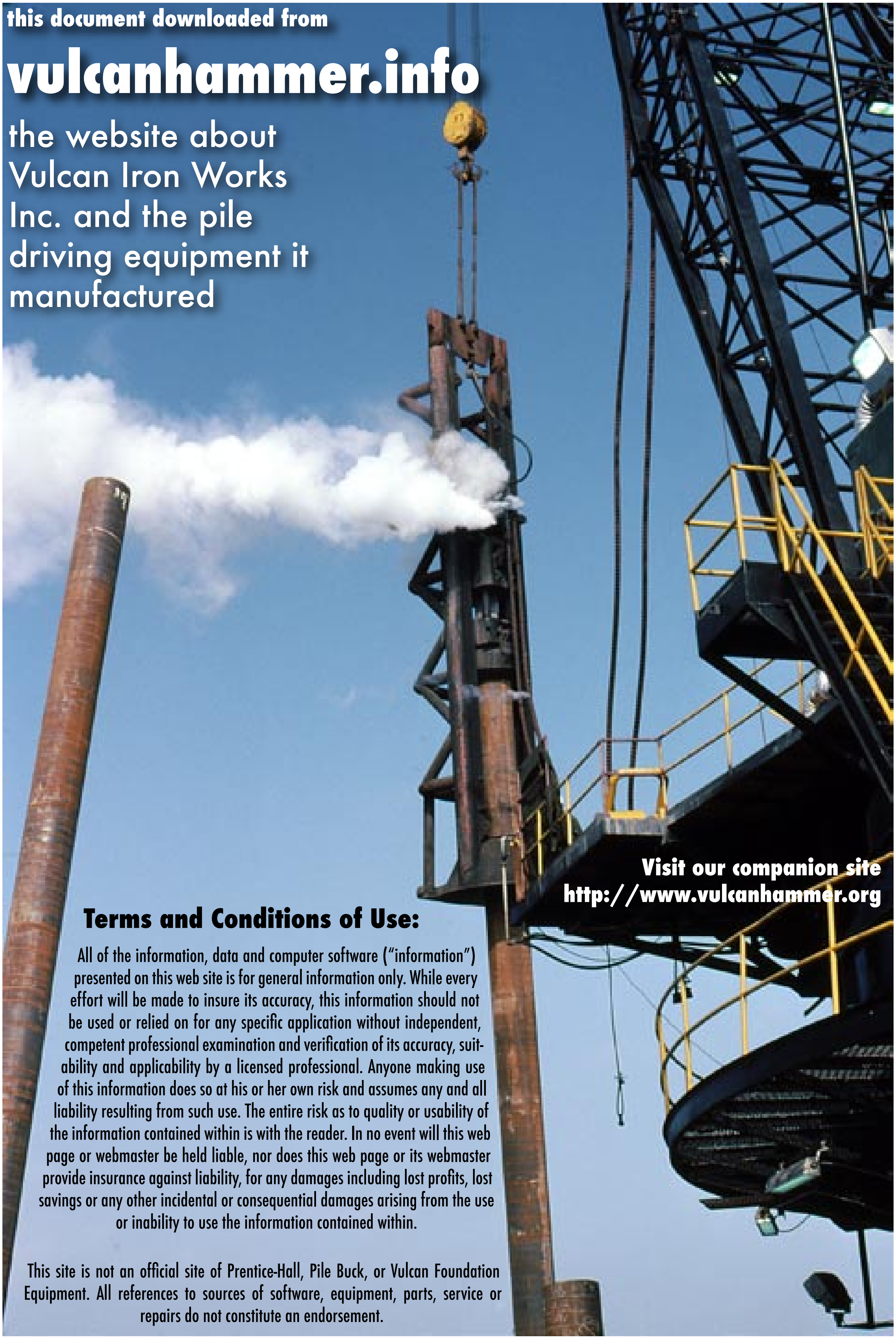

DYNAMIC MEASUREMENT OF PILES

Dynamic formulas were commonly employed to determine dynamic bearing capacity of piles during the driving operation. Numerous such formulas are available. The most common ones are the Engineering news record, Hiley's, Rankine's, Chellis', etc. These formulas have been severely criticized because they incorporated empirical factors whose roots connot be traced. As a result their validity and applicability are questioned.

This problem persisted for a long time. Finally the Ohio Department of Transportation and Federal Highway Administration, understanding the seriousness of the problem sponsored series of research projects at Case Western Reserve University to study the dynamic behaivors of piles and pile driving hammer performances during the driving operation.

The research emphasis can be broken down into three catagories

1. Investigation of the reliable mathematical approach to the problem--Traveling wave solution of the one dimensional linear equation was found to be the most appropriate to the prevailing problem. As a result the Case Method capacity determination was developed.

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2. Method of data acquisition: Electronic equipment such as reusable transducers and a data recording system was devised.

3. Invention of a system for data processing and analysis: A Pile Driving Analyzer (Portable computer-) was built to process and analyze the data right at the job site.

The benefits from the research are tremendous. It has opened a new era in the field of pile driving both on land and offshore. A few of the benefits which are currently performed routinely are as follows:

I. Pile Capacity Determination

A procedure known as the Case Method was developed to determine the pile capacity dynamically for every hammer blow as the pile penetrates through different soil strata. This is possible by electronically measuring force and acceleration of the pile using strain transducers and accelerometers attached to the pile top. The resistance as computed by the Case Method is expressed as follows:

$$R = \frac{F(t_1) + F(t_1 + L/c)}{2} + \frac{Mc}{2L}\left(V(t_1) - V(t_1 + 2L/c)\right)$$

t_1 is the time at impact, v is the velocity of the pile at the pile top, L is the pile length, c is the wave speed in the pile material, M is the mass of the pile and F is the measured force at the pile top. The total resistance R, is the sum of static, Rs, and dynamic, Rd, resistances

$$R = R_s + R_d$$

The dynamic resistance better known as damping force is obtained from

$$R_d = J \times V_{toe}$$

where J is a damping constant which is dependent on the soil type and V_{toe} is the pile toe velocity. It can be shown from wave theory that the pile toe velocity can be calculated as

$$V_{toe} = 2\ V_{top} - \frac{L}{Mc} R$$

where V_{top} is the pile top velocity. The static soil resistance is then obtained by subtracting the calculated damping force, R_d, from the total driving resistance, R,

$$R_s = R - R_d$$

The static resistance is computed automatically from the above expression by the Pile Driving Analyzer and results are printed out for every blow. During the research projects a correlation study of dynamic bearing capacity with that of the capacity obtained statically (such as from load test) were found to be in an excellent agreement.

II. Control Driving Stresses and Damage Detection:

In most cases, piles are subject to high stresses during driving. It is important to control and watch the driving operation very closely. The forces delivered to the pile are computed automatically from the strain readings by a Pile Driving Analyzer and from these forces, the stresses the pile is subject to by every hammer blow is calculated. Thus, it is possible to control the hammer throttle settings or stream pressures if the damage from high driving stresses is likely.

The structural pile damage at any other location along the pile length can be detected by closely watching the force and velocity records on the screen of an oscilloscope (an integral part of the dynamic measuring system).

High tensile stresses are prevalent in concrete piles which might cause structural damge at certain locations along the pile length. If damage is detected from the observation of force and velocity records at an earlier stage of driving transducers may be mounted at that location and stresses investigated as a function of cushion, cap, helmet or even different hammer in an effort to reduce the stresses and continue driving.

In piles already driven to required penetration the Pile Driving Analyzer is effectively used to detect structural damage of the pile by restriking them with only few blows. A long term set up capacity can also be determined from restriking information. This procedure has been used routinely especially on concrete piles where cracks from high tnesile stresses either at the pile splices or in the pile material are likely.

III. Data Acquisition Methods and Their Permanent Storage:

Electronic equipment namely strain transducers and accelerometers are used to measure the strain and acceleration of the pile top. The strain reading is automatically converted to force using the cross sectional area and modulus of elasticity of the pile. The acceleration and force records are continuously displayed on an oscilloscope to check the quality of the records. The acceleration record is intergrated to obtain velocity. Necessary computations of force, pile capacity, transfered energy, maximum velocity, maximum acceleration and other quantities are performed automatically by a Pile Driving Analyzer right at the job site and results printed out on paper tapes. Both force and acceleration records are stored on analog magnetic tape using a portable multi-channel tape recorder. The information recorded is later processed at the office using larger computer. The tapes are then kept as a permanent record to be reached only when need arises.

IV. Hammer Inspection:

The proper performance of hammers is very important in pile driving. The hammer should be capable of embedding the pile to its proper design elevation safely without causing damage to the pile. Hammers are generally selected by their rated energies as defined by hammer manufacturers. All hammers do not deliver their full available energy to the pile. A substantial amount is lost within the hammer system during impacting. Impacting losses results from heat, friction, combustion in-effeciencies such as pre-ignition, ram impact velocity, and in-elastic collisions in drive cap assembly. Only a certain percentage of the rated hammer energy is delivered to the pile. If a poorly performing hammer is used in driving a pile a high blow count is reached and thereby get to a refusal criteria at the early stage of driving. This, of course, is misleading especially when costly alternatives such as drilling, jetting or changing to a larger hammer are to be employed.

In order to define refusal the hammer energy delivered to the pile should be taken into account. The energy delivered to the pile is calculated from the force and velocity records measured at the top of the pile during driving. The maximum energy is computed by a Pile Driving Analyzer from the expression below.

$$E(t) = \int_0^t F(t)\ V(t)\ dt$$

where energy, E(t), force, F(t), and velocity, V(t), are all functions of time. This is the energy available to the pile to do work. By continuously monitoring the friving operation especially hammer performance it is possible to define refusal. This requires that hammer efficiency and blow count should be closely watched simultaneously. Then it is possible to evaluate whether it is soil or the hammer responsible for a change in the blow count.

V. Driveability Survey:

A survey of the driveability of conductor piles is routinely performed by Petro-Dynamics, Inc. from exploration rigs. The force and acceleration records are measured electronically on the conductor pipe while the rig is out for an exploration. These records are analyzed in relation to the type of hammer to be used, the soil type and the resistance to be encountered during the actual driving operation of conductors and main structural legs. This is possible by the use of a computer program known as CAPWAP (Case Pile Wave Analysis Program). In the program the measured velocity obtained by integration of the acceleration record is taken as an input quantity. From this input and an assumed set of soil resistance forces, the pile top force can be computed using a lumped mass-spring system as is commonly used in all pile wave equation programs. By adjusting the resistance forces and balancing them between static and dynamic resistances it is possible to adjust the computed force so that it agrees with the measured force record. The CAPWAP program performs this function automatically.

From this analysis a correct soil parameters can be drawn without running the actual soil boring. Another important feature of the program is that it is possible to estimate the skin-distribution and toe bearing. The portion along the length of the pile, where the skin-resistance distribution is the greatest can be located.

The soil constants drawn from CAPWAP analysis are used as an input in the conventional wave equation analysis. These are two recent wave equation programs, The TTI program and WEAP (Wave Equation Analysis Program). Both programs do an adequate job for air steam hammers. The WEAP program does a more realistic analysis in modelling the thermodynamic process of diesel hammers. The WEAP program is at our disposal. Using this program and the soil constant obtained from CAPWAP analysis it is possible to arrive at the size of hammer to be used and blow count to be expected during driving. Therefore, it suffices to say that driveability survey helps a great deal in planning the driving operation.

For any further information and assistance regarding the Pile Driving Analyzer, dynamic measurement, analysis of conductor, and structural leg piles, please feel free to contact us.

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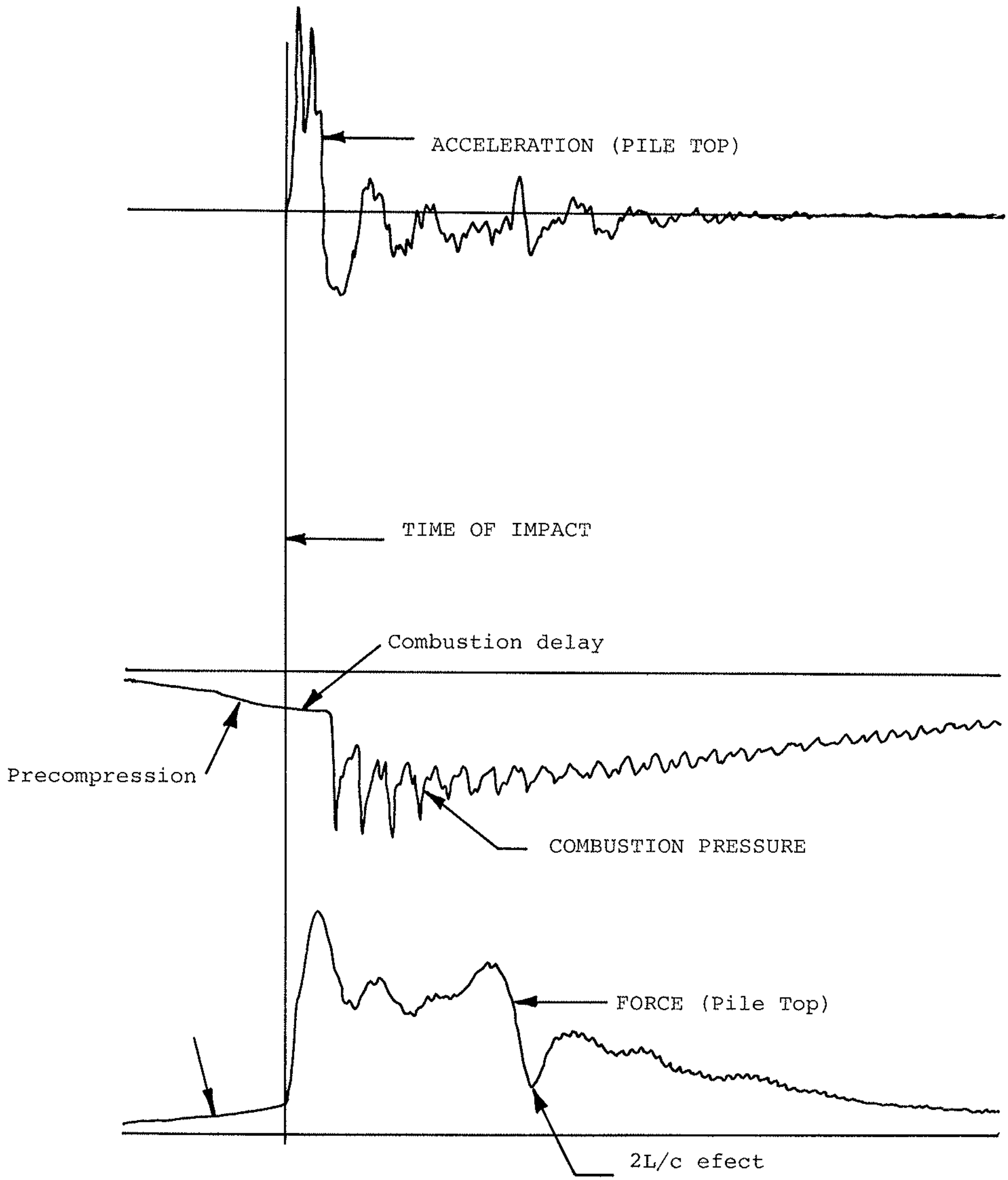
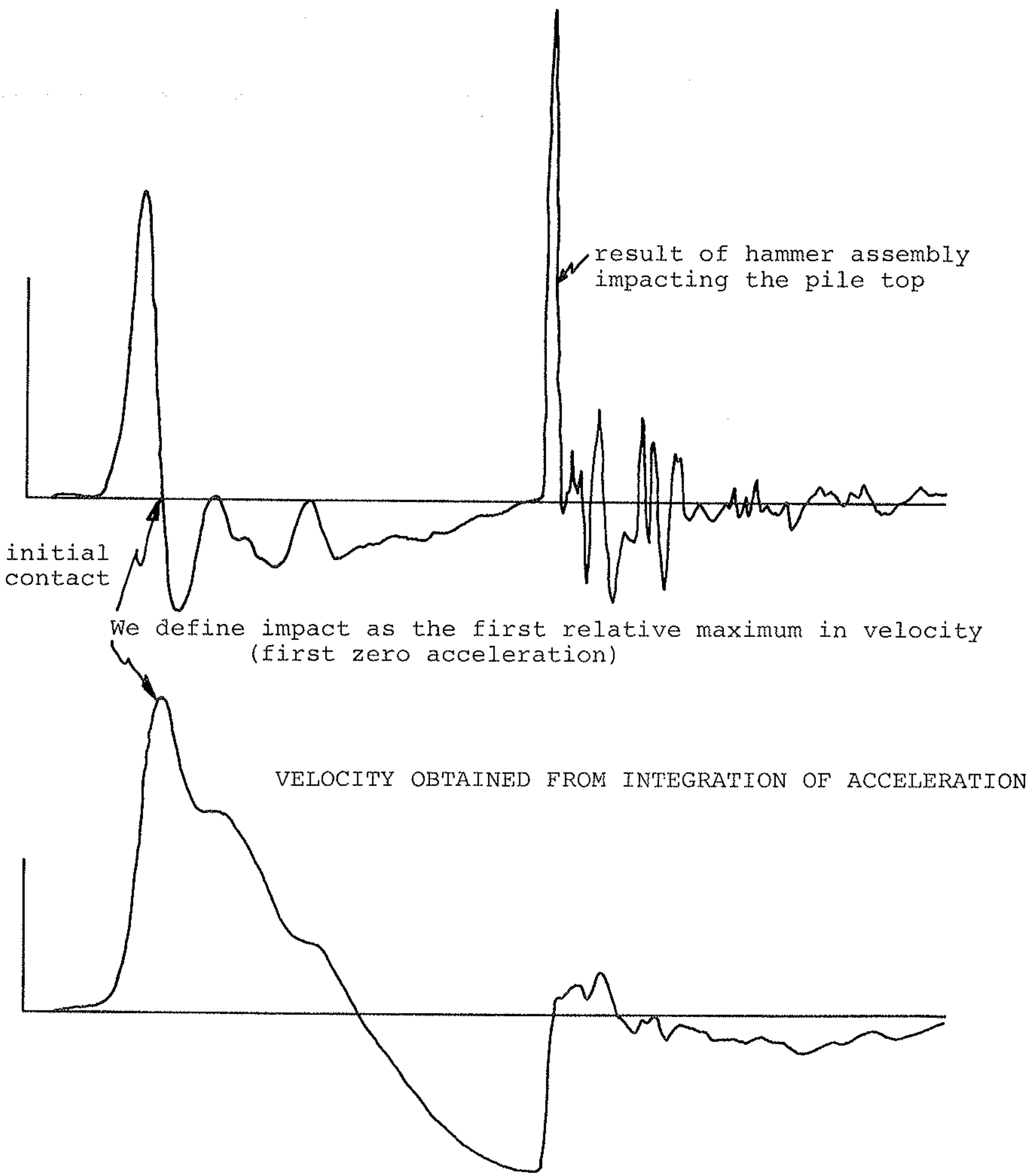
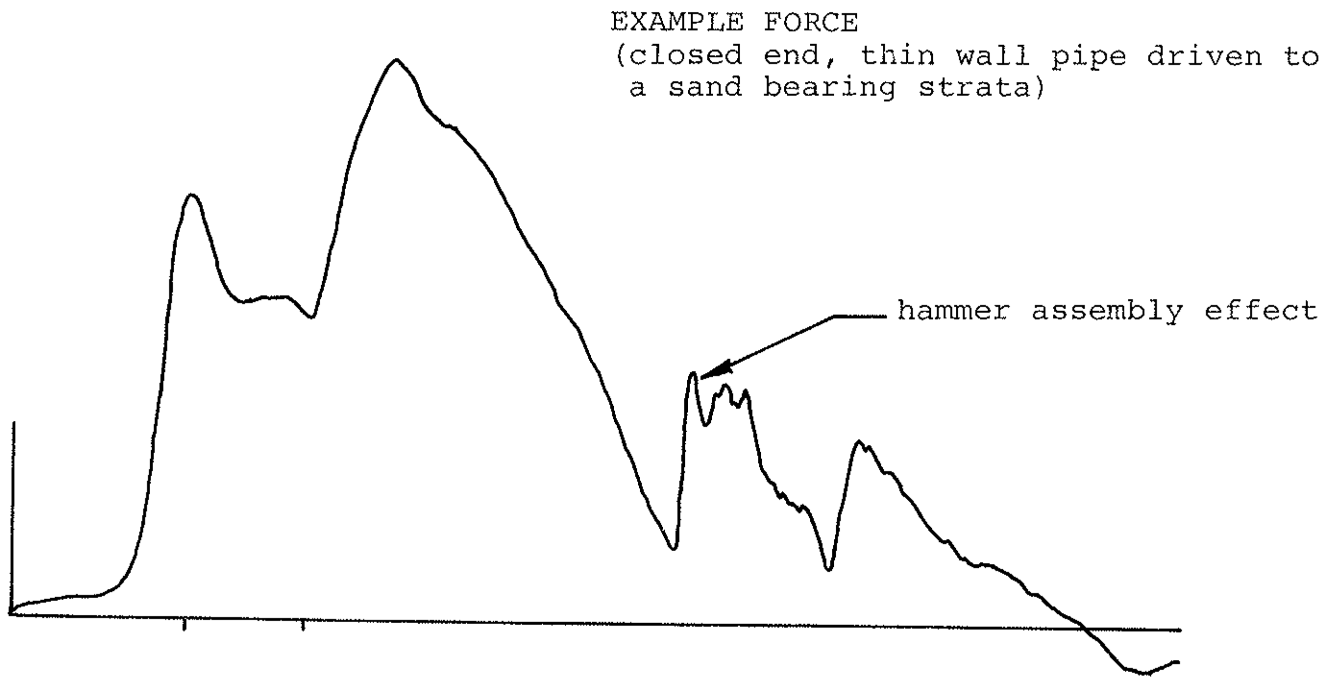
SAMPLE DYNAMIC DATA

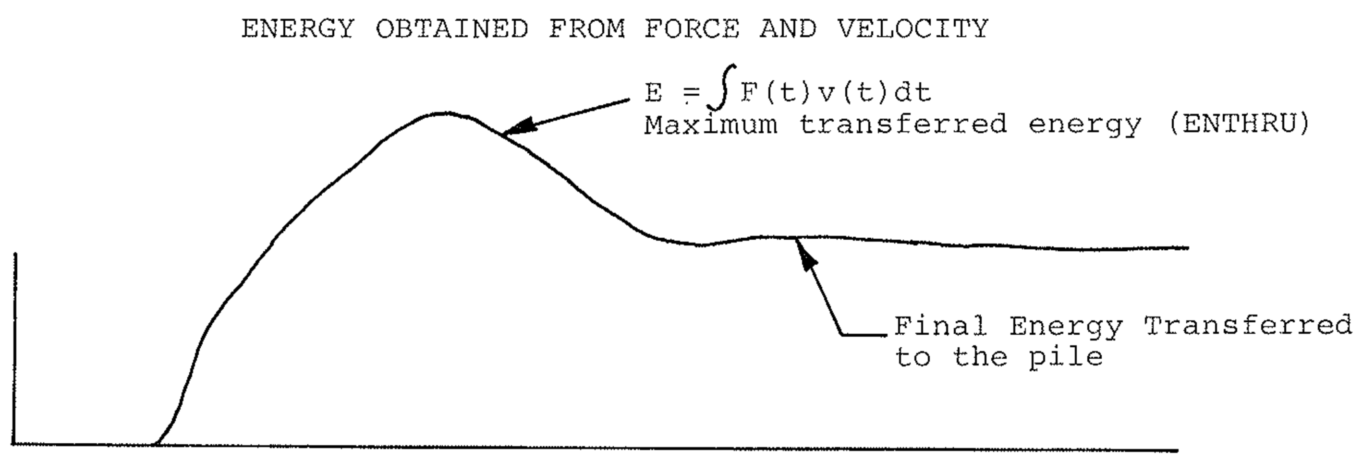


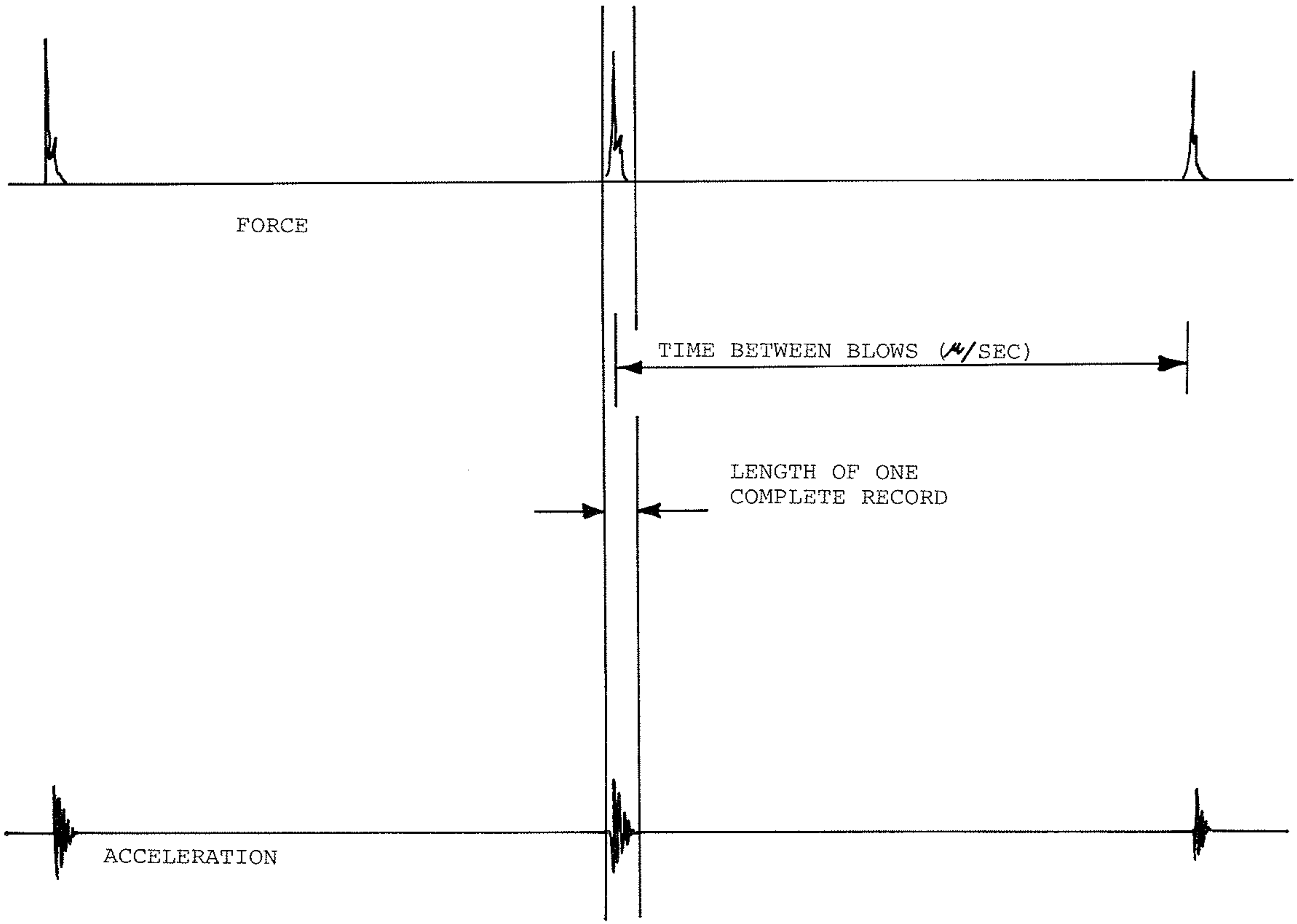
Typical diesel hammer performance on H pile in easy driving

EXAMPLE ACCELERATION

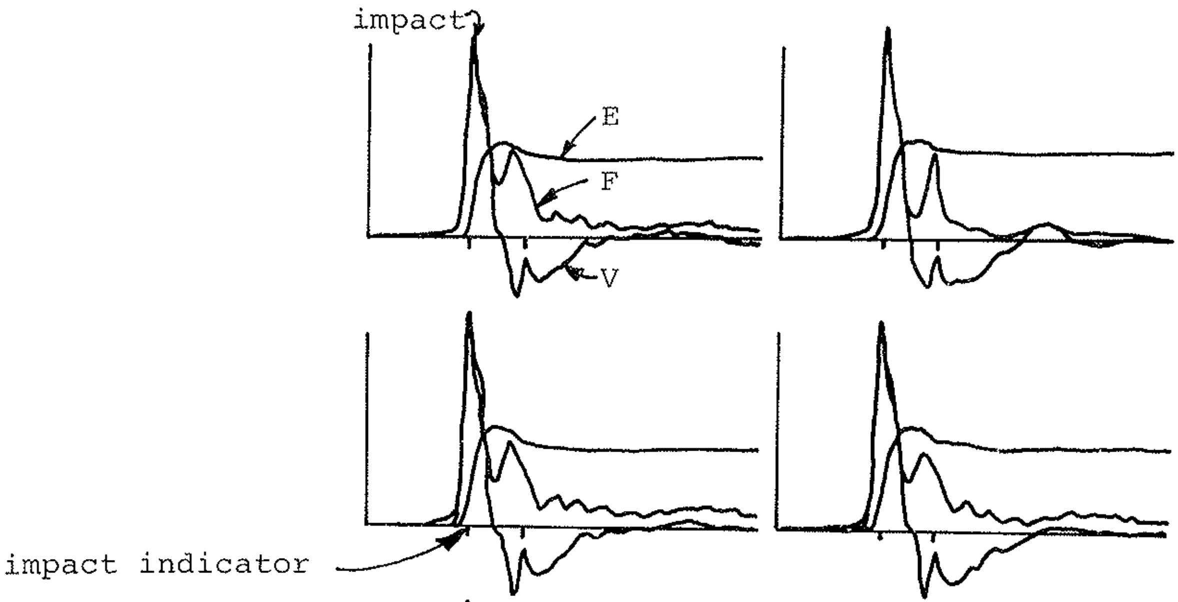


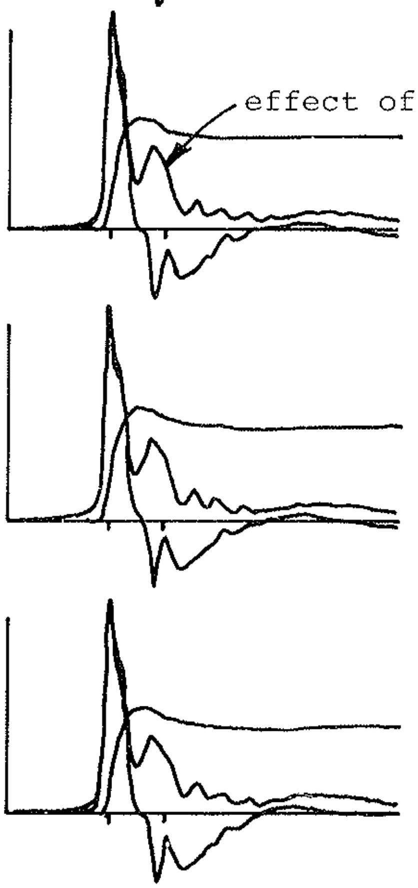

EXAMPLE FORCE
(closed end, thin wall pipe driven to
a sand bearing strata)
hammer assembly effect


ENERGY OBTAINED FROM FORCE AND VELOCITY
E = ∫F(t)v(t)dt
Maximum transferred energy (ENTHRU)
Final Energy Transferred
to the pile



For typical impact hammers, one blow is finished before the next begins.



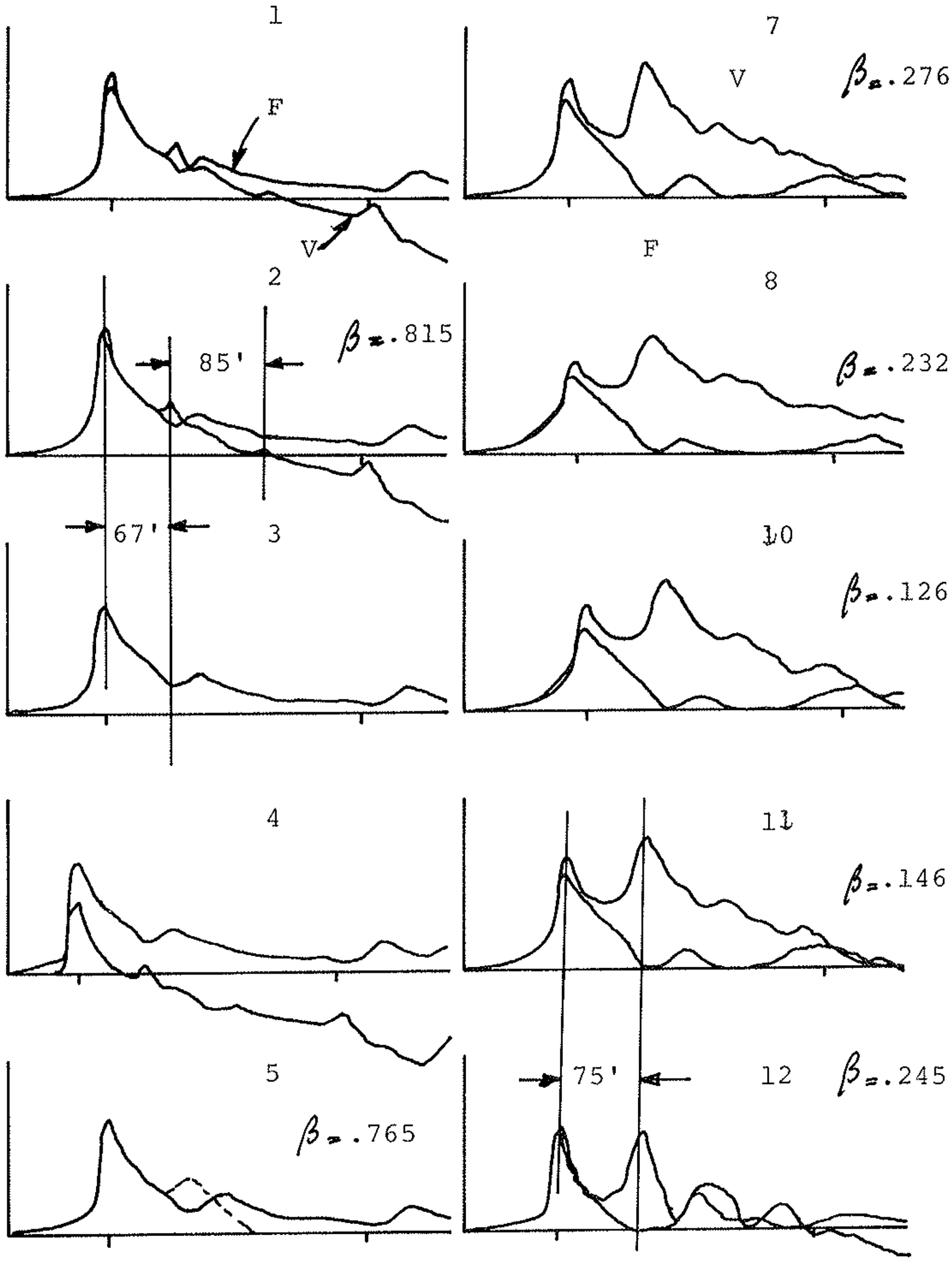


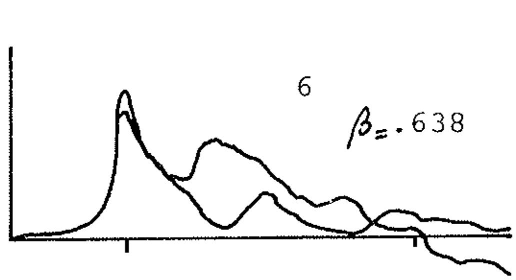
SAMPLE DATA FROM CONCRETE PILE. (Force and velocity x $\frac{EA}{c}$ plotted to same scale)

NOTE:

1. Force and velocity are proportional until the soil resistance effects are felt. At that time for uniform piles the force will increase & velocity decrease relative to each other.
2. At 2L/c, the time of the first arrival of the wave reflection from the pile tip, the velocity shows a relative increase and the force is decreasing. In harder driving it may or may not be possible to detect this behavior.
3. The force for concrete piles is usually maximum at the time of impact.
4. The force is usually relatively inactive after 2L/c for concrete piles due to their high weight.

ONSECUTIVE RECORDS DURING THE DEVELOPMENT OF DAMAGE 219.5' PENETRATION

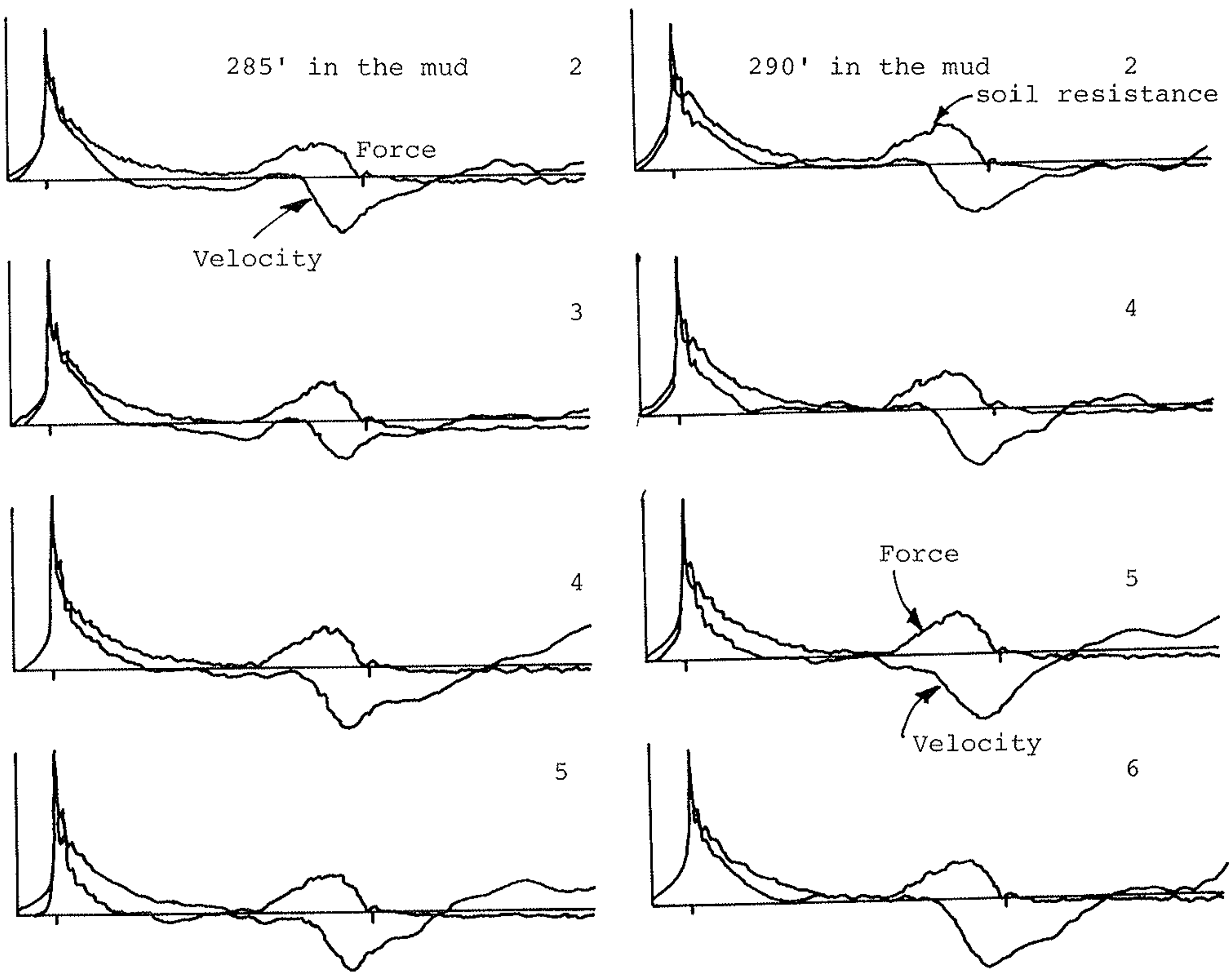


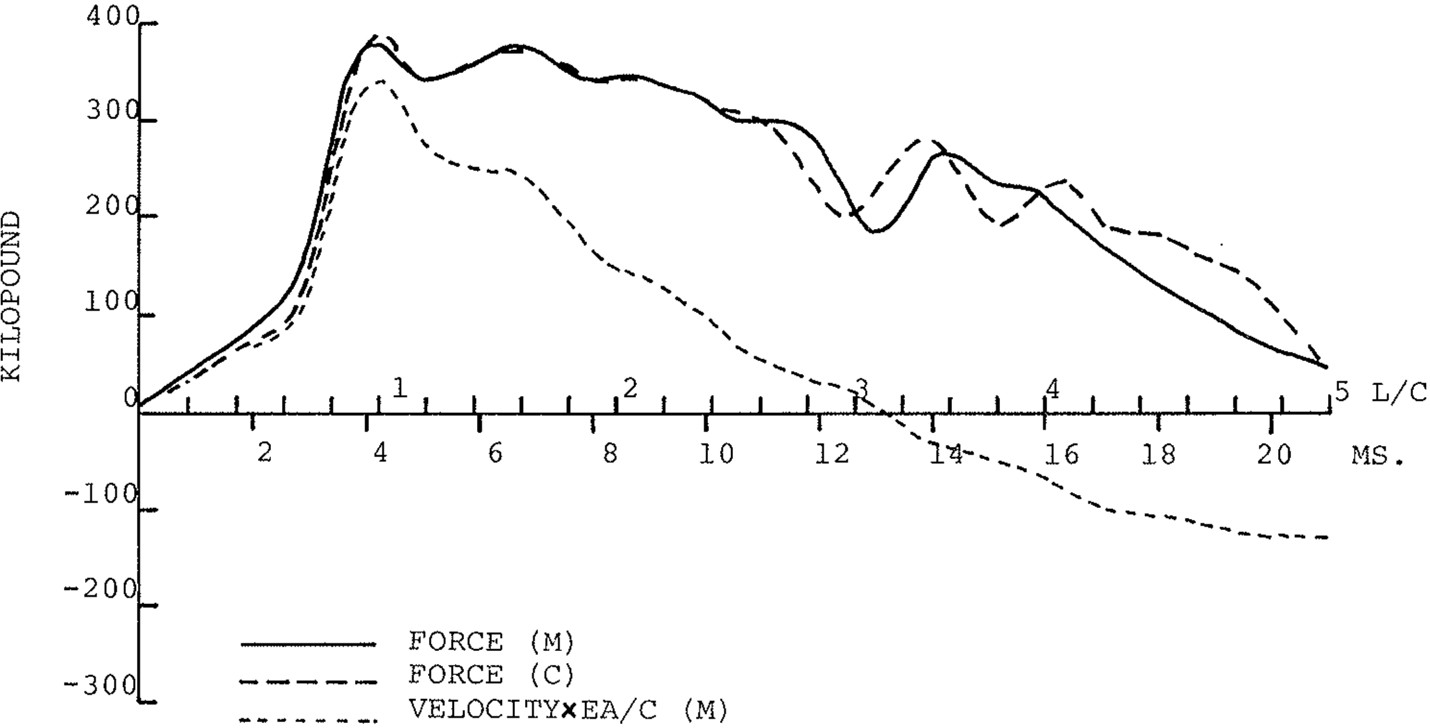


NOTE:

1. Early blows show some reduced section stiffnesses (damage) at two locations in addition to the 2L/c pile end effect. Anytime the force decreases and velocity increases it represents a stiffness reduction (pile end effect or cross section change).
2. β is the portion of the pile section which is still effect.
3. The already damaged pile section due to compressive stresses in driving through a hard layer broke when pile tip entered weak layer and caused tension reflection.

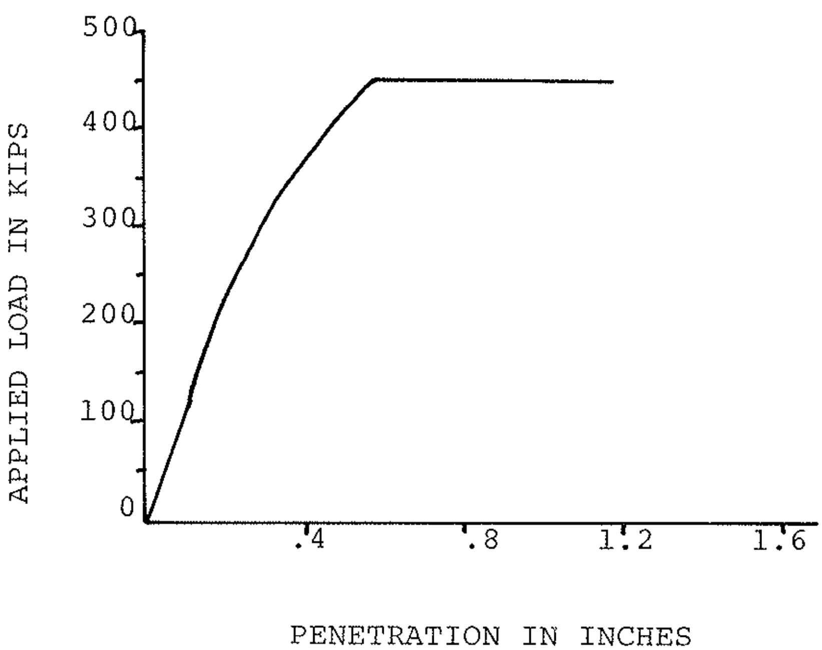
Typical records of force and velocity taken on a conductor pipe processed and plotted using the Case Method.
The conductor had 24" O.D. and ½" wall.
Rig floor to mud line was 507'.
Hammer: Delmag D36-02

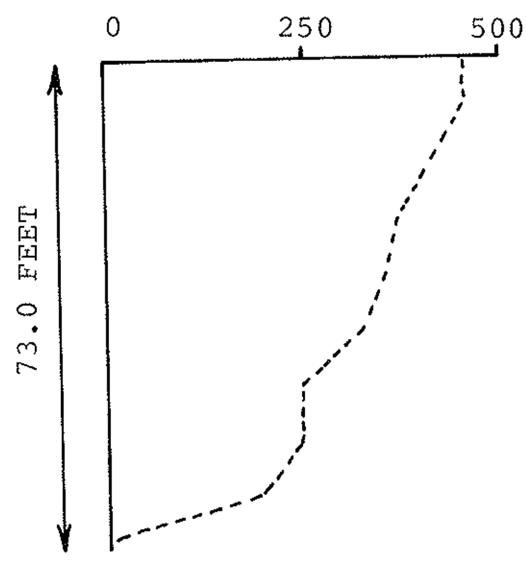




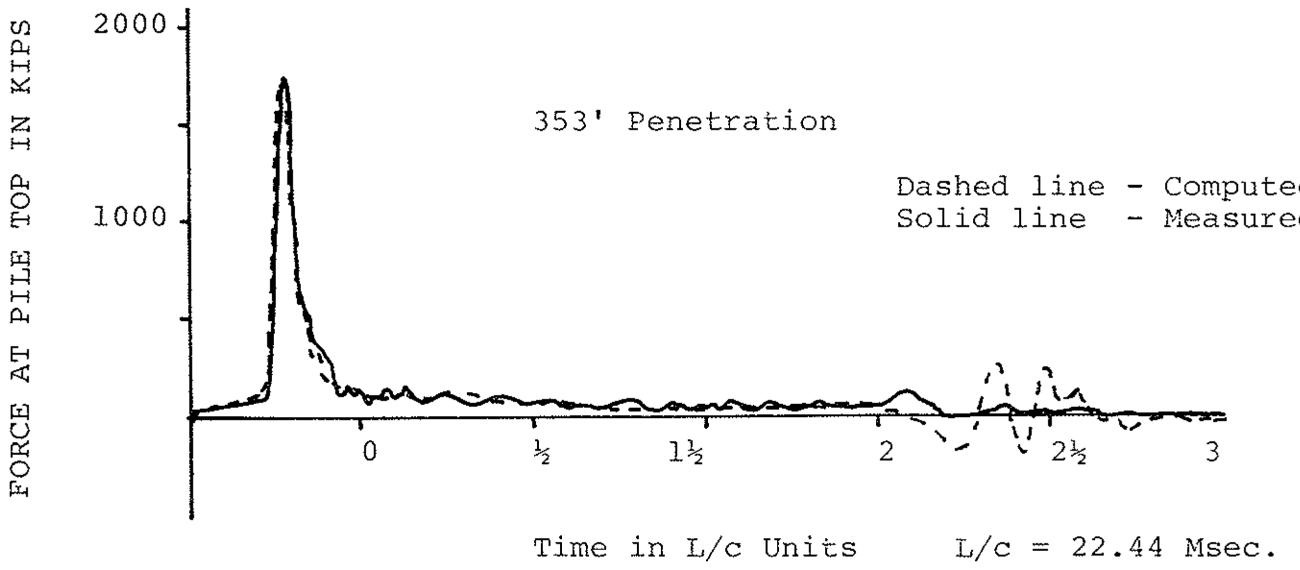
A. PREDICTED LOAD TEST CURVE

B. DISTRIBUTION OF FORCES IN PILE (KIPS)

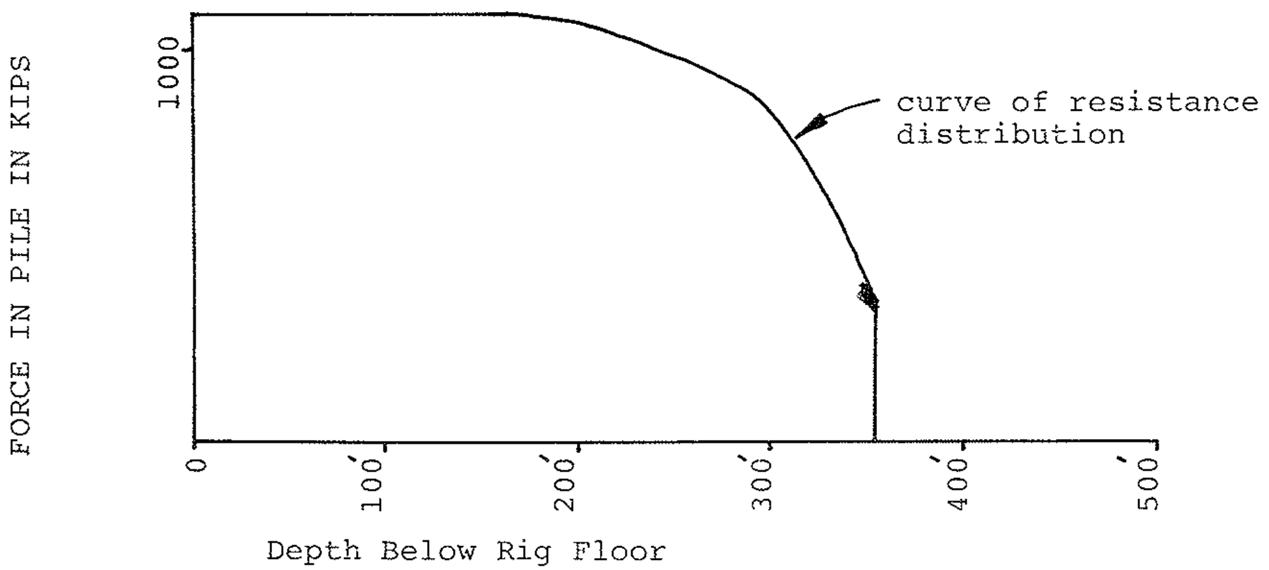




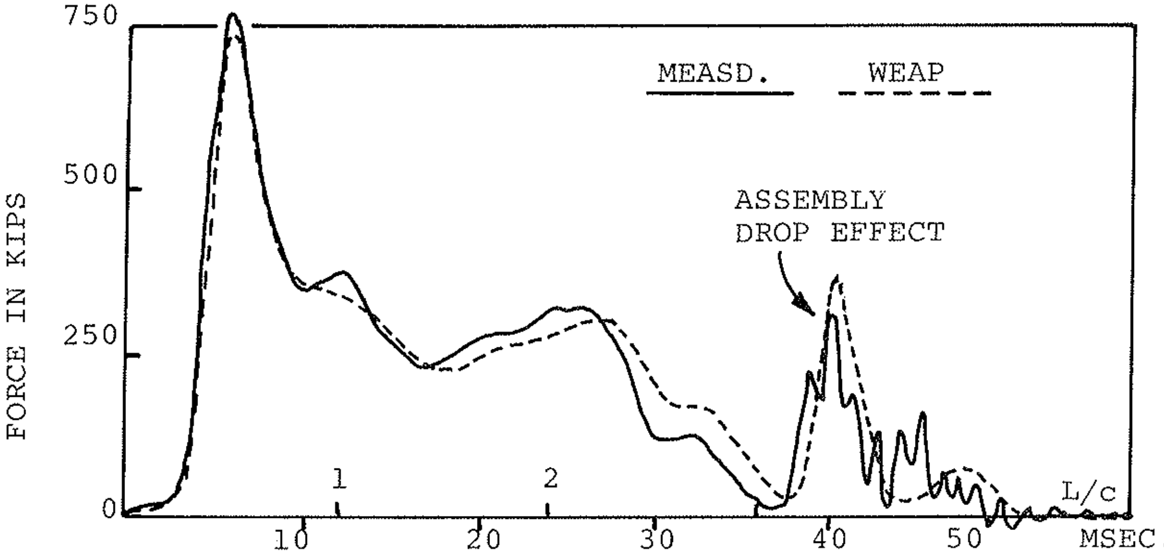
Velocity used as input assuming different soil resistance distributions until the computed force matches the measured force. Resistance distribution producing the best match is most correct.

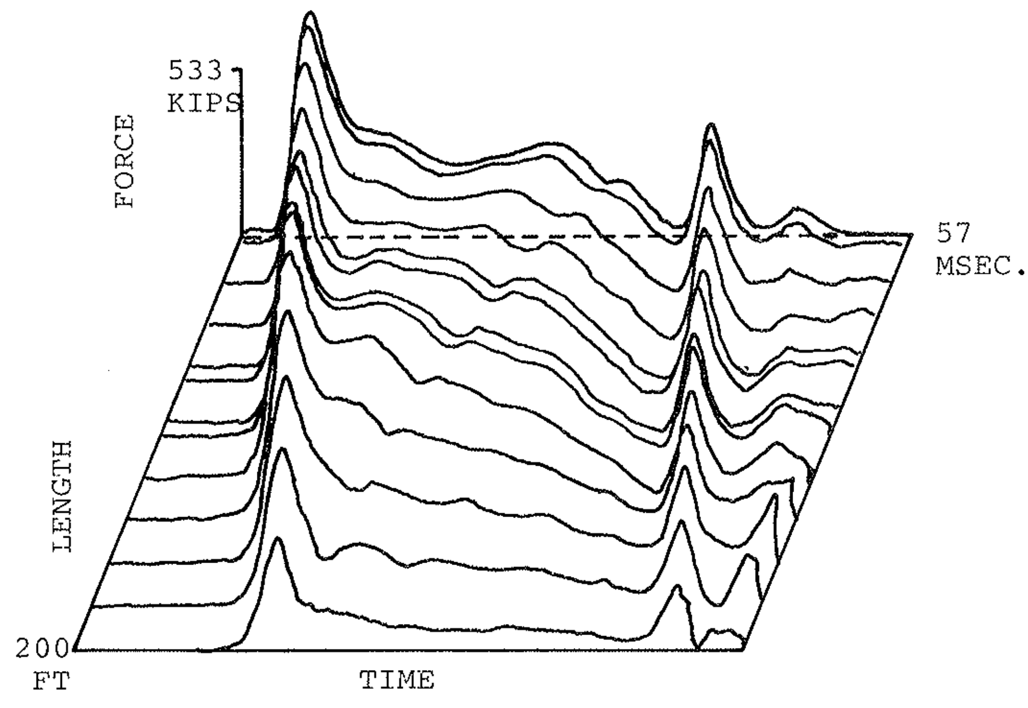


CAPWAP FORCE MATCHES

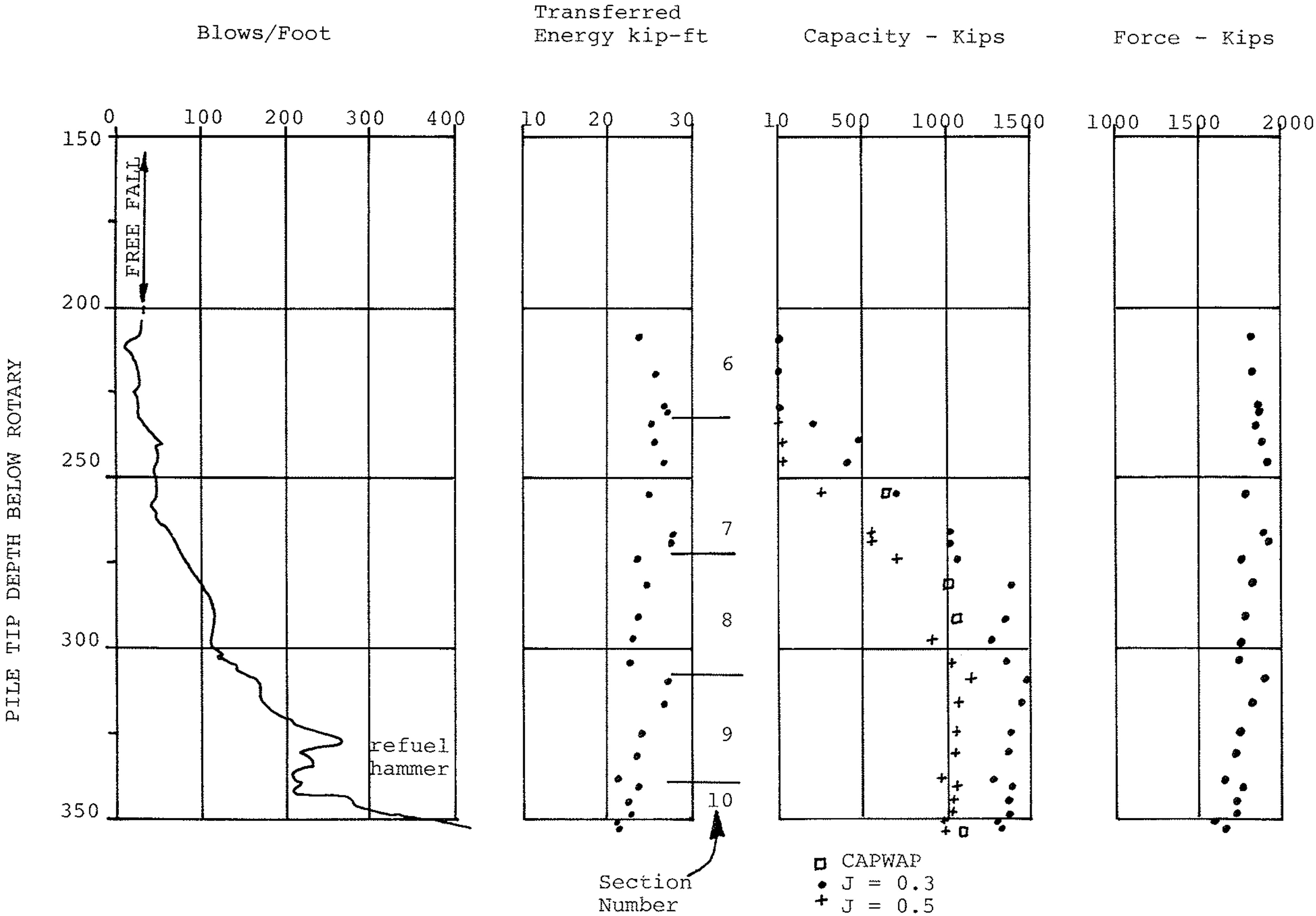


CAPWAP processing result. Hammer: D36-02 - 30" O.D.1" Wall conductor

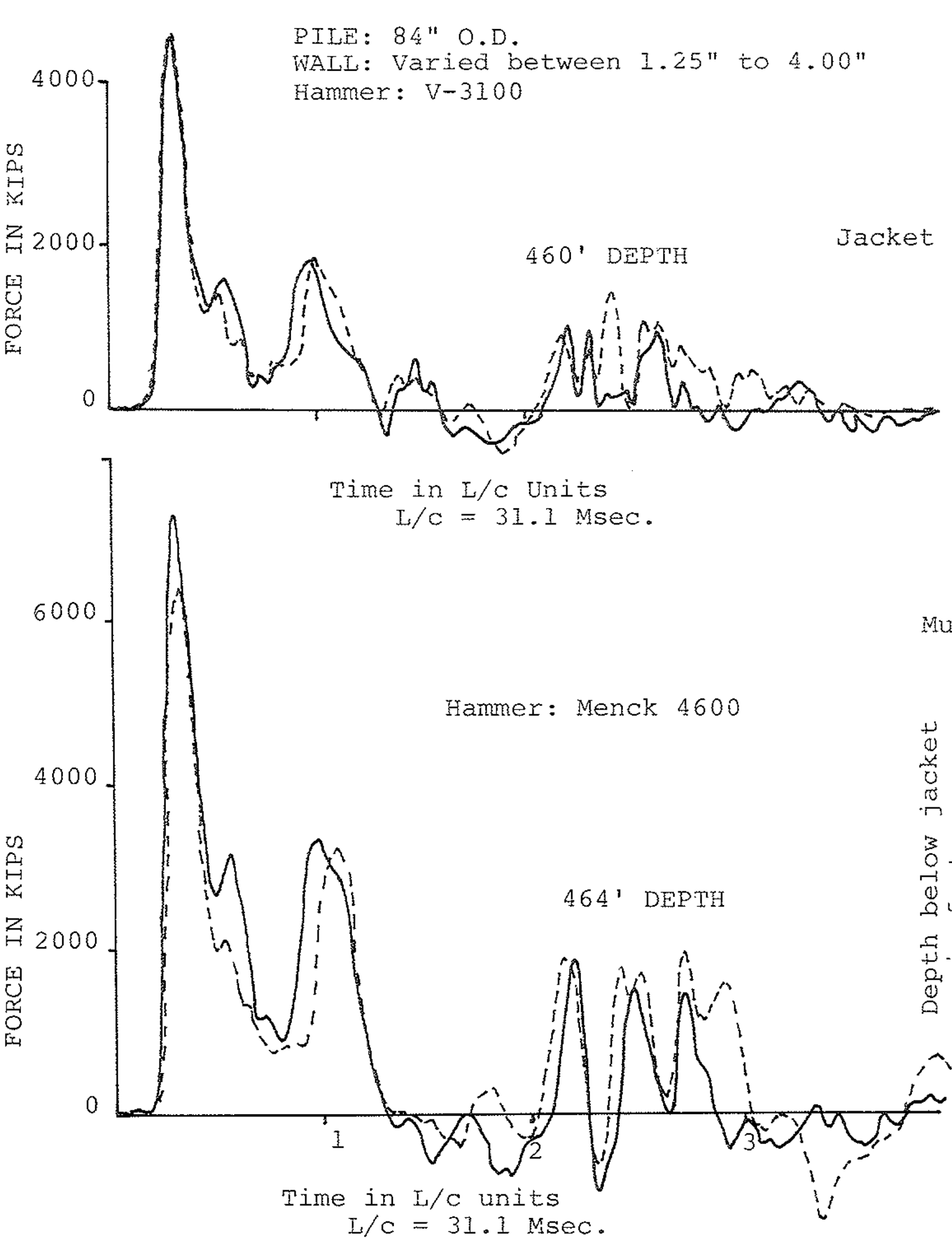




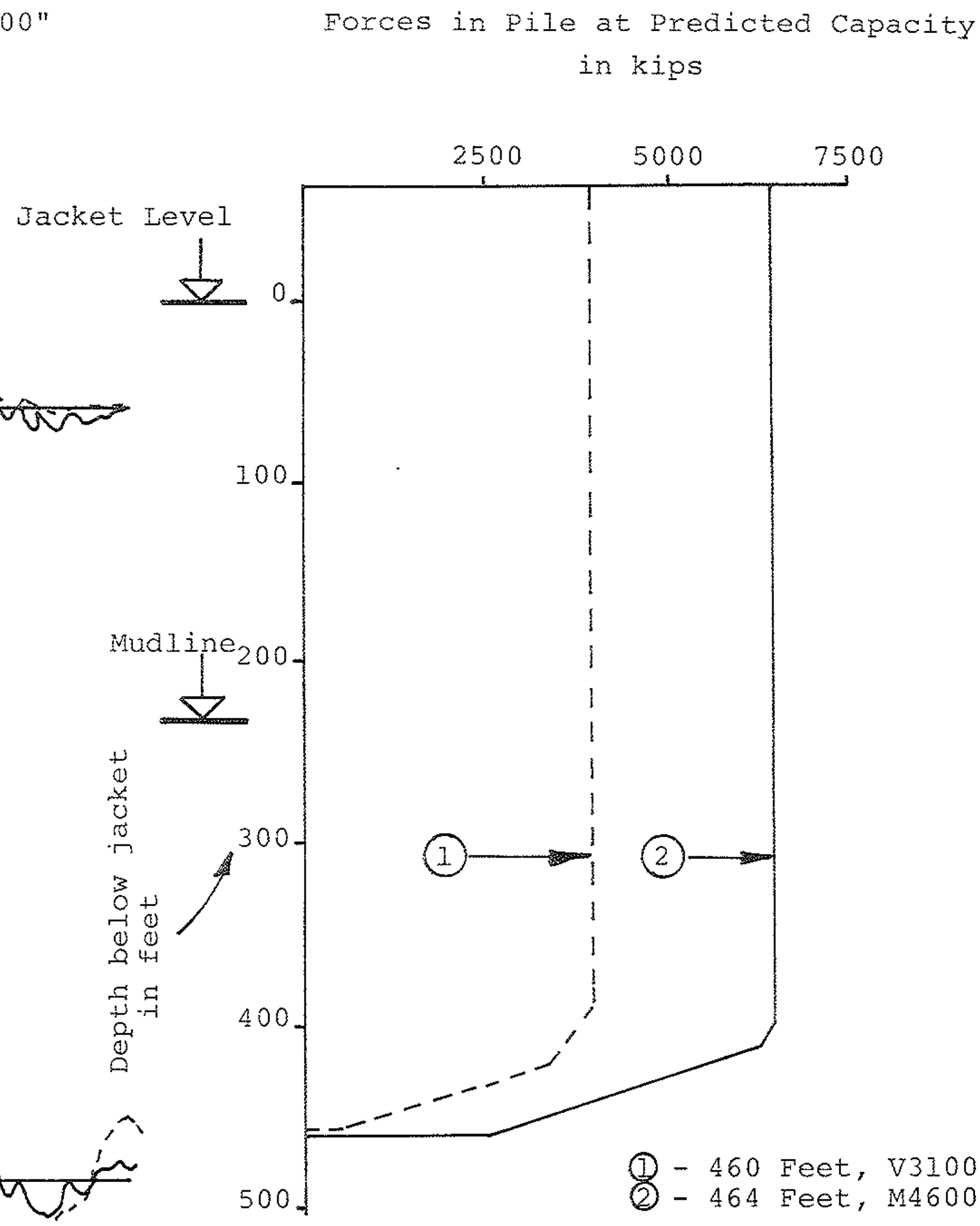
Using results predicted by CAPWAP (i.e. resistance distribution, damping parameters, and quakes) as input parameters a standard wave equation analysis is run and shows good agreement for known soils and a hammer operating properly.



PROCESSING RESULTS OF A CONDUCTOR PIPE 30" O.D. AND 1" WALL, HAMMER: D36-02



CAPWAP Force Matches
Dashed: Computed Force; Solid: Measured Force



Resistance Distribution