MULTIPLE BLOW CAPWAP ANALYSIS OF PILE DYNAMIC RECORDS

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Abstract

Dynamic monitoring of impact driven piles is a routine quality control measure in many countries. Frequently drilled shafts are also tested dynamically in lieu of a more time consuming and expensive static load test. The dynamic records are often collected under a sequence of blows with variable energy levels. Impact driven piles are usually tested during restriking some time after pile installation. Three phenomena therefore occur simultaneously: (a) under each hammer blow shaft resistance and end bearing change because of the dynamic effects on the soil; (b) each hammer blow activates different levels of resistance because of the variable energy and the changing resistance conditions; (c) residual stresses increase with each blow and increasing pile penetrations. Normally, dynamic records of individual blows are analyzed by the CAPWAP method which yields a simulated load test for the situation encountered when one blow was applied to the pile at restrike. Residual stress analyses also consider only this one record under the tacit assumption that the same blow is applied several times. This is reasonable for most end of driving situations.

In the general case the interpretation of the tests could be erroneous if only a single dynamic load application (blow) would be considered. For this reason an analysis type has been developed which analyzes several blows in sequence using the stress state in pile and soil at the end of one blow as the initial condition of the next blow. At the same time, the degradation of the shaft resistance caused by dynamic effects is considered. The result of this combined analysis is a simulated load set curve which consists of several cycles as it is also often generated in an actual static load test. The paper explains details of this analysis and demonstrates it with three example cases.

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Introduction

Engineers in many countries analyze dynamic pile testing records with CAPWAP (GRL, 1993). The analyzed records include pile top force and velocity acquired by means of a Pile Driving Analyzer during pile driving or dynamic load testing to evaluate hammer performance, pile stresses and shaft integrity. The analysis results also yield resistance parameters which can be used for the prediction of static bearing behavior including its immediate load-settlement curve. The procedure is equivalent to a system identification which, given the measured input (impact forces) and response (pile motion) of the pile under a hammer blow, identifies certain soil model parameters. Although the soil model has been greatly expanded beyond Smith's, 1960 original proposal for wave equation analysis, it still contains a static and a dynamic component which are represented by an elasto-plastic spring and a nearly linear dashpot, respectively. The sum of all shaft and toe static resistance equals the total pile bearing capacity.

Drilled shafts are always tested some time after the installation to allow for concrete hardening. When the objective of dynamic testing on impact driven piles is the prediction of long term static bearing capacity, then restrike tests are usually performed. Dynamic effects during pile installation alter the soil resistance, however, after a sufficient waiting time it may be assumed that long term resistance components are present in the beginning of the dynamic test. Restrike tests must be performed with enough hammer energy to activate the shaft resistance and end bearing. However, often the hammer energy is relatively low under the first few hammer blows as the pile cushion is seated and the hammer warmed up, or to prevent pile damage. Thus, appreciable dynamic motions at the pile toe may only occur with later blows while earlier blows may have already altered the soil resistance at upper soil layers. Under certain circumstances the end bearing forces may even build up beyond long term values and then again relax after driving is finished.

Traditional wave equation and standard CAPWAP analyses consider pile and soil stresses as zero at the first instant of hammer impact. It is known, however, that stresses remain locked into pile and soil after the impact is finished. For this reason an important improvement of the standard Smith approach has been the Residual Stress Analysis (RSA). Considering a series of impacts of equal intensities and soil conditions which stay practically constant from blow to blow, the RSA approximately calculates stresses remaining locked into pile and soil between hammer blows. It has been shown by Holloway et al. (1978) and Hery (1983) that consideration of residual stresses improve results from the traditional Smith wave equation approach.

The CAPWAP RSA option gives satisfactory results for most end-of-driving situations where soil conditions remain unchanged between hammer blows and the hammer performs uniformly. An example of an exception would be a pile suddenly encountering rock. Then during the seating of the pile, the driving resistance would increase from blow to blow and the standard RSA would not be representative for any one blow. During restrike testing after a waiting period, since both hammer impacts and soil resistance vary from blow to blow, an RSA cannot be used to represent the early part of this test. This paper addresses the improved modeling of a series of variable hammer blows by "Multiple Blow Analysis (MBA)" with consideration of the residual stresses in pile and soil.

Multiple Blow Analysis (MBA)

A stable situation for blow after blow may be analyzed by a traditional RSA. However, for a meaningful MBA, records must be available which represent either a variable energy, a variable total resistance and/or resistance distribution, or both.

The MBA starts with the first blow assuming a zero stress state, a soil resistance model from standard CAPWAP, and one of the measured signals (force or velocity) imposed on the pile top as a top boundary condition. An RSA for the first record prior to MBA may sometimes be desirable. As in RSA, after the first record is analyzed, a static analysis is performed that determines a static equilibrium condition of the residual stresses. The dynamic and static analysis of the second and later records follow. For each record analyzed, a comparison of the second measured signal with the corresponding computed pile top quantities allows for the calculation of a match quality (MQ) number representing the difference between computed and measured curves, lower MQ values suggest better solutions.

An RSA is a repetitive analysis of the same record. Therefore both pile penetration per blow and elastic pile compression should be identical for each repetitive analysis. If the compression from blow to blow is constant, then RSA convergence has been achieved. In CAPWAP and GRLWEAP a constant penetration value (typically the permanent pile top penetration achieved under one blow) is subtracted from displacement values of all pile segments after each individual static analysis. If convergence has been achieved, this subtracted penetration amount can be compared with the pile penetration per blow. In contrast, since each record may be different in MBA, the displacements of the individual blows cannot be reduced by a constant amount and a convergence check is irrelevant.

Unknowns

Suppose that records of 5 sequential blows are analyzed by CAPWAP. If there is one toe resistance and if the shaft resistance is represented by 10 "soil segments" (typical for a 20 m long pile) and if each resistance force is represented by three unknowns (one ultimate capacity, one quake and one damping factor), then there are 5 blows times 3 variables times 11 resistances or a total of 165 unknowns. In order to reduce the unknowns of the MBA it is assumed that

(a) Damping constants, j_i, and quakes, q_i, do not change from blow to blow.

(b) Ultimate shaft resistance forces, R_{ui}, can degrade monotonically during a restrike, *i.e.*, they can only decrease during a blow but cannot increase between blows.

(c) The ultimate end bearing remains constant throughout the analysis.

The first condition (a) was implied by normal CAPWAP analyses and is equivalent to the SIMBAT approach of Paquet (1988). However, SIMBAT does not consider the distribution of resistance forces, the residual stresses and the shaft resistance degradation.

The second condition (b) allows for the opposite of soil setup, *i.e.*, as the static resistance (which can vary along the pile) is subjected to dynamic motions it can decrease during restrike to a level which is determined by the signal matching of all blows. It is assumed by MBA, that the ultimate soil resistance at segment i is maximum in the beginning of the first blow and that it is then equal to the capacity, R_{ui}. If the waiting time between initial pile installation and dynamic restrike test was long enough then R_{ui} is the long term pile capacity. The degraded ultimate shaft resistance, R_{dui}, of soil segment i is calculated from the long term capacity, R_{ui}, as follows.

$$R_{dui} = R_{ui} \quad \text{for:} \quad u_i \leq q_i$$

$$R_{dui} = f_{ti}\, R_{ui} \quad \text{for:} \quad q_i < u_i \leq 2q_i \qquad (1)$$

$$R_{dui} = f_{ri}\, R_{ui} \quad \text{for:} \quad 2q_i < u_i$$

where u_i is the accumulated pile displacement of all blows analyzed. The capacity reduction factor, f_{ri}, $(0 \leq f_{ri} \leq 1)$, is the lowest degree to which the capacity R_{ui} can degrade. A temporary degradation $f_{ri} \leq f_{ti} \leq 1$, is computed from u_i according to:

$$f_{ti} = 1 - (1 - f_{ri})(u_i/q_i - 1) \quad \text{for:} \quad q_i \leq u_i \leq 2q_i \qquad (2)$$

This relationship is schematically represented in Figure 1. Obviously, the assumption that the capacity degrades fully within the displacement $2q_i$ is arbitrary and may need adjustment after sufficient experience has been gained or depending on soil type.

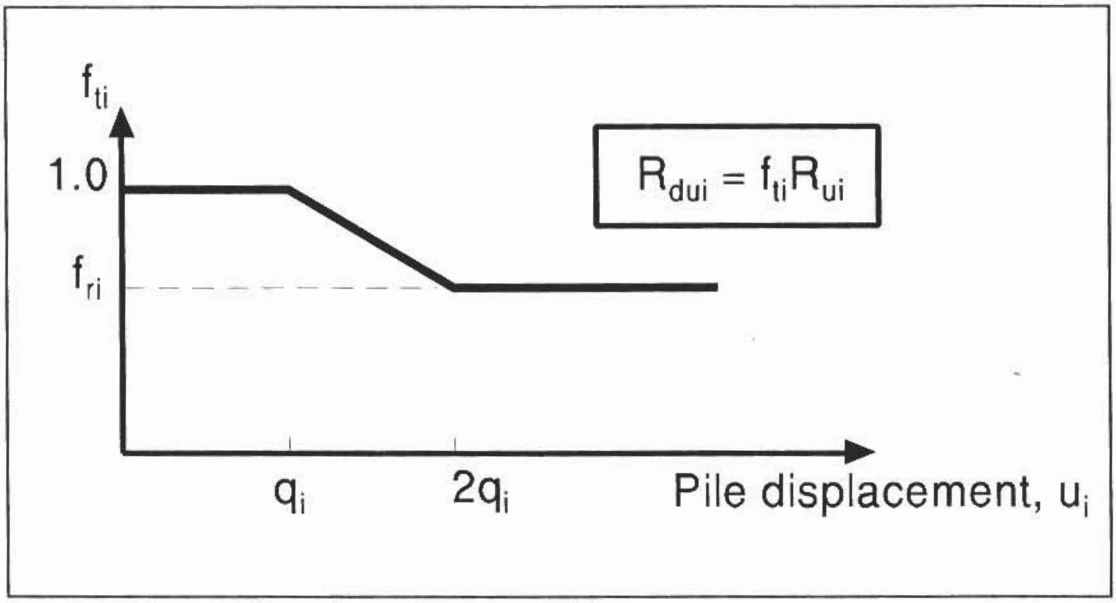

Figure 1: Resistance degradation model

The CAPWAP analysis of a series of blows is performed by a trial matching. However, CAPWAP normally considers each record separately, allowing for different results from blow to blow. MBA adds more "knowns" (by adding more records) while adding as the only unknown the resistance reduction factors. However, the match quality generally is not as good for MBA as for a single blow individually analyzed by the traditional CAPWAP analysis. Obviously, if individual damping factors and quakes are assigned to each blow analyzed, then the signal matching can be improved. However, rather than a detailed matching of one individual record, the important general features of all records are represented by MBA. The average parameters thus calculated may also be more representative in a wave equation analysis which only represents an average pile and soil behavior.

As for condition (c), there are probably cases which would benefit from variable end bearing to reflect a true capacity gain due to pile penetration or soil densification. Furthermore, relaxation of the toe resistance could be represented. This feature would be easily added to MBA, however, it would increase the number of unknowns. However, it is expected that it would be extremely difficult to distinguish a progressively higher activation of capacity from either a true gain or a temporary increase of end bearing.

Procedure

MBA requires the selection of a series of records, measured under successive hammer blows. A traditional CAPWAP matching of the final blow of the series (often this would be the blow with the highest energy) might precede the analysis of the combined set of blows. Damping factors, quakes, unloading parameters, and most importantly capacity values and capacity reduction factors (initially assumed to be 1) are adjusted to yield a satisfactory match of all blows in the series. The signal match of the last blow would be presented in the final results. Its match would be less satisfactory than obtained from the standard CAPWAP analysis.

As the final important step in MBA, the final load set curve using pile stiffnesses, ultimate resistance values and quakes from CAPWAP are calculated. As in a traditional CAPWAP, to calculate this primary settlement curve, the dynamically calculated pile toe displacements are used as a boundary condition and the corresponding pile top forces and displacements are calculated. For the static analysis it is assumed that the soil resistance degradation does not occur even though relatively large sets may be activated. This assumption could be modified since it is known that certain sensitive soils do, in fact, degrade during the static load application. (This phenomenon is called progressive failure.)

Examples

Three examples are presented to demonstrate the benefits and limitations of MBA. The examples were selected to cover three different pile types: a steel H-pile, a prestressed concrete pile and an auger cast pile. The basic pile properties are included in Table 1. Soil types were silty sand over marl for the first two piles and dense sand over silty and clayey sand in the third example. For the first two test piles static load tests indicated approximate failure loads of 1420 and 5120 kN, respectively. Single blow CAPWAP analyses yielded capacities of 1520, 3900 and 2440 kN, for the three piles (see Table 1). The low prediction of the prestressed pile was attributed to incomplete capacity activation as evidenced by very small sets per blow (less than 1 mm per blow). A static load test was not performed for the drilled shaft.

The H-pile was driven and tested with a Vulcan 512 air/steam hammer (53 kN ram weight, 81 kJ rated energy); the hammer transferred only 12 kJ to the pile with the first blow, however, it transferred as much as 31 kJ (38% of rating) with the fifth blow. Seven consecutive blows were analyzed. For these 7 blows CAPWAP indicated a best overall match with a maximum initial capacity of 1540 kN decaying to 1350 kN by the end of the second blow. It remained constant thereafter. For the 12 soil segments of 2 m length each,

Table 1: MBA Results of Example Cases and Comparison with Standard CAPWAP and Load Test			
Test or MBA Blow No.	End of Blow Activated Capacity kN	Reduced Capacity kN	Transferred Energy kJ
Case 1 HP 14x73; L = 24 m			
Loadtest	1420 1520	(blow 7)	
1	1480	1400	12
2	1380	1350	19
3	1350	1350	20
4	1350	1350	28
5	1350	1350	31
6	1350	1350	27
7	1350	1350	25
Case 2 24" PPSC; L = 26.5 m			
Loadtest	5120 3900	(blow 2)	
1	4740	5170	26
2	4750	4620	41
3	4370	3970	43
4	3960	3950	43
5	3950	3950	43
6	3950	3950	43
7	3950	3950	45
8	3950	3950	47
9	3950	3950	46
Case 3 16"dia. Shaft; L = 19.2 m			
Loadtest	N/A 2440	(blow 5)	
1	1140	2780	12
2	1630	2740	19
3	1890	2270	28
4	1830	1870	36
5	1860	1860	53

the reduction factors, f_{ri}, decreased linearly from .95 at the top segment to .85 at the bottom of the pile. For example, the ultimate resistances at the sixth and twelfth (bottom) segment were 31 and 263 kN, respectively, at the beginning of the Multiple Blow Analysis. After the second blow, full capacity reduction had occurred because the total displacements had exceeded twice the quake value of 3.8 mm (.15 inches). With respective reduction factors of 0.90 and 0.85, the ultimate resistances at these two segments had then decreased to 28 and 223 kN, respectively. The total capacity then was reduced from 1540 (347) to 1350 kN (304 kips).

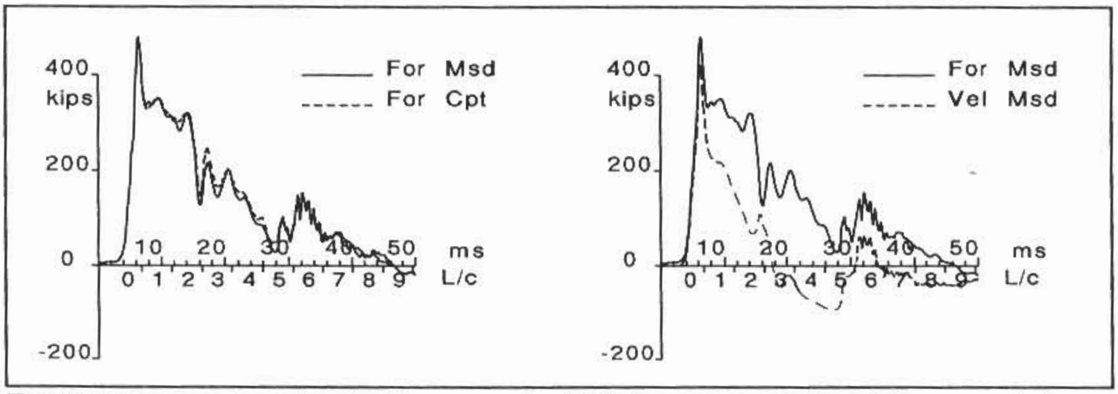

Figure 2: Force and velocity records (right) and associated force match; 1 kip = 4.45 kN.

Figure 2 shows the CAPWAP force match for the last blow analyzed and the corresponding, measured force and velocity curves. The simulated static load tests from all seven blows analyzed were plotted together in Figure 3. Obviously, in this example the standard CAPWAP capacity and the total initial MBA capacity were rather similar. It is expected that most test results, with early activation of the total shaft resistance would fall under this category of tests, *i.e.*, the traditional CAPWAP would be satisfactory.

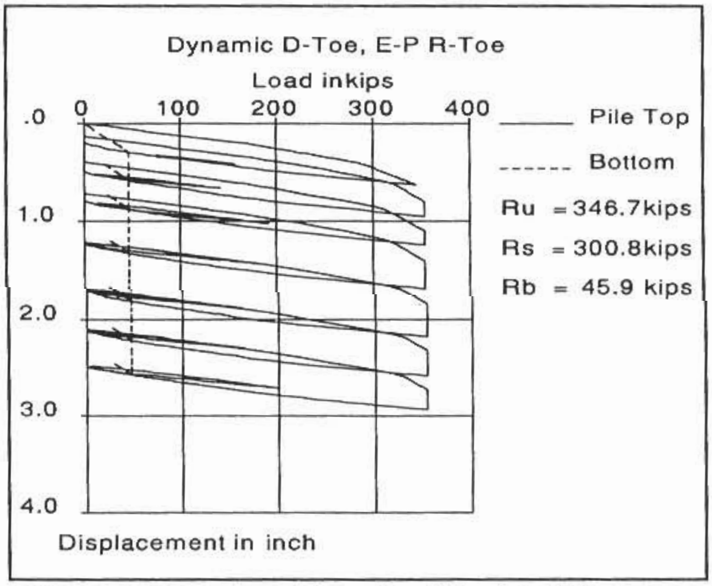

Figure 3: Simulated load test for H-pile; 1 inch = 25.4 mm; 1 kip = 4.45 kN.

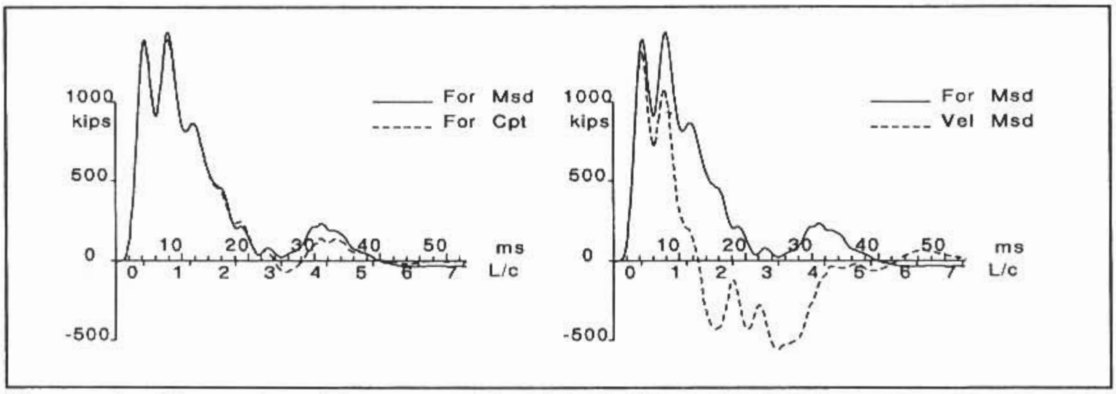

Figure 4: Record and force match of last blow analyzed of 24" PSC pile; 1 kip = 4.45 kN.

The 24 inch PSC pile was tested with a Vulcan 520 air hammer (89 kN ram weight, 136 kJ rated energy). Nine blows were analyzed having relatively uniform transferred energies between 41 and 47 kJ (30 to 35%) except for the first blow of restrike transferring only 26 kJ. Signal match and recorded signals of the last blow analyzed are shown in Figure 4. Figure 5 shows the static simulation analysis for all 9 blows in sequence. The maximum analyzed capacity of 5330 kN (1197 kips) was only present during the first hammer blow. However, this high capacity was never fully activated since capacity reduction in upper soil layers took place already during the first blow while the lower soil layers had not yet been fully loaded to failure. The fourth hammer blow was able to fully activate the remaining soil resistance, however, at that time the capacity was already reduced to 3950 kN. The capacity reduction factors, f_{ri}, varied (from top to bottom) between .65 and .70. This example indicates why the low energy single blow CAPWAP analysis underpredicted: either the capacity is not fully activated by lack of energy for the early blows and/or the capacity of later blows is already degraded by the earlier blows. Please note that Table 1 may indicate for the same blow an activated capacity greater than the reduced ultimate capacity if the reduction occurred during the blow after the higher capacity had been activated (see also Figure 1).

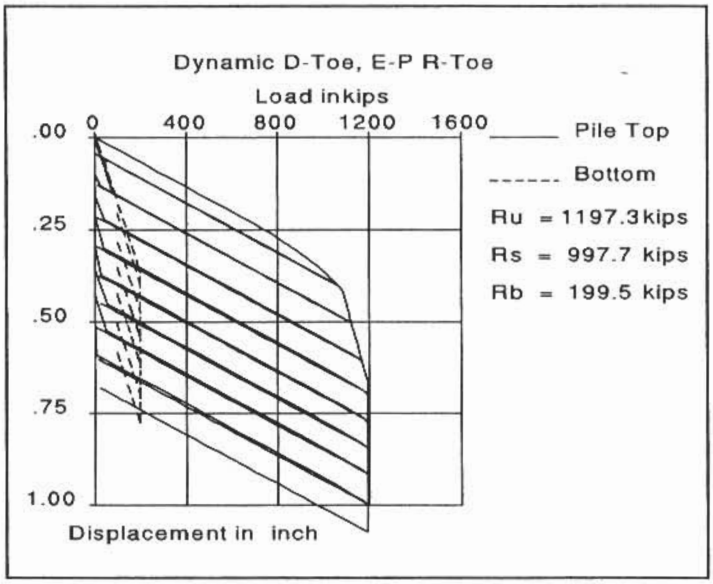

Figure 5: Simulated load test for 24" PSC pile; 1 kip = 4.45 kN; 1 inch = 25.4 mm.

The third example presents results from a dynamic load test performed on a 400 mm (16 inch) diameter auger cast pile. As has become standard practice to improve the reliability of strain readings, four strain transducers and four accelerometers were attached to the exposed pile section approximately 1 m below the pile top. A guided 54 kN (12.2 kips) ram applied the test blows to the shaft top which was protected by a 50 mm (2 inch) thick steel striker plate and a 150 mm (6 inch) thick plywood cushion. Ignoring an initial test blow with very low energy, fall heights were increased from .6 to 2.1 m (2 ft to 7 ft), thus providing potential energies from 33 to 113 kJ (24.4 to 85 kip-ft). The corresponding transferred energies ranged from 12 to 53 kJ or 36 to 46% of the available energy. Figures 6 and 7 show force and velocity records and force matches of the first and the last blow analyzed. Note the high force at impact, relative to the velocity, suggesting a large shaft resistance in the upper pile segments.

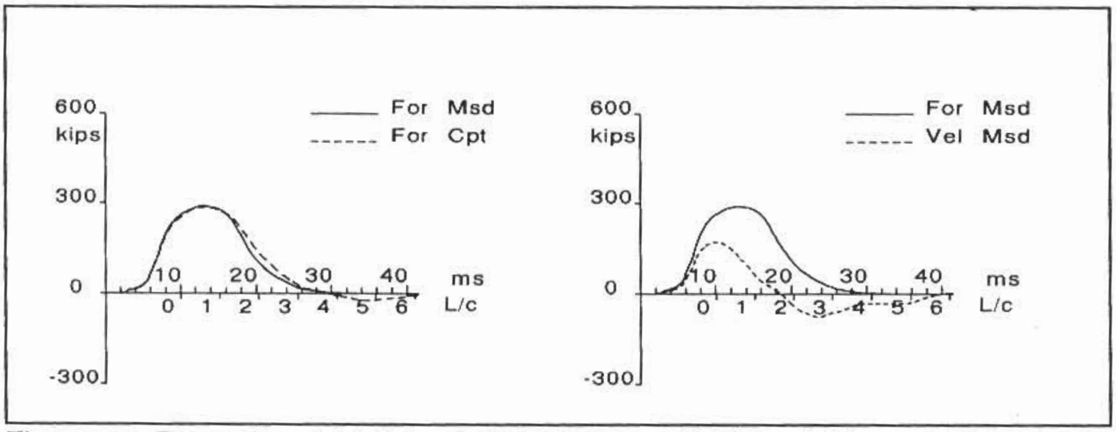

Figure 6: Record and Match of first drilled shaft blow; 1 kip = 4.45 kN.

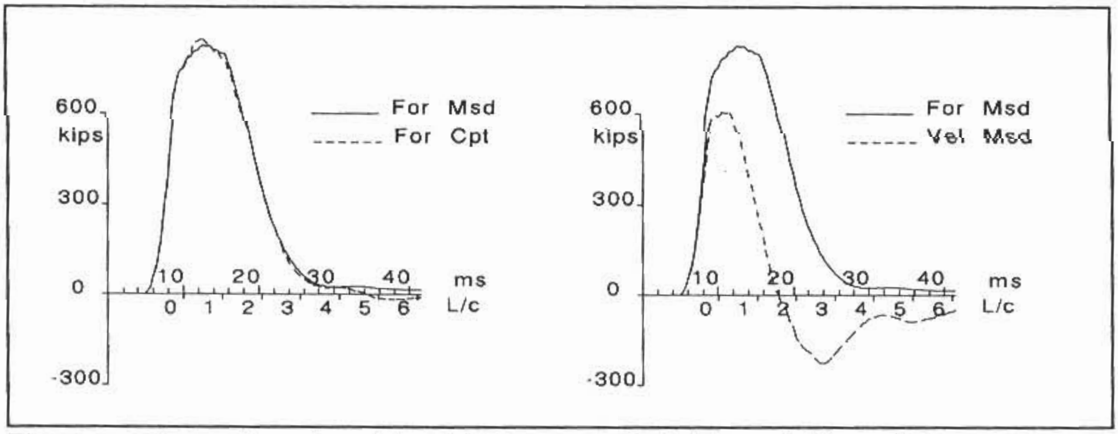

Figure 7: Record and match of last drilled shaft blow; 1 kip = 4.45 kN.

The solution was achieved by assigning capacity reduction factors between 0.5 and 0.6 to all shaft resistance values. The total capacity analyzed under the first blow was 2780 kN, however, only 1140 kN were activated under this first blow. Only the last blow activated the capacity which was then reduced to 1860 kN. Figure 8 and Table 1 show very clearly that most test blows activated only a fraction of the predicted capacity.

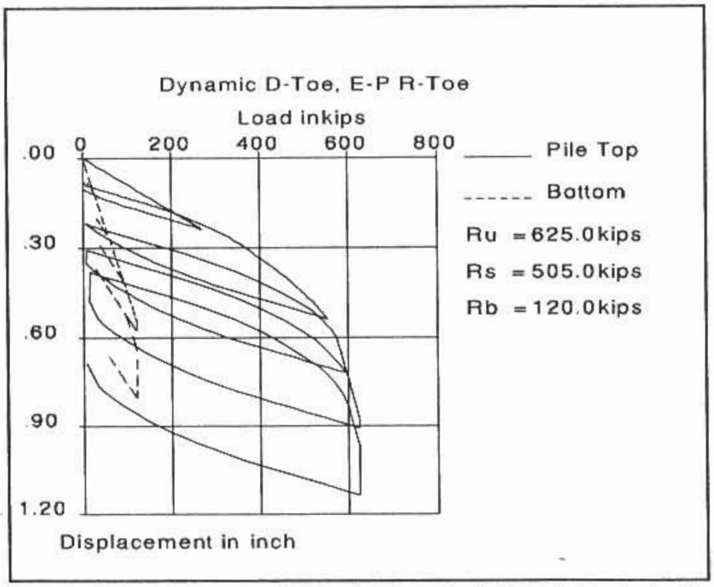

Figure 8: Simulated load test result for drilled shaft; 1 inch= 25.4 mm; 1 kip = 4.45 kN.

Summary

An extension and improvement of the model and procedure for CAPWAP has been presented. This work was necessary since CAPWAP traditionally analyzes only a single blow at one time and ignores the history of residual stresses and soil resistance degradation during testing. The new Multiple Blow Analysis (MBA) method allows for the analysis of up to 10 consecutive hammer blows taken under conditions of variable energy and a static resistance that degrades during the restrike. Such conditions often occur during restrike testing or when drilled shafts are dynamically tested. If the records of the successive blows were nearly identical such as at the end of driving, then the results of MBA would be very similar to those of the standard CAPWAP analysis or CAPWAP with RSA.

The Multiple Blow Analysis considers the residual stresses remaining in the test piles between individual blows. It has been demonstrated that MBA yields reasonably realistic static load-set curves, which include the effects of variable energy of the individual blows analyzed. These static load-set curves were calculated under the assumption of a constant capacity, *i.e.*, a capacity which does not degrade during the static test. It is, however, known that very sensitive soils do indeed lose capacity during static testing, an effect that is sometimes referred to as a progressive failure.

Improvements of this method may be possible if increasing end bearing values from blow to blow would be permitted, representing either the case of an improving end bearing or a temporary gain of capacity which could relax after pile installation or testing. However, it is expected that it would be difficult to extract this information by MBA since during times of early restrike or drilled shaft testing the mobilized end bearing is generally less than ultimate. Therefore, during restrike testing, activated end bearing progressively increases. It is expected that MBA would not allow for a clear distinction between improved resistance activation and either a true or only a temporary increase of the pile toe bearing capacity.

The MBA method has to be cautiously applied particularly when relatively large shaft resistances in the upper layers appear to degrade rapidly. It must be expected that this capacity component degrades even during static applications and therefore does not necessarily contribute to the ultimate pile static capacity. Also, as with all dynamic test results, long term effects such as creep or consolidation are not considered by MBA.

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