Qualitative Evaluation of Force and Velocity Measurements During Pile Driving

Mohamad Hussein[1], and G. G. Goble[2]

Introduction

Simple observations made during impact pile driving are an important and integral part of the pile installation process. The number of hammer blows it takes to advance a pile a given distance into the ground has long been used as an indication of the soil bearing capacity. Visual observations of the ram during hammer operation (stroke, blows per minute, etc.), are taken as a measure of the overall hammer performance. A variation in the blow count (alternating decrease and increase) during driving of a pile into uniform soils is thought to indicate pile damage.

In recent years, however, the advent of electronic devices transformed the evaluation of the pile driving process from an art into a science based on actual field measurements. The techniques most widely accepted today for both measurement and analysis of pile dynamic events were developed under the direction of Professor G. G. Goble at the Case Institute of Technology (now Case Western Reserve University) starting in 1964, and hence, collectively often referred to as the Case Method. The Case Method is based on the measurements of force and velocity of the pile during pile driving or restriking by the hammer. This data provides the bases for evaluating hammer and driving system performance, pile driving stresses, pile structural integrity, and pile bearing capacity. These results are available in real time for each hammer blow by the Pile Driving Analyzer™. An extension of the Case project is also the CAPWAP™ computer program which uses the field measured pile force and velocity data and computes soil resistance forces, damping, and quake values along the shaft and at the toe of the pile.

A great deal of literature has been written about the equipment, analytical methods, electronics, and applications of the Pile Driving Analyzer (1, 2, 3). This paper, however, provides a qualitative performance evaluation of the various components of the pile driving process, given plots of pile top force and velocity histories.

The desired result of this paper is to expose engineers to some of the indications that one can learn by observing the characteristics of the pile top force and velocity history traces. The discussion is divided into three main topcis: 1) soil resistance, 2) pile behavior, and 3) hammer and driving system performance. In each section, example cases

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[1] AM. ASCE, Senior Engineer, Goble Rausche Likins and Associates, Inc., Cleveland, Ohio 44128

[2] M. ASCE, Professor, Department of Civil Engineering, University of Colorado, Boulder, Colorado 80301

will be presented and a list of related published papers will be provided for a more thorough treatment of each topic.

1. Soil Resistance

Verification of the bearing capacity of pile foundations has been performed by various techniques with varying degrees of accuracy. Capacities computed by methods that are based on measured pile force and velocity history traces provide clear indications regarding the soil resistance like: location along the shaft of the pile, whether it is mostly a skin friction or an end bearing pile, relative soil resistance changes with penetration soil set-up, and soil relaxation. A short summary of theoretical background on the effects of soil resistance on the force and velocity traces is deemed appropriate here.

For a uniform, elastic rod impacted at one end, proportionality exists between force and velocity as long as no waves travel in the opposite direction. Thus, for a uniform pile of length L with no soil resistance, the measured pile top force, F, and velocity, V, are related by $F = (EA/c)V$ until time $2L/c$ after impact. The quantity EA/c is known as the pile impedance, where E is the pile material's elastic modulus, A, area, and c, celerity, (stress wave speed). Soil resistance forces cause compressive, upward traveling waves which increase the pile top force and decrease the pile top velocity. The amount of separation, $F - (EA/c)V$, at any time, t, after impact, is caused by the sum of soil resistance acting above a distance, $x = ct/2$ below the pile top.

(Note: Since CAPWAP analysis is capable of separating soil resistance forces acting along the shaft and at the tip of the pile, its results will be employed as a check for the visual interpretations provided for by the following example cases).

The three plots shown in Figure 1 illustrate the effects of soil resistance on the visual characteristics of the pile top force and velocities. The theoretical proportionality between force and velocity is shown to hold for however long it takes for soil resistance waves to reach the pile top (Figure 1a). Figure 1b shows the traces from a pile that appears to be mainly a skin friction pile with soil resistance very close to the pile top; this is indicated by the separation of the force and velocity traces between impact and time 2L/c. (By comparison, CAPWAP showed that this pile had 96% skin friction and 4% end bearing). The effects of soil resistance forces acting both along the length and at the tip of a pile on the force and velocity histories measured at the pile top are shown in Figure 1c. (By comparison, CAPWAP indicated that this pile derives 23% of its capacity in skin friction and 77% from end bearing).

Observing the behavior of the pile top force and velocity records can be of great value when driving a pile to a specified bearing layer. Figure 2 presents traces of force and velocity of three blows during the installation of a closed end pipe pile through a relatively loose layer to a layer of dense sand. Figures 2a, 2b, and 2c represent blows during the very beginning, 5 blows per foot (BPF), middle 20 BPF, and end of driving 200 BPF, respectively. Notice that the multiple reflections of the impact wave at regular 2L/c intervals, lack of separation between impact and time 2L/c later, and the high positive velocity reflection at 2L/c indicate the lack of soil resistance. Figure 2b differs from 2a in many ways: the reflection of the waves at 2L/c time came later than those in Figure 2a (another section of almost equal length had been spliced to the original pile section), the separation between the curves along with the absence of multiple reflection (although one can still see a small reflection at 4L/c) indicate the development of skin friction and that driving had become a little harder. Figure 2c represents the traces after the pile had reached the bearing layer indicated by the positive force (rather than velocity) reflection at 2L/c. Also, notice that the rate of separation becomes greater just to the left of 2L/c indicating the penetration of the pile into stiffer materials near the pile toe.

The long-term bearing capacity of foundation piles driven into soils that have time dependent strength changes can be investigated by studying pile top force and velocity traces representing blows at the end of initial driving and at the beginning of restrike some time after installation. Soils may gain (set-up), or lose capacity with time. Set-up generally occurs along the shaft and relaxation at the tip of the pile.

Apparent soil strength increase (set-up) has been attributed to many factors; loss of soil strength caused by remolding during pile driving is recovered with time, reduced strength during driving may also be caused by the build up of pore water pressures and soil liquification, an oversized hole created around the pile because of nonaxial pile movement during driving also decreases the initial capacity of the pile; with time, however, soil pressures cause the soil to collapse eliminating the hole around the pile and thus, increasing its capacity. Relaxation is a less understood phenomena; it is, however, known to occur when nondisplacement piles are driven into shale, for example.

Figures 3a and 3b illustrate cases of set-up and relaxation, respectively. Traces representing one hammer blow at the end of driving and another during restrike of a pipe pile driven through soft, silty sands show the presence of set-up. This is indicated by the increase in the area of separation between the force and velocity records of the restrike blow as compared to that at the end of driving. The relaxation case, Figure 3b, was adopted from a paper authored by Dr. Bengt Fellenius and published by "Civil Engineering Magazine", (November, 1984). Comparing the force and velocity traces, one can see the effects of relaxation: at 2L/c, a relative decrease in force and increase in velocity, after 2L/c a decrease in the overall (especially the peak) force response.

Another way in which the qualitative study of pile top force and velocity history traces can aid in the understanding of soil behavior is the detection of large soil quakes. In practicality, this is generally referred to as "bouncy driving". This is an unfavorable condition because it renders the driving processes inefficient, allows the development of possibly damaging tensile stresses in concrete piles under apparently high blow counts, makes the computed capacity of the pile incorrectly high if computed by wave equation analysis using standard 0.1 inch quakes. Although high quakes have been associated with large displacement piles driven into saturated, fine grained soils (Likins, 7), cases have been also reported where large quakes have been observed with nondisplacement piles too (Hannigan, 13).

Figure 4 presents the plots of pile top force and velocity history traces during a blow at the end of driving of a 54" cylinder pile driven into sandy, clay soils. The driving resistance was over 10 blows per inch. Although the blow count was very high, the traces show a velocity increase (still positive) relative to force at 2L/c, but a short time after that the velocity goes negative (pile rebound) and the force increases showing a strong, but delayed tip resistance. What the records show is that there is a strong soil resistance reaction of the soil at the pile tip, however, this reaction is delayed in time which translates to pile displacement. (By comparison, CAPWAP analyses showed that the soil quakes along the skin and at the toe were 0.20" and 0.33", respectively. The normal assumed values are 0.1").

The following papers are suggested references for the topic discussed in this section (4, 5, 6, 7).

2. Pile Behavior

The most severe stress conditions that a pile will undergo during its service life are those caused by pile driving. During installation, stresses at any location along the pile may be critical. High compression stresses may be damaging if pile top stresses are high, if the pile is nonuniform, or if the soil resistance is concentrated (at the pile tip, for example). For concrete piles, the tension stresses could be more detrimental than the compression forces. This is especially true during easy driving. Nonaxial hammer impacts may also cause pile distress. After a pile has been installed, a question remains regarding its structural integrity. Records of pile top force and velocity provide insight into the understanding of the pile's behavior during driving.

In almost all applications of dynamic pile testing at least two each of strain transducers and accelerometers are used. Figure 5a (top) presents the force records obtained from two strain gages attached on opposite sides of a 24 inch precast, prestressed, concrete pile. Notice that one side was subjected to about twice the force that the other side was receiving.

Force histories recorded from opposite sides of another 24 inch prestressed, concrete pile are shown in Figure 5b. This figure illustrates a case where the peak force was the same on both sides of the pile, however, the characteristics of each of the force histories are significantly different. The bottom traces for both Figures 5a and 5b represent the average (uniform) and half the difference (bending at the transducer location) between the two forces for each case.

The measurements of force and velocity at the pile top may be used to obtain the maximum tension stress in the pile due to impact stress reflections. This information is invaluable for proper installation of concrete piles having limited tensile strength.

In the case of no resistance, the input compressive force travels the length of the pile and reflects as a tension wave. Soil resistance reduces the magnitude of these reflections. The force in the reflection wave is related to the measured force and velocity at a time 2L/c after impact. This tension wave is reduced by the superposition of the still downward traveling input compressive wave.

The pile in Figure 6 is a 66 inch cylinder pile driven through loose silts. Figure 6a shows the pile top force and velocity history traces during a hammer blow at the beginning of driving. Figure 6b presents the wave down, (F+V)/2, and wave up (F-V)/2, histories as measured at the pile top. Notice that the upward traveling wave is in tension. A procedure that may be used (visually) for the interpretation of force and velocity traces for the pile net tension is given in Figure 6c.

As mentioned earlier, for a uniform pile, the records of pile force and velocity are proportional before stress wave reflections arrive at the pile top from resistance effects or pile toe. However, for a pile that is nonuniform at a location along its length, reflection waves will also be generated. Resistance effects or an increase in pile cross sectional area cause the pile top force to increase relative to the velocity. A cross-sectional reduction causes the opposite effect.

The top plot in Figure 7 illustrates the indication of damage in the force and velocity traces during a hammer blow while installing a prestressed, concrete pile. Approximately 20 blows later, it is quite apparent in the records that the pile has been totally damaged (Figure 7c). The location of damage can be estimated by measuring the time it took the impact wave to reflect from the location of discontinuity.

Traces showing a sudden failure of a welded splice are shown in Figure 8. The traces shown represent force and velocity histories during two consecutive hammer blows.

The following are suggested reading material for this topic (8, 9, 10).

3. Hammer and Driving System Performance

Any analytical pile analysis depends primarily on a realistic prediction of hammer and driving system (hammer cushion, cap, pile cushion) performance. The most direct approach to evaluate the effectiveness of the hammer and driving system in driving a pile is to take force and velocity measurements near the pile top. This data can be processed to yield the actual amount of energy that is being delivered by the driving elements to the pile.

Records of force and velocity histories measured near the pile top may be visually inspected for a qualitative evaluation of the performance of both hammer and driving system.

Figure 9 shows plots of force and velocity histories recorded near the top of a steel pipe pile driven with an open end (single-acting) diesel hammer. The separation of the traces (relative increase in force) before impact reflects the presence of precompression in the hammer combustion chamber. If preignition of the gases before the ram impacts the anvil occurs, this separation will become larger and the quick dynamic rise will be reduced. Preignition causes less ram kinetic energy to be transferred to the pile and it generates high ram strokes, giving the impression of a good hammer operation.

Figure 10 shows traces of pile top force and velocity histories during the operation of a double-acting diesel hammer on a steel pipe pile. Figure 10a represents a blow during normal hammer operation, and Figure 10b a blow after prolonged operation showing hammer preignition.

The behavior of the cushioning elements in the driving system has a large influence on the successful pile driving installation. Figure 11 presents plots of force histories monitored near the top of a concrete pile during two hammer blows. During the first blow the cushion was new (several inches of plywood); the second blow occurred after a period of driving. Notice that the peak force is higher and the rise time (the time between impact and peak value) is shorter for the used cushion.

Conclusion

The Pile Driving Analyzer™ is not a "Black Box" that prints out numbers which are the undisputed solution for every problem. The results should be interpreted in light of an understanding of the quantities measured. Plots of pile top force and velocity history traces provide further valuable information for a qualitative evaluation of the soil, pile, hammer, and driving system components during the pile driving process.

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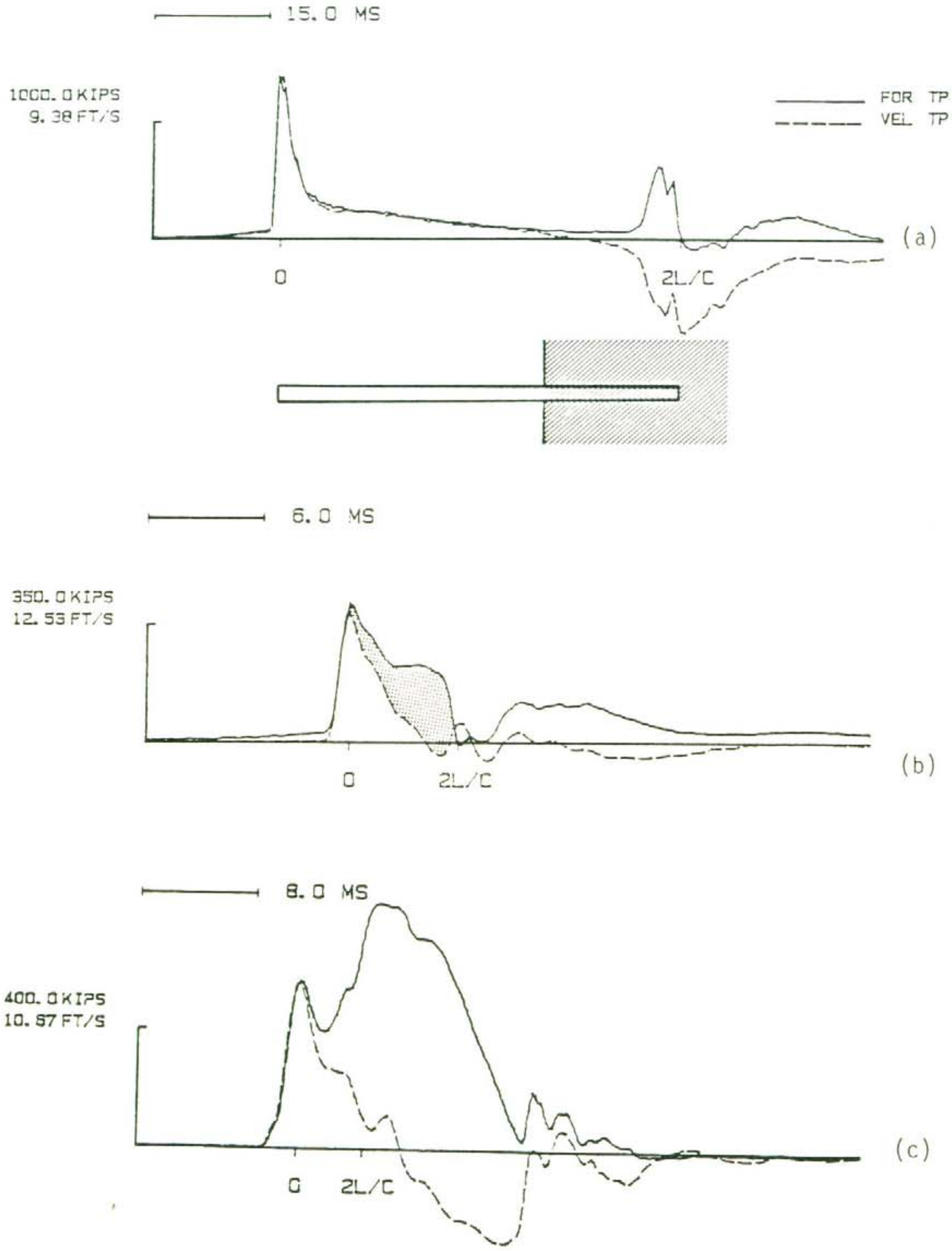

Figure 1: a) Proportionality between force and velocity holds until soil resistance reflections reach the pile top, b) separation between force and velocity between impact and time 2L/c indicates skin friction, c) traces indicate a pile having both skin friction and end bearing.

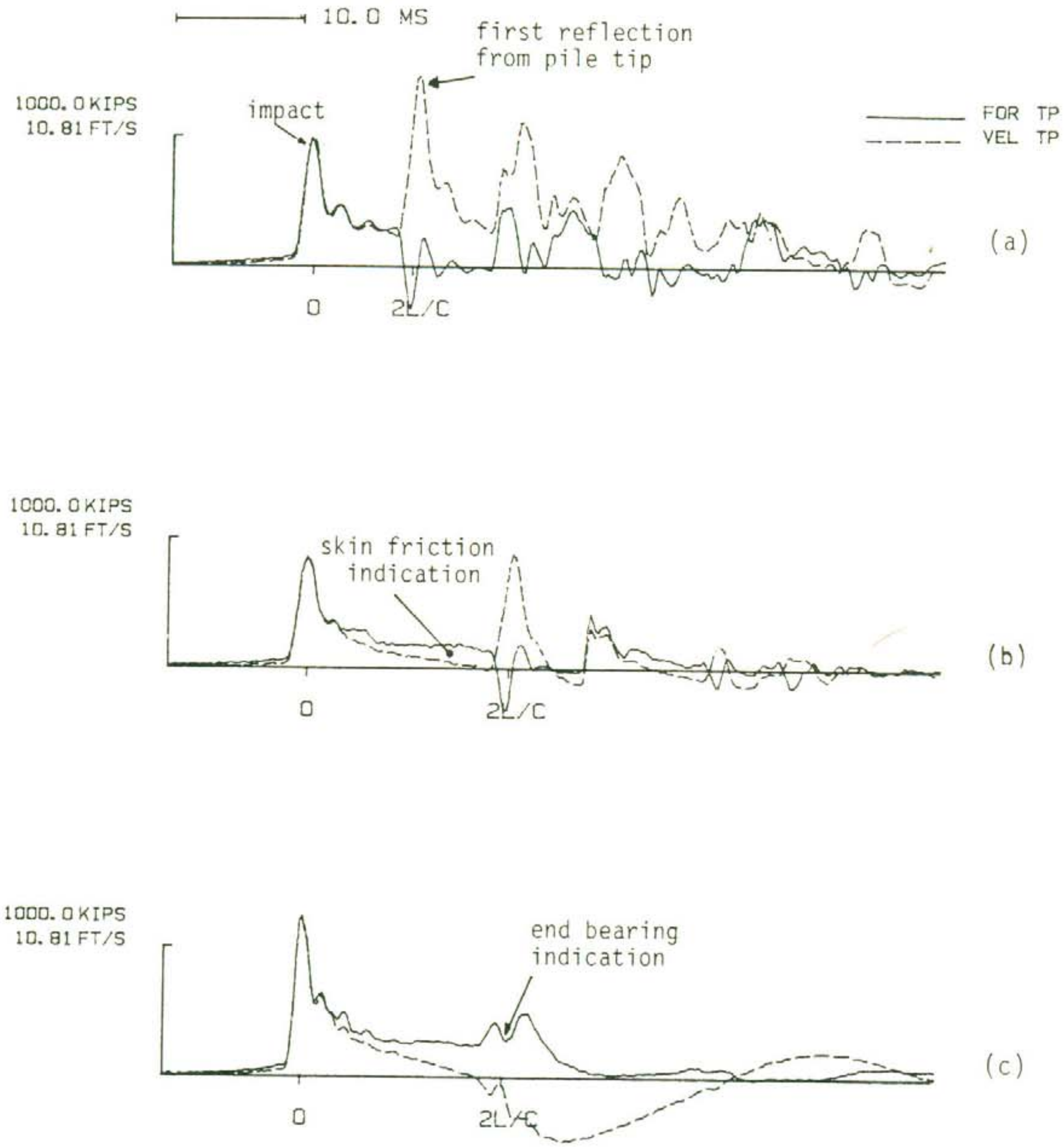

Figure 2: Plots of pile top force and velocity histories representing blows during: a) easy driving, b) somewhat hard driving (notice that 2L/c time is longer after splice), and c) hard driving.

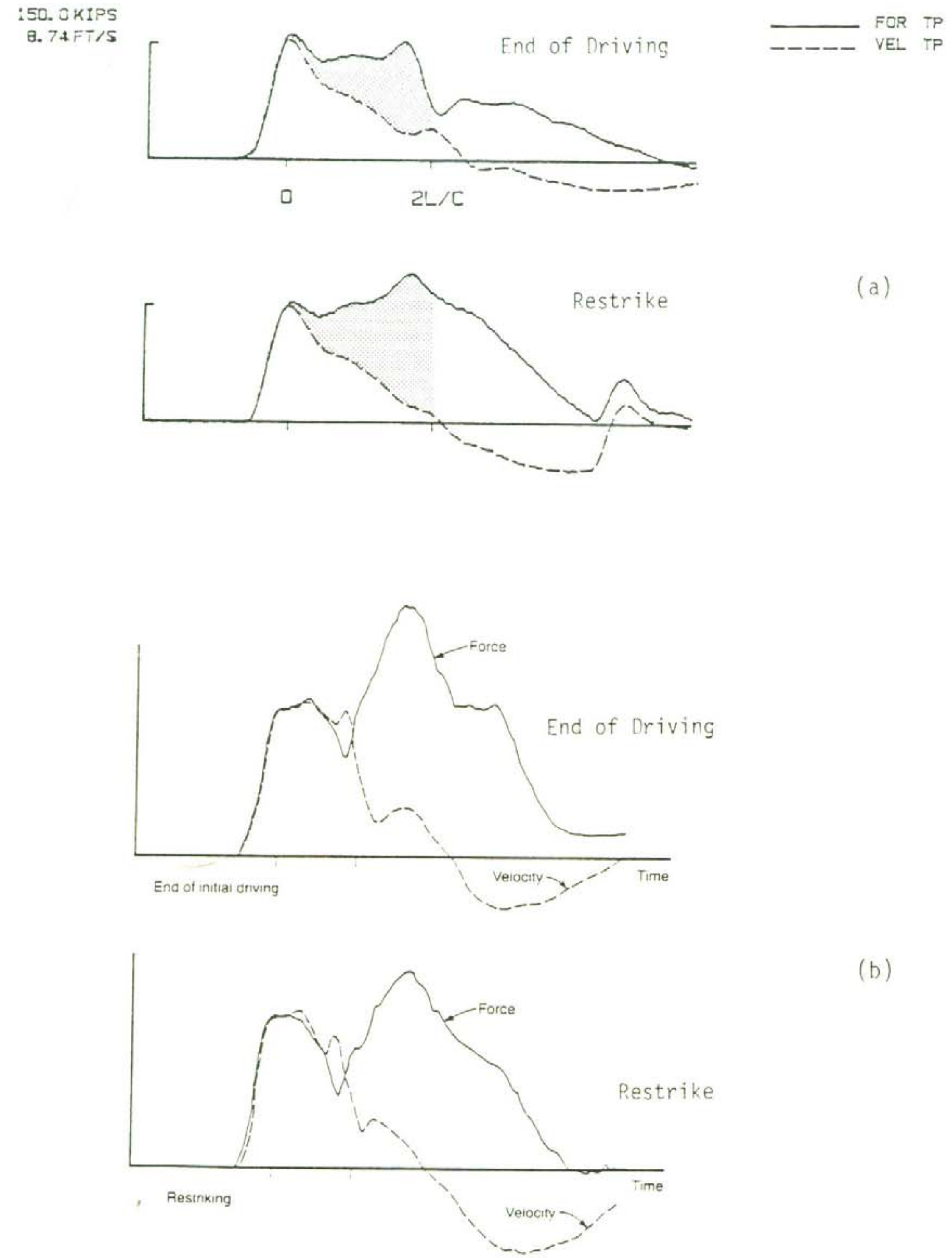

Figure 3: Examples of time dependent soil strength changes effects on pile top force and velocity histories: (a) setup, (b) relaxation (after Fellenius, 1984)

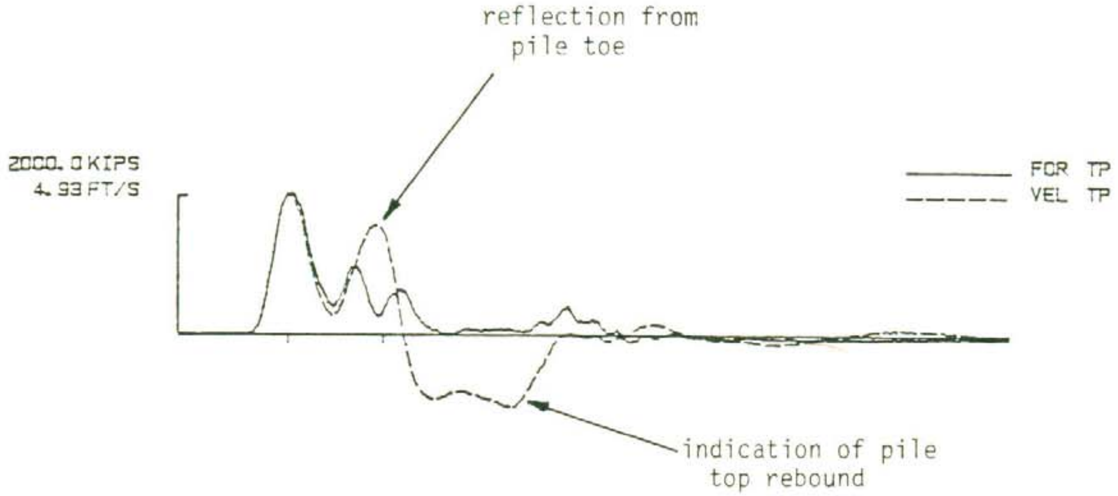

Figure 4: Plots of pile top force and velocity histories showing the presence of large soil quake.

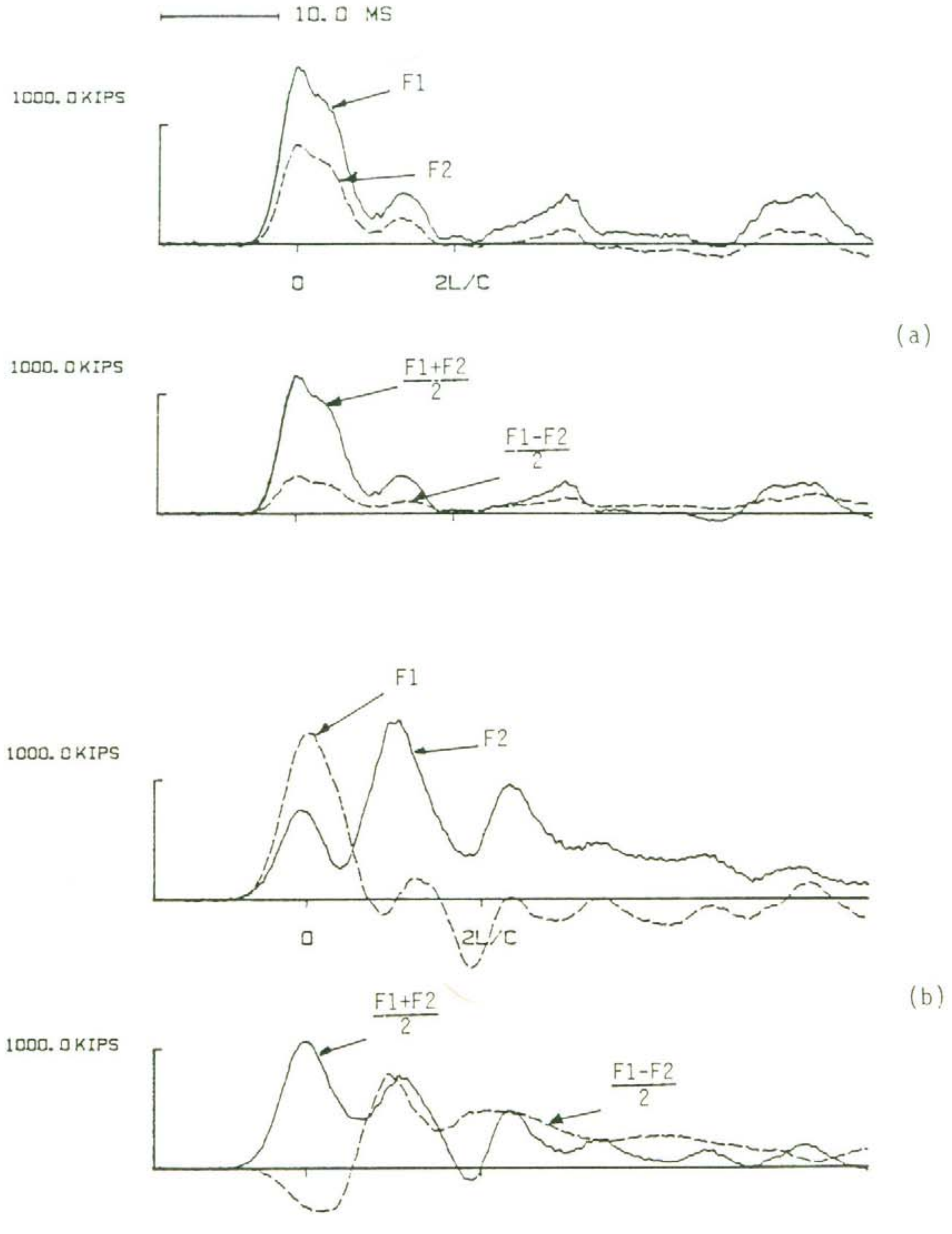

Figure 5: Pile top force history traces showing two cases of non-axial hammer impacts

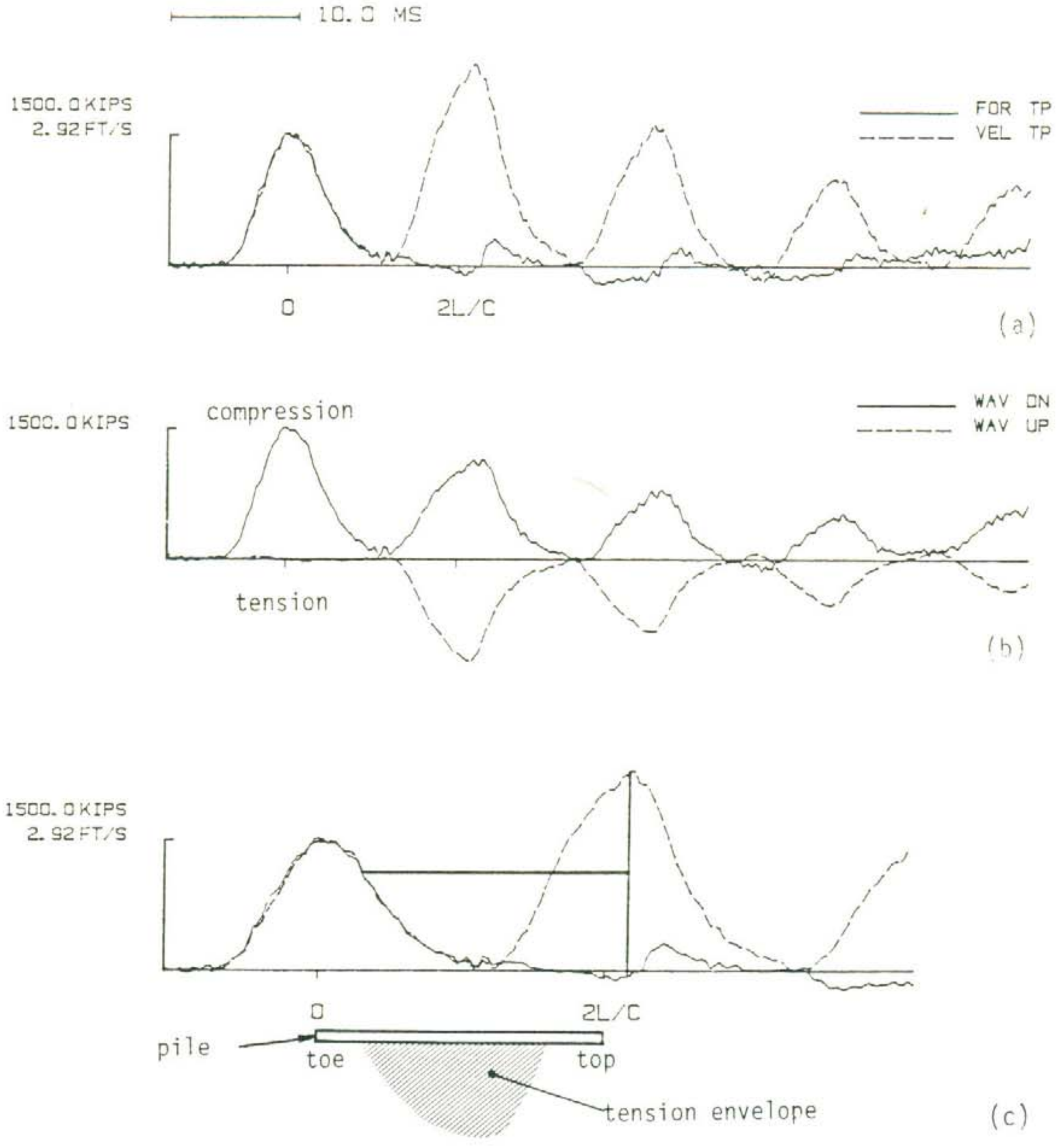

Figure 6: (a) pile top force and velocity history plots during easy driving
(b) wave down (F+V/2) and wave up (F-V/2) histories; notice that wave up is in tension
(c) geometric construction of the tension envelope along the pile length

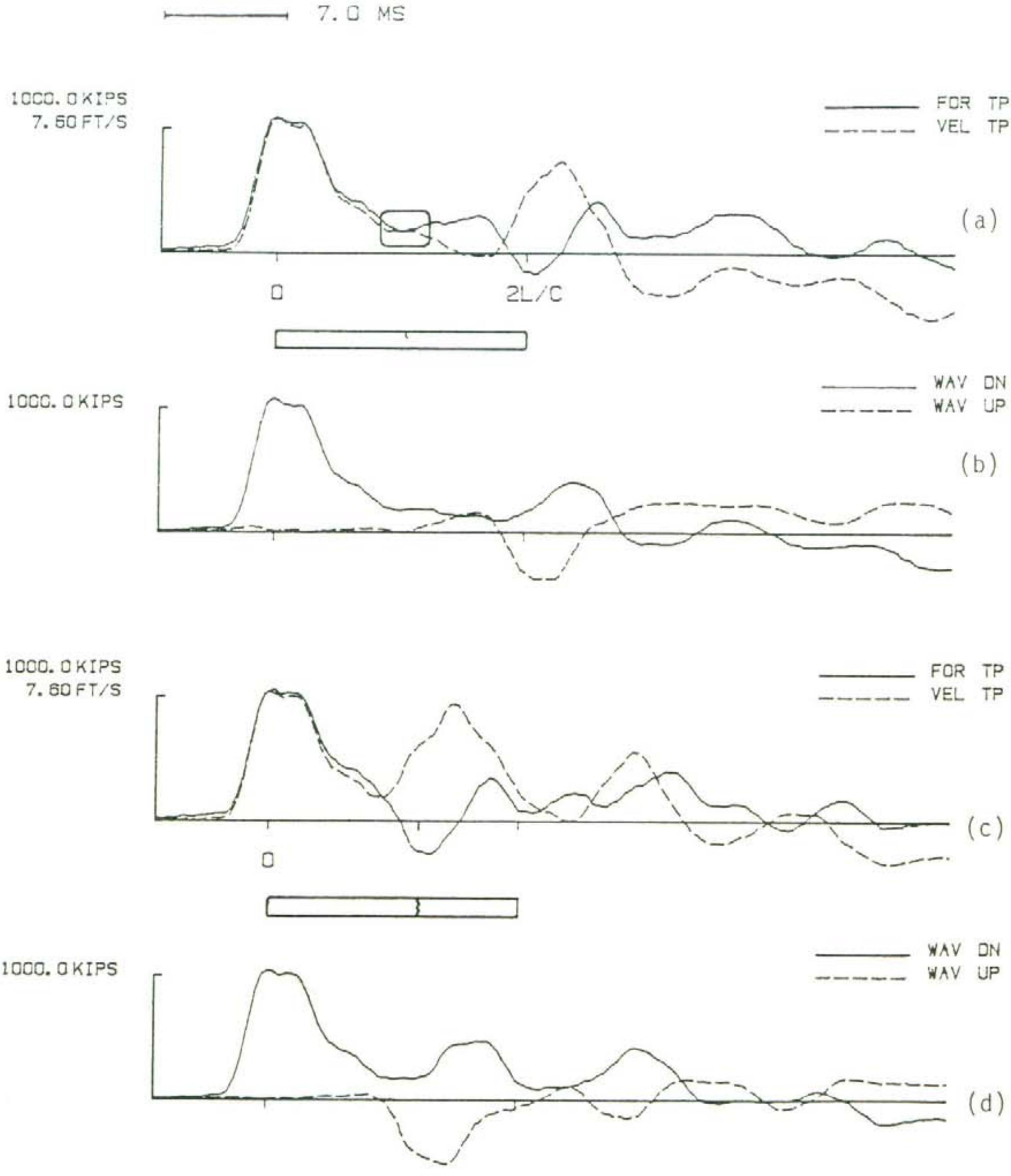

Figure 7: Plots of pile top (a,c) force and velocity (b,d) wave up and wave down histories showing indications of possible pile damage (top 2 figures) and total pile damage (bottom 2 figures) a few hammer blows later.

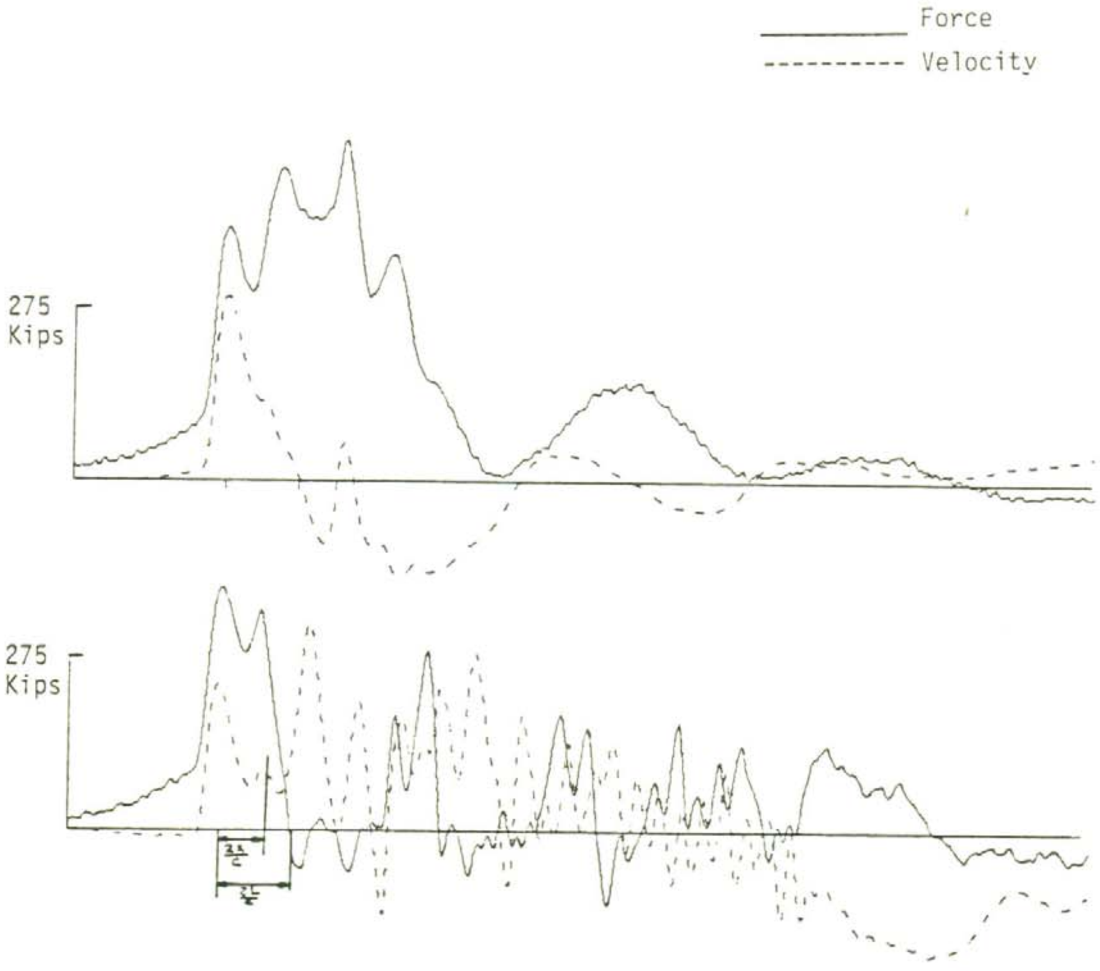

Figure 8: Plots of pile top force and velocity histories representing two consecutive hammer blows. Notice the sudden development of pile damage (bottom figure)

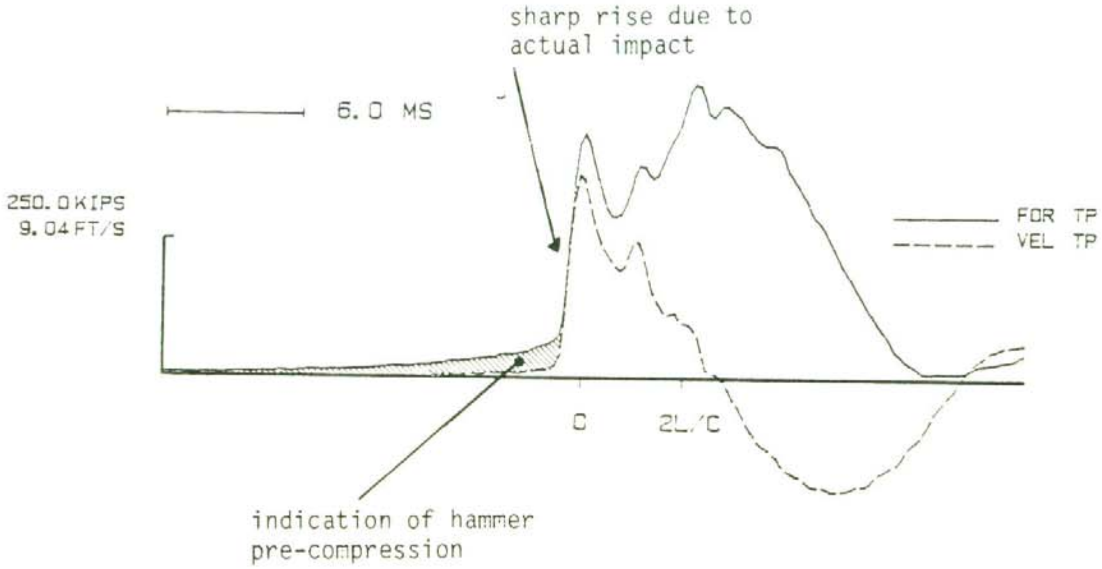

Figure 9: Hammer performance as indicated by the histories of pile top force and velocity

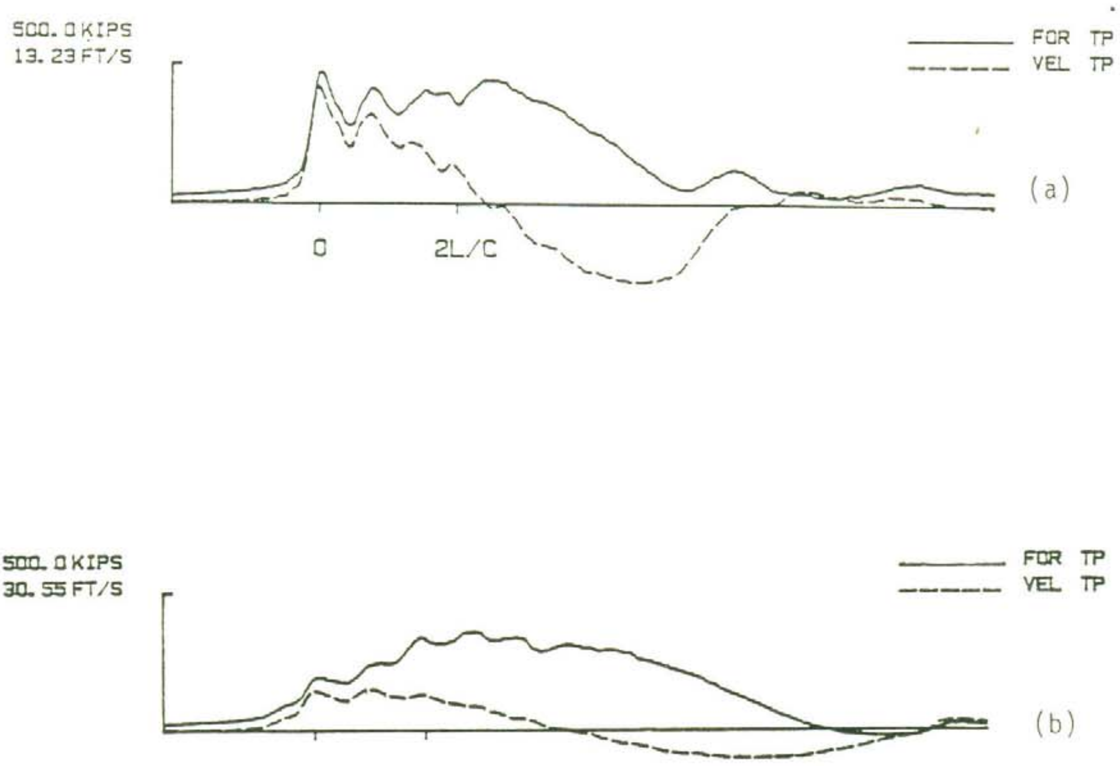

Figure 10: Plots of pile top force and velocity showing:

(a) Traces representing a hammer blow indicating normal hammer operation (with slight precompression)

(b) After prolonged use of the same hammer, traces indicate preignition.

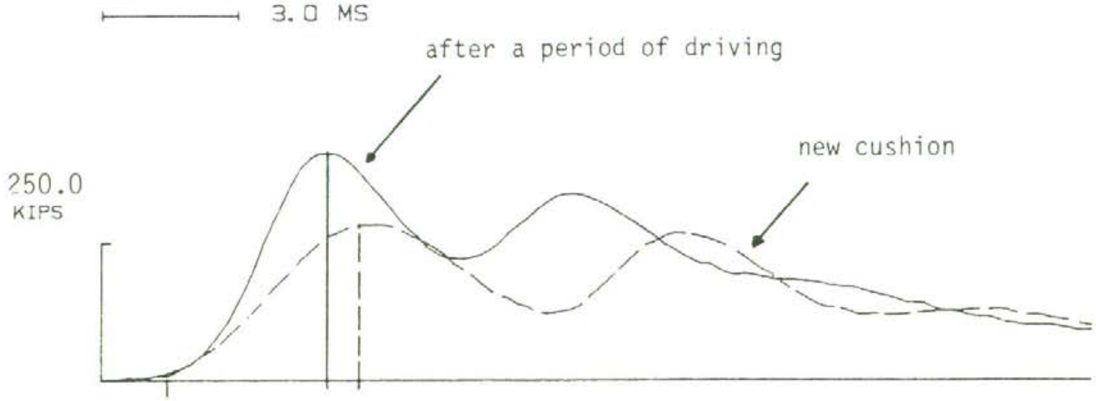

Figure 11: Plots of pile top force histories during two hammer blows. The first was while new pile cushion, and the second after a period of driving.