Application of Pile Driving Analyzer (PDA) and CAPWAP Analysis to Bearing Capacity of Piles

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ABSTRACT

This paper presents briefly the application of dynamic pile testing to bearing capacity determination of a pile embedded in loose to compact sand and silt layers. The possibility of liquefaction of the loose layers as a result of cyclic loads such as earthquake, and therefore, reduction in shaft resistance of the pile are investigated. The Pile Driving Analyzer (PDA) was used for dynamic testing of the pile during driving by the hammer. The data was then further evaluated by the rigorous numerical analysis program CAPWAP to determine the static bearing capacity, and to distinguish between the toe resistance and the distribution of the shaft resistance along the pile. The results at the end of driving and also after a 30-minute wait indicated that the shaft resistance had gained an additional strength of 42% as a result of soil set up.

INTRODUCTION

Piles are vertical or slightly inclined, relatively slender structural foundation members (Fellenius 1990). They transmit loads from the superstructure to the soil layers. Design of pile foundations consists of three parts: bearing capacity, strength of the pile material, and settlement requirements. Bearing capacity or ultimate load of a pile consists of a combination of shaft and toe resistance that develop in response to axial loading. Design for capacity consists of determining the allowable load on the pile by dividing the capacity with a factor of safety.

Adequate determination of bearing capacity of pile foundations plays an important role in the safety, cost-effectiveness, and reliability of such systems. The bearing capacity is often difficult to assess even by means of a static loading test. The traditional methods rely on the estimation of toe and shaft resistance using theoretical soil parameters. For example, α and β methods have been used for determination of shaft resistance of piles on the basis of total stress analysis and effective stress analysis, respectively, as described by Fellenius (1991). There are other methods directly linked to in-situ testing such as Standard Penetration Testing (SPT), vane shear testing, and Cone Penetrometer Testing (CPT). CPT is the one that most directly correlates to a pile, as described in detail by Eslami

(1996), however, scale effects and other factors generally influence the correlation. All these methods are theoretical and their results often differ from actual site conditions, which traditionally caused designers to require larger factor of safety and costly load tests. A considerable amount of saving would be possible for projects involving a large number of piles, if we can more accurately and reliably estimate the bearing capacity of piles, and thus reduce the required factor of safety.

The axial compression testing of a vertical pile is the most common full-scale test performed. These tests are mostly referred to as static load tests. Such tests are time consuming and expensive. Therefore, they are not cost-effective, especially in small projects. Moreover, for large capacity piles and offshore environments the static load tests are practically very difficult to perform.

The wave equation analysis for driven piles provides a direct means of correlating the bearing capacity of a pile with observed penetration resistance. In impacting a pile, a short-duration force wave is induced, giving the pile a downward velocity and resulting in a small penetration of the pile. Obviously, the larger the number of blows necessary to achieve a certain penetration, the stronger the soil.

The full power of the wave equation analysis is only realized when combined with dynamic measurements during pile driving by means of transducers attached below the pile head. The impact by the pile-driving hammer produces strain and acceleration in the pile, which are picked up by the transducers and transmitted via a cable to a data acquisition unit, the Pile Driving Analyzer (PDA) as shown in Figs. 1 and 2 (PAK Users Manual, 1997). The acquisition translates strain and acceleration measurements into force and velocity, displaying these graphically on computer screen. Simultaneously and blow for blow, the energy transferred to the pile is calculated and an estimation is obtained of the bearing capacity of the pile. Correlation with static load tests have shown generally good agreement and in many cases the PDA has routinely reduced (or replaced) static testing.

The preliminary estimates of activated bearing capacity during driving obtained directly from PDA are called CASE Method. CASE Method estimates suitable for the general pile-soil combination are readily available on site. Detailed modeling by CASE Pile Wave Analysis Program (CAPWAP) on selected record is required to determine the most representative CASE Method for the tested piles and to verify the activated bearing capacity. CAPWAP combines measured force and velocity data with wave equation analysis to calculate the soil resistance forces acting on the pile. Because force and velocity measurements are the pile top input excitation, it is not necessary to model the hammer and driving system as in a wave equation analysis. CAPWAP (GRL 1996) models the pile as a series of continuous and uniform segments. Each segment is of uniform cross-section but segments may be different from each other (for modeling non-uniform piles). A soil model similar to Smith's wave equation model (Smith 1960) is assumed, which includes the total resistance and its distribution, damping constants, and quakes. Figure 3 shows a simplified illustration of the CAPWAP soil model for a single segment along the pile shaft. A similar model is used for the toe segment.

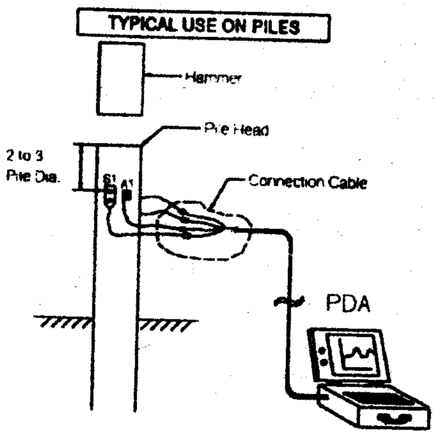

Fig. 1 Schematic of PDA testing system

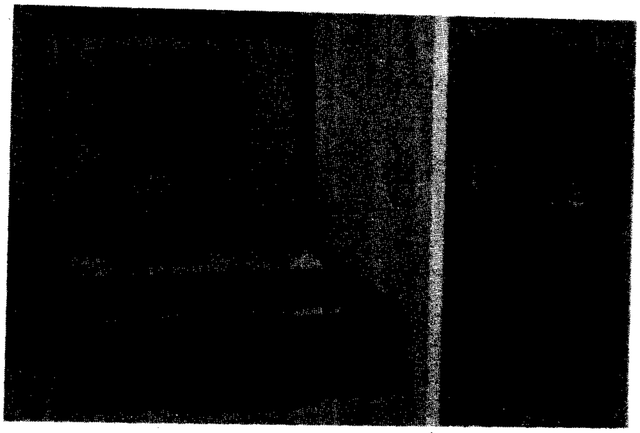

Fig. 2 PDA unit (PAK Model) and gages

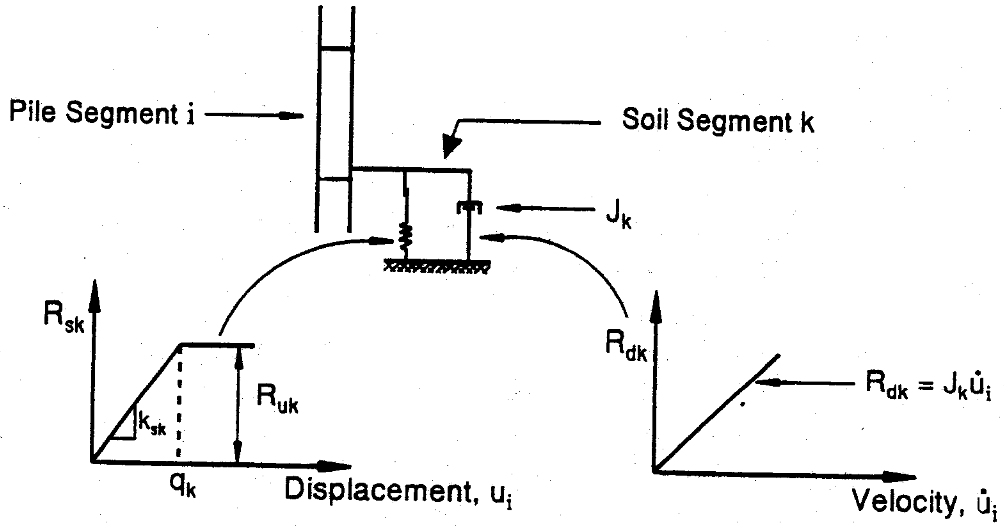

Figure 3. Smith soil resistance model

CAPWAP results are based on the best possible match between a computed pile top variable (e.g. the pile top force) and its measured equivalent. When the match is unsatisfactory, the process of iterations of changing the soil resistance parameters and computing the pile top variable is repeated.

There are several other applications of PDA results as follows:

- Pile Stresses: Measurement of maximum compression force and stress shows if damage to the pile top is likely. Concrete piles are particularly susceptible to damage from tensile stresses during driving.
- Pile integrity: All piles can be investigated for early tension wave reflections caused by pile damage. Low strain testing may be used for rapid testing of a large number of concrete piles or drilled shafts each day. Low strain tests are performed with a small impact device such as a hand-held hammer, a sensitive accelerometer, and Pile Integrity Tester (PIT).
- Hammer Performance: The PDA results can be used to qualify pile driving equipment.

The present paper focuses on presentation of PDA results and also CAPWAP analysis of an index test in a two-lane bridge project in Vancouver, Canada, conducted by AATech Scientific Inc. All the results are presented for a sample pile both during initial driving and also at re-strike after a 30-minute wait at final penetration.

FIELD CONDITIONS AND TEST PROGRAM

The project involved the design of a two-lane bridge to replace the existing single-lane in Vancouver, Canada. The bridge was about 100 m long supported by six piers. Each pier was supported on four steel pipe piles, 610 mm in diameter with a 12.7-mm wall thickness. The piles were closed toe, and were driven to a dense layer at a depth of about 15 to 16 m. The soil at the site location consists mainly of loose to compact sand and silt layers. The contractor was investigating the possibility of using the existing foundation piles to support the larger structure. A potential for liquefaction in the fine sand and silt layers under earthquake loading was suspected.

With the new specifications and standards for earthquake design, a detailed analysis was required for liquefaction potential along the shaft of existing foundation piles to assess the residual capacity under earthquake loading. The designers retained by the contractor required that a test pile similar to the existing ones be driven to the same depth, while monitored using dynamic testing equipment, near one of the piers. The main objective of the test was to evaluate the bearing resistance at the pile toe, which was seated in a dense sand layer, and the distribution of shaft resistance in order to estimate the loss of capacity during earthquake in the liquefiable layers. AATech Scientific Inc. was retained by the contractor upon the recommendation of the designer to perform dynamic testing during initial driving of a test pile (TP1) adjacent to Pier 6, on the south side of the bridge. The test pile was approximately one meter south of Pier 6. The pile was driven to an embedment depth of about 15.25 m. It was left for 30 minutes to allow for some soil set-up, and then it was driven further to an embedment depth of about 15.55 m. The pile was subjected to dynamic monitoring throughout the driving. A 29.8 kN drop hammer was used to drive the test pile.

RESULTS AND DISCUSSION

Two dynamic records from hammer blows at an embedment depth of 15.25 m were selected for presenting in this paper:

1. Blow No. 894 from end of driving, just before the 30-minute wait time.

2. Blow No. 896 that was the first hammer blow delivered when driving was resumed after the wait time.

A CAPWAP analysis performed for Blow #894 (before the 30-minute wait time) showed a mobilized static resistance of about 1,435 kN of which a shaft resistance of 640 kN and a toe resistance of 795 kN are computed. A CAPWAP analysis performed on Blow #896 (restrike after the 30-minute wait time) showed a mobilized static resistance of about 1,743 kN with a shaft resistance of 906 kN and a toe resistance of 837 kN.

In comparison with the restrike CAPWAP analysis (Blow #896), slightly higher damping factors and higher quakes were computed, especially for the pile shaft. This is expected after set-up in most soils.

CAPWAP analysis results are summarized in Table 1. Values of RMX CASE Method estimates with J-factor of 0.4 and 0.5 and RA2 (damping independent method), along with other PDA data (transferred energy, driving stresses, ...) for both hammer blow records are presented in Table 2. In general, the energy transferred to the pile head was about 60 to 65 % of the hammer input at 2.2 m drop height, which is normal behavior with drop hammers.

The driving profile recorded during testing of TP1 is presented in Figure 4. Values of blow count, driving stresses, energy, maximum force, and Case Method Estimate of capacity, are plotted against the embedment depth (penetration) of the pile. Note that RMX CASE Method with 0.4 J-factor is used in the plot. This may not be the exact pile capacity at some penetration depths, however, it describes the relative variation in measured static resistance with embedment depth. Some uneven hammer blows caused by swinging leads are reflected in the driving stress records as spikes, however, driving stresses were maintained within acceptable limits as shown in Figure 4. At embedment depth of about 13.7 m (45 ft), the helmet follower broke off. This also caused spikes in the stresses and CASE Method estimate records. The analyzed blows were selected from a set of blows obtained by stabilizing the leads after each blow and dropping the ram on the centered helmet plate.

A significant increase in measured static resistance was observed after a 30-minute wait period. More increase may be observed after a longer wait period depending on the amount of fines in the soil at the pile location. As indicated in Table 1, the toe resistance increased only 42 kN from 795 kN up to 837 kN at the end of driving and after the 30-minute wait period. On the other hand, the shaft resistance increased by 266 kN that was a considerable increase before and after the 30-minute period. This is an

Table 1: CAPWAP analysis summary

Pile	Blow	Computed resistance (kN)			Smith damping (s/m)		Quake (mm)	
No.	No.	**Total**	Shaft	Toe	Shaft	Toe	Shaft	Toe
TP1	894	**1,435**	640	795	0.80	0.30	2.0	13.0
TP1	896	**1,743**	906	837	0.75	0.29	1.0	11.0

Table 2: PDA Data

Pile	Blow	Total Len.	Emb. Len.	Hammer	EMX	FMX	CSX	CSB	PRES	CASE Method estimates (kN)			CAPWAP
No.	No.	m	m	Drop (m)	kJ	kN	MPa	MPa	Bl./25 mm	RX4	RX5	RA2	kN
TP1	894	18.55	15.25	2.2	40.9	3,920	138	39	2	1,470	1,380	1,830	1,435
TP1	896	18.55	15.25	2.2	39.5	3,350	141	43	3	1,830	1,510	1,980	1,743

Total Len. Total length of the pile at the time of testing
Emb. Len Embedment Length at the time of testing
EMX Maximum energy transferred to the pile head
FMX Maximum force measured
CSX Maximum compressive stress
CSB Compued compressive stress near the pile toe
PRES Penetration resistance (Blows per 25 mm)
RX#/RS# RMX / RSP CASE Method with a J-Factor of #

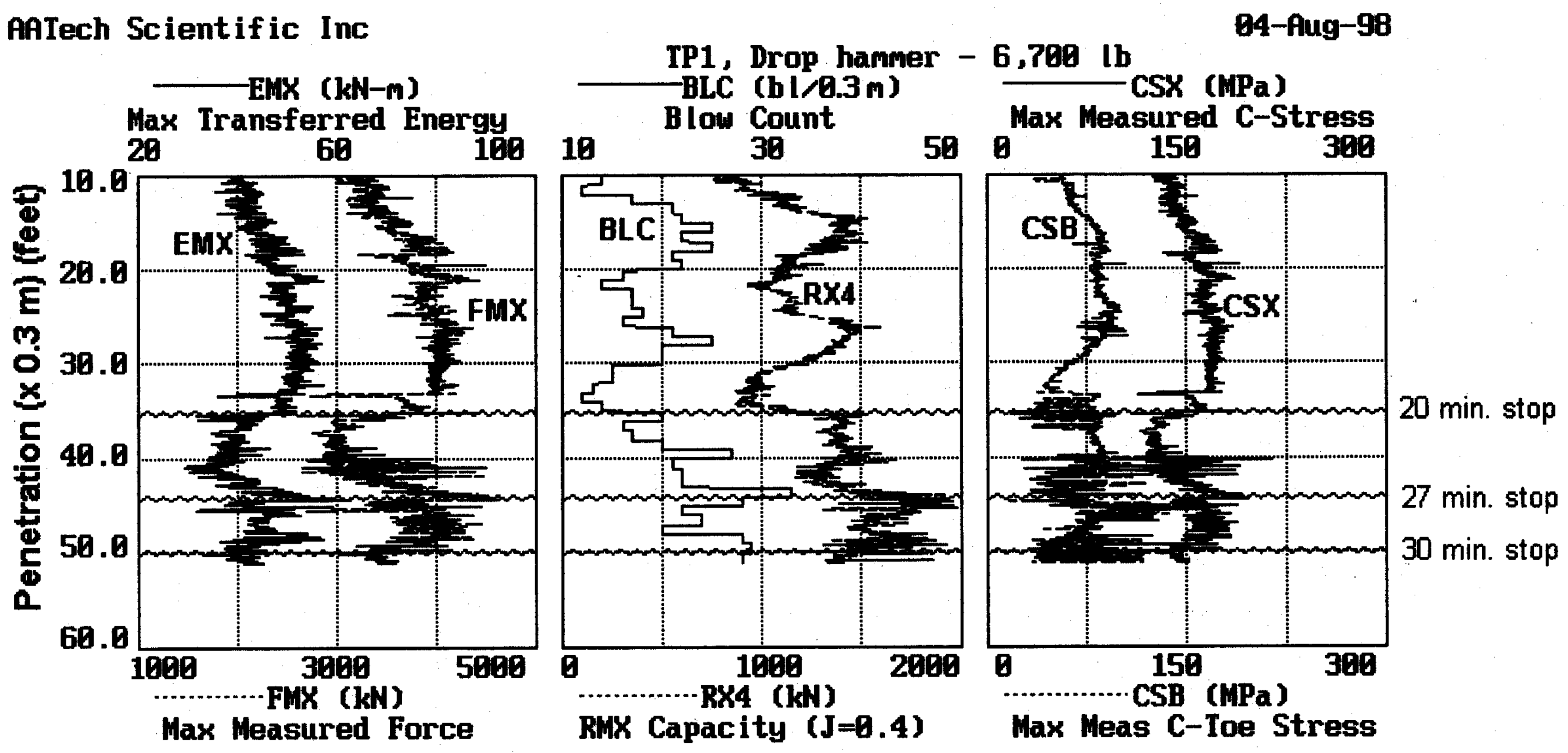

Figure 4: Driving profiles, Pile TP1

indication of liquefiability of the surrounding soil. The toe resistance did not increase much as a result of the soil set-up as the pile toe was driven to a dense sand which would hardly gain strength during set-up time.

Figure 5 presents the PDA and CAPWAP force and velocity results for Blow #894 before the 30-minute wait period. The PDA and CAPWAP methods are based on travelling waves. A force (hammer impact) suddenly applied to the end of a rod (pile) creates a stress wave which travels along the pile at a constant speed (e.g. 5,123 m/s for steel). Thus, the toe of a steel pile of 18.5 m length, struck at time zero, starts to move 3.6 ms later. If the pile toe motion is restricted, a resistance force generates a stress wave. In this example, the toe resistance stress wave arrives at the pile top 7.2 ms after the initial impact. As shown in top right of Fig. 5, the force was applied to the top of the pile at time 6 ms, and arrived at the pile top at time 13.2 ms, that was 7.2 ms after the initial impact. This time is equivalent to 2L/C or the time required for stress and velocity waves to travel to the pile toe and arrive to the pile head again.

From the solution to the linear wave equation, force and velocity are proportional as long as only downward waves exist at the point of measurement. The proportionality factor between force and velocity is the pile impedance, Z=EA/c, in which "E" is the Elastic modulus of the pile, "A" is the cross section area, and "c" is the speed of wave propagation along the pile. Because of this proportionality relationship, the velocity is plotted after multiplication by Z in force units. Consider the top right of Fig. 5 with force and velocity (multiplied by the pile impedance) measured on the pile. The proportionality condition is met at the first velocity peak since no resistance wave has yet been created.

In the same figure, the wave return occurs at time 13.2 ms with a clear increase of velocity and decrease of force. Before that time, the force had gradually increased relative to the velocity. This deviation from proportionality was caused by upward traveling, compressive waves originating from the friction forces. The more rapidly the two signals deviate from each other, the greater the shaft resistance.

The lower right portion of Fig. 5 shows the CAPWAP computed shaft resistance forces. These quantities were plotted individually and as a sum of forces measured in the pile at the predicted ultimate capacity. The pile toe force equals the calculated static toe resistance. Note that the time scale of the measured curves and the length scale of the resistance distribution were chosen such that time of impact is aligned with the pile top location of the resistance plot. Similarly, time to toe wave return and pile toe location were aligned.

The top left portion of Fig. 5 presents the signal matching results of CAPWAP analysis. The measured force wave by PDA device is plotted by solid line. The dashed line indicates the computed force wave obtained by CAPWAP. This signal matching has been obtained by adjusting the various soil parameters. When the wave is well matched, then the calculated bearing capacity and its distribution along the pile shaft is well captured.

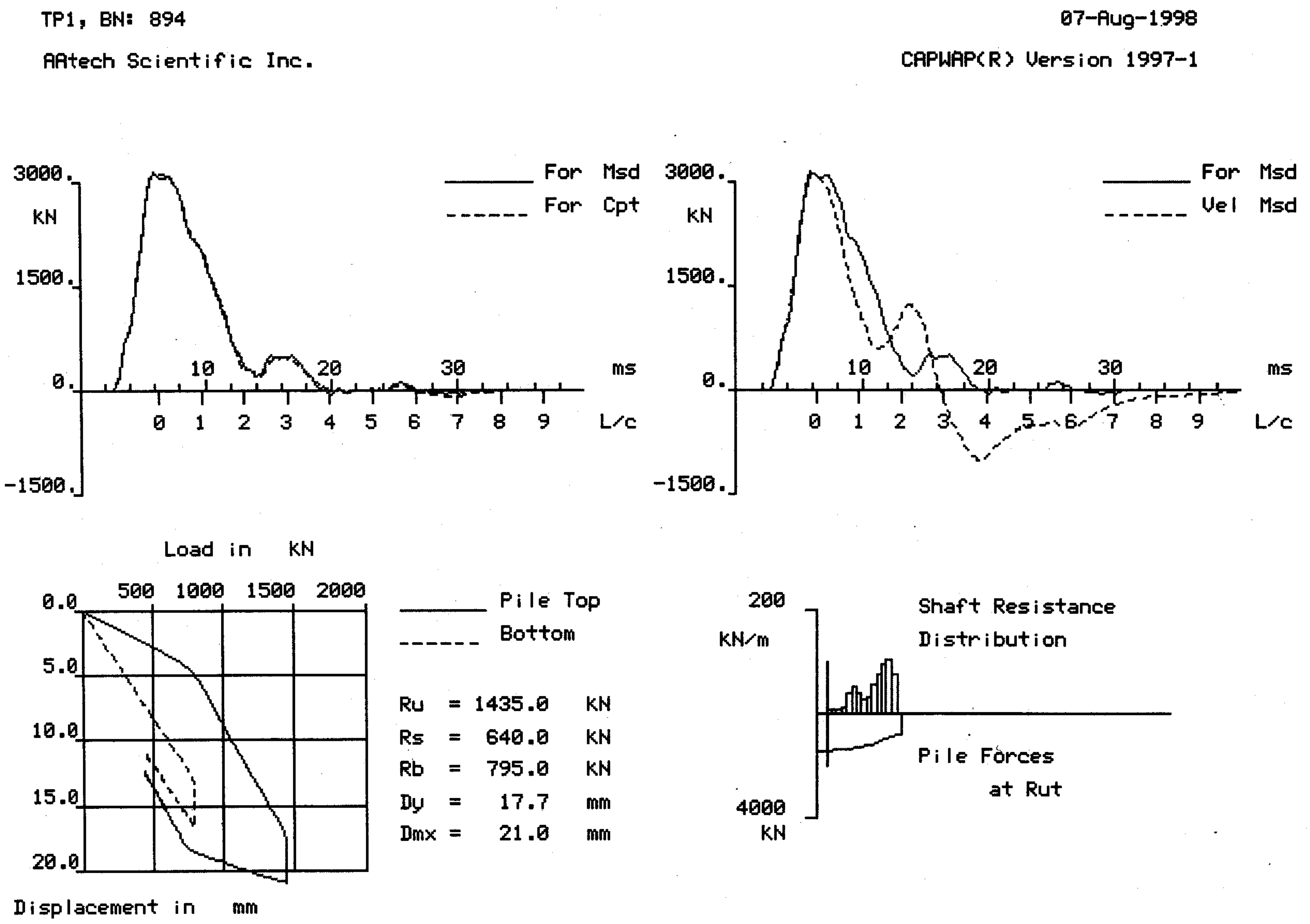

Figure 5. CAPWAP results for PT1 at the end of driving

CONCLUSIONS

Dynamic testing of piles and CAPWAP analysis have become a routine procedure with worldwide application for adequate determination of bearing capacity, integrity testing, hammer performance, and stresses in piles. The quality and reliability of the collected data and the interpretation of results are dependent on the experience level of the testing engineer. The method is adequate and reliable, cost-effective, and fast.

This paper presented a summary of the required equipment and interpretation methods of PDA testing and CAPWAP analysis. The results of dynamic testing of a typical driven pile through layers of silt and sand to be seated in a dense sand layer together with CAPWAP analysis results were presented. It was indicated that the method is capable of distinguishing between the shaft resistance and toe resistance of the pile, can capture the effects of soil set up and study the possibility of liquefaction, and also evaluate the integrity of the pile shaft.

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