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16. Abstract

A study was undertaken on the performance of pile driving systems. First, analytical methods available for routine pile design and installation analysis were summarized (Main Report, V.I). Next, the existing technology for the measurement of performance parameters was reviewed (Main Report, V.II). Third, new measurement systems were evaluated and, finally, recommendations for the development of a new measurement were made (Main Report, V.III). Another facet of the project investigated the actual behavior of pile driving systems based on existing measurements. Depending on hammer type, average wave equation efficiencies were calculated and summarized (Main Report, V.IV).

The third group of results was an inspection manual for pile driving systems, i.e. for impact hammers as well as cushions, helmets, leads, etc. This inspection manual was illustrated by a tape slide show in five parts as a teaching aid for pile driving inspectors. A Saximeter was also delivered as an inspection tool.

This is the Third Volume of the Main Report which comprises four volumes. An Inspection Manual, the narrative of the Tape Slide Show, and a Summary Report were also issued.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Volumes I, II and IV have shown that no simple system currently exists for determining driving system parameters. It is apparent from these reports that the differences between the various types of pile driving hammer configurations may require the measurement of different quantities. Therefore, it is desirable to have a flexible system which may be easily configured for different applications.

There are five categories of driving systems that may require different treatment. In the order of increasing complexity these systems are:

(a) Air/Steam/Hydraulic (ASH) hammers with exposed (visible) ram on steel piles

(b) ASH hammers with fully enclosed (non-visible) ram on steel piles

(c) ASH hammers on non-steel piles

(d) Diesel hammers on steel piles

(e) Diesel hammers on non-steel piles

For ASH hammers with a visible ram, a direct measurement of impact velocity is possible using radar technology. Although the capblock properties would remain unverified, a major source of uncertainty about hammer performance would be removed. The radar device is a simple system, and is described in Volume II. Its integration in the proposed performance monitoring system will be discussed in Chapter 2.

The present study concludes that the radar device is the only feasible direct method for the measurement of impact velocity. However, for other hammer types (except ASH hammers with visible ram), the radar device does not offer a simple solution, and in most cases cannot even be used. Thus, indirect measurements are necessary. The more complex a system, (i.e. the more unknowns that exist), the more measurements are needed for a unique solution. For example, the presence of a pile cushion adds two unknowns, the cushion stiffness and its coefficient of restitution; accelerometer measurements taken on the helmet will allow these quantities to be determined.

As opposed to direct measurement methods, driving system parameters must be computed from indirect measurements. After investigating closed form solutions (Chapter 3), it was decided that the most promising method involved a simple minimization of the differences between computed quantities and corresponding measured data points. The minimization, performed with an automated matching technique, is also described in Chapter 3.

For completeness, Chapter 4 discusses alternate methods, including a laboratory study on ram acceleration measurements. These alternatives are not recommended solutions. Chapter 5 discusses test procedures for the improved concepts, and gives recommendations for a stepwise implementation. Finally, Chapter 6 contains recommendations and conclusions.

2. THE RADAR DEVICE

2.1 Introduction

During the course of this project, Tera, Inc. and McClelland Engineers in Houston, Texas and Pile Dynamics, Inc. of Cleveland, Ohio announced the development of a device for the measurement of ram impact velocity using radar technology. These devices, called the RVM and HPA, were described in Volume II. They are currently used primarily for offshore construction control, that is on large air/steam/hydraulic hammers (ASH) with visible rams driving steel piles. They have also tested SPT soil samples.

Radar is commonly used for enforcement of traffic speed regulations. The technology is, therefore, readily available and only needs minor modifications for pile-hammer applications. The following discussion deals with the preferred integration of this direct measurement tool into practice.

2.2 Possible Applications

For ASH hammers with visible rams, the RVM/HPA radar devices accurately measure velocity of the ram as a function of time. For open end diesel (OED) hammers, ram velocity as a time function may also be measured, although not on a routine basis. If ram velocity were the only factor governing performance, radar measurements would provide sufficient information for construction control. However, cushion and/or capblock materials, often unknown properties, are present and additional indirect measurements must be taken. If these indirect measurements are taken, then the radar device provides redundant information since impact velocity can also be determined from the indirect measurements. Therefore, radar seems to be an ideal tool to calibrate or confirm results from indirect measurements.

Since radar can determine the variation of ram velocity with time, this device may be used very effectively to determine the cause of improper hammer performance. For example, in the case of the OED, the energy losses above the ports can be separated from losses during the compression phase and from actual impact losses. Such detailed investigations should be supplemented by indirect measurements since preignition of only as little as 5 ms can have a major influence on energy transmission, yet is not distinguishable in the radar results.

2.3 Installations

The radar unit must be positioned such that the ram is within its beam cone (approximately 10°) for optimal results. For ASH hammers, the antenna should be installed near the pile and directed upward to the ram (Figure 2.1). If a sufficiently large surface of the ram is not observed by the radar beam, then a target may need to be attached to the ram. The target is a small block of rigid styrofoam with aluminum foil reflective surfaces glued to the side of the ram. The use of massive "targets" is discouraged as they would be a safety hazard. Naturally, the radar device and the target should not vibrate before impact.

As with all devices which use their own position as a reference, it is important that the radar is stable. With the device installed at grade, a ground surface disturbance will probably always occur shortly after impact due to the ground vibrations. An accelerometer installed in the radar device could determine the potential error due to reference vibration. Since the radar does not determine the sign of the velocity, an error cancellation would be difficult, although not impossible for specific applications. An easier solution is to simply shock mount the radar antenna.

For OED hammers, and all other hammers whose ram is only visible from the top, the radar unit may be attached to the hammer leads with the radar beam directed into the cylinder (Figure 2.2). In this case, the problem of reference motion may pose an even more serious problem. In addition, mounting the radar at such height creates a safety hazard, requiring backup safety cables.

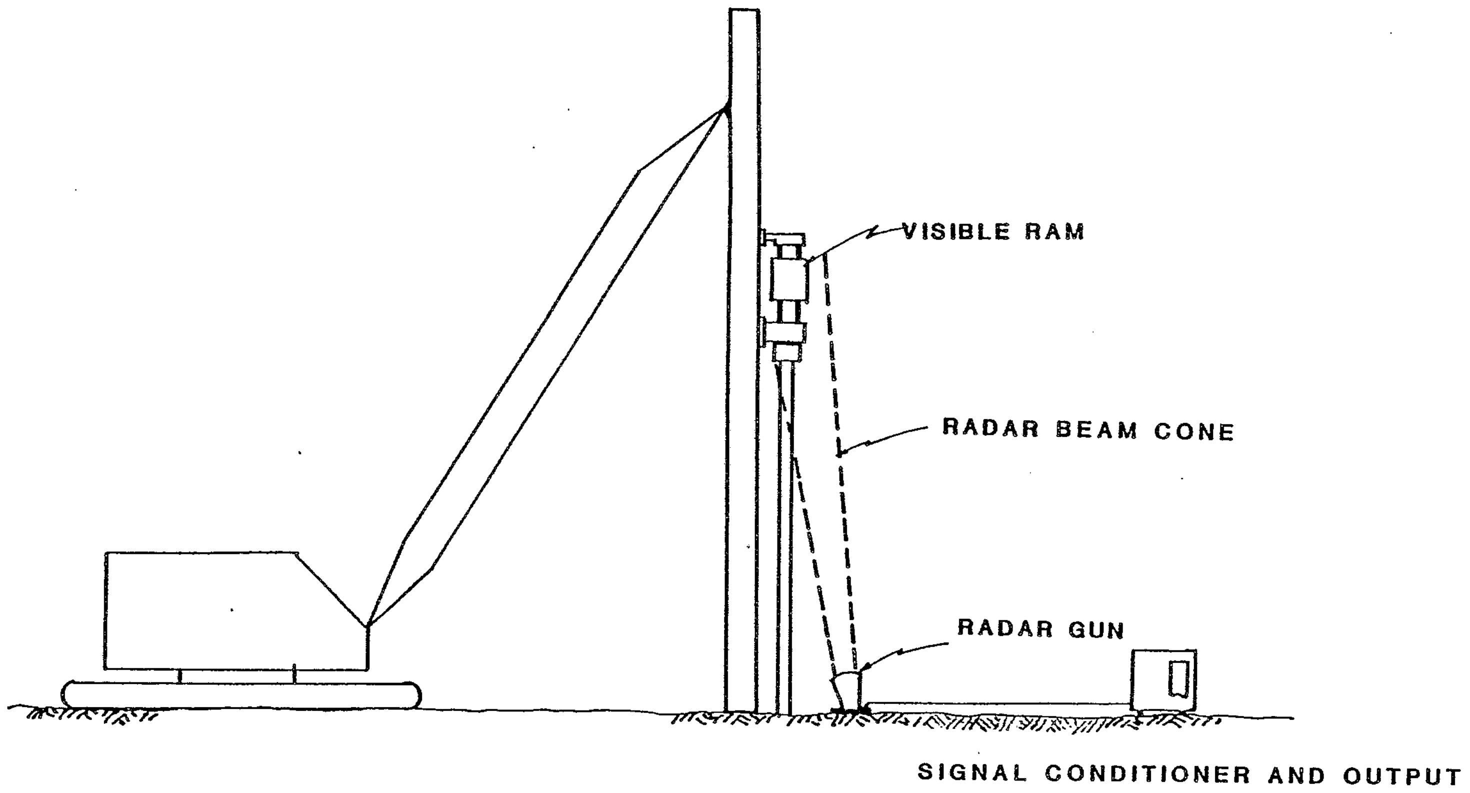

Figure 2.1: Radar Equipment Set Up for ASH Hammers with Visible Ram

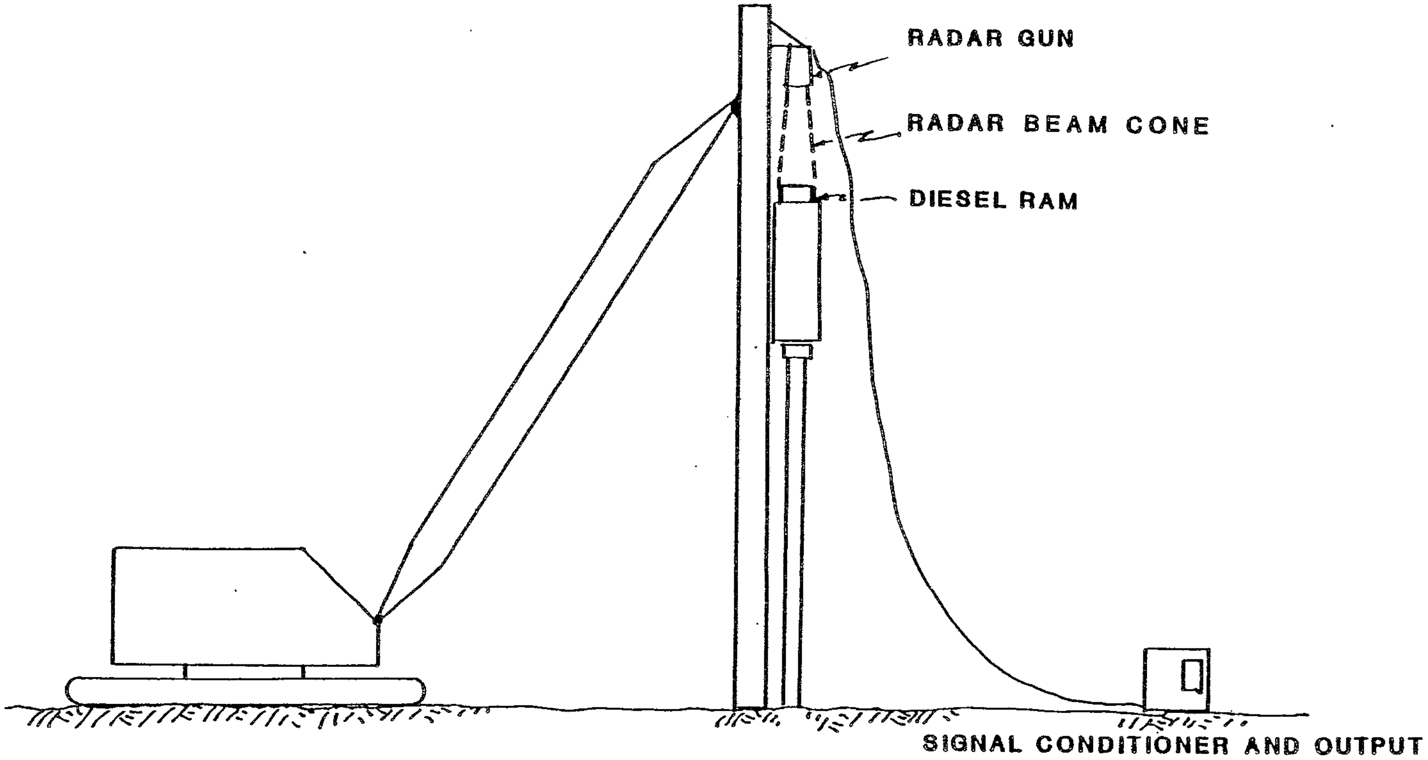

Figure 2.2: Radar Equipment Set Up for Open-End Diesel Hammer

For both ASH and OED applications, only the antenna unit should be located near the hammer. Safety considerations require that the processing unit be located at a safer, more remote distance. This remote processor must include circuitry to convert the Doppler effect to a velocity-proportional signal and must provide readily interpretable output.

2.4 Electronics

Figure 2.3 shows a block diagram of the signal generation and conditioning process. The radar beam contains microwaves of approximate frequency of 10 to 24 GHz. Reflections of this beam from a moving surface are Doppler shifted with the originally emitted signal. For speeds in the range of 1.0 (.3) to 200 ft/s (66 m/s), the shift between the emitted and reflected signal is an audible frequency dependent on the speed of the target. This variable frequency can be converted to a proportional voltage by a frequency to voltage converter. The result is a voltage signal that is proportional to the velocity of the target (in our case, a ram). This signal can then be observed on an oscilloscope, recorded on magnetic tape, written on strip chart or input to a computer or other processor.

The electronics could contain logic to determine and print impact velocity. Optionally, the hammer efficiency could be automatically computed, which would require a microprocessor with input keyboard (for entering the ram weight and rated energy). However, since the applications of radar are limited, these "beautifications" may add undue cost and complexity. A simple chart of the velocity would suffice for energy/efficiency computations.

2.5 Accuracy

The 5% accuracy on velocity quoted by Tera/McClelland engineers (2% by Pile Dynamics) can be relatively easily met if the target reflects a substantial portion of the emitted microwave energy. Equipment calibration errors can be limited to 1%. On-site calibration is easily checked using a free-falling object or tuning forks of known frequency. Major errors will be

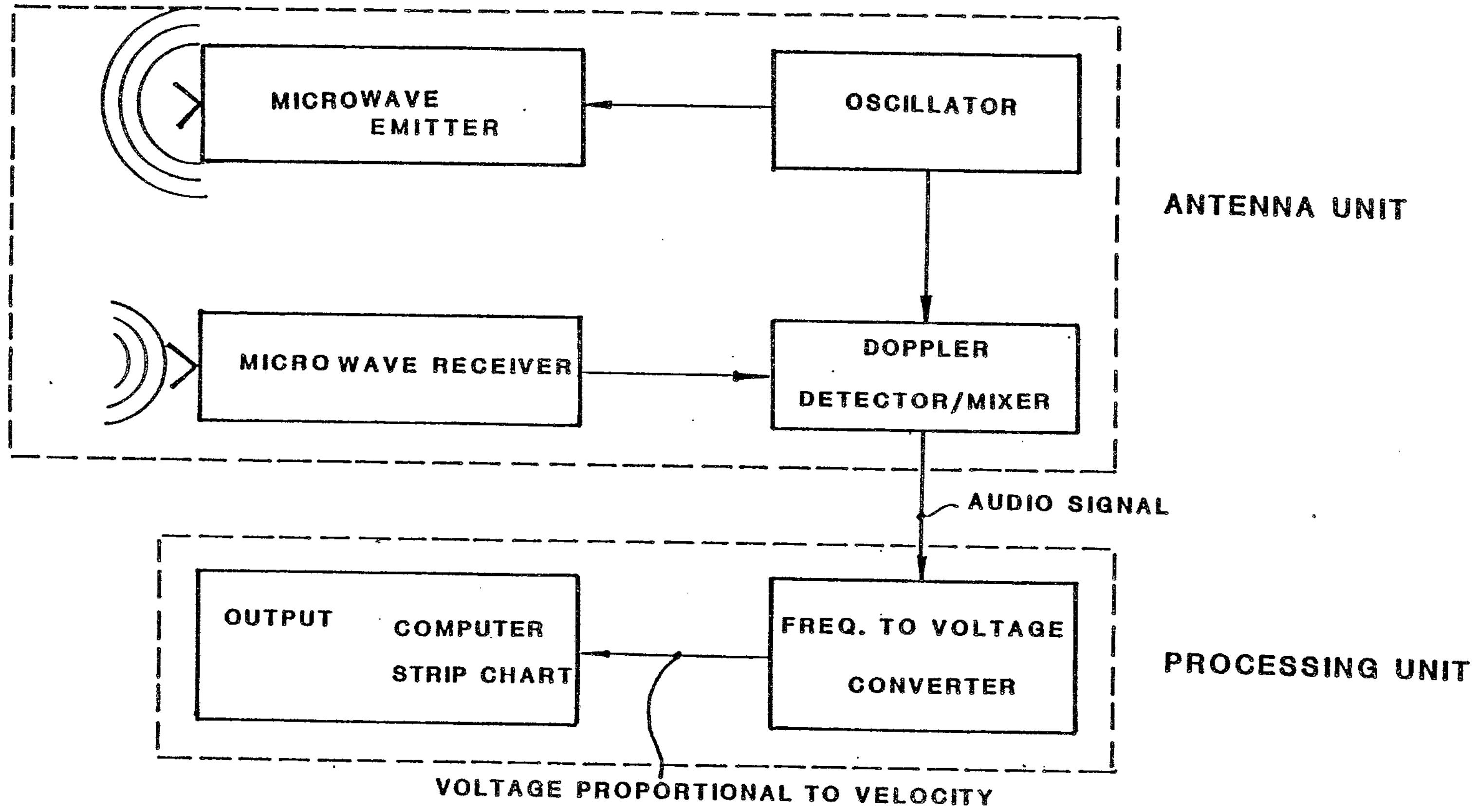

Figure 2.3: Schematic of Radar Based RVM or HPA

caused only by an excessive angle between the direction of ram motion and the direction of the radar beam and by the motion of the radar unit; with proper care, such errors could be minimized.

2.6 Cost

The radar device is available from McClelland for specific piling applications, both as a service (including operator) and for lease. The HPA is also available from Pile Dynamics for a purchase price of $9500. Both the radar device and HPA are also available from their respective manufacturers on a daily rental basis.

3. DRIVING SYSTEM PARAMETERS FROM INDIRECT MEASUREMENTS

3.1 Introduction

The evaluation of hammer and driving system performance from indirect measurements is a relatively complicated procedure. Volumes I, II, and IV have demonstrated currently available methods; they are generally based on the measurement and analysis of certain pile top quantities. Measurements taken on hammer or driving system components have not been attempted previously, because of the unavailability of sufficiently rugged transducers, installation difficulties, and the previously unrecognized need to make the measurements.

During the course of this project, virtually all feasible measurement methods were investigated. The following section shows that accelerometers are the most rugged and most simply installed transducers. Because of the pile top force-velocity proportionality in wave propagation theory, they provide sufficient information to determine characteristic parameters for both hammer and pile cushion, and the ram impact velocity, regardless of the hammer type.

There are two different methods by which driving system parameters can be calculated from acceleration measurements. In either case, the driving system is modeled as in a wave equation analysis. This is both convenient and necessary in order to derive the same values that need to be input into the wave equation computer program. The first method is a closed form solution which directly calculates ram impact velocity, cushion stiffnesses and coefficients of restitution. Naturally, a closed form solution requires very little calculation effort.

The second method applies a series of trial analyses with varied driving system parameters to approximate these parameters. The calculated acceleration (or velocity) values from the analysis are then compared with the corresponding measured quantities. The set of driving system parameters which produce the best approximation of the measurements can be objectively chosen as the most realistic parameters; in order to make an objective choice, minimization techniques can be used on a specified error function which describes the difference between measured and computed motion quantity. Numerous methods for efficiently performing the selection of the trial parameters have been described in the literature, e.g. (Fox, 1).

3.2 Indirect Measurements

Indirect measurements determine the forces or motions at one or more locations within the driving system or at the pile top. In general, strains are measured and then converted to force using the modulus of elasticity and cross sectional area of the material on which the strain was measured. Force measurements require a force transducer which must actually transfer the forces to be measured. These measurements must be made above the pile.

Motions of any driving system component may be obtained by either measuring its displacement or its acceleration. Motion measurements, therefore, do not interfere with the driving system.

3.2.1 Force Measurements

It has been attempted during the course of this project (see also Volume II) to develop or find an easily portable, accurate and inexpensive force transducer. The most important requirement was that this device would be rugged.

Currently available strain gage based transducers, which are thin and lightweight, measure shear in a short beam. This necessitates that the load is transferred through a central "load button" which is small compared to the outside dimensions of the transducer. Because forces are high and the total available space under the ram is small, load button pressures may easily exceed the strength of high strength steel. Furthermore, the transducer may experience loads which are not necessarily centered or axial, and may, therefore, give misleading results.

Among the designs investigated was the piezoelectric force transducer, i.e. a unit which transfers the full load through a quartz crystal and then generates a force proportional voltage. The Schmertmann SPT testing device consists of such a transducer. It is probably more rugged than strain gage based devices, however, it would be expensive for the large forces it would have to withstand. Since the forces generated depend on hammer, pile type and helmet weight, and since allowance would have to be made for eccentric loading, the development of this device would be both too complicated and too costly.

In reviewing the available technology and the rugged demands on the force transducer, it was found that the most serious problems were associated with transducer size and installation difficulties. Most importantly, the use of such a device in the system would be expensive, since a separate force transducer must be dimensioned for each driving system. The necessary number of models with different dimensions and load ranges would therefore be large. The larger units would be exceedingly heavy and difficult to install in the driving system.

Although the above concerns eliminate the force transducer on practical terms as a feasible measurement device, a compelling disadvantage is that any item introduced into the driving system will affect the normal energy transfer. Since force transducers are not part of the driving system in production piles, their inclusion as a measuring device would alter the system parameters, (thus defeating their original purpose). Even though the unit may be flat and lightweight, it will interfere with the hammer unless placed underneath the helmet (air/steam hammer valve timing is sensitive to the thickness of the capblock/striker plate assembly, which would include the force transducer). On the other hand, a transducer located at the pile top may interfere with the helmet/pile adaptors (e.g. for an H-pile the adaptor is usually a profile which matches the pile). In view of these severe limitations, the use of force transducers is discouraged.

3.2.2 Displacement

Displacement is most conveniently measured by electronic theodolite. This measurement is particularly attractive, since it does not require the attachment of any device to the driving system. Major disadvantages are the high cost and the possibility of erroneous measurements due to ground vibration. The price dictates limitations as far as the number of measurements are concerned. Where pile, helmet and hammer motion are to be measured simultaneously, three independent devices are needed. Due to the high costs involved, measurement on opposite hammer/helmet/pile sides would not be taken and non-axial motion components could, therefore, not be excluded.

3.2.3 Acceleration

During the past years, acceleration measurements have become extremely reliable and routine. Early problems with these transducers were primarily due to an inappropriate mounting method which often caused resonance and overloaded the accelerometers internal amplifier. With new technology in mounting assembly, this difficulty has been eliminated.

Today, the accelerometers used in piling measurements are almost exclusively piezoelectric (quartz crystal) units. Although they are available with ranges up to 100,000 g's, even a 5000 g range accelerometer has been used to successfully measure the anvil acceleration of a diesel hammer (metal to metal impact) and integrate it to velocity. Figure 3.1 shows the results.

Acceleration measurements on both the helmet and the top of a concrete pile can be used to compute the pile top cushion compression as a function of time. Because of the proportionality that exists between force and velocity at the pile top, the force is known and the cushion's force-deformation relationship is thus directly obtained from the two acceleration measurements.

In general, it is desirable to integrate the acceleration to velocity, since velocity has well defined ranges (typical ram impact velocities are

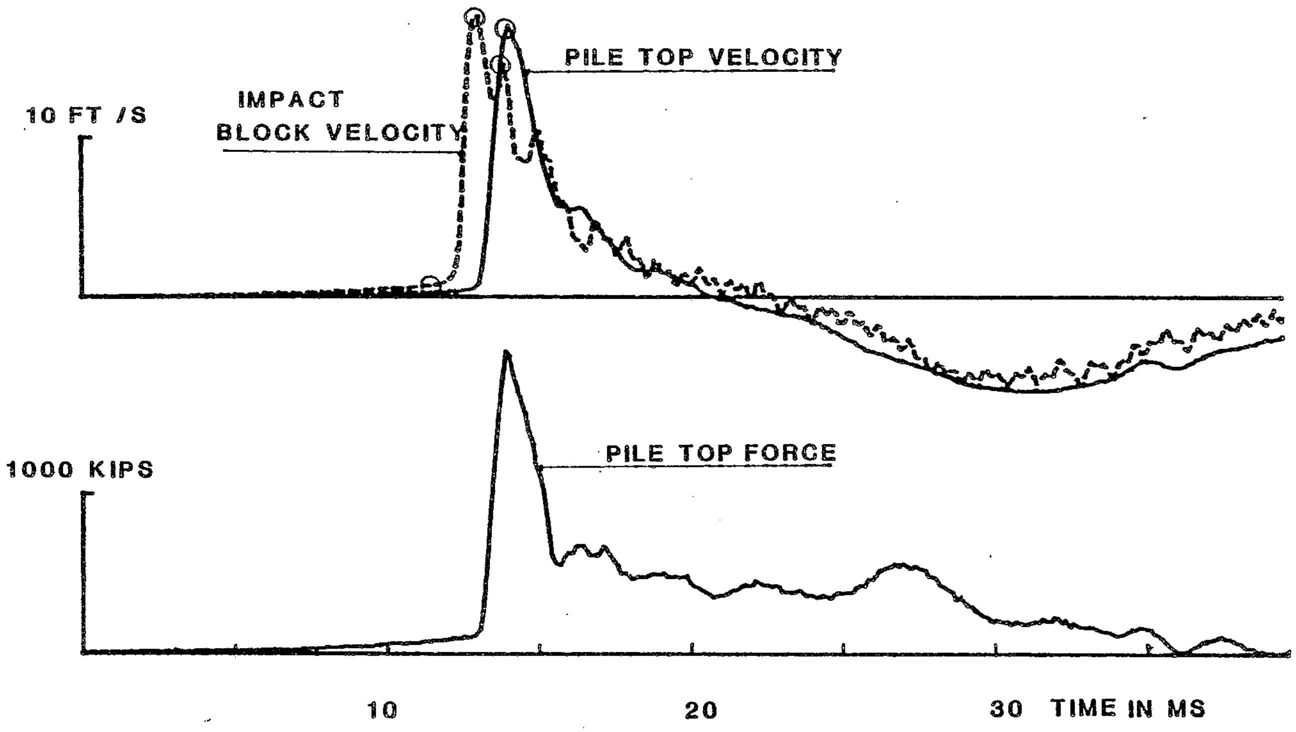

Figure 3.1: Measured Impact Block Velocity, Together with Pile Top Force and Velocity. Measurement Taken on a Delmag D-80 Hammer and 30 x 1 inch Pipe Pile.

(1 kip = 4.5 kN, 1 ft = 0.305 m, 1 inch = 25.4 mm)

Note: 0 indicates data point selected for minimization technique between 10 [3] and 25 ft/s [7.5 m/s]). Integration of acceleration may pose a problem over a long period of time. However, integration for only a few milliseconds after impact is required, in order to obtain driving system parameters making integration errors negligible.

3.2.4 Summary of Preferred Indirect Measurements

As a result of the writers' favorable experiences with piezoelectric accelerometers, and since acceleration measurements are sufficient for hammer and driving system performance evaluations, the measurement system depicted in Figure 3.2 are proposed for various combinations of ASH and diesel hammers on both steel and non-steel piles. The basis of these systems is outlined below:

a. For ASH hammers on steel piles, either pile top or helmet acceleration should be measured. Several tests have shown that simultaneous measurements of helmet and pile top motions are indistinguishable and can therefore be considered interchangeable.

b. For diesel hammers on steel piles, both helmet and impact block acceleration must be measured. The additional measurement is needed since the presence of the impact block introduces an additional element into the driving system.

c. Whenever a pile top cushion is used (as for concrete piles), pile top motion will be different from the helmet motion. Both pile top and helmet accelerations must be measured in such case.

3.3 Closed Form Solutions

3.3.1 Introduction

The objective of indirect measurements at points below the ram is to calculate the ram impact velocity and all driving system parameters. The term

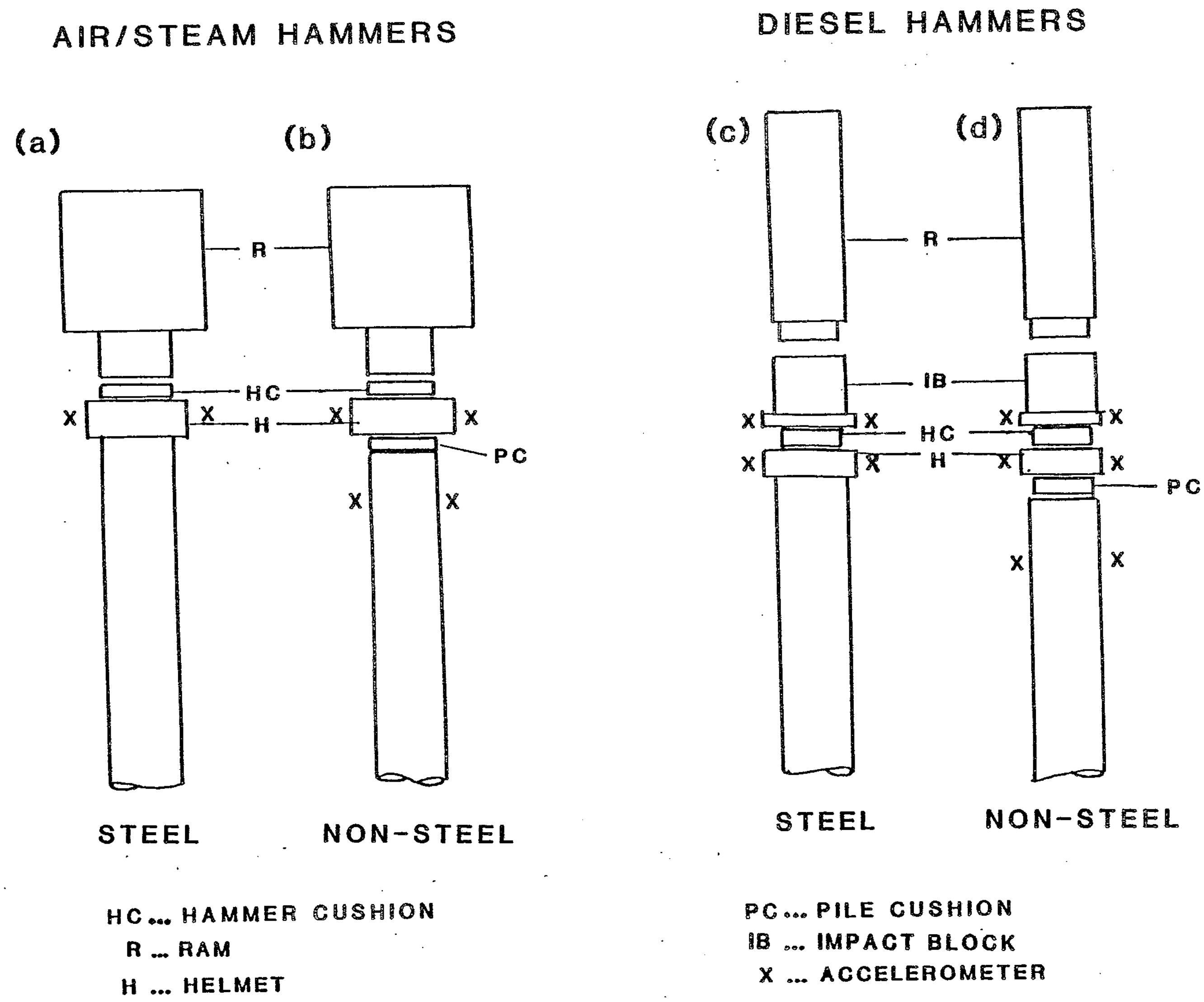

Figure 3.2: Instrumentation of Preferred Indirect Measurement System
(a) ASH on Steel Pile, (b) ASH on Non-Steel Pile,
(c) Diesel on Steel Pile, (d) Diesel on Non-Steel Pile

"closed form" is used to distinguish this method from iterative solution or minimization analyses.

3.3.2 ASH Ram Velocity

The ASH system is most suitable for closed form solutions because of its simplicity. Free body diagrams can be developed for ram, helmet and pile as shown in Figure 3.3.

The primary force acting on the ram during impact is the capblock force. Preadmitted air, steam or hydraulic pressure forces are normally negligible relative to the ram inertia or the capblock force. The capblock force, F_c, may be computed from

$$F_c(t) = m_h 2_h(t) + F_p(t) \tag{3.1}$$

where m_h is the helmet mass, a_n is the helmet acceleration and F_p is the pile top force. At any time during the early impact (before the maximum pile top velocity has been reached), the pile top force is

$$F_p(t) = EA/c\ v_p(t) = Z\ v_p(t) \tag{3.2}$$

Of course, EA/c is the pile impedance and v_p is the pile top velocity.

The capblock force reaches a maximum shortly after the time of maximum helmet acceleration. Denoting this instant in time by the subscript "I" and time of impact by the subscript "i", the impulse momentum relationship

$$m_r v_{ri} = m_r v_{rI} + \int_i^I F_c(t)dt \tag{3.3}$$

shows the difference between ram velocities, v_r at impact and time "I" is related to the capblock force impulse. Substituting 3.1 into 3.3 and rearranging terms leads to

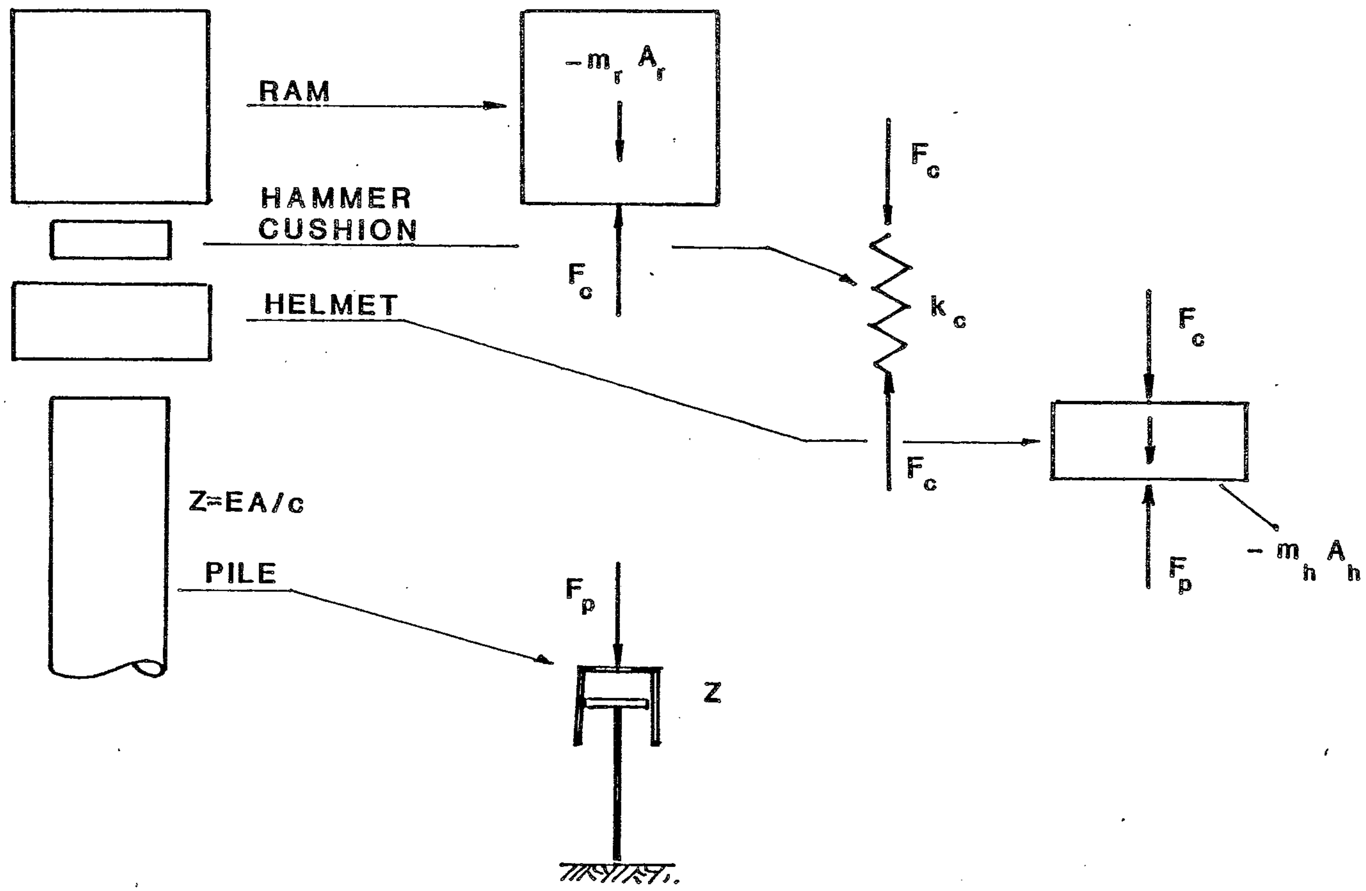

Figure 3.3: Free Body Diagrams for ASH Hammer on a Steel Pile

$$v_{ri} = v_{rI} + (1/m_r)[m_h \int_i^I o_h(t)dt + \int_i^I F_p(t)dt] \qquad (3.4)$$

Substiuting Eq. 3.2 leads to:

$$v_{ri} = v_{rI} + (1/m_r)[m_h \int_i^I o_{hI}(t)dt + Z \int_i^I v_p(t)dt] \qquad (3.5a)$$

The first integral in Equation 3.5a is the helmet velocity at time I, while the second integral is the pile top displacement at the same time. Thus, Equation 3.5a can alternatively be written

$$v_{ri} = v_{rI} + (m_h/m_r)v_{hI} + (Z/m_r)u_{pI} \qquad (3.5b)$$

At the time when the maximum hammer cushion force has been reached, the hammer cushion starts to expand. At this time, the displacement difference is a maximum, implying helmet and ram have identical velocities

$$v_{rI} = v_{hI} \qquad (3.6)$$

Eq. 3.5b can now be rewritten to yield the ram impact velocity directly.

$$v_{ri} = v_{hI}(1 + m_h/m_r) + Zu_{pI}/m_r \qquad (3.7)$$

For steel piles, pile top and helmet velocities are almost identical, and rise times are very short. For concrete piles with soft cushions, the second term on the righthand side of the above expression is usually very small. This computation can be automated to produce results in real time.

For plotted records, approximate results may be obtained using the following manual procedure (Figure 3.4):

(a) Passing a straight line through the rising edge of the helmet velocity, the time t_I is defined where the measured curve shows a deviation to the right.

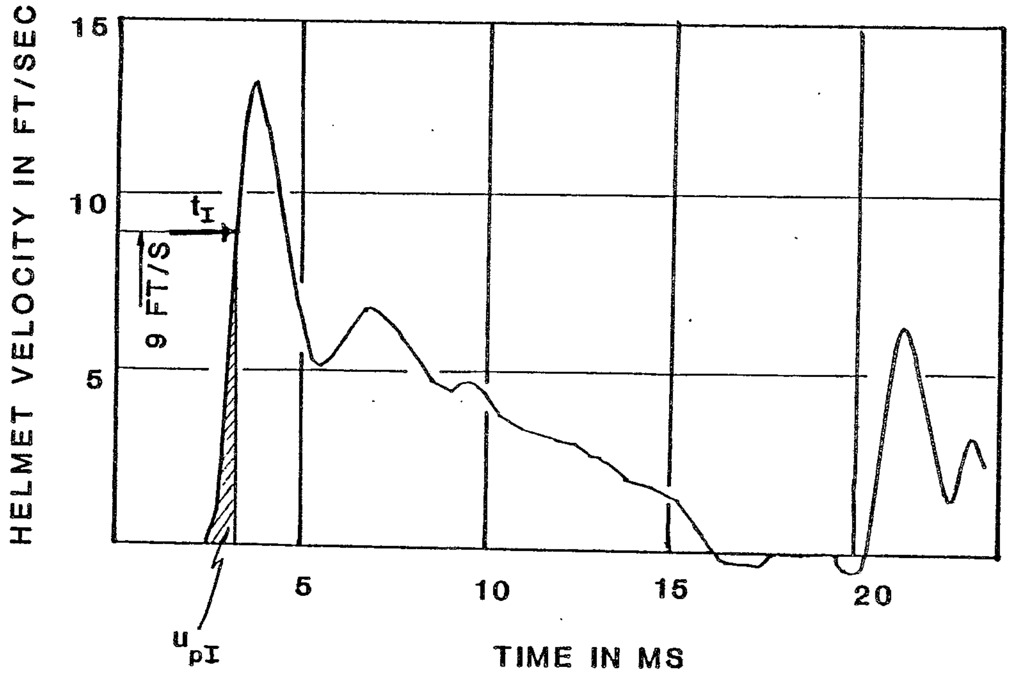

Figure 3.4: Sample Evaluation of Eq. 3.7 from Plotted Record. Ram Weight was 10 kip and Helmet Weight 1.58 kips, Pile Impedance 29.4 kips/ft/s. From plot $V_I = 9$ ft/s

$u_{pI} = 2.4/1000$ ft

$v_{ri} = 9\ (1+1.58/10) + (2.4/1000)\ (29.4)\ (32.2)\ /\ 1.58 = 11.9$ ft/s

(1 ft = 0.305 m, 1 kip = 4.5 kN)

(b) The velocity at time t_I is multiplied by the quantity $(1 + m_h/m_r)$.

(c) The area underneath the pile top velocity until time t_I is multiplied by Z/m_r and added to the result from (b).

In an automated procedure where the accelerations are available in digital form, Equation 3.7 can produce accurate results provided the digitizing frequency (the number of digital samples per unit time) is sufficiently high or adequate interpolation routines are used.

3.3.3 ASH Capblock Properties

Referring to Figure 3.3 and the free body diagrams of the ASH system, the following solutions can be immediately obtained. The ram acceleration is

$$a_r(t) = F_c(t)/m_r \tag{3.8}$$

Using Eq. 3.1 and the pile top force-velocity proportionality, one obtains

$$a_r(t) = [m_h a_h(t) + Zv_p(t)]/m_r \tag{3.9}$$

Since all quantities on the right hand side of Eq. 3.9 are known, the ram displacement can be obtained by double integration. The capblock compression can be computed from the ram and helmet displacement difference. By computing both capblock force and compression as a function of time, a plot of the capblock's force-deformation behavior is obtained. An example is given in Figure 3.5. Note, however, that the results are limited to the time where pile top force and velocity are proportional. This means that for long rise times (soft capblocks) only a loading stiffness may be calculated.

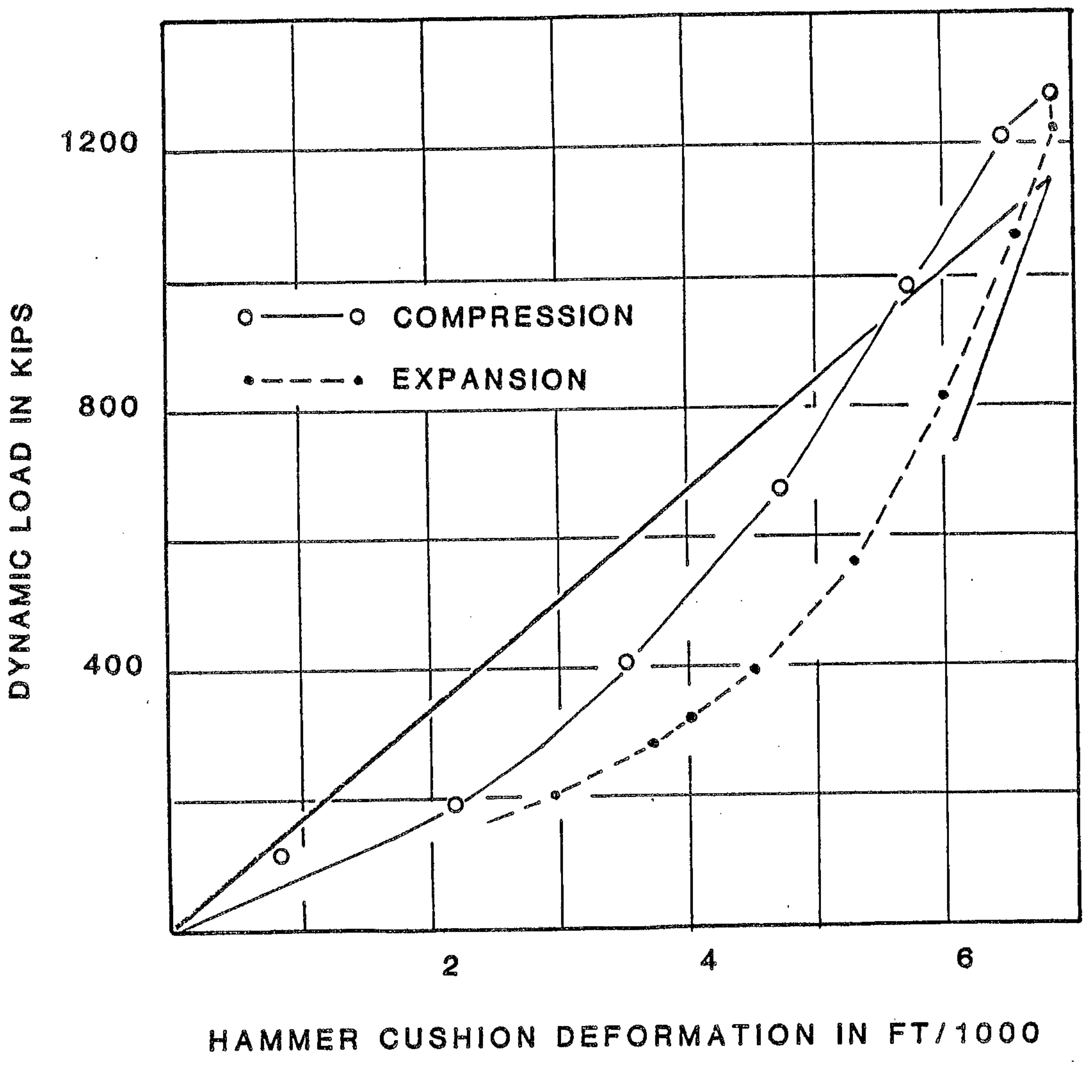

Figure 3.5: Hammer Cushion Force Deformation Curve Obtained in Closed Form from Pile Top Velocity. The Solid Line is the Plot of Minimization Technique Results (Section 3.5.1)

(1 ft = 0.305 m, 1 kip = 4.5 kN)

3.3.4 Pile Cushion Properties

With both helmet and pile top velocity available, the pile cushion compression is known at any time. The early part of the pile velocity curve, at least up to the first major maximum in the pile velocity, may be transformed to force using the pile impedance. Thus, cushion force and cushion compression (the difference between the helmet and pile top displacement) are both known, and as in the case of the capblock, may be plotted against each other, and the loading stiffness of the cushion obtained.

The pile cushion's coefficient of restitution requires analysis over a long period of time after the first maximum compression. During that time, the pile top force usually differs from the pile top velocity due to reflections. Thus, for a complete loading-unloading curve, the pile top forces must also be measured. It is questionable, however, whether curves obtained in that manner produce accurate coefficient of restitution values.

Consider the load deformation curve of a plywood cushion in Figure 3.6. This curve was obtained from measurements of pile top force and velocity and helmet velocity. The unloading behavior does not clearly show defined loading and unloading slopes. Thus successful calculation of the coefficient of restitution, as the square root of the ratio of unloading to loading stiffness, is not possible. However, the coefficient of restitution can be computed from the area under the load deformation curve which provides a measure of total energy dissipation.

In summary, the acceleration measurements alone allow for a determination of an average cushion loading stiffness, but not for the calculation of energy losses in the cushion. Energy losses in the cushion may be determined from combined force and acceleration measurements. It should be noted that the cushion's coefficient of restitution is not needed for the computation of hammer efficiency.

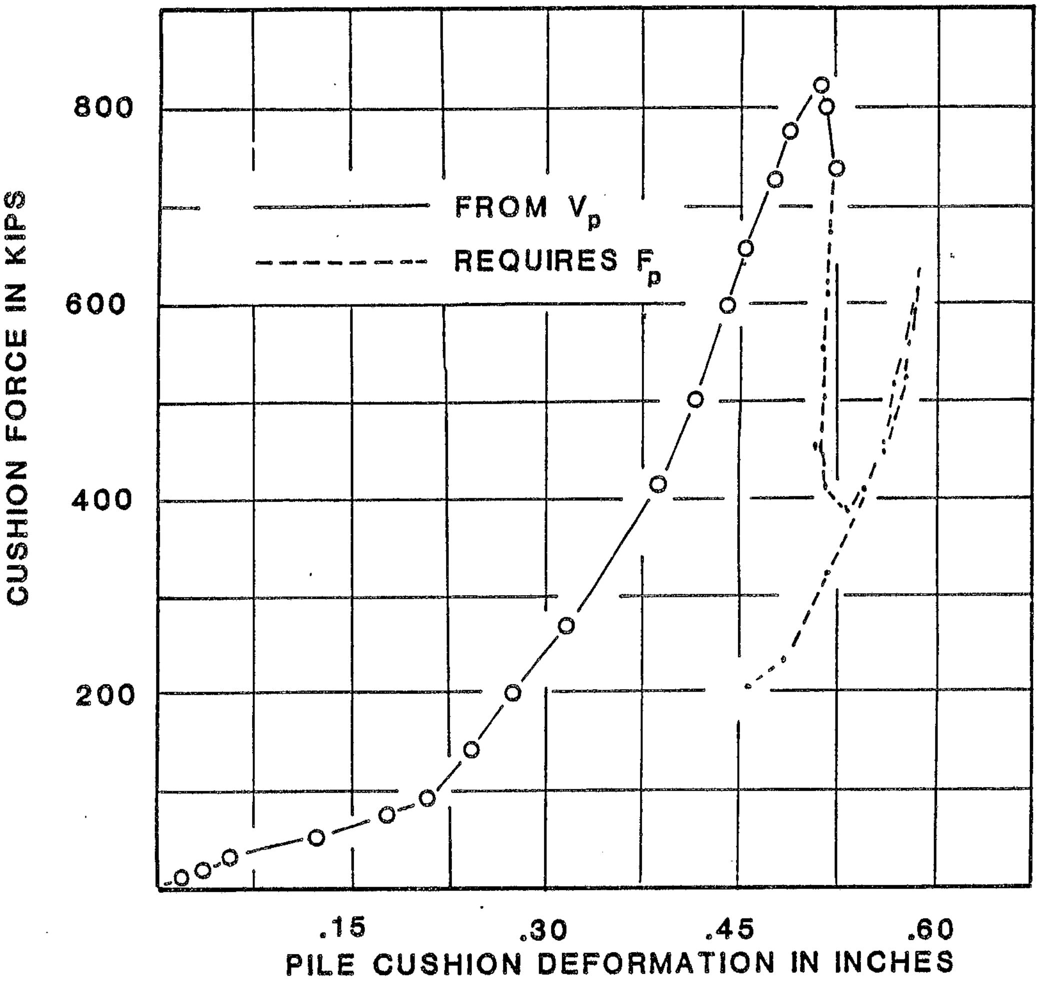

Figure 3.6: Force Deformation Curve for 7.5 inch thick Plywood Cushion. Note that Dashed Curve Portion May Only be Obtained from Pile Top Force, F_p, While First Part is Derived from Pile Top Velocity, V_p
(1 inch = 25.4 mm, 1 kip = 4.5 kN)

3.3.5 Diesel Ram Impact Velocity

The measurement system for a diesel hammer must include acceleration of the impact block. Figure 3.7 shows the free body diagram of this system. Figure 3.1 shows both typical impact block and helmet (pile top) velocity curves. During the rise of the impact block velocity, the helmet velocity is still small. This phase shift between impact block and helmet velocity is caused by the slow response of capblock materials.

The absence of any force except the ram-impact block force, allows for a closed form solution for the ram impact velocity. However, the problem is complicated by the length of the diesel ram. It is therefore convenient to consider the ram as a long elastic rod of length, L_r, and the impact block a rigid body. Then, with the St Venant solution (Timoshenko and Goodier, 2), one can express the velocity of the impact block as

$$v_{ib}(t) = v_{ri}[1 - e^{-T(m_r/m_{ib})}] \tag{3.10}$$

where T is the nondimensionalized time. Equation 3.10 is valid for the first $2L_r/c$ of the ram. The ram impact velocity may be calculated by measuring the impact block velocity.

To obtain accurate results, such calculations impose stringent demands on the quality of the measurements, in particular, on the frequency response of the signal conditioning equipment. Furthermore, the relatively long impact block of some hammers makes the assumption of a rigid impact block incorrect and the alternative use of minimization techniques may be more reasonable in these cases.

The ram impact velocity is not necessarily the most important parameter to be obtained from a diesel hammer performance test. Often the goal is to obtain a wave equation efficiency value. In the WEAP program, the hammer efficiency, e_h, is used to calculate the ram velocity at the ports, v_{rp}, from

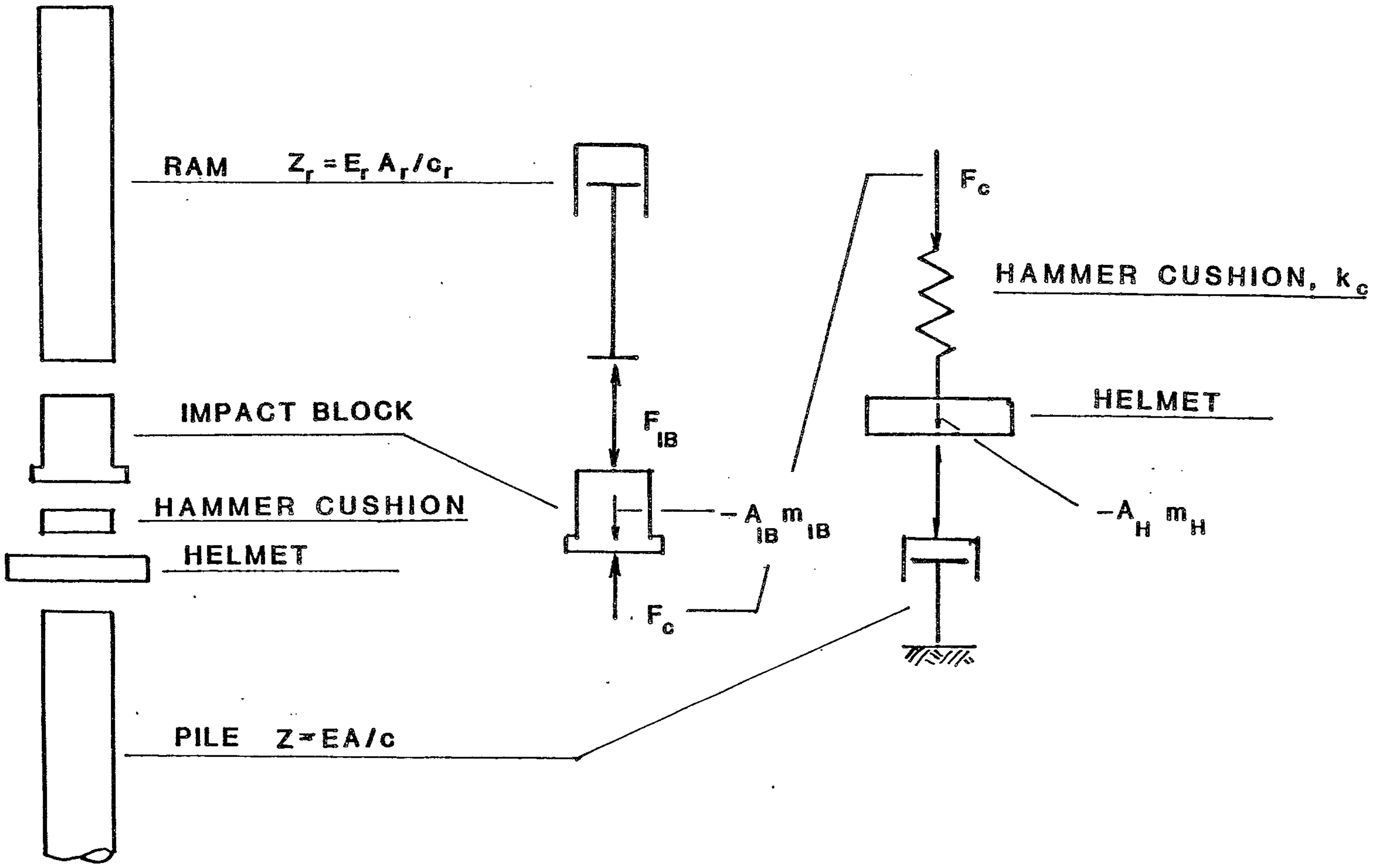

Figure 3.7: Free Body Diagram For Diesel Hammer on a Steel Pile

$$v_{rp} = [2g(h-h_c)e_h]^{1/2} \tag{3.11}$$

where g is the acceleration due to gravity, h is the stroke length, and h_c is the compressive stroke. In WEAP no losses other than gas compression losses are considered during the compression phase, because of the relatively short length of the compression stroke. Thus, with E_k being the ram energy at impact, E_{tc} the energy transferred before impact through the capblock, and E_g the gas compression energy, the ram energy at the ports is

$$E_p = E_k + E_{tc} + E_g - W_r h_c \tag{3.12}$$

and the WEAP hammer efficiency is

$$e_h = E_p/[(h-h_c)W_r] \tag{3.13}$$

The gas compression energy may be computed from

$$E_g = p_{atm}V_{in}[(1-(1-B)^{(exp-1)})/((exp-1)(1-B)^{(exp-1)}] \tag{3.14}$$

where p_{atm} is the atmospheric pressure, V_{in} is the compression chamber volume at the time of port closure, exp is the adiabatic gas expansion coefficient (estimated to be 1.35) and

$$B = h_c A_c/V_{in} \tag{3.15}$$

where A_c is the internal cross sectional area of the hammer cylinder.

The WEAP hammer efficiency can be calculated from Eq. 3.12 and 3.13 since all the energy terms can be determined either directly from the acceleration measurements or by computation. It should be cautioned, however, that this efficiency would not be accurate if the theoretical and actual combustion pressure at impact differ substantially due, to preignition.

3.3.6 Derivation Of Other Driving System Parameters For Diesel Hammers

Capblock stiffness may be determined directly since both helmet and impact block velocity are measured, and the capblock force may be found as in Section 3.1. For non-steel piles, cushion properties are obtained as for ASH hammers.

3.4 Minimization Techniques

3.4.1 Introduction

There are basic differences between the analytical treatment of ASH and diesel hammers. Furthermore, separate considerations are necessary for systems with and without pile cushions. However, the method of determination of driving system parameters for wave equation analysis by minimization is always as follows:

(a) From the measured quantities, select a set of significant values (forces or velocities of specified locations at defined times).

(b) Set up a wave equation model.

(c) Assume a set of driving system parameters (impact velocity, cushion stiffness, etc.).

(d) Analyze the model.

(e) Compare the equivalent computed and measured values and compute the different values for an error or "objective" function.

(f) Repeat steps 3, 4 and 5 in a systematic fashion for all reasonable combinations of driving system parameters.

(g) Select the solution (driving system parameters) for which the objective function is minimized (lowest error).

3.4.2 Selection of Data Points

After integrating the acceleration record to obtain velocity, at least three quantities should be selected from the resulting velocity curves to solve for the three unknowns, ram impact velocity, capblock stiffness and coefficient of restitution. It has been found that the following values provide the most important information regarding the driving system performance.

(a) From the Helmet Velocity

(a1) First major maximum after impact, v_{hm}

(This value is related to the ram impact velocity).

(a2) Time from onset to maximum (rise time), t_{pr}

(The rise time varies primarily with the capblock stiffness).

(a3) Velocity at a time t_{pr} (but not more than 2 milliseconds) after the impact, v_{h2}

(This velocity value varies with the coefficient of restitution).

(b) From the Impact Block Velocity

(b1) The value immediately preceding impact, v_{ibo}

(Since diesel hammers produce a velocity before impact due to compression, this initial value must be known).

(b2) Maximum impact block velocity, v_{ibm}

(This value is closely related to the ram impact velocity).

(b3) Second impact block peak velocity, v_{ib2}

(Because of the vibration of the ram, the impact block velocity displays a characteristic sawtooth shape after the first maximum (Figure 3.1). The value of the second maximum is related to the capblock properties).

A diesel hammer's compression phase (time between port closure and impact) is often responsible for poor hammer energy transfer. The absolute velocity values are not sufficient to determine the compression phase forces; either the pile strains (forces) or the hammer pressure must also be known. In order to avoid this problem, the velocity values taken from the measured curves are referenced to the velocities immediately preceding impact. Thus, changes of velocity rather than actual magnitudes are used to calculate the ram impact velocity. The resulting ram impact velocity is then added to the velocity value preceding impact.

The solution for diesel hammers on concrete piles represents the most complex situation. However, pile cushion properties can be obtained directly if helmet and pile top velocity are known. The problem of finding capblock properties and impact velocities proceeds as for the case of a steel pile.

3.4.3 Analytical Model of Driving System

After the characteristic measured values have been selected, trial analyses are performed for an assumed set of driving system parameters. Comparisons of measured and computed velocities and times are then made.

Figure 3.8 contains an ASH hammer model with all necessary parameters defined. A similar diesel hammer model is shown in Figure 3.9. For diesel hammers, a thermodynamic model of the hammer with compression, combustion and expansion phases must also be included. The calculations follow the usual

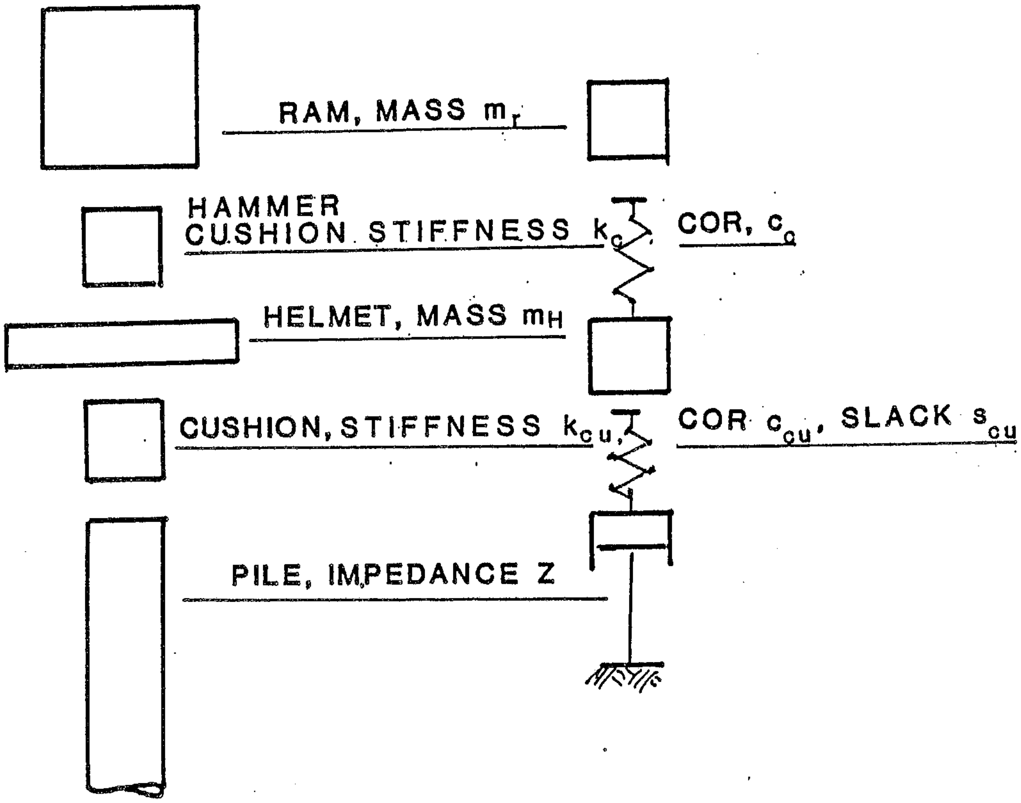

Figure 3.8: The ASH Hammer Model for Driving System Parameter Determination by Minimization

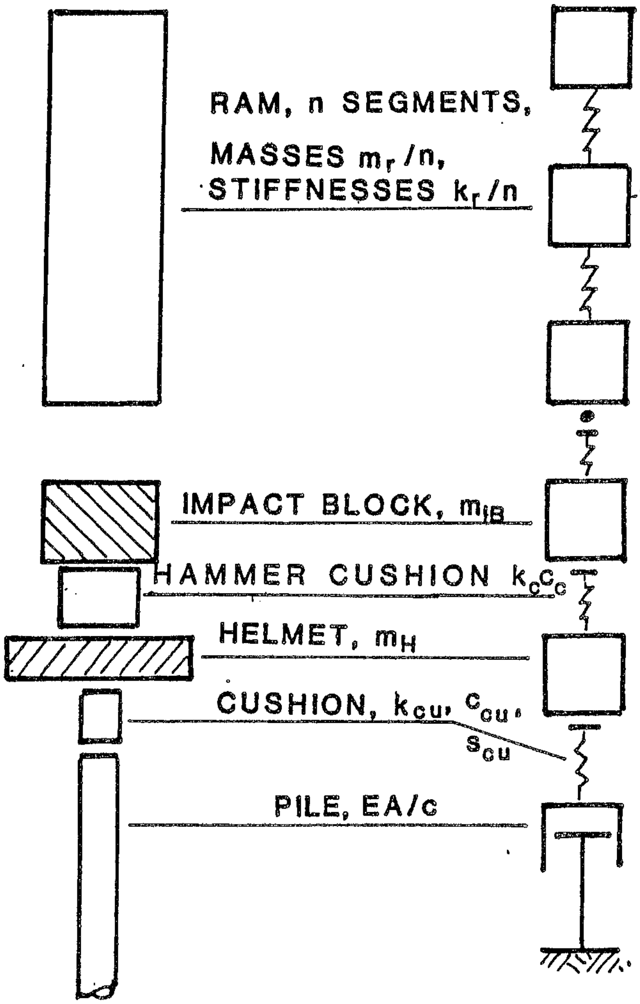

Figure 3.9: The Diesel Hammer Model for Driving System Parameter Determination by Minimization

wave equation algorithms and, for that reason, no further mathematical details are given here (see Volume I).

In summary, the computational models used in the simulation and data matching process are very similar to those of the Smith wave equation approach. This ensures that the results from this hammer performance evaluation is directly applicable to wave equation analysis.

3.4.4 Objective Function

An objective function is a summation of terms, each of which should become small during the minimization process. In the current application, each of these terms would be the difference between corresponding and measured computed quantities.

For ASH hammers, only helmet motions need to be considered; pile cushion properties will not enter the computations. The objective function is defined as

$$G_a = e_t + e_{hm} + e_{h2} \tag{3.16}$$

where the e-values are absolute differences between the hammer velocity parameters defined in 3.4.2, multiplied by weighting values for proper scaling. The terms represent the weighted difference between measured and computed rise time e_t, the maximum helmet velocity e_{hm}, and the helmet velocity - one rise time or at most two milliseconds after maximum e_{h2}.

For the diesel hammer, the equation also must include impact block observations.

$$G_d = e_t + e_{hm} + e_{h2} + e_{ibm} + e_{ib2} \tag{3.17}$$

where the differences e_{ibm} and e_{ib2} pertain to maximum and second peak impact block velocities, respectively.

The minimization process is complete after searching through all reasonable combinations of driving system parameters. The set of parameters producing the smallest value of the objective function is assumed to be the best solution. The searching process can be made efficient by employing modern minimization techniques or by applying knowledge about the interaction of differences with physical parameters. Furthermore, it is probably unnecessary to calculate the various parameters to an accuracy greater than 2%. Using a microcomputer such as an IBM PC, the complete minimization search can be completed in a few seconds for ASH hammers and in less than one minute for diesel hammers.

3.5 Examples

3.5.1 Air Hammer on Steel Pile

Measurements were obtained on a 147 foot (44.8 m) steel pipe pile driven by a Vulcan 010 hammer. This hammer has a 10 kip (45 kN) ram weight, a 3.25 ft (.99 m) stroke and a rated energy of 32.5 kip-ft (44.6 kN-m). The pile's cross sectional area was 16.4 in^2 (106 cm^2).

The driving system consisted of 7 inches (175 mm) of Force 10 material (E_c = 440 ksi or 3040 MN/m^2, c_c = .7, A_c = 220 $inch^2$ or 1419 cm^2). Using this data, the capblock had a theoretical stiffness of 13830 kips/inch (2475 kN/mm). This capblock material consists of compressible knitted metal and in practice may have a higher elastic modulus and a lower thickness than published data suggests. The cap weight was 1.58 kips (7.1 kN).

The measured pile top force and velocity records are shown in Figure 3.10. Since there was no pile cushion present, helmet and pile top velocity can be assumed to be identical. The force record is not needed in the context of this work, but it shows (dashed line) that the data points selected for minimization were taken at times when proportionality between pile top force and velocity were still valid.

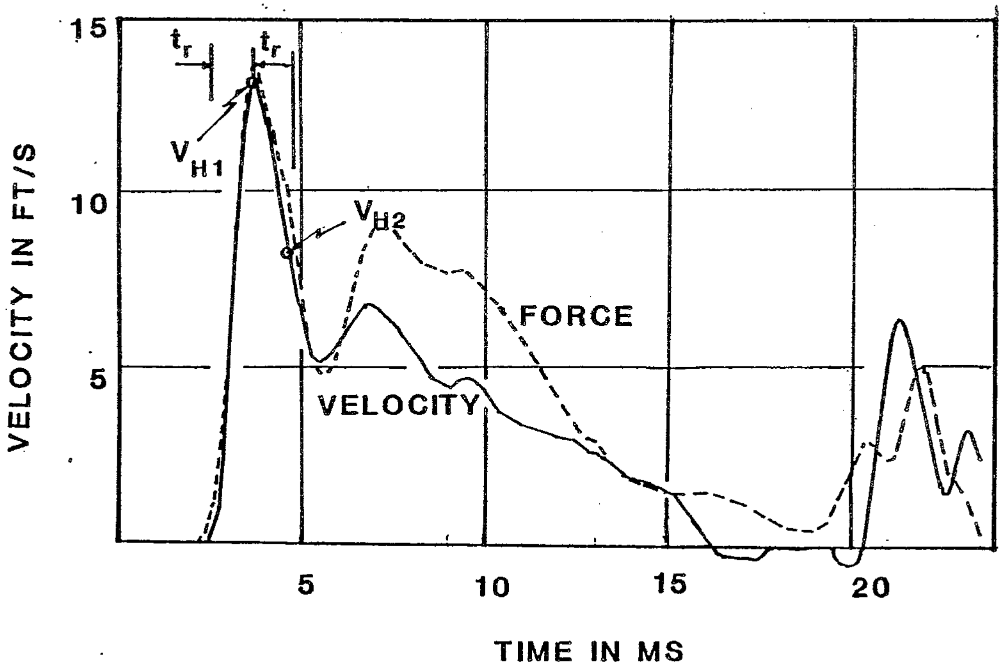

Figure 3.10: Example of Hammer and Driving System Performance Parameters From Velocity Records. The Observations are Rise Time, t_r = 1.1 ms; Peak Velocity, V_{H1} = 13.2 ft/s and Velocity at Time $2t_r$, V_{H2} = 8.7 ft/s

(1ft = 0.3048 m)

The manual, closed form solution yielded a ram impact velocity of 11.9 ft/s or 3.63 m/s, (note: this example was used in Figure 3.4). However, the determination of the point of maximum compression is usually rather inaccurate. In fact, the time t_I could have easily been shifted slightly in either direction which would have caused relatively large variations in the computed impact velocities. This example demonstrates the need for very accurate measurements for a closed form solution. The closed form approach may also be utilized to obtain point by point the capblock force-deformation relationship. The resulting curve was shown in Figure 3.5.

Using the minimization method, an impact velocity of 12.6 ft/s (3.84 m/s) with capblock properties of k_c = 13,776 kips/inch (2465 kN/mm) and c_c = 0.5 for stiffness and coefficient of restitution, respectively, were obtained. The corresponding loading and unloading stiffnesses are indicated in Figure 3.5. Obviously, the minimization technique approximates as well as possible the actual capblock behavior over the range analyzed.

In summary the following efficiencies were determined:

Closed form: $e_h = 0.68$

Minimization: $e_h = 0.76$

Measured transfer efficiency: $e_t = 0.54$ (note that this efficiency includes driving system losses)

In performing this work, it became obvious that the closed form solution can only give reasonably accurate results if high speed digital processing techniques are utilized. For the minimization technique, the accuracy will also be affected by the digitization frequency, and should also be better in an automated mode. For manual analyses, the data is analyzed only after tape recording - a process that usually involves filtering at relatively low frequencies - and results of the computations should, therefore, only be used as a guide.

3.5.2 Air Hammer on Concrete Pile

The data set was obtained on a 20x20 inch square prestressed concrete pile being driven by a Vulcan 020 hammer having a 20 kip (91 kN) ram weight, a stroke of 3 ft (0.91 m) and a 60 kip-ft (82.8 kN-m) rated energy. The pile was 52 feet (15.8 m) long and had an elastic modulus of 5050 ksi (35,600 MN/m^2). The helmet had a weight of 5.5 kips (25 kN) and the capblock consisted of three 20x20 inch (508x508mm) sheets of 2 inch (50 mm) thick blue polymer. The properties of this material were estimated to be E_c = 300 ksi (2113 MN/m^2), c_c = 0.8, capblock stiffness k_c of 20,000 kips/inch (3680 kN/mm).

Figure 3.11 shows the measured helmet and pile top velocities together with the pile top force. These curves were used to directly determine the force deformation relationship of the pile top cushion previously shown in Figure 3.6. This cushion consisted of 7.5 inches (190 mm) of plywood.

In Figure 3.12 the loading stiffness of Figure 3.6 has been approximated by two linear portions of 20% and 100% stiffness, k_{cu}. The transition from low to high stiffness took place at a deformation of .27 inches (6.9 mm). The high stiffness was k_{cu} = 3,000 kips/inch (540 kN/mm). The pile top was chamfered 3 inches and it is therefore reasonable to assume an effective cushion cross sectional area A_{cu} = 289 inch^2 (1864 cm^2). Based on an E_{cu} = 50 ksi (352 MN/m^2), a cushion stiffness k_{cu} = 2,000 kips/inch (3,600 kN/cm) would have been expected. However, the cushion was already partially compressed at the time of testing.

The data points for the minimization were indicated in Figure 3.11. They included also two points from the pile top velocity curve. The minimization results yielded an impact velocity of 11.4 ft/s (3.47 m/s), a capblock

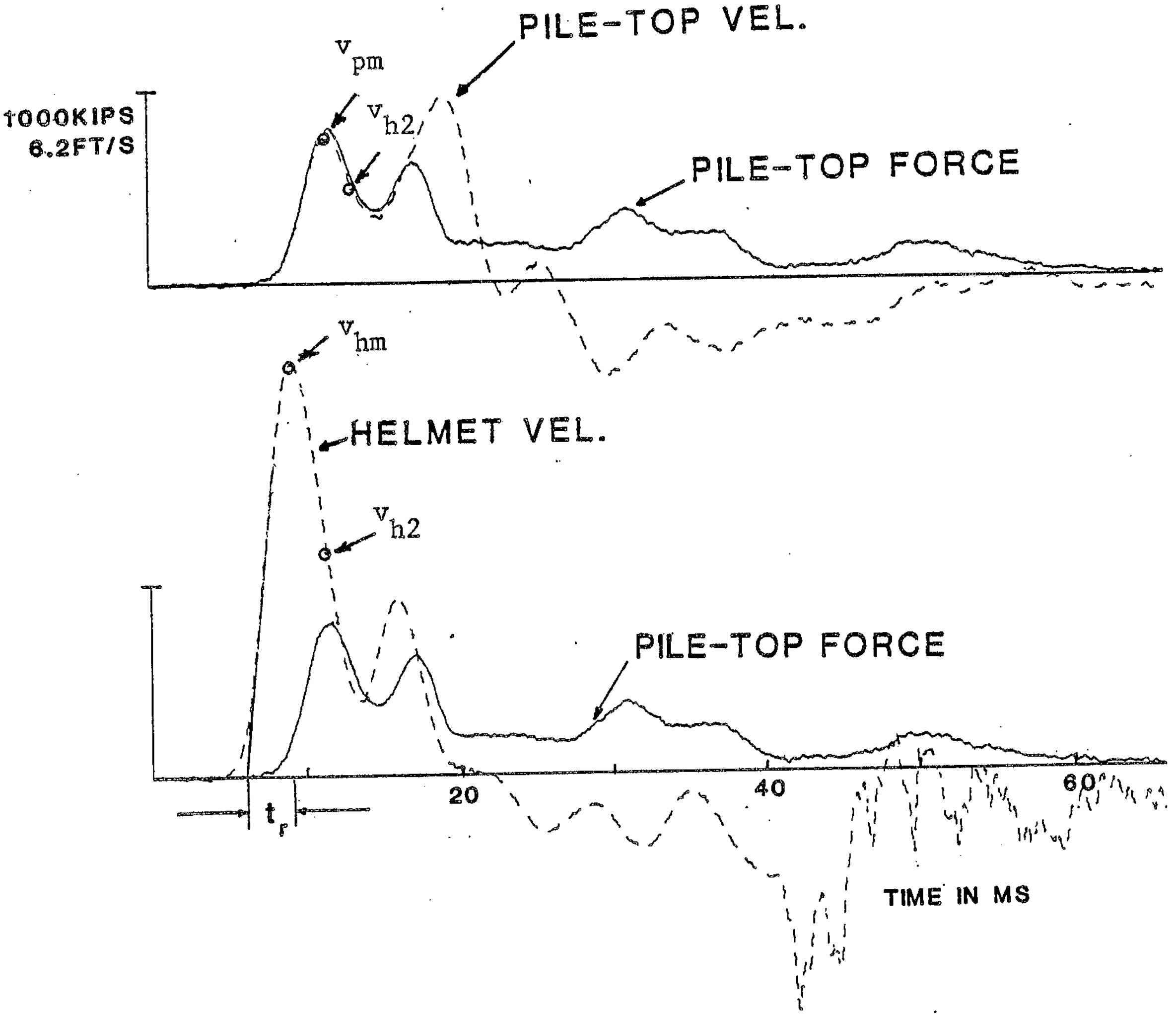

Figure 3.11: Records of Helmet Velocity, Pile Top Velocity and Pile Top Force Taken at and Above a Concrete Pile Under a Vulcan 020 Hammer

(1 ft = 0.305 m, 1 kip = 4.5 kN)

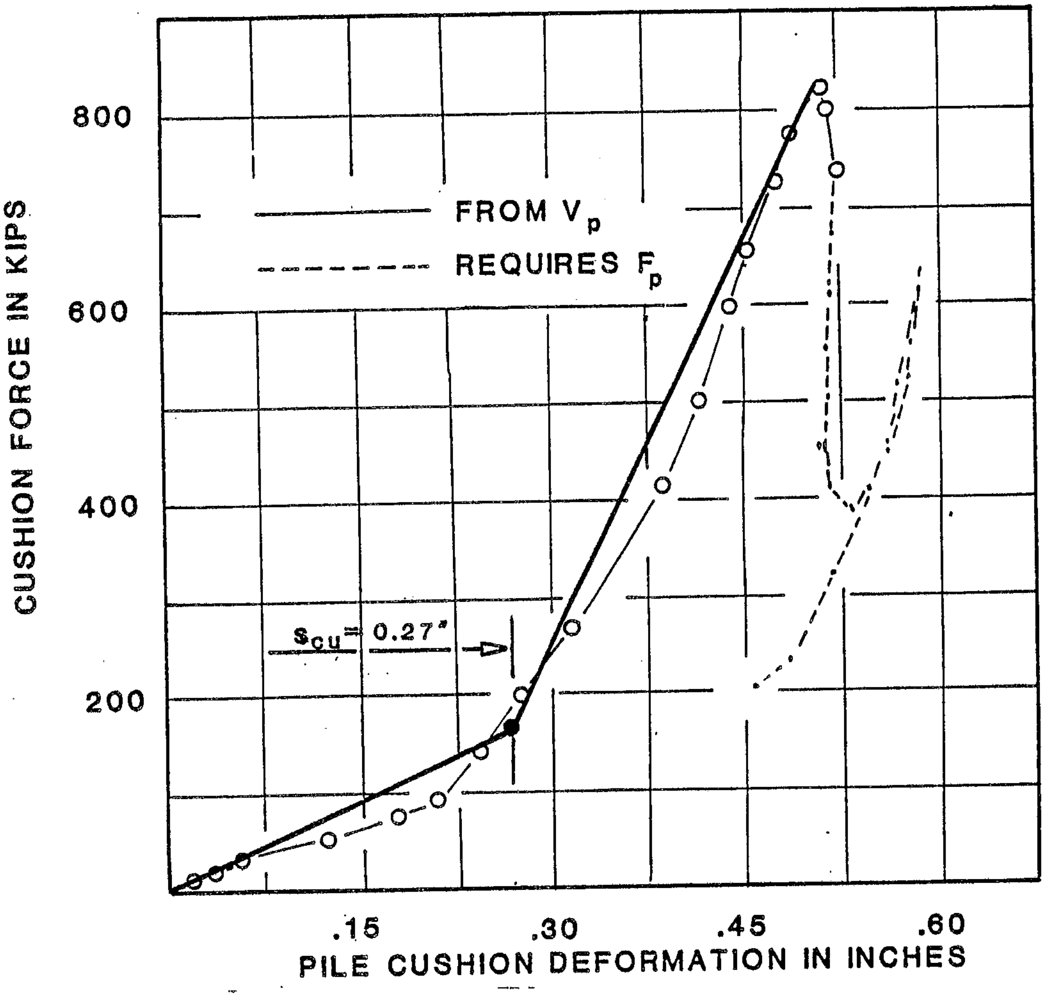

Figure 3.12: Approximation of Dynamic Force Deformation Curve of a Pile Cushion by Two Straight Lines

(1 inch = 25.4 mm, 1 kip = 4.5 kN)

stiffness of 9,800 kips/inch (17,500 kN/cm) and a coefficient of restitution of 0.8.

The following efficiencies were obtained:

From minimization: $e_h = .68$

From closed form solution: $e_h = .77$ (Note that the second term of Eq. 3.7 did not need to be considered, since the force under the helmet was practically zero at the time of maximum compression).

Transfer efficiency: $e_t = .40$

3.5.3 Diesel Hammer on Steel Pile

Impact block and pile top velocity were measured under a Delmag D-80-12 hammer on a 30 x 1 (762 x 25 mm) inch steel pile of at least 250 feet (76 m) length. The capblock consisted of two 1 inch (25 mm) thick, 23 inch (584 mm) diameter conbest sheets, with an elastic modulus of 560 ksi (3945 MN/m^2) , and a 116,000 kips/inch (20.8 MN/mm) capblock stiffness.

Figure 3.1 shows impact block and pile top velocities plotted together and pile top force (which was not used in these computations). The data points selected for minimization are indicated by circles. Closed form solutions were not attempted, since the tape recorder's filtering frequency was below the impact block's natural frequency.

The minimization technique resulted in the following values:

The ram impact velocity, relative to the impact block velocity, was 19.6 ft/s (6 m/s). Adding the impact block velocity prior to impact of 0.4 ft/s (0.12 m/s), the ram had a total velocity at impact of 20.0 ft/s (6.1 m/s). The ram kinetic energy at impact was, therefore, 124 k-ft (172 kJ). Adding the gas compression energy and subtracting the compressive stroke energy, the ram's kinetic energy at the ports was found to be 144.9 kip-ft (201 kJ).

The actual ram stroke was 10.8 ft (3.29m), yielding a theoretical ram energy at the ports of 177 kip-ft (245 kJ). Thus, the WEAP wave equation efficiency was $e_h = 0.82$. The actual energy transfer efficiency into the pile was 37%.

The same hammer at its lowest fuel setting had only an 8 ft (2.44m) stroke. A similar analysis gave a hammer efficiency of $e_h = 0.71$. The capblock stiffness was 63,000 (11.3) and 56,000 kips/inch (10.0 MN/mm) for hammer setting 4 and 1, respectively. The difference between these two values is reasonable considering the different stress levels in the capblock. The relatively low stiffness values, compared to that determined from the elastic modulus, confirms similar experiences with wave equation analyses and comparison measurements.

The coefficient of restitution values were .38 and .51 for the higher and lower hammer setting, respectively. Apparently there was a trade-off in the minimization analysis between coefficient of restitution and efficiency values, i.e. if one value was high then the other was low. Both coefficients are, however, rather low. In addition to energy dissipation in the capblock, they probably also account for losses at the ram-impact block, impact block-striker plate and helmet-pile top interfaces. Considering the surprisingly high ram kinetic energy (compared with the energy transferred to the pile), such a low coefficient of restitution is reasonable.

3.6 Proposed Embodiment

Schematic diagrams of the proposed system are shown in Figures 3.13(a) and (b). In the most complex case, three pairs of accelerometers are needed. They have to be attached on opposite sides of the impact block, helmet and/or pile top. To date, accelerometers were directly bolted to the helmet and/or impact block, which required the drilling of a 1/4 inch (6mm) hole. Some contractors may be hesitant to allow drilling into this equipment, particu-

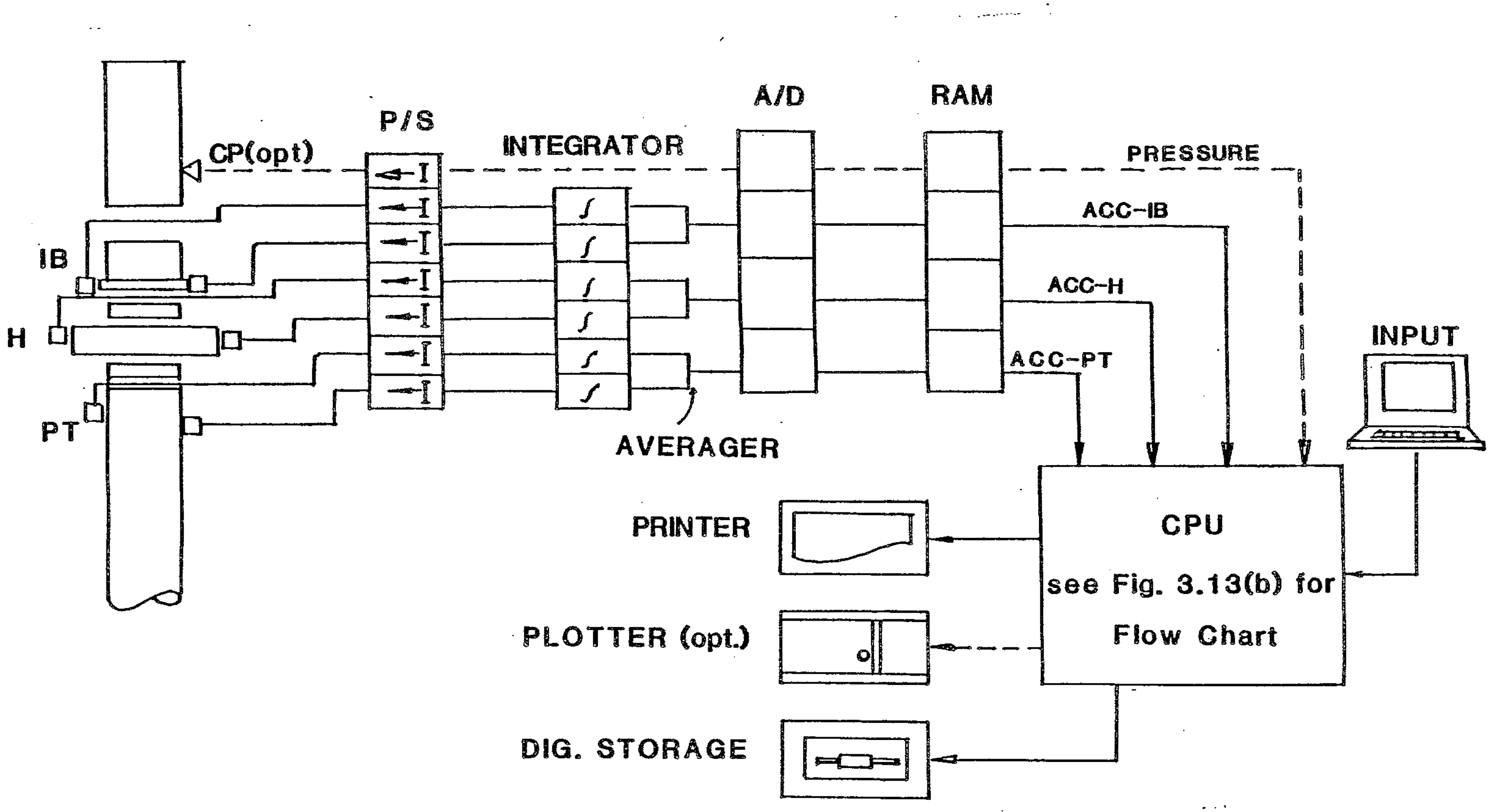

Figure 3.13(a): Schematic of Preferred Indirect Measurement System Hardware

CP ... Combustion Pressure Transducer
IB ... Impact Block
H ... Helmet
PT ... Pile Top Accelerometers
A/D .. Analog to Digital Converter
RAM .. Random Access Memory
CPU .. Central Processing Unit
P/S .. Power Supply

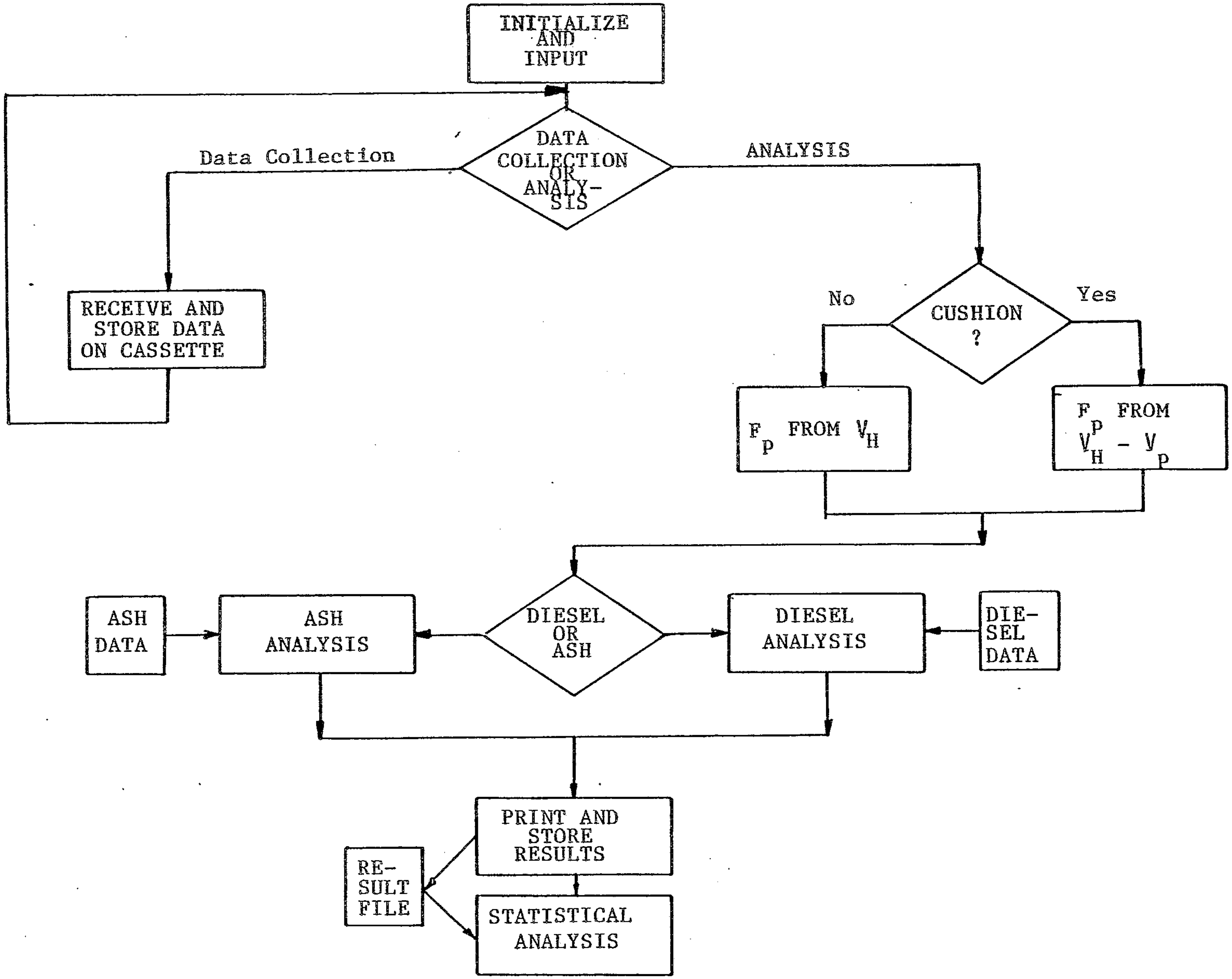

Figure 3.13(b): Flow Chart for Microprocessor Based Data Collection and Analysis Program

larly if it is rented. As an alternative, a small steel strip with tapped hole, could be welded to the helmet or impact block. This strip would then receive the accelerometer.

The accelerometers can be powered by a simple battery supply. Corresponding signals are averaged. They are then conditioned by a low pass filter of approximately 5,000 Hz cut-off frequency. Further analog signal conditioning consists of a high pass filter (approximately 1 Hz) and an integrator. Such technology is readily available (e.g. in a Pile Driving Analyzer).

Using a microprocessor the three signals are simultaneously converted to digital form. A digitizing frequency of at least 10,000 Hz is recommended. There are advantages to using three individual analog-to-digital (A/D) converters rather than multiplexing the three signals and converting them in one A/D unit. This ensures that commonly available A/D chips are adequate, and that the data can be easily stored in three dedicated RAMs (Random Access Memories). The microprocessor must be programmed to capture approximately 500 values per channel at the leading edge of the trace. This corresponds to 25 milliseconds, and is necessary to retain the complete diesel compression phase. However, only 100 data points per channel need to be stored after impact.

Using the same microprocessor, the driving system parameters can then be computed. Closed form solutions can easily be obtained between blows. An alternate mode of operation would be to use the microcomputer to accept the digital data and store it on diskette or other storage device for later use.

3.7 Discussion of the Preferred Method

The method of accelerometer measurement on impact block, helmet and/or pile top is simple in concept. The electronics for signal conditioning, digitizing and analysis is available. The results would include both driving system and hammer performance parameters.

A disadvantage of the proposed system is that cable connections to hammer, and in the case of concrete piles, to the pile top are required. However, the problem is not serious since all hammers already have operating lines. The hammer could easily be moved from pile to pile without disconnecting the cable. However, the cable connection to the pile-top accelerometer complicates the operation to some degree. Since the accuracy of the system is currently unknown, it would be beneficial to initially correlate the system against a radar monitor.

3.8 Configuration and Cost of the Measurement System

The system must include several accelerometers types. Piezoelectric accelerometers with 20,000 g range would be preferred to measure impact block and helmet accelerations. They could also be used for steel pile top velocity measurements. Six units should be adequate and would include backup. For the measurement of concrete pile top velocity, 2000 g accelerometers are recommended; three units would allow for sufficient backup. Up to six channels of signal conditioning integration would be necessary. Analog to digital conversion for up to 3 channels and computational capability with printed output would complete the requirements. The microprocessor could be a general purpose minicomputer, such as the IBM PC. The advantages of such a microprocessor would include off the shelf availability (although the A/D would probably have to be a custom-designed unit due to conversion rate requirements) and flexibility in programming. Alternatively, a special purpose device similar to a Pile Driving Analyzer (although much less complicated) could be considered. Advantages of the special purpose device would be size, portability, ruggedness, and probably speed of operation, since all features would be contained within a single unit. Either system must be capable of printing output.

The estimated cost of either system would be approximately $20,000 to $25,000. Options should be included at a later time so that the testing of the basic system can be expedited. The pressure data processing would require an additional channel of power supply and analog/digital conversion at a cost of approximately $2500. The real time determination of the hammer speed would cost an additional $1000, and plotting capability would add approximately $2000 to the cost.

4. ALTERNATIVE METHODS

4.1 Introduction

A number of alternative methods for hammer and/or driving system performance evaluations were investigated. They included both direct and indirect measurement techniques. This chapter contains a summary of the findings from these investigations.

The greatest effort in alternative system investigations was devoted to a study of accelerometers mounted on a falling weight and computations of the change of velocity from the resulting signal. This method is comparable to inertial guidance systems used in aerospace technology. Section 4.2 summarizes laboratory studies and related conclusions.

Sections 4.3, 4.4 and 4.5 deal with direct, indirect and indicator measurements, respectively. In Section 4.6, the proposed measurement system outlined in Sections 3.6 and 3.7 is compared with the alternative methods; and justified as the most feasible solution on this basis.

4.2 Ram Acceleration

4.2.1 General Remarks

Accelerometers have become increasingly sensitive and rugged. Their signal conditioning is simple and they are light in weight. Furthermore, they are successfully used for the guidance of satellites where integration over long time periods is necessary. It therefore appeared appropriate to investigate the use of direct measurements of acceleration. The following laboratory efforts were undertaken to investigate the technical feasibility of this concept.

4.2.2 Measurements on a Falling Mass

The objective of this study was to determine the velocity of a falling weight using an accelerometer mounted on the weight. This device could be employed with satisfactory accuracy as a direct measurement tool for evaluating hammer performance.

4.2.2.1 General Description of the Test Set-Up

The test apparatus consisted of a cylindrical solid weight that could move freely inside a slightly larger diameter circular tube. The accelerometer was mounted firmly on the weight near the center of the top surface. The accelerometer leads exited the tube through a vertical slot. Two pairs of light emitting diodes (LED) and photoreceptors were mounted near the base of the tube, spaced vertically. This system measured the time of passage of the weight through the lower part of the tube. The output from the test apparatus was recorded on a strip chart.

The accelerometer used was manufactured by Entran Devices, Inc., Fairfield, New Jersey. It was the EGAX-10 model with a useable range of ±10 gravities (g) and an overrange of ±10,000 g without sustaining damage. This measurement capability is achieved with a semiconductor strain gage on a cantilever beam. The overrange protection was achieved by displacement stops. The unit was viscously dampened at 0.7 of the critical value. The response was linear to about 700 hz.

The accelerometer was mounted on the steel weight using high grade rubber cement. Initially, strain gage cement was used, but apparently formed too rigid a bond and was easily broken at the high accelerations produced when the weight impacted the bottom of the tube. The rubber cement formed a small "cushion" which only affected the accelerometer measurements during the high accelerations at impact. This was not of concern since only the velocity immediately <u>before</u> impact was to be measured.

The lead wires from the accelerometer were first attached to the flat top of the weight, run up the center post and then through the slot in the tube. Great care was taken to ensure that the leads were not damaged and that they did not affect the free fall of the weight during the test.

The second velocity measurement was accomplished by using a timer in combination with the two vertically spaced LED-photoreceptor pairs. The LEDs and photoreceptors were on opposite sides of the tube. The LED emitted a light which activated the photoreceptor until blocked by the falling weight. At that time, the output from the photoreceptor would change. Knowing the distance between the two LED-photoreceptor pairs and the time between the voltage change of these pairs, the average velocity of the weight was calculated.

A full bridge signal conditioner powered the accelerometer and amplified the output signal. A bridge excitation of 15 volts was used with a 100 Hz filter and a gain of 150. The output from the amplifier was then taken directly to the strip chart recorder (visicorder).

The strip chart recorder used eight inch wide strip paper, and produced three traces: one from each LED-photoreceptor pair, and one from the accelerometer. The recorder was run at rates of 20 or 40 inches per second (508 or 1016 mm/s). The entire experimental setup is shown in Figures 4.1, 4.2 and 4.3.

4.2.2.2 Methods

A check was first made on the accuracy of the timer system and the calibration of the accelerometer. This was accomplished by supporting the weight at an accurately measured height in the tube using a string and hook above. The height was measured from the midline between the two LED-photoreceptor pairs. The strip chart recorder was started and the string cut. Knowing the height and the theoretical acceleration of gravity, the velocity of the weight at the midpoint of the timer was calculated. The velocity according to the

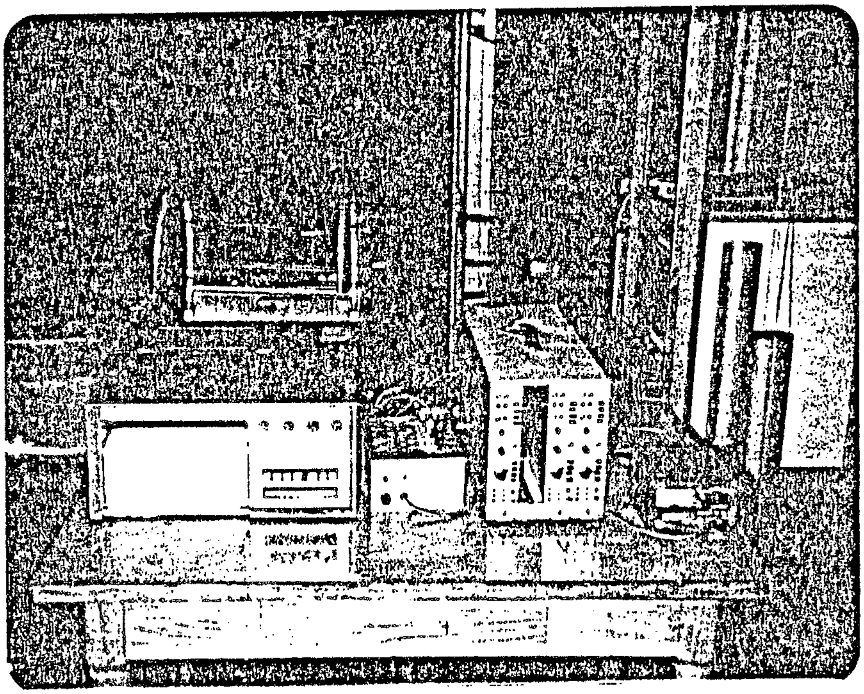

Figure 4.1: Strip Chart Recorder, Amplifier, and Timer Electronics

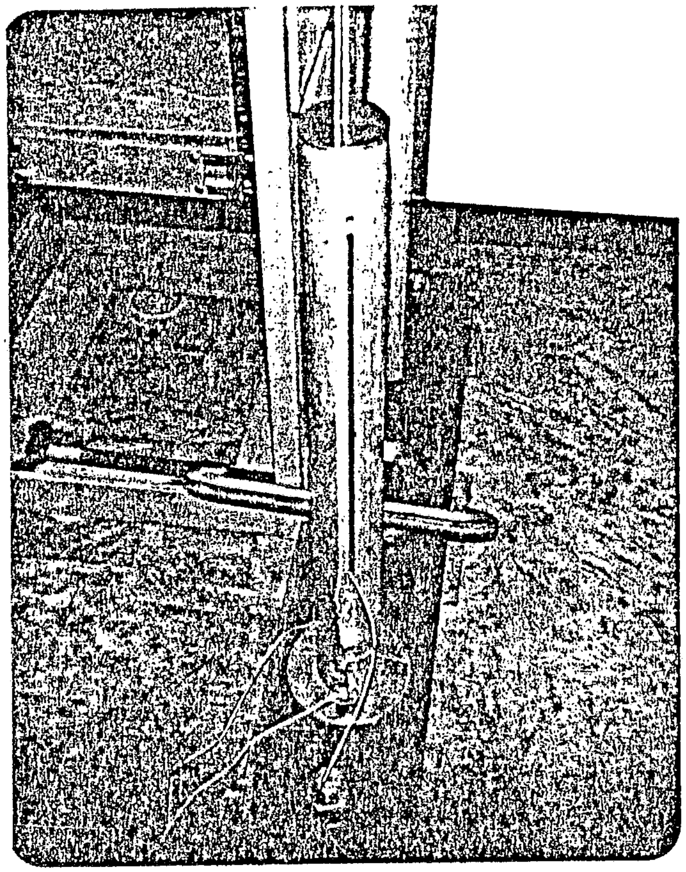

Figure 4,2: Drop Tube With Timer and Accelerometer Attached

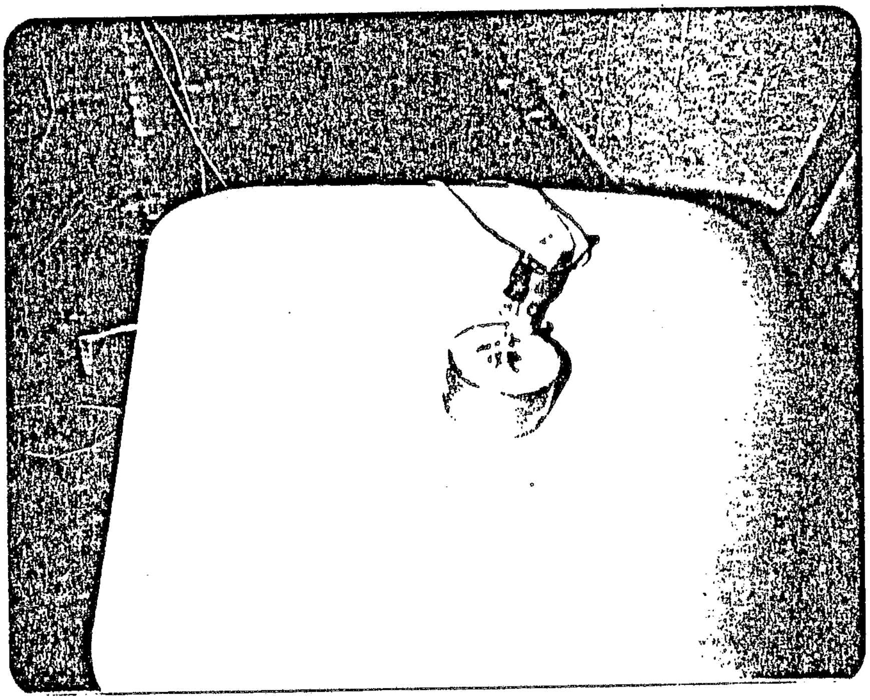

Figure 4.3: Mounted Accelerometer

timer was also calculated, and the two compared. A sample strip chart output is shown in Figure 4.4.

The accelerometer was calibrated using a simple test. The strip chart speed was changed to two inches per second (50.8 mm/s). The weight (with accelerometer mounted) was placed on a flat table for about four seconds, then picked up and put flat against the bottom of the table, upside down. About four seconds later the weight was replaced in its original position for another four seconds. The variation in the output on the strip chart from the upright to the inverted position represented two gravities. This variation was then used to calibrate the output of the accelerometer. A sample of the signal from the accelerometer caliration test is shown in Figure 4.5.

The actual tests were performed to ascertain whether the velocity of the weight could be accurately determined from the accelerometer. The tests were performed as follows. The strip chart speed was set to either 20 or 40 inches per second (508 or 1016 mm/s). The integrating amplifier and power supply for the accelerometer were turned on well in advance of the tests to ensure stability of results. The weight was rigged by running a connected string out of the top of the tube, over a ring, and down to the operator. The operator pulled the string sharply and then released it immediately. The weight would rise about twenty inches (508 mm) and then free-fall to impact with the base of the tube. The accelerometer output was continuously recorded. The test was performed several times to obtain a good sample of data points. A sample measurement is shown in Figure 4.6.

Each entire acceleration curve was manually integrated until impact to obtain the velocity of the weight immediately before impact. The data from the two photoreceptor pairs allowed calculation of the average velocity of the weight between LEDs. These two independent determinations were then compared.

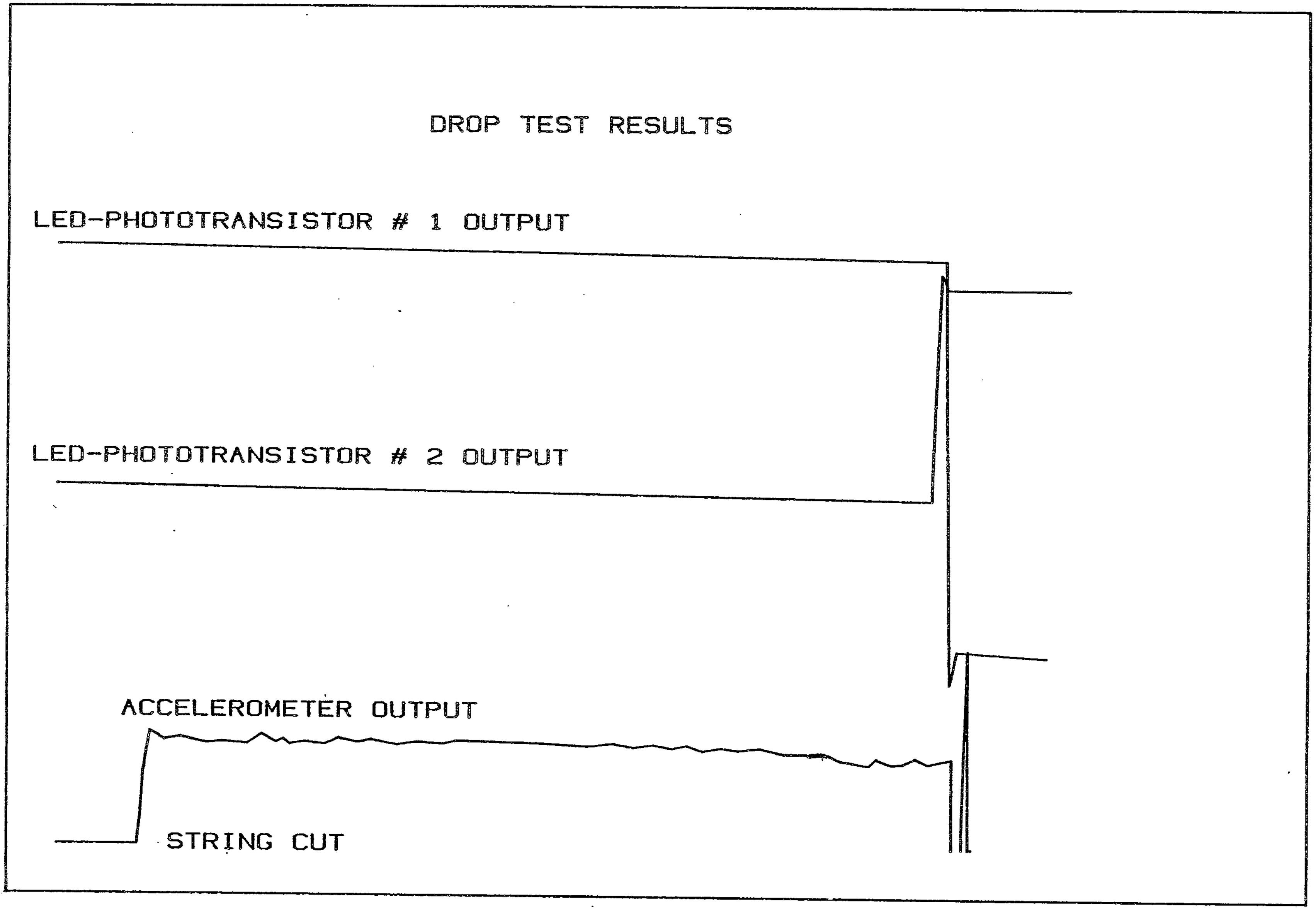

Figure 4.4: Sample Strip Chart Output With Timer and Accelerometer Measurements

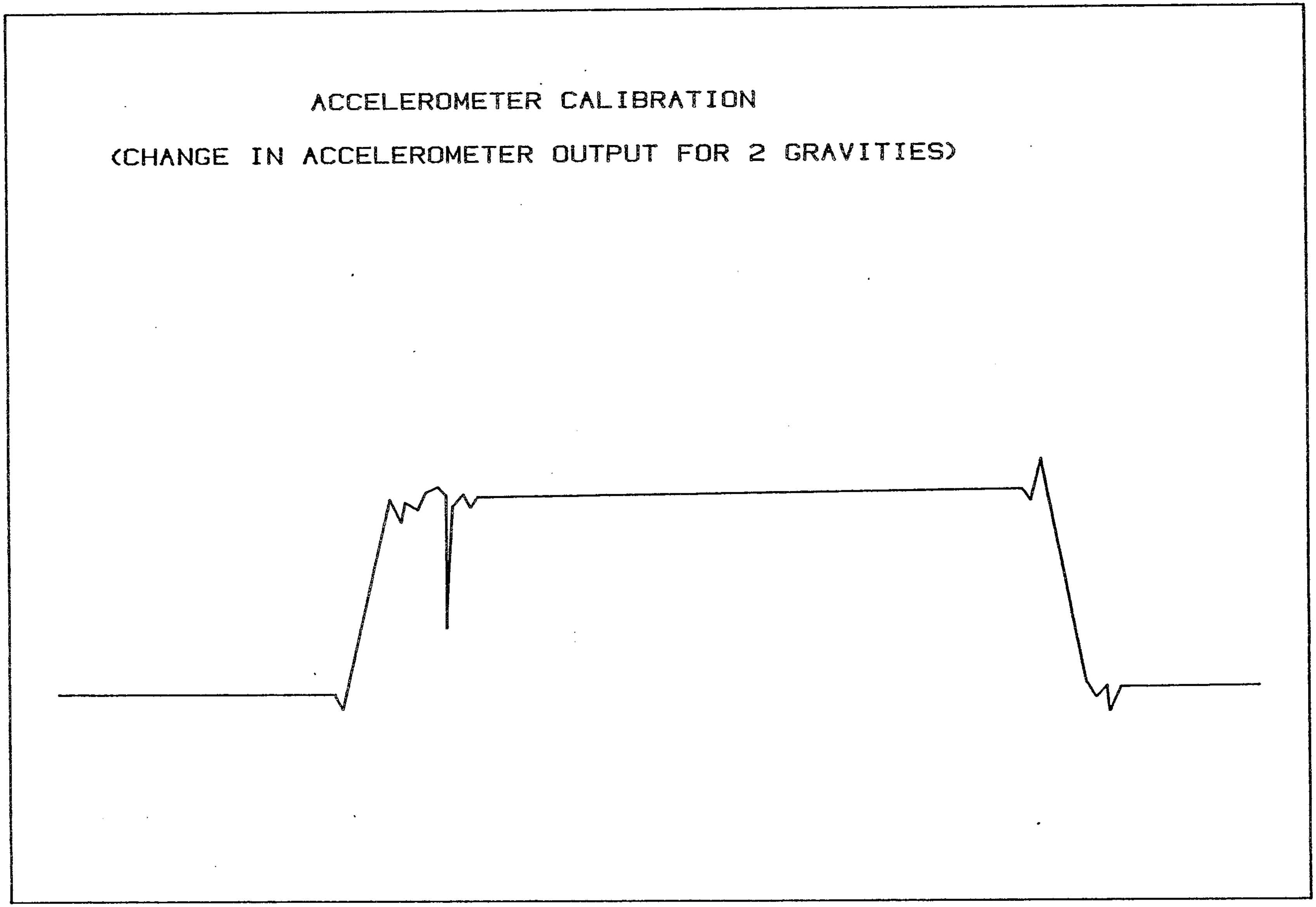

Figure 4.5: Accelerometer Calibration Test

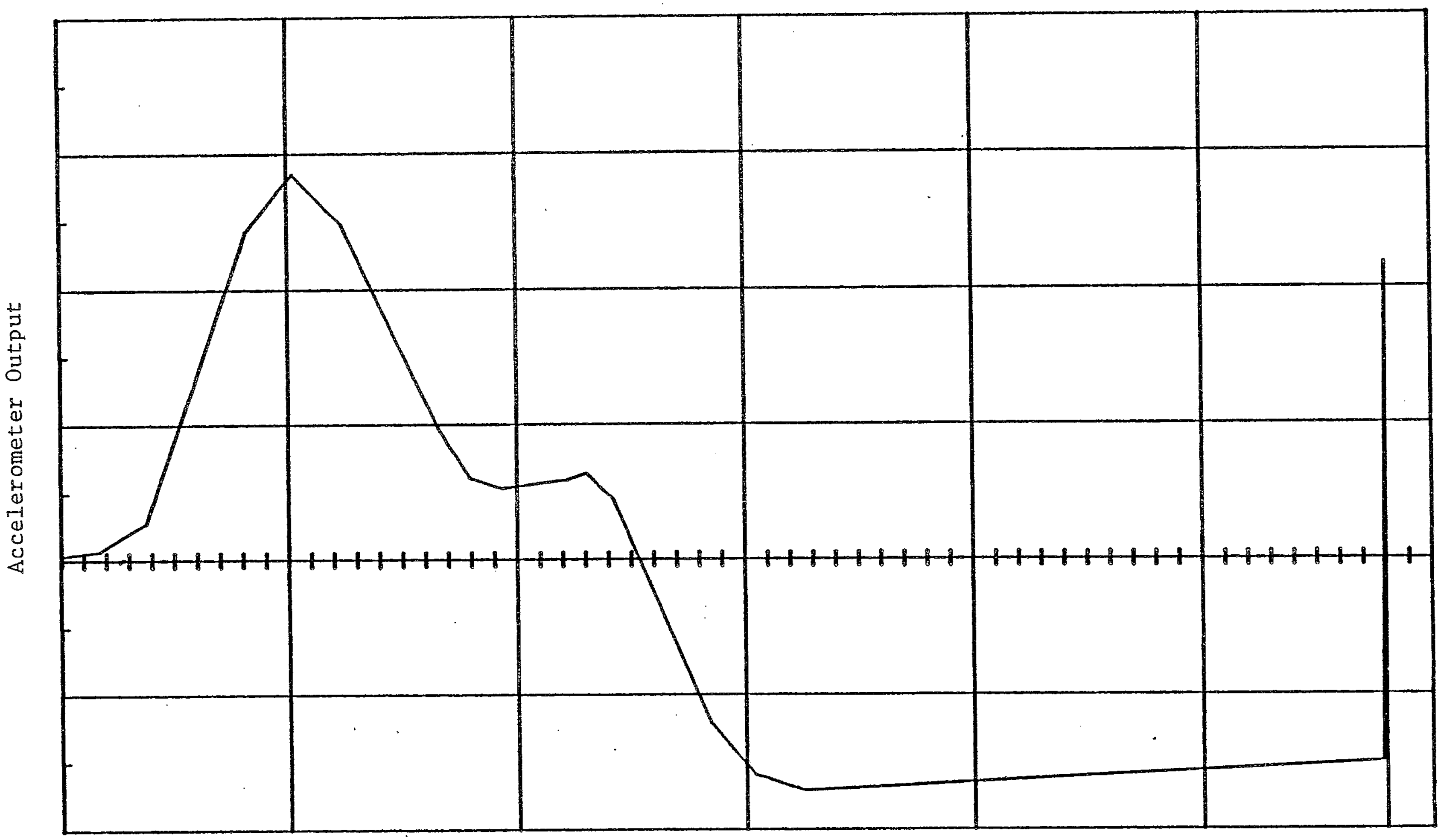

Figure 4.6: Sample Accelerometer Output

Table 4.1: Two-g Accelerometer Calibration

Test Number	Sensitivity mv/g
1	7.67
2	7.67
3	7.68
4	7.75
Mean	7.69
Standard Deviation	.038
Coefficient of Variation	0.5%
Manufacturer's Calibration	7.90

Table 4.2: Free Fall Calibration
(1 ft/s = .3048 m/s; 1 in = 25.4 mm)

Test No.	Chart Speed	Time Increment ($\times 10^{-3}$ sec)	Fall Height (in)	Velocity from Timer V_{tim} (ft/sec)	Theoretical Velocity V_{thr} (ft/sec)	Difference $(V_{tim}-V_{thr}/V_{thr}$ (%)
1	20	4.7	22.5	13.3	11.0	20.9
2	20	5.0	19.0	12.5	10.1	23.8
3	20	4.6	19.3	13.6	10.2	33.0
4	40	4.6	23.4	13.6	11.2	21.4
5	40	5.2	15.9	12.0	9.2	30.4
6	40	5.4	21.1	11.7	10.7	9.4
				Mean Difference		24.0
				Standard Deviation		8.4

Table 4.3: Velocity Test
(1 ft/s = .3048 m/s)

Test No.	Accelerometer Measurement V_{acc} (ft/sec)	Timer Measurement V_{tim} (ft/sec)	Corrected Timer Measurement* V_{time} (ft/sec)	Difference $\frac{(V_{acc}-V_{time})}{V_{time}}$ (%)
1	10.67	12.26	9.32	+14.5
2	8.51	9.19	6.98	+21.9
3	8.51	10.40	7.90	+7.7
4	9.07	11.40	8.66	+4.7
5	8.64	11.36	8.63	+0.1
6	10.20	12.50	9.50	+7.4
7	9.01	12.50	9.50	-5.2
8	8.92	10.42	7.92	+12.5
			Mean	+8.0

* (0.76 V_{tim})

4.2.2.3 Results

The results of the two-g accelerometer calibration tests are given in Table 4.1. Remarkable repeatability was achieved with a coefficient of variation of only 0.5%. The manufacturer's calibration was 7.90 mv/g. Thus, the difference between the two calibrations was 2.66%, an acceptable performance.

The results of the calibration of the light beam timer system are given in Table 4.2. In the six tests there was a mean difference of 24% with a standard deviation of 8.4%. The measured value was consistently larger than the theoretical value. The difference was probably due to the effective distance measurement between the LED-photoreceptor pairs.

A total of eight final tests were performed. The results are given in Table 4.3. Using the correction obtained in the calibration tests, an average difference of 8.0% was obtained, with the accelerometer giving higher results than the corrected timer measurement. As the timer measured the velocity a short distance above the impact, a correction should be applied to the timer-derived velocity. Assuming free fall in the remaining distance, the difference between the velocity measurements is reduced to 6.6%. The standard deviation was less than 8.0%.

These tests indicate that an instrument could probably be developed that would give satisfactory results (say ±5%). The system could be used on all hammers except those that have a completely enclosed ram.

4.2.3 Rating of Ram Acceleration Measurements

The laboratory study suggests that continuous integration of ram acceleration could lead to an impact velocity value with an accuracy better than 10%. The advantage of this direct measurement would be its low cost.

Unfortunately, however, there are also disadvantages. First, since telemetry does not yet seem feasible, a physical connection is required between the moving ram and signal conditioner. Enclosed rams could not be evaluated using this method. Installation would often be difficult since the accelerometer must be fastened to the ram; for diesel hammers, this means at the ram top.

Finally and most importantly, although single blows would produce reliable data, it would be difficult to obtain accurate velocity values over consecutive blows. Since the ram is continuously moving, it is difficult to determine a reference zero velocity. The same accelerometer capable of the sensitivity necessary to track the rise and fall of the ram cannot be used to continue the velocity computation during impact, where very high accelerations are present. The sensitive accelerometer could be used to obtain the velocity difference, but since the initial rebound velocity is not known, the impact velocity could not be determined.

4.3 Other Alternative Direct Methods

Chapter 2 recommended the radar device as the simplest and most economical method of direct ram velocity measurement. Since radar technology is readily available, proven accurate, and reliable for hammer performance measurements, similar systems using sound waves or infrared need not be investigated.

Alternate solutions are (a) an accelerometer mounted on the ram (as discussed above), (b) an optical theodolite, (c) a digital device which counts each movement of known magnitude, (d) the use of an LVDT and (e) the measurement of a force in a spring being compressed by the ram motion.

4.3.1 The Optical Theodolite (OT)

Volume II discussed this device in considerable detail. Its primary advantage is that monitoring can be achieved without physical connection to the ram. Also, the output would include the maximum stroke, a distinct advantage for diesels.

Errors due to ground motion would be of similar magnitude for both the radar device and the OT. The determination of velocity at impact may not be as accurate as the device itself, because of the need for a displacement range that is greater than the hammer stroke. Also, visibility is a problem in low light and due to obstructions present on all sites (pile crew members, crane, leads, other piles etc.). A clear target must be painted or mounted on the ram and should be kept relatively clean. It would not be possible to monitor enclosed rams.

The cost of the OT including special purpose electronics (to allow differentiation) would be much higher than a mass produced radar device. It is primarily for reasons of cost and accuracy that the OT is not preferred to the radar device.

4.3.2 Digital Counters

Remarkable progress has been made in digital displacement transducers. Several hammer monitoring devices, such as Fugro's or Menck's, take advantage of this technology.

Fugro's device measures displacement only at a single ram position, and its resolution is relatively poor. Menck installs a grooved bar which emits pulses at certain displacement intervals in a few of its hammer models. In either case, installation in different hammer models is always difficult.

There are a number of general purpose devices available. They would require data transmission by cable and the mounting of two items to ram and assembly (cylinder). The best such system has a grooved bar which may be very thin and flexible and provides for resolutions better than a fraction of an inch. This would be attached to the ram. A sensor would then be attached to the cylinder and connected to the signal conditioner with cable. Although it is conceivable that this technology will be utilized in the future, it is only recommended if it is factory installed during manufacture. The operator would simply attach a cable to a standard plug on the hammer and then obtain results from an inexpensive read out device.

4.3.3 LVDT

LVDTs convert the relative position of a core to a coil, similar to the digital displacement device. Although the LVDT is less expensive, it suffers from a lack of accuracy for large range motions. Since digital devices are more accurate and more rugged, the LVDT is not a feasible solution.

4.3.4 Spring

The measurement of force in a spring as it undergoes compression has been used for many years to measure displacement or velocity.

Two design configurations are possible. First, the spring could be long and rigidly attached to both ram and reference (assembly or cylinder). In this case the relatively soft spring would have to undergo rather large deformations. This softness would be a disadvantage since it would give rise to low natural spring frequencies which would need to dampened. The spring would have to be installed in a long pipe containing the dampening medium (similar to a shock absorber). Other obvious technical problems exist with this system; different spring types would be required depending on the hammer stroke. Accuracy would be questionable.

A second type of spring would be short and therefore activated only during the last few inches of ram descent. The advantage of this relatively sturdy spring would be a much simpler design. Its accuracy would be good. The major disadvantages would again be installation problems and the dampening of shock waves. The system could only be recommended for factory installation. Installation of a digital displacement transducer would be preferable.

4.4 Alternate Indirect Measurements

Chapter 3 already treated the subject of indirect measurements in detail. It was found that acceleration measurements have the best chance for success because of the simplicity and ruggedness of the accelerometers used, and the relatively small number of models required to cope with all piling configurations.

Force transducer installation is much more complicated than accelerometer attachment. Force transducers are not available in the required configuration and would, therefore, need to be custom made for a specific driving system. It was furthermore determined that any device inserted in the driving system could cause a change in hammer performance thus completely eliminating the use of <u>any</u> device of this type.

Fortunately, impact force values can be determined from acceleration measurements. For a given stroke the most important contribution to the force on the hammer is the inertia of the helmet. However, it is doubtful if a force level is indicative of the quality of hammer performance. The evaluation methods discussed in Chapter 3 would be superior. The study of the Kuemmel Method (Volume I) may be cited as proof.

In summary, measurement of acceleration provides the most economical and complete simple solution. As discussed in Chapter 3, acceleration measurements provide for sufficient information to evaluate hammer and driving system performance. No other single system can offer such a complete solution.

4.5 Indicator Measurements

4.5.1 Pressure

Among the indicator measurements, only pressure is of any value to the evaluation of hammer performance. However, pressure alone cannot be used to determine energy output or transfer to the pile.

4.5.1.1 ASH hammers

For ASH hammers, pressure of the power medium at the intake would be a valuable parameter. Unfortunately, measurement is not simple for the following reasons:

(a) This measurement is static in nature, i.e. there is no recurring reference value (such as a zero or atmospheric pressure) between blows. Thus, any drift of the transducer or the signal conditioning equipment could lead to significant errors. This also eliminates the use of simple quartz crystal transducers, because of their relatively short time constant. On the other hand, the use of strain gage - based pressure transducers is complicated by the need for temperature compensation, since hammer temperatures change significantly during operation.

(b) Installation of such transducers would be difficult. In general, there are no suitable fittings on the hammer and it would be necessary to drill into the hammer's casting. It is recommended that such transducer installation should be made by the hammer manufacturer.

The value of these measurements is marginal except to verify the adequacy of the power supply. This measurement would not be sufficient to indicate a hammer's performance.

4.5.1.2 Diesel Combustion Pressure

For diesel hammers, combustion chamber pressure measurements are generally taken using piezoelectric pressure transducers. This pressure measurement is of value when indirect accelerometer measurements are taken since it eliminates the necessity to model the hammer's thermodynamic model, and thereby increases the precision of the calculations. A disadvantage is that not all hammers have readily accessible combustion chambers. It is therefore again recommended that the manufacturer provide a transducer-compatible tapped hole to avoid conflict with the manufacturer's warranty.

Diesel combustion pressure by itself may be a misleading quantity unless the observer is intimately familiar with the particular hammer type. For example, preignition may be normal for one hammer type, but represent a malfunction in another. This measurement can therefore only be recommended in conjunction with detailed calculations and/or data banks and would therefore require a microprocessor based analysis system as proposed for the acceleration measurements.

4.5.2 Blows per Minute

This measurement is relatively easy to take, and should be automatically monitored for any pile driving project. For ASH hammers it may serve as an indicator of the reasons for poor performance, for open-end diesel hammers, it allows for a calculation of potential energy. Even for closed-end diesels, blows per minute is related to the effective hammer stroke.

It is dangerous to rely solely on blows per minute as a performance indicator for diesel hammers. As explained in the Volume I, undesirable preignition may actually cause high strokes (thus low blows per minute), which is also an indication of good pile capacity. The high strokes caused by preignition are characterized by correspondingly low energy transfer and may therefore result in higher than expected blow counts, even for dangerously low capacity. There is a danger, therefore, when using blow rate as an indication of energy transfer, that both energy transfer and pile capacity will be overestimated.

To be sufficiently accurate, either the blows must be counted for a whole minute, a stopwatch must be used for at least 10 strokes, or an electronic device which can time consecutive impacts with excellent precision must be employed. The techniques to obtain this information are very simple, and the cost is always acceptably low.

4.6 Conclusions

The various methods discussed in this chapter have some merits, but their disadvantages compared with the radar-based direct or accelerometer-based indirect systems make them less attractive. Of the other systems, only the optical theodelite and the digital displacement transducer have real merit. Because of the low cost, blows per minute is recommended as the best indicator measurement.

Among the indirect measurement systems, only the method discussed in Chapter 3 is sufficiently simple for routine operation. Since direct methods are not applicable to all hammer types, the indirect accelerometer based system is favored. In an initial phase, it should be combined with the RVM system.

5. SUMMARY OF THE PREFERRED MEASUREMENT SYSTEM

5.1 General Remarks

The preceding chapters have justified the development of a system which includes both a direct measurement device (the radar device), and an indirect system, based on piezoelectric accelerometers. The latter system will be referred to as AMS for Acceleration Monitoring System. In this chapter, the implementation of both the radar device and AMS will be discussed.

Because of different hammer and/or pile configurations, there is no single standard method for hammer and driving system investigations. Furthermore, the quantities to be measured in any investigation may vary, e.g. hammer impact velocity only, cushion properties, or the energy transfer through the driving system.

The radar device can only be used for ASH hammers with a visible ram. For all other systems, the AMS is required. However, during a transition period, the radar device may also be used on open-end diesels.

5.2 Test Procedure

5.2.1 Radar Measurements

The system will consist of the antenna or wave emitter and receiver (both in one unit), a cable and a processing unit. The processing unit may provide either a digital ram impact velocity or a continuous analog output for strip charts, oscilloscopes or tape recorders.

The antenna is placed near the toe of the pile and directed toward the ram. If the ram does not expose a sufficiently large area, then a target must be mounted on the ram. Care must be taken that this target is well fastened, and does not move relative to the ram.

During ram motion, the ram impact velocity is read from the strip chart or from the digital output of the radar device. Simple calculations give the ram kinetic energy. Efficiency can then be computed from the rated energy. Although these calculations are easy, the operator could also have a chart relating hammer efficiency to impact velocity for each hammer.

A continuous analog output of ram velocity may be used to detect specific hammer malfunctions. For example, a long slow change of velocity may indicate excessive friction, while a fast change just before impact is caused by preadmission (improper hammer cushion thickness).

5.2.2 AMS Measurements for ASH Hammers on Steel Piles

The contractor is required to weld two small steel plates, containing tapped holes and a cable attachment hook, on opposite sides of the helmet. One accelerometer is then bolted to each plate and connected to a single cable supported by the hook. The contractor then proceeds normally with the pile driving operation.

The signal cable is connected to a signal conditioning unit which is precalibrated for the helmet accelerometers and includes an A/D unit (analog to digital converter). The digital data is input to a microprocessor. The microprocessor is initialized by specifying the hammer type to be tested, the pile area and the helmet weight. Such simplicity is possible since all relevant hammer data can be already stored in a read-only-memory (ROM) section of the microprocessor.

As pile driving proceeds, closed form solutions would be made for each blow. The microprocessor stores selected records (actually only very short record portions of at most 10 ms duration) in RAM (random access memory) or, optionally, on digital disk or other mass-storage device.

After the test, the microprocessor can analyze any digital record by either closed form or minimization methods and display the ram impact velocity, capblock stiffness and coefficient of restitution. An optional plotter may plot the capblock force deformation curve or a histogram of results, e.g. the number of blows having wave equation efficiencies occurring within a certain percentage band.

5.2.3 AMS Measurements for Diesel Hammers on Steel Piles

The contractor welds two small steel plates containing tapped holes to both the impact block and helmet. Four identical accelerometers, two marked "IB" and two marked "H", are attached. The remaining system is the same as for the ASH hammers. Outputs include the capblock stiffness or, optionally, its force deformation curve, the capblock coefficient of restitution, the ram impact velocity, and the WEAP wave equation efficiency.

5.2.4 AMS Measurements for ASH Hammers on Concrete Piles

In addition to all the measurements on steel piles, two accelerometers must also be attached to the pile. These accelerometers are of higher sensitivity and will be marked "P". A separate signal cable will extend from the pile to the operator's work station. The cable and accelerometers are protected by covers while the pile is set in the leads. Alternatively, this test may start when the pile has been driven until the pile top can be easily accessed (i.e., near the end of driving).

Initialization of signal conditioning and microprocessor are also similar to the AMS measurements on steel piles. A pile top cushion option will also require that a pile elastic modulus is entered, or may be automatically computed from wavespeed in easy to moderate driving conditions. The cushion force is directly dependent on the pile's elastic modulus. However, cushion force errors hardly affect the hammer performance results, since the cushion force is low compared to the capblock force during the time period considered.

The results of the ASH test also provide ram velocity and capblock properties. Cushion stiffness or an optional cushion force deformation curve may be obtained. Although pile cushion properties are very important to energy transfer to the pile, they are not required for hammer/capblock analysis and therefore the pile acceleration measurements could be eliminated.

5.2.5 AMS Measurements for Diesel Hammers on Concrete Piles

A total of three sets of two accelerometers each are attached to the impact block, helmet and pile top. Again, as in the case of ASH hammers on concrete piles, it is necessary to use a separate signal cable for the pile accelerometers and to protect these units. As above, pile acceleration measurements are optional, but highly recommended.

Results will include the ram impact velocity, WEAP efficiency, and capblock or cushion properties.

5.3 Extensions

5.3.1 Pressure Measurements for Diesels

A pressure transducer attached to the diesel hammer, together with the standard AMS instrumentation, will allow direct evaluation of preignition problems. Since the microprocessor will have the hammer's thermodynamic data stored, a comparison of theoretical and actual performance is possible.

The pressure-volume relationship can be computed and plotted for the crucial time period shortly before and after impact. This option requires one additional channel of signal processing and A/D. The remaining work is software controlled.

5.3.2 Blows per Minute

Naturally, the measurements allow for the accurate determination of the hammer speed for each blow. This feature would require that the microprocessor detect the occurrence of a blow, and determine the time between blows. This time could be converted to an equivalent blows per minute value.

The blows per minute result would aid in the diagnosis of hammer troubles for any type of hammer. In addition, it may be used for stroke calculations for open-end diesels. The AMS method would compute WEAP hammer efficiency based on this stroke value.

5.4 Personnel

Either the radar device or AMS may be operated by a single technician. In both cases, cooperation from the contractor is required, and permanent records may be obtained (e.g. cassette tape, floppy disk, strip chart etc.). An experienced engineer should review these records in the laboratory.

5.5 Calibration/Verification Testing

The radar may be calibrated by dropping an object falling a known distance in the direction of the radar antenna or by means of standard tuning forks. With proper targets for ASH and diesel hammers, this calibration should be sufficient. Of course, a controlled test which includes complete Case Method measurements and the Pile Driving Analyzer should also be conducted.

The accelerometers used by AMS are factory calibrated. In fact, they may be chosen such that their calibration factors are extremely close making them interchangeable.

The computational method of the AMS system must be verified under a number of conditions. At first, the simplest case, being that of ASH hammers on steel piles, should be tested both by the radar device and AMS. Furthermore, force measurements in the pile should be taken simultaneously for a complete Case Method evaluation.

The second system to be verified should be the case of diesel hammers on steel piles. This is the most important application for AMS, since diesel hammers are very common and the radar device is not applicable on a routine basis. For verification, however, an open-end hammer should be chosen, and the radar device used as an independent check. Pile top force records and combustion pressure should also be measured.

Finally, AMS measurements should be made on driving systems which include a pile cushion. This should be done first under ASH hammers with the radar device, and later on the diesel hammers. Because the fuel injection system of diesel hammers can make a large difference to performance, pressure measurements are recommended whenever an unknown hammer type is tested.

6. CONCLUSIONS AND RECOMMENDATIONS

The investigations performed and described in this report have shown that a simple measurement system may be built for the performance investigation of all types of impact hammers and cushioning. All components (accelerometers) attached to the driving system are already in routine use for pile testing. The only questionable attachment will be the "target" on rams for radar monitoring. It is hoped that the AMS will eventually replace the radar device, since AMS provides more information. The proposed AMS takes advantage of state of the art digital and microprocessor technology. This means that high flexibility is assured, since most further developments can simply be done with software. AMS has many advantages over all existing technology. The best overall driving system monitor is the Case Method of pile top measurements, however, it is intended for only a sample (typically 5%) of all piles on a site. Existing hammer monitoring devices measure only ram velocity at impact (or in some cases before impact, which is less than ideal) and thus ignore other very important driving system parameters.

The simple AMS system will provide not only ram velocity but also capblock and cushion properties. These parameters are the primary unknowns affecting wave equation analysis accuracy. AMS would output the values directly in the form required by wave analyses. The AMS system could be used to monitor every pile and would not interfere with the normal pile driving operation.

The cost of a complete system including accelerometers, signal conditioning and microprocessor is rather modest. The benefit to cost ratio should be high.

It is not possible to eliminate cable connections to driving system components and piles. With the current state of electronics, telemetry may cause more problems than cables. Since other lines are already attached to every hammer to control operation, the additional cable should not be a problem.

It is recommended that prototype construction begin by purchasing radar antenna with associated electronics as soon as possible. In a first step of the AMS development, results using accelerometers, existing signal conditioning, and a tape recorder should be obtained and compared with radar measurements on construction sites. A standard microcomputer would then suffice to evaluate the data in the preferred automated manner in the laboratory. The necessary programs are already available (see Chapter 3). In this way, it will be possible to work in parallel on the refinement of both hardware and software.

The data collection efforts will result in a large number of hammer and cushion material parameters. These parameters may aid in wave equation predictions if they are collected and continuously updated in an organized, statistical manner. For example, hammer efficiency values could be averaged for certain hammer types and driving conditions. It is therefore suggested to start as soon as possible with the design of a data bank for both hammers and capblock cushion material.

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