efficiency between roughly 2/3 of standard recommendations and 100% by also modifying stiffness and/or CoR of the hammer or pile cushion as needed. In general, combinations of k_D, CoR and η_H must be tried for a match of transferred energy and maximum stresses.
2. To effect a driving system stiffness change, modify the elastic modulus of either hammer cushions (steel piles) or pile cushions (concrete piles) but not both.
3. CoR of softer cushion materials generally affects transferred energy more than stresses, adjust CoR of the pile cushion if present, but do not reduce it below 0.1.
4. Final blow count adjustments generally require damping factors and/or quakes which differ somewhat from those from PDA-CW. Attempt to change as few and quantities and as little as possible and choose combinations near PDA-CW calculated values. Keep in mind that an increased shaft damping causes higher top compressive stresses and an increased toe quake causes increased tension stresses.
5. Sometimes it may be necessary to switch from standard Smith damping to viscous damping.

Matching of an end of driving situation leads to the SRD, if no substantial driving interruption has occurred a short time prior to EOD. Analysis of a redriving situation yields the long term R_U if the data had been acquired after a sufficiently long waiting time after EOD. In many cases, the results lead to an intermediate value between SRD and R_U.

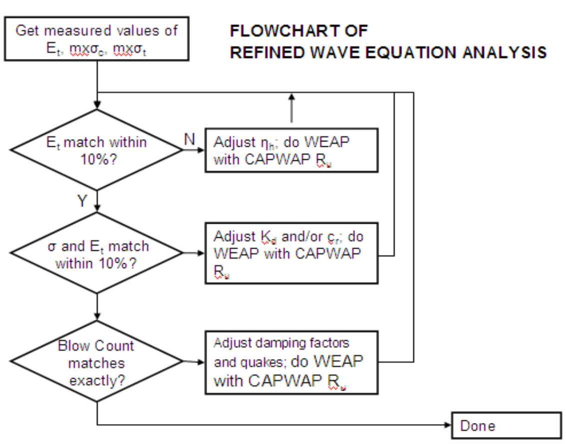

Figure 1. Flow chart for REWE

3.2 Recommendations for Blow Count-Depth Matching (BCDM)

As shown in Figure 2, the basis for calculating long term capacity using this BCDM procedure is a complete blow count vs depth record, often an average taken from comparable pile installations at the same site. For example, on offshore platform installations, four or six main piles or even more skirt piles may have identical geometries and they are driven with the same hammers into comparable soil strata. The installation records must include the hammer model and its energy setting. Ideally, measurements were taken (and maybe refined wave equation analysis had been done) for improved knowledge of hammer efficiency and driving system performance. Furthermore, driving interruption durations or restrike waiting times must be documented. The procedure described here assumes that no measurements were taken during driving. If PDA-CW results existed, BCDM would not be necessary and a more direct calculation of pile bearing capacity would be possible.

As a first step, the static soil resistance, the associated dynamic soil resistance parameters and the soil setup factors for the various layers have to be evaluated. The static resistance should be as realistic as possible, i.e. not include any hidden safety factors (this is not a design analysis). A difficult and important assumption concerns the end bearing. Depending on pile diameter and density or hardness of soil, no plugging (a complete soil plug moves up relative to and inside of the pile), partial plugging or full plugging may be anticipated. Thus, not only the unit end bearing but also the effective area has to be estimated which is either the pile toe steel area (no plugging), the full end area (plugging) or an intermediate value.

A driveability analysis is then performed which will produce an estimate of blow count vs depth. This result should include "before" and "after" driving interruption analyses for the same depth(s) for which GRLWEAP would produce the corresponding blow count changes. The "after" waiting analyses generally correspond to a partial soil setup situation which allows for a refinement of the long term unit shaft resistance values while the blow counts during continuous driving help establish the setup factors for the shaft resistance. Sudden changes in blow count are interpreted as changes in end bearing. Again it will be necessary to modify both unit end bearing and toe area values to match those portions of the driving record. It is recommended to match internal friction inside a pipe pile on the driving shoe (or over 5 pile diameters for uniform piles), if the pile is analyzed unplugged.

As for REWE it is difficult to give a very detailed BCDM procedure because of the great variety of pile driving situations which has to be simulated. Eventually, the blow counts of the whole driving record should be matched although the very early driving portions, say the driving of the first pile section with low blow counts, is of minor importance and can be skipped.

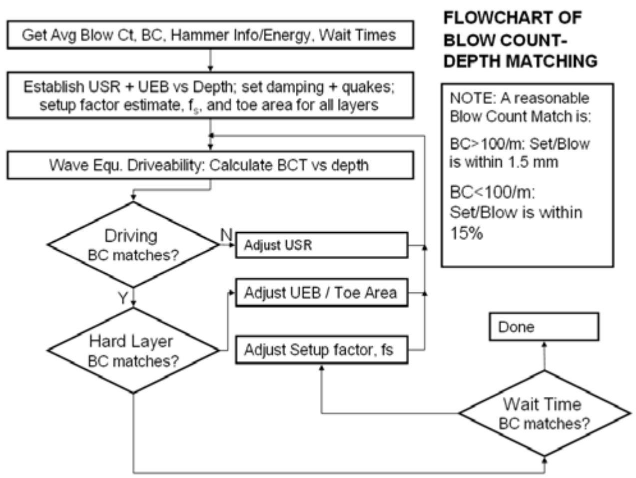

Figure 2. Flow chart for BCDM

3.3 Refined Wave Equation (REWE) Example

As an illustration of the typical REWE analysis procedure, the case of an offshore platform leg pile will be presented having a 1067 mm outer diameter and a wall thickness varying between 38 and 44 mm. The pile was assembled from 3 add-ons for a final total length of 100 m. Dynamic monitoring with a Pile Driving Analyzer was conducted throughout the driving process. At the end of driving, the pile achieved a penetration of 42 m with a reported end of drive blow count of 17 blows per 0.25m. The soil boring performed near the installation site indicated alternating layers of calcareous or carbonate clays and silty calcareous sands. The clay deposits increased in strength with depth with unconfined compressive strength values ranging from 100 to 450 kPa. The sand layers were described as medium dense to dense and also with increasing strength with depth.

A Menck MHU 500T hydraulic hammer drove the test pile. According to the manufacturer's literature, the MHU 500T has a ram weight of 294 kN and a rated maximum rated energy of 550 kJ. However, the maximum hammer energy is normally limited to a maximum delivered energy of 500 kJ. These two energy values correspond to equivalent ram strokes of 1.87 and 1.70 m, respectively. No hammer cushion is used with this hammer model. The helmet weight was assumed to be 104.8 kN.

During the final installation sequence, dynamic measurements of strain and acceleration were taken 3.5 m below the head of the P3 add-on. Two strain transducers and two piezoresistive accelerometers were bolted to diametrically opposite sides of the piles to monitor strain and acceleration. These strain and acceleration signals were conditioned and converted to forces and velocities by the PDA. For each hammer blow, the PDA calculated values for the maximum hammer energy transferred to the pile, the maximum compression stress at the gage location, and estimates of the pile capacity by the Case Method. A record from the end of driving was then subjected to signal matching analysis by CAPWAP indicating a 10.1 MN total ultimate capacity and 2.0 MN end bearing. Damping and quake results are shown in Table 1.

The force and velocity record (velocity was scaled by multiplication with the pile impedance), subjected to signal matching, is shown in Figure 3 together with a schematic representation of the variation of the pile cross sectional area (Pile top at the left hand side) clearly indicating the increased areas at the stabbing guide locations between the three pile sections. After achieving a satisfactory match between measured and computed pile top quantities, CAPWAP also simulates a static load test (Figure 4) which corresponds to the situation at the time of testing. Time dependent capacity changes such as an increase due to soil setup are not included in this result.

Table 1. Measurement and CAPWAP results together with corresponding GRLWEAP input and output values

Quantity	Default/ Measured/ Computed	GRLWEAP First Trial	GRLWEAP Final
Capacity Total/Toe (MN)	10.1/2.0	10.1/2.0+	10.1/2.0
Damping Shaft/Toe (s/m)	0.5/1.3	0.5/1.3	**0.4/1.0**
Quake Shaft/ Toe (mm)	2.0/15	2.0/15	2.0/15
Hammer Energy (kJ)	500	500	500
Hammer Equivalent Stroke (m)	1.70	1.70	1.70
Hammer Efficiency	0.95	0.95	**1.0**
Dr. System Stiffness (kN/mm)	N/A*	N/A	**8,000**
Dr. System Coefft. of Restitution	N/A	N/A	**0.93**
Pile Top Stress (MPa)	224	243	225
Transferred Energy (kJ)	473	429	473
Blow Count (Blows/0.25 m)	17	23	17
***** N/I: No Input – rigid assumption; + N/C: No Change			

The next step in the REWE procedure requires setting up the wave equation hammer, pile and soil model. In the present case, the MHU500T hammer model was recalled from the wave equation program and its ram stroke reduced to the contractor specified value of 1.70 m. Other input included default values such as a hammer efficiency of 0.95 (hammer internally measured kinetic energy), a zero driving system stiffness (no hammer cushion) and the PDA-CW calculated soil resistance parameters. As shown in Table 1, the first trial analysis resulted in a low transferred energy (429 vs 473 kJ measured), a high top stress (243 vs 225 measured) and a high blow count (23 vs 17 bl/0.25 m measured). Figure 5 shows a schematic representation of the wave equation model analyzed. Increasing the hammer efficiency for stress matching, the upper limit of 1.0 required a simultaneous adjustment of the driving system parameters (stiffness to 8000 kN/mm and coefficient of restitution to 0.93) which may be explained by helmet bending and ram/helmet interface behavior. It should be mentioned here that instead of increasing the efficiency by 5%, the equivalent stroke also could have been increased by 5% and the result would have been the same. It is recommended, however, as long as reasonable results can be obtained, to fix the field equivalent stroke input (i.e., energy setting) as set by the pile drivers. This quantity can be used for construction control while the hammer efficiency is a theoretical quantity needed to explain phenomena which cannot be controlled. A hammer efficiency of 1 may, however, mean that the energy setting on the hammer was reading somewhat low (the equivalent stroke was probably somewhat higher). After making the above adjustments, the resulting stress and transferred energy match was practically perfect, however, in order to match the blow count, a reduction of the PDA-CW calculated damping factors by roughly 20% was also needed. It should be emphasized that it is not always possible to achieve as good a match of all quantities observed as in this example. Figure 6 shows the wave equation calculated pile top force and velocity values for comparison with those measured and shown in Figure 3.

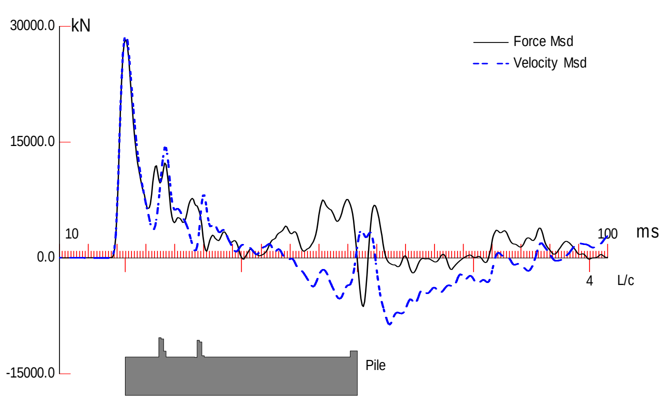

Figure 3. Force and velocity records and schematic pile representation

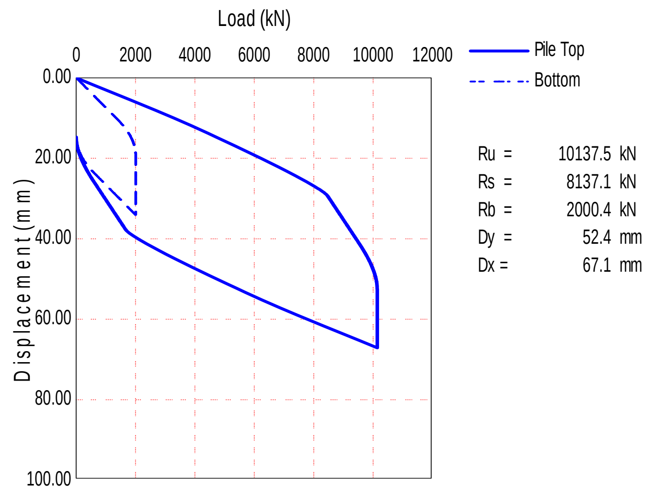

Figure 4. CAPWAP calculated load set curve

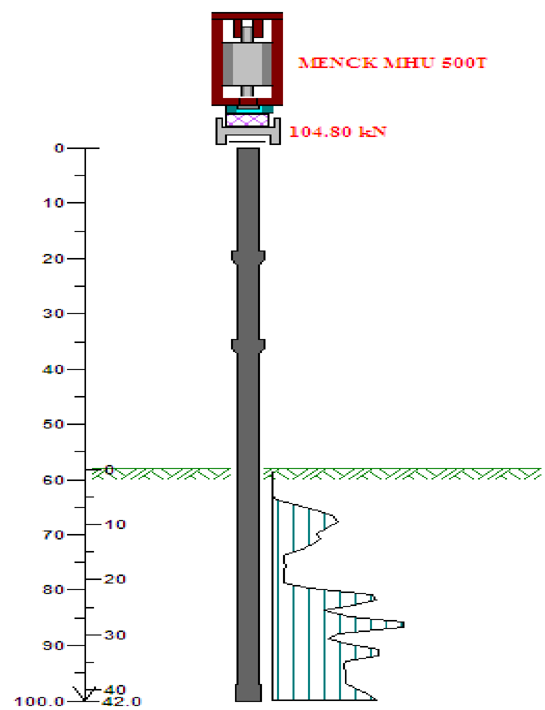

Figure 5. Wave equation model

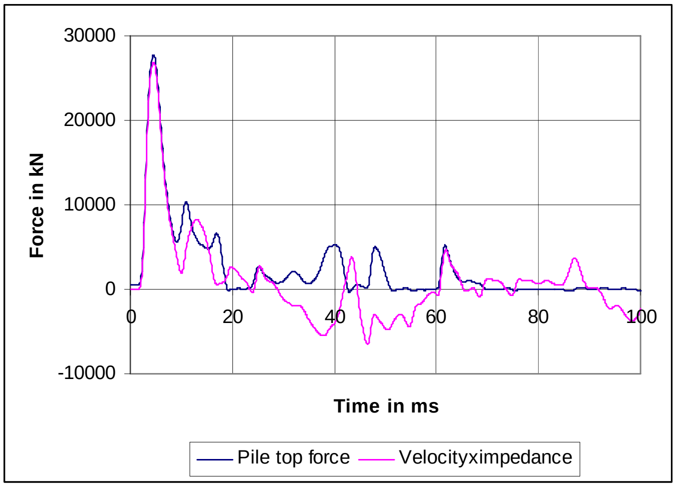

Figure 6. Wave equation calculated pile top force and velocity

3.4 Example of Blow Count-Depth Matching (BCDM)

For the sake of brevity, the following demonstration of the BCDM procedure utilizes the REWE example data, i.e. 1067x38 mm non-uniform pipe piles driven by the MHU 500T in a soil consisting of interspersed layers of sand and clay. During installation the contractor adjusted the hammer energy as driving resistance increased for an efficient and safe installation. Note that, in the present case, dynamic pile monitoring was conducted providing additional information which may or may not be available when the BCDM procedure is applied. To determine the piles Long Term Static Resistance (LTSR), blow count vs depth must be recorded along with exact information about any driving interruptions. Also, if dynamic monitoring was not conducted, hammer energy settings for the whole driving sequence must be known.

Figure 7 shows the unit shaft resistance as initially obtained from the geotechnical analysis; similarly, the statically calculated unit end bearing is shown in Figure 8, both as a function of depth. Figure 9 is a plot of the observed blow count. It clearly indicates, at a depth of approximately 30 m, strong driving resistance gains during the 10 hour waiting period caused by the splicing operations of the last pile section.

The above described procedure, i.e., wave equation analyses based on the assumption of GRLWEAP recommended standard damping factors and quakes, was then followed to determine iteratively shaft resistance and end bearing vs depth during driving (SRD) and a shaft resistance setup factor such that the blow counts before and after the driving interruption would be matched. For the shaft resistance, only external friction was considered. The setup time was set to 24 and 400 hours for sand and clay, respectively.

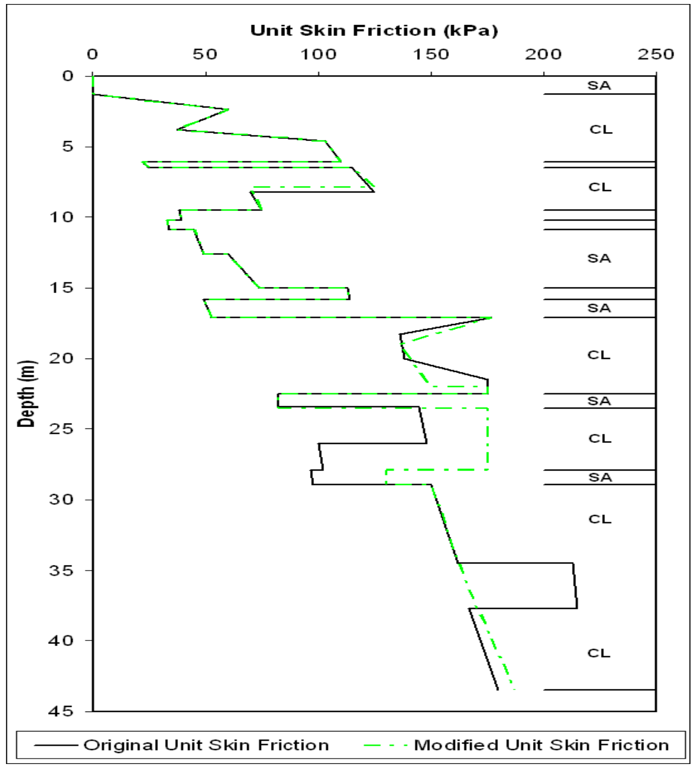

Figure 7. Initially assumed and final unit shaft resistance together with calculated soil setup factor from BCDM

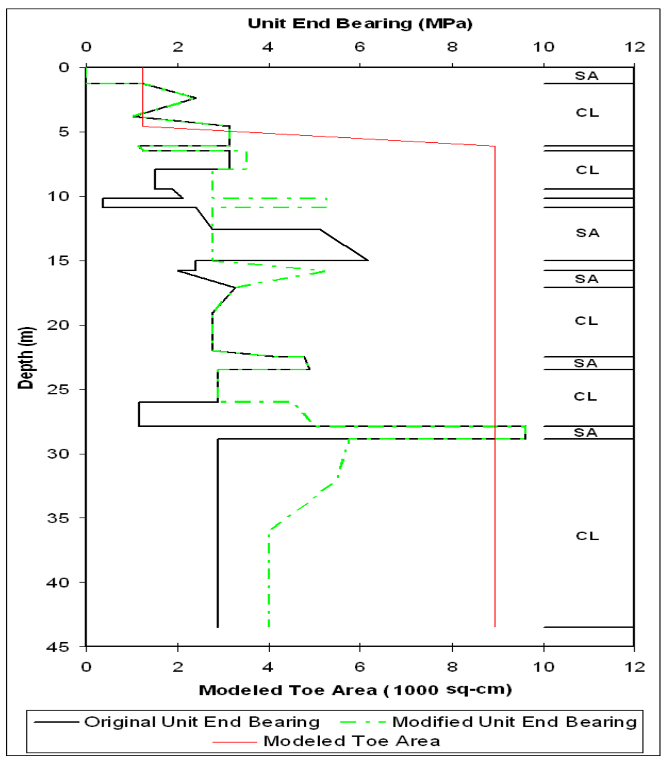

Figure 8. Initially assumed and final end bearing together with assumed toe bearing area from BCDM

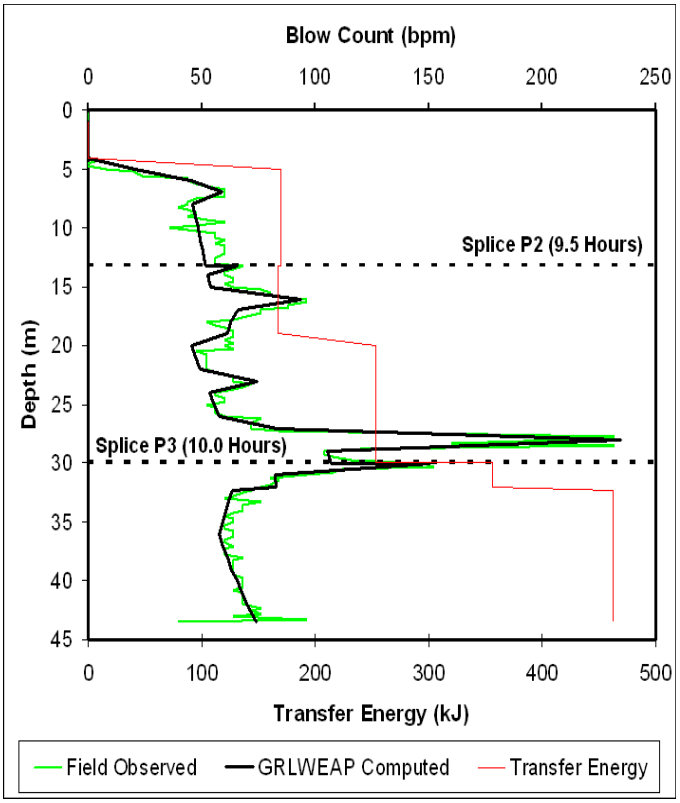

Figure 9. Blow count match and transferred hammer energy from BCDM

Through trial and error analyses, the BCDM procedure determined a unit shaft resistance (see Figure 7), a total end bearing which divided by the modeled toe area would produce the unit end bearing (Figure 8), and the setup factors of 1.5 and 3.0 for the sands and clays, respectively. Note that the static analysis unit end bearing values were only modified when the pile was assumed fully plugged; all other increases in end bearing were modeled at partial plugging. Also, for the end bearing, it was assumed that no change would happen during the driving interruption. Note, however, that the procedure cannot determine the actual unit toe resistance when partial plugging occurs because the toe area over which the unit end bearing acts is not known. For the present pile size the toe quake could vary between 2.5 mm for unplugged (non-displacement pile) and 18 mm for the fully plugged (displacement pile). It should be added here, however, that additional static analyses should and could be made to assess the potential for and magnitude of the fully plugged end bearing.

Obviously, achieving a good match involves a good deal of trial and error analyses. In the present case the unit shaft resistance of Figure 7, the unit end bearing values of Figure 8, and the shaft resistance setup factors of 1.5 for sands and 3.0 for clays produced the blow count match of Figure 9. According to this procedure, the total capacity at the end of driving was 10.1 MN and the long term resistance estimate was 21.3 MN. Obviously, in this case, the soil setup provides a very significant portion of the long term pile bearing capacity. The BCDM procedure relied on the calculation of the long term capacity on soil setup effects apparent from resistance gains occurring during driving interruptions prior to reaching the final penetration. Obviously, a restrike test after the pile has reached its final depth would yield a much more reliable prediction of long term pile bearing capacity.

It should also be mentioned that, in this example, the perfect agreement between the EOD capacity values predicted by BCDM and PDA-CW (both were 10.1 MN) was a coincidence. Some difference between these calculated capacities will normally occur. This must be expected because these two methods are based on completely different input values.

4 SUMMARY AND CONCLUSIONS

This paper describes two procedures to calculate soil resistance parameters from observations and measurements made during pile driving. Both procedures require numerous trial and error analyses and it is obvious that the results are non-unique and require experience and care in the selection of various parameters.

The first procedure is the so-called refined wave equation analysis (REWE). It is based on dynamic measurements taken during driving near the pile top and an associated signal matching analysis. The REWE results in a bearing graph (relationship between bearing capacity and blow count) whose energy input and soil response has been verified by the dynamic measurements and analyses. This bearing graph can be used to determine the bearing capacity of other similar piles driven at the same site to different blow counts, or it can be easily modified to represent driving with either a different energy setting, a different hammer or even a somewhat different pile geometry (although the pile diameter and pile toe penetration should not differ significantly since that would likely cause a different behavior of soil and possibly even the driving system). Note that this method can also be applied to restrike records (or those obtained after an interruption of pile driving). In this case the signal matching will help predict the long term capacity of the foundation piles.

The second procedure is called Blow Count-Depth Matching (BCDM). It requires knowledge of the blow count vs depth including hammer model, hammer energy setting (or transferred energy from dynamic monitoring although in that case signal matching methods, e.g., CAPWAP would be possible, easier to use and more accurate) and the duration of driving interruptions. This procedure is useful for bearing capacity assessment when no dynamic measurements have been taken during the installation of the piles. It also attempts to predict long term bearing capacity from soil setup effects occurring during interruptions of pile driving. Of course, far reaching assumptions have to be made as far as hammer, driving system and soil performance are concerned, limiting the reliability of this approach. However, the BCDM generates the best possible information given the limitations of the available information.

None of the wave equation methods described produces unique results. It is therefore strongly recommended to use these results in conjunction with static analyses and experiences gathered under similar circumstances.

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