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PILE DRIVING MEASUREMENTS ON THE HEATHER PLATFORM INSTALLATION

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ABSTRACT

The first leg piles of the Heather Platform were instrumented using strain transducers and accelerometers that were attached to the pile just below its top. The signals were processed in real time providing for a hammer blow a printed output of hammer energy in the pile, maximum pile top force and other quantities. The signals were also recorded on analog magnetic tape.

A detailed analysis was performed in the laboratory on a digital computer. Using wave equation type pile and soil models and both force and acceleration data, the soil resistance distribution was determined.

The Heather Platform piles were driven through two followers connected by gravity. Stress wave effects from the connectors were studied and losses to the impact wave were determined.

INTRODUCTION

The first piles driven at a new installation site provide long awaited data regarding the driveability and pile bearing capacity. Ram stroke and blow count, however, may be insufficient observations when pile driving does not proceed as expected. Then the determination of dynamic quantities such as pile stresses, hammer energy output, and soil resistance may be extremely valuable for decision making.

For this reason Unionoil Company of Great Britain contracted with the writer's firm for providing both dynamic measurement and data processing services during the initial pile driving operation at the Heather A Platform. The measurements consisted of both pile top force and acceleration. They were field processed by a Pile Driving Analyzer. This unit printed for every blow maxima of pile top force, energy, and velocity among other quantities. Also, the pile bearing capacity was determined by the Case Method (1).

The pile driving operation was rather successful; i.e., blow counts were as low as optimistic predictions. In fact, it was surprising that the blow count did not increase with depth, a characteristic behavior of friction piles. Other questions such as the efficiency of gravity connectors called for answers. Thus, a laboratory analysis of the field data was warranted. Experimental and analytical methods, results, and conclusions are described here. Results are presented in the SI unit system except for direct field observations: penetrations in feet, blow counts in blows per foot.

References and illustrations at end of paper.

BACKGROUND

General Remarks

Both instrumentation and processing methods were developed at Case Western Reserve University in Cleveland, Ohio under a grant from the Ohio Department of Transportation. The system is described in more detail in References 1 and 2; however, a short description follows.

Instrumentation

Two each accelerometers and strain transducers were attached on opposite sides of the pile for cancellation of gross bending. The accelerometers were piezoelectric with built-in amplifiers. The strain transducers were diamond-shaped, flexible aluminum frames of 3 inch (7.62 mm) gage length. Resistance strain gages were attached in points of stress concentration on these frames and formed a full Wheatstone bridge.

Figure 1 shows schematically the field measurement and processing system. The signals of the two accelerometers (a) and strain transducers (b), all attached to the pile (c) by means of quarter inch bolts, were led through a combination box (d) and signal cable (e) to a Pile Driving Analyzer (f). This unit conditioned, amplified, calibrated, and integrated the signals and then determined the following values in analog form:

(i) Maxima of force, velocity, and acceleration.

(ii) The peak value of the energy transferred into the pile.

(iii) The pile bearing capacity according to the Case Method (see next section).

Three selected quantities were printed digitally. The signals (g), see Figure 1, were also monitored on an oscilloscope (j) and stored on an analog magnetic tape (h) together with voice records (i).

Analytical Methods

(i) The Case Method uses the values of force and velocity at the time of both impact and wave return. It then determines a total bearing capacity value with consideration of an estimated soil damping contribution.

(ii) The CAPWAP method (Case Pile Wave Analysis Program) uses the velocity records as a pile top boundary condition and performs a wave equation type (3) analysis. In addition a soil resistance distribution is assumed. If this assumed resistance distribution is correct then a good agreement between measured and computed pile top force is obtained. Thus by iteratively improving the pile top force match, one finds the most likely set of soil strength parameters that produce the measured data. Further details on this method are described in Reference 4.

(iii) Energy transferred to the pile is usually computed by time integrating the product of force and velocity. For piles having sufficient length above the mudline the integration can also be done on the square of either force or velocity. For greatest accuracy the force records are preferred since they are not the result of another integration. The latter method was used for the present data.

TEST DETAILS

The tests were conducted during the final stages of driving. Both Menck hammer models used are described in Table 1(a). All three piles tested were of almost identical lengths, i.e., 96.0 meters (315 feet). Each was driven using followers of 51.8 meters (170 feet) and 61.0 meters (200 feet) in length. The total pile length under the hammer was therefore 208.8 meters (685 feet). More accurate pile dimensions are given in Table 1(b).

The transducers were installed 7.6 meters (25 feet) below the pile top (i.e. the top of the long follower). At that location neighboring pad eyes protected the gages to a certain degree. Also a 2-inch wide ring on the pile's outside just six inches below the gages was thought to provide protection. The gages were attached using quarter-inch diameter tapped holes.

The first pile, No. B5-5, was driven to final grade on May 28, 1977. Records were taken continuously under two different Menck M-8000 hammers during the last 27 meters (90 feet) of pile driving. After approximately 12 meters (40 feet) had been driven the gages on one side of the pile were sheared off, probably by a dropping sling; in addition a cable support was cut and the full cable weight caused the remaining accelerometer to be pulled into a position transverse to the pile axis. It was still possible, however, to get complete data for approximately 15 meters (50 feet) of driving. In addition strain records from one pile side were recorded throughout the whole test.

The second pile, No. B1-5, was driven to final grade on May 31, 1977. It was tested during the last 21.3 meters (70 feet) of driving both under an M-8000 and M-12500 hammer. Steel protections welded to the follower prevented any damage by dropping objects; however, the lead cable connector bearing against these protections loosened towards the end of the test causing erratic data.

The third and last pile tested, No. A5-3, was driven to final penetration on June 2, 1977. Both an M-8000 and M-12500 hammer were again used. Transducers were installed on one pile side only because of time limitations. Towards the end of the test the main cable's insulation wore out at the rather sharp edge of the follower's pickup ring and the signal leads were cut or shorted. Even though complete data was not obtained, sufficient information was collected for accomplishing the objectives stated above.

RESULTS FROM DATA PROCESSING

Besides field processing using the above described Analyzer, further laboratory analyses were conducted. Selected records were automatically digitized at a rate of 8000 samples per second. Force and velocity were plotted and again extreme values and Case Method bearing capacities were determined. Usually five blows were processed at a chosen penetration. Results of all consistent records were averaged and then listed in Table 2. Examples of force and velocity plots are shown in Figures 2 and 3.

Complete results are not listed for B5-5 when no acceleration data was available. Also, for B1-5 at 142 feet, the sensitive energy computations became unreliable since the loosening cable connector started to produce some electronic noise.

Finally, three records from two different piles were selected for CAPWAP analyses. Force and velocity records, both of good quality, were not available for all penetrations. However, since the records, including the blow count, did not change substantially during the last 10 meters (30 feet) of driving, the results obtained should be representative of the final pile bearing capacity.

Table 3 lists CAPWAP results. The resulting resistance distributions are shown in more detail in Figure 4. There the ultimate capacity determined for the individual pile segments are plotted as a function of depth. Note that the piles are segmented into 99 elements of approximately 2 meters length each.

Figure 5 shows two force matches from CAPWAP. Both matches are for the same pile (B1-5), driven by both the M-8000 and the M-12500 hammers. The agreement between the force curves is rather good, with minor differences at the time when the impact wave returns to the pile top, i.e. at time 2L/c (twice the pile length divided by the wave speed). From wave mechanics it is known that the disagreement at 2L/c does not indicate an improper prediction of the resistance distribution but rather an uncertainty in damping force or the soil model.

DISCUSSION OF RESULTS

Gravity Connector Effects

Figures 2(a) and (b) show two records each of pile top force and velocity, the latter multiplied by the pile impedance $I = EA/c$ (E, A, and c are the pile's elastic modulus, cross sectional area, and wave speed, respectively). Clearly the measured forces and velocities at the pile top are proportional as long as no upwards traveling stress wave (e.g., from soil resistance, nonuniformities, pile bottom, etc.)

reaches the point of measurement. This proportionality must exist, according to theoretical considerations; and it establishes a quality check on the data.

Figures 2(a) and (b) show a first distinct deviation from the proportionality approximately 20 milliseconds after impact. Converting to distance using a wave speed of 5,121 m/s, it is found that this wave effect was caused by the upper gravity connector. The lower connector similarly affected the pile top records

The gravity connector consisted of a male fitting of approximately 4000 kg weight. The contact surfaces were machined for an efficient energy transfer. It is therefore not surprising that Figure 2(a) shows an increase in force relative to the velocity, i.e., a compression wave effect caused by the connectors' inertia[1].

An exception in Figure 2(b) is the upper connector effect. Here, after a slight delay, the velocity increases relative to the force. Thus a tension wave effect reached the pile top indicating that there was at least a partial gap at the bearing surfaces of the connectors. The delay was caused by the superposition of the inertia effect.

The records can also be quantitatively evaluated. For example, integrating the velocity of the returned wave a gap size of approximately one millimeter is found (or a 1:750 deviation from axial alignment if one pipe edge touches). The energy of the upward reflected wave due to inertia (the force being about ten percent of that at impact and lasting approximately half the impact duration was approximately 0.5 percent of the impact energy. For the simultaneous gap and inertia effect quantitative estimates of losses are not as simply obtained because of the simultaneous occurrence of tensile and compressive reflections. However, for the records analyzed the energy loss certainly did not exceed two percent for a connector.

Poor alignment of the contact surface creates high local stresses and possibly plastification. Associated energy losses cannot be determined from the records; they were, however, only rarely discovered in the records and are therefore considered an exception.

EFFECTS OF SKIN FRICTION ON PILE TOP RECORDS

Figure 3 shows force records taken at three different penetrations of pile No. B5-5. All three records were obtained under the same hammer model and indeed the impact pulses are rather similar. The record with the high frequency oscillations (106 feet) was taken shortly after a replacement hammer with new, stiff capblock was put in operation.

The main difference between the records is the time of occurrence of skin resistance force effects at the pile top. As indicated in Figure 3 the time of the increase of the force is a good indicator of the depth of pile penetration; however, accurate results must take into account the speed of loading at impact. Note that L_B is the pile length over which resistance acts.

[1]For further discussions of forces acting along a pile and the effects of pile top force and velocity, see Reference 2.

Other interesting details of Figure 3 are first the quick increase of the resistance force effect (indicating concentrated friction) and then the rather constant or even decreasing behavior (small resistance at pile bottom). It must be added that a pile top force increase is only caused by soil resistance if the pile top velocity decreases simultaneously.

HAMMER PERFORMANCE AND PILE STRESSES

Table 2 lists efficiencies for the data sets processed. Here efficiency is the percentage of the rated energy, given in Table 1(a), transferred into the pile. It is, therefore, different from the usual wave equation definition which considers the ram energy available just before impact.

The results of Table 2 suggest that the energies in the pile were higher than forty percent and exceeded sixty percent under favorable circumstances. For the data sets processed the M-12500 hammer never reached an efficiency as high as the smaller model. However, considering the absolute energy values, the M-12500 supplied considerably more energy than the M-8000 (10.7 vs. 7.4 MJ). Also, the comparison of the two hammer models may not be quite fair since less accurate data was available for the M-12500.

Converting the maximum force values to stress, one obtains at most 176 N/mm^2, a value that is sufficiently safe against yield. However, these are pile top stresses and the relatively concentrated nature of the soil resistance may give rise to somewhat higher pile stresses below the mudline. The CAPWAP analyses discussed below indicate an absolute stress maximum that was four to ten percent above the maximum pile top stress and occurred 18 meters (60 feet) to 26 meters (85 feet) above the pile bottom.

BEARING CAPACITY

The Case Method requires the assumption of a damping factor. The influence of the damping factor J on the results is demonstrated by the J = 0 and J = .2 columns in Table 2. Actually J = .2 is appropriate for soils of relatively low plasticity (e.g. silty sands). However, any other result can be obtained from the two given values by linear extrapolation.

Comparing the CAPWAP predictions of total bearing capacity (Table 3) with those of Table 2, one realizes that for pile No. B1-5, 79 feet, a J = .1 damping factor would be appropriate. The bearing capacities at the deeper penetrations correspond to J = .4 (not given in Table 2). Thus the damping resistance of the soil appeared to increase with depth. Naturally this conclusion can also be drawn from the damping values given in Table 3.

The CAPWAP resistance distribution (Figure 4) shows most of the resistance acting at the pile skin above 100 feet penetration. Below that depth even the end bearing was rather negligible. The bearing capacity for the 79 feet depth, pile No. B1-5, apparently included some setup capacity since the skin friction was here higher than for the 124 feet depth. Such setup also explains the change in damping parameters and quakes. Note that the 79 feet records were taken after a three-hour waiting period. Note also that the damping parameters are given in Table 3 both in dimensionless form (divided by EA/c) and according to the better known Smith definition (3).

As far as indicated by the analyses performed, an approximate bearing capacity of 40 MN should be available at the time of driving. It is expected that this capacity is also available for uplift because of the rather negligible end bearing. Additional capacity should be regained, especially in the upper strata, within a short time after driving. The CAPWAP results illustrated by Figure 4 further support this conclusion by the apparent loss of friction in the upper strata while friction is gained at deeper penetrations.

SUMMARY AND CONCLUSIONS

The experimental and analytical work described in this paper supports the following conclusions.

1. Each gravity connector used to drive the Heather A leg piles through followers consumed less than two percent of energy in most instances. It was found that one connection was not well aligned and produced tension reflections. In such a case the energy loss is not as easily determined and may include unknown plastification losses at the contact point due to high local stresses.

2. The hammers performed well transferring at least 40 and at most 62 percent of the rated energy into the pile. The smaller hammer (M-8000) had higher efficiencies than the larger one (M-12500). The pile stresses did not exceed 200 N/mm^2.

3. The final bearing capacity of the piles was at least 40 MN. This capacity was also available for uplift because of a very low end bearing capacity. The skin friction acted primarily over the upper 100 feet of penetration. Additional bearing capacity from set up can be expected especially at higher elevations where friction was apparently lost during the driving operation. The presence of set up was evidenced by a record taken after a waiting period and analyzed by the CAPWAP method.

ACKNOWLEDGEMENTS

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TABLE 1: TEST DETAILS

(a) Hammers

Model	Ram Weight kg	Stroke m	Energy MJ
M-8000	80000	1.50	12.0
M-12500	125000	1.75	21.9

(b) Test Piles

Number	LENGTH First Follower m	LENGTH Second Follower m	LENGTH Pile m	Outside Diameter m	Wall Thickness mm
B5-5	52.0	60.6	96.1	1.52	63.5
B1-5	51.9	60.7	96.0	1.52	63.5
A3-5	52.1	61.1	96.4	1.52	63.5

TABLE 2: SUMMARY OF PROCESSING RESULTS

(a) Pile B5-5

Penetration ft	No. of Blows	Maximum Velocity m/s	Maximum Force MN	Bearing Capacity J=0.0 MN	Bearing Capacity J=0.2 MN	Hammer Efficiency %	Blow Count Bl/ft	Hammer Model
66	5	3.16	39.2	44	37	44	117	8000
73	5	3.65	43.0	48	40	55	<100	8000
106	4	2.92	41.2	44	37	62	110	8000[1]
116	2	--	43.7	--	--	56	120	8000
119	4	--	43.5	--	--	61	105	8000
126	4	--	43.4	--	--	61	114	8000
131	3	--	42.3	--	--	58	120	8000
137	2	--	40.8	--	--	54	130	8000
144	3	--	42.0	--	--	51	159	8000

(Note: for penetrations 116 through 144, accelerometer aligned perpendicular to pile axis)

(b) Pile B1-5

Penetration ft	No. of Blows	Maximum Velocity m/s	Maximum Force MN	Bearing Capacity J=0.0 MN	Bearing Capacity J=0.2 MN	Hammer Efficiency %	Blow Count Bl/ft	Hammer Model
79	5	3.28	38.3	45	38	47	>120	8000
92	5	3.25	38.9	45	38	47	72	8000
124	5	3.62	41.2	47	40	40	< 60	12500
142	5	3.80	51.2	57	47	--[2]	44	12500

(c) Pile A3-5

Penetration ft	No. of Blows	Maximum Velocity m/s	Maximum Force MN	Bearing Capacity J=0.0 MN	Bearing Capacity J=0.2 MN	Hammer Efficiency %	Blow Count Bl/ft	Hammer Model
92	5	3.50	40.7	49	42	51	95	8000
103	5	3.44	41.2	48	41	54	122	8000
109	5	4.04	50.3	57	48	50	91	12500
118	5	3.71	43.2	52	45	43	140	12500
129	4	3.89	47.9	56	48	44	102	12500
134	3	3.86	46.9	55	47	49	101	12500

[1]After hammer exchange
[2]Unreliable energy results

TABLE 3: RESULTS FROM CAPWAP ANALYSIS

Pile No.	Penetration ft	Bearing Capacity Skin MN	Bearing Capacity Toe MN	Bearing Capacity Total MN	Damping Parameters Case Skin	Damping Parameters Case Toe	Damping Parameters Smith* Skin s/ft	Damping Parameters Smith* Toe s/ft	Quake Skin mm	Quake Toe mm
B1-5	79	37.1	4.6	41.8	.20	.60	.02	.48	0.5	5.0
B1-5	124	35.9	.5	36.4	.90	.05	.09	.41	1.8	5.0
A3-5	134	38.5	1.1	39.6	.75	.05	.07	.18	0.6	5.0

*1 s/ft = 3.28 s/m

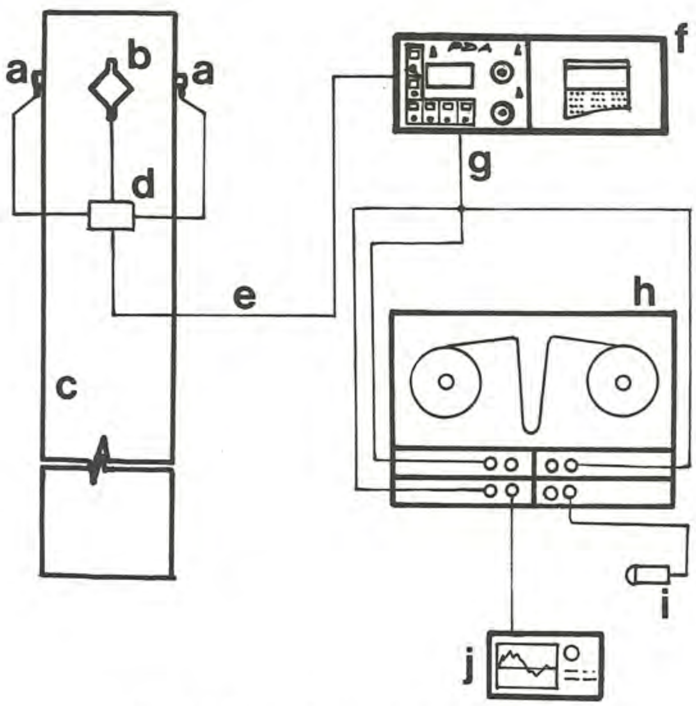

Fig. 1 - Schematic of instrumentation.

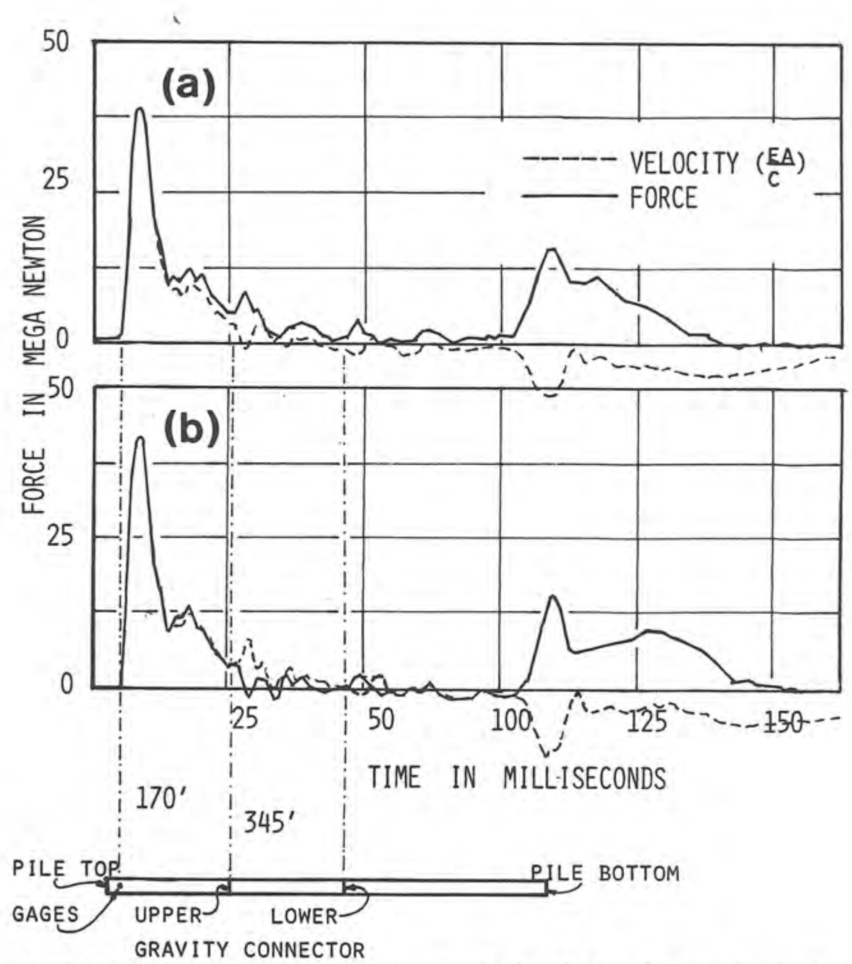

Fig. 2 - Effects of gravity connectors on both pile top force and velocity; (a)Pile B1-5, 79 feet; (b) B5-5, 73 feet penetration.

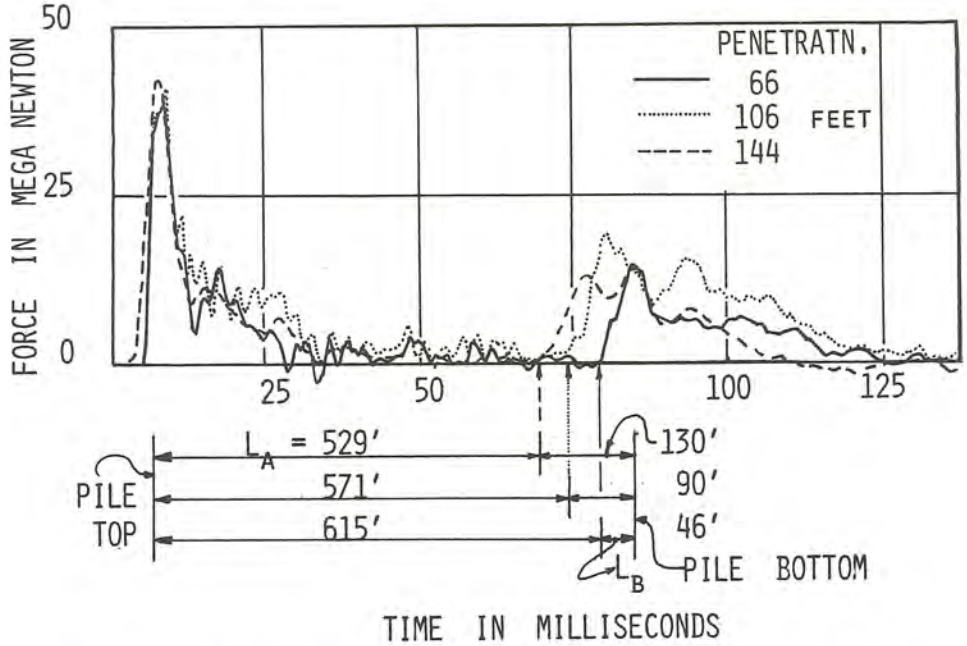

Fig. 3 - Effect of skin friction on pile top force; pile B5-5, M-8000 hammer.

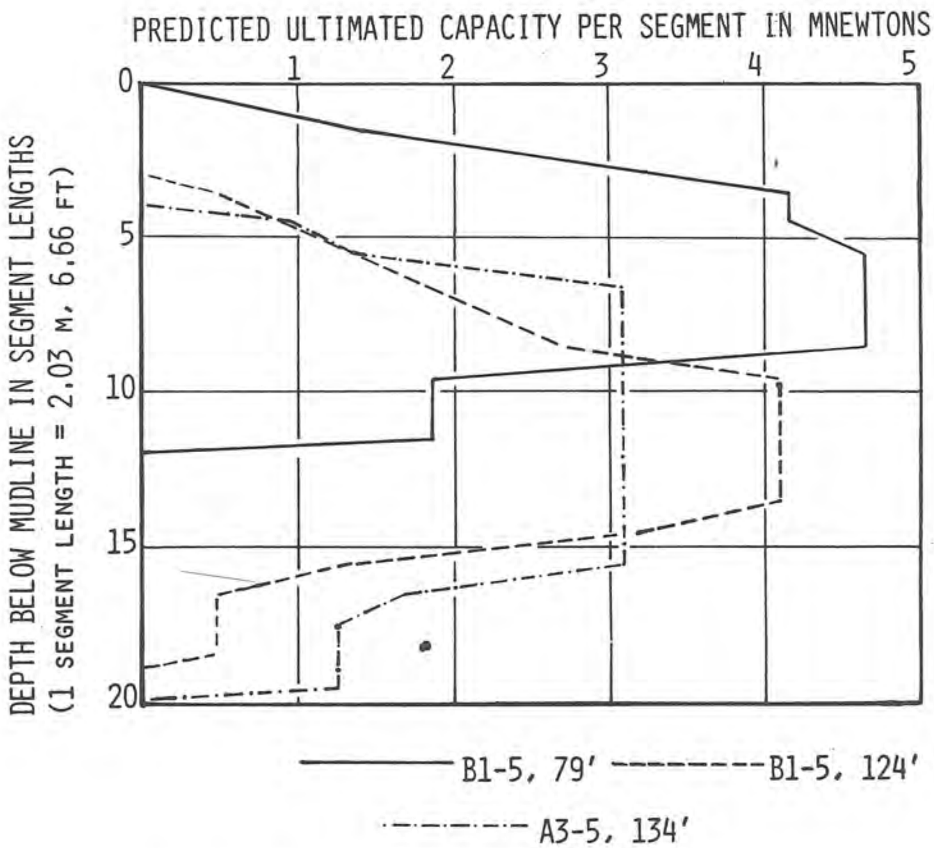

Fig. 4 - Capwap resistance distribution results.

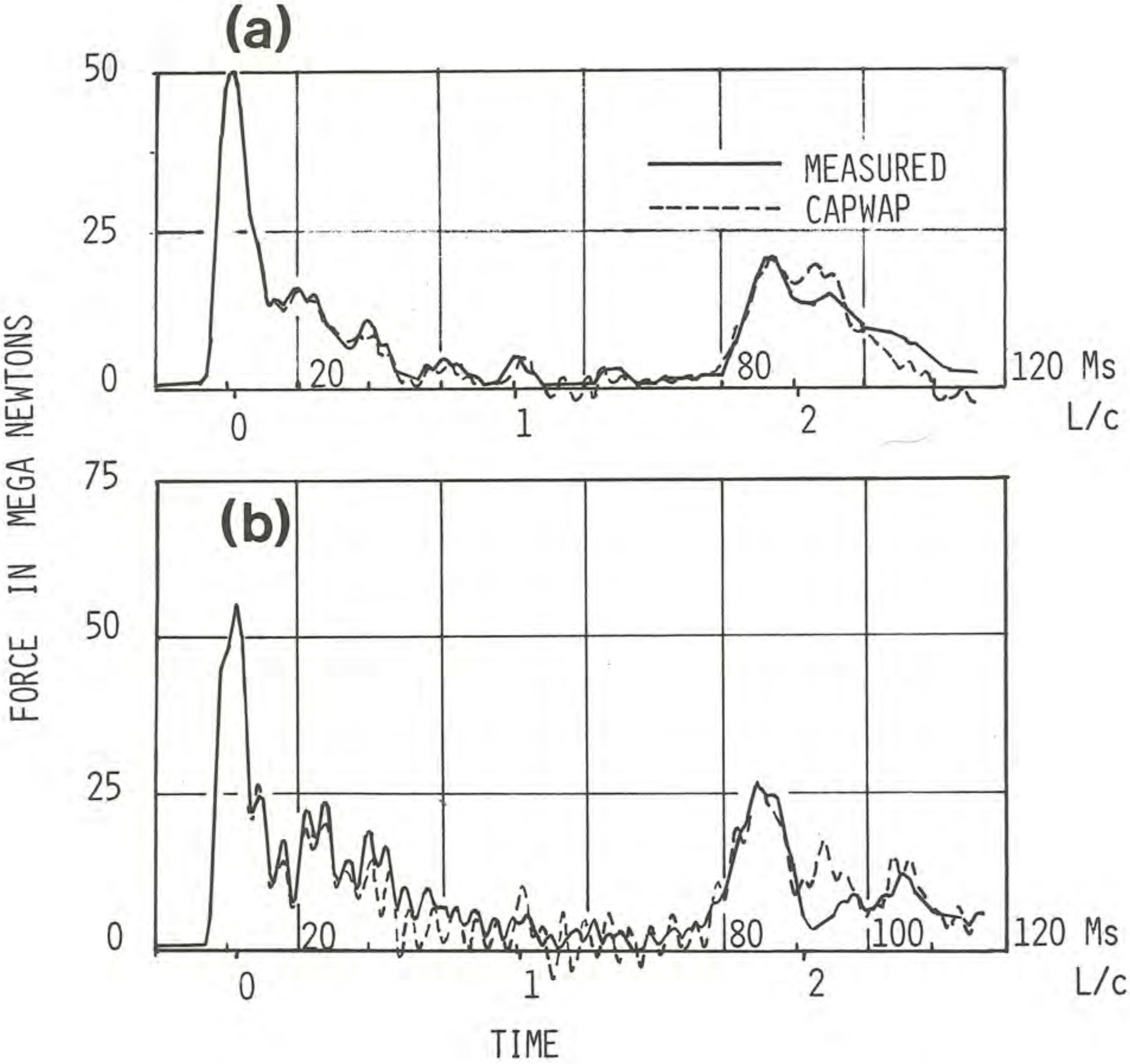

Fig. 5 - Two examples of pile top force matches obtained by CAPWAP; (a) Pile B1-5, 79 feet; (b) B1-5, 124 feet penetration.