A COMPARISON OF PULSE ECHO AND TRANSIENT RESPONSE PILE INTEGRITY TEST METHODS

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INTRODUCTION

Foundation engineers need an inexpensive and quick method for the integrity testing of foundation piles when installation difficulties are expected or problems arise during construction. Both driven piles and drilled shafts may undergo serious damage during construction. When this is suspected, selected or even all piles on a construction site may require evaluation. However, in general, special advance preparations such as the installation of inspection tubes are not economically feasible.

When a concrete pile, either precast and driven or drilled and cast in situ, is struck with a small hammer, a stress wave is generated which travels down the shaft to the pile bottom where it is reflected. When the reflected stress wave returns to the pile top, a measurable pile top motion occurs. If this reflection occurs at the correct time and if no other earlier reflection waves are received at the pile top, then the pile shaft is probably free of major defects. Utilizing this concept, the so-called "Low-Strain Method of Dynamic Pile Testing" was developed. In contrast, the "High Strain Method" measures pile top forces and velocities under a large impact hammer. A comparison of high strain and low strain results is given in Reference (1).

When a lightweight hand held hammer strikes the pile top, a small pile top motion (velocity) is generated. The associated pile strains are of such a low magnitude that they would be measured in the pile only with great difficulty. However, the force applied by the hammer can be easily measured by instrumenting the hammer itself. Primarily, the velocity record and to a lesser

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degree the force record contains information about the location and magnitude of pile nonuniformities. Under the assumption of proportional force and velocity records (2), and for short duration impact pulses, the velocity record may be sufficient. One of the distinguishing features of the Transient Response Method (TRM) is that it requires the measurement of both velocity and force while the Pulse Echo Method (PEM) only relies on velocity records. A second difference is the display of the TRM results in the frequency domain. PEM offers powerful record enhancement techniques and presents the resulting curves as a function of time.

The authors have realized that both methods have some advantages and have therefore combined the two methods into a third method which is referred to as P.I.T.-FV. All three methods are presented. Using records taken on a drilled shaft with a known cross sectional change, the features of all three methods will be demonstrated.

STRESS WAVE PROPAGATION IN A PILE

An impact applied to the pile top generates a momentary compression and a particle motion of the pile top surface. The compression is related to the force, F; the motion causes a particle velocity, v. In concrete, the stress wave travels along the pile with a stress wave speed, c, ranging from 10 to 15 ft/ms (3.3 to 5.0 m/ms). As shown by St. Venant (3), the stress wave speed in a long slender rod is given by

$$c^2 = E/\rho \tag{1}$$

where E is the pile's elastic modulus and ρ its mass density. The low strain methods have also been applied to timber piles. Due to the high surface area to cross sectional area ratio, steel piles which are not filled with concrete are very difficult to test using low strain methods. Steel piles are more easily tested with impacts of actual pile driving hammers (high strain method).

The traveling wave solution to the one-dimensional wave equation has been discussed in detail by St. Venant and many others (4). It forms the basis on which interpretation techniques have been founded for both high strain and low strain pile test methods. Figure 1 shows, in the form of a time-depth plot, the path of a stress wave in the pile, illustrating the arrival times of reflection waves at the pile top. Both cross sectional changes and soil resistance forces generate reflection waves. The pile top velocity is affected by and therefore indicates the arrival of both tensile and compressive reflection waves.

THE PULSE ECHO METHOD

This is probably the simplest test method as far as instrumentation and testing effort is concerned. Figure 2 shows a photograph of the so-called P.I.T.-SC (Pile Integrity Tester - Self Contained, because it is battery powered). Important hardware components also include a hand held hammer with an integral plastic cushion and an accelerometer. The processor shown in Figure 2 provides signal conditioning, digital signal processing, digital signal storage and, for output, an LCD screen and a built-in graphics printer. Various configurations of this system are possible. For example, the signal conditioning can be connected directly to a standard portable PC with A/D capability. Output can also be produced on a pen plotter.

The first and sometimes most important step for any low strain test is the preparation of the pile top surface. In fact, depending on the construction method, it may be necessary to remove several inches or feet of the upper concrete if it has been contaminated with soil, bentonite slurry or other foreign materials during construction. After a clean, healthy and hard concrete top surface has been created, the accelerometer is attached to the pile top surface with a thin layer of a soft paste like vaseline, petro wax, *etc.*

After this preparation, an impact with the hand held hammer is applied. The impact generates accelerations in the 10 to 100 g range, pile strains around 10^{-5}, velocities near .1 ft/s and displacements less than .001 inches. The velocities contain the most useful and usable information. Therefore, accelerations produced by several hammer blows are integrated and displayed on the processor's screen. Figure 3 shows, as an example, records from a specially prepared 20.5 ft (6.2 m) long drilled shaft with 18 inch (460 mm) nominal diameter installed in stiff to very stiff silty clays. Over the bottom 5 feet (1.5 m) of the shaft, the cross sectional area was purposely reduced to 15 inches (380 mm) diameter; this is a 30 percent area reduction. Consistent records are selected, averaged, scaled and then redisplayed. Averaging reinforces repetitive information from real cross section changes while reducing random noise effect. For the example case of Figure 3, the average pile top velocity is shown together with two individual records in Figure 4(a) as a function of both time and length. The length scale is calculated from the time scale by multiplication with an assumed wave speed.

The test engineer inspects the average velocity signal. The first check concerns the "toe signal". If the reflection from the pile toe is not readily apparent (as in the example of Figure 4(a)), then the velocity is multiplied with an amplification function whose magnitude is unity at impact and which increases exponentially with time until it reaches its maximum intensity at time 2L/c after impact (2L/c is the time which the stress wave requires to travel the pile length, L, and return). In Figure 4(b), an amplification of 10 was used. Note how both the cross sectional reduction and the pile toe now provide clearly identifiable signals. For longer piles or stronger soils, even higher amplification factors are often used; this requires however, special purpose signal conditioning with very low noise and high resolution A/D units operating at fast sampling rates to be successful. If the toe signal is apparent, then it is possible to confirm the originally assumed wave speed.

A clearly indicated toe signal together with a fairly steady velocity trace between the impact and toe signal are signs of a sound pile. Traces with strong variations may indicate the presence of a pile cross section change or soil resistance changes. For example, relative increases in pile top velocity may be the result of either a cross sectional decrease or a soft soil layer. The pile impedance (EA/c) is the product of cross sectional area, A, and elastic modulus, E, divided by the wave speed and is therefore a measure of the pile cross sectional size and quality. Thus, an impedance reduction can be due to a decrease either in area or in the modulus or concrete strength. Further inspection of Figure 4(b) concerns the evidence of impedance reductions along the pile length at about 14 ft (4.2 m) below the top. Correct quantitative interpretations may require signal matching and comparison with records of other piles at the same site (See section on P.I.T.-WAP signal matching).

The TRANSIENT RESPONSE METHOD

The TRM requires that both the pile top motion and the impact force be measured. This concept has been borrowed from standard Non-Destructive Testing technology. In fact, the first applications on piles required the measurement of force and velocity under a steady state vibrator which could apply substantial forces at variable frequencies (5). However, the force frequency spectrum of a hand held impact hammer is flat over a wide frequency band (see Figure 5). A simple hammer can therefore adequately produce those frequency components to test both well constructed or defective piles with TRM methods. Although general purpose equipment (Spectrum Analyzer) can be used in conjunction with velocity and force sensors, the equipment described for the Pulse-Echo Method is capable of the necessary signal conditioning and analysis provided the simple hammer is instrumented to measure the impact force.

The standard result of TRM is a plot of the ratio of velocity to force (which is the so-called Mobility) spectrum. The mobility is really the inverse of the impedance and therefore an indication of the pile's velocity response to a particular excitation force.

A mobility peak occurs at a frequency indicative of a positive change of velocity caused by reflection from the pile toe or an intermediate impedance reduction. Furthermore, dividing the velocity by frequency leads to displacement. Dividing force by displacement at a given frequency leads to a stiffness value. Thus, in practice, low frequency values are divided by the associated mobility yielding a so-called dynamic stiffness, E_d. This quantity increases with decreasing pile toe response. A low pile toe response is the result of high soil resistance. However, it may also be the result of high soil or internal pile damping and is therefore only indirectly related to quantitative pile bearing capacity. However, E_d is calculated since it does provide a qualitative result for the evaluation of pile quality. Figure 6 shows the Mobility Spectrum for the present example case and the E_d value for the 32 Hz (frequency is selected by the movable cursor, T1).

In both PEM and TRM, the effects from "ringing" due to reinforcement protruding from the pile top can be minimized using appropriate filtering techniques.

P.I.T.-FV

The P.I.T.-FV Method is a combination of PEM and TRM. The equipment necessary is the same as for TRM. Both force and velocity records are displayed as a function of time. However, instead of the averaged and amplified velocity, the difference between average velocity and average force (divided by impedance) is calculated and then amplified exponentially (by a factor of 10 for the example case shown in Figure 7). The toe (at 20.5 ft, 6.2 m) and planned cross sectional reduction at 14 ft (4.3 m) are readily apparent in this record. In this curve, any defect near the pile top is more apparent while it may be hidden inside the impact pulse in the normal PEM.

After the display of the average, amplified force velocity difference, the mobility is calculated as in TRM (Figure 6). Unfortunately, the mobility spectrum cannot be calculated for the **amplified** velocity curve. Apparently the shape of the amplification function affects the spectrum and incorrect conclusions would be drawn. Therefore, a weak toe response will result in a mobility spectrum with little information about the basic pile frequency.

P.I.T-FV provides the engineer with the additional spectra of velocity and force. An example of the force spectrum was shown in Figure 5. Since the mobility is velocity divided by force, the velocity spectrum differs substantially from the mobility spectrum only at higher frequencies where the force spectrum becomes progressively smaller. In the lower frequency range, velocity and mobility spectra are nearly identical because of the flatness of the force spectrum.

Figure 8 shows the P.I.T.-FV velocity spectrum calculated from the velocity time curve. The velocity spectrum lends itself to further analysis if this curve displays prominent and repetitive peaks at integer multiples of the basic frequency. The transform of the velocity spectrum therefore directly indicates the length due to reflections from the pile toe (Figure 9). If other prominent frequency components are contained in the velocity spectrum, due to impedance changes along the shaft for example, then several peaks may result. Obviously, the mobility or velocity spectrum is not as easily interpreted. Again, the amplified velocity cannot be analyzed in this manner. P.I.T.-FV offers this important additional result as an aid in interpretation. In the example presented here, the cross sectional reduction is easily observed in the high marker, and the pile toe with a smaller reflection.

CALCULATED RESPONSE

The low strain pile integrity test methods yield some form of pile top motion curve. Interpretation of these curves is left to the more or less experienced engineer. An invaluable aid in the interpretation effort are similar curves analytically developed. The special purpose computer program, P.I.T.-WAP (Pile Integrity Testing Wave Analysis Program), was written using CAPWAPC (CAse Pile Wave Analysis Program -Continuous version) (6) as a starting code, requires that the description of pile and soil are input, and generates as an output pile top velocity *vs.* time or the mobility spectrum. A voluminous catalogue of these calculated responses was compiled as a guide for record interpretation. Only one of many demonstration cases is discussed in the following.

Figure 10 shows the calculated curves for a pile with sufficient uniform shaft resistance to reduce the pile toe reflection to a small pulse. The pile was 20 ft (6.1 m) in length. With a wave speed of 13 ft/ms, the wave travel time (2L/c) was approximately 3.1 ms. The corresponding frequency is 325 Hz. This frequency is apparent in the uniform case (Figure 10). Piles with an impedance reduction (Figure 11) and with an impedance increase (Figure 12) over the lower quarter of the pile were also analyzed. A pile impedance versus depth profile separates time from frequency plots. The beginning of the cross sectional change, in Figures 11 and 12, produces a pile top reflection at 2.3 ms or 430 Hz. Unfortunately, no really clear response frequency is apparent in the corresponding spectra. The output sheet also includes E_d values at five different frequencies.

P.I.T.-WAP SIGNAL MATCHING

The P.I.T.-WAP program can also be employed in the interpretation of measured P.I.T.-FV velocity or velocity and force records. Suppose that the measured force record is imposed as a pile top boundary condition for an analytical model of pile and soil. One result of this analysis would be the calculated pile top velocity. Comparison of the measured with the computed velocity allows the engineer to gain insight regarding the pile impedance variations. Reanalyzing with a variable impedance pile model should therefore lead to an improved match of measured and calculated pile top velocity. The process of changing impedance and reanalyzing is continued until a good match is achieved. At that point, the most likely pile impedance profile has been determined. The difficulty of this simulation is that the soil resistance effects also influence the pile top velocity. However, comparison of the records of several piles may help identify the normal soil response effect.

Typically, P.I.T.-WAP divides the pile in continuous segments of approximately 10 inches (250 mm) length. The program automatically calculates the pile impedance of all segments after the engineer has decided on a soil resistance model. Note that due to the very low magnitude force inputs, this soil resistance model bears no close relationship with static resistance or with damping magnitudes encountered during pile driving. On the other hand, for accurate pile impedance predictions, it is important to realistically model the effect of soil resistance on pile top variables. Generally, it is possible to extract these relative soil resistance parameters from P.I.T.-FV tests on reference piles. These parameters are then used to analyze neighboring piles with impedance variations.

The results from P.I.T.-WAP include both a printed listing and a plot of soil resistance parameters and pile impedance values along the pile length. Furthermore, the "match plot quality" of measured and computed pile top velocities allows the engineer to evaluate the reliability of his conclusions. Figure 13 illustrates the results obtained from P.I.T.-WAP matching of the records of the example test pile of Figure 4. The plot includes the velocity match, the predicted cross sectional variation (an unplanned impedance increase from 10 to 15 ft was calculated), the actual measured force and velocity curves, and the resistance distribution assumed for the analysis.

COMPARISON OF METHODS

All three methods have nearly the same testing effort. P.I.T.-FV or TRM require the **calibrated** force and velocity measurement and therefore somewhat more care than PEM. Of course, equipment and software of P.I.T.-FV and TRM are also more complicated than PEM. In all methods, pile preparation and the assistance of the pile contractor is usually minimal, allowing the test of many piles to be quickly performed at a low cost. It is not beyond reach to test every pile on some sites and thus low strain testing can be used as a quality assurance method.

Depending on the sensors and hammer used, the response recorded by the three methods may differ. It is sometimes even a matter of luck to find the best pile top locations for impact and motion sensing. Contaminated or cracked concrete may adversely affect the measurement results. However, if the measurement engineers have the same experience, apply the same amount of care, select the same pile top location for measurement and use a hammer with the same properties, the pile top velocity records will probably be very similar. However, the various engineers may prefer to choose different filtering characteristics for their signal processing equipment and software. The velocity may therefore represent impedance variations over short distances to different degrees.

A very important difference occurs when the pile toe response is very small. PEM and P.I.T.-FV can exploit the exponential amplification over time, which greatly enhances the record and therefore the power of these methods. TRM cannot resort to this relatively simple numerical enhancement. Observation of a toe signal at least gives assurance of a certain pile length. For piles which are long compared to their diameter, or for piles in soils with very high resistance characteristics , exponential amplification may be the only possible method to obtain a clear presentation of the pile toe signal. Using PEM or P.I.T.-FV, a guideline limit of 30 pile diameters for the pile length is often quoted. In practice, prestressed piles of unlimited length to diameter ratios can be tested prior to installation. Even in soft soils this limiting ratio is often successfully exceeded. In high shaft resistance soils, it may not be possible to detect a pile toe response even at ratios of only 20. However, even if the toe is not readily observed, defects in the upper portion of the shaft (statistically the most likely location of defects) can still be detected and thus the test is still of value. Several examples of the range of usefulness are given in Reference (7).

For all three methods the following shortcoming exist. First, the length information obtained from a toe signal (or a governing frequency) is only as accurate as the wave speed value assumed in the processing of the records. Even at sites where concrete quality if well maintained, wave speed variations of 10% are not uncommon. A pile length calculated from a toe signal is therefore only well known within plus or minus 5%. Second, certain reflections produce secondary and even tertiary wave reflections. For example, if an impedance reduction occurs in the middle of the pile, then what may appear to be the pile toe response may actually be a secondary reflection of the mid-pile defect. For piles with severe cracks or manufactured mechanical joints, the stress wave will, in general, not be transmitted below the "gap" and therefore the pile below this "defect" cannot be evaluated. Third, piles with multiple or highly variable cross section changes are difficult to analyze. Piles which are still rigidly attached to other parts of the structure can sometimes be analyzed successfully, but often the analysis is much more difficult.

The additional force measurement of P.I.T.-FV and TRM definitely provides supplemental information of cross sectional changes occurring near the pile top, *i.e.*, during the distance covered by the impact signal. The extra expense of the force measurement is, therefore, worthwhile whenever questions arise as to the integrity of upper (say 5 ft, 1.5 m) pile portion.

The record presentation in the frequency domain may, on occasion, be of benefit. For example, important record components may be hidden in a steady state signal caused by pile top or reinforcement vibration. They also provide information on dynamic stiffness although no low strain method can truly give quantitative information on the ultimate capacity of a pile. In general, however, the interpretation of time records is much simpler than that of frequency records. Time records can also be simply analyzed by the P.I.T.-WAP signal matching technique.

SUMMARY AND CONCLUSIONS

Three different methods were presented which rely on low strain measurements taken on a pile struck by a hand held hammer. These methods are quickly and simply applied at low cost and do not require special preparations during pile construction, making them a good quality assurance tool. The Pulse Echo Method has the advantage that very small toe response signals on long piles can be enhanced. The Transient Response Method provides additional information for integrity evaluation near the pile top. P.I.T.-FV combines the advantages of both methods and provides direct length indication by the second transform of velocity. It also provides the necessary information for signal matching with the P.I.T.-WAP simulation program. TRM and P.I.T.-FV provide relative or quantitative pile stiffness information; however, these values are of limited value for capacity evaluation.

All three methods have similar limitations, which include a generally unknown wave speed and therefore an uncertainty as to the exact location of pile defects or pile toe. Piles with highly variable cross sections are difficult to analyze. Multiple reflections from the same location may mask the wave reflections from lower locations or from the pile toe. It appears that these methods may provide information that can be expressed as follows:

A) No significant defect was apparent in the records (the record showed a pile toe response and no other significant reflection prior to the pile toe response was apparent).

B) No significant defect was apparent in the records, however, the full pile length was not tested since no pile toe reflection was apparent.

C) Significant impedance changes were noted. Their magnitude was approximately x% at a depth of y ft. However, a pile toe response was clearly indicated. The pile may therefore be of limited value.

D) Significant impedance changes were noted and a pile toe signal was not apparent. The pile is highly questionable and additional tests or the replacement of the pile is suggested.

It must be noted that inconclusive test results are also possible, particularly, when very large impedance increases (*e.g.*, a large bulge or outgrowth in shaft diameter in a soft fill) near the pile top prevent a clear stress wave transmission. Some inconclusive results stem from inadequate pile top preparation in obtaining a good testing surface. Of course, such a pile is perfectly capable of performing its service task; however, successful low strain testing would require additional pile top preparation.

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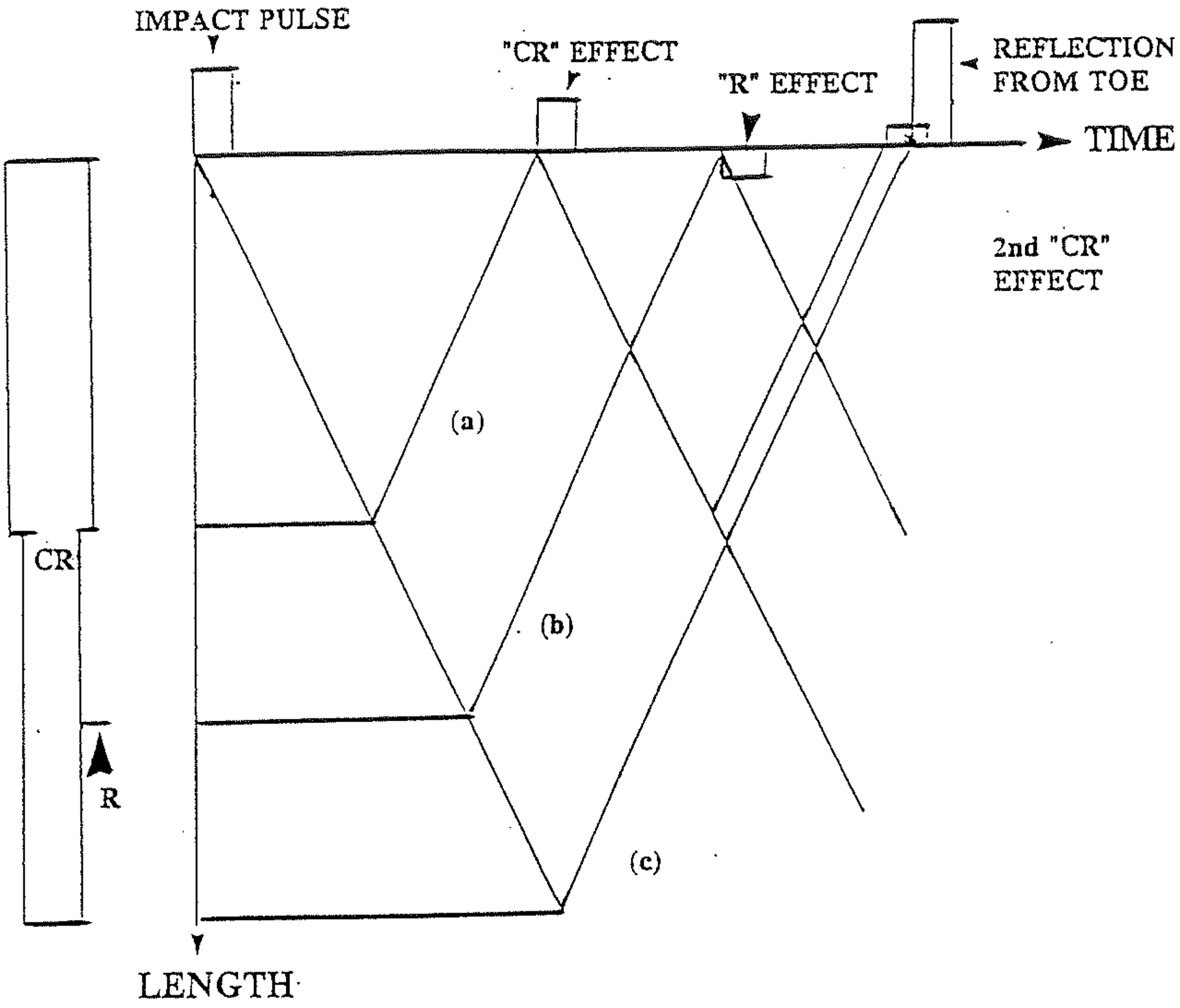


Figure 1: Impact Pulse and Reflections from (a) Cross-sectional Reduction, CR, (b) Shaft Resistance, R (modelled velocity proportional) and (c) Pile Toe.

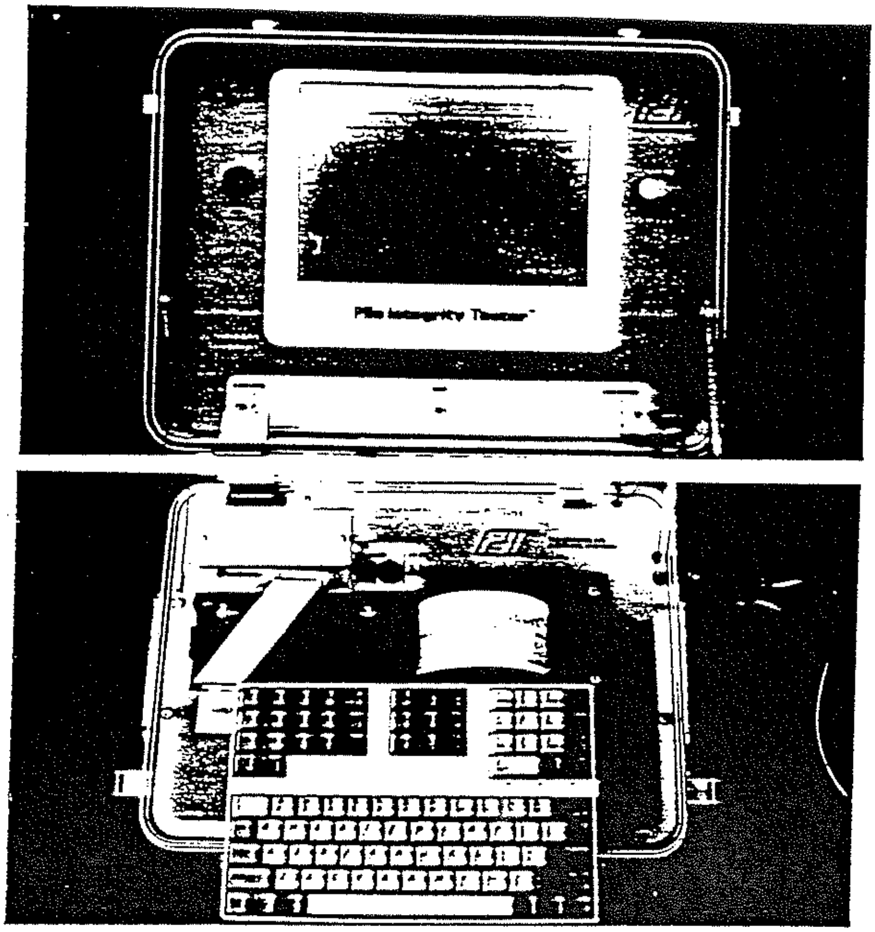


Figure 2: Photograph of P.I.T.-SC, Pile Integrity Tester - Self Contained. Top lid contains LCD screen, bottom picture shows Battery, Keyboard and Printer.

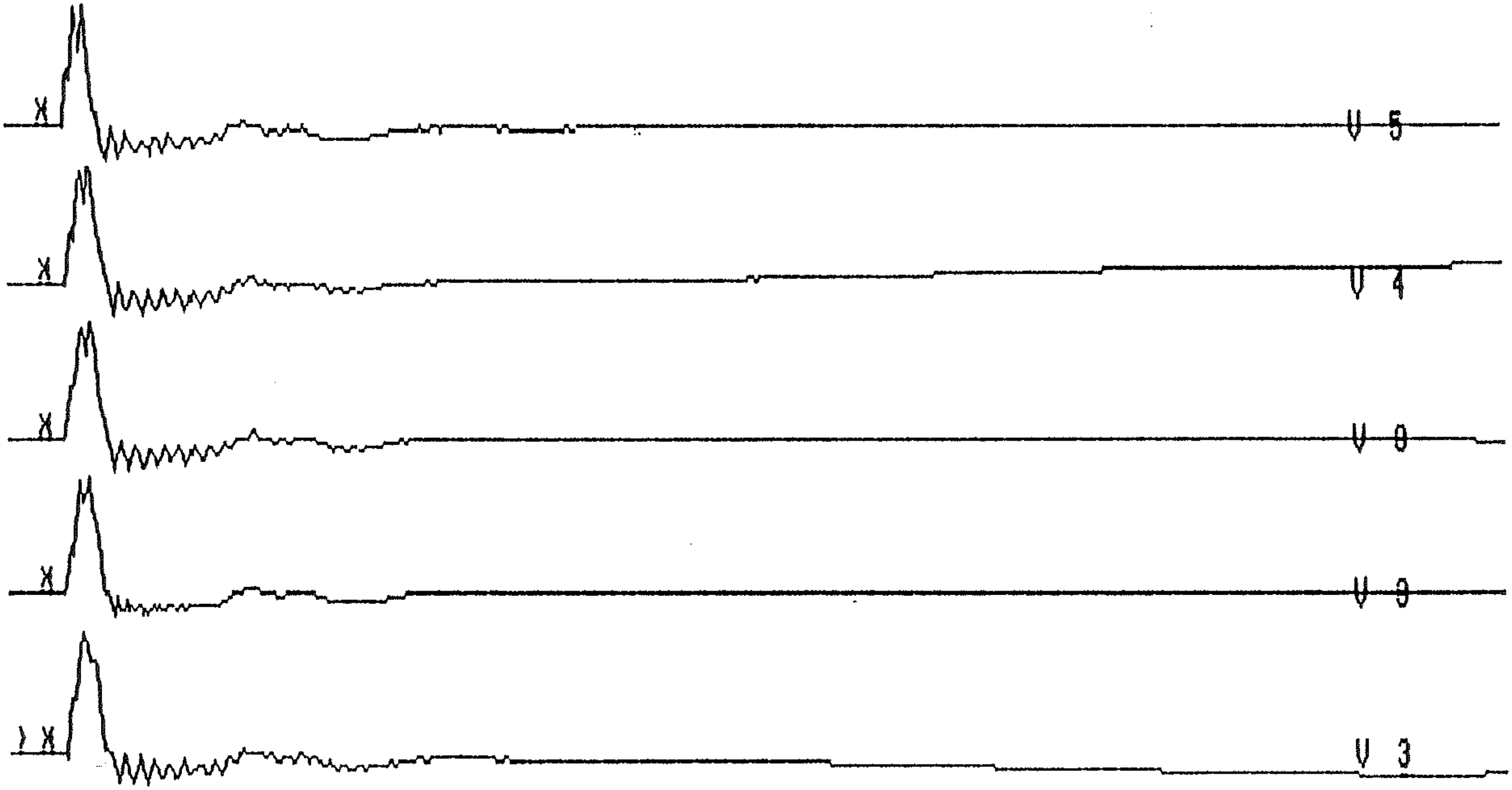
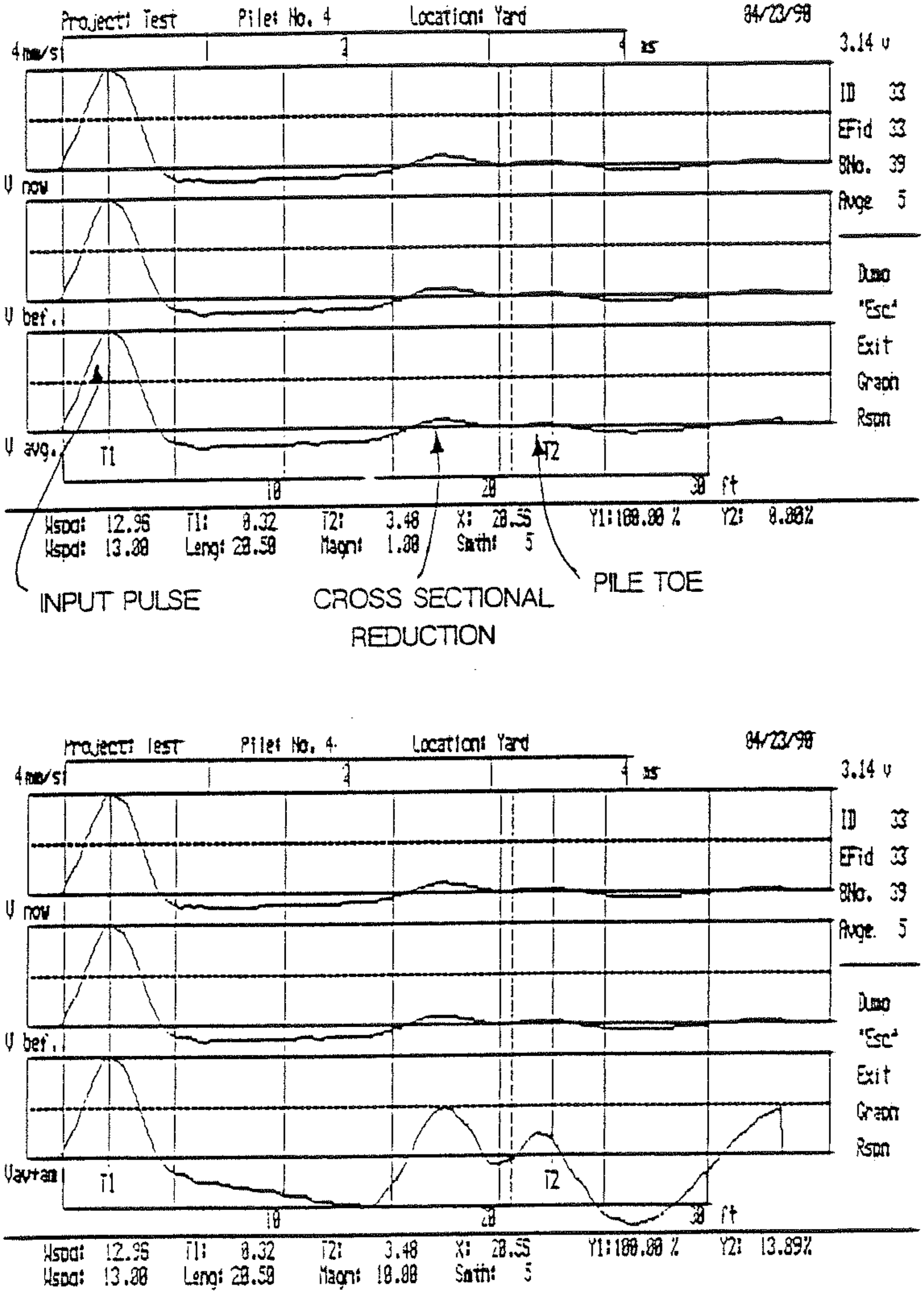


Figure 3: Unprocessed Velocity Records with Maximum Voltage Level and Selection Marks (*). All Selected Curves will be Averaged, Stored and Redisplayed as Shown in Figure 4.



```
Wspd: 12.96   T1:   0.32   T2:    3.48   X: 20.55   Y1:100.00 %   Y2:  0.00%
Wspd: 13.00   Leng: 20.50  Magn:  1.00   Smth:  5
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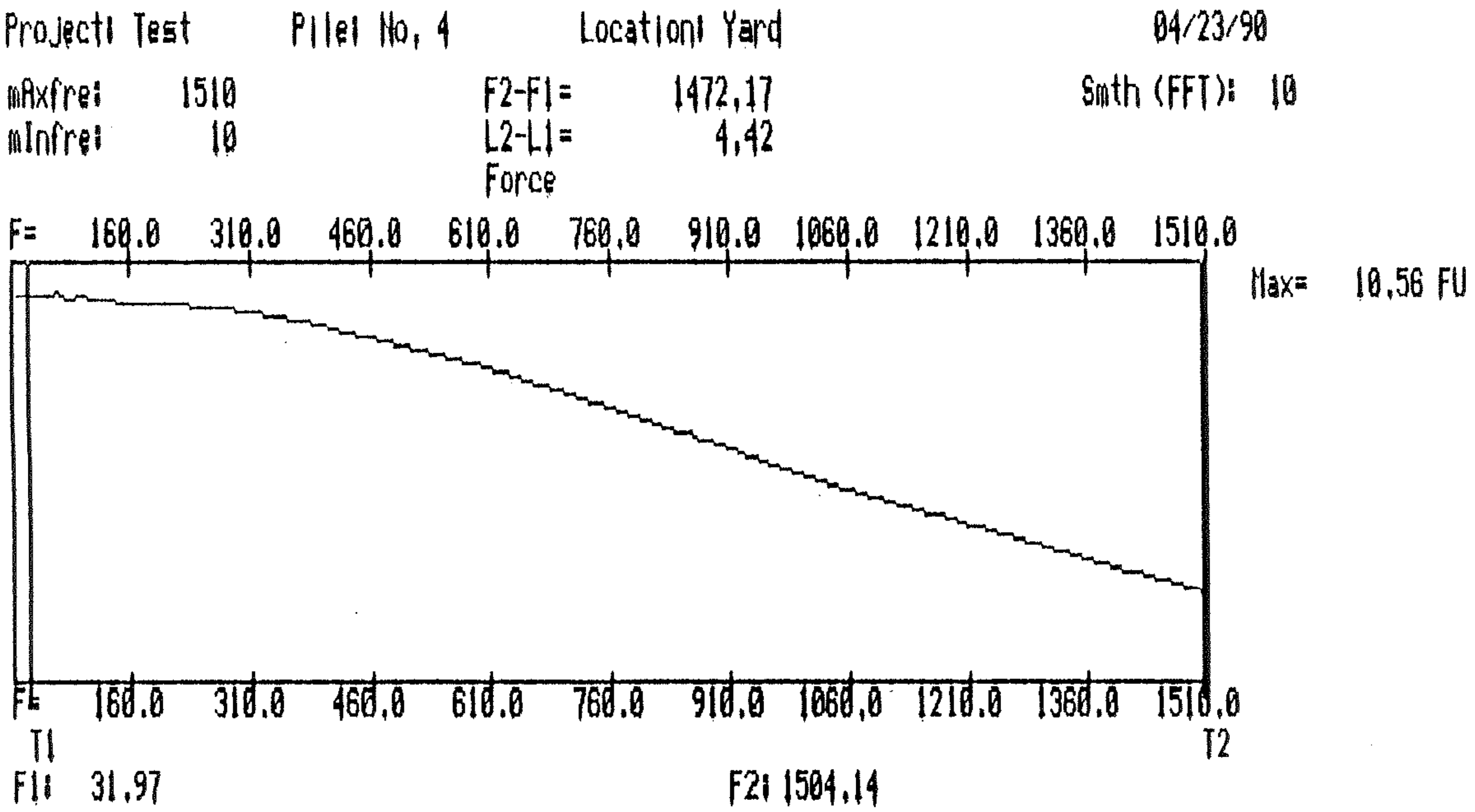
```
Wspd: 12.96   T1:   0.32   T2:    3.48   X: 20.55   Y1:100.00 %   Y2: 13.89%
Wspd: 13.00   Leng: 20.50  Magn: 10.00   Smth:  5
```

Figure 4: P.I.T.-SC display of 2 individual velocity records and (a) the averaged and (b) the averaged and amplified curves.



```
Project: Test        Pile: No. 4        Location: Yard                 04/23/90

mAxfre:     1510                F2-F1=      1472.17              Smth (FFT):  10
mInfre:       10                L2-L1=         4.42
                                Force
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Figure 5: Frequency (F, in Hz) Spectrum of a Force Record obtained on an Instrumented Hammer.

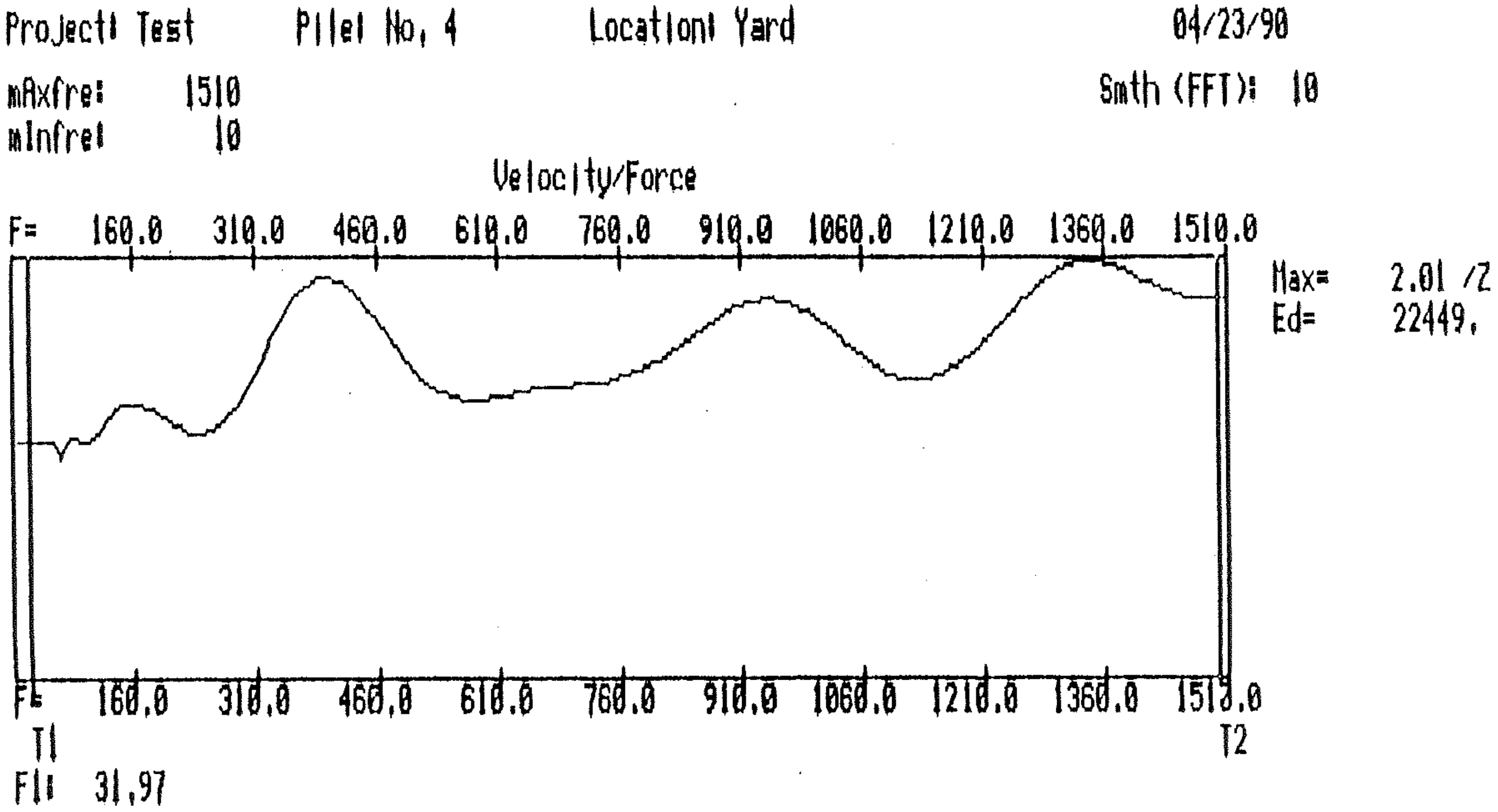
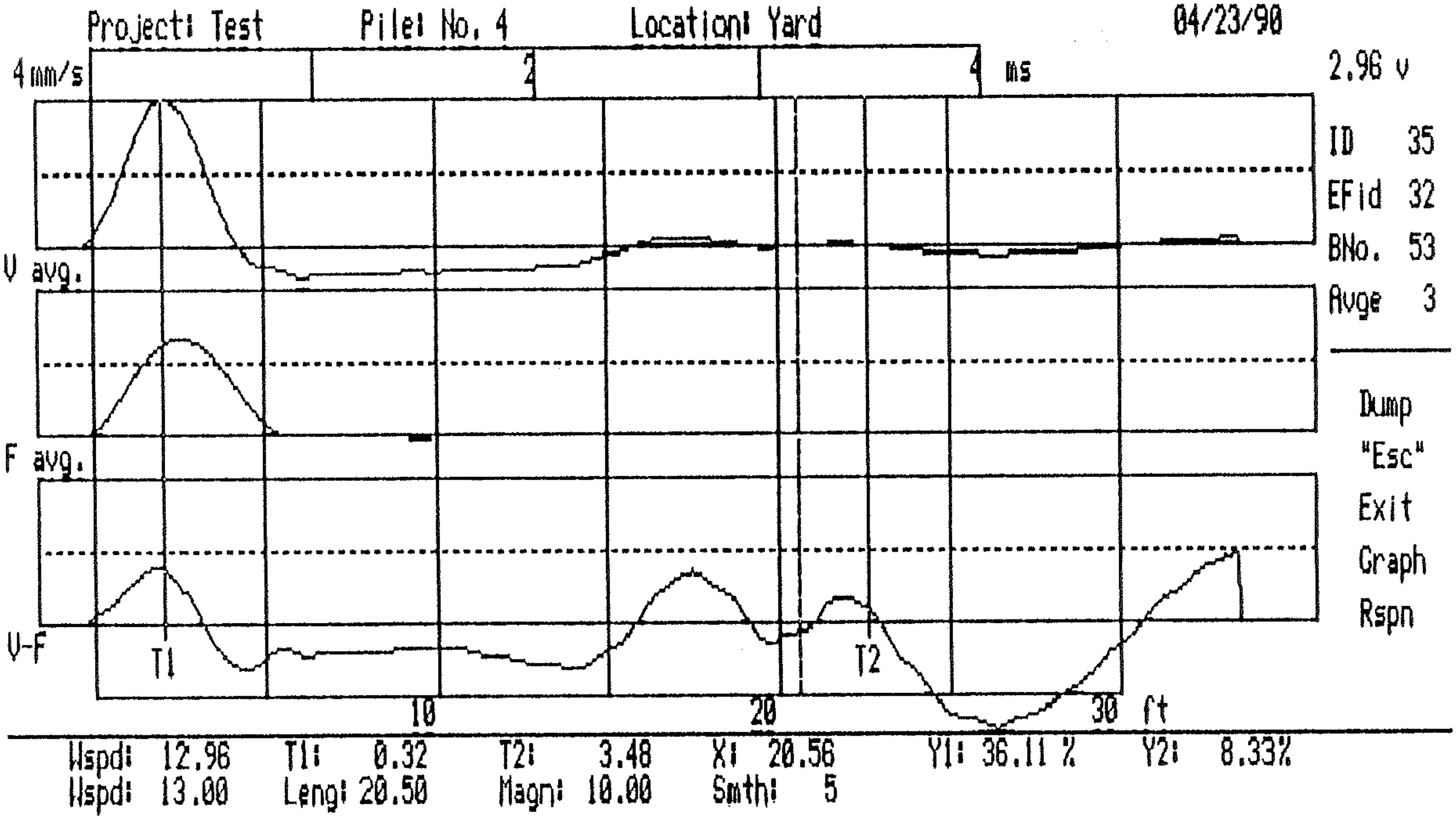


Figure 6: Mobility of 20.5 ft Non-Unifrom Pile. Ed stiffness is 22449 kips/ft at 32 Hz Frequency.



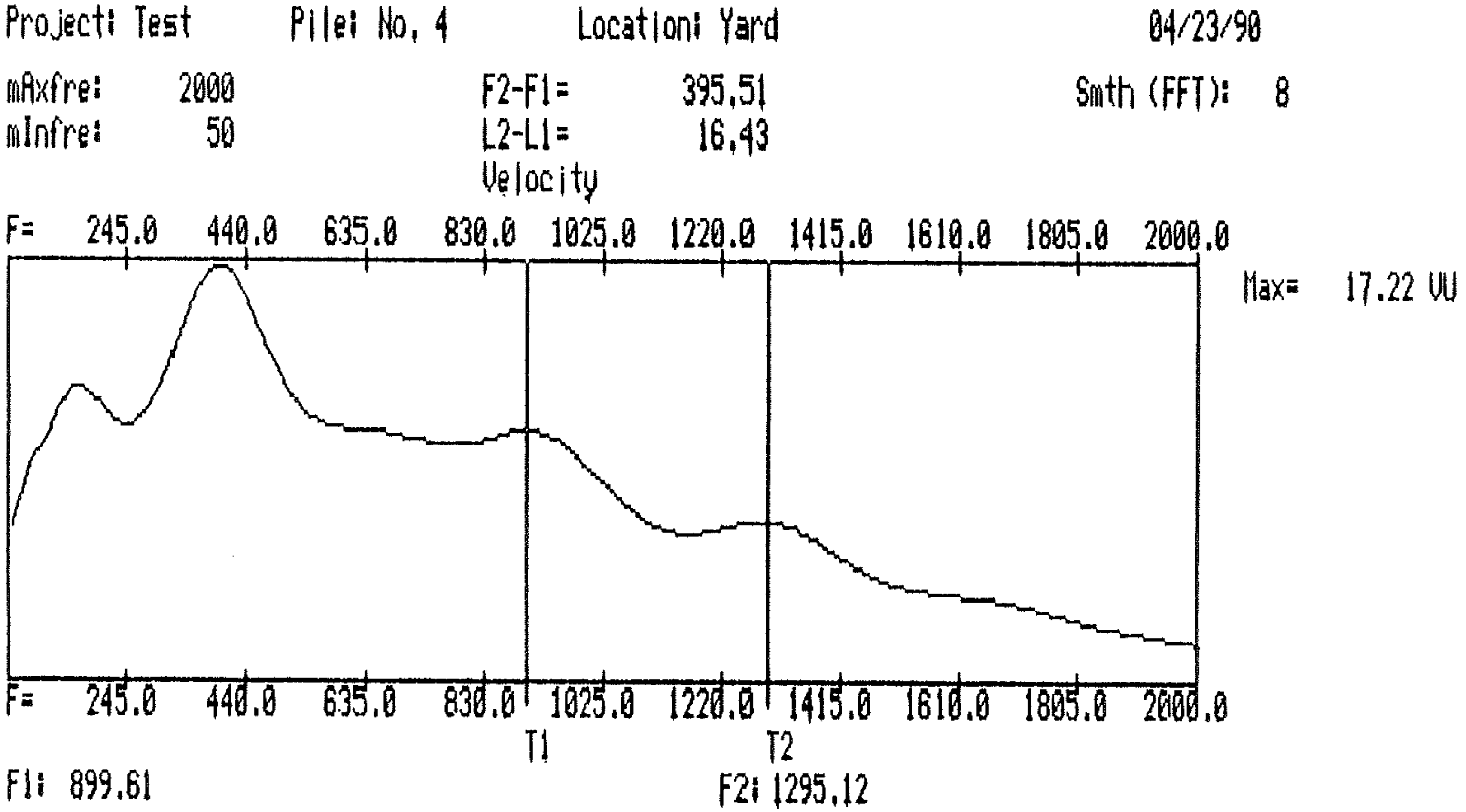
Project: Test Pile: No. 4 Location: Yard 04/23/90

2.96 v

ID 35
EFid 32
BNo. 53
Avge 3

Wspd: 12.96 T1: 0.32 T2: 3.48 X: 20.56 Y1: 36.11 % Y2: 8.33%
Wspd: 13.00 Leng: 20.50 Magn: 10.00 Smth: 5

Figure 7: Screen Display of Average Velocity, Average Force and Average Velocity Minus Force, Amplified Expoenetially. Magnification at Dotted Line (2L/c) is 10. Cross sectional Reduction and Pile Toe are Apparent at 14 and 20.5 ft depth. Positive V-F at Impact Indicates Slight Pile Top Impedance Reduction.



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Project: Test      Pile: No. 4        Location: Yard                    04/23/90
mAxfre:     2000              F2-F1=      395.51              Smth (FFT):   8
mInfre:       50              L2-L1=       16.43
                              Velocity
                                                                Max=   17.22 VU
F1: 899.61                                   F2: 1295.12
```

Figure 8: Velocity Spectrum; This Spectrum Divided by the Force Spectrum of Figure 5, Yields the Mobility Spectrum of Figure 7. Cursors were Set to a Frequency Interval Indicating a Length of 16.4 ft.

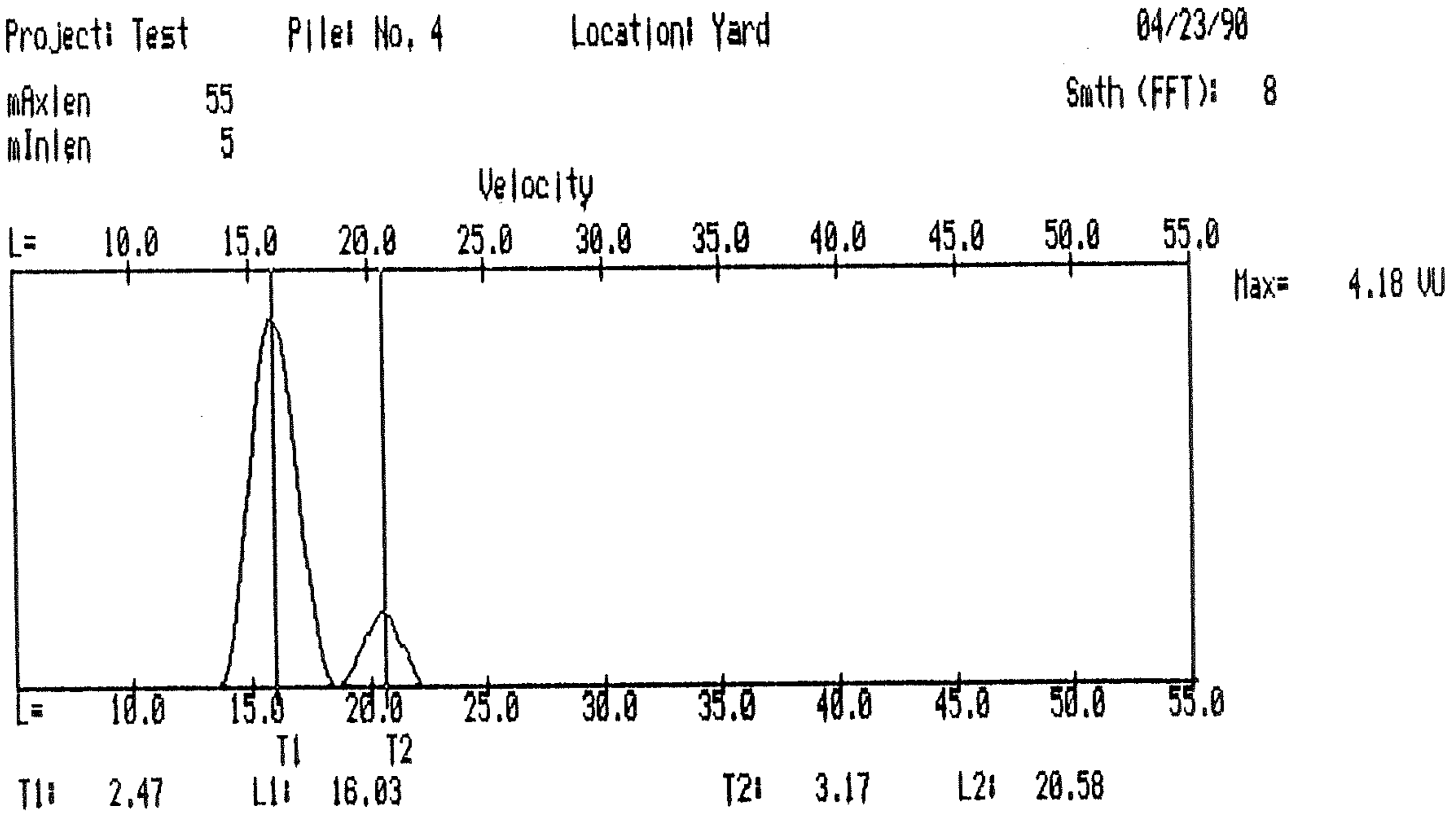
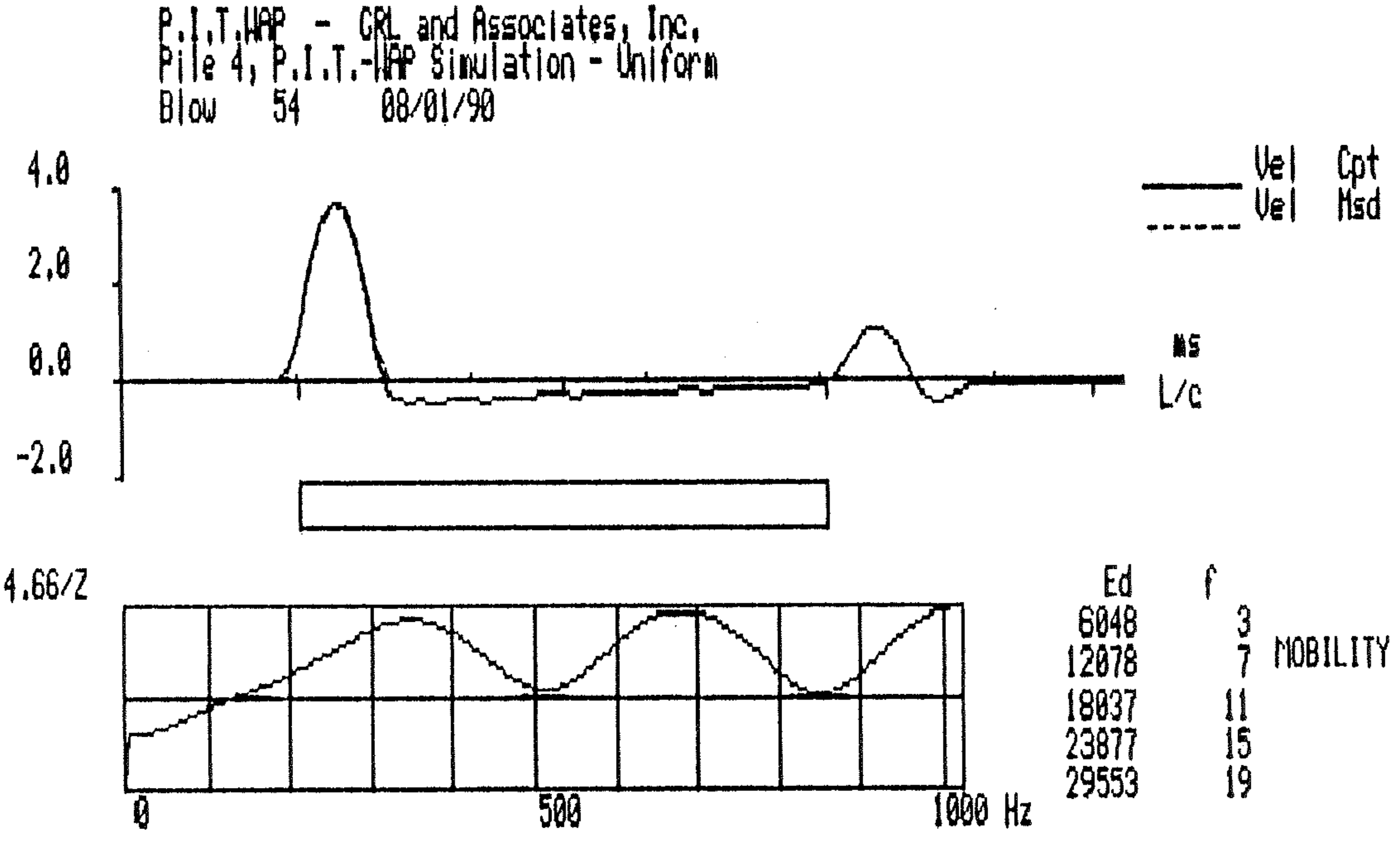
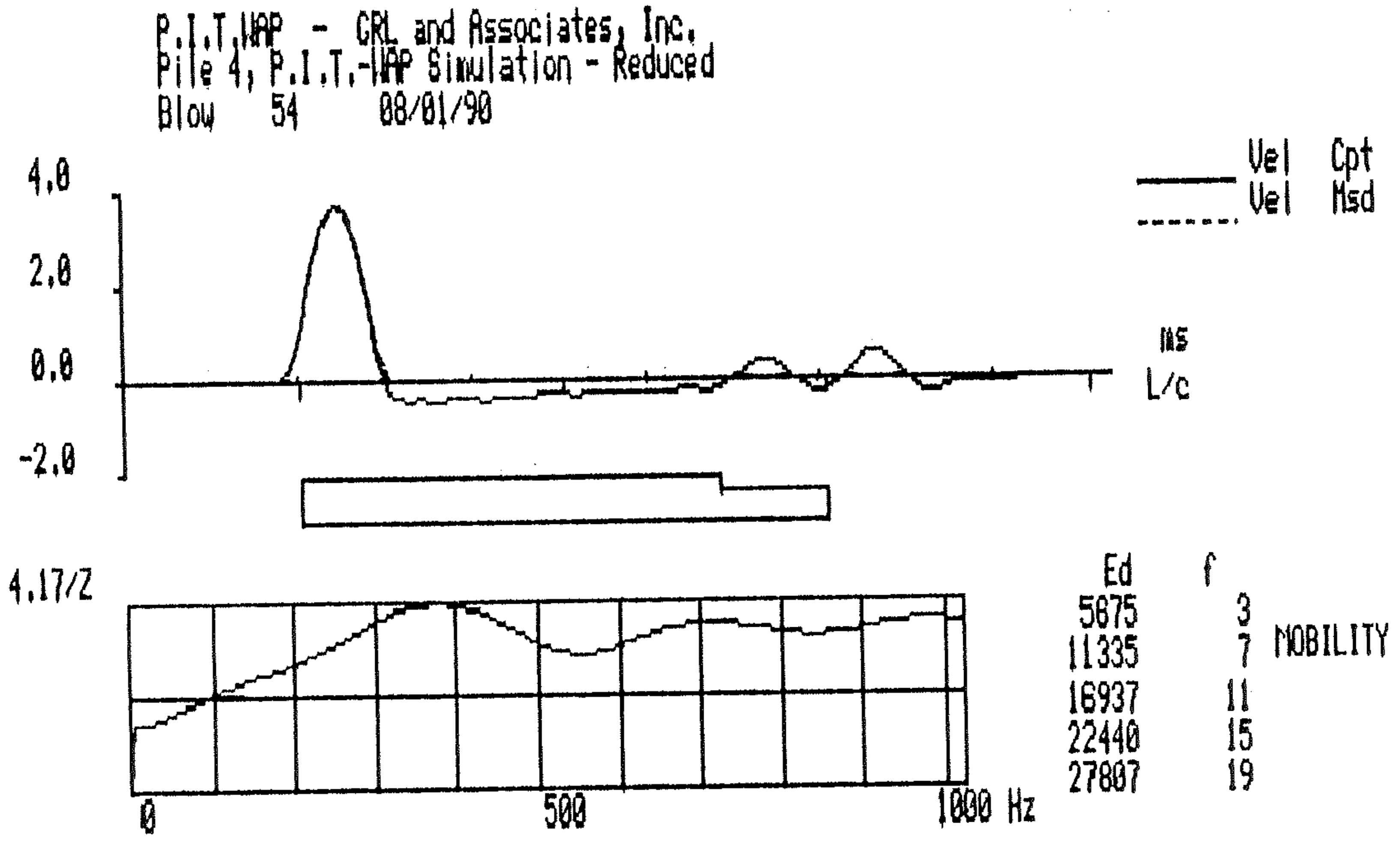


Figure 9: Reflectors from Fourier Transform of Velocity Spectrum. The T1 and T2 Cursors were set to the Non-Uniformity Indicator at 16 ft (built at 15 ft) and the Length Indicator which is Exact.


P.I.T.WAP - CRL and Associates, Inc.
Pile 4, P.I.T.-WAP Simulation - Uniform
Blow 54 08/01/90

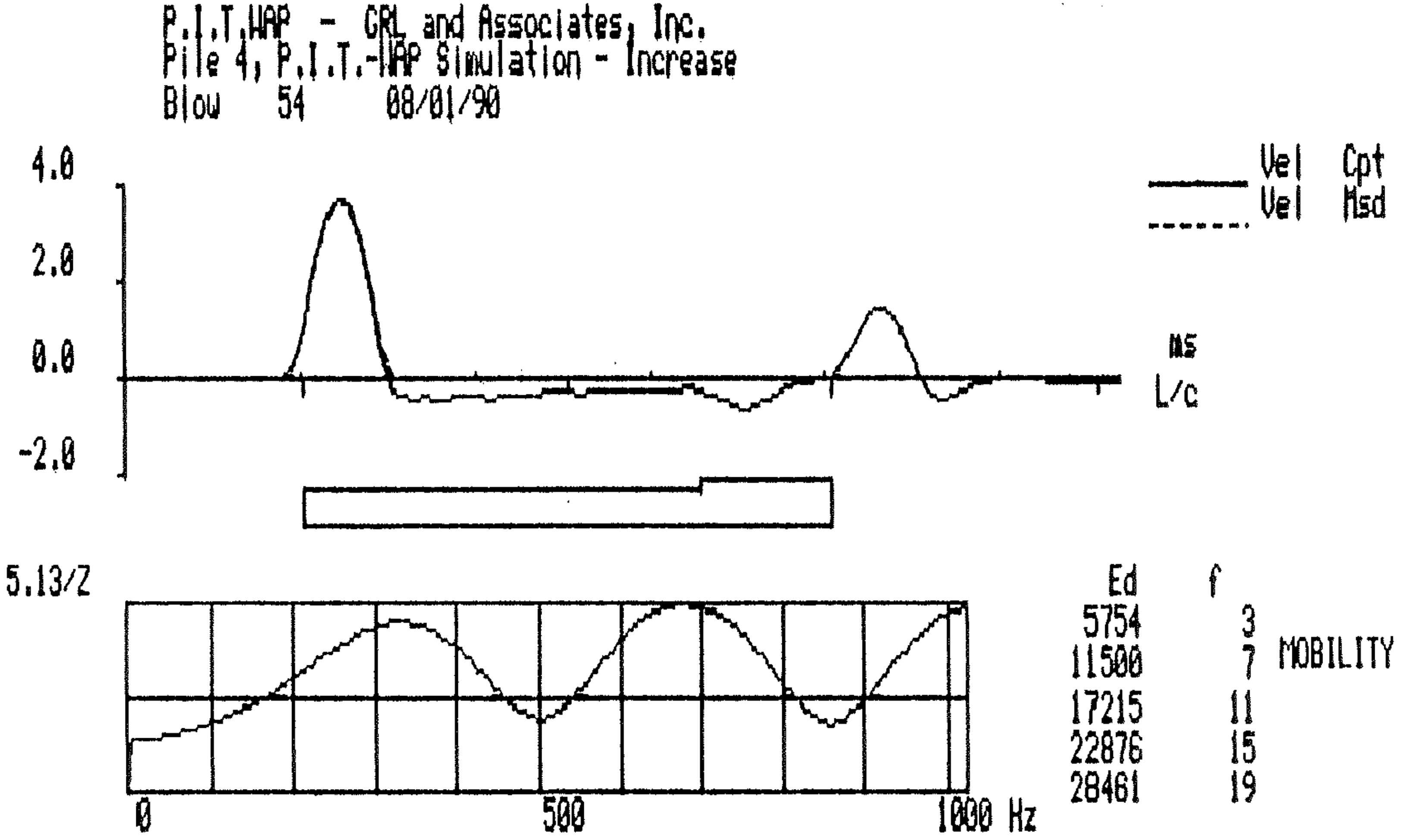
Ed	f
6048	3
12078	7
18037	11
23877	15
29553	19

Figure 10: Results from P.I.T.-WAP Simulation for Uniform 20 ft Pile.


```
P.I.T.WAP  -  CRL and Associates, Inc.
Pile 4, P.I.T.-WAP Simulation - Reduced
Blow   54     08/01/90
```

```
   Ed     f
 5675     3
11335     7
16937    11
22440    15
27807    19
```

Figure 11: Results from P.I.T.-WAP Simulation for Pile with Reduced Impedance from 15 to 20 ft.



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P.I.T.WAP  -  GRL and Associates, Inc.
Pile 4, P.I.T.-WAP Simulation - Increase
Blow   54     08/01/90
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Ed	f
5754	3
11500	7
17215	11
22876	15
28461	19

Figure 12: Results from P.I.T.-WAP Simulation for Pile with Increased Cross sectional between 15 and 20 ft Depth.

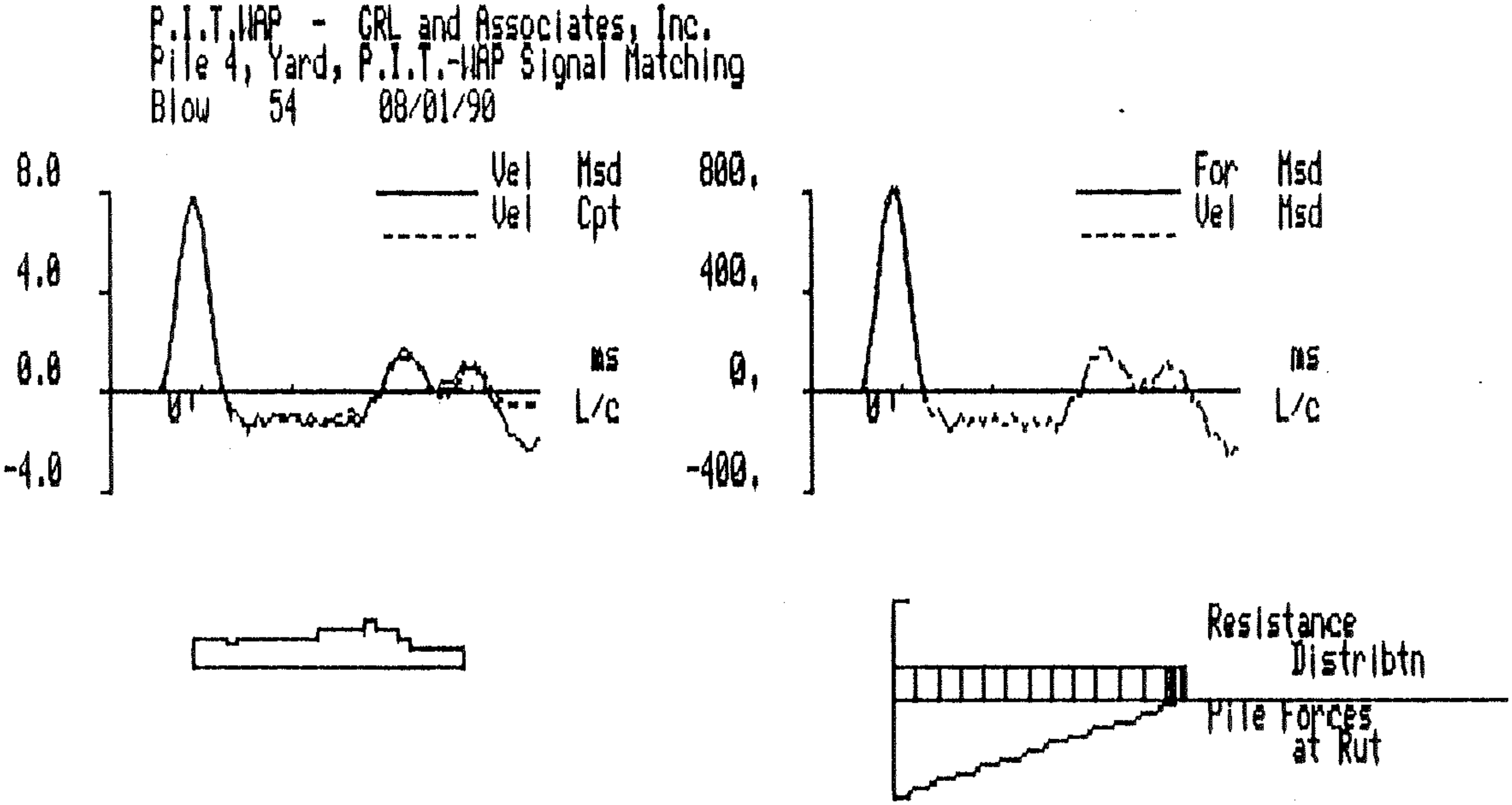

Figure 13: Results from P.I.T.-WAP Matching. From Upper Left, Clockwise: Match of Computed and Measured Velocity, Measured Velocity, Assumed Uniform Resistance Distribution, Predicted Pile Profile (if Higher Resistance is Used at Lower Pile than Less Impedance Increase would Result before Cross sectional Reduction.

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