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PILE DRIVING ANALYSIS— STATE OF THE ART

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STUDY 2-5-62-33
PILING BEHAVIOR

PILE DRIVING ANALYSIS
STATE OF THE ART

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Foreword

The information contained herein was developed on the Research Study 2-5-62-33 entitled "Piling Behavior" which is a cooperative research endeavor sponsored jointly by the Texas Highway Department and the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads, and also by the authors as evidenced by the number of publications during the past seven years of intense study and research. The broad objective of the project was to fully develop the computer solution of the wave equation and its use for pile driving analysis, to determine values for the significant parameters involved to enable engineers to predict driving stresses in piling during driving, and to estimate the static soil resistance to penetration on piling at the time of driving from driving resistance records.

The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the Bureau of Public Roads.

Acknowledgments

Since this report is intended to summarize the research efforts and experience gained by the authors over a seven-year period, it is impossible to mention all of the persons, companies, and agencies without whose cooperation and support no "state of the art" in the analysis of piling by the wave equation would exist.

The greatest debt of gratitude is due Mr. E. A. L. Smith, Chief Mechanical Engineer of Raymond International (now retired), who not only first proposed the method of analysis but also maintained a continuing interest throughout the work and contributed significantly to the accomplishments of the research. His advice and guidance, based on his extensive field experience, and his intimate knowledge of the wave equation have proven invaluable throughout all phases of the research.

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Several graduate students and research assistants contributed significantly to the accomplishment of this work. They were Tom P. Airhart, Gary N. Reeves, Paul C. Chan, Carl F. Raba, Gary Gibson, I. H. Sulaiman, James R. Finley, M. T. Al-Layla, and John Miller.

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CHAPTER I

Introduction

The tremendous increase in the use of piles in both landbased and offshore foundation structures and the appearance of new pile driving methods have created great engineering interest in finding more reliable methods for the analysis and design of piles. Ever since Isaac published his paper, "Reinforced Concrete Pile Formula," in 1931,[1.1*] it has been recognized that the behavior of piling during driving does not follow the simple Newtonian impact as assumed by many simplified pile driving formulas, but rather is governed by the one dimensional wave equation. Unfortunately, an exact mathematical solution to the wave equation was not possible for most practical pile driving problems.

In 1950, E. A. L. Smith[1.2] developed a tractable solution to the wave equation which could be used to solve extremely complex pile driving problems. The solution was based on a discrete element idealization of the actual hammer-pile-soil system coupled with the use of a high speed digital computer. In a paper published in 1960, [1.3] he dealt exclusively with the application of wave theory to the investigation of the dynamic behavior of piling during driving. From that time to the present the authors have engaged in research dealing with wave equation analysis. The major objectives of these studies were as follows:

1. To develop a computer program based upon a procedure developed by Smith to provide the engineer with a mathematical tool with which to investigate the behavior of a pile during driving.

2. To conduct field tests to obtain experimental data with which to correlate the theoretical solution.

3. To make an orderly theoretical computer investigation of the influence of various parameters on the behavior of piles during driving and to present the results in the form of charts, diagrams or tables for direct application by office design engineers.

4. To present recommendations concerning good driving practices which would prevent cracking and spalling of prestressed concrete piles during driving.

5. To determine the dynamic load-deformation properties of various pile cushion materials which had tacitly been assumed linear.

6. To determine the dynamic load-deformation properties of soils required by the wave equation analysis.

7. To generalize Smith's original method of analysis and to develop the full potential of the solution by using the most recent and accurate parameter values determined experimentally.

8. To illustrate the significance of the parameters involved, such as the stiffness and coefficient of restitution of the cushion, ram velocity, material damping in the pile, etc., and to determine the quantitative effect of these parameters where possible.

9. To study and if possible evaluate the actual energy output for various pile driving hammers, the magnitudes of which were subject to much disagreement.

10. To develop the computer solution for the wave equation so that it may be used to estimate the resistance to penetration of piling at the time of driving from the driving records.

11. To develop a comprehensive users manual for the final computer program to enable its use by others.

*Numerical superscripts refer to corresponding items in the References.

CHAPTER II

Pile Driving Analysis

2.1 General

The rapidly increasing use of pile foundations and the appearance of new pile driving techniques have caused great interest among engineers in finding more reliable methods of pile analysis and design. As noted by Dunham,[2.4] "A pile driving formula is an attempt to evaluate the resistance of a pile to the dynamic forces applied upon it during the driving and to estimate from this the statical longitudinal load that the pile can support safely as a part of the permanent substructure."

In 1851, Sanders (Army Corps of Engineers) proposed the first dynamic pile driving formula by equating the total energy of the ram at the instant of impact to the work done in forcing down the pile, that is, the product of the weight of the ram and the stroke was assumed equal to the product of the ultimate soil resistance by the distance through which the pile moved. Sanders applied a safety factor of 8 to this ultimate soil resistance to determine an assumed safe load capacity for the pile. Since that time, a multitude of formulas have been proposed, some of which are semirational, others being

strictly empirical. Many of the formulas proposed attempt to account for various impact losses through the cushion, capblock, pile, and soil.

When restricted to a particular soil, pile, and driving condition for which correlation factors were derived, dynamic formulas are often able to predict ultimate bearing capacities which agree with observed test loads. However, since several hundred pile driving formulas have been proposed there is usually the problem of choosing an appropriate or suitable one.[2.3] Also distressing is the fact that in many cases no dynamic formula yields acceptable results; for example, long heavy piles generally show much greater ultimate loads than predicted by pile driving equations.[2.5] This has become increasingly significant since prestressed concrete piles 172 ft long and 54 in. in diameter have been successfully driven,[2.6] and more and more large diameter steel piles several hundred feet long are being used in offshore platforms. Numerous field tests have shown that the use of pile driving formulas may well lead to a foundation design ranging from wasteful to dangerous.[2.4]

Driving stresses are also of major importance in the design of piles, yet compressive stresses are commonly determined simply by dividing the ultimate driving resistance by the cross-sectional area of the pile.[2.7,2.8] Furthermore, conventional pile driving analyses are unable to calculate tensile stresses, which are of the utmost importance in the driving of precast or prestressed concrete piles. This method of stress analysis completely overlooks the true nature of the problem and computed stresses almost never agree with experimental values.[2.7,2.9] Tensile failures of piles have been noted on numerous occasions[2.7,2.10 2.11] and the absence of a reliable method of stress analysis has proven to be a serious problem.

Although most engineers today realize that pile driving formulas have serious limitations and cannot be depended upon to give accurate results, they are still used for lack of an adequate substitute. For further discussion of pile formulas in general, the reader is referred to the work of Chellis.[2.5]

Isaacs[2.1] is thought to have first pointed out the occurrence of wave action in piling during driving. He proposed a solution to the wave equation assuming that the point of the pile was fixed and that side resistance was absent. These assumptions were so restrictive that the solution was probably never used in practice. Cummings[2.10] in an earlier writing noted that although the pile driving formulas were based on numerous erroneous assumptions and that only the wave equation could be expected to yield accurate results for all driving conditions, he also pointed out that such solutions involved "long and complicated mathematical expressions so that their use for practical problems wou'd involve laborous, numerical calculations." In fact, with the advent of a multitude of different type driving hammers and driving conditions, an exact solution to the wave equation was not known.

2.2 Smith's Numerical Solution of the Wave Equation

In 1950, Smith[2.2] proposed a more realistic solution to the problem of longitudinal impact. This solution is

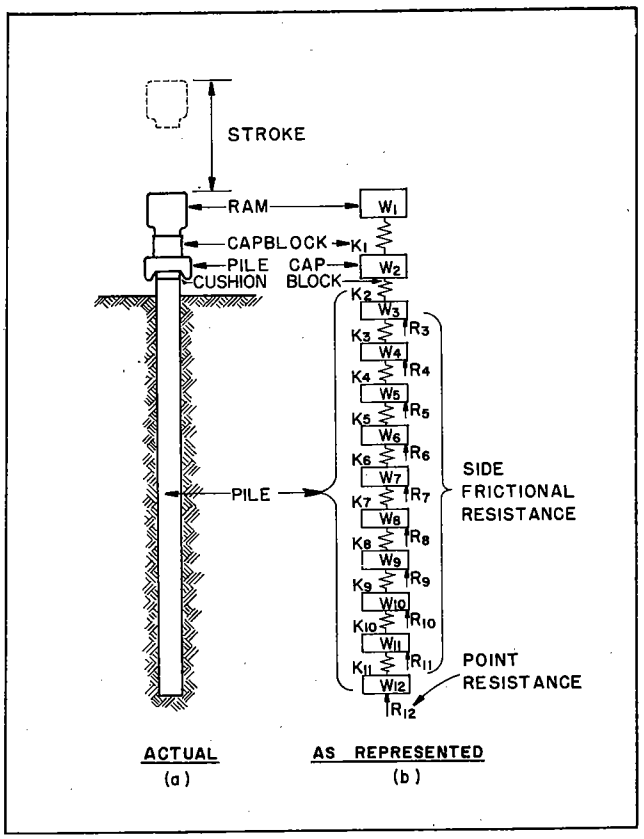


Figure 2.1. Method of representing pile for purpose of analysis (after Smith).

based on dividing the distributed mass of the pile into a number of concentrated weights W(1) through W(p), which are connected by weightless springs K(1) through K(p−1), with the addition of soil resistance acting on the masses, as illustrated in Figure 2.1(b). Time is also divided into small increments.

Smith's proposed solution involved the idealization of the actual continuous pile shown in Figure 2.1(a), as a series of weights and springs as shown in Figure 2.1(b). For the idealized system he set up a series of equations of motion in the form of finite difference equations which were easily solved using high-speed digital computers. Smith extended his original method of analysis to include various nonlineal parameters such as elasto-plastic soil resistance including velocity damping and others.

Figure 2.1 illustrates the idealization of the pile system suggested by Smith. In general, the system is considered to be composed of (see Figure 2.1(a)):

1. A ram, to which an initial velocity is imparted by the pile driver;
2. A capblock (cushioning material);
3. A pile cap;
4. A cushion block (cushioning material);
5. A pile; and
6. The supporting medium, or soil.

In Figure 2.1(b) are shown the idealizations for the various components of the actual pile. The ram, capblock, pile cap, cushion block, and pile are pictured as appropriate discrete weights and springs. The frictional soil resistance on the side of the pile is represented by a series of side springs; the point resistance is accounted for by a single spring at the point of the pile. The characteristics of these various components will be discussed in greater detail later in this report.

Actual situations may deviate from that illustrated in Figure 2.1. For example, a cushion block may not be used or an anvil may be placed between the ram and capblock. However, such cases are readily accommodated.

Internal Springs. The ram, capblock, pile cap, and cushion block may in general be considered to consist of "internal" springs, although in the representation of Figure 2.1(b) the ram and the pile cap are assumed rigid (a reasonable assumption for many practical cases).

Figures 2.2(a) and 2.2(b) suggest different possibilities for representing the load-deformation characteristics of the internal springs. In Figure 2.2(a), the material is considered to experience no internal damping. In Figure 2.2(b) the material is assumed to have internal damping according to the linear relationship shown.

External Springs. The resistance to dynamic loading afforded by the soil in shear along the outer surface of the pile and in bearing at the point of the pile is extremely complex. Figure 2.3 shows the load-deformation characteristics assumed for the soil in Smith's procedure, exclusive of damping effects. The path OABCDEFG represents loading and unloading in side friction. For the point, only compressive loading may take place and the loading and unloading path would be along OABCF.

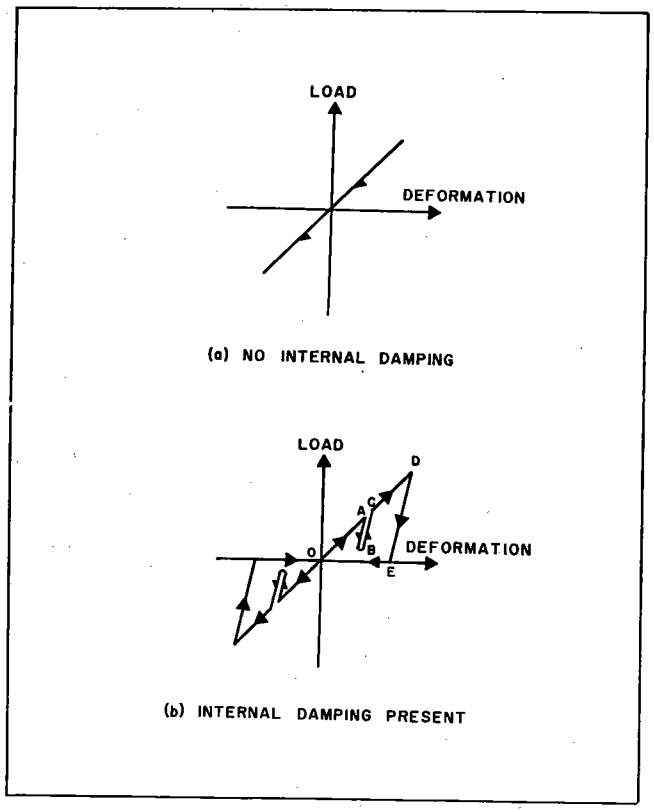


Figure 2.2. Load-deformation relationships for internal springs.

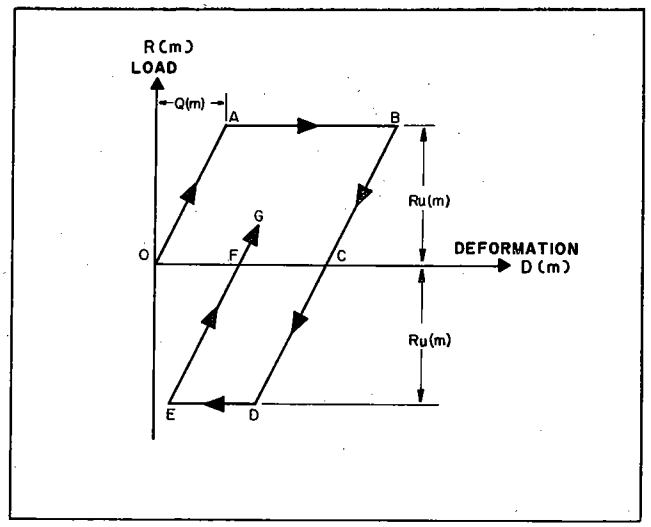


Figure 2.3. Load-deformation characteristics assumed for soil spring m.

It is seen that the characteristics of Figure 2.3 are defined essentially by the quantities "Q" and "Ru." "Q" is termed the soil quake and represents the maximum deformation which may occur elastically. "Ru" is the ultimate ground resistance, or the load at which the soil spring behaves purely plastically.

A load-deformation diagram of the type in Figure 2.3 may be established separately for each spring. Thus, K'(m) equals Ru(m) divided by Q(m), where K'(m) is the spring constant (during elastic deformation) for external spring m.

Basic Equations. Equations (2.3) through (2.7) were developed by Smith.[2.2]

$$D(m,t) = D(m,t-1) + 12\Delta t\ V(m,t-1) \quad (2.3)$$

$$C(m,t) = D(m,t) - D(m+1,t) \quad (2.4)$$

$$F(m,t) = C(m,t)\ K(m) \quad (2.5)$$

$$R(m,t) = [D(m,t) - D'(m,t)]\ K'(m)\ [1 + J(m)\ V(m,t-1)] \quad (2.6)$$

$$V(m,t) = V(m,t-1) + [F(m-1,t) - F(m,t) - R(m,t)]\ \frac{g\Delta t}{W(m)} \quad (2.7)$$

where

( ) = functional designation;

m = element number;

t = number of time interval;

Δt = size of time interval (sec);

C(m,t) = compression of internal spring m in time interval t (in.);

$D(m,t)$ = displacement of element m in time interval t (in.);

$D'(m,t)$ = plastic displacement of external soil spring m in time interval t (in.);

$F(m,t)$ = force in internal spring m in time interval t(lb);

g = acceleration due to gravity (ft/sec^2);

$J(m)$ = damping constant of soil at element m (sec/ft);

$K(m)$ = spring constant associated with internal spring m (lb/in.);

$K'(m)$ = spring constant associated with external soil spring m (lb/in.);

$R(m,t)$ = force exerted by external spring m on element m in time interval t (lb);

$V(m,t)$ = velocity of element m in time interval t (ft/sec); and

$W(m)$ = weight of element m (lb).

This notation differs slightly from that used by Smith. Also, Smith restricts the soil damping constant J to two values, one for the point of the pile in bearing and one for the side of the pile in friction. While the present knowledge of damping behavior of soils perhaps does not justify greater refinement, it is reasonable to use this notation as a function of m for the sake of generality.

The use of a spring constant $K(m)$ implies a load-deformation behavior of the sort shown in Figure 2.2(a). For this situation, $K(m)$ is the slope of the straight line. Smith develops special relationships to account for internal damping in the capblock and the cushion block. He obtains instead of Equation 2.5 the following equation:

$$F(m,t) = \frac{K(m)}{[e(m)]^2} C(m,t) - \left[\frac{1}{[e(m)]^2} - 1\right] K(m)\ C(m,t)_{max} \qquad (2.8)$$

where

$e(m)$ = coefficient of restitution of internal spring m; and

$C(m,t)_{max}$ = temporary maximum value of $C(m,t)$.

With reference to Figure 2.1, Equation (2.8) would be applicable in the calculation of the forces in internal springs $m = 1$ and $m = 2$. The load-deformation relationship characterized by Equation (2.8) is illustrated by the path OABCDEO in Figure 2.2(b). For a pile cap or a cushion block, no tensile forces can exist; consequently, only this part of the diagram applies. Intermittent unloading-loading is typified by the path ABC, established by control of the quantity $C(m,t)_{max}$ in Equation (2.8). The slopes of lines AB, BC, and DE depend upon the coefficient of restitution $e(m)$.

The computations proceed as follows:

1. The initial velocity of the ram is determined from the properties of the pile driver. Other time-dependent quantities are initialized at zero or to satisfy static equilibrium conditions.

2. Displacements $D(m,1)$ are calculated by Equation (2.3). It is to be noted that $V(1,0)$ is the initial velocity of the ram.

3. Compressions $C(m,1)$ are calculated by Equation (2.4).

4. Internal spring forces $F(m,1)$ are calculated by Equation (2.5) or Equation (2.8) as appropriate.

5. External spring forces $R(m,1)$ are calculated by Equation (2.6).

6. Velocities $V(m,1)$ are calculated by Equation (2.7).

7. The cycle is repeated for successive time intervals.

In Equation (2.6), the plastic deformation $D'(m,t)$ for a given external spring follows Figure (2.3) and may be determined by special routines. For example, when $D(m,t)$ is less than $Q(m)$, $D'(m,t)$ is zero; when $D(m,t)$ is greater than $Q(m)$ along line AB (see Figure 2.3), $D'(m,t)$ is equal to $D(m,t) - Q(m)$.

Smith notes that Equation (2.6) produces no damping when $D(m,t) - D'(m,t)$ becomes zero. He suggests an alternate equation to be used after $D(m,t)$ first becomes equal to $Q(m)$:

$$R(m,t) = [D(m,t) - D'(m,t)]\ K'(m) + J(m)\ K'(m)\ Q(m)\ V(m,t-1) \qquad (2.9)$$

Care must be used to satisfy conditions at the head and point of the pile. Consider Equation (2.5). When $m = p$, where p is number of the last element of the pile, $K(p)$ must be set equal to zero since there is no $F(p,t)$ force (see Figure 1.1). Beneath the point of the pile, the soil spring must be prevented from exerting tension on the pile point. In applying Equation (2.7) to the ram ($m = 1$), one should set $F(0,t)$ equal to zero.

For the idealization of Figure 2.1, it is apparent that the spring associated with $K(2)$ represents both the cushion block and the top element of the pile. Its spring rate may be obtained by the following equation:

$$\frac{1}{K(2)} = \frac{1}{K(2)_{cushion}} + \frac{1}{K(2)_{pile}} \qquad (2.10)$$

A more complete discussion of digital computer programming details and recommended values for various physical quantities are given in the Appendices.

From the point of view of basic mechanics, the wave equation solution is a method of analysis well founded physically and mathematically.

2.3 Critical Time Interval

The accuracy of the discrete-element solution is also related to the size of the time increment Δt. Heising,[2.13] in his discussion of the equation of motion for free longitudinal vibrations in a continuous elastic bar, points

out that the discrete-element solution is an exact solution of the partial differential equation when

$$\Delta t = \frac{\Delta L}{\sqrt{E/\rho}}$$

where ΔL is the segment length. Smith [3.2] draws a similar conclusion and has expressed the critical time interval as follows:

$$\Delta t = \frac{1}{19.648}\sqrt{\frac{W_{(m+1)}}{K(m)}} \qquad (2.11a)$$

or

$$\Delta t = \frac{1}{19.648}\sqrt{\frac{W_{(m)}}{K_m}} \qquad (2.11b)$$

If a time increment larger than that given by Equation 2.11 is used, the discrete-element solution will diverge and no valid results can be obtained. As pointed out by Smith, in this case the numerical calculation of the discrete-element stress wave does not progress as rapidly as the actual stress wave. Consequently, the value of Δt given by Equation (2.11) is called the "critical" value.

Heising[2.13] has also pointed out that when

$$\Delta t < \frac{\Delta L}{\sqrt{\frac{E}{\rho}}}$$

is used in a discrete-element solution, a less accurate solution is obtained for the continuous bar. As Δt becomes progressively smaller, the solution approaches the actual behavior of the discrete-element system (segment lengths equal to ΔL) used to simulate the pile.

This in general leads to a less accurate solution for the longitudinal vibrations of a slender continuous bar. If, however, the discrete-element system were divided into a large number of segments, the behavior of this simulated pile would be essentially the same as that of the slender continuous bar irrespective of how small Δt becomes, provided

$$\frac{\Delta L}{\sqrt{\frac{E}{\rho}}} \geq \Delta t > 0$$

This means that if the pile is divided into only a few segments, the accuracy of the solution will be more sensitive to the choice of Δt than if it is divided into many segments. For practical problems, a choice of Δt equal to about one-half the "critical" value appears suitable since inelastic springs and materials of different densities and elastic moduli are usually involved.

2.4 Effect of Gravity

The procedure as originally presented by Smith did not account for the static weight of the pile. In other words, at $t = 0$ all springs, both internal and external, exert zero force. Stated symbolically,

$$F(m,0) = R(m,0) = 0$$

If the effect of gravity is to be included, these forces must be given initial values to produce equilibrium of the system. Strictly speaking, these initial values should be those in effect as a result of the previous blow. However, not only would it be awkward to "keep books" on the pile throughout the driving so as to identify the initial conditions for successive blows, but it is highly questionable that this refinement is justified in light of other uncertainties which exist.

A relatively simple scheme has been developed as a means of getting the gravity effect into the computations.

Smith suggests that the external (soil) springs be assumed to resist the static weight of the system according to the relationship

$$R(m,0) = [Ru(m)/Ru(total)]\,[W(total)] \qquad (2.12)$$

where

W(total) = total static weight resisted by soil (lb); and

Ru(total) = total ultimate ground resistance (lb).

The quantity W(total) is found by

$$W(total) = W(b) + F(c) + \sum_{m=2}^{m=p} W(m) \qquad (2.13)$$

where

W(b) = weight of body of hammer, excluding ram (lb); and

F(c) = force exerted by compressed gases, as under the ram of a diesel hammer (lb).

The internal forces which initially exist in the pile may now be obtained:

$$F(1,0) = W(b) + F(c) \qquad (2.14)$$

and in general,

$$F(m,0) = F(m-1,0) + W(m) - R(m,0) \qquad (2.15)$$

In the absence of compressed gases and hammer weight resting on the pile system, the right-hand side of Equation (2.14) is zero.

The amount that each internal spring m is compressed may now be expressed

$$C(m,0) = F(m,0)/K(m) \qquad (2.16)$$

By working upward from the point, one finds displacements from

$$D(p,0) = R(p,0)/K'(p) \qquad (2.17)$$

$$D(m,0) = D(m+1,0) + C(m,0) \quad (m \neq p) \qquad (2.18)$$

For the inclusion of gravity, Equation (2.7) should be modified as follows:

$$V(m,t) = V(m,t-1) + [F(m-1,t) - F(m,t) - R(m,t) + W(m)]\,\frac{g\Delta t}{W(m)} \qquad (2.19)$$

In order that the initial conditions of the external springs be compatible with the assumed initial forces R(m,0) and initial displacements D(m,0), plastic displacements D'(m,0) should be set equal to $D(m,0) - R(m,0)/K'(m)$.

CHAPTER III

Pile Driving Hammers

3.1 Energy Output of Impact Hammer

One of the most significant parameters involved in pile driving is the energy output of the hammer. This energy output must be known or assumed before the wave equation or dynamic formula can be applied. Although most manufacturers of pile driving equipment furnish maximum energy ratings for their hammers, these are usually downgraded by foundation experts for various reasons. A number of conditions such as poor hammer condition, lack of lubrication, and wear are known to seriously reduce energy output of a hammer. In addition, the energy output of many hammers can be controlled by regulating the steam pressure or quantity of diesel fuel supplied to the hammer. Therefore, a method was needed to determine a simple and uniform method which would accurately predict the energy output of a variety of hammers in general use. Towards this purpose, the information generated by the Michigan State Highway Commission in 1965 and presented in their paper entitled "A Performance Investigation of Pile Driving Hammers and Piles" by the Office of Testing and Research, was used. These data were analyzed by the wave equation to determine the pile driver energy which would have been required to produce the reported behavior.[3.3]

3.2 Determination of Hammer Energy Output

Diesel Hammers. At present the manufacturers of diesel hammers arrive at the energy delivered per blow by two different methods. One manufacturer feels that "Since the amount of (diesel) fuel injected per blow is constant, the compression pressure is constant, and the temperature constant, the energy delivered to the piling is also constant."[3.1] The energy output per blow is thus computed as the kinetic energy of the falling ram plus the explosive energy found by thermodynamics. Other manufacturers simply give the energy output per blow as the product of the weight of the ram-piston W_R and the length of the stroke h, or the equivalent stroke in the case of closed-end diesel hammers.

The energy ratings given by these two methods differ considerably since the ram stroke h varies greatly thereby causing much controversy as to which, if either, method is correct and what energy output should be used in dynamic pile analysis.

In conventional single acting steam hammers the steam pressure or energy is used to raise the ram for each blow. The magnitude of the steam force is too small to force the pile downward and consequently it works only on the ram to restore its potential energy, W_R x h, for the next blow. In a diesel hammer, on the other hand, the diesel explosive pressure used to raise the ram is, for a short time at least, relatively large (see Figure 3.1).

While this explosive force works on the ram to restore its potential energy W_R x h, the initially large explosive pressure also does some useful work on the pile given by:

$$E_e = \int F \, ds \qquad (3.1)$$

where F = the explosive force, and

ds = the infinitesimal distance through which the force acts.

Since the total energy output is the sum of the kinetic energy at impact plus the work done by the explosive force.

$$E_{total} = E_k + E_e \qquad (3.2)$$

where E_{total} = the total energy output per blow,

E_k = the kinetic energy of the ram at the instant of impact,

and E_e = the diesel explosive energy which does *useful work* on the pile.

It has been noted that after the ram passes the exhaust ports, the energy required to compress the air-fuel mixture is nearly identical to that gained by the remaining fall (d) of the ram.[3.1] Therefore, the velocity of the ram at the exhaust ports is essentially the same as at impact, and the kinetic energy at impact can be closely approximated by:

$$E_k = W_R \, (h - d)$$

where W_R = the ram weight,

h = the total observed stroke of the ram, and

d = the distance the ram moves after closing the exhaust ports and impacts with the anvil.

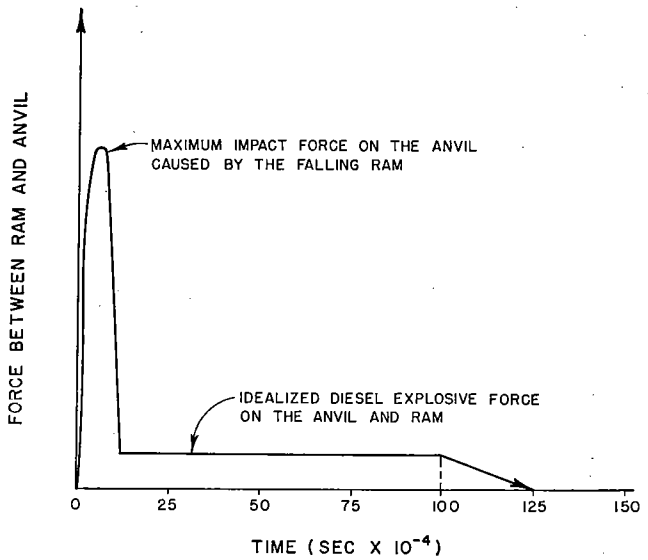


Figure 3.1. Typical force vs time curve for a diesel hammer.

The total amount of explosive energy $E_{e(total)}$ is dependent upon the amount of diesel fuel injected, compression pressure, and temperature; and therefore, may vary somewhat.

Unfortunately, the wave equation must be used in each case to determine the exact magnitude of E_e since it not only depends on the hammer characteristics, but also on the characteristics of the anvil, helmet, cushion, pile, and soil resistance. However, values of E_e determined by the wave equation for several typical pile problems indicates that it is usually small in proportion to the total explosive energy output per blow, and furthermore, that it is on the same order of magnitude as $W_R \times d$. Thus, Equation (3.1) can be simplified by assuming:

$$E_e = W_R \times d \qquad (3.4)$$

Substituting Equations (3.3) and (3.4) into Equation (3.1) gives:

$$E_{total} = E_k + E_e = W_R (h - d) + W_R d \qquad (3.5)$$

so that:

$$E_{total} = W_R h \qquad (3.6)$$

The results given by this equation were compared with experimental values and the average efficiency was found to be 100%.

Steam Hammers. Using the same equation for comparison with experimental values indicated an efficiency rating of 60% for the single-acting steam hammers, and 87% for the double-acting hammer, based on an energy output given by:

$$E_{total} = W_R h \qquad (3.7)$$

In order to determine an equivalent ram stroke for the double-acting hammers, the internal steam pressure above the ram which is forcing it down must be taken into consideration. The manufacturers of such hammers state that the maximum steam pressure or force should not exceed the weight of the housing or casing, or the housing may be lifted off the pile. Thus the maximum downward force on the ram is limited to the total weight of the ram and housing.

Since these forces both act on the ram as it falls through the actual ram stroke h, they add kinetic energy to the ram, which is given by:

$$E_{total} = W_R h + F_R h \qquad (3.8)$$

where W_R = the ram weight,
F_R = a steam force not exceeding the weight of the hammer housing, and
h = the observed or actual ram stroke.

Since the actual steam pressure is not always applied at the rated maximum, the actual steam force can be expressed as:

$$F_R = \left(\frac{p}{P_{rated}} \right) W_H \qquad (3.9)$$

where W_H = the hammer housing weight,
p = the operating pressure, and
P_{rated} = the maximum rated steam pressure.

The total energy output is then given by

$$E_{total} = W_R h + \left(\frac{p}{P_{rated}} \right) W_H h \qquad (3.10)$$

This can be reduced in terms of Equation (3.7) by using an equivalent stroke h_e which will give the same energy output as Equation (3.10).

Thus:

$$E_{total} = W_R h_e \qquad (3.11)$$

Setting Equations (3.10) and (3.11) equal yields

$$W_R h_e = W_R h + \left(\frac{p}{P_{rated}} W_H \right) h$$

$$= h \left[W_R + \frac{p}{P_{rated}} W_H \right]$$

or solving for the equivalent stroke:

$$h_e = h \left[1 + \frac{p}{P_{rated}} \times \frac{W_H}{W_R} \right] \qquad (3.12)$$

Conclusions. The preceding discussion has shown that it is possible to determine reasonable values of hammer energy output simply by taking the product of the ram weight and its observed or equivalent stroke, and applying an efficiency factor. This method of energy rating can be applied to all types of impact pile drivers with reasonable accuracy.

A brief summary of this simple procedure for arriving at hammer energies and initial ram velocities is as follows:

Open End Diesel Hammers

$$E = W_R h (e)$$
$$V_R = \sqrt{2g (h-d) (e)}$$

where W_R = ram weight
V_R = initial ram velocity
h = observed total stroke of ram
d = Distance from anvil to exhaust ports
e = efficiency of open end diesel hammers, approximately 100% when energy is computed by this method.

Closed End Diesel Hammers

$$E^* = W_R h_e (e)$$
$$V_R = \sqrt{2g (h_e-d) (e)}$$

where W_R = ram weight
V_R = initial ram velocity
h_e = equivalent stroke derived from bounce chamber pressure gage
d = distance from anvil to exhaust ports
e = efficiency of closed end diesel hammers, approximately 100% when energy is computed by this method.

Double-Acting Steam Hammers

$$E = W_R h_e (e)$$
$$V = \sqrt{2g h_e (e)}$$

*Note: For the Link Belt Hammers, this energy can be read directly from the manufacturer's chart using bounce chamber pressure gage.

where W_R = ram weight

h_e = equivalent ram stroke

$$= h \left[1 + \frac{p}{P_{rated}} \times \frac{W_H}{W_R} \right]$$

h = actual or physical ram stroke

p = operating steam pressure

P_{rated} = maximum steam pressure recommended by manufacturer.

W_H = weight of hammer housing

e = efficiency of double-acting steam hammers, approximately 85% by this method.

Single-Acting Steam Hammers

$$E = W_R \, h \, (e)$$

$$V_R = \sqrt{2g \, h \, (e)}$$

where W_R = ram weight

h = ram stroke

e = efficiency of single-acting steam hammers, normally recommended around 75% to 85%. In a study of the Michigan data, a figure of 60% was found. The writers feel the 60% figure is unusually low and would not recommend it as a typical value.

A summary of the properties and operating characteristics of various hammers is given in Table 3.1.

3.3 Significance of Driving Accessories

In 1965 the Michigan State Highway Commission completed an extensive research program designed to obtain a better understanding of the complex problem of pile driving. Though a number of specific objectives were given, one was of primary importance. As noted by Housel,[3.2] "Hammer energy actually delivered to the pile, as compared with the manufacturer's rated energy, was the focal point of a major portion of this investigation of pile-driving hammers." In other words, they hoped to determine the energy delivered to the pile and to compare these values with the manufacturer's ratings.

The energy transmitted to the pile was termed "ENTHRU" by the investigators and was determined by the summation

$$\text{ENTHRU} = \Sigma F \Delta S$$

Where F, the average force on the top of the pile during a short interval of time, was measured by a specially designed load cell, and ΔS, the incremental movement of the head of the pile during this time interval, was found using displacement transducers and/or reduced from accelerometer data. It should be pointed out that ENTHRU is not the total energy output of the hammer blow, but only a measure of that portion of the energy delivered below the load-cell assembly.

Many variables influence the value of ENTHRU. As was noted in the Michigan report: "Hammer type and operating conditions; pile type, mass, rigidity, and length; and the type and condition of cap blocks were all factors that affect ENTHRU, but when, how, and how much could not be ascertained with any degree of

TABLE 3.1. SUMMARY OF HAMMER PROPERTIES AND OPERATING CHARACTERISTICS

Hammer Manufacturer	Hammer Type	Maximum Rated Energy (ft lb)	Ram Weight (lb)	Hammer Housing Weight (lb)	Anvil Weight (lb)	Maximum or Equivalent Stroke (ft)	d (ft)	Rated Steam Pressure (psi)	Maximum Explosive Pressure (lb)	Cap Block Normally Specified
Vulcan	#1	15,000	5,000	4,700		3.00				
	014	42,000	14,000	13,500		3.00				
	50C	15,100	5,000	6,800		3.02		120		
	80C	24,450	8,000	9,885		3.06		120		
	140C	36,000	14,000	13,984		2.58		140		
Link Belt	312	18,000	3,857		1188	4.66	0.50		98,000	5 Micarta disks 1" x 10⅞" dia.
	520	30,000	5,070		1179	5.93	0.83		98,000	
MKT Corp	DE20	16,000	2,000		640	8.00	0.92		46,300	nylon disk 2" x 9" dia.
	DE30	22,400	2,800		775	8.00	1.04		98,000	nylon disk 2" x 19" dia.
	DE40	32,000	4,000		1350	8.00	1.17		138,000	nylon disk 2" x 24" dia.
Delmag	D-12	22,500	2,750		754	8.19	1.25		93,700	15" x 15" x 5" German Oak
	D-22	39,700	4,850		1147	8.19	1.48		158,700	15" x 15" x 5" German Oak

certainty." However, the wave equation can account for each of these factors so that their effects can be determined.

The maximum displacement of the head of the pile was also reported and was designated LIMSET. Oscillographic records of force vs time measured in the load cell were also reported. Since force was measured only at the load cell, the single maximum observed values for each case was called FMAX.

The wave equation can be used to determine (among other quantities) the displacement D(m,t) of mass "m" at time "t", as well as the force F(m,t) acting on any mass "m" at time "t." Thus the equation for ENTHRU at any point in the system can be determined by simply letting the computer calculate the equation previously mentioned:

$$\text{ENTHRU} = \Sigma F \Delta S$$

or in terms of the wave equation:

$$\text{ENTHRU(m)} = \Sigma \left[\frac{F(m,t) + F(m,t-1)}{2.0} \right] \times [D(m+1,t) - D(m+1,t-1)]$$

where ENTHRU (m) = the work done on any mass (m + 1),

m = the mass number, and

t = the time interval number.

ENTHRU is greatly influenced by several parameters, especially the type, condition, and coefficient of restitution of the cushion, and the weight of extra driving caps.

It has been shown,[3.3] that the coefficient of restitution alone can change ENTHRU by 20%, simply by changing e from 0.2 to 0.6. Nor is this variation in e unlikely since cushion condition varied from new to "badly burnt" and "chips added."

The wave equation was therefore used to analyze certain Michigan problems to determine the influence of cushion stiffness, e, additional driving cap weights, driving resistance encountered, etc.

Table 3.5 shows how ENTHRU and SET increases when the load cell assembly is removed from Michigan piles.

TABLE 3.2. EFFECT OF CUSHION STIFFNESS ON ENERGY TRANSMITTED TO THE PILE (ENTHRU)

		ENTHRU (kip ft)			
Ram Velocity (ft/sec)	RUT (kip)	Cushion Stiffness (kip/in.) 540	1080	2700	27,000
8	30	3.0	3.0	3.0	2.9
	90	3.1	3.2	3.3	2.9
	150	3.0	3.2	3.3	3.0
12	30	6.6	6.4	7.1	6.4
	90	7.0	7.1	7.2	6.4
	150	6.9	7.2	7.4	6.7
16	30	11.8	11.9	12.2	11.3
	90	12.3	12.6	12.8	11.5
	150	12.4	12.9	13.2	11.4

TABLE 3.3. EFFECT OF CUSHION STIFFNESS ON THE MAXIMUM FORCE MEASURED AT THE LOAD CELL (FMAX)

		FMAX (kip)			
Ram Velocity (ft/sec)	RUT (kip)	Cushion Stiffness (kip/in.) 540	1080	2700	27,000
8	30	132	185	261	779
	90	137	185	261	779
	150	143	186	261	779
12	30	198	278	391	1,169
	90	205	278	391	1,169
	150	215	279	391	1,169
16	30	264	371	522	1,558
	90	275	371	522	1,558
	150	288	371	522	1,558

From Table 3.2, it can be seen that ENTHRU does not always increase with increasing cushion stiffness, and furthermore, the maximum increase in ENTHRU noted here is relatively small—only about 10%.

When different cushions are used, the coefficient of restitution will probably change. Since the coefficient of restitution of the cushion may affect ENTHRU, a number of cases were solved with "e" ranging from 0.2 to 0.6. As shown in Tables 3.6 and 3.7, an increase in "e" from 0.2 to 0.6 normally increases ENTHRU from 18 to 20%, while increasing the permanent set from 6 to 11%. Thus, for the case shown, the coefficient of restitution of the cushion has a greater influence on rate of penetration and ENTHRU than does its stiffness. This same effect was noted in the other solutions, and the cases shown in Tables 3.6 and 3.7 are typical of the results found in other cases.

As can be seen from Table 3.3, any increase in cushion stiffness also increases the driving stress. Thus, according to the wave equation, increasing the cushion stiffness to increase the rate of penetration (for example by not replacing the cushion until it has been beaten to a fraction of its original height or by omitting the cushion entirely) is both inefficient and poor practice because of the high stresses induced in the pile. It would be better to use a cushion having a high coefficient of restitution and a low cushion stiffness in order to increase ENTHRU and to limit the driving stress.

Unfortunately, the tremendous variety of driving accessories precludes general conclusions to be drawn

TABLE 3.4. EFFECT OF CUSHION STIFFNESS ON THE MAXIMUM DISPLACEMENT OF THE HEAD OF THE PILE (LIMSET)

		LIMSET (in.)			
Ram Velocity (ft/sec)	RUT (kip)	Cushion Stiffness (kip/in.) 540	1080	2700	27,000
8	30	1.09	1.08	1.08	1.13
	90	0.44	0.44	0.45	0.45
	150	0.32	0.33	0.33	0.33
12	30	2.21	2.14	2.19	2.25
	90	0.80	0.82	0.84	0.84
	150	0.55	0.57	0.58	0.58
16	30	3.62	3.59	3.63	3.68
	90	1.30	1.31	1.32	1.34
	150	0.85	0.87	0.88	0.90

TABLE 3.5 EFFECT OF REMOVING LOAD CELL ON ENTHRU, LIMSET, AND PERMANENT SET OF PILE

Case[3.3]	Ram Velocity (ft/sec)	ENTHRU (kip ft)		LIMSET (in.)		PERMANENT SET (in.)	
		With Load Cell	Without Load Cell	With Load Cell	Without Load Cell	With Load Cell	Without Load Cell
DTP-15, 80.5	8	1.5	1.6	0.27	0.34	0.23	0.25
	12	3.3	3.6	0.53	0.67	0.57	0.57
	16	5.8	6.5	1.02	1.03	0.94	0.97
	20	9.1	10.1	1.54	1.54	1.43	1.47
DLTP-8, 80.2	8	3.1	3.8	0.62	0.71	0.51	0.62
	12	7.1	8.5	1.15	1.32	1.06	1.29
	16	12.5	15.1	1.91	2.10	1.82	2.15
	20	19.5	23.6	2.70	3.08	2.65	3.13

from wave equation analyses in all but the most general of terms.

Although the effect of driving accessories is quite variable, it was generally noted that the inclusion of additional elements between the driving hammer and the pile and/or the inclusion of heavier driving accessories consistently decreased both the energy transmitted to the head of the pile and the permanent set per blow of the hammer. Increasing cushion stiffness will increase compressive and tensile stresses induced in a pile during driving.

3.4 Explosive Pressure in Diesel Hammers

In order to account for the effect of explosive force in diesel hammers, the force between the ram and the anvil is assumed to reach some maximum due to the impact between the ram and anvil, and then decrease. However, should this impact force tend to decrease below some specified minimum, it is assumed that the diesel explosive pressure maintains this specified minimum force between the ram and anvil for a given time, after which the force tapers to zero. As shown in Figure 3.1, the force between the ram and anvil reaches some maximum due to the steel on steel impact, afterwards the force decreases to the minimum diesel explosive force on the anvil. This force is maintained for 10 milliseconds, thereafter decreasing to zero at 12.5 milliseconds. The properties of this curve, including values of the minimum explosive force and time over which this force acts, were determined from the manufacturer's published literature for the diesel hammers.

The effect of explosive pressure was found to be extremely variable, possibly more so than the effect of the driving accessories, and few conclusions could be drawn. The only consistent effect that could be observed was that if the maximum impact force induced by the falling ram was insufficient to produce permanent set, the addition of explosive force had little or no effect on the solution. In other words, unless the particular hammer, driving accessories, pile, and soil conditions were such that it was possible to get the pile moving, the explosive force, being so much smaller than the maximum impact force, had no effect.

TABLE 3.6. EFFECT OF COEFFICIENT OF RESTITUTION ON MAXIMUM POINT DISPLACEMENT

Pile I.D.	RUT (kip)	Ram Velocity (ft/sec)	Maximum Point Displacement (in.)			Maximum Change (%)
			e = 0.2	e = 0.4	e = 0.6	
BLTP-6; 10.0	30	12	2.13	2.14	2.36	10
		16	3.38	3.47	3.58	6
		20	4.73	4.93	5.17	8
BLTP-6; 57.9	150	12	0.46	0.48	0.50	8
		16	0.73	0.76	0.81	10
		20	1.05	1.10	1.18	11

TABLE 3.7. EFFECT OF COEFFICIENT OF RESTITUTION ON ENTHRU

Pile I.D.	RUT (kip)	Ram Velocity (ft/sec)	ENTHRU (kip ft)			Maximum Change (%)
			e = 0.2	e = 0.4	e = 0.6	
BLTP-6; 10.0	30	12	6.0	6.5	7.3	18
		16	10.5	11.8	12.8	18
		20	16.5	17.4	20.0	17
BLTP-6; 57.9	150	12	6.7	7.2	8.2	18
		16	11.6	12.7	14.5	20
		20	18.2	19.7	22.4	19

However, the addition of explosive pressure increased the permanent set of the pile in some cases where the maximum impact force is sufficient to start the pile moving; on the other hand, its addition was found ineffective in an equal number of circumstances.

The explosive forces assumed to be acting within various diesel hammers are listed in Table 3.1. These forces were determined by experiment, personal correspondence with the hammer manufacturers, and from their published literature.

3.5 Effect of Ram Elasticity

In 1960, when Smith first proposed his numerical solution to the wave equation for application to pile driving problems, he suggested that since the ram is usually short in length, it can in many cases be represented by a single weight having infinite stiffness. The example illustrated in Figure 2.1 makes this assumption, since K(1) represents the spring constant of only the capblock, the elasticity of the ram having been neglected. Smith also noted that if greater accuracy was desired, the ram could also be divided into a series of weights and springs, as is the pile.

As noted in Figures 3.2 and 3.3, there is a significant difference between the steam or drop hammers and diesel hammers, i.e., the steam hammer normally strikes a relatively soft capblock, whereas the diesel hammer involves steel on steel impact between the ram and anvil.

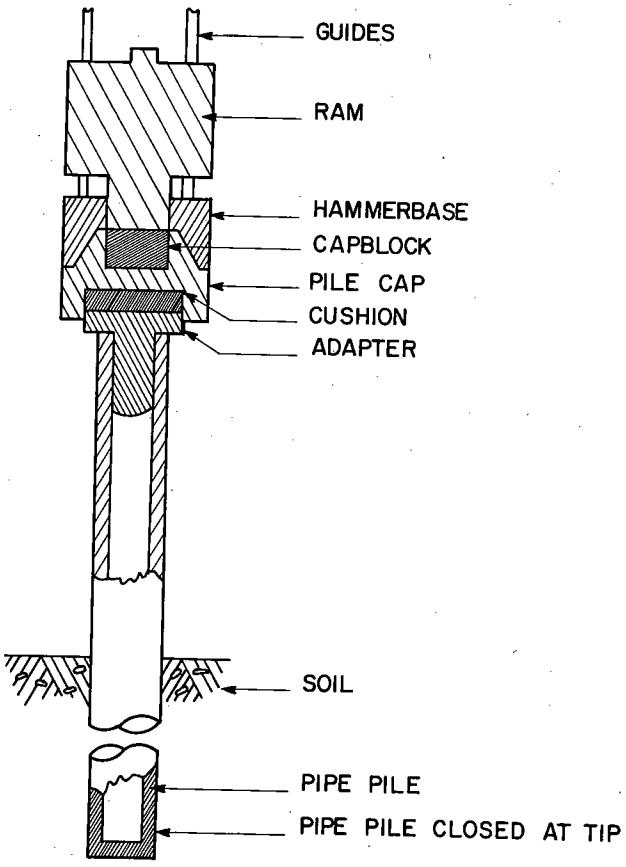


Figure 3.2. Steam hammer.

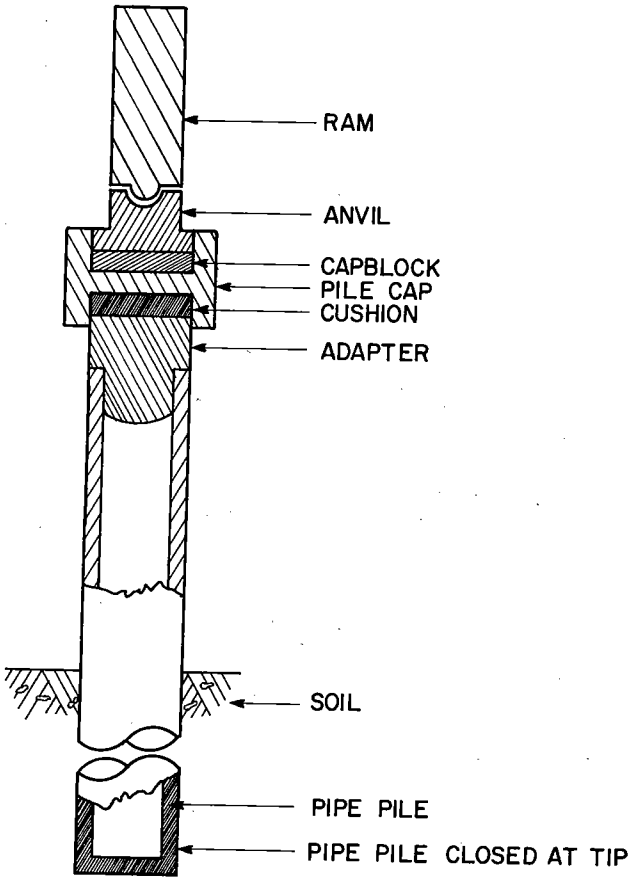


Figure 3.3. Diesel hammer.

To determine the influence of dividing the ram into a number of segments, several ram lengths ranging from 2 to 10 ft were assumed, driving a 100-ft pile having point resistance only. The total weight of the pile being driven varied from 1500 to 10,000 lb, while the ultimate soil resistance ranged from 0 to 10,000 lb. The cushion was assumed to have a stiffness of 2,000 kips per in.

Table 3.8 lists the results found for a typical problem solved in this study, the problem consisting of a 10-ft long ram traveling at 20 fps striking a cushion with a stiffness of 2000 kips per in. The pile used was a 100-ft 12H53 steel pile, driven by a 5,000-lb ram.

TABLE 3.8. EFFECT OF BREAKING THE RAM INTO SEGMENTS WHEN RAM STRIKES A CUSHION OR CAPBLOCK

Number of Ram Divisions	Length of Pile Segments (ft)	Maximum Compressive Force in Pile (kip)	Maximum Tensile Force in Pile (kip)	Maximum Point Displacement (in.)
1	10.0	305.4	273.9	3.019
1	5.0	273.8	245.9	3.042
1	2.5	265.6	224.8	3.053
1	1.25	263.1	219.0	3.057
2	1.25	262.6	218.8	3.058
10	1.25	262.9	218.5	3.059

TABLE 3.9. EFFECT OF BREAKING RAM INTO SEGMENTS WHEN RAM STRIKES A STEEL ANVIL

Anvil Weight	Ram Length	Number of Ram Divisions	Length of Each Ram Segment	Maximum Compressive Force on Pile			Maximum Point Displacement
				At Head	At Center	At Tip	
lb	ft		ft	kip	kip	kip	in.
2000	10	1	10.0	513	513	884	0.207
		2	5.0	437	438	774	0.159
		5	2.0	373	373	674	0.124
		10	1	375	375	678	0.125
	8	1	8.0	478	478	833	0.183
		4	2.0	359	359	648	0.117
		8	1.0	360	360	651	0.118
	6	1	6.0	430	430	763	0.155
		3	2.0	344	344	621	0.110
		6	1.0	342	342	616	0.109
1000	10	1	10.0	508	509	878	0.160
		2	5.0	451	451	789	0.159
		5	2.0	381	382	691	0.151
		10	1.0	371	372	681	0.153
	8	1	8.0	487	488	846	0.151
		4	2.0	443	444	785	0.144
		8	1.0	369	370	675	0.134
		10	0.8	337	338	665	0.133
	6	1	6.0	457	457	798	0.137
		3	2.0	361	362	666	0.128
		6	1.0	316	316	562	0.109
		10	0.6	320	320	611	0.113

No pile cap was included in the solution, the cushion being placed directly between the hammer and the head of the pile. Since the ram was divided into very short lengths, the pile was also divided into short segments.

As shown in Table 3.8, the solution is not changed to any significant extent whether the ram is divided into 1, 2, or 10 segments. The time interval was held constant in each case.

In the case of a diesel hammer, the ram strikes directly on a steel anvil rather than on a cushion. This makes the choice of a spring rate between the ram and anvil difficult because the impact occurs between two steel elements. The most obvious solution is to place a spring having a rate dictated by the elasticity of the ram and/or anvil. A second possible solution is to break the ram into a series of weights and springs as is the pile.

To determine when the ram should be divided, a parameter study was run in which the ram length varied between 6 and 10 ft, and the anvil weight varied from 1,000 to 2,000 lb. In each case the ram parameter was held constant and the ram was divided equally into segment lengths as noted in Table 3.9. These variables were picked because of their possible influence on the solution.

The pile used was again a 12H53 point bearing pile having a cushion of 2,000 kip per in. spring rate placed between the anvil and the head of the pile. The soil parameters used were RU = 500 kips, Q = 0.1 in., and J = 0.15 sec. per ft. These factors were held constant for all problems listed in Tables 3.8 and 3.9.

The most obvious result shown in Table 3.9 is that when the steel ram impacts directly on a steel anvil, dividing the ram into segments has a marked effect on the solution.

An unexpected result of the study was that even when the ram was short, breaking it into segments still effected the solution. As seen in Table 3.9, the solutions for forces and displacements for both 6 through 10 ft ram lengths continue to change until a ram segment length of 2 ft was reached for the 2,000-lb anvil and a segment length of 1 ft for the 1,000-lb anvil was reached.

CHAPTER IV

Capblock and Cushions

4.1 Methods Used to Determine Capblock and Cushion Properties

As used here, the word "capblock" refers to the material placed between the pile driving hammer and the steel helmet. The term "cushion" refers to the material placed between the steel helmet and pile (usually used only when driving concrete piles).

Although a capblock and cushion serve several purposes, their primary function is to limit impact stresses in both the pile and hammer. In general, it has

been found that a wood capblock is quite effective in reducing driving stresses, more so than a relatively stiff capblock material such as Micarta. However, the stiffer Micarta is usually more durable and transmits a greater percentage of the hammer's energy to the pile because of its higher coefficient of restitution.

For example, when fourteen different cases of the Michigan study were solved by the wave equation, the Micarta assemblies averaged 14% more efficient than capblock assemblies of wood. However, the increased cushion stiffness in some of these cases increased the impact stresses to a point where damage to the pile or hammer might result during driving. The increase in stress was particularly important when concrete or prestressed concrete piles were driven. When driving concrete piles, it is also frequently necessary to include cushioning material between the helmet and the head of the pile to distribute the impact load uniformly over the surface of the pile head and prevent spalling.

To apply the wave equation to pile driving, Smith assumed that the cushion's stress-strain curve was a series of straight lines as shown in Figure 4.1. Although this curve was found to be sufficiently accurate to predict maximum compressive stresses in the pile, the shape of the stress wave often disagreed with that of the actual stress wave. To eliminate the effects of soil resistance several test piles were suspended horizontally above the ground. These test piles were instrumented with strain gages at several points along the length of the pile, and especially at the head of the pile. A cushion was placed at the head of the pile which was then hit by a horizontally swinging ram, and displacements, forces, and accelerations of both the ram and head of the pile were measured. Thus, by knowing the force at the head of the pile and the relative displacement between the ram and the head of the pile, the force exerted in the cushion

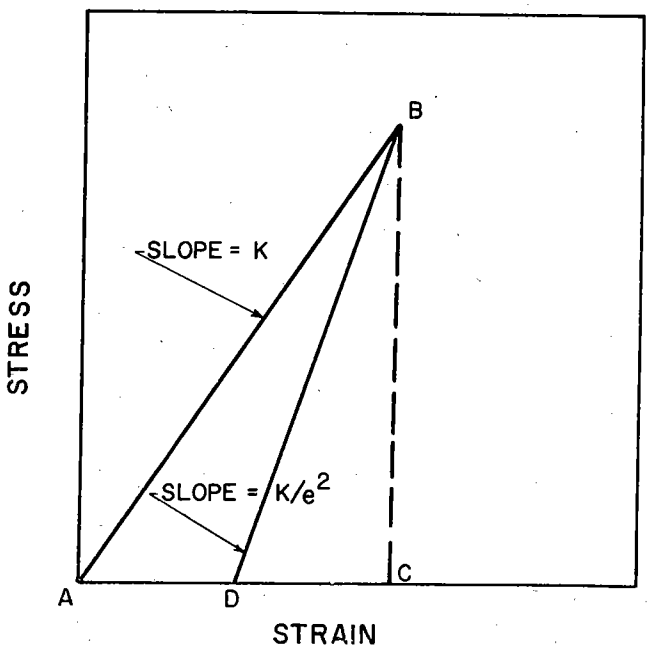


Figure 4.1. Stress-strain curve for a cushion block.

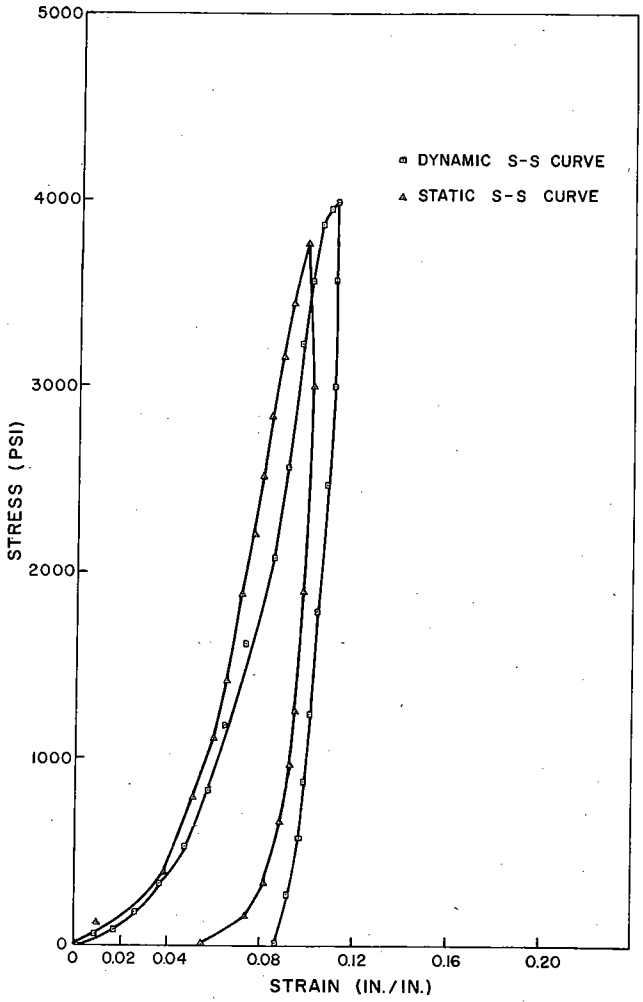


Figure 4.2. Dynamic and static stress-strain curves for a fir cushion.

and the compression in the cushion at all times could be calculated. Thus the cushion's stress-strain diagram could be plotted to determine whether or not it was actually a straight line.

Using this method, the dynamic stress-strain properties were measured for several types of cushions.

It was further determined that the stress-strain curves were not linear as was assumed by Smith, but rather appeared as shown in Figure 4.2. Because it was extremely difficult to determine the dynamic stress-strain curve by this method, a cushion test stand was constructed as shown in Figure 4.3 in an attempt to simplify the procedure.

Since it was not known how much the rigidity of the pedestal affected the cushion's behavior, several cushions whose stress-strain curve had been previously determined by the first method were checked. These studies indicated that the curves determined by either method were similar and that the cushion test stand could be used to accurately study the dynamic load-deformation properties of cushioning material.

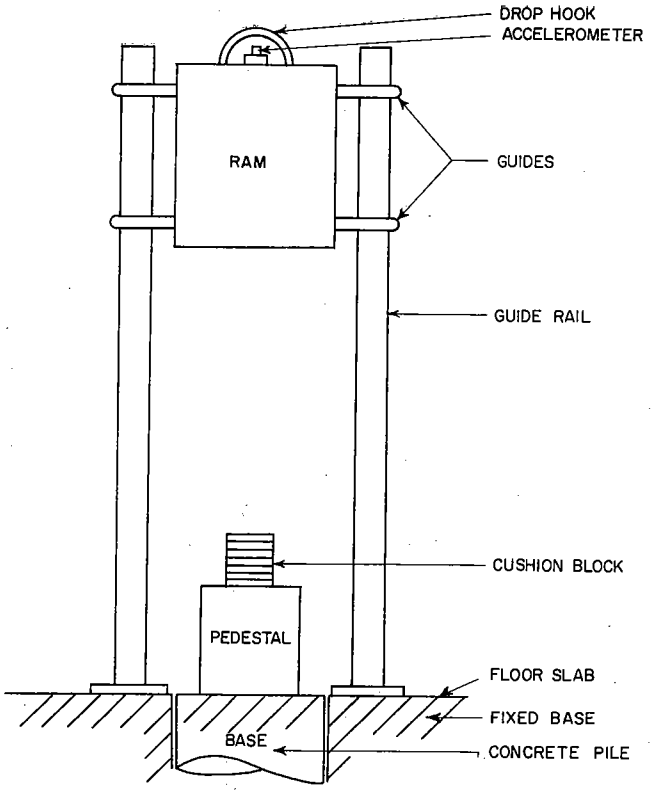


Figure 4.3. Cushion test stand.

Throughout this investigation, a static stress-strain curve was also determined for each of the cushions. Surprisingly, the static and dynamic stress-strain curves for wood cushions agreed remarkably well. A typical example of this agreement is shown in Figure 4.2. The stress-strain curves for a number of other materials commonly used as pile cushions and capblocks, namely oak, Micarta, and asbestos are shown by Figures 4.4-4.6.

4.2 Idealized Load-Deformation Properties

The major difficulty encountered in trying to use the dynamic curves determined for the various cushion materials was that it was extremely difficult to input the information required by the wave equation. Although the initial portion of the curve was nearly parabolic, the top segment and unloading portion were extremely complex. This prevented the curve from being input in equation form, and required numerous points on the curve to be specified.

Fortunately, it was found that the wave equation accurately predicted both the shape and magnitude of the stress wave induced in the pile even if a linear force-deformation curve was assumed for the cushion, so long as the loading portion was based on the secant modulus of elasticity for the material (as opposed to the initial, final, or average modulus of elasticity), and the unloading portion of the curve was based on the actual dynamic coefficient of restitution. Typical secant moduli of elasticity and coefficient of restitution values for various materials are presented in Table 4.1.

TABLE 4.1. TYPICAL SECANT MODULI OF ELASTICITY (E) AND COEFFICIENTS OF RESTITUTION (e) OF VARIOUS PILE CUSHIONING MATERIAL

	E psi	e
Micarta Plastic	450,000	.80
Oak (Green)	45,000*	.50
Asbestos Discs	45,000	.50
Fir Plywood	35,000*	.40
Pine Plywood	25,000*	.30
Gum	30,000*	.25

*Properties of wood with load applied perpendicular to wood grain.

4.3 Coefficient of Restitution

Although the cushion is needed to limit the driving stresses in both hammer and pile, its internal damping reduces the available driving energy transmitted to the head of the pile. Figure 4.1 illustrates this energy loss, with the input energy being given by the area ABC while the energy output is given by area BCD. This energy loss is commonly termed coefficient of restitution of the cushion "e", in which

$$e = \sqrt{\frac{\text{Area BCD}}{\text{Area ABD}}}$$

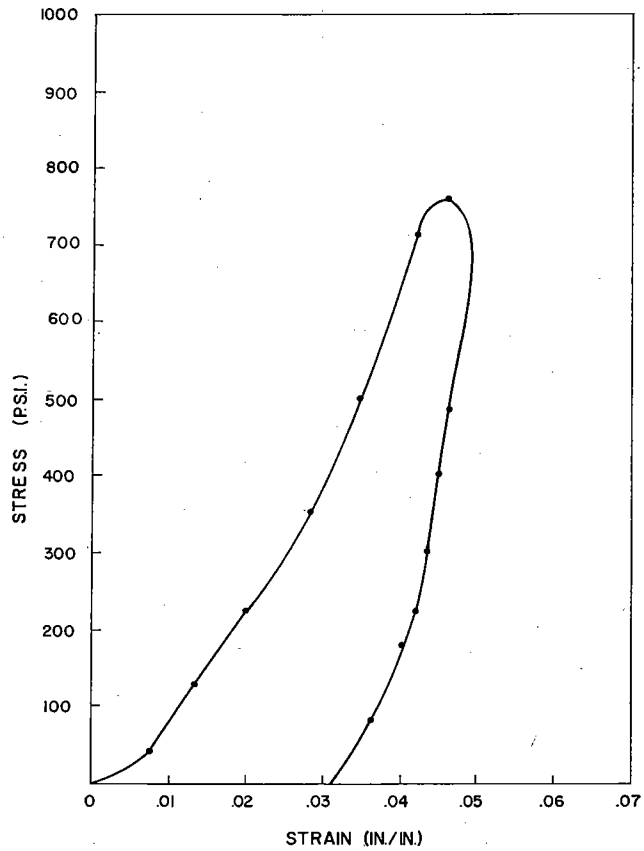


Figure 4.4. Dynamic stress-strain curve for an oak cushion.

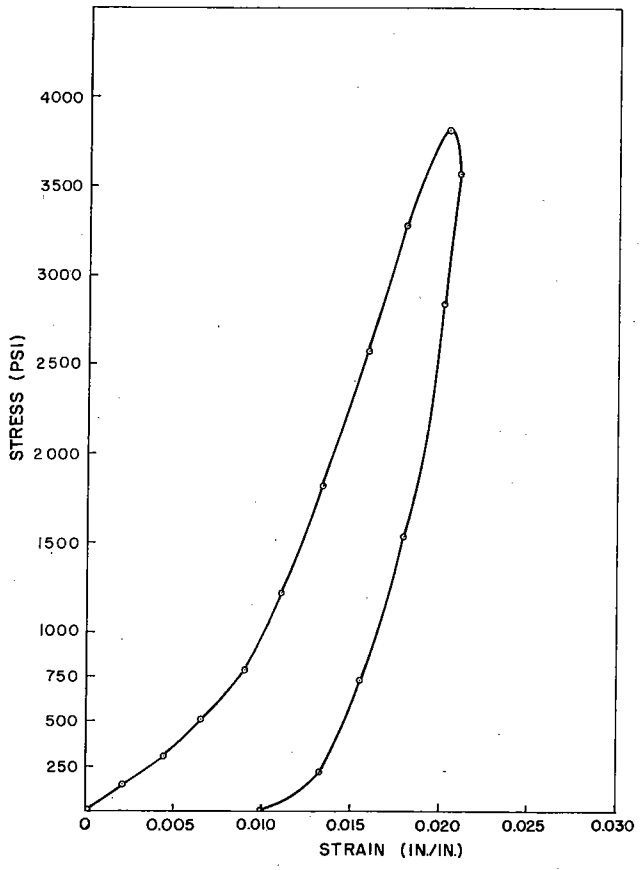


Figure 4.5. Dynamic stress-strain curve for a micarta cushion.

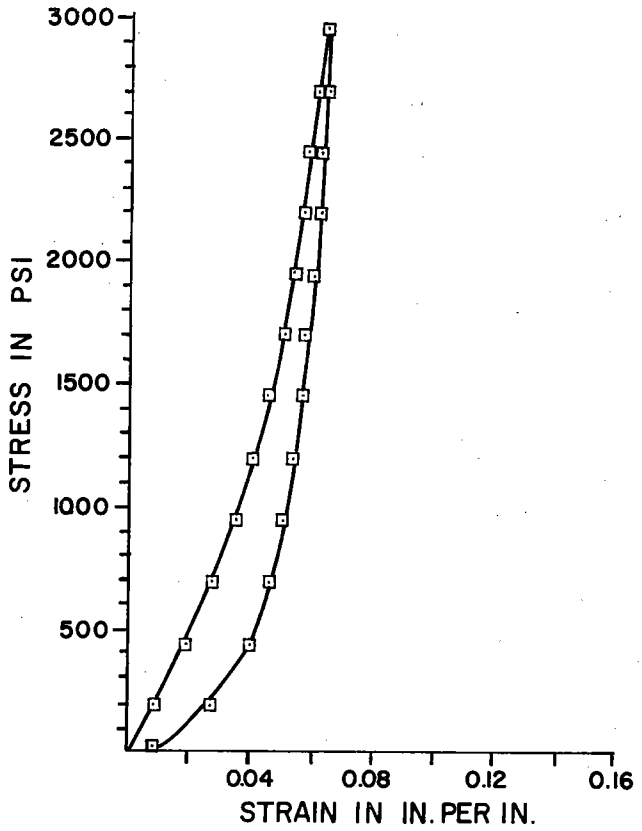


Figure 4.6. Stress vs strain for garlock asbestos cushion.

Once the coefficient of restitution for the material is known, the slope of the unloading curve can be determined as noted in Figure 4.1.

For practical pile driving problems, secant moduli of elasticity values for well consolidated cushions should be used. Table 4.1 shows typical secant moduli of well consolidated wood cushions. Table 4.1 also lists the coefficient of restitution for the materials which should be used when analyzing the problem by the wave equation.

CHAPTER V

Stress Waves in Piling

5.1 Comparison with Laboratory Experiments

As noted in the preceding section, several test piles were instrumented and suspended horizontally above the ground. This example pile was a steel pile, 85 ft in length with a cross-sectional area of 21.46 sq. in. The cushion was oak, 7 in. thick. The ram had a weight of 2128 lb and a velocity of 13.98 fps. The cushion was clamped to the head of the pile and then struck by a horizontally swinging ram. The pile was instrumented with strain gages at six points along the pile, and displacements and accelerations of both the ram and head of the pile were also measured.

In order to utilize Smith's solution to the wave equation, the following information is normally required:

1. The initial velocity and weight of the ram,
2. The actual dynamic stress-strain curve for the cushion,
3. The area and length of the pile, and
4. The density and modulus of elasticity of the pile.

Since the stress-strain curve for the cushion was unknown, the numerical solution was rewritten such that it was not needed. This was possible since the pile was instrumented with a strain gage approximately 1 ft from the head of the pile which recorded the actual stress

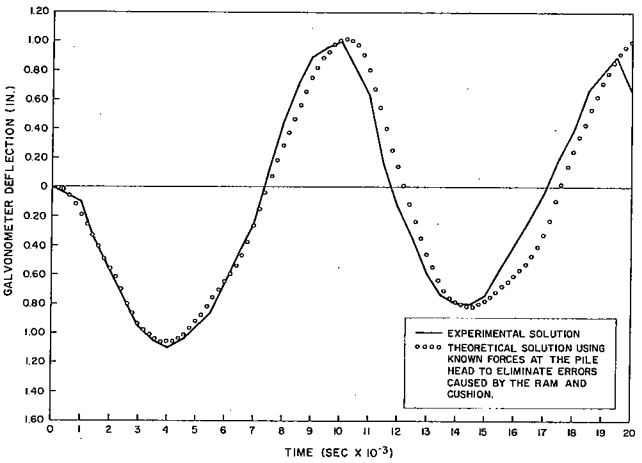


Figure 5.1. Theoretical vs experimental solution. Strain 25 ft from pile head.

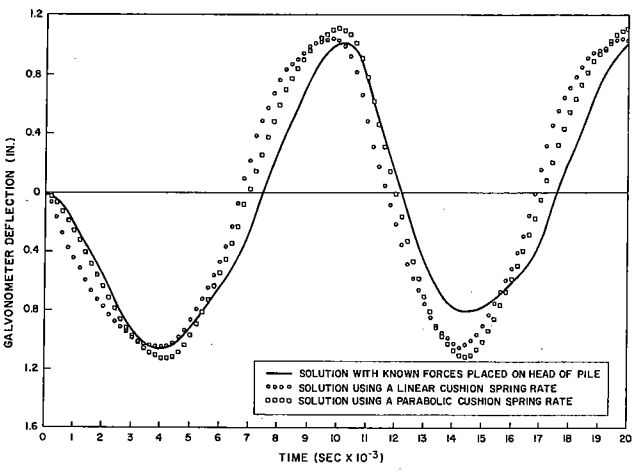


Figure 5.3. Theoretical vs experimental solution for strains 25 ft from the pile head.

induced in pile by the ram and cushion. The force measured at the head of the pile was then placed directly at the head of the pile and the wave equation was used to compute stresses and displacements at all of the gage points along the pile. Figures 5.1 and 5.2 present typical comparisons between the experimental results and wave equation solutions at two points on the pile, and illustrate the degree of accuracy obtained by use of the wave equation.

It must be emphasized that this excellent correlation between experimental and theoretical results was in effect obtained by using the actual dynamic load-deformation curve for that particular case. However, as mentioned earlier, the stress-strain curve for the cushion is normally assumed to be linear as shown in Figure 4.1.

To determine how much the use of the linear stress-strain curve will affect the solution, the previous case was rerun using the straight line stress-strain curves. As noted in Figures 5.3 and 5.4, the solutions for the linear and nonlinear cushion assumptions agreed favorably. The use of the straight line assumption is reasonable since it gives fairly accurate results for both maximum tensile and compressive stresses. Furthermore, it predicts the shape of the stress wave reasonably well.

5.2 Significance of Material Damping in the Pile

Other parameters were often varied in an attempt to obtain more accurate results, one of which was the material damping capacity of the pile material. However, most suspended pile cases studied strongly indicated that damping would be negligible because of the extremely low rate of decay of the stress wave in the pile. The only pile in which damping was thought to be significant was a lightweight concrete pile with a static modulus of elasticity of 3.96×10^6 and a "sonic" modulus of elasticity of 4.63×10^6 psi. This problem was chosen since E_s was relatively larger than E, indicating the possibility of rather high damping. It can be seen in Figure 5.5 that the magnitude of the experimental results diminishes slightly after four cycles. The magnitude of the theoretical solution with damping neglected would not. Figure 5.5 compares the experimental and theoretical solutions for stresses when Smith's proposed method of damping is included. In this case, the ex-

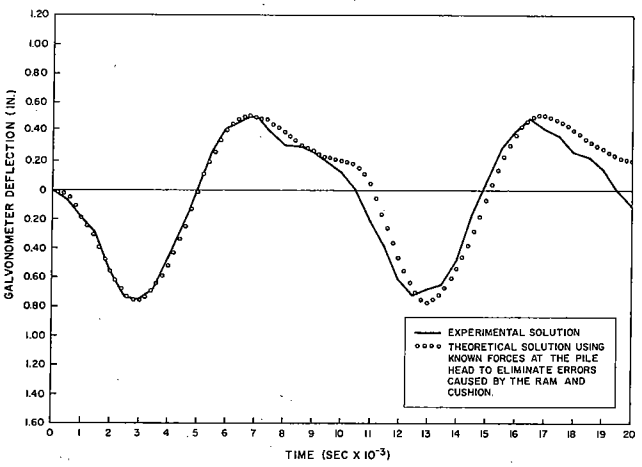


Figure 5.2. Theoretical vs experimental solution. Strain 52 ft from pile head.

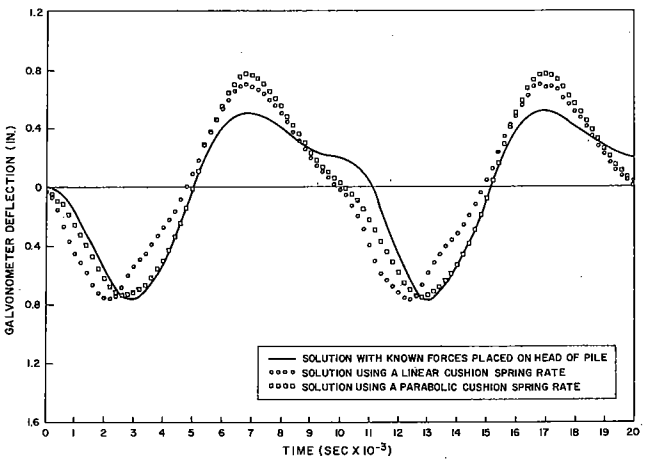


Figure 5.4. Theoretical vs experimental solution for strains 52 ft from the pile head.

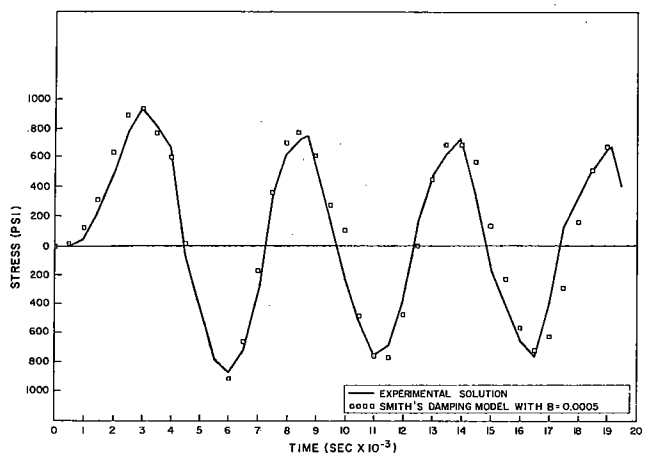


Figure 5.5. Comparison of experimental and theoretical solutions for stresses 25 ft from the pile head.

perimental and theoretical solutions are in excellent agreement, both in wave shape and rate of decay.

Although it is extremely interesting to be able to predict the dynamic behavior of piling with such accuracy, most practically the primary interest is in the maximum stresses induced in the pile which occur during the first or second pass of the stress wave along the pile. During this time, the effects of damping are extremely small even for the lightweight aggregate pile, and are apparently of no practical importance. Whether this conclusion will be accurate for timber or other piles having much higher damping capacities than either steel or concrete piles is unknown. A higher damping capacity could affect the results earlier in the solution and thus be of significance.

It should be emphasized that the above conclusions are valid only for normal pile driving conditions. If the wave must be studied for an extended period of time, damping in the pile may be significant and should be accounted for.

CHAPTER VI

Soil Properties

6.1 General

A limited amount of work has been done on soil properties and their effects on the wave equation solution of the piling behavior problem. A total of three research reports concerning soil properties have been published by the Texas Transportation Institute during the "Piling Behavior" study. Research Reports 33-7 and 33-7A[6.1, 6.2] give the results of a series of laboratory dynamic (impact) and static tests conducted on saturated sands. Research Report 33-8[6.3] gives the results of a field test on a full scale instrumented pile in clay. A brief summary of the results of these tests are given in this chapter.

6.2 Equations to Describe Soil Behavior

Examination of Equation (6.1) shows that Smith's equation describes a type of Kelvin rheological model as shown in Figure 6.1.

$$R(m,t) = [D(m,t) - D'(m,t)]K'(m) \\ [1 + J(m)\ V(m,t-1)] \qquad (6.1)$$

The soil spring behaves elastically until the deformation D(m,t) equals Q and then it yields plastically with a load-deformation property as shown in Figure 6.2(a). The dashpot J develops a resisting force proportional to the velocity of loading V. Smith has modified the true Kelvin model slightly as shown by Equation (6.2). This equation will produce a dynamic load-deformation behavior shown by path OABCDEF in Figure 6.2(b). If terms in Equation (6.1) are examined, it can be seen that Smith's dashpot force is given by

$$[D(m,t) - D'(m,t)]\ K'(m)\ [J(m)\ V(m,t-1)]$$

The dimensions of J are sec/ft and it is assumed to be independent of the total soil resistance or size of the pile. It is also assumed to be constant for a given soil under given conditions as is the static shear strength of the soil from which Ru on a pile segment is determined. Ru is defined as the maximum soil resistance on a pile segment.

Smith notes that Equation (6.1) produces no damping when D(m,t) − D'(m,t) becomes zero. He suggests an alternate equation to be used after D(m,t) first becomes equal to Q(m):

$$R(m,t) = [D(m,t) - D'(m,t)]\ K'(m) \\ + J(m)\ Ru(m)\ V(m,t-1) \qquad (6.2)$$

Care must be used to satisfy conditions at the point of the pile. Consider Equation (6.1) when m = p, where p is the number of the last element of the pile. K(p) is used as the point soil spring and J(p) as the point soil damping constant. Also at the point of the

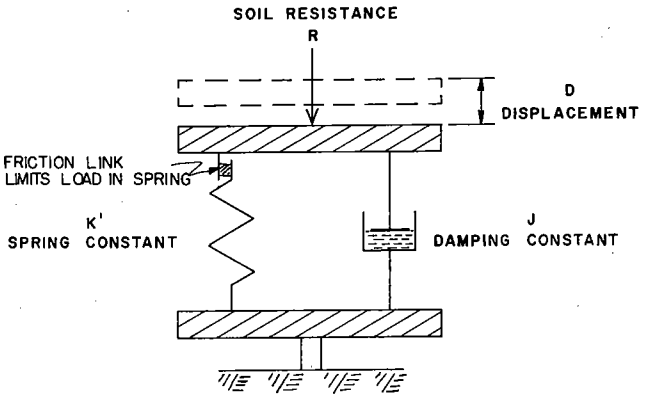
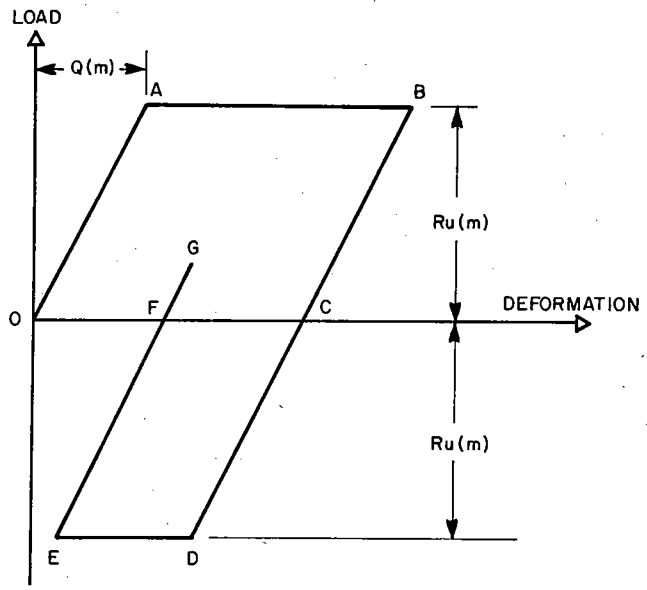


Figure 6.1. Model used by Smith to describe soil resistance on pile.

pile, the soil spring must be prevented from exerting tension on the pile point. The point soil resistance will follow the path OABCFG in Figure 6.2(b). It should be kept in mind that at the pile point the soil is loaded in compression or bearing. The damping constant J(p) in bearing is believed to be larger than the damping constant J(m) in friction along the side of the pile.

6.3 Soil Parameters to Describe Dynamic Soil Resistance During Pile Driving

The soil parameters used to describe the soil resistance in the wave equation are Ru, Q, and J.



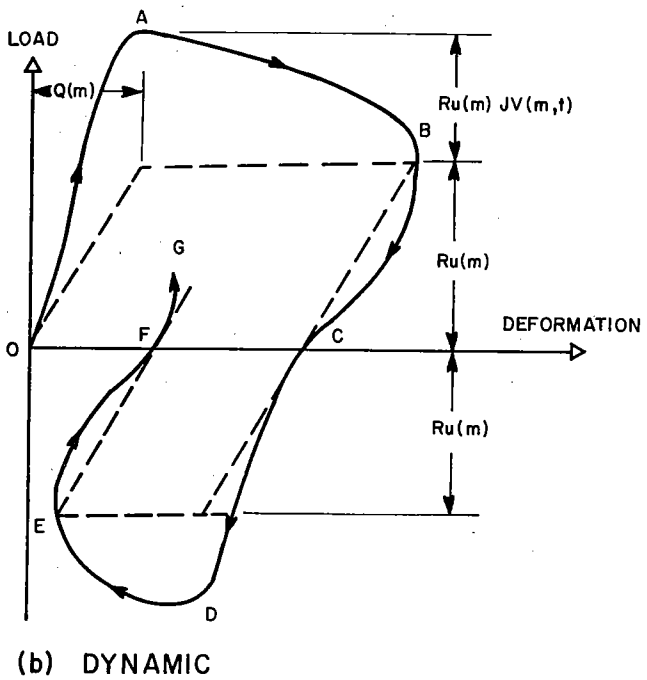


Figure 6.2. Load-deformation characteristics of soil.

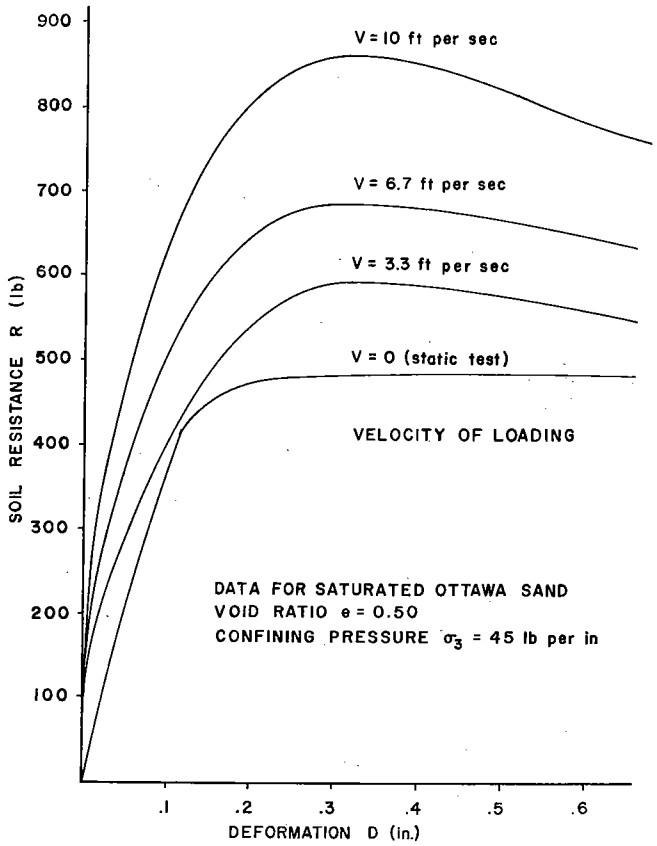


Figure 6.3. Load-deformation properties of Ottawa sand determined by triaxial tests (specimens nominally 3 in. in diam. by 6.5 in. high).

Soil Resistance "Ru." For the side or friction soil resistance, Ru is determined by the maximum static soil adhesion or friction against the side of a given pile segment by:

$$Ru(m) = fs \; \Sigma_o \; \Delta L \qquad (6.3)$$

where

fs = maximum soil adhesion or friction (lb/ft^2),
Σ_o = perimeter of pile segment (ft), and
ΔL = length of pile segment (ft).

In cohesionless materials (sands and gravels)

$$fs = \bar{\sigma} \tan \phi' \qquad (6.4)$$

where

$\bar{\sigma}$ = effective normal stress against the side of the pile (lb per ft^2), and
ϕ' = angle of friction between soil and pile (degrees).

In cohesive soils (clays) fs during driving is the remolded adhesion strength between the soil and pile.

At the point of the pile Ru is determined by the maximum static bearing strength of the soil and is found by

$$Ru = (Qu)\,(Ap) \qquad (6.5)$$

where

Qu = ultimate bearing strength of soil (lb/ft^2), and
Ap = area of pile point (ft^2).

In cohesive soils (clays) it is believed that the undisturbed strength of the soil may be used conservatively to determine Qu, since the material at the pile point is in the process of being compacted and may even have a higher bearing value.

Quake "Q". The value of Q, the elastic deformation of the soil is difficult to determine for various types of soils conditions. Various sources of data indicate that values of Q in both friction and point bearing probably range from 0.05 in. to 0.15 in.

Chellis[6.4] indicates that the most typical value for average pile driving conditions is Q = 0.10 in. If the soil strata immediately underlying the pile tip is very soft, it is possible for Q to go as high as 0.2 in. or more. At the present state of the art of pile driving technology it is recommended that a value of Q = 0.10 in. be used for computer simulation of friction and point soil resistance. However, in particular situations where more precise values of Q are known, they should be used.

Damping Constant "J". The Texas Transportation Institute has conducted static and dynamic tests on cohesionless soil samples to determine if Smith's rheological model adequately describes the load-deformation properties of these soils. Triaxial soil tests were conducted on Ottawa sand at different loading velocities. Figure 6.3 shows typical results from a series of such tests.

Figure 6.4 shows additional data concerning the increase in soil strength as the rate of loading is increased. Since these tests were confined compression tests it is believed that they simulate to some extent the soil behavior at the pile point. The J value increases as the sand density increases (void ratio e decreases) and it increases as the effective confining stress $\overline{\sigma_3}$ increases.

$$\overline{\sigma_3} = \sigma_3 - u$$

where

σ_3 = total confining pressure, and

u = pore water pressure.

For saturated Ottawa sand specimens, J(p) varied from about 0.01 to 0.12. When the sand was dry J(p) was nominally equal to zero. These values of J(p) for

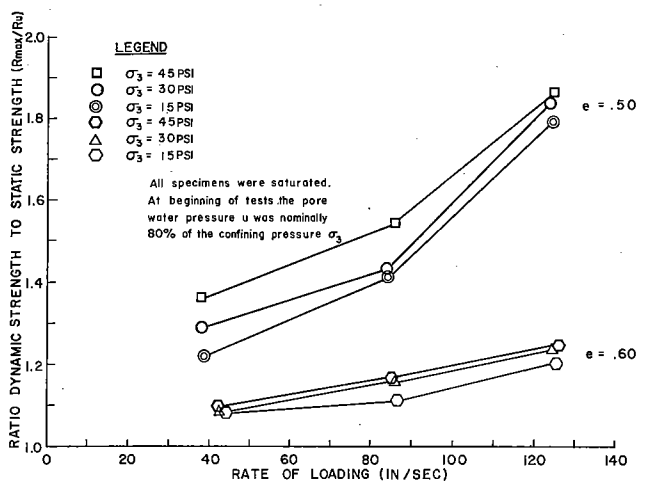


Figure 6.4. Increase in strength vs rate of loading-Ottawa sand.

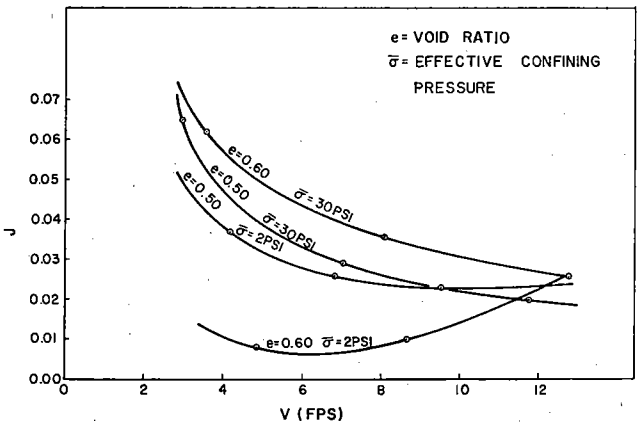


Figure 6.5. "J" versus "V" for Ottawa sand.

sand are in reasonable agreement with those recommended by Smith[6.5] and Forehand and Reese[6.6] (0.1 to 0.4).

The value of J(p) for cohesive soils (clays) is not presently known. The very limited data available indicate it is at least equal to that for sand. Forehand and Reese believe it ranges from 0.5 to 1.0.

There are no data now available to indicate the value of J(m) in friction along the side of the pile. Smith believes it is smaller than J(p) and recommends J(m) values in friction of about 1/3 those at the point. Research is under way at Texas A&M University which should indicate the value of J in friction. At the present time J(m) in friction or adhesion is assumed to be 1/3 of J(p).

6.4 Laboratory Tests on Sands

During the laboratory tests in saturated sands, attention was given to the determination of the soil damping constant. The peak dynamic resistance of the soil at the pile point can be represented in equation form for Smith's mathematical model as follows:

$$P_{dynamic} = P_{static} [1 + (J)(V)] \qquad (6.6)$$

where: $P_{dynamic}$ = peak load developed in dynamically loaded sample at a constant velocity, V;

P_{static} = peak load developed in statically loaded sample;

J = a damping constant; and

V = impact velocity of the dynamic load.

The laboratory tests on sands were conducted in such a manner that $P_{dynamic}$, P_{static}, and V were measured, and consequently it was possible to evaluate J for a given set of test conditions.

The laboratory tests conducted on saturated sands were conducted with the sand sample subjected to triaxial confinement. Particular attention was given to the effects of variable loading velocities, initial sample densities, and effective initial confining pressures. The machine used for testing was developed for this particular research and a complete description of the machine

and the instrumentation used is given in Research Report 33-7A.[6.2]

The results of the study of Ottawa sand are summarized in Figure 6.5. Application of Smith's mathematical model with the experimental data yields a damping factor, J, which varies from 0.01 to 0.07. For two other sands tested, Arkansas sand and Victoria sand, the value of J varied from 0.04 to 0.15. These values of J are not constant, and therefore Smith's equation did not accurately predict peak dynamic loads for the ranges of loading velocities (3 to 12 fps) used in these tests.

Additional tests have been conducted on these sands at loading velocities from 0 to 3 fps. Also, a series of tests have been conducted on clays at loading velocities of from 0 to 12 fps. This work has been accomplished under a new research study entitled "Bearing Capacity of Axially Loaded Piles." The tests on clays have shown that the use of Smith's original equation (Equation 6.2) yields a variable J value as was the case in sands. However, if Smith's equation is modified by raising the velocity, V, to some power, n, less than 1.0, a reasonably constant value of J can be obtained for the full range of loading velocities of from 0 to 12 fps. The proposed modified equation is as follows:

$$P_{dynamic} = P_{static} [1 + (J)(V)^n] \qquad (6.7)$$

6.5 Static Soil Resistance After Pile Driving (Time Effect)

Immediately after driving, the total static soil resistance or bearing capacity of the pile equals the sum of the Ru values discussed previously. Thus, Ru(total) is the bearing capacity immediately after driving.

$$Ru(total) = \sum_{m=1}^{m=p} Ru(m)$$

where

Ru(m) = soil adhesion or friction on segments m = 1 to m = p − 1 (lb), (note that this is the strength of the disturbed or remolded soil along the side of the pile), and

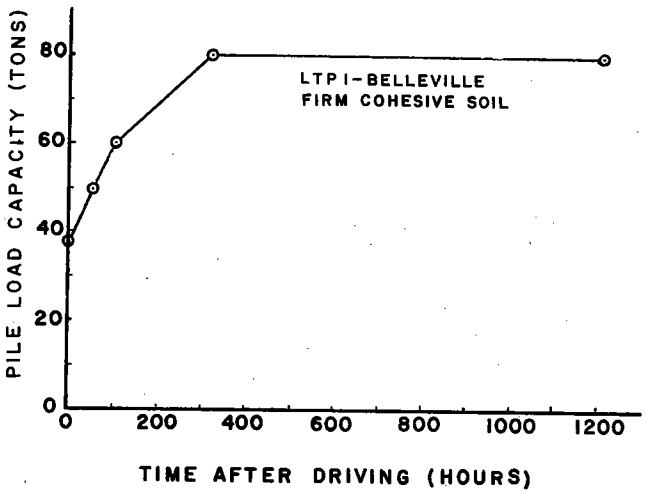


Figure 6.6. "Setup" or recovery of strength after driving in cohesive soil (after reference 6.7).

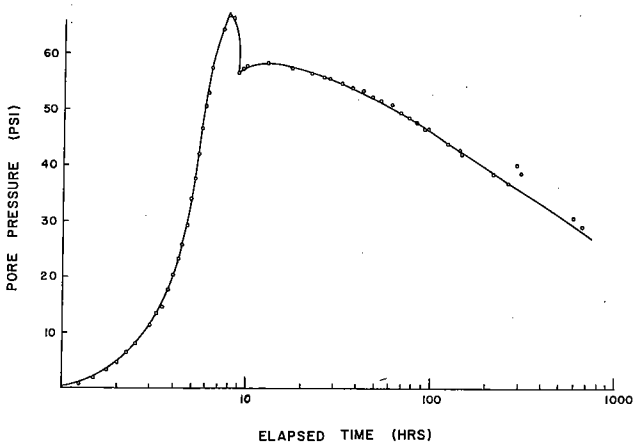


Figure 6.7. Pore pressure measurements in clay stratum —50' depth.

Ru(p) = bearing or compressive strength of soil at the pile point m = p (lb). Note this is taken as the strength of the soil in an undisturbed condition which should be conservative.

As time elapses after driving, Ru(m) for m = 1 to p − 1 may increase as the disturbed or remolded soil along the side of the pile reconsolidates and the excess pore water pressure dissipates back to an equilibrium condition. In cohesive soils (clays) the increase in strength upon reconsolidation (sometimes referred to as "setup") is often considerable.

The bearing capacity of the pile will increase as the remolded or disturbed clay along the side of the pile reconsolidates and gains strength, since the adhesion or friction strength of clay is generally restored with the passage of time. Loading tests at increasing intervals of time show that ultimate adhesion is approximately equal to the undisturbed cohesion. Therefore, the amount of increase in bearing capacity with time is related to the sensitivity and reconsolidation of the clay*.

Figure 6.6 illustrates the time effect or "setup" of a pile driven in a cohesive soil. In cohesionless soils (sands and gravels) the friction strength of the soil will usually change very little. Normally, the value of Ru(p) at the pile point changes very little.

6.6 Field Test in Clay

The purpose of the field test study[6.3] was to investigate the failure mechanisms of clay soils subjected to dynamic and static loading. A test pile instrumented with pressure transducers, strain gages, and accelerometers was driven into a saturated clay at a site in Beaumont, Texas.[6.5]

Measurements of strains and accelerations of the pile were taken during driving. Pore pressure measurements were made at the pile-soil interface for a continuous period of 30 days after driving. Figure 6.7 shows a typical plot of pore pressure versus elapsed time in the clay stratum at a 50 ft depth. Strain measurements were

*Sensitivity of clay = $\frac{\text{undisturbed strength}}{\text{remolded strength}}$

made during static load tests at 13 days and 30 days after driving. Soil borings were made for the in-situ, remolded, and reconsolidated conditions, and at specific radial distances from the pile. Conventional tests were conducted on the soil samples to measure the changes in engineering properties for the different conditions.

A mode of failure was established in this study for a cohesive soil involved in the load response of a pile-soil system. The behavior of the soil in this study indicates that soil disturbances which involve new soil particle arrangement and altered engineering properties are limited to a distance from the center of the pile of approximately 4.5 radii.[6.5] This relationship can be expressed as follows:

$$\frac{r}{r_1} < 4.5 \qquad (6.8)$$

where: r = radial distance from pile center; and
r_1 = radius of pile.

Results of this study also suggest that the time after driving required for piles of different radii to attain comparable percentages of their ultimate bearing capacity can be expressed as follows:

$$\frac{r_1^2}{r_2^2} = \frac{T_1}{T_2} \qquad (6.9)$$

where: r_1 = radius of pile 1;
r_2 = radius of pile 2;
T_1 = time for pile 1 to attain a stated percentage of ultimate bearing capacity; and
T_2 = time for pile 2 to attain the same percentage of ultimate bearing capacity.

CHAPTER VII

Use of the Wave Equation to Predict Pile Load Bearing Capacity At Time of Driving

7.1 Introduction

In general, engineers are interested in the static load carrying capacity of the driven pile. In the past the engineer has often had to rely on judgement based on simplified dynamic pile equations such as the Hiley or Engineering News formulas. By the wave equation method of analysis a much more realistic engineering estimate can be made using information generated by the program.

The previous chapters have shown how the hammer pile-soil system can be simulated and analyzed by the wave equation to determine the dynamic behavior of piling during driving. *With this simulation the driving stresses and penetration of the pile can be computed.*

7.2 Wave Equation Method

In the field the pile penetration or permanent set per blow (in. per blow) is observed and this can be translated into the static soil resistance through the use of the wave equation.

Consider the following example:

PILE: 72 ft steel step taper pile

HAMMER: No. 00 Raymond
Efficiency = 80%
Ram Weight = 10,000 lb
Energy = 32,500 ft lb

CAPBLOCK: Micarta
K = 6,600,000 lb/in.
e = 0.8

ASSUMED SOIL PARAMETERS:

J(p) point = 0.15 sec/ft Q(p) point = 0.10 in.

J(m) side = 0.05 sec/ft Q(m) side = 0.10 in.

Soil is a soft marine deposit of fine sand, silt, and muck, with the pile point founded on a dense layer of sand and gravel.

ASSUMED SOIL DISTRIBUTION:

Curve I: 25% side friction (triangular distribution) 75% point bearing.

Curve II: 10% side friction (triangular distribution) 90% point bearing.

This information is used to simulate the system to be analyzed by the wave equation. A total soil resistance Ru(total) is assumed by the computer for analysis in the work. It then computes the pile penetration or "permanent set" when driven against this Ru (total). The reciprocal of "permanent set" is usually computed to convert this to blows per in.

The computer program then selects a larger Ru(total) and computes the corresponding blows per in. This is done several times until enough points are generated to develop a curve relating blows per in. to Ru(total) as shown in Figure 7.1 (two curves for the two different assumed distributions of soil resistance are shown).

In the field if driving had ceased when the resistance to penetration was 10 blows per in. (a permanent set equal to 0.1 in. per blow), then the ultimate pile load bearing capacity immediately after driving should have been approximately 370 to 380 tons as shown on Figure 7.1. It is again emphasized that this Ru(total) is the total *static* soil resistance encountered during driving, since the increased dynamic resistance was considered in the analysis by use of J. If the soil resistance is predominantly due to cohesionless materials such as sands and gravels, the time effect or soil "setup" which tends to increase the pile bearing capacity will be small

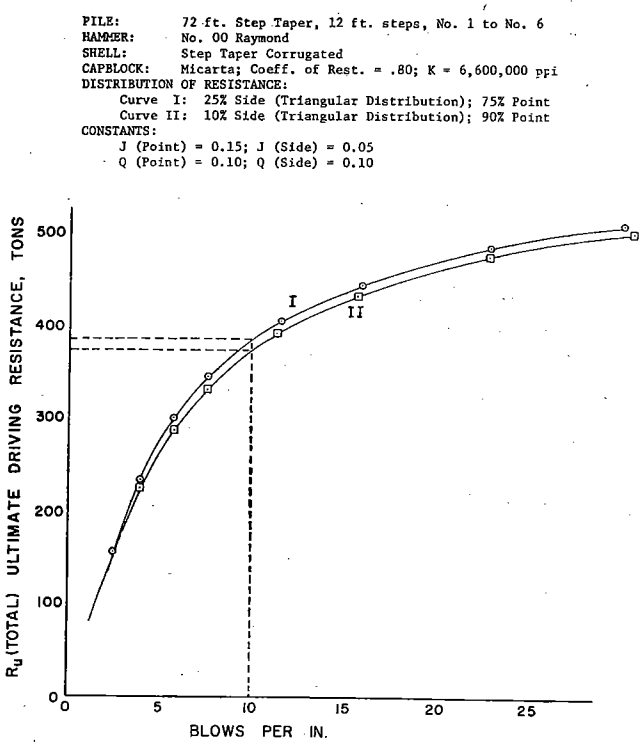


Figure 7.1. Ultimate driving resistance vs blows per inch for an example problem.

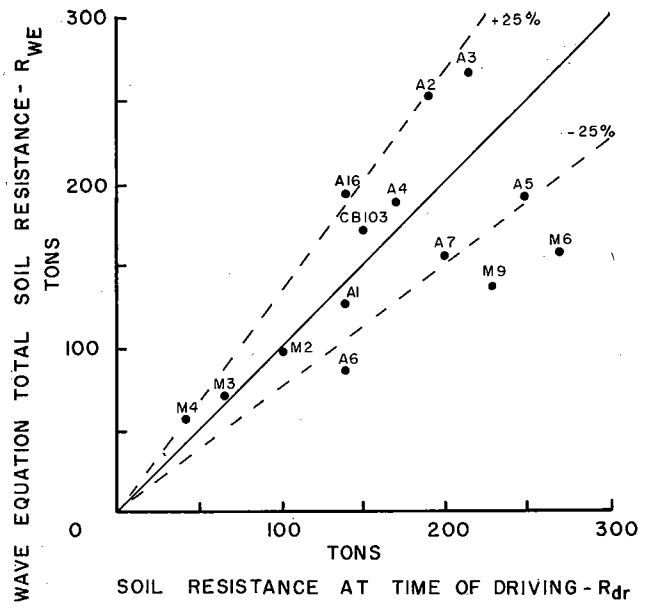


Figure 7.2. Comparison of wave equation predicted soil resistance to soil resistance determined by load tests for piles driven in sands. (Data from table 7.1.)

or negligible. If the soil is a cohesive clay, the time effect or soil "setup" might increase the bearing capacity as discussed in Chapter VI. The magnitude of this "setup" can be estimated if the "sensitivity" and reconsolidation of the clay is known. It can also be conservatively disregarded since the "setup" bearing capacity is usually greater than that predicted by a curve similar to Figure 7.1.

In developing the curves of Figure 7.1, it was necessary to assume the following soil parameters:

1. Distribution of soil resistance
2. Soil Quake "Q"
3. Soil damping constant "J"

As illustrated by Curves I and II on Figure 7.1, small variations in the distribution of soil resistance between side friction and point bearing will not affect the wave equation results significantly. All that is re-

TABLE 7.1. ERRORS CAUSED BY ASSUMING $J(\text{point}) = 0.1$ AND $J'(\text{side}) = \frac{J(\text{point})}{3}$ FOR SAND (For Sand-Supported Piles Only)

Location	Load Test Pile	R_{dr}* (Resistance at Time of Driving) (kips)	R_{WE} (Indicated Soil Resistance) (kips)	% Error in R_{dr} $\left(\frac{R_{WE} - R_{dr}}{R_{dr}}\right)$ (100)
Arkansas	1	280	255	− 9
	2	380	495	+30
	3	430	530	+23
	4	340	370	+ 9
	5	500	380	−24
	6	280	170	−39
	7	400	310	−23
	16	280	380	+36
Copano Bay	103	300	320	+ 7
Muskegon	2	200	195	− 3
	3	110	145	+32
	4	85	110	+29
	6	540	310	−43
	9	470	270	−43
			Total	13501

Mean or Average % Error $= \frac{13501}{14} = 25\%$

*R_{dr} for piles driven in sands was assumed equal to the actual load test measurements since no "setup" was considered.

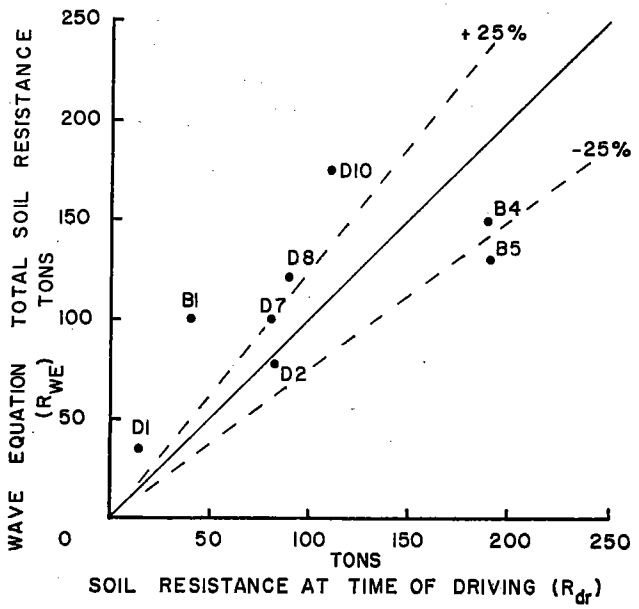


Figure 7.3. Comparison of wave equation predicted soil resistance to soil resistance determined by load tests for piles driven in clay. (Data from table 7.2.)

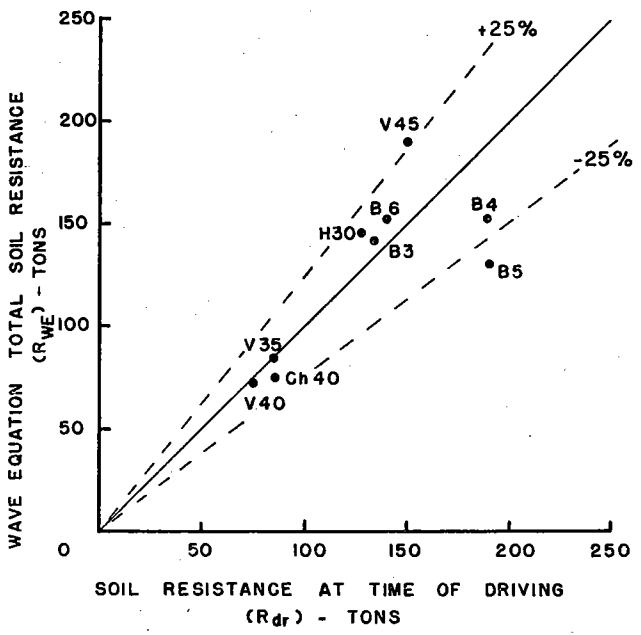


Figure 7.4. Comparison of wave equation predicted soil resistance to soil resistance determined by load tests for piles driven in both sand and clay. (Data from table 7.3.)

quired is a reasonable estimate of the situation. For most conditions an assumption of soil quake Q = 0.1 in. is satisfactory (see Chapter VI). The value of J(m) is assumed to be 1/3 of J(p).

7.3 Comparison of Predictions with Field Tests

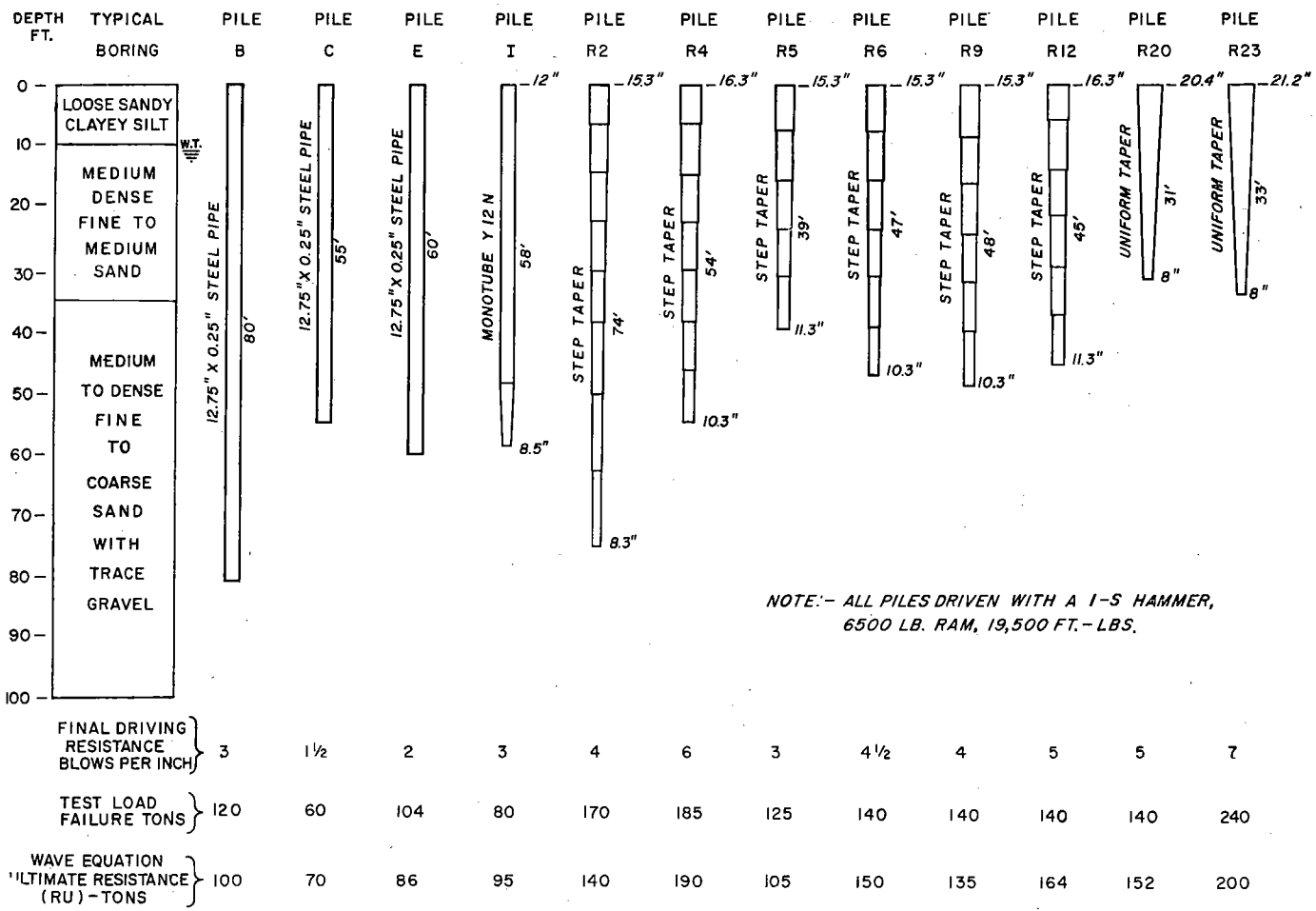
Correlations of wave equation solutions with full-scale load tests to failure have provided a degree of confidence in the previously described method of predicting static bearing capacity.

For the sand-supported piles (Table 7.1) damping constants of J(point) = 0.1 and J'(side) = J(point)/3 were found to give the best correlation. Figure 7.2 shows the accuracy of the correlation to be approximately ±25%. In Table 7.2, for clay-supported piles

TABLE 7.2. ERROR CAUSED BY ASSUMING J(point) = 0.3 AND J'(side) = $\frac{J(point)}{3}$ FOR CLAY (For Clay-Supported Piles Only)

Location	Load Test Pile	R_{lt} (Load Test Resistance) (kips)	R_{dr}*** (Resistance at time of driving) (kips)	R_{WE} (Indicated soil resistance) (kips)	% Error in R_{dr} $\left(\frac{R_{WE} - R_{dr}}{R_{dr}}\right)$ (100)
Belleville	1**	160	80	200	+150
	4*	690	379	305	− 19
	5*	692	381	260	− 32
Detroit	1**	56	28	70	+156
	2	330	165	155	− 6
	7	318	159	205	+ 29
	8	360	180	240	+ 33
	10	450	225	250	+ 11
					Total = 436
				Average % Error = $\frac{436}{8}$	= 54.5%

*90% clay-supported piles.
**The test values for these piles were questionable.
***R_{dr} for piles driven in clay were actual load test measurements corrected to account for soil "set-up."



	B	C	E	I	R2	R4	R5	R6	R9	R12	R20	R23
FINAL DRIVING RESISTANCE BLOWS PER INCH	3	1½	2	3	4	6	3	4½	4	5	5	7
TEST LOAD FAILURE TONS	120	60	104	80	170	185	125	140	140	140	140	240
WAVE EQUATION ULTIMATE RESISTANCE (RU) - TONS	100	70	86	95	140	190	105	150	135	164	152	200

Q = 0.1 in. and J(point) = 0.15, J(side) = 0.05. Soil resistance was assumed to be 50% at the point and 50% friction distributed uniformly over the embedded length below a depth of 10 ft. Hammer efficiency assumed to be 80%.

Figure 7.5. Summary of piles tested to failure in sands.

TABLE 7.3. ERRORS CAUSED BY ASSUMING A COMBINED J(point) = 0.1 FOR SAND AND J(point) = 0.3 FOR CLAY USING EQ. 7.1 (For Piles Supported by Both Sand and Clay)

Location	Load Test Pile	ΔR_{clay} × 0.3	ΔR_{sand} × 0.1	J(point) (sec/ft)	R_{lt} (Load Test Resistance) (kips)	R_{dr}** (Resistance at Time of Driving) (kips)	R_{WE} (Indicated Soil Resistance) (kips)	% Error in R_{dr} $\left(\frac{R_{WE} - R_{dr}}{R_{dr}}\right)$ (100)
Victoria	35	0.090	0.070	0.16	208	176	170	− 3%
	40	0.087	0.071	0.16	160	136	148	+ 9%
	45	0.093	0.069	0.16	352	300	380	+27%
Chocolate Bayou	40	0.126	0.058	0.18	210	166	150	−10%
	60	0.120	0.060	0.18	*	*	740	
Houston Copano Bay	30	0.153	0.049	0.20	340	255	290	+14%
	58	0.252	0.016	0.27	*	*	260	
Belleville	3	0.102	0.066	0.17	342	284	265	− 7%
	4	0.270	0.010	0.28	690	379	305	−20%
	5	0.270	0.010	0.28	692	381	260	−32%
	6	0.192	0.036	0.23	412	280	305	+ 9%
Muskegon	7	0.090	0.070	0.16	*	*	320	
	8	0.090	0.070	0.16	*	*	295	
							Total =	131

Average % Error = $\frac{131}{9}$ = 14.5%

*Indicates piles which exceeded the testing equipment's capacity, and could not be load-tested to failure.
**R_{dr} for these piles were actual load test measurements corrected to account for soil "setup."

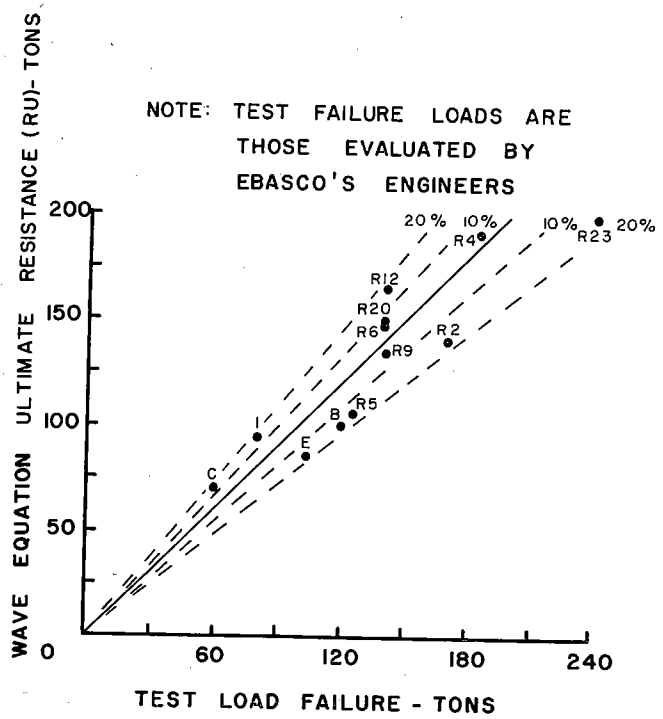


Figure 7.6. Wave equation ultimate resistance vs test load failure (after Ref. 7.2, data from Fig. 7.5) (sands).

the damping constants J(point) = 0.3 and J'(side) = J(point)/3 gave the best correlation. The accuracy of the correlation is shown in Figure 7.3 to be approximately ±50%.

If more than one soil was involved the damping constant used was a weighted average calculated from

$$J(\text{point}) = \Sigma [R_i \times J(\text{point})_i] \qquad (7.1)$$

where R_i = the ratio of the amount of resistance of each type of soil "i", to the total soil resistance, both determined after setup has ceased, and

$$J'(\text{side}) = \frac{J(\text{point})}{3}$$

Table 7.3 shows the damping constant that was calculated from Equation 7.1 using J(point) = 0.3 for clay and J(point) = 0.1 for sand. The accuracy of the correlation, as shown in Figure 7.4 was approximately ±25%.

Mosley[7.2] has found a similar correlation with 12 piles driven in sand. Figure 7.5 is a summary of the piles tested. Figure 7.6 shows that all resistances on these piles fall within ±20% of that predicted by the wave equation.

CHAPTER VIII

Prediction of Driving Stresses

8.1 Introduction

In Appendix A the exact solution for the stress wave introduced into a long slender elastic pile is derived using the classical one-dimensional wave equation. The solution of this equation depends upon certain assumptions. It is assumed that the pile is prismatic with lateral dimensions small in comparison to its length (Poisson's effects can be neglected), that the pile and cushion material are linearly elastic, and the ram has infinite rigidity (assumed to be a rigid body). The equation which governs the stress amplitude in most practical cases, shows that the magnitude of the stress induced at the head of the pile, by the falling ram, is directly proportional to the velocity of the ram at impact. The equation further shows that the stiffnesses of the cushion and pile also have a significant effect on the magnitude of the stress generated. The soil resistance on the side and at the point of the pile will also affect the magnitude of the stresses in the pile.

Chapter II discusses Smith's numerical solution of the one-dimensional wave equation. This particular technique for solving the wave equation is much simpler for application to problems which can have inelastic cushions and material properties as well as soil on the side and point of the pile. Chapter V discusses the generation of stress waves in piling, the significance of material damping in the pile and the effects of pile dimensions on driveability.

This chapter demonstrates the validity of Smith's numerical solution by comparing its results with the theoretical solution of Appendix A and with field data.

8.2 Comparison of Smith's Numerical Solution with the Classical Solution

For the purpose of correlation, consider a concrete pile, square in cross-section, with an area of 489 in.^{2} and 90 ft long. The modulus of elasticity of the pile material is assumed to be 5 x 10^6 psi. The pile is considered to be free at the top with the bottom end fixed rigidly against movement. No side resistance is present.

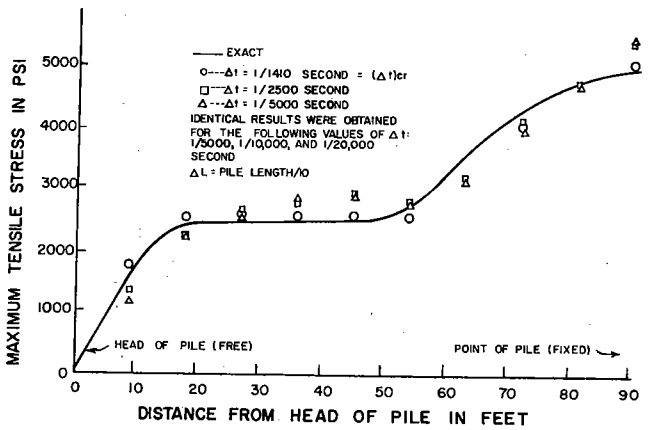


Figure 8.1. Maximum tensile stress along the pile.

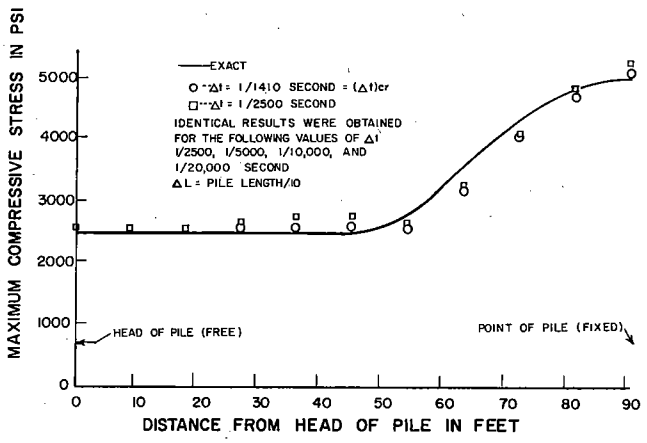


Figure 8.2. Maximum compressive stress along the pile.

The following information is also applicable to the correlation:

Weight of the ram = 11,500 lb,

Velocity of the ram = 14.45 fps

Cushion block stiffness = 3,930,000 lb/in.,

Coefficient of restitution of the cushion block = 1.00

Solutions have been obtained for the exact solution of the one-dimensional wave equation and for Smith's numerical method using 10 segments. Previous studies[8.1] had shown that segment lengths of L/10 would yield accurate results. Figures 8.1 and 8.2 show comparisons of the maximum tensile stress and maximum compressive stress, respectively, versus position along the length of the pile. Note the time interval used (time differencing interval used in the numerical solution) for solutions shown is varied from 1/1410 seconds (this is the critical time differencing interval) to 1/20,000 seconds. Note that when the differencing interval became very small, i.e., 1/5000 seconds, the accuracy of the solution was not improved. Note also that the numerical solution is very close to the exact solution. Other comparisons have been made for the stresses at other points in the pile and for other combinations of the end boundary conditions.[8.1] Heising[8.2] and Smith[8.3] have shown that the discrete-element numerical solution is an exact solution of the one-dimensional wave equation when

$$\Delta t = \frac{\Delta L}{\sqrt{E/\rho}}$$

where,

Δt = critical time differencing interval,

ΔL = segment length,

E = modulus of elasticity, and

ρ = mass density of the pile material.

This time interval is the "critical" time interval. For practical problems, a choice of Δt = one-half the "critical value," appears suitable since inelastic springs, materials of different densities, and elastic moduli are usually involved.

8.3 Correlations of Smith's Solution with Field Measurements

In previous reports[8.4, 8.5] the writers have shown several correlations of the wave equation with stresses measured in piles during the time of driving in the field. Typical examples of these correlations are shown in Figures 8.3 and 8.4. The significant conclusions drawn from these tests are as follows:

1. The maximum compressive stresses occurred at the head of the pile.

2. Maximum tensile stresses were found to occur near the midpoint of the piles.

3. The computed compressive stresses and displacements agree very well with the measured data.

4. The computed tensile stresses appeared high but in view of the unknown dynamic properties of the soil, concrete, and cushioning materials involved in the problem, the quantitative comparisons shown were considered good.

8.4 Effect of Hammer Type and Simulation Method

It has been shown[8.7] (see Chapter III) that the ram of a pile hammer can be idealized as a rigid body provided it strikes on a capblock or cushion. If the ram strikes directly on steel, as in the case of the diesel hammers, the accuracy of the solution for stresses is improved by breaking the ram into segments.

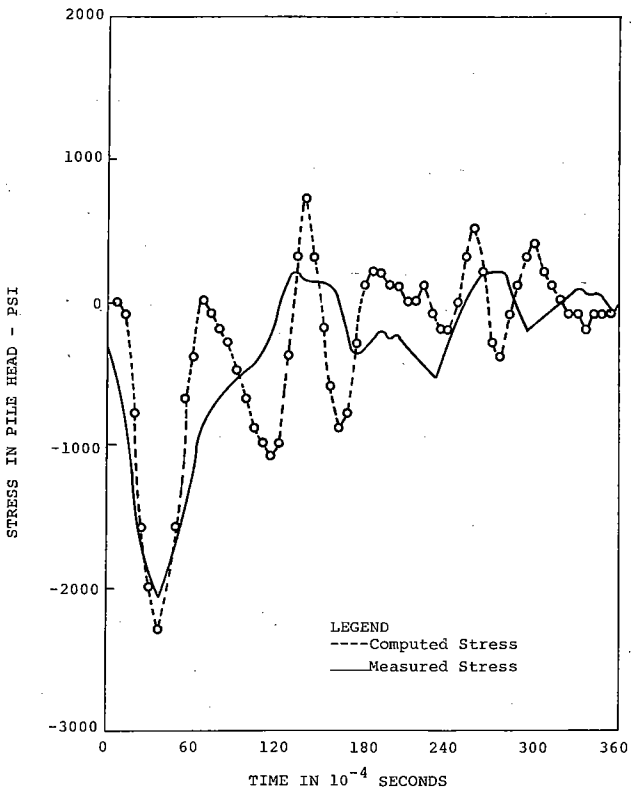


Figure 8.3. Stress in pile head vs time for test pile.

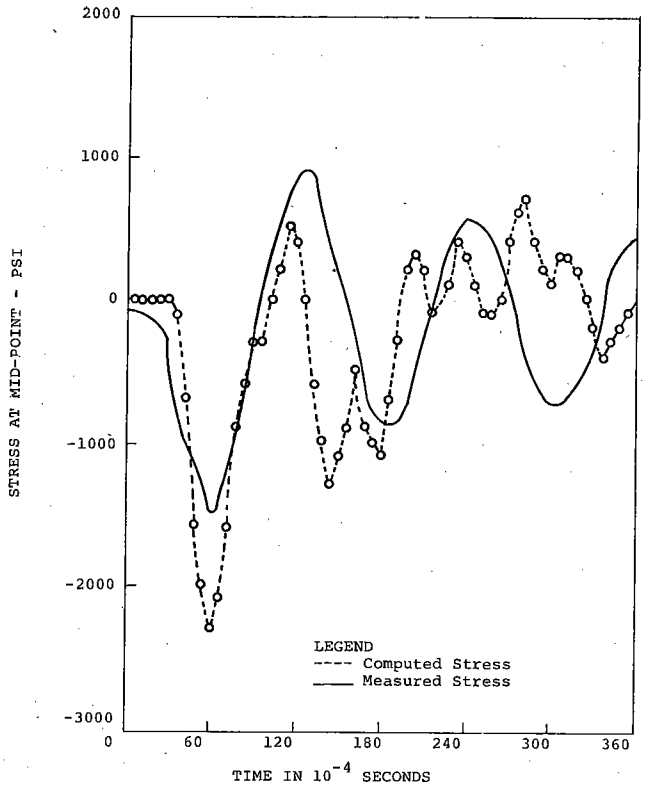


Figure 8.4. Stress at mid-length of pile vs time for test pile.

For diesel hammers, the explosive force used to raise the hammer for the next blow does work on the pile and should be included.

In all hammer simulations, all parts which are in the force transmission chain should be included. The housing and other parts which do not serve to transmit the driving energy may be neglected.

Refer to Appendix B, Tables B.1 and B.2, for recommended values for use in the simulation.

8.5 Effect of Soil Resistance

If soil borings are available, the distribution of the soil resistance on the pile should be estimated from soil shear strength data. In general, piles in uniform cohesive soils will have the soil resistance distributed uniformly in side friction with about 10 to 20% point resistance. Cohesionless soils can generally be simulated with a triangular friction distribution with about 40% in side friction and 60% of the total resistance at the point. The actual distributions used will, of course, depend on the properties of the soils, pile length, type, etc., and should be studied for each case. It is important to note, however, that the soil distribution will affect the magnitude of the driving stresses. This is particularly true for the reflected tensile stresses. In most investigations for driving stresses, it is best to vary the distribution over the expected range and choose the most conservative result. Reflected tensile stresses are highest when the soil resistance acting at the pile point is small.

8.6 Effects of Cushion Stiffness, Coefficient of Restitution, and Pile Material Damping

It has been shown[8.6] (see Chapter IV) that the actual load deformation curve for a cushion is not a straight line, but is parabolic. However, a straight line which has a slope given by the secant modulus will give reasonably accurate results. The cushion's dynamic coefficient of restitution was found to agree with commonly recommended values. It has also been shown that the effect of internal damping in the concrete and steel piles will usually have a negligible effect on the driving stresses.

8.7 Fundamental Driving Stress Considerations

The purpose of this discussion is to briefly describe and discuss the phenomena of impact stresses during driving.

Compressive Stresses. High compressive stress at the head of the pile can be caused by the following:

1. Insufficient cushioning material between the pile driving ram and the pile will result in a very high compressive stress on impact.

2. When a pile is struck by a ram at a very high velocity, or from a very high drop, a stress wave of high magnitude is produced. This stress is directly proportional to the ram velocity.

If the pile is idealized as a long elastic rod, with an elastic cushion on top an equation for the compressive stress can be developed (see Appendix A). The approximate equations for the maximum compressive stress at the pile head are as follows:

Notations used are:

σ_o max = maximum compressive stress at pile head (psi),

W = ram weight (lb),

V = ram impact velocity (in./sec),
$= \sqrt{2gh}$,

h = ram free fall (in.),

g = acceleration due to gravity, 386 in./sec^2,

K = cushion stiffness (lb/in.),
$= \frac{Ac\ Ec}{tc}$

A_c = cross-sectional area of cushion (in.^{2}),

E_c = modulus of elasticity of cushion (psi),

t_c = initial uncompressed thickness of cushion (in.),

t = time (sec),

A = cross-sectional area of pile (in.^{2}),

E = modulus of elasticity of pile (psi),

L_p = length of pile (in.),

γ = unit weight of pile (lb/in.^{3}),

$$n = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}}$$

$$p = \sqrt{\frac{Kg}{W}}$$

Case I. $n<p$

$$\sigma_o \text{ max} = \frac{-KV}{A}\,\frac{e^{-nt}}{\sqrt{p^2-n^2}}\,\sin\,(t\sqrt{p^2-n^2}) \qquad (8\text{-}1)$$

where t is found from the expression

$$\tan\,(t\sqrt{p^2-n^2}) = \frac{\sqrt{p^2-n^2}}{n}$$

Case II. $n = p$

$$\sigma_o \text{ max} = -\left[\frac{KV}{nA} - \frac{W}{A}\right] e^{-1} \qquad (8.2)$$

Case III. $n>p$

$$\sigma_o \text{ max} = -\frac{KV}{A}\,\frac{e^{-nt}}{\sqrt{n^2-p^2}}\sinh\,(t\sqrt{n^2-p^2}) \qquad (8.3)$$

where t is found from the expression

$$\tanh\,(t\sqrt{n^2-p^2}) = \frac{\sqrt{n^2-p^2}}{n}$$

Equations (8.1), (8.2), or (8.3) can be used to determine the maximum compressive stress at the pile head. For most practical pile problems n will be less than p and Equation (8.1) will be used. However, this is not always the case. For a given pile these equations can be used to determine a desirable combination of ram weight W, ram velocity V, and cushion stiffness K so as not to exceed a given allowable compressive stress at the pile head.

To illustrate the use of the equations consider the following situation.

Given:

Concrete Pile

$L_p = 65$ ft

$A = 200$ in.^{2}

$\gamma = 0.0868$ lb/in.^{3} (150 lb/ft^3)

$E = 5.00 \times 10^6$ psi

Green oak cushion, grain horizontal

$A_c = 200$ in.^{2}

$E_c = 45{,}000$ psi (for properties of wood see Chapter IV)

$t_c = 3.0$ in.

$K = \frac{A_cE_c}{t_c} = 3.0 \times 10^6$ lb/in.

Steel ram

$W = 5000$ lb

$h = 36$ in.

$V = \sqrt{2gh} = 167$ in./sec

$g = 386$ in./sec^2

Calculations:

$$n = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}} = 224 \text{ sec}^{-1}$$

$$p = \sqrt{\frac{Kg}{W}} = 481 \text{ sec}^{-1}$$

Since $n<p$ Equation 8.1 of Case I applies.

$$\tan\,(t\sqrt{p^2-n^2}) = \frac{\sqrt{p^2-n^2}}{n} = \frac{425}{224} = 1.896$$

so $t\sqrt{p^2-n^2} = 62.2°$ or 1.085 radians

$t = .00255$ sec

Using Equation 8.1

$$\sigma_o \text{ max} = \frac{-KV}{A}\,\frac{e^{-nt}}{\sqrt{p^2-n^2}}\,\sin\,(t\sqrt{p^2-n^2})$$

$$= \frac{3 \times 10^6 \times 167\ e^{-.244 \times .00255}}{200 \times 425}\,(\sin 62.2°)$$

$\sigma_o \text{ max} = 2920$ psi

Using these equations, Tables 8.1 and 8.2 were developed to illustrate the effect of ram weight and velocity on driving stresses. Table 8.1 shows the variation of the driving stress (compressive) with the ram weight and ram velocity. It can be seen that the stress magnitude also increases with ram weight, however, this is usually not of serious consequence. Table 8.2 shows the variation of driving stress (compression) with ram weight and ram driving energy. At a constant driving energy the driving stress decreases as the ram weight increases. Therefore, it is better to obtain driving energy with a heavy ram and short stroke than use a light ram and large stroke.

3. When the top of the pile is not perpendicular to the longitudinal axis of the pile, the ram impacting force will be eccentric and may cause very high stress concentrations.

4. If the reinforcing steel in a concrete pile is not cut flush with the end of the pile, high stress concentrations may result in the concrete adjacent to the reinforcing. The ram impact force may be transmitted to the concrete through the projecting reinforcing steel.

5. Lack of adequate spiral reinforcing at the head of a concrete pile and also at the pile point may lead

TABLE 8.1. VARIATION OF DRIVING STRESS WITH RAM WEIGHT AND VELOCITY

Result from Equation 8.1 for 65 ft long concrete pile, 200 in.^{2} area, and 3 in. wood cushion. Stresses shown are maximum compression at pile head. $E_c = 45{,}000$ psi.

Ram Weight	Ram Velocity, ft/sec—Stroke, ft			
lb	11.4 - 2	13.9 - 3	16.1 - 4	18.0 - 5
2,000	1,790 psi	2,200 psi	2,540 psi	2,840 psi
5,000	2,380 psi	2,920 psi	3,380 psi	3,780 psi
10,000	2,830 psi	3,470 psi	4,000 psi	4,480 psi
20,000	3,250 psi	3,980 psi	4,600 psi	5,150 psi

TABLE 8.2. VARIATION OF DRIVING STRESS WITH RAM WEIGHT AND RAM ENERGY

Results from Equation 8.1 for 65 ft long concrete pile, 200 in.^{2} area, and 3 in. wood cushion. Stresses shown are maximum compression at pile head. E_c = 45,000 psi.

Ram Weight lb	Driving Energy ft - lb	
	20,000	40,000
2,000	4,010 psi	5,680 psi
5,000	3,380 psi	4,780 psi
10,000	2,830 psi	4,000 psi
20,000	2,290 psi	3,250 psi

to spalling or splitting. In prestressed concrete piles anchorage of the strands is being developed in these areas, and transverse tensile stresses are present. If no spiral reinforcing is used, the pile head may spall or split on impact of the ram.

6. Fatigue of the pile material can be caused by a large number of blows at a very high stress level.

7. If the top edges and corners of a concrete pile are not chamfered the edges or corners are likely to spall on impact of the ram.

Yielding of steel or spalling of concrete at the point of the pile can be caused by extremely hard driving resistance at the point. This type resistance may be encountered when founding the pile point on bed rock. Compressive stress under such driving conditions can be twice the magnitude of that produced at the head of the pile by the hammer impact (see Figure 8.2).

Tension. Transverse cracking of a concrete pile due to a reflected tensile stress wave is a complex phenomenon usually occurring in long piles (50 ft or over). It may occur in the upper end, midlength, or lower end of the pile. It can occur when driving in a very soft soil or when the driving resistance is extremely hard or rigid at the point such as in bearing on solid rock.

When a pile driver ram strikes the head of a pile or the cushion on top, a compressive stress is produced at the head of the pile. This compressive stress travels down the pile at a velocity

$$c = \sqrt{E/\rho}$$

where

c = velocity of the stress wave through the pile material in in./sec,

E = modulus of elasticity of the pile material in psi, and

ρ = mass density of the pile material in lb-sec^2/in.^{4}

The intensity of the stress wave (σ_o max.) can be determined by Equations 8.1, 8.2, or 8.3 and depends on the weight of the ram, velocity of the ram, stiffness of the cushion, and stiffness of the pile. Since in a given concrete pile the stress wave travels at a constant velocity (about 13,000 to 15,000 ft/sec) the length of the stress wave (L_s) will depend on the length of time (t_s) the ram is in contact with the cushion or pile head. A heavy ram will stay in contact with the cushion or pile head for a longer time than a light ram, thus producing a longer stress wave. If a ram strikes a thick soft cushion, it will also stay in contact for a longer period of time than when it strikes a thin hard cushion. For Case I (when $n<p$ which is typical for most practical concrete pile conditions) the length of the stress wave can be calculated by the equation which follows.

$$L_s = ct_s$$

or

$$L_s = \frac{c}{\sqrt{p^2 - n^2}}\,\pi \qquad (8.4)$$

where L_s = length of stress wave (in.) and

t_s = time of contact of ram (sec).

Figure 8.5(b) shows the compressive stress wave building up while the ram is in contact with the cushion. After the ram rebounds clear of the cushion, the compressive stress wave is completely formed and travels down the length of the pile as shown by Figure 8.5(c). When the compressive stress wave reaches the point of the pile, it will be reflected back up the pile in some manner depending on the soil resistance. If the point of the pile is experiencing little or no resistance from the soil, it will be reflected back up the pile as a tensile stress wave as shown in Figure 8.6(a). If the point of the pile is completely free, the reflected tensile wave will be of the same magnitude and length as the initial compressive wave. As shown in Figure 8.6(a) these two waves may overlap each other. The net stress at a particular point on the pile at a particular time will be the algebraic sum of the initial compressive (−) stress wave and reflected tensile (+) stress wave. Whether

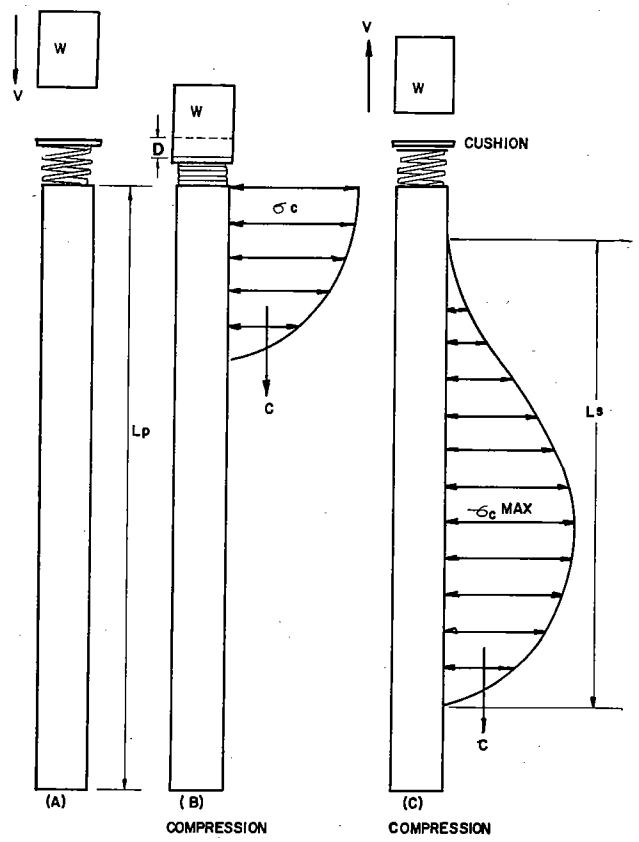


Figure 8.5. Idealized stress wave produced when ram strikes cushion at head of concrete pile.

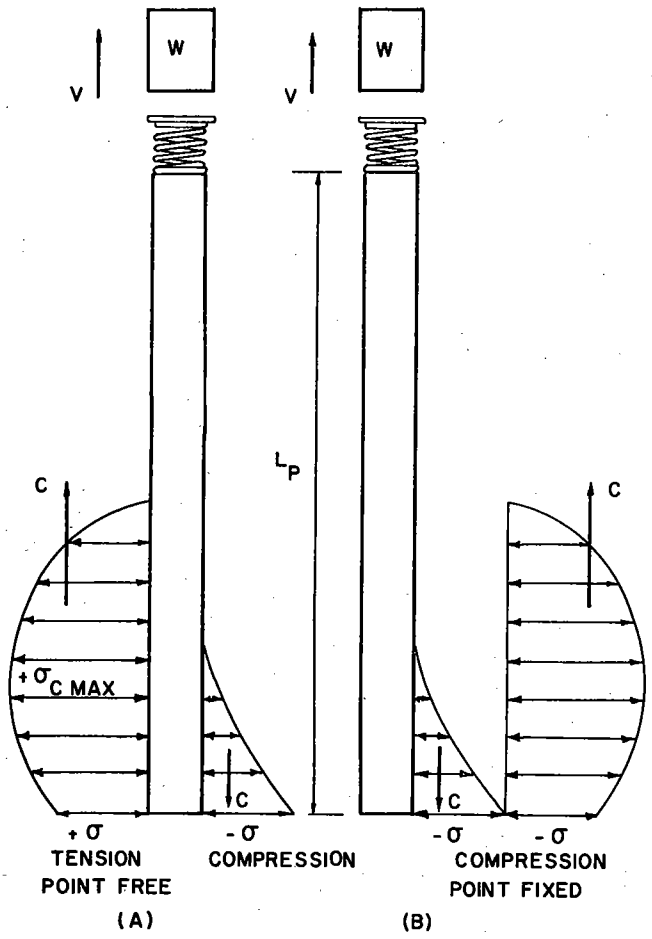


Figure 8.6. Reflection of stress wave on a long pile.

or not the pile will ever experience critical tensile stresses will depend on the pile length (L_p) relative to the length of the stress wave (L_s) and on material damping. If the pile is long compared to the length of the stress wave, critical tensile stresses may occur at certain points. When a heavy ram strikes a thick soft cushion, the stress wave may be around 150 ft in length. When a light ram strikes a thin hard cushion it may be only 50 or 60 ft in length.

The results of a theoretical study on ideal piles with the point free of soil resistance has shown that the maximum reflected tensile stress (σ_t max.) can be computed approximately by Equations 8.5 and 8.6 given below.

$$\sigma_t \text{ max.} = \sigma_o \text{ max.} \qquad (8.5)$$

when $$L_s/L_p \leq 2$$

and $$\sigma_t \text{ max.} = \frac{8\ \sigma_o \text{ max.}}{(L_s/L_p)^3} \qquad (8.6)$$

when $$L_s/L_p \geq 2$$

Figure 8.8 shows in dimensionless parameters how σ_t max. is affected by σ_c max., the length of the stress wave L_s, and the length of the pile L_p. The data points shown were computed using stress wave theory (Appendix A) and piles with a free point. These values are conservative since material damping of the pile and soil resistance will tend to reduce them.

If the point soil resistance is hard or very firm, the initial compressive stress wave traveling down the pile will be reflected back up the pile also as a compressive stress wave, as shown in Figure 8.6(b). If the point of the pile is fixed from movement, the reflected compressive stress wave will be on the same magnitude and length as the initial compressive stress wave. As shown in Figure 8.6(b) these two stress waves may overlap each other at certain points. The net compressive stress at a particular point at a particular time will be the algebraic sum of the initial compressive (—) stress wave and the reflected compressive (—) stress wave. (Note that under these conditions the maximum compressive stress at the pile point can be twice that produced at the pile head by ram impact.) Tensile stress will not occur here until the compressive stress wave is reflected from the free head of the pile back down the pile as a tensile stress wave (similar to the reflection shown at the free point in Figure 8.6(a)). It is possible for critical tensile stress to occur near the pile head in this case; however, damping characteristics of the surrounding soil may reduce the magnitude of this reflected tensile stress wave by this time. Such failures have occurred, however.

Figure 8.7 shows the reflection of the initial compressive (—) stress wave from the point of a relatively short pile. If the pile is short compared to the length of the stress wave (L_s) critical tensile stresses are not likely to occur. In Figure 8.7(a) the reflected tensile (+) stress wave overlaps the initial compressive (—) stress wave coming down the pile. Since the net stress at any point is the algebraic sum of the two, they tend to cancel each other and critical tension is not likely to occur. A similar phenomenon will occur when the reflected compressive (—) stress wave from the point is likely to find the ram still in contact with the pile head when it arrives there. In such a case, little or no reflected tensile stress wave will occur. In Figure 8.7(b) the initial compressive (—) stress wave is being reflected

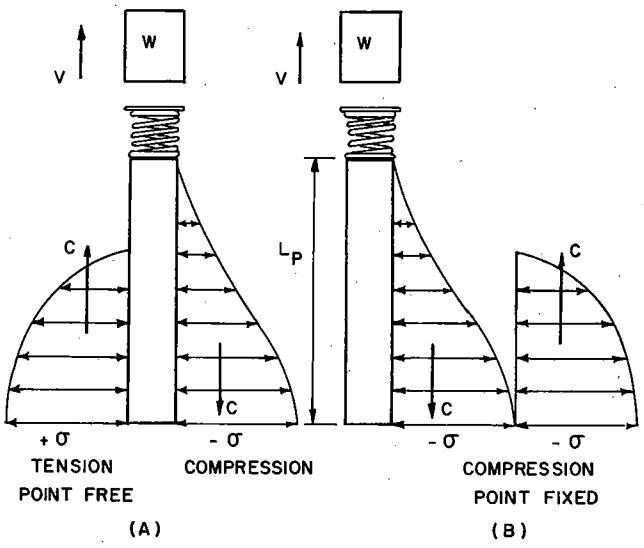


Figure 8.7. Reflection of stress wave along a short pile.

from the fixed point also as a compressive (—) stress wave. In this case also, little or no reflected tensile stress will occur.

The cases illustrated by Figures 8.6 and 8.7 are highly idealized and simplified, but they should indicate some of the basic factors which can cause tensile stress failures in concrete piles. In summary, tensile cracking of concrete piles can be caused by the following:

1. When insufficient cushioning material is used between the pile driver's steel helmet or cap and the concrete pile, a stress wave of high magnitude and of short length is produced, both characteristics being undesirable.

2. When a pile is struck by a ram at a very high velocity, or from a very high drop, a stress wave of high magnitude is produced. The stress is proportional to the ram velocity.

3. When the tensile strength of the concrete pile is too low to resist a reflected tensile stress, severe cracking can occur.

4. When little or no soil resistance at the point of long piles is present during driving, critical tensile stresses may occur in the lower half or near mid-length of the pile.

5. When hard driving resistance is encountered at the point of long piles, critical tensile stresses may occur in the upper half of the pile when the tensile stress is reflected from the pile head.

Torsion. Spiral or transverse cracking of concrete piles can be caused by a combination of torsion and reflected tensile stress. Diagonal tensile stress resulting from a twisting moment applied to the pile can by itself cause pile failure. However, if reflected tensile stresses occur during driving and they combine with diagonal tensile stress due to torsion the situation can become even more critical. Torsion on the pile may be caused by the following:

1. The helmet or pile cap fitting too tightly on the pile, preventing it from rotating slightly due to soil action on the embedded portion of the pile.

2. Excessive restraint of the pile in the leads and rotation of the leads.

8.8 Summary of Fundamental Driving Stress Considerations

From the preceding discussion some very basic and fundamental considerations have been revealed.

These fundamentals for good design and driving practices for piles and particularly for concrete piles can be summarized as follows:

1. Use adequate cushioning material between the pile driver's ram and the pile head. For concrete piles three or four inches of wood cushioning material (green oak, gum, pine or fir plywood, etc.) may be adequate for short (50 ft or less) piles with reasonably good point soil resistances. Six to eight inches or more of wood cushioning material may be required when driving longer concrete piles in very soft soil. The wood cushioning material should be placed on top of the pile with the grain horizontal and inspected to see that it is in good condition. When it begins to become highly compressed, charred or burned, it should be replaced. Some specifications require a new cushion on every pile. If driving is extremely hard, the cushion may have to be replaced several times during driving of a single pile. Use of an adequate cushion is usually a very economical means of controlling driving stresses.

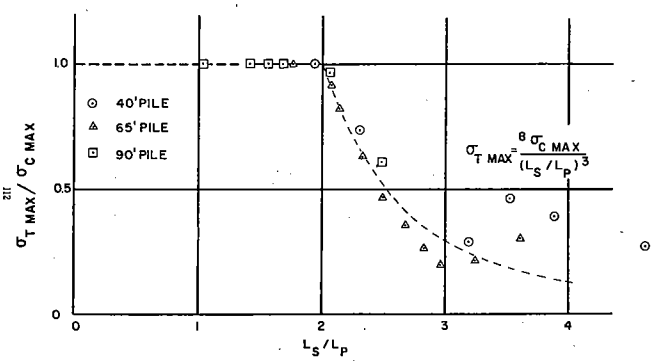


Figure 8.8. Effect of ratio of stress wave length on maximum tensile stress for pile with point free.

2. Driving stresses can be reduced by using a heavy ram with a low impact velocity (short stroke) to obtain the desired driving energy rather than a light ram with a high impact velocity (large stroke). Driving stresses are proportional to the ram impact velocity. The maximum compressive stress can be determined approximately by Equations (8.1), (8.2), or (8.3).

3. Reduce the ram velocity or stroke during early driving when light soil resistance is encountered. Anticipate soft driving or at the first sign of easy driving reduce the ram velocity or stroke to avoid critical tensile stresses. This is very effective when driving long concrete piles through very soft soil layers. When the point of the pile is free of resistance, the maximum tensile stress can be determined approximately by using Equations (8.5) or (8.6).

4. If pre-drilling or jetting is permitted in placing concrete piles, ensure that the pile point is well seated with reasonable soil resistance at the point before full driving energy is used. Driving and jetting of concrete piles should not be done simultaneously.

5. Ensure that the pile driving helmet or cap fits loosely around pile top so that the pile may rotate slightly without binding within the driving head to prevent torsional stress.

6. Ensure that the pile is straight and not cambered. High flexural stresses may result during driving of a crooked pile.

7. Ensure that the top of the pile is square or perpendicular to the longitudinal axis of the pile.

8. Cut ends of prestressing or reinforcing steel in concrete piles flush with the end of the pile head to prevent their direct loading by the ram stroke.

9. Use adequate spiral reinforcing at the head and tip of concrete piles to reduce tendency of pile to split or spall.

10. Use adequate amount of prestress in prestressed concrete piles or reinforcement in ordinary precast concrete piles to resist reflected tensile stresses.

11. Chamfer top and bottom edges and corners of concrete piles to reduce tendency of concrete to spall.

CHAPTER IX

Use of the Wave Equation for Parameter Studies

9.1 Introduction

The wave equation can be used effectively to evaluate the effects of the numerous parameters which affect the behavior of a pile during driving. For example: the determination of the optimum pile driver to drive a given pile to a specified soil resistance, the determination of the pile stiffness which will yield the most efficient use of a specified pile hammer and cushion assembly, the determination of the optimum cushion stiffness to make the most efficient utilization of a specified pile hammer and driving assembly to drive a specific pile, and to determine the effects of various distributions of soil side and point resistance on the pile bearing capacity, driving stresses, and penetration per blow.

9.2 Significant Parameters

The parameters which are known to significantly affect the behavior of a pile during driving are as follows:

(1) The pile driving hammer

- a. stiffness and weight of the pile driver's ram.
- b. the energy of the falling ram which is dependent upon the ram weight, the effective drop and the mechanical efficiency of the hammer.
- c. in the case of a diesel hammer, the weight of the anvil and the impulse of the explosive force.
- d. the stiffness of the capblock, which is dependent upon its mechanical properties, thickness, cross sectional area, and mechanical conditioning effects caused by repeated blows of the hammer.
- e. the weight of the pile helmet and the stiffness of the cushion between the helmet and the pile. In the case of steel piles the cushion is usually omitted.
- f. the coefficient of restitution of the capblock and cushion influence the shape of the wave induced in the pile and hence affects the magnitude of the stresses which are generated.

(2) The pile

- a. the length of the pile.
- b. the stiffness of the pile which is a function of its cross sectional area and the modulus of elasticity of the pile material.
- c. the weight of the pile, specifically the distribution of the weight.
- d. the existence of physical joints in the pile which cannot transmit tension.

(3) The soil

- a. soil quake at the point.
- b. soil quake in side friction.
- c. damping constant of the soil at the point.
- d. damping constant of the soil in friction.
- e. distribution of point and side frictional resistance.

9.3 Examples of Parameter Studies

The most notable parameter study which has been reported to date is that presented by Hirsch.[9.1] In that report, the results of 2,106 problems are presented graphically. This study was oriented toward providing information on the effects of ram weight and energy, stiffness of cushion blocks, length of pile, soil resistance, and distribution of soil resistance on the driving behavior of representative square concrete piles. Figures 9.1 and 9.2 show representative curves from this study. The results of this study have played a very significant part in formulating recommended driving practices for prestressed concrete piles.[9.2]

Parameter studies of this type have been used by others. McClelland, Focht, and Emrich[9.3] have used the wave equation to investigate the characteristics of available pile hammers for obtaining pile penetrations sufficient to support the heavy loads required in offshore construction. The parameters varied in this study were the pile length above the mud line, pile penetration, and the ratio of the soil resistance at the pile point to the total soil resistance, (see Figure 9.3 (a)). The results of this study enabled the authors to determine the pile driving limit versus the design load capacity as shown in Figure 9.4 (a) and (b). Figure 9.3 (b) shows the results of one study to determine the effects of varying the unembedded portion of a pile whose total length was held constant. Figure 9.3 (c) is for the same pile, but with the unembedded length held constant and the embedded length varied. Figure 9.3 (d) gives the results when the ratio of point soil resistance to total resistance is varied.

In Research Report 33-10[9.4] the writers used the wave equation to determine the soil damping values for various soils encountered in field tests. In this particular parameter study the pile, hammer-soil system was held constant and the soil damping values were varied. By generating an ultimate soil resistance, Ru (total) versus blows/in. curve the appropriate soil damping properties could be determined by comparing the computer generated solution with the measured data taken from a full-scale field test pile (see Figure 9.5). This study yielded representative values of the soil damping constants for the soil at the point of the pile and the soil in side friction.

It is not necessary that all parameters for a particular pile installation be known. For example, several

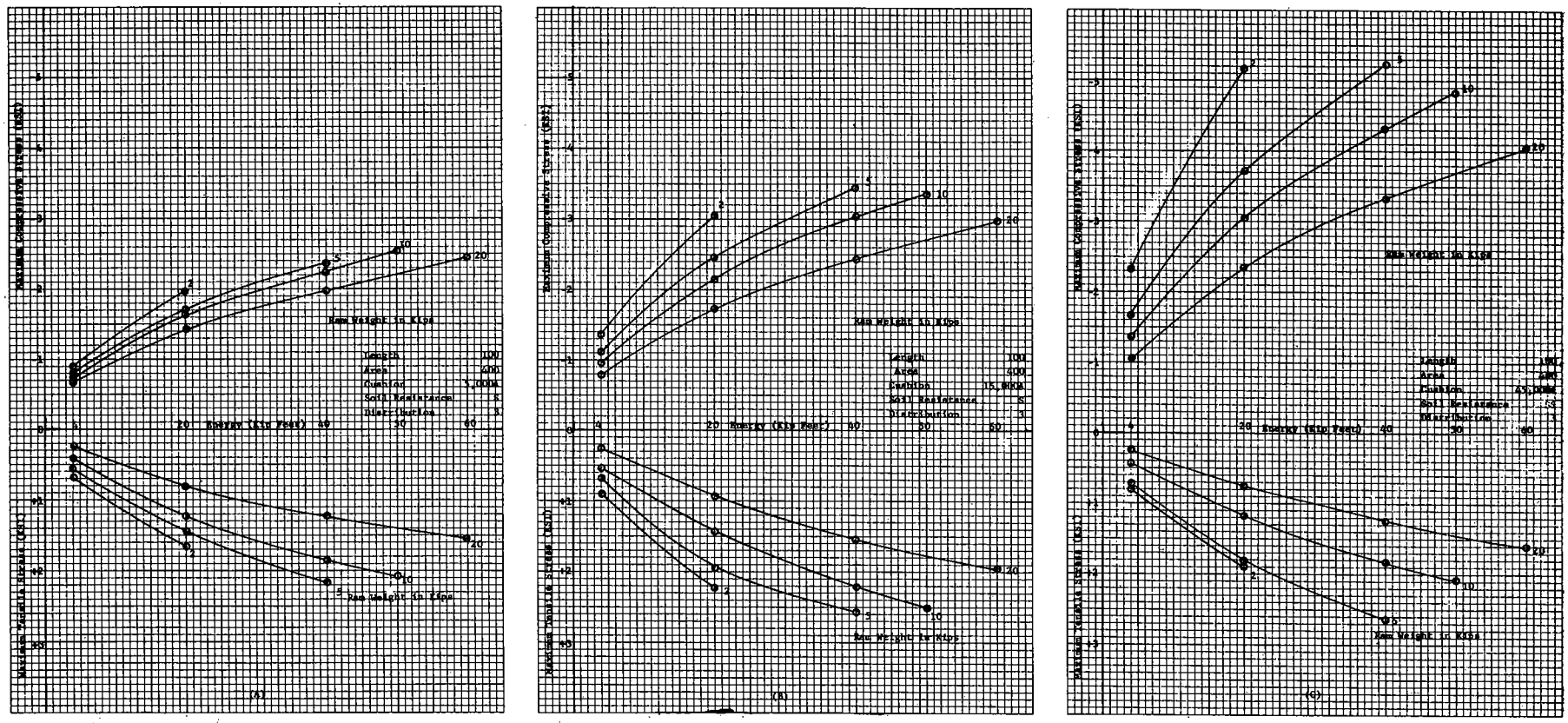


Figure 9.1. Effect of cushion stiffness, ram weight and driving energy on stresses. Square pile with uniformly distributed soil resistance of 107 tons.

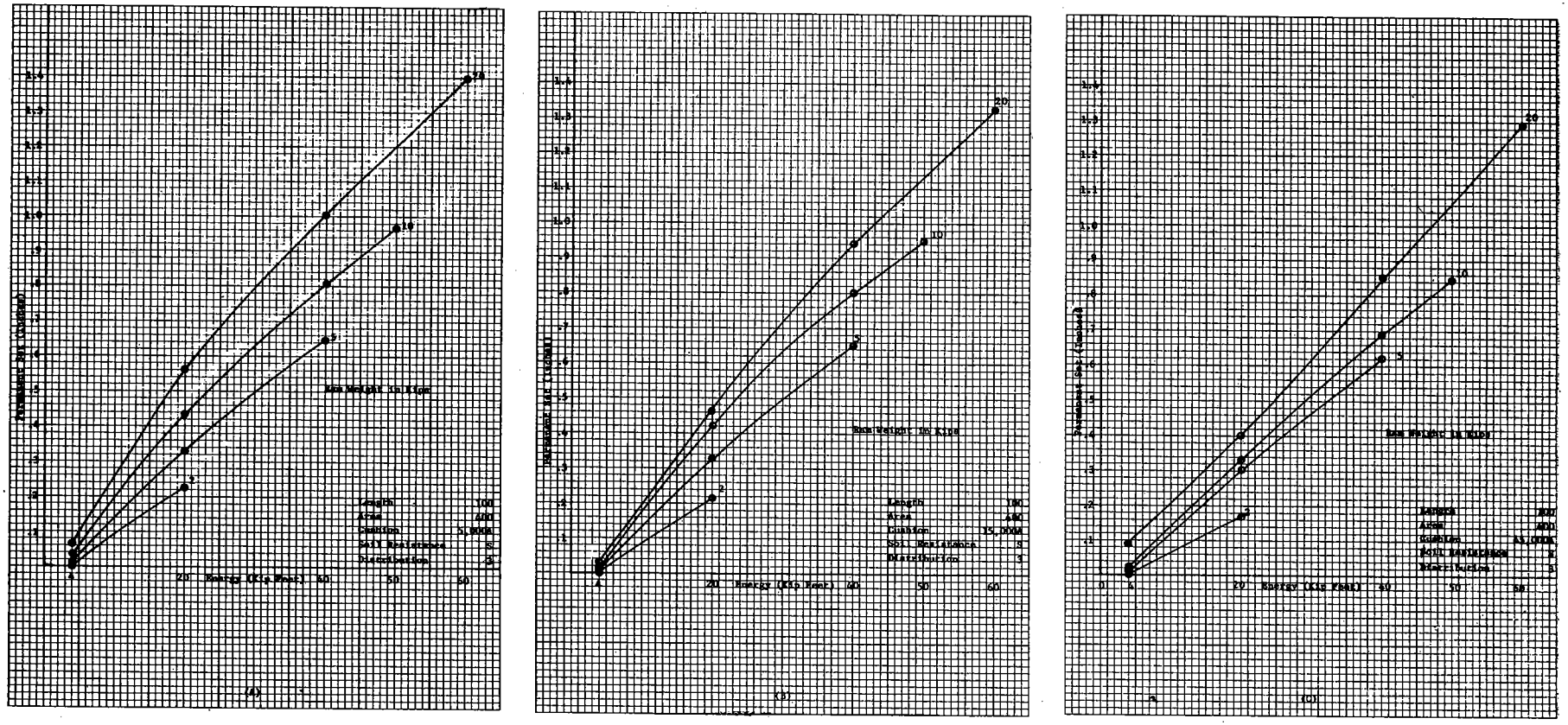


Figure 9.2. Effect of cushion stiffness, ram weight and driving energy on permanent set. Square pile with uniformly distributed soil resistance of 107 tons.

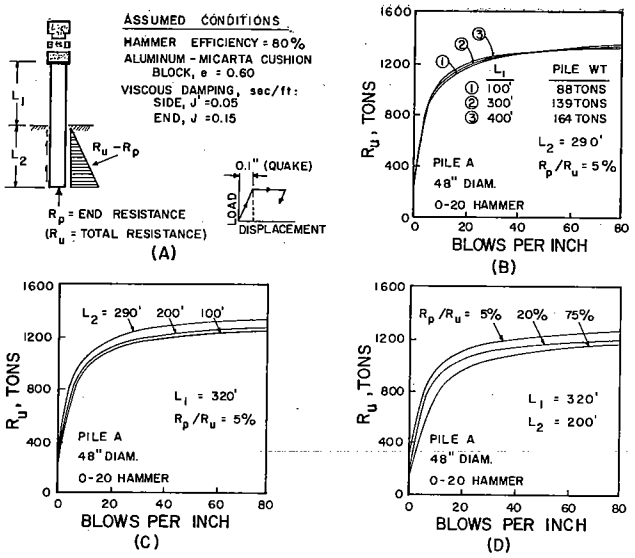


Figure 9.3. Computer analysis of pile hammer effectiveness in overcoming soil resistance, R_u, when driving pile under varying conditions: (A) computer input representing conditions of problem; (B) variations in pile length above ground; (C) variations in pile penetration; (D) variations in distribution of soil resistance, R_u (from Ref. 9.3).

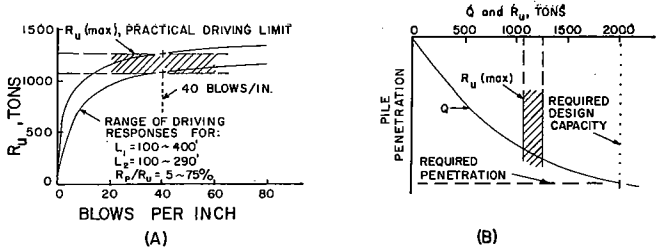


Figure 9.4. Evaluation of 0-20 hammer (60,000 ft-lb) for driving pile to develop ultimate capacity of 2000 tons: (A) summary of wave equation analysis (Fig. 9.3) establishing approximate pile driving limit, R_u (max); (B) comparison of R_u (max) with required design capacity (from Ref. 9.3).

problems can be solved in which the unknown parameter is varied between the upper and lower limits. These limits can usually be established with a reasonable amount of engineering judgement. Parameter studies of this type were conducted by the authors[9.5] in studies of the effect of ram elasticity and in the correlation and analysis of the Michigan pile data.

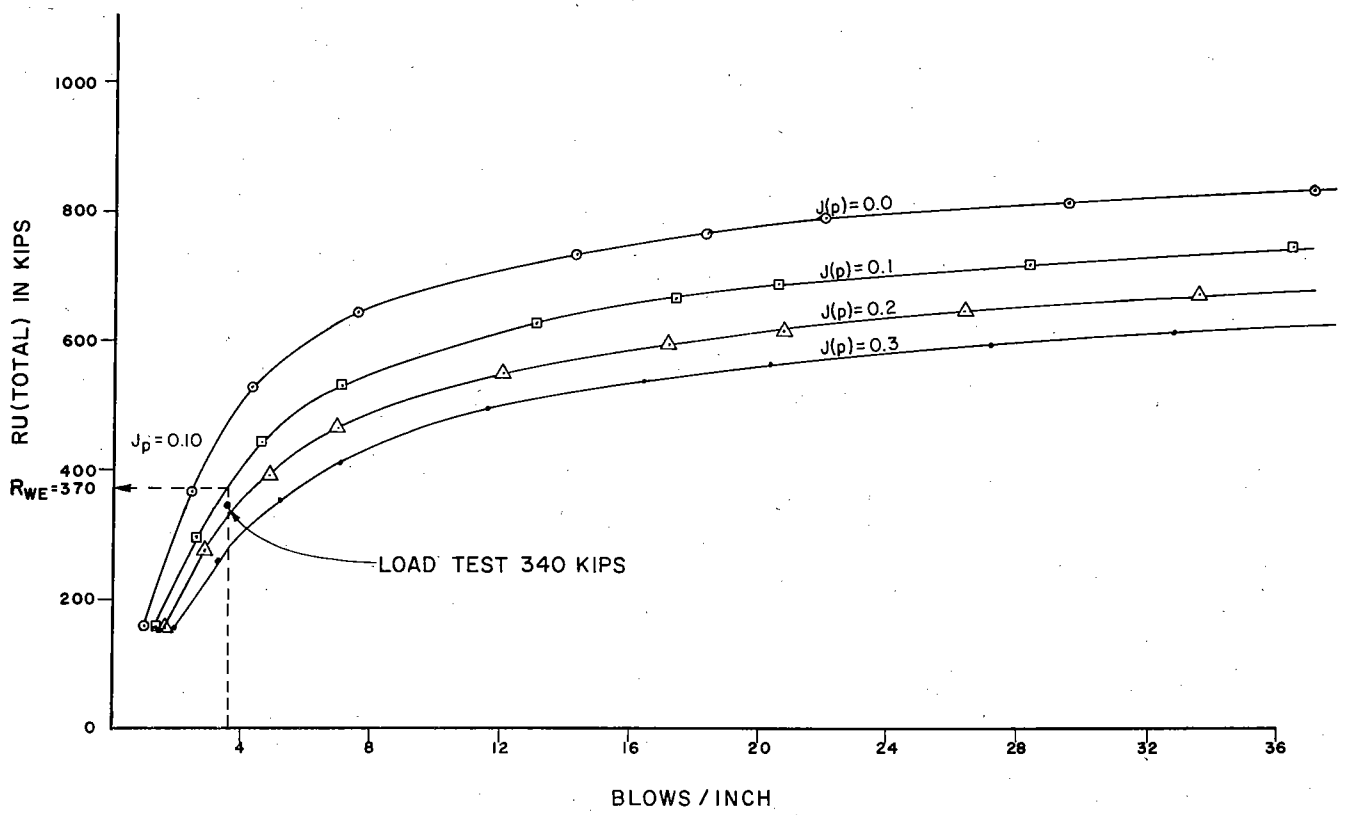


Figure 9.5. Blows/inch vs. R_u (total) for Arkansas load test pile 4.

CHAPTER X

Summary and Conclusions

The numerical computer solution of the one dimensional wave equation can be used with reasonable confidence for the analysis of pile driving problems. The wave equation can be used to predict impact stresses in a pile during driving and can also be used to estimate the static soil resistance on a pile at the time of driving from driving records.

By using this method of analysis, the effects of significant parameters such as type and size of pile driving hammer, driving assemblies (capblock, helmet, cushion block, etc.), type and size of pile, and soil condition can be evaluated during the foundation design stage. From such an analysis appropriate piles and driving equipment can be selected to correct or avoid expensive and time consuming construction problems such as excessive driving stresses or pile breakage and inadequate equipment to achieve desired penetration or bearing capacity.

A thorough discussion of the significant parameters involved in pile driving has been presented in this report. Some of the significant conclusions are as follows:

1. The elasticity of the ram was found to have a negligible effect on the solution in the case of steam, drop, and other hammers in which steel on steel impact between the ram and anvil is not present. However, in the case of diesel hammers, steel on steel impact does occur, and in this case, if the elasticity of the ram is disregarded, a conservative solution for driving stresses and permanent set results. When the elasticity of the ram is accounted for, maximum driving stresses and point displacements may be reduced as much as 20%.

2. Comparisons with the Michigan pile study indicated that a relatively simple yet accurate method of determining the energy output for pile driving hammers can be used. It was determined that for the cases investigated, a simple equation relating energy output for both diesel and steam hammers gave accurate results. This equation is

$$E = (W_R)\ (h)\ (e)$$

where

W_R = ram weight,

h = actual observed total ram stroke (or the equivalent stroke for double acting steam hammers and closed end diesel hammers), and

e = efficiency of the hammer in question.

The efficiencies determined during the course of this investigation were 100% for diesel hammers, 87% for double acting steam hammers, and 60% for single acting steam hammers. The writers feel that 60% was unusually low for the single acting hammer and would not recommend it as a typical value. An efficiency of 80% is believed to be more typical for the single acting steam hammer.

3. Comparisons between field test results and the numerical solution of the wave equation proposed by Smith were indeed encouraging. To date, the wave equation has been compared with the results of thousands of actual field tests performed throughout the country. Among the more significant were the comparisons with the Michigan pile study which dealt almost exclusively with extremely long, slender steel piles, a wide variety of prestressed concrete piles driven in the Gulf Coast area for the Texas Highway Department. Extensive correlation and research has and is being conducted by many contractors, petroleum companies, and others interested in the economical design of pile foundations.

4. The driving accessories significantly affect the piling behavior. For this reason, their selection should be carefully considered and analyzed whenever possible.

5. The effect of explosive pressure in diesel hammers varies greatly depending on the condition and characteristics of the hammer, anvil, helmet, cushion, pile, and soil resistance, especially regarding the increased permanent set per blow claimed by the manufacturer. In general, when the driving resistance is large (which is usually the case near the end of driving) the explosive pressure does not have a large effect on the pile penetration per blow.

6. Three methods were used to determine cushion properties in this report. These included actual full-scale cushion tests dynamically loaded between a ram and pile, tests performed using a cushion test stand in which a ram was dropped on the cushion specimen which had been placed on a concrete pedestal atop a large concrete base embedded in the floor, and finally static tests. It was found that the two dynamic testing methods used yielded almost identical results. It was also found that for a given material, the dynamic curves during the loading of the specimens were almost identical to the corresponding static curves. Static tests can be used to determine cushion stiffness, but not for the coefficient of restitution. Typical properties are presented in Chapter IV.

7. It was shown in Chapter IV that the stress-strain diagrams for the material used as cushions are not linearly related to compression. Instead, the curve is closely parabolic during the loading phase. However, use of the exact load-deformation curve for the cushion is both time consuming and cumbersome, and its use is relatively impractical.

8. It was found that the load-deformation diagram of the cushion could be idealized by a straight line having a slope based on the secant modulus of elasticity of the material.

9. The dynamic coefficient of restitution for the cushion materials studied herein were found to agree generally with commonly recommended values.

10. When the wave equation was compared with the results of laboratory experiments, the numerical solution to the wave equation proposed by Smith was found to be extremely accurate.

11. The effect of internal damping in concrete and

steel piles was found to be negligible for the cases studied, although, if necessary, it can be accurately accounted for by the wave equation.

12. The effect of pile dimensions on ability to drive the pile varied greatly. In general, it was found that the stiffer the pile, the greater soil resistance to penetration it can overcome.

13. The wave equation can be used to estimate soil resistance on a pile *at the time of driving*. Before long-term bearing capacity can be extrapolated from this soil resistance at the time of driving, however, engineers must consider the effect of soil "setup" or possible soil "relaxation" which is a function of time, soil type and condition, and size or type of pile, and other time effects which might be of importance.

APPENDIX A

Development of Equations for Impact Stresses in a Long, Slender, Elastic Pile

A1 Introduction

The study of the behavior of piling has received considerable attention in the past, but only since 1960 when Smith[1,3] adapted the general theory of stress wave propagation to pile driving problems, was it possible to accurately determine the magnitudes of stress induced in the pile during driving. Smith's method utilized a high-speed electronic digital computer to generate the solution, and while the calculations involved are simple, it can often prove to be an expensive method of solution. Therefore, it is the purpose of this Appendix to develop a series of equations from which a solution to a limited number of piles can be obtained without the use or expense of a computer.

A2 One Dimensional Wave Equation

Unlike a number of other approaches to the problem, wave theory does not involve a formula in the usual sense, but rather is based on the classical, one-dimensional wave equation.

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \qquad \text{(A.1a)}$$

where

c = the stress wave velocity = $\sqrt{E/\rho}$,
E = the modulus of elasticity of the pile material,
ρ = the mass density of the pile,

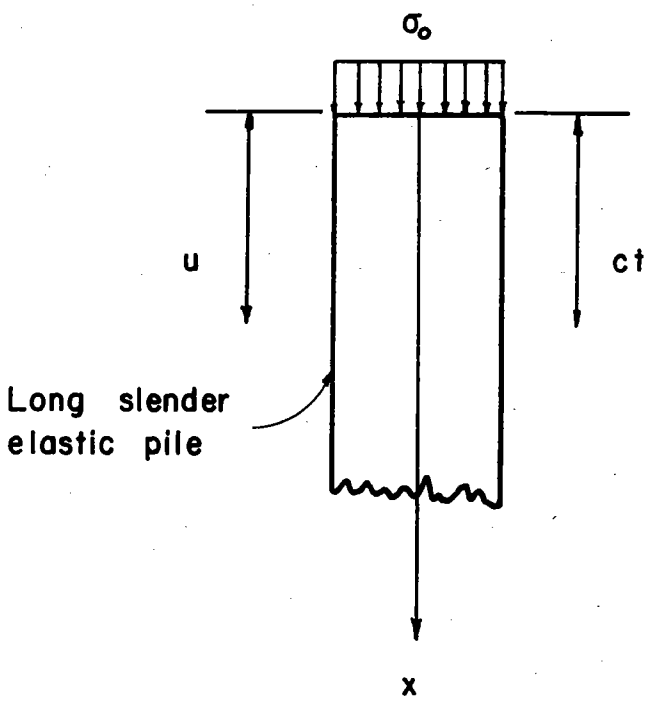


Figure A.1.

u = the longitudinal displacement of a point on the pile in the X-direction, and
t = time.

Figure A1 demonstrates the variables mentioned above.

It has been shown that any function $f(x + ct)$, or $f(x - ct)$ is a solution to the above differential equation. Further, the general solution is given by

$$u = f(x + ct) + f_1(x - ct)$$

From this solution, it can be shown that

$$\sigma = - \frac{E}{c} \frac{du}{dt} \qquad \text{(A.1b)}$$

where

σ = the stress in the pile.

The negative sign is used to denote compressive stress. Usually an elastic cushion is placed between the pile driving ram and the head of the pile in order to reduce the impact stresses in the pile (Figure A2). The falling ram first strikes the cushion which in turn applies a force to the head of the pile. The sum of the forces on the hammer are given by

$$F_v = W - P = M \frac{d^2 z}{dt^2}$$

where

M = the ram mass,
W = the ram weight,
P = force exerted between the head of the pile and the cushion,
t = time, and
z = displacement of the ram.

This equation can now be written in the form

$$P = M \left(g - \frac{d^2 z}{dt^2} \right) \qquad \text{(A.2)}$$

where

g = acceleration due to gravity, and
$W = Mg$

Considering the ram as being infinitely stiff, the displacement of the ram, z, and the displacement of the head of the pile u_o defines the total compression in the cushion at any time. Therefore,

$$\text{Cushion compression} = z - u_o$$

Assuming the cushion to be linearly elastic, with a spring constant of K lb per in., then the cushion compression is given by:

$$\text{Cushion compression} = P/K.$$

Therefore,

$$z = u_o + \frac{P}{K} \qquad \text{(A.3)}$$

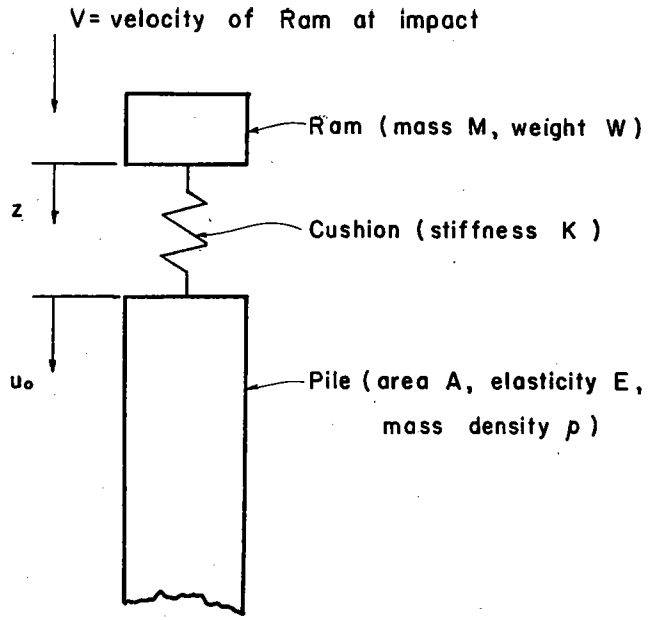


Figure A.2.

Differentiating Equation A.3 with respect to time we find

$$\frac{d^2z}{dt^2} = \frac{d^2u_o}{dt^2} + \left(\frac{1}{K}\right)\frac{d^2P}{dt^2} \qquad (A.4)$$

Combining Equation A.2 and A.4 gives

$$P = M\left[g - \frac{d^2u_o}{dt^2} - \frac{1}{K}\frac{d^2P}{dt^2}\right] \qquad (A.5)$$

Noting Equation A.1(b) it follows that

$$\sigma_o = -\frac{E}{c}\frac{du_o}{dt} \qquad (A.6)$$

where

σ_o = the stress at the pile head, and

u_o = the displacement of the pile head.

Since σ_o equals $-\frac{P}{A}$, where A is the cross-sectional area of the pile, it is seen that

$$P = \frac{AE}{c}\frac{du_o}{dt} \qquad (A.7)$$

Differentiating Equation A.7 twice with respect to time gives

$$\frac{d^2P}{dt^2} = \frac{AE}{c}\frac{d^3u_o}{dt^3} \qquad (A.8)$$

Substituting Equations A.7 and A.8 into Equation A.5 yields

$$\frac{AE}{c}\frac{du_o}{dt} = M\left[g - \frac{d^2u_o}{dt^2} - \frac{AE}{cK}\frac{d^3u_o}{dt^3}\right]$$

Since V_o is equal to $\frac{du_o}{dt}$, where V_o is the velocity of the head of the pile, it is found that

$$\frac{AEV_o}{c} = M\left[g - \frac{dV_o}{dt} - \frac{AE}{cK}\frac{d^2V_o}{dt^2}\right] \qquad (A.9)$$

Equation A.9 may be rewritten in the following form:

$$\frac{Md^2V_o}{dt^2} + \frac{McK}{AE}\frac{dV_o}{dt} + KV_o = \frac{cKMg}{AE} \qquad (A.10)$$

which is the basic differential equation to be solved.

A3 Boundary Conditions

In order to satisfy the boundary conditions, it is necessary to set $V_o = 0$ at time $t = 0$. Further, at $t = 0$ we find that

$$\dot{z} = V$$

and

$$\dot{u}_o = 0$$

where V is the initial ram velocity and the dotted quantities denote differentiation with respect to time. From Equation A.3, we see that at $t = 0$,

$$P = K(z - u_o)$$

Differentiating this equation with respect to time, we find

$$\dot{P} = K(\dot{z} - \dot{u}_o)$$

and

$$\dot{P} = KV \text{ at } t = 0$$

From Equation A.7, we note that $P = \frac{AE}{c}V_o$, so that

$$\dot{P} = \frac{AE}{c}\dot{V}_o$$

Therefore, at time $t = 0$,

$$\dot{V}_o = \frac{KVc}{AE}$$

In summary, the boundary conditions at time $t = 0$ are given by Equations A.11 and A.12.

$$V_o = 0 \qquad (A.11)$$

$$\dot{V}_o = \frac{KVc}{AE} \qquad (A.12)$$

A4 Solving the Basic Differential Equation

The general solution of the differential Equation A.10 is obtained by combining the homogeneous solution V_h, and the particular solution Vp.

The particular solution to Equation A.10 is given by

$$Vp = \frac{cMg}{AE} \qquad (A.13)$$

The homogeneous solution to Equation A.10 is determined as follows:

$$\ddot{V}_h + 2n\dot{V}_h + p^2V_h = 0 \qquad (A.14)$$

where

$$n = \frac{cK}{2AE} = \frac{K}{2A}\sqrt{\frac{g}{E\rho}}$$

$$p^2 = \frac{K}{M} = \frac{Kg}{W}$$

$$\ddot{V}_h = \frac{d^2V_h}{dt^2}$$

$$\dot{V}_h = \frac{dV_h}{dt}$$

We shall now investigate solutions for this case having the form

$$V_h = Ae^{mt} \qquad (A.15)$$

By substituting Equation A.15 into Equation A.10, we obtain

$$m^2 + 2nm + p^2 = 0$$

and therefore

$$m = -n \pm \sqrt{n^2 - p^2} \qquad (A.16)$$

Three possible variations to this solution will now be considered.

CASE I ($n < p$)

The first case is where n is less than p. When n is less than p, the roots of Equation A.17 are given by

$$m = -n \pm i\sqrt{p^2 - n^2}$$

The homogeneous solution to Equation A.11 then becomes

$$V_h = e^{-nt}\left(A_1 \sin t\sqrt{p^2 - n^2} + A_2 \cos t\sqrt{p^2 - n^2}\right)$$

And the general solution is given by

$$V_o = V_h + \frac{cMg}{AE} \qquad (A.17)$$

Applying the boundary conditions noted by Equations A.14 to A.17 we find

$$0 = A_2 + \frac{cMg}{AE}$$

$$A_2 = \frac{-cMg}{AE}$$

Applying the boundary conditions of Equation A.12 to Equation A.17 results in

$$\dot{V}_o = -ne^{-nt}(A_1 \sin t\sqrt{p^2 - n^2} + A_2 \cos t\sqrt{p^2 - n^2}) + e^{-nt}(A_1\sqrt{p^2 - n^2}\cos t\sqrt{p^2 - n^2} - A_2\sqrt{p^2 - n^2}\sin t\sqrt{p^2 - n^2})$$

$$\frac{KVc}{AE} = -nA_2 + A_1\sqrt{p^2 - n^2}$$

$$A_1 = \left[\frac{KVc}{AE} - \frac{ncMg}{AE}\right]\frac{1}{\sqrt{p^2 - n^2}}$$

or

$$A_1 = \frac{c}{AE\sqrt{p^2 - n^2}}\,[KV - nMg]$$

Rewriting Equation A.17 using the values of A_1, as noted above, yields

$$V_o = \frac{cKV}{AE\sqrt{p^2 - n^2}}\,e^{-nt}\sin t\sqrt{p^2 - n^2} + \frac{cMg}{AE}\left[1 - e^{-nt}\left[\cos t\sqrt{p^2 - n^2} + \frac{n}{\sqrt{p^2 - n^2}}\sin t\sqrt{p^2 - n^2}\right]\right] \qquad (A.18)$$

Substituting Equation A.18 into Equation A.6 gives the final solution for the stress at the head of the pile when the value of n is less than p.

$$\sigma_o = \frac{-KVe^{-nt}}{A\sqrt{p^2 - n^2}}\sin t\sqrt{p^2 - n^2} + \frac{W}{A}\left[1 - e^{-nt}\left(\cos t\sqrt{p^2 - n^2} + \frac{n}{\sqrt{p^2 - n^2}}\sin t\sqrt{p^2 - n^2}\right)\right] \qquad (A.19)$$

where

$$n = \frac{cK}{2AE} = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}}$$

$$p = \sqrt{\frac{Kg}{W}}$$

Equation A.19 gives the solution for the stress at the head of the pile at all times after impact.

CASE II ($n = p$)

The second case is when n is equal to p in which case the solution of the homogeneous differential equation (Equation A.14) assumes the form

$$V_h = A_1 e^{-nt} + A_2 te^{-nt}$$

$$V_h = e^{-nt}(A_1 + A_2 t) \qquad (A.20)$$

The complete solution for this case is given by

$$V_o = V_h + V_p$$

$$V_o = e^{-nt}(A_1 + A_2 t) + \frac{cMg}{AE} \qquad (A.21)$$

Substituting the required boundary conditions given by Equation A.11 and A.12, we find that

$$0 = A_1 + \frac{cMg}{AE}$$

$$A_1 = \frac{-cMg}{AE}$$

Using the boundary condition given by Equation A.12, we determine

$$\dot{V}_o = -ne^{-nt}A_1 - ne^{-nt}A_2 t + A_2 e^{-nt}$$

When t is equal to 0, we find that

$$+ \frac{ncMg}{AE} + A_2 = \frac{KVc}{AE}$$

$$A_2 = \frac{KVc}{AE} - \frac{ncMg}{AE}$$

$$A_2 = \frac{c}{AE}(KV - nMg)$$

Rewriting Equation A.21, using the values of A_1 and A_2, as given above, yields

$$V_o = e^{-nt}\left[\frac{-cMg}{AE} + \frac{ct}{AE}(KV - nMg)\right] + \frac{cMg}{AE} \qquad (A.22)$$

Substituting Equation A.22 into Equation A.6 gives

$$\sigma_o = \frac{-t}{A}(KV - nMg)\, e^{-nt} - \frac{Mg}{A}(1 - e^{-nt})$$

or:

$$\sigma_o = \frac{-t}{A}(KV - nW)\, e^{-nt} - \frac{W}{A}(1 - e^{nt}) \qquad (A.23)$$

where

$$n = \frac{cK}{2AE} = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}},$$

$$p = \sqrt{\frac{Kg}{W}}, \text{ and}$$

γ = unit weight of pile material

Equation (A.23) gives the compressive stress at the head of the pile, as a function of time for the case when n is equal to p.

CASE III (n > p)

The third and final case is where n is greater than p. For this condition, the solution of the homogeneous differential equation, given by Equation (A.14), assumes the form

$$V_h = e^{-nt}\left[A_1\, e^{t\sqrt{n^2 - p^2}} + A_2\, e^{t\sqrt{n^2 - p^2}}\right]$$

or

$$V_h = e^{-nt}\left[A_1 \sinh t\sqrt{n^2 - p^2} + A_2 \cosh t\sqrt{n^2 - p^2}\right]$$

The general solution then becomes

$$V_o = V_h + V_p$$

$$V_o = e^{-nt}\left(A_1 \sinh t\sqrt{n^2 - p^2} + A_2 \cosh t\sqrt{n^2 - p^2}\right) + \frac{cMg}{AE} \qquad (A.24)$$

Applying the boundary conditions required by Equation A.11 yields

$$0 = A_2 + \frac{cMg}{AE}$$

$$A_2 = \frac{-cMg}{AE}$$

Substituting the required boundary condition given by Equation A.12 then gives

$$\dot{V}_o = -ne^{-nt}\left(A_1 \sinh t\sqrt{n^2 - p^2} + A_2 \cosh t\sqrt{n^2 - p^2}\right) + e^{-nt}\left(A_1\sqrt{n^2 - p^2}\cosh t\sqrt{n^2 - p^2} + A_2\sqrt{n^2 - p^2}\sinh t\sqrt{n^2 - p^2}\right)$$

then:

$$\frac{KVc}{AE} = -nA_2 + A_1\sqrt{n^2 - p^2}$$

and:

$$A_1 = \left[\frac{KVc}{AE} - \frac{ncMg}{AE}\right]\frac{1}{\sqrt{n^2 - p^2}}$$

Rewriting Equation A.24 gives

$$V_o = \frac{KVc\ e^{-nt}}{AE\sqrt{n^2 - p^2}}\sinh t\sqrt{n^2 - p^2} + \frac{cMg}{AE}\left[1 - e^{-nt}\left(\cosh t\sqrt{n^2 - p^2} + \frac{n \sinh t\sqrt{n^2 - p^2}}{\sqrt{n^2 - p^2}}\right)\right] \qquad (A.25)$$

Substituting Equation A.25 into Equation A.6 gives

$$\sigma_o = \frac{-KV}{A\sqrt{n^2 - p^2}}\, e^{-nt} \sinh t\sqrt{n^2 - p^2} \qquad (A.26)$$

$$\frac{-W}{A}\left[1 - e^{-nt}\left(\cosh t\sqrt{n^2 - p^2} + \frac{n}{\sqrt{n^2 - p^2}}\sinh t\sqrt{n^2 - p^2}\right)\right] \qquad (A.26)$$

where

$$n = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}}, \text{ and}$$

$$p = \sqrt{\frac{Kg}{W}}$$

Equation A.26 gives the stress at the head of the pile as a function of time in the case where n is greater than p.

A5 Maximum Compressive Stress at the Head of the Pile

To compute the maximum compressive stress at the pile head, Equations A.19, A.23, and A.26 are required.

Numerical studies of these equations have shown that if the last term in each equation is omitted, little accuracy is lost, and the expression becomes relatively simple. Since it is necessary to know the time, t, at which the maximum stress occurs, Equations A.19, A.23, and A.26 will be differentiated with respect to time and set equal to 0. This in turn will allow the maximum

stress to be found. The following notations are again used:

W = the ram weight (lb)
V = the ram impact velocity (in./sec) = $\sqrt{2gh}$,
K = cushion stiffness (lb per in.) = $\frac{A_c E_c}{t_c}$
t = time (seconds)
A = the cross-sectional area of the pile (in.^{2})
E = modulus of elasticity of the pile (psi)
γ = unit weight of the pile (lb per in.^{3})
g = acceleration due to gravity (386 in. per sec^2)
h = the free fall of the ram (in.)
A_c = the cross-sectional area of the cushion (in.^{2})
E_c = the modulus of elasticity of the cushion (psi)
t_c = cushion thickness (in.)

$$n = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}}$$

$$p = \sqrt{\frac{Kg}{W}}$$

In order to further simplify the solutions, the following approximate equations for the maximum compressive stress are presented:

Case 1 (where n is less than p)

$$\sigma_o \text{ (max)} = \frac{-KV}{A\sqrt{p^2 - n^2}} e^{-nt} \sin (t\sqrt{p^2 - n^2}) \qquad \text{(A.27)}$$

where t is given by the equation

$$\tan (t\sqrt{p^2 - n^2}) = \frac{\sqrt{p^2 - n^2}}{n}$$

Case 2 (where n is equal to p)

$$\sigma_o \text{ (max)} = -\left[\frac{KV}{nA} - \frac{W}{A}\right] e^{-1} \qquad \text{(A.28)}$$

where the value of t was given by

$$t = \frac{1}{n}$$

Case 3 (where n is greater than p)

$$\sigma_o \text{ (max)} = \frac{-KV}{A\sqrt{n^2 - p^2}} e^{-nt} \sinh (t\sqrt{n^2 - p^2}) \qquad \text{(A.29)}$$

where t is found from the expression

$$\tanh t\sqrt{n^2 - p^2} = \frac{\sqrt{n^2 - p^2}}{n}$$

Equations A.27, A.28, and A.29 can be used to determine the maximum compressive stress at the head of the pile. In most practical pile problems, n will be less than p, and Equation A.27 will most often be used, although this is not always the case.

For a given pile these equations can be used to determine the proper combination of ram weight, W, ram velocity, V, and the required cushion stiffness, K, in order to prevent excessive stresses at the head of the pile. In most cases, there is some minimum amount of driving energy which must be available to drive the pile. For example, the maximum energy output available to a drop hammer is given by its kinetic energy at the instant of impact. Therefore,

$$\text{K.E.} = W\frac{V^2}{2g}$$

should be equal to or greater than the energy required. It would appear that the most efficient way to increase hammer energy would be by increasing the ram velocity V. However, Equations A.27, A.28, and A.29 show that the maximum compressive stress at the head of the pile will increase proportionally with velocity. On the other hand, to increase driving energy the maximum compressive stress at the head of the pile increases slightly as W increases. It is therefore desirable (considering driving stresses) to increase the ram weight, W, if the pile driving situation requires that the driving energy be increased. Once the ram weight and its velocity at impact have been selected, the spring rate of the cushion (K) can be varied to hold the maximum compressive stress within allowable limits.

A6 Length of the Stress Wave

It is known that the magnitude of the reflected stresses in a pile will be a function of the length of the stress wave and the length of the pile. The length of this stress wave is easily found from Equations A.19, A.23, and A.26.

If the last term is again omitted in each of these equations, little accuracy is lost and relatively simple expressions are obtained for the stress at the head of the pile. Omitting the last term in Equation A.19 yields

$$\sigma_o = \frac{-KV}{A\sqrt{p^2 - n^2}} e^{-nt} \sin t\sqrt{p^2 - n^2} \qquad \text{(A.30)}$$

Equation A.30 is seen to equal 0 at time t equals 0 and again at

$$t = \frac{\pi}{\sqrt{p^2 - n^2}}$$

Thus, the second of these equations gives the duration of the impulse stress.

Noting Equation A.1 a, the stress wave velocity, c, is found to be

$$c = \sqrt{\frac{E}{\rho}}$$

The length of the stress wave, L_s, is then obtained from

$$L_s = ct = \frac{\pi\sqrt{\frac{E}{\rho}}}{\sqrt{p^2 - n^2}}$$

$$L_s = \pi\sqrt{\frac{Eg}{\gamma(p^2 - n^2)}} \text{ for } n < p \qquad \text{(A.31)}$$

Similarly use Equations A.23 and A.26 to establish that when n = p and n > p the stress wave is infinitely long

$$L_s = \infty$$

APPENDIX B

Wave Equation Computer Program Utilization Manual

B1 Introduction

This appendix describes the utilization of the computer program for the application of the one-dimensional wave equation to the investigation of a pile during driving.

The program can be used to obtain the following information for one blow of the pile driver's ram for any specified soil resistance:

1. Stresses in the pile.
2. Displacement of the pile (penetration per blow).
3. Static load capacity of the pile for specified soil resistance and distribution. This capacity is the static resistance at the time of driving and does not reflect soil set-up due to consolidation.

The program is valuable in that system parameters ignored before (in pile driving formulas) can be included, and their effects investigated. It makes possible an engineering evaluation of driving equipment and pile type, rather than relying only upon experience and judgement.

In order to simulate a given system, the following information is essential:

1. Pile driver.
   a) energy and efficiency of hammer,
   b) weight and dimensions of ram,
   c) weight and dimensions of anvil (if included),
   d) dimensions and mechanical properties of capblocks,
   e) weight and dimensions of pile cap helmet,
   f) and dimensions and mechanical properties of cushion.
2. Dimensions, weight, and mechanical properties of the pile.
3. Soil medium.
   a) embedment of pile,
   b) distribution of frictional soil resistance over the embedded length of the pile expressed as a percentage of the total static soil resistance,
   c) Point soil resistance expressed as a percentage of the total static soil resistance,
   d) ultimate elastic displacement for the soil on the side and point of pile,
   e) and the damping constant for the soil on the side and point of the pile.

It should be recognized that the solution obtained with the program represents the results for one blow of the hammer at the specified soil embedment and soil resistance.

The techniques for idealization can be categorized in three groups:

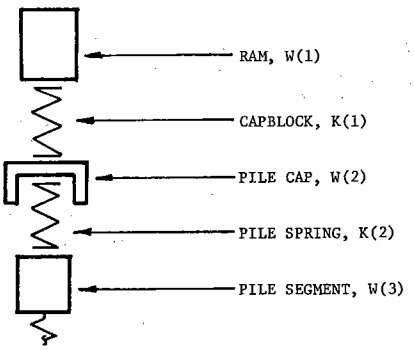
1. the hammer and driving accessories,
2. the pile, and
3. the soil.

B2 Idealization of Hammers

The program is formulated to handle drop hammers, single, double, and differential acting steam hammers and diesel hammers that operate on the head of the pile. The techniques presented in this section are general in scope and are presented for illustration. Appendix B gives the idealizations and pertinent information for the most common hammers.

Figures B1 through B3 describe the idealization for the following cases:

1. Case I —Ram, capblock, pile cap, and pile (Figure B1).
2. Case II —Ram, capblock, pile cap, cushion, and pile (Figure B2).
3. Case III—Ram, anvil, capblock, pile cap, and pile (Figure B3).



Calculations for idealization

W(1) = weight of ram, (lb)

$K(1) = \frac{A(1)\ E(1)}{L(1)}$, stiffness of the capblock, (lb/in)

Where

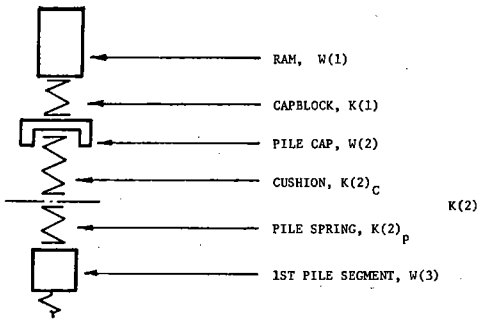
A(1) = cross sectional area of the capblock, (in^2)

E(1) = modulus of elasticity of the capblock, (psi)

L(1) = thickness of the capblock, (in)

Note: See Table 4.1 for capblock properties.

Figure B.1. Case I—ram, capblock, and pile cap.



Calculations for idealization

W(1) = Weight of ram, (lb)

K(1) = Stiffness of the Capblock, (lb/in.)

$K(2)_C$ = Stiffness of cushion, (lb/in.)

$K(2)_p$ = Stiffness of pile spring, (lb/in.)

$K(2) = \frac{K(2)_C \; K(2)_p}{K(2)_C + K(2)_p}$, combined stiffness of $K(2)_C$ and $K(2)_p$ in series.

Note: See Table 4.1 for capblock and cushion properties.

$K_C = \frac{AE}{L}$

where

A = cross-section area of cushion, $in.^2$

E = secant modulus of elasticity of cushion material, psi

L = thickness of cushion, in.

Figure B.2. Case II — ram, capblock, pile cap, and cushion.

B3 Ram Kinetic Energies

The kinetic energy of the ram for specific hammer types can be calculated as follows:

1. Drop hammers and single acting steam hammers:

$$E_H = W(1)\ (h)\ (e_f) \qquad (B.1)$$

where

E_H = ram kinetic energy, (ft-lb)

$W(1)$ = ram weight, (lb)

h = ram stroke, (ft)

e_f = hammer mechanical efficiency (usually between 0.75 and 0.85 for most single acting hammers).

2. Differential and double-acting steam hammers:

$$E_H = h \left[1 + \frac{p_{actual}}{p_{rated}} \cdot \frac{W(h)}{W(1)} \right] W(1)\ e_f \qquad (B.2)$$

where

h = actual ram stroke, (ft)

p_{actual} = actual steam pressure, (psi)

p_{rated} = manufacturers rated steam pressure, (psi)

$W(h)$ = hammer housing weight, (lb)

$W(1)$ = ram weight, (lb)

e_f = efficiency is approximately 85% for these hammers.

3. Diesel hammers:

$$E_H = W(1)\ (h_e - C) \cdot (e_f) \qquad (B.3)$$

where

h_e = actual ram stroke for open-end hammers, and the effective stroke (includes effect of bounce chamber pressure) for closed-end hammers, (ft). The energy E_H for the closed-end Link Belt hammers can be read directly from the manufacturer's chart using bounce chamber pressure),

e_f = efficiency of diesel hammers is approximately 100%

C = distance from bottom-dead-center of anvil to exhaust ports, (ft).

Work done on the pile by the diesel explosive force is automatically accounted for by using an explosive pressure (see Sample Problem and Table 2).

Calculations for idealization

$W(1)$ = weight of ram, (lb)

$K(1) = \frac{A(1)\ E(1)}{L(1)}$, stiffness of the capblock, (lb/in.)

Where

$A(1)$ = cross sectional area of the capblock, (in^2)

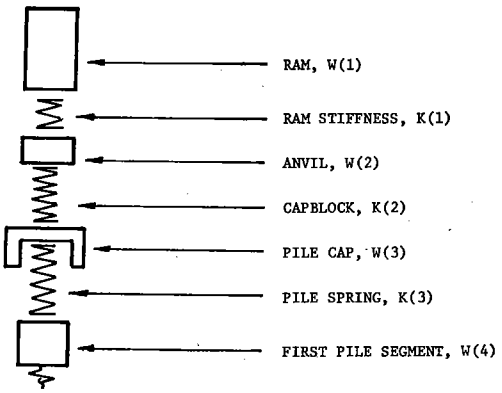
$E(1)$ = modulus of elasticity of the capblock (psi)

$L(1)$ = thickness of the capblock, (in)

Note: See Table 4.1 for capblock properties.

Calculations for idealization

$W(1)$ = Weight of ram, lb)



Calculations for idealization

W(1) = Weight of ram, (lb.)

$K(1) = \frac{A(1)\ E(1)}{L(1)}$, the stiffness of the ram, (lb./in.)

where A(1) = ram cross sectional area, (in.)

E(1) = modulus of elasticity of ram material, (psi)

L(1) = length of ram, (in.)

This calculation assumes that the pile cap and anvil are rigid.

Figure B.3. Case III—ram, anvil, capblock, and pile cap.

$K(1)$ = Stiffness of the Capblock, (lb/in.)

$K(2)_C$ = Stiffness of cushion, (lb/in.)

$K(2)_p$ = Stiffness of pile spring, (lb/in.)

$K(2) = \frac{K(2)_C \quad K(2)_p}{K(2)_C + K(2)_p}$, combined stiffness of $K(2)_C$ and $K(2)_p$ in series.

Note: See Table 4.1 for capblock and cushion properties.

$$K_C = \frac{AE}{L}$$

where

A = cross-sectional area of cushion, in.^{2}

E = secant modulus of elasticity of cushion material, psi

L = thickness of cushion, in.

Calculations for idealization

$W(1)$ = Weight of ram, (lb)

$K(1) = \frac{A(1) \quad E(1)}{L(1)}$, the stiffness of the ram, (lb/in.)

where

$A(1)$ = ram cross sectional area, (in.)

$E(1)$ = modulus of elasticity of ram material, (psi)

$L(1)$ = length of ram, (in.)

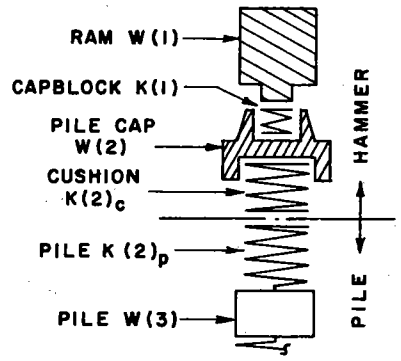
This calculation assumes that the pile cap is rigid.

In the hammer idealization, note that the parts composing the pile driver are physically separated, i.e., the ram is capable of transmitting compressive force to the anvil but not tension. The same is true of the interface between the anvil and pile cap, and the pile cap and the head of the pile. The program contains provisions for eliminating the capability of transmitting tensile forces between adjacent segments. The mechanics of this provision are more fully explained in the following section.

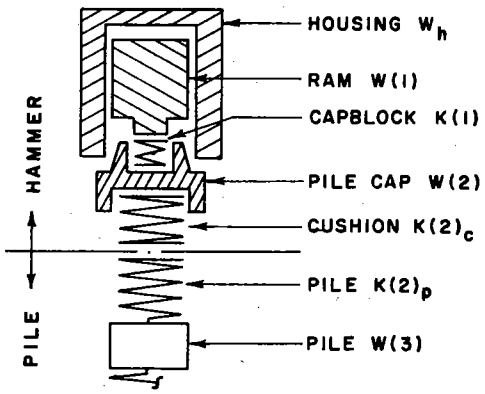
Tables B1 and B2 list the information needed for the simulation of the most common types of pile driving hammers.

B4 Methods of Including Coefficient of Restitution in Capblock and Cushion Springs

In the case where $K(1)$ is a capblock (Cases I, II, and III), and $K(2)$ is a cushion (Case II), it is desirable to include the energy loss due the coefficient of restitution of the particular material.



DROP HAMMERS
SINGLE ACTING STEAM HAMMERS
(A)



DOUBLE AND DIFFERENTIAL ACTING
STEAM HAMMERS
(B)

TABLE B1 DROP HAMMERS AND STEAM HAMMERS

HAMMER	TYPE	W (1) (LB.)	W (2)* (LB.)	W(h) (LB.)	K (1) (LB./IN.)	K (2)c (LB./IN.)	$K(2)_p$ (LB./IN.)	STROKE h, (FT.)	Prated (PSI)	EFF. e_f
MKT S3	A	3000	—	—	DEPENDS ON MATERIAL PROPERTIES & DIMENSIONS	DEPENDS ON MATERIAL PROPERTIES & DIMENSIONS	$K(2)_p = \frac{A(2)\,E(2)}{L(2)}$	3.00	—	0.80
MKT S5	A	5000	—	—				3.25	—	0.80
VULCAN 1	A	5000	1000	—				3.00	—	0.80
VULCAN 2	A	3000	1000	—				2.42	—	0.80
VULCAN 30C	B	3000	1000	4036				1.04	120	0.85
VULCAN 50C	B	5000	1000	6800				1.29	120	0.85
VULCAN 80C	B	8000	2000	9885				1.38	120	0.85
VULCAN 140C	B	14000	—	13984				1.29	140	0.85

* REPRESENTATIVE VALUES FOR PILE NORMALLY USED IN HIGHWAY CONSTRUCTION

In Figure B4 the coefficient of restitution is defined as

$$e = \sqrt{\frac{\text{Area BCD}}{\text{Area ABC}}} = \sqrt{\frac{\text{Energy output}}{\text{Energy input}}} \qquad (B.5)$$

In Case II it is necessary to combine springs $K(2)_C$ and $K(2)_P$ to determine the equivalent spring $K(2)$. In this instance it is also necessary to determine the coefficient of restitution of the combined springs. The stiffness of the spring in the restitution phase is the slope of the line DB in Figure B4.

$$K_{DB} = \frac{F_B}{\Delta_C - \Delta_D} \qquad (B.6)$$

Since,

Energy output = Area BCD = $F_B\,(\Delta_C - \Delta_D)/2$

Energy input = Area ABC = $F_B\,(\Delta_C)/2$

$$e^2 = \frac{F_B(\Delta_C - \Delta_D)}{F_B\,(\Delta_C)} = \frac{\frac{F_B}{\Delta_C}}{\frac{F_B}{(\Delta_C - \Delta_D)}} = \frac{K_{AB}}{K_{DB}}$$

or

$$K_{DB} = \frac{K_{AB}}{e^2} \qquad (B.7)$$

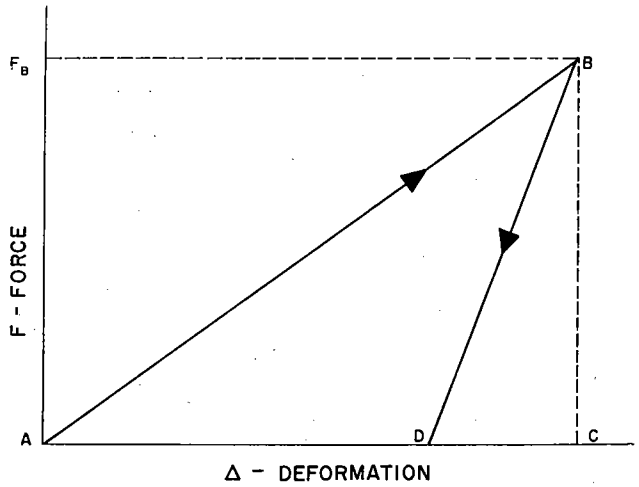
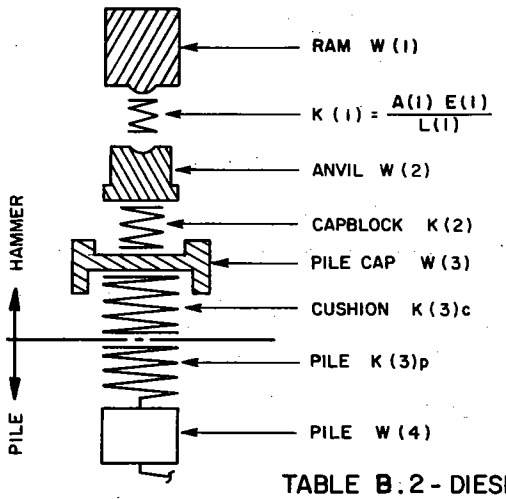


Figure B.4. Definition of coefficient of restitution.

The combined restitution stiffness of $K(2)_C$ and $K(2)_P$ can be determined from,

$$\frac{1}{K(2)} = \frac{1}{K(2)_C} + \frac{1}{K(2)_P}$$ (for restitution phase DB in Figure B4)



NOTES FOR TABLE B.2

* for actual stroke use field observations (may vary from 4.0 to 8.0 ft.)

** determine from bounce chamber pressure ($h_e = E/W(1)$ where E = Indicated Energy)

† average values

TABLE B.2 - DIESEL HAMMERS

TYPE HAMMER	W(1) (LB.)	W(2) (LB.)	W(3)† (LB.)	K(1) x10⁶ (LB./IN.)	K(2) x10⁶ (LB./IN.)	$K(3)_C$	$K(3)_P$	MAX h_e (FT.)	C (FT.)	E_n (FT.-LB.)	EXPLOSIVE FORCE (LB.)	e_f
MKT DE-20	2000	640	1300		14.2	VARIES	$K(3) = \frac{A(3)\,E(3)}{L(3)}$	8.00*	0.92	$E_n = W(1)(h_e - C)$ DEPENDS ON RAM STROKE h_e	46300	1.00
MKT DE-30	2800	775	690	38.7	63.8			8.00*	1.04		98000	1.00
MKT DE-40	4000	1350	1000		101.0			8.00*	1.16		138000	1.00
DELMAG D 5	1100	330	1000	18.5	13.6			8.00*	0.83		46300	1.00
DELMAG D 12	2750	816	All sq. concrete	31.5	18.6			8.00*	1.08		93700	1.00
DELMAG D 22	4850	1576	All wood	49.7	23.8			8.00*	1.08		158700	1.00
DELMAG D 44	9500	4081	All H-bearing	106.2	56.5			8.00*	1.19		200000	1.00
LINK-BELT 180	1724	377	All pipe	44.5	15.5			4.63**	0.64		81000	1.00
LINK-BELT 312	3857	1188		142.5	18.6			3.87**	0.50		98000	1.00
LINK-BELT 440	4000	705		138.0	18.6			4.55**	1.25		98000	1.00
LINK-BELT 520	5070	1179		108.5	18.6			5.20**	0.83		98000	1.00

from Equation (A-7),

$$\frac{e(2)^2}{K(2)} = \frac{e(2)_C^2}{K(2)_C} + \frac{e(2)_p^2}{K(2)_p}$$

$$e(2)^2 = \frac{K(2)}{K(2)_C\ K(2)_p}\left[e(2)_C^2\ K(2)_p + e(2)_p^2\ K(2)_C\right]$$

since $$K(2) = \frac{K(2)_C\ K(2)_p}{K(2)_C + K(2)_p}$$

$$e(2) = \sqrt{\frac{1}{K(2)_C + K(2)_p}\left[e(2)_C^2\ K(2)_p + K(2)_C\ e(2)_p^2\right]} \qquad (B.8)$$

B5 Idealization of Piles

The idealization of the pile is handled by breaking the continuous pile into discrete segments. Each segment is represented by its weight and spring representing the total segment stiffness. In Figure B5, the weight representing the segment is assumed to be concentrated at the end of the segment away from the point of impact. This places the spring on top of the weight whose stiffness it represents, i.e., K(2) is associated with W(3).

Piles should be broken into segments not to exceed approximately 10 feet in lengths, but into not less than five segments. The stiffness of each pile segment spring is calculated from

$$K(m-1) = \frac{A(m)\ E(m)}{L(m)} \qquad (B.9)$$

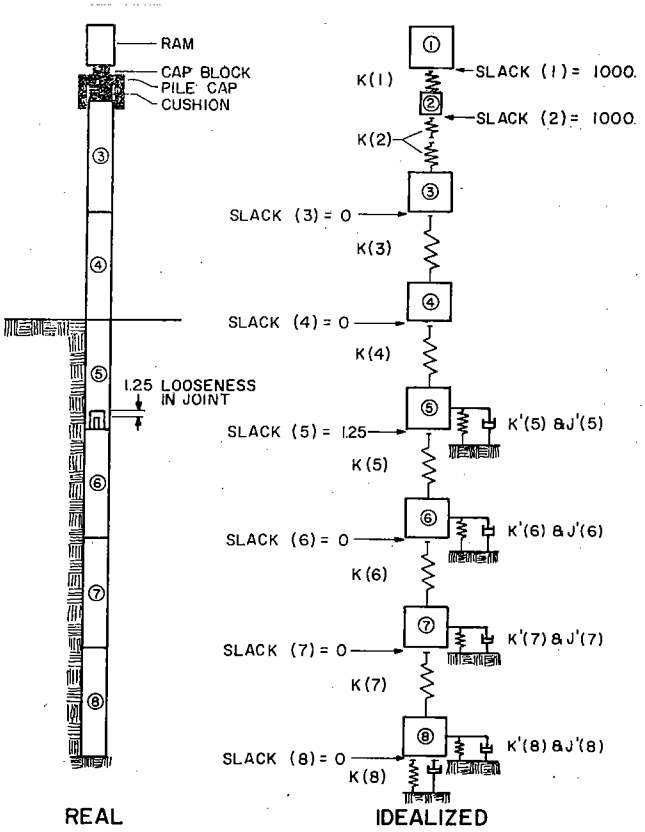


Figure B.5. Pile idealization.

where

K(m−1) = spring stiffness for segment m, (lb/in.)

A(m) = cross sectional area of segment m, (in.²)

E(m) = modulus of elasticity of the material of segment m, (psi)

L(m) = length of segment m, (in.)

The weight of each pile segment is calculated by

$$W(m) = A(m)\ L(m)\ \alpha$$

where

α = unit weight of pile material, (lb/in.)

If the pile is tapered, the average value of A(m) should be used.

The program has provisions for handling cases where the physical construction of the pile prohibits the transmission of tensile stresses or is capable of transmitting tensile stresses only after a specified movement of a mechanical joint (joint slack or looseness). These conditions occur with certain types of pile splices. The program provides for this eventuality by entering the following:

1) If a joint (a joint is defined as the interface between two segments) can transmit tension, the slack or looseness is entered as SLACK (m) = 0. (Refer to Figure B5)

2) If a joint is completely loose, no tension can be transmitted and SLACK (m) should be made a very large number, i.e., SLACK (m) = 1000.0.

3) If a joint is capable of moving 1.25 in. before transmitting tension, SLACK (m) = 1.25, i.e., the physical value of the slack or looseness in a joint is entered in inches.

The SLACK (m) values are always associated with spring K(m). In Figure B5, if tension can be transmitted across the interface between segments 3 and 4, the slack value would be associated with spring K(3), i.e., SLACK (3) = 0.

The interfaces between the various parts composing the pile driver (ram, capblock, pile cap, its.) which cannot transmit tension are also handled by setting the SLACK values equal to 1000.

B6 Explanation of Data Input Sheets

Data for the Pile Driving Analysis program is entered on two sheets. Page 1 contains data pertaining to the physical parameters of a particular pile. Page 2 is used to vary the soil, pile driver, or cushion characteristics for the pile described on page 1. Examples of the data sheets follow the explanation.

Page 1

Case No. = Any combination of up to six alphabetic or numerical characters used for identifying information. These characters will identify all problems associated with the pile data entered on sheets 1 and 2.

No. of Probs. = Total number of problems listed on page 2.

1/DELTA T = This space may be left blank in most cases as the program calculates the critical time interval from the parameters of the system. The value calculated is

$$1/\text{DELTA T} = 2(19.698\ \sqrt{K/W})$$

If, however, one desires to use a specific 1/DELTA T, it may be entered. The problem will then compare the entered value with the critical value calculated by the above formula and use the larger of the two. This is done so that the user cannot inadvertently enter a value too small and hence introduce instability into the numerical process.

P = Total number of weights including ram of hammer, follower, and helmet, etc.

SLACK (1) = This indicates a specified looseness between W(1) and W(2) in inches. This is the amount of movement required before K(1) will take tension. If there is complete tensile freedom of K(1), then enter SLACK (1) = 1000. **Leave blank if option 3 is "2".**

SLACK (2), SLACK (3) = see notes on Slack (1).

Option 1 = This is an option for the manual entry of the cross sectional area of each segment.

(a) Enter "1" and all AREAS will automatically be set equal to 1.00. In this case, draw a horizontal line through all AREA rows on the middle portion of page 1. **If "1" is used, do not enter areas in AREA rows.**

(b) Enter "2" if the cross sectional area of each segment is to be entered manually in the AREA rows. In this case enter AREAS (1) to (P) inclusive.

Option 2 = This is an option for the manual entry of soil resistances.

(a) Enter "2" if the soil resistances (expressed as a percentage of the total soil resistance) are to be entered manually in the RU rows. The RU values are entered from (1) to (P + 1) inclusive. Note that (P + 1) is the point resistance and all others are side resistances. **The total of all RU percentages entered must total 100%.**

(b) Enter "1" if the soil resistances are not listed in the RU rows but are indicated under Option 12 on page 2.

Option 3 = This is an option for manual entry of the SLACK values.

(a) Enter "1" if SLACK values from SLACK (4) to SLACK (P − 1) are all 0.00 (indicating K(4) to K(P − 1) can take tension). In this case only SLACK (1) to SLACK (3) are entered in row 1. Draw a horizontal line through all SLACK rows in the lower portion of page 1. **In this case do not enter any values in the Slack rows.**

(b) Enter "2" if SLACK values are to be entered manually. In this case, SLACK (1) to SLACK (3) in row 1 may be left blank.

Option 4 = This is an option on the routine used to simulate the material behavior of springs K(1), K(2), and K(3).

(a) Enter "1" for use of Smith's routine 3 and 4.

(b) Enter "2" for use of Texas A&M's routine.[4] It is suggested that Option 4 = 2. Option 4 may be left blank in which case it is automatically set equal to 2.

IPRINT = This is an option on the amount of data printed out when the long form output is used (Option 15 = 2). If Option 15 = 2, IPRINT is the print interval expressed as the number of time intervals. As an example, if a print out is required every 10th time interval, 10 would be entered for IPRINT. If Option 15 is "1" or "3", leave IPRINT blank.

NSEG 1 = NSEG 1 is the mass number of the first pile segment. If NSEG 1 is left blank, NSEG 1 = 2 will be used by the program.

The total weight of each segment, in pounds, is entered in the rows marked W(2), W(3), ... W(24). The weights, W's, are entered for 2 to P inclusive. Note that W(1) is not entered as it will be included on page 2.

The spring stiffness of each segment, in lb/in., is entered in the rows marked K(1), K(2), ... K(24). The stiffnesses, K's, are entered from 1 to P − 1 inclusive. Spring K(P) is the soil spring at the pile tip and is calculated by the program from the soil data entered on Page 2.

If Option 1 = 2, the average area of each segment must be entered in the rows marked A(1), A(2), ... A(24). The units of A should be consistent with the stress units desired in the output. The basic force unit of the output is the pound. The areas, A's, are entered from 1 to P inclusive. A(P − 1) and A(P) in most instances will be the same. Areas of segments of the hammer are usually entered as A(1) = 1.00, etc., since stress values obtained for these segments are not usually of concern. If Option 1 = 1, the area row should be marked through with a solid horizontal line indicating no data cards are to be included.

If Option 2 = 2, the side soil resistance on each segment, expressed as a percentage of the total soil resistance, is entered in the rows marked RU(1), RU(2), . . . RU(24). The soil resistances, RU's, are entered from 1 to P + 1 inclusive. The value of RU (P + 1) is the pile tip resistance. Mark out all rows when Option 2 = 1.

If Option 3 = 2, the physical slack or looseness, expressed in inches, is entered in each row marked SLACK (1), SLACK (2), ... SLACK (24). SLACK's are entered from 1 to P − 1 inclusive. If there is no slack, enter 0.0; if there is complete looseness, enter 1000.0. SLACK (P) is automatically set equal to 1000.0 since the point soil spring cannot take tension. If Option 3 = 1, mark out all rows.

Note that the forms have 24 spaces for W's, K's, A's, RU's, and SLACK's. The program is capable of handling a pile with a maximum of 149 segments. Additional cards may be added to each parameter as needed.

Page 2

W(1) = The weight of the pile driver's ram in pounds.

NC = The number of the spring for which K(NC) is being varied.

K(NC) = The spring constant of the spring being varied in lbs/in. Only one spring can take on variable values per case.

EFF = The efficiency of the pile hammer.

ENERGY = Kinetic energy of the falling ram calculated by Equation B-1, B-2, or B-3.

ERES (1) = The coefficient of restitution of spring K(1)

ERES (2) = The coefficient of restitution of spring K(2)

ERES (3) = The coefficient of restitution of spring K(3)

RU (TOTAL) = This space should be used only when Option 11 = 2. In this case RU (TOTAL) is the desired ultimate pile resistance in pounds. When Option 11 = 1, leave this entry blank.

% RU (TOTAL AT POINT = The percentage of the total pile soil resistance, RU(TOTAL), under the point of the pile. This value is entered as a percentage.

MO = If Option 12 is "1" or "2", enter the number of the first pile segment acted upon by soil resistance. This space may be left blank if Option 12 = 3, i.e., RU's are read in on page 1.

Q POINT = Quake of the soil at the point. Normally "0.10" is used.

Q SIDE = Quake of the soil on the side of the pile. Normally "0.10" is used.

J POINT = Damping constant for the soil at the point.

J SIDE = Damping constant for the soil on the side of the pile.

FEXP = The diesel explosive force (in pounds) which acts on the ram and anvil of a diesel hammer. In the case where no explosive force exists, as with drop hammers or steam hammers, leave FEXP blank.

Option 11 = This option provides for single or multiple calculations.

(a) Enter "1" if multiple calculations for RU(TOTAL) VS BLOW/IN., data are desired. The computer will assign suitable values of RU (TOTAL). **Leave RU(TOTAL) space on page 2 blank.**

(b) Enter "2" if single calculation is to be made with RU(TOTAL) value entered on page 2.

Option 12 = This option is used for designation of the distribution of side friction on the pile.

(a) Enter "1" for a uniform distribution of side friction from segment MO to P.

(b) Enter "2" for a triangular distribution of side friction from segment MO to P.

(c) Enter "3" if Option 2 = 2, i.3., RU values are entered on page 1.

Option 13 = This option provides for computer plotted curves using the data gen-

PILE DRIVING ANALYSIS
TEXAS A&M UNIVERSITY

OPTIONS: AREAS | RU'S | SLACK | 1 2 3 4 | IPRINT USED WHEN OPTION 5=2 | NSEGI

BY: _____ DATE: _____ PAGE # 1 OF 2

	CASE NO.	NO. OF PROBS.	10	20	30	40	60	70	80
			I/DELTA T	P	SLACK (1)	SLACK (2)	SLACK(3)		
LBS.	W (1)	W (2)	W (3)	W (4)	W (5)	W (6)	W (7)	W (8)	
	W (9)	W (10)	W (11)	W (12)	W (13)	W (14)	W (15)	W (16)	
	W (17)	W (18)	W (19)	W (20)	W (21)	W (22)	W (23)	W (24)	
LBS./IN.	K (1)	K (2)	K (3)	K (4)	K (5)	K (6)	K (7)	K (8)	
	K (9)	K (10)	K (11)	K (12)	K (13)	K (14)	K (15)	K (16)	
	K (17)	K (18)	K (19)	K (20)	K (21)	K (22)	K (23)	K (24)	
SQ. IN.	AREA (1)	AREA (2)	AREA (3)	AREA (4)	AREA (5)	AREA (6)	AREA (7)	AREA (8)	
	AREA (9)	AREA (10)	AREA (11)	AREA (12)	AREA (13)	AREA (14)	AREA (15)	AREA (16)	
	AREA (17)	AREA (18)	AREA (19)	AREA (20)	AREA (21)	AREA (22)	AREA (23)	AREA (24)	
%	RU (1) %	RU (2) %	RU (3) %	RU (4) %	RU (5) %	RU (6) %	RU (7) %	RU (8) %	
	RU (9) %	RU (10) %	RU (11) %	RU (12) %	RU (13) %	RU (14) %	RU (15) %	RU (16) %	
	RU (17) %	RU (18) %	RU (19) %	RU (20) %	RU (21) %	RU (22) %	RU (23) %	RU (24) %	
INCHES	SLACK (1)	SLACK (2)	SLACK (3)	SLACK (4)	SLACK (5)	SLACK (6)	SLACK (7)	SLACK (8)	
	SLACK (9)	SLACK (10)	SLACK (11)	SLACK (12)	SLACK (13)	SLACK (14)	SLACK (15)	SLACK (16)	
	SLACK (17)	SLACK (18)	SLACK (19)	SLACK (20)	SLACK (21)	SLACK (22)	SLACK (23)	SLACK (24)	

NOTES: ONE OR MORE PROBLEMS MUST BE LISTED ON PAGE 2
W'S AND AREAS 1 TO P INCL.; K'S AND SLACK'S 1 TO P-1 INCL.; RU'S 1 TO P+1 INCL. (P+1 IS % RU UNDER POINT OF PILE.)

erated for RU(TOTAL) VS BLOW/IN. (Option 11 = 1).
(a) Enter "1" for computer plot of data. If no plot is desired, leave blank.

Option 14 = This is used to include or exclude gravity in the calculations.
(a) Enter "1" if the forces of gravity are to be included in the calculations.
(b) Enter "2" if the forces of gravity are to be excluded from the calculation. This alternate in effect excludes the weight of the pile from the calculations. It is used when the pile driver is in a horizontal position or for an extreme batter.

Option 15 = This option provides for versatility in the output format.
(a) Enter "1" for a normal data printout.
(b) Enter "2" for extra detail in printout. This alternate gives pertinent stresses, deformations, velocities, etc., at the print interval, specified as IPRINT on page 1.
(c) Enter "3" for short output. This alternate gives only a tabular summary of BLOW/IN. VS RU(TOTAL). **Option 15 = 3 should be used only when Option 11 = 2.**

SPECIAL NOTE Where anything listed for Problem 1 is to be repeated for Problem 2, 3, etc., draw an arrow down through the last problem to indicate repetition.

B7 Comments on Data Input

On page 2 of the input forms, provisions are made for varying the stiffness of any spring, K(1) through K(P — 1), in the hammer or pile idealization. This is accomplished by entering the number of the spring to be changed in the NC column and then the stiffness of spring K(NC) in the K(NC) column. As soon as this problem is completed, the spring stiffnesses, K(NC) will be reset automatically to the value on page 1 of the input forms.

The program is capable of handling pile idealizations with a maximum of 149 segments. There is no limit on the number of problems that can be run for each case.

Sample Problem

Consider the pile shown in Figure B-6.

Pile: 16 in. square prestressed concrete pile, 26 ft in length. The modulus of the concrete is 7.82×10^6 psi and its unit weight is 154 lb/ft^3. The pile is assumed to be embedded for its full length.

Pile hammer: Hypothetical diesel hammer with 4850 lb ram with an input ram kinetic energy of 39,800 ft lb. The explosive force produced by the diesel fuel is 158,700 lb. The stiffness of the ram is given as 42.25×10^6 lb/in. The anvil is assumed rigid and weighs 1150 lb. The capblock stiffness is 24.5×10^6 lb/in.

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TEXAS A&M UNIVERSITY

BY: _____ DATE: _____ PAGE # 2 OF 2

PROB	W(I) POUNDS	NC	K(NC) POUNDS/INCH	EFF.	ENERGY	ERES (1)	ERES (2)	ERES (3)	RU (TOTAL) POUNDS	% AT POINT	MO	Q POINT	Q SIDE	J POINT	J SIDE	FEXP	OPTIONS 11 12 13 14 15
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	
14																	
15																	
16																	
17																	
18																	
19																	
20																	

NOTE: IF OPTION #11 = 1, RU (TOTAL) NOT REQUIRED

NO. OF CALCULATIONS
RESISTANCE
PLOT
GRAVITY
PRINT OUT

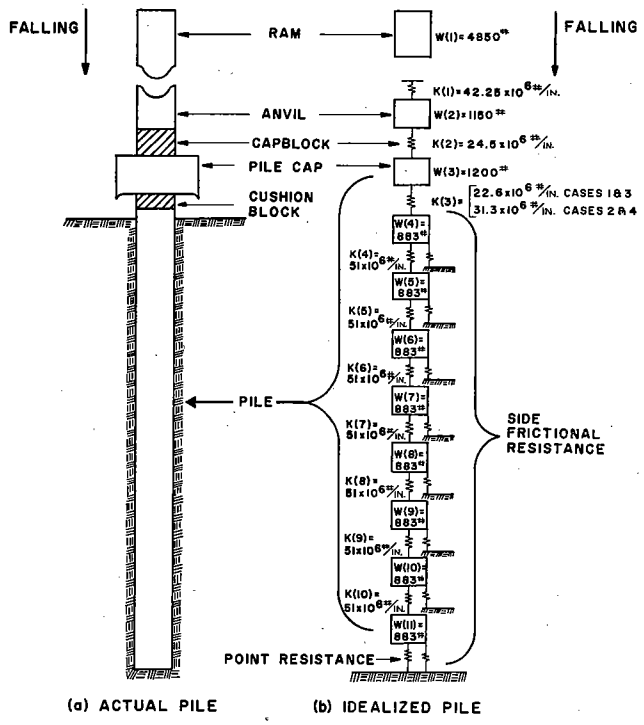


Figure B.6. Sample problem.

In order to illustrate the utilization of the input data sheets and explain the output data sheets, four problems are considered.

Problem 1 and Problem 2 are concerned with the driving effects produced by two different cushions. The object of these two cases is to determine the dynamic-static resistance curves (RU(TOTAL) VS BLOWS/IN.) for one blow of the hammer. In Problem 1, the cushion is assumed to have a cross sectional area equal to that of the pile, is 6¼ in. thick and has a modulus of elasticity of 1.0×10^6 psi. In Problem 2 the cushion area and properties are the same as in Problem 1, but the thickness is 3⅛ in. In Problem 1 and 2 the soil side friction is assumed to have a triangular distribution with 10% point resistance. The soil constants are:

(a) $Q = Q' = 0.10$ in.

(b) $J = 0.15$ sec./ft.

(c) $J' = 0.05$ sec./ft.

Problems 3 and 4 illustrate the use of program to investigate the penetration of a pile to 200 tons of static soil resistance produced by one blow of the hammer. In Problem 3 the soil resistance is distributed uniformly along the side with 10% at the point. The cushion is the same as in Case 1. In Problem 4 the soil has a triangular distribution along the side with 10% soil resistance (same as Problem 2). The cushion is the same as in Problem 2. Problem 4 will also illustrate the use of the output option (OPTION 15).

The following calculations illustrate the computations for the hammer and pile idealization.

(a) Pile: The pile is broken into eight equal length segments of 39 in. The spring stiffness for each segment is,

$$K(3)_p = \frac{A(3)_p E(3)_p}{L(3)_p}$$

where

$A(3)_p = 254$ in.^{2}

$E(3)_p = 7.32 \times 10^6$ psi

$L(3)_p = 39$ in.

therefore

$$K(3)_p = \frac{(254)\ (7.32 \times 10^6)}{39} = 51.0 \times 10^6 \text{ lb/in.}$$

(b) Cushion: Spring K(3) in Figure B6 (b) represents the combined stiffness of the cushion and first pile segment.

In Problem 1 and 3

$$K(3)_C = \frac{A(3)_C\ E(3)_C}{L(3)_C}$$

where

$A(3)_C = 254$ in.^{2}

$E(3)_C = 1.00 \times 10^6$ psi

$L(3)_C = 6.25$ in.

then

$$K(3)_C = \frac{(254)\ (1 \times 10^6)}{6.25} = 40.5 \times 10^6 \text{ lb/in.}$$

The combined stiffness of $K(3)_C$ and $K(3)_p$ is

$$K(3) = \frac{K(3)_C \times K(3)_p}{K(3)_C + K(3)_p} = \frac{(40.5)\quad (51.0)\ (10^6)}{(40.5 + 51.0)\ (10^6)}$$

$$K(3) = 22.6 \times 10^6 \text{ lb/in.}$$

The coefficient of restitution for the combined springs is assumed to be 0.50.

For Problem 2 and 4 similar calculation yields

$$K(3) = 31.3 \times 10^6 \text{ lb/in.}$$

The output data sheets are completed as follows:

Page 1 (Same for all 4 problems)

No. of Problems = 4, there are 4 problems to be solved on page 2.

1/DELTA T	= 0.0, since the program will calculate the correct value.
P	= 11, there are 11 weights (3 for the hammer and 8 for the pile).
SLACK'S	= all set equal to 1000 since there is complete looseness between the ram, anvil, capblock, pile cap, cushion, and pile head.
OPTION 1	= 2, all areas are entered manually in AREA rows.
OPTION 2	= 1, since OPTION 12 is used to describe the soil distribution.
OPTION 3	= 1, all pile segments are connected, hence SLACK (4) to SLACK (10) = 0.0.
OPTION 4	= left blank since it is desired to use the A&M routine.
IPRINT	= 10, in Problem 4, OPTION 15 = 2, it is desired to print output every 10 iterations.
NSEG1	= 4, the first pile segment, see Figure B6 (b).
W'S	= enter the weight of each element in lb. Note that W(1) is blank since it will be entered on page 2.

K'S = enter all spring stiffnesses for the pile system considered to be basic, i.e., the program will automatically reset the stiffnesses to these values after each problem on page 2.

A'S = enter all cross sectional areas of pile segments only.

Page 2—Problem 1

W(1) = 4850 lb., the ram weight.

NC = 3, the cushion spring number, see Figure B6 (b).

K(NC) =
K(3) = 22,500,000, the stiffness of the combined springs.

EFF = 1.00, diesel hammers are considered to be 100% efficient.

ENERGY = 39,800, the input energy for this particular hammer blow.

ERES(1) = 0.60, coefficient of restitution of steel on steel impact.

ERES(2) = 0.80, coefficient of restitution of cap-block material.

ERES(3) = 0.50, coefficient of restitution of combined cushion and first pile spring.

RU(TOTAL) = leave blank, since OPTION 11 = 1, i.e., the program will generate suitable values for curve generation.

% AT
POINT = 10%.

MO = 4, the first pile segment with side soil resistance.

QPOINT = 0.10, Q.

QSIDE = 0.10, Q'.

JPOINT = 0.15, J.

JSIDE = 0.05, J'.

FEXP = 158,700, lb. the diesel explosive force.

OPTION 11 = 1, for program generated RU(TOTAL) VS BLOWS/IN. curve.

OPTION 12 = 2, for triangular side soil resistance distribution.

OPTION 13 = leave blank since computer plotted curve is not desired.

OPTION 14 = 1, to indicate gravity.

OPTION 15 = 1, for normal data output.

Page 2, Problem 2

Only the value of K(3), is changed.

NC = 3
K(NC) = 31,300,000.
K(3) = 3.

Page 2, Problem 3

The value of K(3) and the OPTIONS are changed.

NC = 3.
K(NC) =
K(3) = 22,500,000.

RU(TOTAL) = 400,000 lb for a 200 ton total static soil resistance.

OPTION 11 = 2, for single calculation using RU (TOTAL) = 400,000.

OPTION 12 = 1, for uniform side soil resistance distribution.

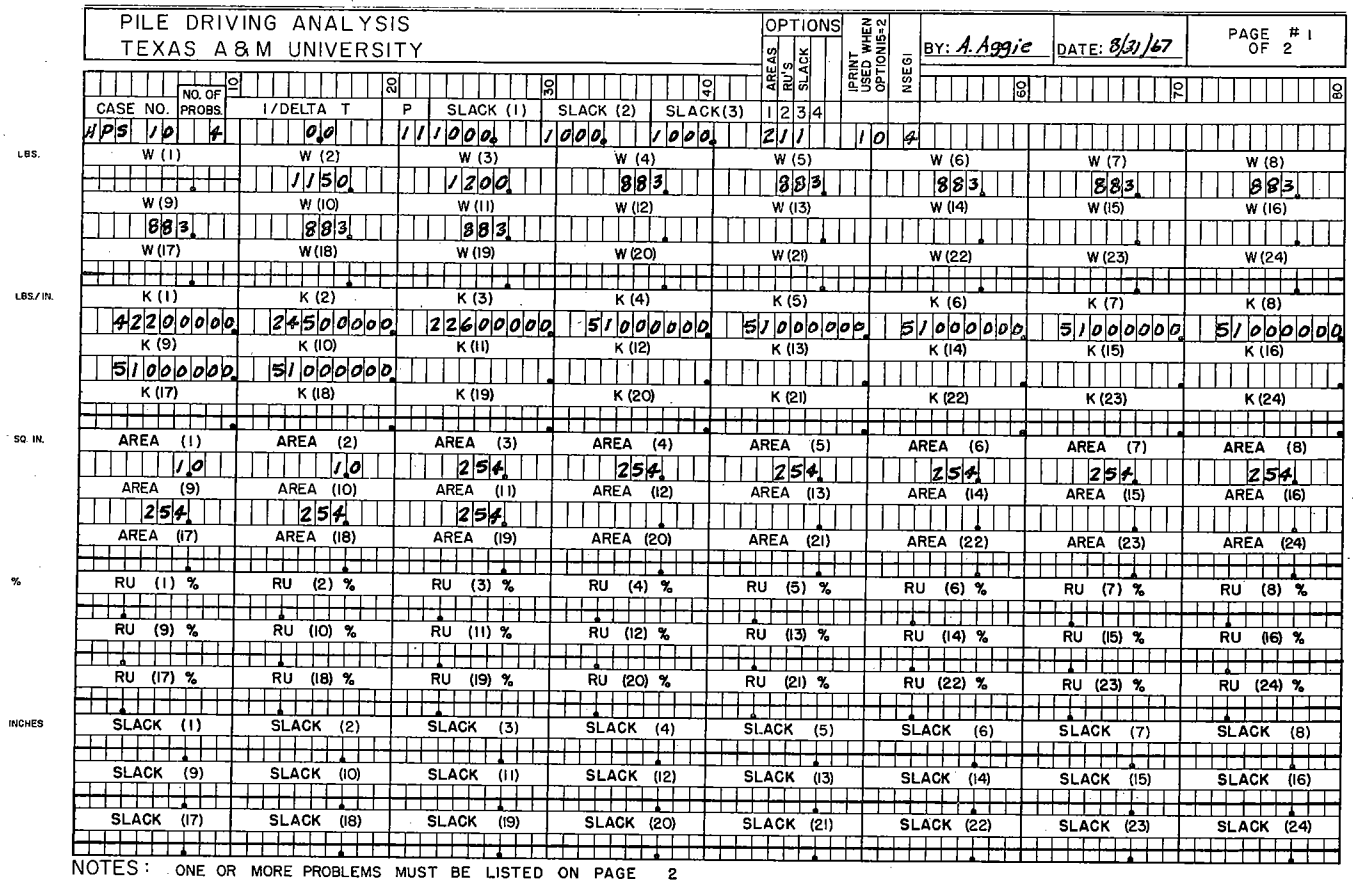
Page 2, Problem 4

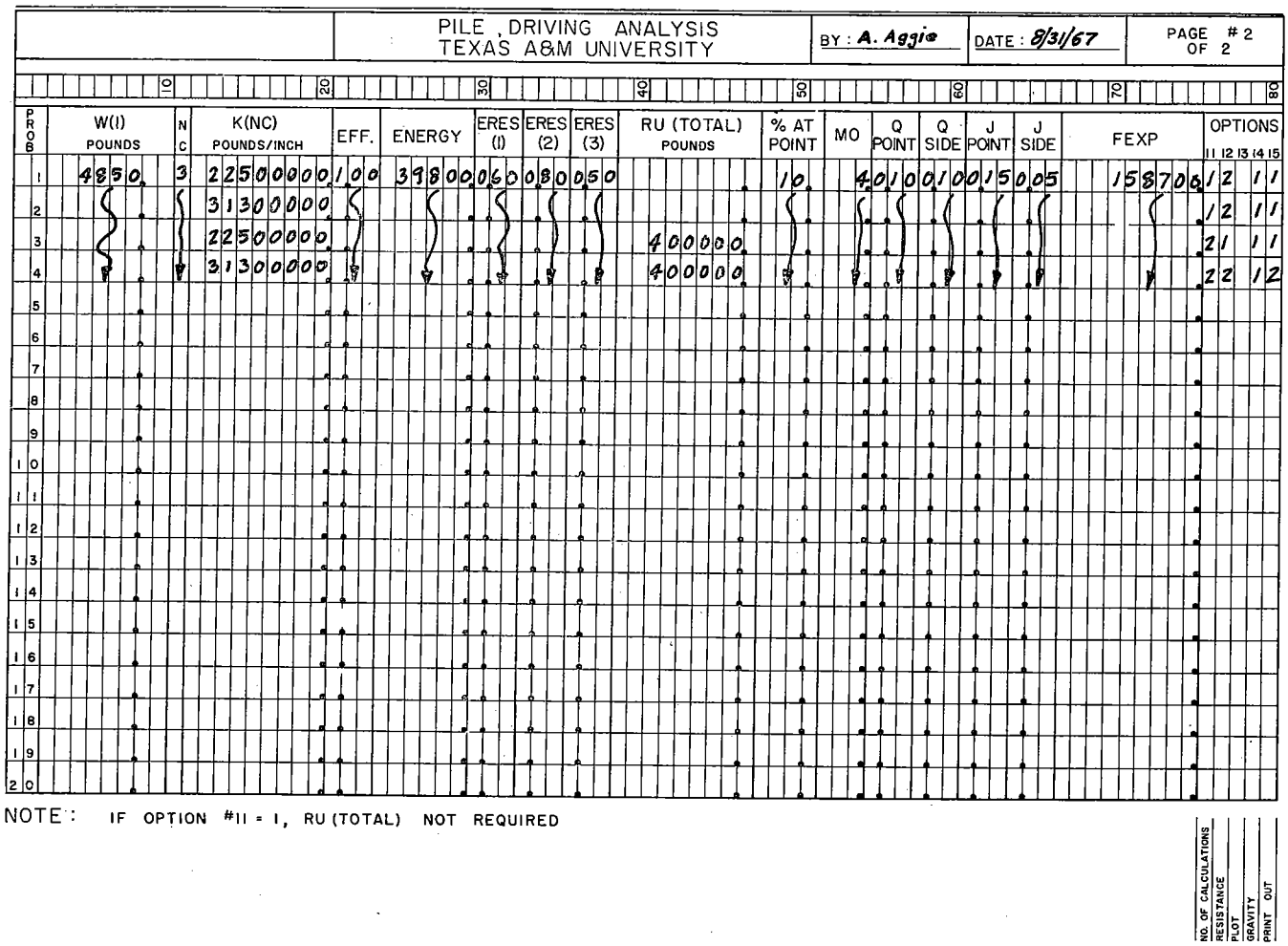
In this problem the cushion and the options are changed.

NC = 3
K(NC) =
K(3) = 31,300,000

OPTION 12 = 2, for triangular side soil resistance distribution.

OPTION 15 = 2, for output at interval expressed by IPRINT on page 1.





The output for the four sample problems are shown in Figures B7 through B-11. Figure B7 is the output for one point on the RU(TOTAL) VS BLOWS/IN. curve generated for Problem 1. The block of data on the upper part of the figure is a printout of the input data. The RU(TOTAL) value of 1,040,962.1 is the total static soil resistance for which this problem was run. This value was generated by the program and is only one point of 10 used to develop the data for the total RU(TOTAL) VS BLOWS/INCH curve shown in

```
TEXAS A * M UNIVERSITY          PILE DRIVING ANALYSIS      CASE NO.HSP 10      PROBLEM NO.   1 OF   4
  1/DELTA T   P     OPTIONS     1    2    3    4              11   12   13   14   15          EXP. FORCE
     9443.9   11                2    1    1    2               1    2    0    1    1           158700.
ENERGY     HAMMER EFFIENCY        RU(TOTAL)   PERCENT UNDER POINT   MO  Q(POINT)  Q(SIDE)  J(POINT)  J(SIDE)     N2
 39800.00       1.00              1040962.1          10.0            4      0.10      0.10      0.15      0.05     125
 M        W(M)        K(M)          AREA(M)        RU(M)        SLACK(M)   ERES(M)   VSTART(M)   KPRIME(M)
 1      4850.000  0.4220000E 08       1.000          0.0        1000.000     0.60      22.99     0.0
 2      1150.000  0.2450000E 08       1.000          0.0        1000.000     0.80       0.0      0.0
 3      1200.000  0.2250000E 08     254.000          0.0        1000.000     0.50       0.0      0.0
 4       883.000  0.5100000E 08     254.000      14638.531         0.0        1.00       0.0      0.1463853E 06
 5       883.000  0.5100000E 08     254.000      43915.594         0.0        1.00       0.0      0.4391561E 06
 6       883.000  0.5100000E 08     254.000      73192.625         0.0        1.00       0.0      0.7319265E 06
 7       883.000  0.5100000E 08     254.000     102469.687         0.0        1.00       0.0      0.1024697E 07
 8       883.000  0.5100000E 08     254.000     131746.750         0.0        1.00       0.0      0.1317467E 07
 9       883.000  0.5100000E 08     254.000     161023.812         0.0        1.00       0.0      0.1610238E 07
10       883.000  0.5100000E 08     254.000     190300.875         0.0        1.00       0.0      0.1903009E 07
11       883.000  0.1040962E 07     254.000     219577.937      1000.000      1.00       0.0      0.2195780E 07
12        -0.0      -0.0             -0.0      104096.125        -0.0        -0.0       -0.0      0.0

SEGMENT      AREA      TIME N   MAX C STRESS      TIME N MAX T STRESS      DMAX(M)       D(M)         V(M)
  1          1.000        4      2883699.            0          -0.0       0.487338    0.486179      -0.50
  2          1.000        7      2245092.            0          -0.0       0.430214    0.430214       4.07
  3        254.000       11         7432.           42          -0.0       0.359616    0.359616      -1.17
  4        254.000       13         7324.            0          -0.0       0.238627    0.223646      -3.80
  5        254.000       15         7107.            0          -0.0       0.231331    0.211913      -1.14
  6        254.000       17         6883.            0          -0.0       0.215890    0.204061       0.57
  7        254.000       19         6633.           34            1.       0.203751    0.198904      -2.68
  8        254.000       21         6344.           34          172.       0.190195    0.188150      -2.55
  9        254.000       23         5834.           29         1973.       0.182027    0.174308       0.39
 10        254.000       35         4195.           30         2491.       0.172878    0.168807      -0.03
 11        254.000       27         1320.            0          -0.0       0.167608    0.166761      -1.43
PERMANENT SET OF PILE =      0.06760806 INCHES    NUMBER OF BLOWS PER INCH =      14.79113579    TOTAL INTERVALS =      49
```

Figure B.7. Normal output (option 15=1) for Prob. 1.

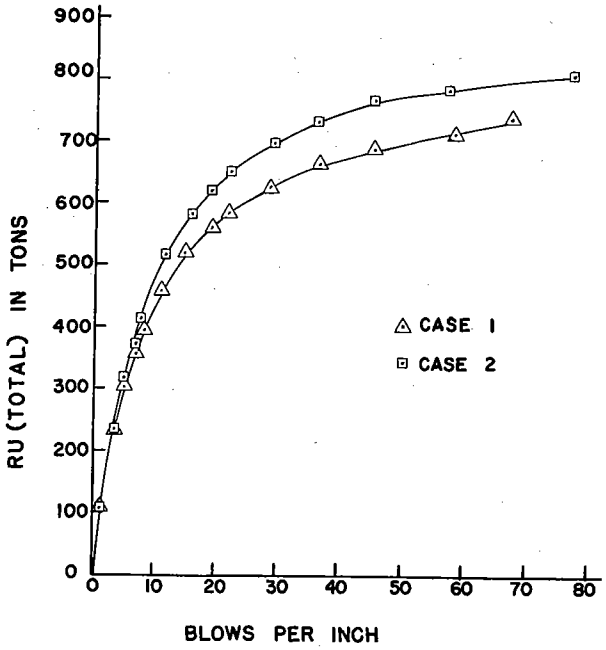


Figure B.8. Effect of varying cushion stiffness.

Figure B8. The second block of data shows the maximum compressive and tensile stresses and the maximum displacement of each segment. The column labeled TIMEN is the time interval at which the maximum compressive stress (MAX C STRESS) occurred, i.e., the maximum compressive stress of 7432 psi occurred in segment 5 at time interval 11 (11/9443.9 sec.). Similar data is printed for each point on the RU(TOTAL) VS BLOWS/IN. shown in Figure B8.

Figure B9 shows the summary of the data for the RU(TOTAL) VS BLOWS/IN. for Problems 1 and 2. Data of this type can be used to construct curves like that shown in Figure B8. These curves can be used to compare the effects of cushion stiffness (the cushion stiffness, $K(3)_C$, in Problem 2 was twice that in Problem 1). Note the stiffer cushion (Problem 2) produces the most efficient driving since for a specified resistance the penetration per blow is larger (BLOWS/IN. is smaller).

Figure B-10 is a typical output when RU(TOTAL) is specified. The maximum penetration of the point of the pile under one blow of the hammer is 0.473011 in., listed under DMAX(M), and the permanent set is 0.473011-0.100000 (the ground quake Q) or 0.373011 in. Note that the input data is listed as well as the maximum stresses and the displacement of each segment.

Figure B-11 is a sampling of the output when data is desired at some specified interval (OPTION 15 = 2, IPRINT = 1). The input information is listed in the first block of data. The next two blocks show the stresses at time interval N = 0 and N = 1. The data is defined as follows:

D(M)	=	displacement of each mass point, (in.),
C(M)	=	the compression in each spring, (in.),
STRESS(M)	=	stress in each segment, (psi),
F(M)	=	force in each spring, (lb),
R(M)	=	force in each soil spring, (lb),
W(M)	=	weight of each segment, (lb),
V(M)	=	velocity of each segment, (fps),
DPRIME(M)	=	elastic displacement of soil, (in.),

PILE DRIVING ANALYSIS CASE NUMBER HSP 10 PROBLEM NUMBER 1
QPOINT = 0.10 JPOINT = 0.15

BLOWS PER IN.	RUTOTAL	POINT FORCE	MAX C STRESS	SEG	MAX T STRESS	SEG
1.0733	213593.- 107.T	92981.	7321.	4	4411.	10
3.3072	462346.- 231.T	185557.	7322.	4	3706.	10
4.9401	601539.- 301.T	232773.	7322.	4	3358.	10
6.6525	708095.- 354.T	266561.	7323.	4	3112.	10
8.1351	785875.- 393.T	285066.	7323.	4	2955.	10
10.7809	917031.- 459.T	312727.	7324.	4	2708.	10
14.7911	1040962.- 520.T	335193.	7324.	4	2491.	10
18.8100	1118220.- 559.T	350215.	7324.	4	2362.	10
21.5075	1166279.- 583.T	359397.	7324.	4	2285.	10
28.2780	1255360.- 628.T	375508.	7325.	4	2148.	10
36.2405	1321145.- 661.T	386685.	7325.	4	2051.	10
44.9512	1371145.- 686.T	394790.	7325.	4	1981.	10
58.1772	1421145.- 711.T	402573.	7325.	4	1908.	10
67.8860	1471145.- 736.T	410044.	7325.	4	1836.	10

PILE DRIVING ANALYSIS CASE NUMBER HSP 10 PROBLEM NUMBER 2
QPOINT = 0.10 JPOINT = 0.15

BLOWS PER IN.	RUTOTAL	POINT FORCE	MAX C STRESS	SEG	MAX T STRESS	SEG
1.0377	213593.- 107.T	96645.	7664.	4	4171.	10
3.1615	470888.- 235.T	196306.	7663.	4	3412.	10
4.8150	622323.- 311.T	247556.	7662.	4	3083.	10
6.5367	736804.- 368.T	283048.	7662.	4	2857.	10
7.5466	819918.- 410.T	307190.	7661.	4	2703.	10
11.4121	1025674.- 513.T	361561.	7661.	4	2352.	10
15.8643	1158745.- 579.T	392988.	7660.	4	2145.	10
18.7758	1233466.- 617.T	409456.	7660.	4	2035.	10
22.0974	1297626.- 649.T	420576.	7659.	4	1950.	10
29.3317	1394207.- 697.T	430297.	7659.	4	1840.	10
36.8446	1460959.- 730.T	436023.	7659.	4	1766.	10
45.1832	1510959.- 755.T	439816.	7659.	4	1713.	10
57.8852	1560959.- 780.T	443210.	7658.	4	1663.	10
77.6870	1610959.- 805.T	446224.	7658.	4	1613.	10

Figure B.9. Summary output for RU (total) vs blows/in. (option 11=1) for Prob. 1 and 2.

```
TEXAS A * M UNIVERSITY        PILE DRIVING ANALYSIS     CASE NO.HSP 10     PROBLEM NO.   3 OF   4
  1/DELTA T   P     OPTIONS    1    2    3    4              11   12   13   14   15          EXP. FORCE
    9443.9   11               2    1    1    2               2    1    0    1    1           158700.
ENERGY     HAMMER EFFIENCY        RU(TOTAL)   PERCENT UNDER POINT    MO  Q(POINT)  Q(SIDE)  J(POINT)  J(SIDE)     N2
 39600.00       1.00              400000.0            10.0             4      0.10      0.10      0.15     0.05    142
 M        W(M)          K(M)        AREA(M)       RU(M)        SLACK(M)   ERES(M)  VSTART(M)   KPRIME(M)
 1     4850.000  0.4220000E 08        1.000         0.0        1000.000      0.60      22.99  0.0
 2     1150.000  0.2450000E 08        1.000         0.0        1000.000      0.80       0.0   0.0
 3     1200.000  0.2250000E 08      254.000         0.0        1000.000      0.50       0.0   0.0
 4      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
 5      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
 6      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
 7      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
 8      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
 9      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
10      883.000  0.5100000E 08      254.000    45000.000          0.0         1.00       0.0   0.4500001E 06
11      883.000  0.3999999E 06      254.000    45000.000       1000.000       1.00       0.0   0.4500001E 06
12       -0.0    -0.0                -0.0     39999.984          -0.0        -0.0        -0.0   0.0

SEGMENT      AREA     TIME N  MAX C STRESS      TIME N MAX T STRESS      DMAX(M)      D(M)         V(M)
 1           1.000       4     2883701.              0        -0.0      0.502888   0.375493       -4.67
 2           1.000       7     2245095.             93        -0.0      0.688212   0.688212        1.00
 3         254.000      11        7445.             97        -0.0      0.608394   0.606307        1.22
 4         254.000      13        7258.             41        2537.     0.497042   0.495229       -2.50
 5         254.000      15        7017.             39        3001.     0.489747   0.489520       -0.17
 6         254.000      17        6826.             38        2655.     0.484540   0.484376        1.46
 7         254.000      19        6656.             35        2477.     0.481653   0.481653        0.52
 8         254.000      21        6493.             34        3081.     0.479475   0.479301       -0.90
 9         254.000      23        6133.             29        3078.     0.474198   0.473951        0.21
10         254.000      24        4278.             30        4194.     0.475263   0.470868        1.83
11         254.000      27         647.              0        -0.0      0.473911   0.473011       -1.43
PERMANENT SET OF PILE =      0.37391138 INCHES    NUMBER OF BLOWS PER INCH =       2.67442989    TOTAL INTERVALS =       98
```

Figure B.10. Normal output for single RU (total) (option 11 = 2) for Prob. 3.

KPRIME(M) = soil spring stiffness, (lb/in.),
FMAXC(M) = maximum compressive force in segment, (lb), and
FMAXT(M) = maximum tensile force in segment, (lb).

Time interval N = 0 is for the pile under the influence of gravity alone. The particular output listed in Figure B-11 shows that the point of the pile of Problem 4 would penetrate 0.002353 in. under gravity alone.

```
TEXAS A * M UNIVERSITY        PILE DRIVING ANALYSIS     CASE NO.HSP 10     PROBLEM NO.   4 OF   4
  1/DELTA T   P     OPTIONS    1    2    3    4              11   12   13   14   15          EXP. FORCE
    9443.9   11               2    1    1    2               2    2    0    1    2           158700.
ENERGY     HAMMER EFFIENCY        RU(TOTAL)   PERCENT UNDER POINT    MO  Q(POINT)  Q(SIDE)  J(POINT)  J(SIDE)     N2
 39600.00       1.00              400000.0            10.0             4      0.10      0.10      0.15     0.05    140
 M        W(M)          K(M)        AREA(M)       RU(M)        SLACK(M)   ERES(M)  VSTART(M)   KPRIME(M)
 1     4850.000  0.4220000E 08        1.000         0.0        1000.000      0.60      22.99  0.0
 2     1150.000  0.2450000E 08        1.000         0.0        1000.000      0.80       0.0   0.0
 3     1200.000  0.3130000E 08      254.000         0.0        1000.000      0.50       0.0   0.0
 4      883.000  0.5100000E 08      254.000     5625.000          0.0         1.00       0.0   0.5625002E 05
 5      883.000  0.5100000E 08      254.000    16875.000          0.0         1.00       0.0   0.1687500E 06
 6      883.000  0.5100000E 08      254.000    28125.000          0.0         1.00       0.0   0.2812501E 06
 7      883.000  0.5100000E 08      254.000    39375.000          0.0         1.00       0.0   0.3937501E 06
 8      883.000  0.5100000E 08      254.000    50625.000          0.0         1.00       0.0   0.5062501E 06
 9      883.000  0.5100000E 08      254.000    61875.000          0.0         1.00       0.0   0.6187502E 06
10      883.000  0.5100000E 08      254.000    73125.000          0.0         1.00       0.0   0.7312502E 06
11      883.000  0.3999999E 06      254.000    84375.000       1000.000       1.00       0.0   0.8437502E 06
12       -0.0    -0.0                -0.0     39999.984          -0.0        -0.0        -0.0   0.0

TIME INTERVAL N =      0      NET PENETRATION =    0.0          N1 =   140     N2 =
SEGMENT M      D(M)          C(M)     STRESS(M)       F(M)        R(M)      W(M)        V(M)   DPRIME(M)  KPRIME(M)   FMAXC(M)   FMAXT(M)
      1     0.002919      0.0             0.0          0.0         0.0    4850.00   22.988647   0.000566        0.0         0.0        0.0
      2     0.002919      0.000047     1150.        1150.          0.0    1150.00    0.0        0.000566        0.0         0.0        0.0
      3     0.002873      0.000075        9.        2350.          0.0    1200.00    0.0        0.000519        0.0         0.0        0.0
      4     0.002797      0.000061       12.        3101.        132.      883.00    0.0        0.000444    56250.          0.0        0.0
      5     0.002737      0.000070       14.        3586.        397.      883.00    0.0        0.000383   168750.          0.0        0.0
      6     0.002666      0.000075       15.        3808.        662.      883.00    0.0        0.000313   281250.          0.0        0.0
      7     0.002592      0.000074       15.        3764.        927.      883.00    0.0        0.000238   393750.          0.0        0.0
      8     0.002518      0.000068       14.        3455.       1191.      883.00    0.0        0.000164   506250.          0.0        0.0
      9     0.002450      0.000057       11.        2882.       1456.      883.00    0.0        0.000097   618750.          0.0        0.0
     10     0.002394      0.000040        8.        2044.       1721.      883.00    0.0        0.000040   731250.          0.0        0.0
     11     0.002353      0.0             4.         941.       1986.      883.00    0.0        0.0        843750.          0.0        0.0

TIME INTERVAL N =      1      NET PENETRATION =    0.0          N1 =   140     N2 =
SEGMENT M      D(M)          C(M)     STRESS(M)       F(M)        R(M)      W(M)        V(M)   DPRIME(M)  KPRIME(M)   FMAXC(M)   FMAXT(M)
      1     0.032130      0.029211  1232689.     1232689.          0.0    4850.00   22.126266   0.000566        0.0   1232689.          0.0
      2     0.002919      0.000047     1150.        1150.          0.0    1150.00    3.651348   0.000566        0.0      1150.          0.0
      3     0.002873      0.000075        9.        2350.          0.0    1200.00    0.000000   0.000519        0.0      2350.          0.0
      4     0.002797      0.000061       12.        3101.        132.      883.00   -0.000000   0.000444    56250.      3101.          0.0
      5     0.002737      0.000070       14.        3586.        397.      883.00   -0.000000   0.000383   168750.      3586.          0.0
      6     0.002666      0.000075       15.        3808.        662.      883.00    0.000000   0.000313   281250.      3808.          0.0
      7     0.002592      0.000074       15.        3764.        927.      883.00    0.000000   0.000238   393750.      3764.          0.0
      8     0.002518      0.000068       14.        3455.       1191.      883.00    0.000000   0.000164   506250.      3455.          0.0
      9     0.002450      0.000057       11.        2882.       1456.      883.00   -0.000000   0.000097   618750.      2882.          0.0
     10     0.002394      0.000040        8.        2044.       1721.      883.00    0.000000   0.000040   731250.      2044.          0.0
     11     0.002353      0.0             4.         941.       1986.      883.00   -0.000000   0.0        843750.       941.          0.0
```

Figure B.11. Detailed output for single RU (total) (option 15 = 2) for Prob. 4.

APPENDIX C

OS-360 Fortran IV Program Statements

The listing that follows is known as an XREF listing. Each statement is numbered, for reference, consecutively from the first to the last statement. The variables and program statement numbers are indexed by their reference number. This listing facilitates finding each variable in the program and makes the logic much easier to follow.

A flow diagram of the program logic is included for reference.

```
                C     TEXAS A * M UNIVERSITY
                C     PILE DRIVING ANALYSIS BY THE WAVE EQUATION
                C     TEXAS A AND M PROGRAM REVISED 12/1/65 BY EAS
                C     PERMANENT SET,BLOWS PER INCH
                C     LOOSE,TIGHT,OR LIMITED MOTION AT JOINTS
                C     MAXIMUM STRESSES OR FORCES
                C     IOPT USED FOR OPTION.
                C     I,JT,JTM,LAMP,LAY,LT,LACK, ARE USED FOR CONTROL
                C     X AT END OF NAME = LAST PRECEDING VALUE EXCEPT IN MAX = MAXIMUM
                C     N ALWAYS MEANS NUMBER OF TIME INTERVAL.
                C     NOTATION FOLLOWS SMITHS ASCE PAPER CLOSELY. TO DECODE NOTE THAT
                C         NFMAXT = NO. OF TIME INTERVAL WHERE FORCE = MAXIMUM IN TENSION
ISN 0002         5000 REAL JPOINT,JSIDE,K,KPRIME,NPASS,NP1,KHOLD,CASE*8
ISN 0003         5001 INTEGER P,PPLUS1,PLESS1,PROB,PROBS
ISN 0004         5002 DIMENSION AREA(150),C(150),CX(150),CMAX(150),D(150),DX(150)
                     1 ,EMAX(150),DPRIME(150),ERES(150),F(150),FX(150),FMAXC(150),
                     2 FMAXT(150),K(150),KPRIME(150),LAM(150),NDMAX(150),
                     3 NFMAXC(150),NFMAXT(150),R(150),RU(150),SLACK(150),
                     4 UBLOWS(150),UFMAXC(150),URUTTL(150),V(150),
                     5  W(150),RULIST(150),RUHIL(30),RWENR(30),RWMICH(30),
                     6 XPLOT(50),YPLOT(50),STRESS(150),KHOLD(150),
                     7 FCMAX(50),NCMAX(50),FTMAX(50),NTMAX(50)
                C     24 OF EACH OF ABOVE SUFFICIENT FOR USUAL PROBLEMS
                C---- INPUT -- GENERAL
ISN 0005         5010 READ(5,5113) CASE,PROBS,TTDELT,P,SLACK(1),SLACK(2),SLACK(3),IOPT1,
                     1 IOPT2,IOPT3,IOPT4,IPRINT,NSEG1
ISN 0006              WRITE(6,5003)
ISN 0007         5003 FORMAT(1H1)
ISN 0008              IF(TTDELT.LE.0.) TTDELT=1.0
ISN 0010              IF(IOPT4.LE.0) IOPT4=2
ISN 0012              IF(IPRINT.LE.0) IPRINT=1
ISN 0014              IF(NSEG1.LE.0) NSEG1=2
ISN 0016              TDELTA=TTDELT
ISN 0017         5020 DELTAT =1./TDELTA
ISN 0018         5021 PPLUS1 = P+1
ISN 0019         5022 PLESS1 = P-1
ISN 0020         5030 READ  (5,5114)(W(M),M=1,P)
ISN 0021         5031 W(PPLUS1) = -0.0
                C-----CALCULATE PILE WEIGHT
ISN 0022              WPILE=0.
ISN 0023              DO 6 JT=NSEG1,P
ISN 0024             6 WPILE=WPILE+W(JT)
ISN 0025         5040 READ  (5,5115)(K(M),M=1,PLESS1)
                C     K(P) IS DETERMINED AT 5184
ISN 0026         5041 K(PPLUS1) = -0.0
ISN 0027         5083 DO 5084 M=1,P
ISN 0028              KHOLD(M)=K(M)
ISN 0029         5084 AREA(M) = 1.0
ISN 0030         5086 AREA(PPLUS1) = -0.0
ISN 0031         5087 IF(IOPT1-2)5090,5088,5088
ISN 0032         5088 READ  (5,5114)(AREA(M),M=1,P)
ISN 0033              IF(AREA(1).LE.0.) AREA(1)=1.0
ISN 0035              IF(AREA(P).LE.0.) AREA(P)=1.0
ISN 0037         5090 IF(IOPT2-2)5100,5092,5092
ISN 0038         5092 READ (5,5116)(RULIST(M),M=1,PPLUS1)
ISN 0039         5100 IF(IOPT3-2)5101,5104,5104
ISN 0040         5101 DO 5102 M=4,PLESS1
ISN 0041         5102 SLACK(M) = 0.0
ISN 0042         5103 GO TO 5105
ISN 0043         5104 READ (5,5114)(SLACK(M),M=1,PLESS1)
ISN 0044         5105 SLACK(P) = 1000.0
ISN 0045         5106 SLACK(PPLUS1) =  -0.0
ISN 0046         5110 DO 5111 M=4,P
ISN 0047         5111 ERES(M) = 1.0
ISN 0048         5112 ERES(PPLUS1) = -0.0
ISN 0049         5113 FORMAT(A6,I3,F10.4,I3,3F7.3,4I1,1X13,I2)
ISN 0050         5114 FORMAT(8F10.3)
ISN 0051         5115 FORMAT(8F10.0)
ISN 0052         5116 FORMAT(8F10.7)
ISN 0053         5117 FORMAT (I2,F8.2,I1,F9.0,F3.2,F6.0,3F3.2,F9.1,F4.1,I3,4F3.2,F9.0
                     1,5I1)
ISN 0054         5118 FORMAT(1H0,5H CASE,A7,4X,5H PROB,A6,74H RU PERCENTAGES ON DATA SHE
                     1ET PAGE 1 SHOULD TOTAL 100.0 BUT ACTUALLY TOTAL,F15.7)
                C---- DO 5570 SOLVES PROBLEMS ONE AFTER ANOTHER
ISN 0055              NC=1
ISN 0056         5120 DO 5570  I=1,PROBS
ISN 0057              K(NC)=KHOLD(NC)
ISN 0058         5121 READ(5,5117) PROB,W(1),NC,K(NC),EFF,ENERGY,ERES(1),ERES(2),ERES(3)
                     1 ,RUSUM,PERCNT,MO,QPOINT,QSIDE,JPOINT,JSIDE,FEXP,IOPT11,
                     2 IOPT12,IOPT13,IOPT14,IOPT15
ISN 0059              IF(IOPT12.LE.0) IOPT12=3
ISN 0061              VSTART= SQRT(64.4*EFF*(ENERGY/W(1)))
ISN 0062              DO 9009 M=1,50
ISN 0063              FTMAX(M)=0.
ISN 0064         9009 FCMAX(M)=0.
ISN 0065              NKCNT=0
ISN 0066         5140 RUTTLX = 0.0
ISN 0067         5141 BLOWSX = 0.0
ISN 0068         5150 V(1) = VSTART
ISN 0069         5152 LT = 0
                C---- FIRST DETERMINE VALUE OF RUTOTL
ISN 0070         5154 IF(IOPT11-2)5151,5160,5151
```

```
                C     FOR CURVE PLOTTING
ISN 0071         5151 RUTOTL = W(1)* V(1)**2/12.0
ISN 0072         5153 GO TO 5170
                C     FOR SINGLE PROBLEM
ISN 0073         5160 RUTOTL=RUSUM
ISN 0074              GO TO 5170
                C     COMPUTER CYCLES FROM 707 NEAR END OF PROGRAM
ISN 0075          701 SLOPE = (RUTOTL-RUTTLX)/(BLOWS-BLOWSX)
ISN 0076              SLOPE=AMAX1(10000.,SLOPE)
ISN 0077              IF(BLOWS-7.0)5164,702,702
ISN 0078         5164 IF(IOPT4-2)5165,703,703
ISN 0079          702 IF(BLOWS-20.0)704,704,705
ISN 0080         5165 DB = 1.00
ISN 0081              GO TO 706
ISN 0082          703 DB = 1.25
ISN 0083              GO TO 706
ISN 0084          704 DB = 2.5
ISN 0085              GO TO 706
ISN 0086          705 DB = 5.0
ISN 0087              GO TO 706
ISN 0088          706 RUTTLX = RUTOTL
ISN 0089              RUTOTL = RUTTLX+(DB*SLOPE)
ISN 0090              BLOWSX = BLOWS
                C---- SECOND DETERMINE ALL VALUES OF RU(M)
ISN 0091         5170 DO 13 M=1,MO
ISN 0092           13 RU(M) = 0.0
ISN 0093         5171 RUPINT = (PERCNT/100.0)*RUTOTL
ISN 0094         5172 IF(IOPT12-2)143,146,5176
                C     FOR UNIFORM DISTRIBUTION
ISN 0095          143 DO 144 M=MO,P
ISN 0096          144 RU(M) = (RUTOTL-RUPINT)/FLOAT(P-MO+1)
ISN 0097         5173 RU(PPLUS1) = RUPINT
ISN 0098              GO TO 713
                C     FOR TRIANGULAR DISTRIBUTION
ISN 0099          146 DO 145 M=MO,P
ISN 0100          145 RU(M) = (2.0*(RUTOTL-RUPINT)*(FLOAT(M-MO)+0.5))/(FLOAT(P-MO+1))**2
ISN 0101         5175 RU(PPLUS1) = RUPINT
ISN 0102              GO TO 713
                C     FOR DISTRIBUTION PER RU LIST ON DATA SHEET
ISN 0103         5176 TOTAL = 0.0
ISN 0104              DO 5177 M=1,PPLUS1
ISN 0105         5177 TOTAL = TOTAL+RULIST(M)
ISN 0106         5178 IF((ABS(TOTAL-100.0))-2.0)5180,5180,5179
ISN 0107         5179 WRITE  (6,5118)CASE,PROB,TOTAL
ISN 0108              GO TO 5570
ISN 0109         5180 DO 5181 M=1,PPLUS1
ISN 0110         5181 RU(M) = (RULIST(M)/100.0)*RUTOTL
ISN 0111              GO TO 713
                C---- THIRD DETERMINE STARTING VALUES OF V(M)
ISN 0112          713 V(1)=VSTART
ISN 0113              DO 180 M=2,P
ISN 0114          180 V(M) = 0.0
ISN 0115         5183 V(PPLUS1) = -0.0
                C---- FOURTH DETERMINE VALUE FOR K(P)
ISN 0116         5184 K(P) = RU(PPLUS1)/QPOINT
                C     FIFTH CHANGE CYCLE COUNT
ISN 0117         5186 LT = LT + 1
                C----CHECK ON DELTAT
ISN 0118              CALL DELTCK(NPASS,TTDELT,P,W,K,TDELTA,DELTAT,N2)
                C----END DELTAT CHECK
                C---- ASSIGN OTHER VALUES REQUIRED (TEXAS A AND M REP1)
ISN 0119              DO 5218 M=1,P
ISN 0120            32 KPRIME(M) =RU(M)/QSIDE
ISN 0121              C(M) = 0.0
ISN 0122              F(M) = 0.0
ISN 0123              CMAX(M) = 0.0
ISN 0124              LAM(M)=1
ISN 0125              D(M) = 0.0
ISN 0126              NFMAXC(M) = 0
ISN 0127              NFMAXT(M) = 0
ISN 0128              DMAX(M) = 0.0
ISN 0129              NDMAX(M) = 0
ISN 0130              FMAXC(M) = 0.0
ISN 0131              FMAXT(M) = 0.0
ISN 0132              R(M) = 0.0
ISN 0133         5218 DPRIME(M) = 0.0
ISN 0134              KPRIME(PPLUS1)=0.
ISN 0135              DPRIMP = 0.0
ISN 0136              LAMP   = 1
                C---- SIXTH PRINT INPUT FOR ONE PROBLEM
ISN 0137         5190 WRITE  (6,5200)CASE,PROB,PROBS
ISN 0138         5191 WRITE  (6,5201)
ISN 0139         5192 WRITE(6,5202) TDELTA,P,IOPT1,IOPT2,IOPT3,IOPT4,      IOPT11,
                    1 IOPT12,IOPT13,IOPT14,IOPT15,FEXP
ISN 0140         5193 WRITE  (6,5203)
ISN 0141         5194 WRITE(6,5204) ENERGY,EFF,RUTOTL,PERCNT,MO,QPOINT,QSIDE,JPOINT,JSI
                    1DE,N2
ISN 0142         5195 WRITE  (6,5205)
ISN 0143         5196 WRITE (6,5206)(M,W(M),K(M),AREA(M),RU(M),SLACK(M),ERES(M),
                    1     V(M),KPRIME(M),M=1,PPLUS1)
ISN 0144         5200 FORMAT(///27H TEXAS A * M UNIVERSITY    ,3X,22H PILE DRIVING ANALY
                    1SIS,4X,9H CASE NO.,A7,3X,12H PROBLEM NO.,I4,3H OF,I4)
ISN 0145         5201 FORMAT(2X10H 1/DELTA T3X1HP4X62HOPTIONS     1    2    3    4
                    1      11   12   13   14   1510X10HEXP. FORCE)
ISN 0146         5202 FORMAT(F11.1,I5,11X4I5,10X5I5,F18.0)
ISN 0147         5203 FORMAT(113H ENERGY    HAMMER EFFIENCY       RU(TOTAL)   PERCENT UN
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                  IDER POINT   MO  Q(POINT)  Q(SIDE)  J(POINT)  J(SIDE)    N2)
ISN 0148       5204 FORMAT(2F10.2,10XF12.1,F16.1,I11,F10.2,F9.2,F10.2,F9.2,I7)
ISN 0149       5206 FORMAT(I3, F14.3,E15.7,F10.3,2F14.3,F9.2,F11.2,E15.7)
ISN 0150       5205 FORMAT(3H  M,7X,5H W(M),7X,5H K(M),7X,8H AREA(M),6X,6H RU(M),7X,41
                   1H SLACK(M)  ERES(M)  VSTART(M)   KPRIME(M))
                  C---- EFFECT OF GRAVITY BEFORE RAM STRIKES--TEXAS A AND M SMITHS GRAVITY
ISN 0151       5258 IF(IOPT14-2)5220,5221,5221
ISN 0152       5220 WTOTAL = 0.0
ISN 0153            RTOTAL = 0.0
ISN 0154            DO 5 JT=2,PPLUS1
ISN 0155            WTOTAL = WTOTAL + W(JT)
ISN 0156          5 RTOTAL = RTOTAL + RU(JT)
ISN 0157            DO 8 JT = 2,PLESS1
ISN 0158            R(JT) = (RU(JT)*WTOTAL)/RTOTAL
ISN 0159          8 F(JT) =  F(JT-1)+W(JT)-R(JT)
ISN 0160            IF(K(P))67,66,67
ISN 0161         66 IF(KPRIME(P))67,63,67
ISN 0162         67 D(P) = (F(PLESS1)+W(P))/(KPRIME(P)+K(P))
ISN 0163            IF(QSIDE-D(P))64,65,65
ISN 0164         64 R(P) = RU(P)
ISN 0165            F(P) = F(PLESS1) + W(P) - R(P)
ISN 0166            D(P) = F(P)/K(P)
ISN 0167            GO TO 63
ISN 0168         65 R(P) = D(P)*KPRIME(P)
ISN 0169            F(P) = D(P)* K(P)
ISN 0170         63 CONTINUE
ISN 0171            DO 111 JT = 1,PLESS1
ISN 0172            JTM = P-JT
ISN 0173            C(JTM) = F(JTM)/K(JTM)
ISN 0174            D(JTM) = D(JTM+1)+C(JTM)
ISN 0175            DPRIME(JTM) = D(JTM)-WTOTAL*QSIDE/RTOTAL
ISN 0176        111 CONTINUE
ISN 0177            DO 8000 M=1,P
ISN 0178       8000 STRESS(M)=F(M)/AREA(M)
ISN 0179       5221 N=0
ISN 0180            LAY = 1
ISN 0181       5230 IF(IOPT15-2)5240,5231,5240
ISN 0182       5231 WRITE(6,5234)N,DPRIMP,N2
ISN 0183       5232 WRITE  (6,5235)
ISN 0184       5233 WRITE(6,5236)(M,D(M),C(M),STRESS(M),F(M),R(M),W(M),V(M),DPRIME(M),
                   1KPRIME(M),FMAXC(M),FMAXT(M),M=1,P)
ISN 0185            NKCNT=0
ISN 0186       5234 FORMAT(//18H TIME INTERVAL N =I6,7X18HNET PENETRATION = F10.6,
                   17X5HN1 = I5,5X5HN2 = I5)
ISN 0187       5235 FORMAT(120H SEGMENT M      D(M)       C(M)   STRESS(M)       F(M)
                   1 R(M)       W(M)       V(M) DPRIME(M) KPRIME(M)  FMAXC(M)  FMAXT(M))
ISN 0188       5236 FORMAT(I8,F11.6,F10.6,F11.0,2F10.0,F10.2,2F10.6,3F10.0)
                  C---- DYNAMIC COMPUTATION BASED ON SMITHS PAPER MODIFIED (TEXAS REPN)
ISN 0189       5240 LACK = 1
ISN 0190       5241 DO 68 M=1,P
                  C      68 IS BETWEEN 5439 AND 5440
ISN 0191            D(M) = D(M)+V(M)*12.0*DELTAT
ISN 0192            IF(DMAX(M)-D(M))20,21,21
ISN 0193         20 DMAX(M) = D(M)
ISN 0194            NDMAX(M) = N + 1
ISN 0195         21 CX(M) = C(M)
ISN 0196            IF(M-P)34,5400,34
ISN 0197         34 C(M) = D(M)-D(M+1)-V(M+1)*12.0*DELTAT
                  C      STATEMENT 34 MUST USE A COMPUTED VALUE FOR THE ACTUAL D(M+1)
ISN 0198       5242 IF(C(M))5243,30,30
ISN 0199       5243 IF(ABS(C(M))-SLACK(M))5244,5244,5246
ISN 0200       5244 C(M) = 0.0
ISN 0201       5245 GO TO 30
ISN 0202       5246 C(M) = C(M)+SLACK(M)
                  C      NOTE THAT ONLY A NEGATIVE VALUE OF C(M) RESULTS FROM 5246
ISN 0203         30 FX(M) = F(M)
                  C      A TEXAS ROUTINE FOR B(M) IS OMITTED HERE
ISN 0204       5250 IF(IOPT4-2)5300,36,5300
                  C---- 36 TO 35 IS A TEXAS ROUTINE REPLACING SMITH ROUTINE 3 OR 4
ISN 0205         36 IF(ABS(ERES(M)-1.0)-.00001)38,38,14
ISN 0206         38 F(M) = C(M)*K(M)
ISN 0207            GO TO 5400
ISN 0208         14 IF(C(M)-CX(M))12,35,15
ISN 0209         15 F(M) = FX(M)+((C(M)-CX(M))*K(M))
ISN 0210            GO TO 35
ISN 0211         12 F(M) = FX(M)+((C(M)-CX(M))*K(M)/ERES(M)**2)
ISN 0212         35 F(M) = AMAX1(0.0,F(M))
ISN 0213            GO TO 5400
                  C      A TEXAS ROUTINE FOR GAMMA IS OMITTED HERE
                  C---- SMITH ROUTINE 3 OR 4
ISN 0214       5300 IF(ERES(M)-1.00)5302,5301,5301
ISN 0215       5301 F(M) = C(M)*K(M)
ISN 0216            GO TO 5400
ISN 0217       5302 IF(C(M))5303,5303,5304
ISN 0218       5303 F(M) = 0.0
ISN 0219            GO TO 5400
ISN 0220       5304 IF(C(M)-CMAX(M))5306,5305,5305
ISN 0221       5305 CMAX(M) = C(M)
ISN 0222            F(M) = C(M)*K(M)
ISN 0223            GO TO 5400
ISN 0224       5306 F(M)=(K(M)/ERES(M)**2)*C(M)-(1./ERES(M)**2-1.)*K(M)*CMAX(M)
ISN 0225            F(M) = AMAX1(F(M),0.0)
ISN 0226            GO TO 5400
ISN 0227       5400 IF(M.GT.1) GO TO 48
ISN 0229            IF(FEXP.LE.0.) GO TO 48
ISN 0231            NP1=N+1
```

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ISN 0232            IF(NP1.GT.(0.0125/DELTAT)) GO TO 48
ISN 0234            IF(NP1-0.01/DELTAT)46,46,90
ISN 0235         46 IF(F(1)-FX(1))47,48,48
ISN 0236         47 F(1)=AMAX1(F(1),FEXP,0.)
ISN 0237            GO TO 48
ISN 0238         90 F(1)=AMAX1(0.0,FEXP*(1.0-(DELTAT*(NP1-0.01/DELTAT)/0.0025)))
ISN 0239         48 IF(KPRIME(M))50,55,50
ISN 0240         50 IF(DPRIME(M)-D(M)+QSIDE)51,52,52
ISN 0241         51 DPRIME(M) = D(M)-QSIDE
ISN 0242         52 CONTINUE
ISN 0243            IF(DPRIME(M)-D(M)-QSIDE)53,53,54
ISN 0244         54 DPRIME(M) = D(M)+QSIDE
ISN 0245         53 CONTINUE
ISN 0246       5410 LAP  =   LAM(M)
ISN 0247            GO TO(10,57),LAP
ISN 0248         10 IF(D(M)-DPRIME(M)-QSIDE)56,57,57
ISN 0249         56 R(M) = (D(M)-DPRIME(M))*KPRIME(M)*(1.0+JSIDE*V(M))
ISN 0250            GO TO 55
ISN 0251         57 R(M) = (D(M)-DPRIME(M)+JSIDE*QSIDE*V(M))*KPRIME(M)
ISN 0252            LAM(M)   = 2
ISN 0253         55 CONTINUE
ISN 0254         73 IF(M-P)71,74,71
ISN 0255         74 IF(DPRIMP-D(P)+QPOINT)75,76,76
ISN 0256         75 DPRIMP = D(P)-QPOINT
ISN 0257         76 CONTINUE
ISN 0258            LAMP = LAMP
ISN 0259            GO TO (77,78),LAMP
ISN 0260         77 IF(D(P)-DPRIMP-QPOINT)79,78,78
ISN 0261         79 F(P) = (D(P)-DPRIMP)*K(P)*(1.0+JPOINT*V(P))
ISN 0262            GO TO 171
ISN 0263         78 F(P) = (D(P)-DPRIMP+JPOINT*QPOINT*V(P))*K(P)
ISN 0264            LAMP   = 2
ISN 0265        171 F(P) = AMAX1(0.0,F(P))
ISN 0266         71 CONTINUE
                C     GRAVITY OPTION
ISN 0267       5420 IF(IOPT14-2)5421,5423,5423
ISN 0268       5421 IF(LACK-2)58,72,72
ISN 0269         58 V(1) = V(1)-(F(1)+R(1)-W(1))*32.17*DELTAT/W(1)
ISN 0270            LACK = 2
ISN 0271            GO TO 5429
ISN 0272         72 V(M) = V(M)+(F(M-1)-F(M)-R(M)+W(M))*32.17*DELTAT/W(M)
ISN 0273       5422 GO TO 5429
ISN 0274       5423 IF(LACK-2)5424,5427,5427
ISN 0275       5424 V(1) = V(1)-(F(1)+R(1))*32.17*DELTAT/W(1)
ISN 0276       5425 LACK = 2
ISN 0277            GO TO 5429
ISN 0278       5427 V(M) = V(M)+(F(M-1)-F(M)-R(M))*32.17*DELTAT/W(M)
ISN 0279       5429 CONTINUE
ISN 0280            IF(M.GT.1) GO TO 5430
ISN 0282            IF(F(1).LE.0..AND.V(1).LE.-0.1) V(1)=-VSTART
ISN 0284       5430 FMAXC(M) = AMAX1(FMAXC(M),F(M))
ISN 0285            FMAXT(M) = AMIN1(FMAXT(M),F(M))
ISN 0286       5439 IF(FMAXC(M)-F(M))166,167,166
ISN 0287        167 NFMAXC(M) = N+1
ISN 0288        166 IF(FMAXT(M)-F(M))68,69,68
ISN 0289         69 NFMAXT(M) = N+1
ISN 0290         68 STRESS(M)=F(M)/AREA(M)
ISN 0291            N=N+1
                C     THIS IS END OF DO 68 STARTING AT 5241
ISN 0292       5440 IF(IOPT15-2)5444,5441,5444
ISN 0293       5441 IF(N-1)7000,7001,7000
ISN 0294       7000 NKONT=NKONT+1
ISN 0295            IF(NKONT-IPRINT)5444,7001,5444
ISN 0296       7001 WRITE  (6,5234)N,DPRIMP,N2
ISN 0297            WRITE  (6,5235)
ISN 0298            WRITE(6,5236)(M,D(M),C(M),STRESS(M),F(M),R(M),W(M),V(M),DPRIME(M),
                   1KPRIME(M),FMAXC(M),FMAXT(M),M=1,P)
ISN 0299       7003 NKONT=0
ISN 0300       5444 GO TO (5443,192),LAY
ISN 0301       5443 IF((V(P)+0.1).GT.0.) GO TO 192
ISN 0303            WV=0.0
ISN 0304            DO 193 JA=NSEG1,P
ISN 0305        193 WV=WV+W(JA)*V(JA)
ISN 0306            IF(V(1).LT.0..AND.WV.LT.0..AND.DMAX(P).GT.D(P)) GO TO 190
ISN 0308            GO TO 192
ISN 0309        190 LAY=2
ISN 0310            GO TO (192,194,192),IOPT15
ISN 0311        194 WRITE(6,5234) N,DPRIMP,N2
ISN 0312            WRITE(6,5235)
ISN 0313            WRITE(6,5236)(M,D(M),C(M),STRESS(M),F(M),R(M),W(M),V(M),DPRIME(M),
                   1KPRIME(M),FMAXC(M),FMAXT(M),M=1,P)
ISN 0314        192 IF(V(2)/VSTART-3.1)61,60,60
ISN 0315         60 WRITE  (6, 105)
ISN 0316        105 FORMAT(74H  THE RATIO OF THE VELOCITY OF W(2) TO THE VELOCITY OF T
                   1HE RAM EXCEEDS 3.1)
ISN 0317            GO TO 5570
ISN 0318         61 IF(V(P)/VSTART-3.1)163,62,62
ISN 0319         62 WRITE  (6, 106)
ISN 0320            GO TO 5570
ISN 0321        106 FORMAT(74H  THE RATIO OF THE VELOCITY OF W(P) TO THE VELOCITY OF T
                   1HE RAM EXCEEDS 3.1)
               C --- END OF TEXAS REPN
ISN 0322        163 CONTINUE
ISN 0323            IF(LAY.EQ.2) GO TO 5447
ISN 0325            IF(N-N2)5240,5447,5447
               C---- 5240 CYCLES FOR NEXT TIME INTERVAL
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ISN 0326       5447 DO 5449 M=1,P
ISN 0327       5448 FMAXC(M) = FMAXC(M)/AREA(M)
ISN 0328       5449 FMAXT(M)=FMAXT(M)/(-AREA(M))
ISN 0329            GO TO(5442,5442,5553),IOPT15
ISN 0330       5442 WRITE  (6,2105)
ISN 0331       5550 WRITE(6,2106)(M,AREA(M),NFMAXC(M),FMAXC(M),NFMAXT(M),FMAXT(M),DMAX
                   1(M),D(M),V(M),M=1,P)
ISN 0332            BLOWS=0.0
ISN 0333       5553 IF(DPRIMP.GT.0.0) BLOWS=1.0/DPRIMP
ISN 0335       5551 UBLOWS(LT) = BLOWS
ISN 0336            URUTTL(LT) = RUTOTL
ISN 0337            UFMAXC(LT) = FMAXC(P)*AREA(P)
               C    INITIAL U ABOVE IDENTIFIES FIGURES USED IN SUMMARY
ISN 0338            GO TO(5552,5552, 150),IOPT15
ISN 0339       5552 WRITE (6,2107)DPRIMP,BLOWS,N
ISN 0340       2105 FORMAT(//103H SEGMENT     AREA     TIME N  MAX C STRESS      TIME N
                   1 MAX T STRESS      CMAX(M)       D(M)          V(M))
ISN 0341       2106 FORMAT(I3,F15.3,I8,F12.0,I14,F12.0,F16.6,F10.6,F13.2)
ISN 0342       2107 FORMAT(24H PERMANENT SET OF PILE =F15.8, 38H INCHES    NUMBER OF B
                  1LOWS PER INCH = F16.8,22H    TOTAL INTERVALS = I8)
ISN 0343        150 CONTINUE
ISN 0344       5558 DO 5563 M=NSEG1,P
ISN 0345            FTMAX(LT)=AMAX1(FTMAX(LT),FMAXT(M))
ISN 0346            FCMAX(LT)=AMAX1(FCMAX(LT),FMAXC(M))
ISN 0347            IF(FCMAX(LT)-FMAXC(M))5560,5561,5560
ISN 0348       5561 NCMAX(LT)=M
ISN 0349       5560 IF(FTMAX(LT)-FMAXT(M))5563,5562,5563
ISN 0350       5562 NTMAX(LT)=M
ISN 0351       5563 CONTINUE
ISN 0352       5555 IF(IOPT11-2)5556,5570,5570
ISN 0353       5556 IF (DPRIMP-0.001)59,707,707
ISN 0354        707 IF (BLOWS-60.0)701,701,59
ISN 0355         59 CONTINUE
ISN 0356            WRITE (6,803) CASE,PROB
ISN 0357            WRITE (6,804) QPOINT,JPOINT
ISN 0358            WRITE (6,805)
ISN 0359            DO 801 J=1,LT
ISN 0360            URUTON=URUTTL(J)/2000.
ISN 0361        801 WRITE(6,802) UBLOWS(J),URUTTL(J),URUTON,UFMAXC(J),FCMAX(J),NCMAX(J
                   2),FTMAX(J),NTMAX(J)
ISN 0362        802 FORMAT(4XF7.4,F10.0,1H-F5.0,1HTF13.0,F13.0,4XI2,F13.0,4XI2)
ISN 0363        803 FORMAT (1HO,10X,22H PILE DRIVING ANALYSIS,
                   1  10X,12H CASE NUMBER,3X,A6,10X,15H PROBLEM NUMBER,3X,I3)
ISN 0364        804 FORMAT(19X,9HQPOINT = F5.2,11X,9HJPOINT = F5.2)
ISN 0365        805 FORMAT(2X13HBLOWS PER IN.2X7HRUTOTAL7X11HPOINT FORCE2X12HMAX C STR
                   1ESS2X3HSEG2X12HMAX T STRESS2X3HSEG//)
               C-----PLOTTING ROUTINE
ISN 0366            IF(IOPT13-1)5570,5574,5574
ISN 0367        5574 CALL DRAW(WTOTAL,QRUTTL,UBLOWS,LT,CASE,PROB)
               C-----END PLOTTING ROUTINE
ISN 0368        5570 WRITE(6,5572)
               C    DO 5570 STARTS AT 5120
ISN 0369        5572 FORMAT(1H1)
ISN 0370        5571 GO TO 5010
ISN 0371            END
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*****F O R T R A N C R O S S R E F E R E N C E L I S T I N G*****

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SYMBOL  INTERNAL STATEMENT NUMBERS
C       0004  0121  0173  0174  0184  0195  0197  0198  0199  0200  0202  0202  0206  0208  0209  0211  0215  0217  0220
        0221  0222  0224  0298  0313
D       0004  0125  0162  0163  0166  0168  0169  0174  0174  0175  0184  0191  0191  0192  0193  0197  0197  0240  0241
        0243  0244  0248  0249  0251  0255  0256  0260  0261  0263  0298  0306  0313  0331
F       0004  0122  0159  0159  0162  0165  0165  0166  0169  0173  0178  0184  0203  0206  0209  0211  0212  0212  0215
        0218  0222  0224  0225  0225  0235  0236  0236  0238  0261  0263  0265  0265  0269  0272  0272  0275  0278  0278
        0282  0284  0285  0286  0288  0290  0298  0313
I       0056
J       0359  0360  0361  0361  0361  0361  0361  0361  0361
K       0002  0004  0025  0026  0028  0057  0058  0116  0118  0143  0160  0162  0166  0169  0173  0206  0209  0211  0215
        0222  0224  0224  0261  0263
M       0020  0020  0020  0025  0025  0025  0027  0028  0028  0029  0032  0032  0032  0038  0038  0038  0040  0041  0043
        0043  0043  0046  0047  0062  0063  0064  0091  0092  0095  0096  0099  0100  0100  0104  0105  0109  0110  0110
        0113  0114  0119  0120  0120  0121  0122  0123  0124  0125  0126  0127  0128  0129  0130  0131  0132  0133  0143
        0143  0143  0143  0143  0143  0143  0143  0143  0143  0143  0177  0178  0178  0178  0184  0184  0184  0184  0184
        0184  0184  0184  0184  0184  0184  0184  0184  0184  0190  0191  0191  0191  0192  0192  0193  0193  0194  0195
        0195  0196  0197  0197  0197  0197  0198  0199  0199  0200  0202  0202  0202  0203  0203  0205  0206  0206  0206
        0206  0208  0209  0209  0209  0209  0209  0211  0211  0211  0211  0211  0211  0212  0212  0214  0215  0215  0215
        0217  0218  0220  0220  0221  0221  0222  0222  0222  0224  0224  0224  0224  0224  0224  0224  0225  0225  0227
        0239  0240  0240  0241  0241  0243  0243  0244  0244  0246  0248  0248  0249  0249  0249  0249  0249  0251  0251
        0251  0251  0251  0252  0254  0272  0272  0272  0272  0272  0272  0272  0278  0278  0278  0278  0278  0278  0280
        0284  0284  0284  0285  0285  0285  0286  0286  0287  0288  0288  0289  0290  0290  0290  0298  0298  0298  0298
        0298  0298  0298  0298  0298  0298  0298  0298  0298  0298  0313  0313  0313  0313  0313  0313  0313  0313  0313
        0313  0313  0313  0313  0313  0326  0327  0327  0327  0328  0328  0328  0331  0331  0331  0331  0331  0331  0331
        0331  0331  0331  0331  0344  0345  0346  0347  0348  0349  0350
N       0179  0182  0194  0231  0287  0289  0291  0291  0293  0296  0311  0325  0339
P       0003  0005  0018  0019  0020  0023  0027  0032  0035  0035  0044  0046  0095  0096  0099  0100  0113  0116  0118
        0119  0139  0160  0161  0162  0162  0162  0162  0163  0164  0164  0165  0165  0165  0166  0166  0166  0168  0168
        0168  0169  0169  0169  0172  0177  0184  0190  0196  0254  0255  0256  0260  0261  0261  0261  0261  0263  0263
        0263  0264  0265  0265  0298  0301  0304  0306  0306  0313  0318  0326  0331  0337  0337  0344
R       0004  0132  0158  0159  0164  0165  0168  0184  0249  0251  0269  0272  0275  0278  0298  0313
V       0004  0068  0071  0112  0114  0115  0143  0184  0191  0197  0249  0251  0261  0263  0269  0269  0272  0272  0275
        0275  0278  0278  0282  0282  0298  0301  0305  0306  0313  0314  0318  0331
W       0004  0020  0021  0024  0058  0061  0071  0118  0143  0155  0159  0162  0165  0184  0269  0269  0272  0272  0275
        0275  0298  0305  0313
CX      0004  0195  0208  0209  0211
DB      0080  0082  0084  0086  0089
DX      0004
FX      0004  0203  0209  0211  0235
JA      0304  0305  0305
JT      0023  0024  0154  0155  0156  0157  0158  0158  0159  0159  0159  0159  0171  0172
LT      0069  0117  0117  0335  0336  0337  0345  0345  0346  0346  0347  0348  0349  0350  0359  0367
MC      0058  0091  0095  0096  0099  0100  0100  0141
NC      0055  0057  0057  0058  0058
N2      0118  0141  0182  0296  0311  0325
RU      0004  0092  0096  0097  0100  0101  0110  0116  0120  0143  0156  0158  0164
```

*****FORTRAN CROSS REFERENCE LISTING*****

SYMBOL	INTERNAL STATEMENT NUMBERS														
WV	0303	0305	0305	0306											
ABS	0106	0199	0205												
EFF	0058	0061	0141												
JTM	0172	0173	0173	0173	0174	0174	0174	0175	0175						
LAM	0004	0124	0246	0252											
LAP	0246	0247													
LAY	0180	0300	0309	0323											
NP1	0002	0231	0232	0234	0238										
AREA	0004	0029	0030	0032	0033	0033	0035	0035	0143	0178	0290	0327	0328	0331	0337
CASE	0002	0005	0107	0137	0356	0367									
CMAX	0004	0123	0220	0221	0224										
DMAX	0004	0128	0192	0193	0306	0331									
DRAW	0367														
ERES	0004	0047	0048	0058	0058	0058	0143	0205	0211	0214	0224	0224			
FEXP	0058	0139	0229	0236	0238										
LACK	0189	0268	0270	0274	0276										
LAMP	0136	0258	0258	0259	0264										
PROB	0003	0058	0107	0137	0356	0367									
SQRT	0061														
AMAX1	0076	0212	0225	0236	0238	0265	0284	0345	0346						
AMIN1	0285														
BLOWS	0075	0077	0079	0090	0332	0333	0335	0339	0354						
FCMAX	0004	0064	0346	0346	0347	0361									
FLOAT	0096	0100	0100												
FMAXC	0004	0130	0184	0284	0284	0286	0298	0313	0327	0327	0331	0337	0346	0347	
FMAXT	0004	0131	0184	0285	0285	0288	0298	0313	0328	0328	0331	0345	0349		
FTMAX	0004	0063	0345	0345	0349	0361									
IOPT1	0005	0031	0139												
IOPT2	0005	0037	0139												
IOPT3	0005	0039	0139												
IOPT4	0005	0010	0010	0079	0139	0204									
JSIDE	0002	0058	0141	0249	0251										
KHOLD	0002	0004	0028	0057											
NCMAX	0004	0348	0361												
NDMAX	0004	0129	0194												
NKONT	0065	0185	0294	0294	0295	0299									
NPASS	0002	0118													
NSEG1	0005	0014	0014	0023	0304	0344									
NTMAX	0004	0350	0361												
PROBS	0003	0005	0056	0137											
QSIDE	0058	0120	0141	0163	0175	0240	0241	0243	0244	0248	0251				
RUHIL	0004														
RUSUM	0058	0073													
RWENR	0004														
SLACK	0004	0005	0005	0005	0041	0043	0044	0045	0143	0199	0202				
SLOPE	0075	0076	0076	0089											

*****FORTRAN CROSS REFERENCE LISTING*****

SYMBOL	INTERNAL STATEMENT NUMBERS														
TOTAL	0103	0105	0105	0106	0107										
WPILE	0022	0024	0024												
XPLOT	0004														
YPLOT	0004														
BLOWSX	0067	0075	0090												
DELTAT	0017	0118	0191	0197	0232	0234	0238	0238	0269	0272	0275	0278			
DELTCK	0118														
DPRIME	0004	0133	0175	0184	0240	0241	0243	0244	0248	0249	0251	0298	0313		
DPRIMP	0135	0182	0255	0256	0260	0261	0263	0296	0311	0333	0333	0339	0353		
ENERGY	0058	0061	0141												
IOPT11	0058	0070	0139	0352											
IOPT12	0058	0059	0059	0094	0139										
IOPT13	0058	0139	0366												
IOPT14	0058	0139	0151	0267											
IOPT15	0058	0139	0181	0292	0310	0329	0338								
IPRINT	0005	0012	0012	0295											
JPOINT	0002	0058	0141	0261	0263	0357									
KPRIME	0002	0004	0120	0134	0143	0161	0162	0168	0184	0239	0249	0251	0298	0313	
NFMAXC	0004	0126	0287	0331											
NFMAXT	0004	0127	0289	0331											
PERCNT	0058	0093	0141												
PLESS1	0003	0019	0025	0040	0043	0157	0162	0165	0171						
PPLUS1	0003	0018	0021	0026	0030	0038	0045	0048	0097	0101	0104	0109	0115	0116	0134	0143	0154
QPOINT	0058	0116	0141	0255	0256	0260	0263	0357							
RTOTAL	0153	0156	0156	0158	0175										
RULIST	0004	0038	0105	0110											
RUPINT	0093	0096	0097	0100	0101										
RUTOTL	0071	0073	0075	0088	0089	0093	0096	0100	0110	0141	0336				
RUTTLX	0066	0075	0088	0089											
RWHICH	0004														
STRESS	0004	0178	0184	0290	0298	0313									
TDELTA	0016	0017	0118	0139											
TTDELT	0005	0008	0008	0016	0118										
URLOWS	0004	0335	0361	0367											
UFMAXC	0004	0337	0361												
URUTON	0360	0361													
URUTTL	0004	0336	0360	0361	0367										
VSTART	0061	0068	0112	0282	0314	0318									
WTOTAL	0152	0155	0155	0158	0175	0367									

*****FORTRAN CROSS REFERENCE LISTING*****

LABEL	DEFINED	REFERENCES					
5	0156	0154					
6	0024	0023					
8	0159	0157					
10	0248	0247					
12	0211	0208					
13	0092	0091					
14	0208	0205					
15	0209	0208					
20	0193	0192					
21	0195	0192	0192				
30	0203	0198	0198	0201			
32	0120						
34	0197	0196	0196				
35	0212	0208	0210				
36	0205	0204					
38	0206	0205	0205				
46	0235	0234	0234				
47	0236	0235					
48	0239	0227	0229	0232	0235	0235	0237
50	0240	0239	0239				
51	0241	0240					
52	0242	0240	0240				
53	0245	0243	0243				
54	0244	0243					
55	0253	0239	0250				
56	0249	0248					
57	0251	0247	0248	0248			
58	0269	0268					
59	0355	0353	0354				
60	0315	0314	0314				
61	0318	0314					
62	0319	0318	0318				
63	0170	0161	0167				
64	0164	0163					
65	0168	0163	0163				
66	0161	0160					
67	0162	0160	0160	0161	0161		
68	0290	0190	0288	0288			
69	0289	0288					
71	0266	0254	0254				
72	0272	0268	0268				
73	0254						
74	0255	0254					
75	0256	0255					
76	0257	0255	0255				
77	0260	0259					

*****FORTRAN CROSS REFERENCE LISTING*****

LABEL	DEFINED	REFERENCES				
78	0263	0259	0260	0260		
79	0261	0260				
90	0238	0234				
105	0316	0315				
106	0321	0319				
111	0176	0171				
143	0095	0094				
144	0096	0095				
145	0100	0099				
146	0099	0094				
150	0343	0338				
163	0322	0318				
166	0288	0286	0286			
167	0287	0286				
171	0265	0262				
180	0114	0113				
190	0309	0306				
192	0314	0300	0301	0308	0310	0310
193	0305	0304				
194	0311	0310				
701	0075	0354	0354			
702	0079	0077	0077			
703	0082	0078	0078			
704	0084	0079	0079			
705	0086	0079				
706	0088	0081	0083	0085	0087	
707	0354	0353	0353			
713	0112	0098	0102	0111		
801	0361	0359				
802	0362	0361				
803	0363	0356				
804	0364	0357				
805	0365	0358				
2105	0340	0330				
2106	0341	0331				
2107	0342	0339				
5003	0007	0006				
5010	0005	0370				
5020	0017					
5021	0018					
5022	0019					
5030	0020					
5031	0021					
5040	0025					
5041	0026					
5083	0027					

*****FORTRAN CROSS REFERENCE LISTING*****

LABEL	DEFINED	REFERENCES
5084	0029	0027
5086	0030	
5087	0031	
5088	0032	0031 0031
5090	0037	0031
5092	0038	0037 0037
5100	0039	0037
5101	0040	0039
5102	0041	0040
5103	0042	
5104	0043	0039 0039
5105	0044	0042
5106	0045	
5110	0046	
5111	0047	0046
5112	0048	
5113	0049	0005
5114	0050	0020 0032 0043
5115	0051	0025
5116	0052	0038
5117	0053	0058
5118	0054	0107
5120	0056	
5121	0058	
5140	0066	
5141	0067	
5150	0068	
5151	0071	0070 0070
5152	0069	
5153	0072	
5154	0070	
5160	0073	0070
5164	0078	0077
5165	0080	0078
5170	0091	0072 0074
5171	0093	
5172	0094	
5173	0097	
5175	0101	
5176	0103	0094
5177	0105	0104
5178	0106	
5179	0107	0106
5180	0109	0106 0106
5181	0110	0109
5183	0115	

*****FORTRAN CROSS REFERENCE LISTING*****

LABEL	DEFINED	REFERENCES
5184	0116	
5186	0117	
5190	0137	
5191	0138	
5192	0139	
5193	0140	
5194	0141	
5195	0142	
5196	0143	
5200	0144	0137
5201	0145	0138
5202	0146	0139
5203	0147	0140
5204	0148	0141
5205	0150	0142
5206	0149	0143
5218	0133	0119
5220	0152	0151
5221	0179	0151 0151
5230	0181	
5231	0182	0181
5232	0183	
5233	0184	
5234	0186	0182 0296 0311
5235	0187	0183 0297 0312
5236	0188	0184 0298 0313
5240	0189	0181 0181 0325
5241	0190	
5242	0198	
5243	0199	0198
5244	0200	0199 0199
5245	0201	
5246	0202	0199
5250	0204	
5258	0151	
5300	0214	0204 0204
5301	0215	0214 0214
5302	0217	0214
5303	0218	0217 0217
5304	0220	0217
5305	0221	0220 0220
5306	0224	0220
5400	0227	0196 0207 0213 0216 0219 0223 0226
5410	0246	
5420	0267	
5421	0268	0267

*****F O R T R A N C R O S S R E F E R E N C E L I S T I N G*****

LABEL	DEFINED	REFERENCES
5422	0273	
5423	0274	0267 0267
5424	0275	0274
5425	0276	
5427	0278	0274 0274
5429	0279	0271 0273 0277
5430	0284	0280
5439	0286	
5440	0292	
5441	0293	0292
5442	0330	0329 0329
5443	0301	0300
5444	0300	0292 0292 0295 0295
5447	0326	0323 0325 0325
5448	0327	
5449	0328	0326
5550	0331	
5551	0335	
5552	0339	0338 0338
5553	0333	0329
5555	0352	
5556	0353	0352
5558	0344	
5560	0349	0347 0347
5561	0348	0347
5562	0350	0349
5563	0351	0344 0349 0349
5570	0368	0056 0108 0317 0320 0352 0352 0366
5571	0370	
5572	0369	0368
5574	0367	0366 0366
7000	0294	0293 0293
7001	0296	0293 0295
7003	0299	
8000	0178	0177
9009	0064	0062

OS/360 FORTRAN H

```
        COMPILER OPTIONS - NAME= MAIN,OPT=00,LINECNT=50,SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID,XREF
ISN 0002            SUBROUTINE DRAW(WTOTAL,URUTTL,UBLOWS,LT,CASE,PROB)
ISN 0003            DIMENSION URUTTL(150),UBLOWS(150),YPLOT(51),XPLOT(51)
ISN 0004       5574 YPLOT(1)=WTOTAL
ISN 0005            XPLOT(1)=0.
ISN 0006            LTP1=LT+1
ISN 0007            DO 5573 IP=1,LT
ISN 0008            YPLOT(IP+1)=URUTTL(IP)/2000.
ISN 0009       5573 XPLOT(IP+1)=UBLOWS(IP)
ISN 0010            YMAX=YPLOT(LTP1)
ISN 0011            N2=N2
ISN 0012            IF(YMAX.LE.400.) GO TO 3
ISN 0014            IF(YMAX.LE.800.) GO TO 4
ISN 0016            IF(YMAX.LE.1600.) GO TO 5
ISN 0018            IF(YMAX.LE.3200.) GO TO 6
ISN 0020          3 DY=50.
ISN 0021            GO TO 10
ISN 0022          4 DY=100.
ISN 0023            GO TO 10
ISN 0024          5 DY=200.
ISN 0025            GO TO 10
ISN 0026          6 DY=400.
ISN 0027         10 DX=10.
ISN 0028            PPROB=PROB
ISN 0029            RETURN
ISN 0030            END
```

*****F O R T R A N C R O S S R E F E R E N C E L I S T I N G*****

SYMBOL	INTERNAL STATEMENT NUMBERS
DX	0027
DY	0020 0022 0024 0026
IP	0007 0008 0008 0009 0009
LT	0002 0006 0007
N2	0011 0011
CASE	0002
DRAW	0002
LTP1	0006 0010
PROB	0002 0028
YMAX	0010 0012 0014 0016 0018
PPROB	0028
XPLOT	0003 0005 0009
YPLOT	0003 0004 0008 0010
UBLOWS	0002 0003 0009
URUTTL	0002 0003 0008
WTOTAL	0002 0004

```
                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****

 LABEL   DEFINED   REFERENCES
     3    0020      0012
     4    0022      0014
     5    0024      0016
     6    0026      0018
    10    0027      0021  0023  0025
  5573    0009      0007
  5574    0004

****** END OF COMPILATION ******


                                        OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=50,SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID,XREF
   ISN 0002            SUBROUTINE DELTCK(NPASS,TTDELT,P,W,K,TDELTA,DELTAT,N2)
   ISN 0003            REAL K,NPASS
   ISN 0004            INTEGER P,PLESS1
   ISN 0005            DIMENSION W(150),K(150),DELT1(300)
   ISN 0006            PLESS1=P-1
   ISN 0007            N=2*P-1
   ISN 0008            SUM=0.
   ISN 0009            TMIN=1.
   ISN 0010            TDELTA=TTDELT
   ISN 0011            DELTAT=1./TDELTA
   ISN 0012            DO 1 M=1,PLESS1
   ISN 0013            DELT1(M)=SQRT(W(M+1)/K(M))/19.648
   ISN 0014            NN=PLESS1+M
   ISN 0015          1 DELT1(NN)=SQRT(W(M)/K(M))/19.648
   ISN 0016            IF(K(P).GT.0.) GO TO 2
   ISN 0018            DELT1(N)=1.0
   ISN 0019            GO TO 3
   ISN 0020          2 DELT1(N)=SQRT(W(P)/K(P))/19.648
   ISN 0021          3 DO 4 M=1,N
   ISN 0022          4 TMIN=AMIN1(TMIN,DELT1(M))
   ISN 0023            IF(TMIN/2.-DELTAT)5,6,6
   ISN 0024.         5 DELTAT=TMIN/2.
   ISN 0025            TDELTA=1.0/DELTAT
   ISN 0026          6 DO 7 M=1,N
   ISN 0027          7 SUM=SUM+DELT1(M)
   ISN 0028            N2=4.0*SUM/(2.0*DELTAT)
   ISN 0029            RETURN
   ISN 0030            END

                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****

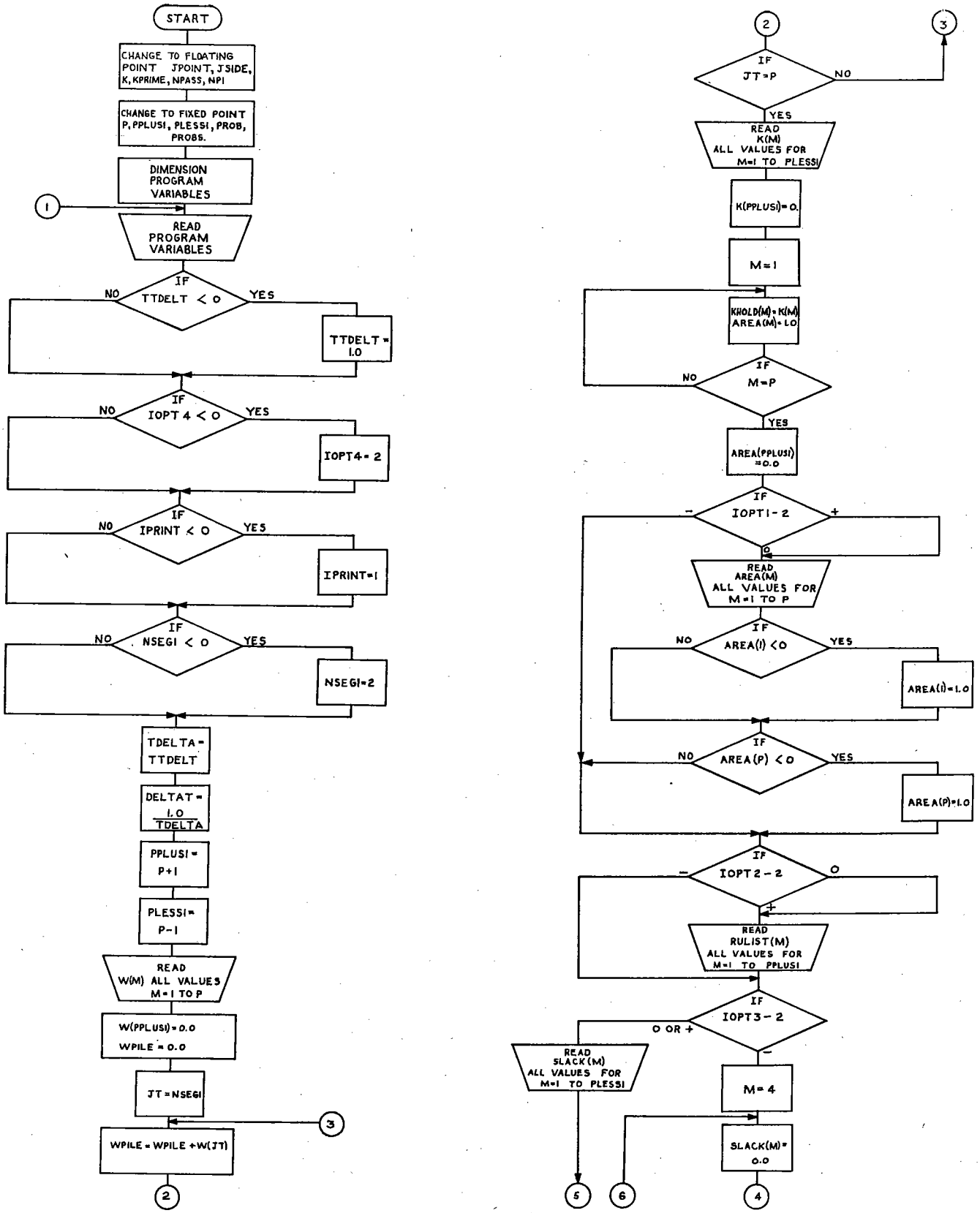
 SYMBOL   INTERNAL STATEMENT NUMBERS
 K        0002  0003  0005  0013  0015  0016  0020
 M        0012  0013  0013  0013  0014  0015  0015  0021  0022  0026  0027
 N        0007  0018  0020  0021  0026
 P        0002  0004  0006  0007  0016  0020  0020
 W        0002  0005  0013  0015  0020
 NN       0014  0015
 N2       0002  0026
 SUM      0008  0027  0027  0028
 SQRT     0013  0015  0020
 TMIN     0009  0022  0022  0023  0024
 AMIN1    0022
 DELT1    0005  0013  0015  0018  0020  0022  0027
 NPASS    0002  0003
 DELTAT   0002  0011  0023  0024  0025  0028
 DELTCK   0002
 PLESS1   0004  0006  0012  0014
 TDELTA   0002  0010  0011  0025
 TTDELT   0002  0010

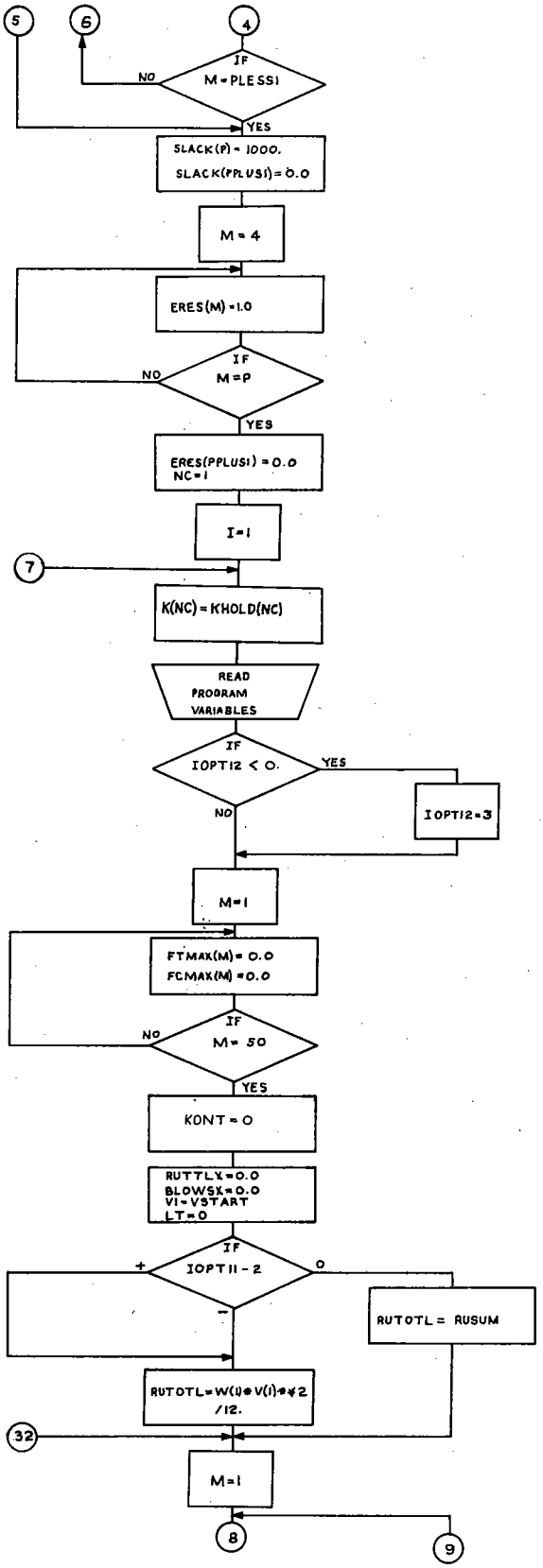
                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****

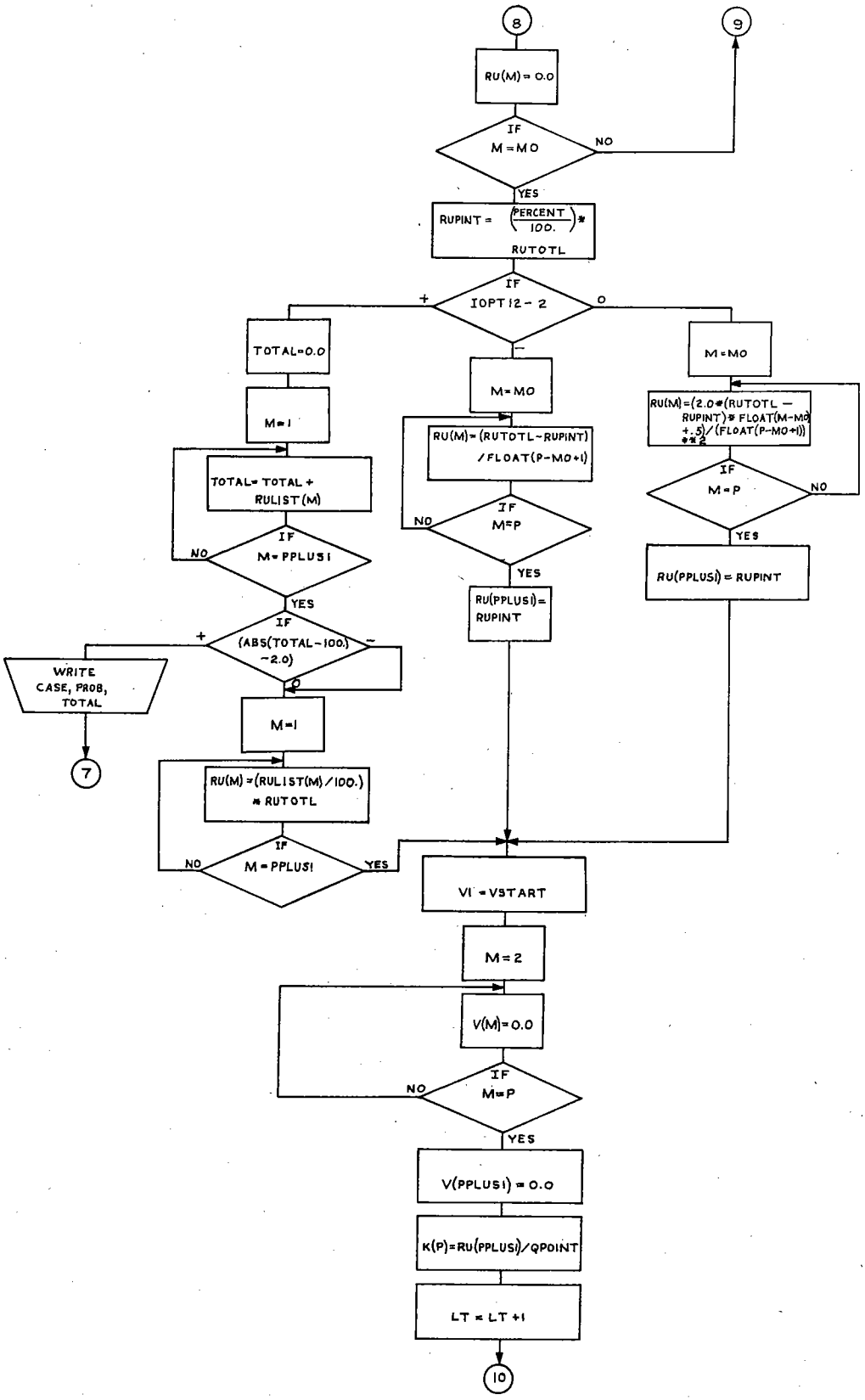
 LABEL   DEFINED   REFERENCES
     1    0015      0012
     2    0020      0016
     3    0021      0019
     4    0022      0021
     5    0024      0023
     6    0026      0023  0023
     7    0027      0026

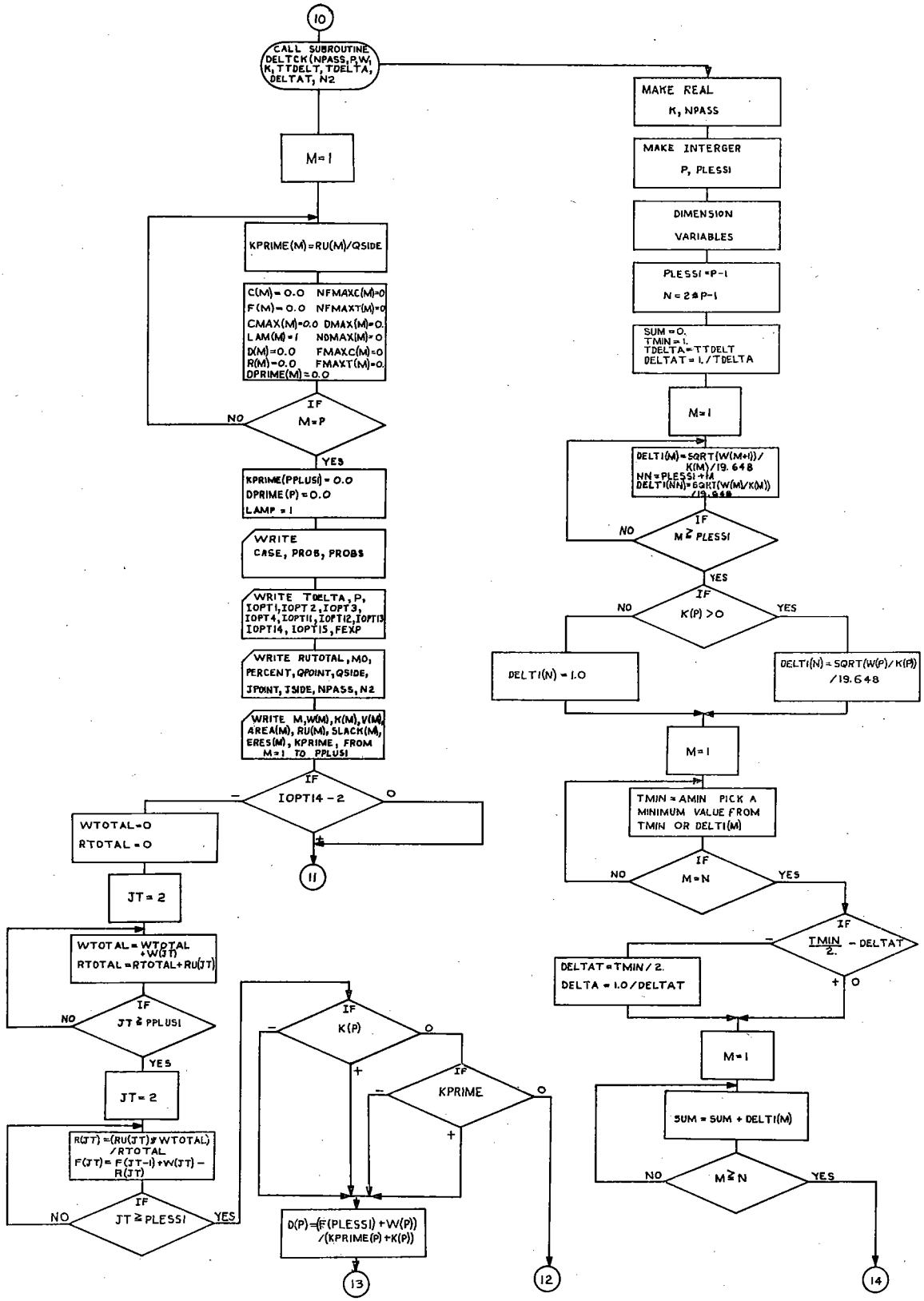
****** END OF COMPILATION ******

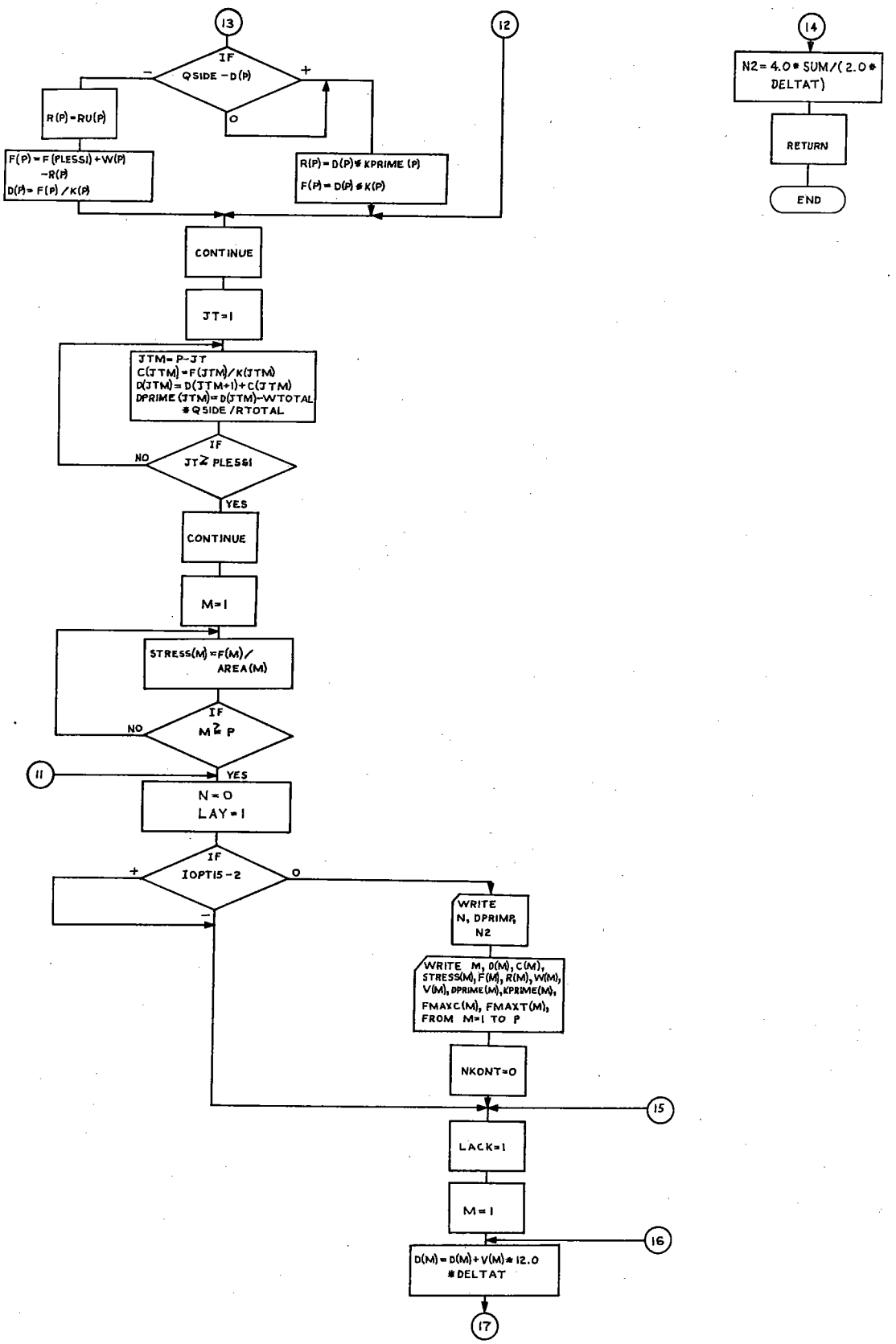

IEF285I   SYS68134.T145405.RP001.A49394.R0000444        DELETED
IEF285I   VOL SER NOS= 555555.
IEF285I   SYS68134.T145405.RP001.A49394.R0000445        DELETED
IEF285I   VOL SER NOS= STUBAU.
IEF285I   SYSOUT                                        SYSOUT
IEF285I   VOL SER NOS=       .
IEF285I   SYS68134.T145405.RP001.A49394.LOADSET         PASSED
IEF285I   VOL SER NOS= 666666.
IEF285I   SYS68134.T145405.RP001.A49394.LOADSET         DELETED
IEF285I   VOL SER NOS= 666666.
```

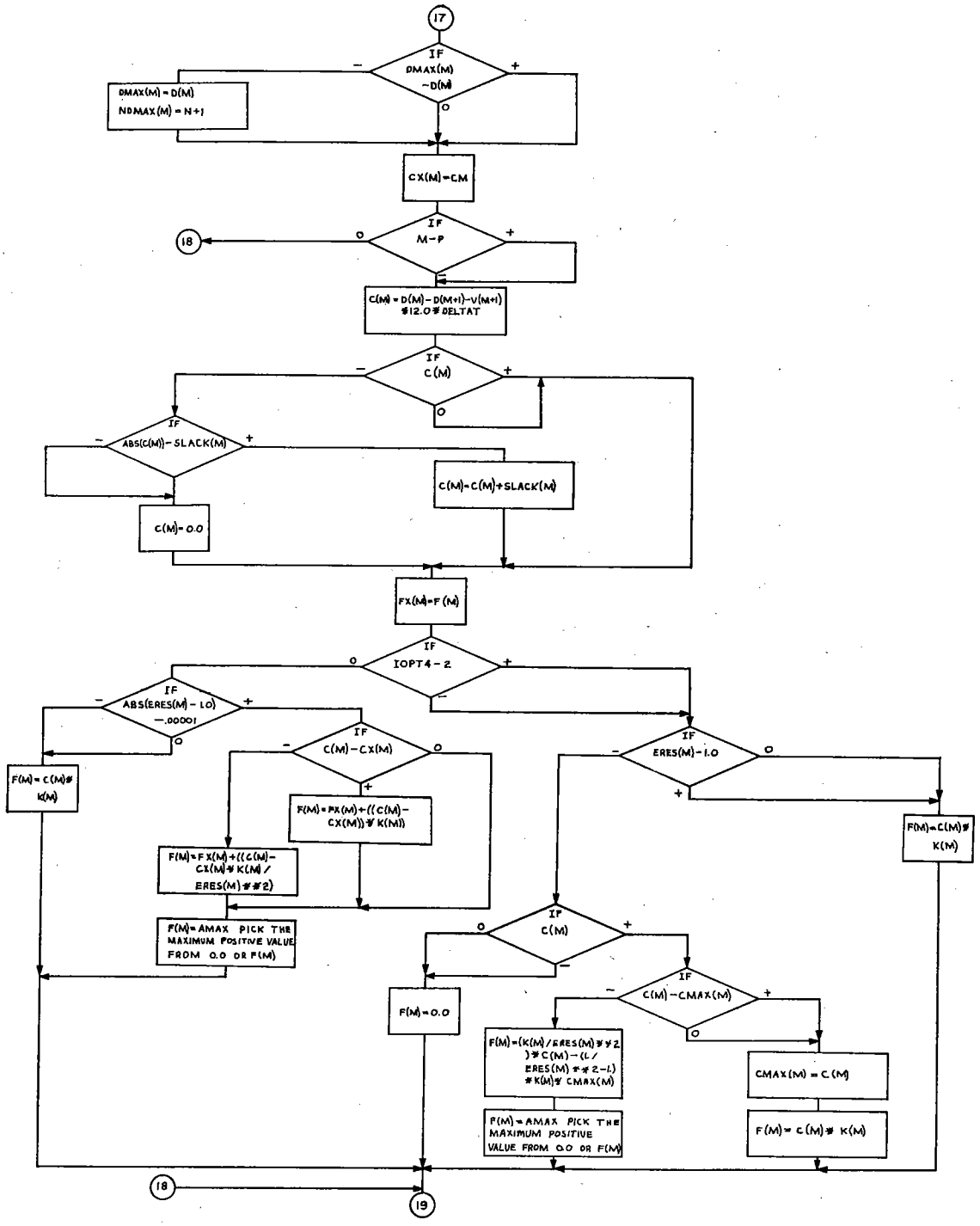

START
CHANGE TO FLOATING POINT JPOINT, JSIDE, K, KPRIME, NPASS, NPI
CHANGE TO FIXED POINT P, PPLUSI, PLESSI, PROB, PROBS.
DIMENSION PROGRAM VARIABLES
1
READ PROGRAM VARIABLES
IF TTDELT < 0
NO
YES
TTDELT = 1.0
IF IOPT 4 < 0
IOPT4 = 2
IF IPRINT < 0
IPRINT=1
IF NSEGI < 0
NSEGI=2
TDELTA = TTDELT
DELTAT = 1.0 / TDELTA
PPLUSI = P+1
PLESSI = P-1
READ W(M) ALL VALUES M=1 TO P
W(PPLUSI) = 0.0
WPILE = 0.0
JT = NSEGI
3
WPILE = WPILE + W(JT)
2
IF JT=P
READ K(M) ALL VALUES FOR M=1 TO PLESSI
K(PPLUSI) = 0.
M=1
KHOLD(M) = K(M)
AREA(M) = 1.0
IF M=P
AREA(PPLUSI) = 0.0
IF IOPT1 - 2
READ AREA(M) ALL VALUES FOR M=1 TO P
IF AREA(I) <0
AREA(I) = 1.0
IF AREA(P) <0
AREA(P)=1.0
IF IOPT2 - 2
READ RULIST(M) ALL VALUES FOR M=1 TO PPLUSI
IF IOPT3 - 2
0 OR +
READ SLACK(M) ALL VALUES FOR M=1 TO PLESSI
M = 4
SLACK(M) = 0.0
5
6
4

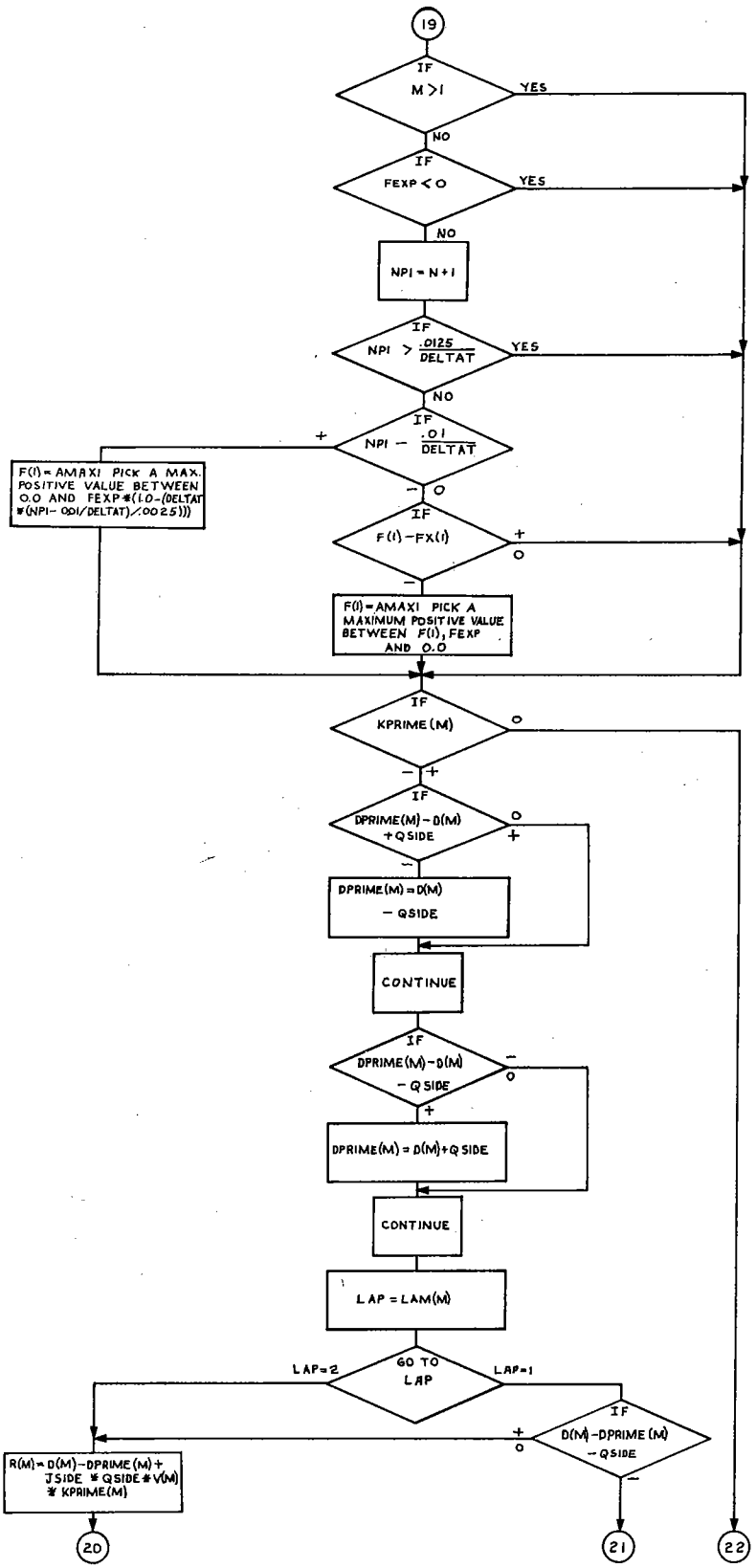

5
6
4
IF
M = PLESS1
NO
YES
SLACK(P) = 1000.
SLACK(PPLUS1) = 0.0
M = 4
ERES(M) = 1.0
IF
M = P
NO
YES
ERES(PPLUS1) = 0.0
NC = 1
I = 1
7
K(NC) = KHOLD(NC)
READ
PROGRAM
VARIABLES
IF
IOPT12 < 0.
YES
NO
IOPT12 = 3
M = 1
FTMAX(M) = 0.0
FCMAX(M) = 0.0
IF
M = 50
NO
YES
KONT = 0
RUTTLX = 0.0
BLOWSX = 0.0
VI = VSTART
LT = 0
IF
IOPT11 - 2
+
-
0
RUTOTL = RUSUM
RUTOTL = W(I) * V(I) ** 2
/12.
32
M = 1
8
9

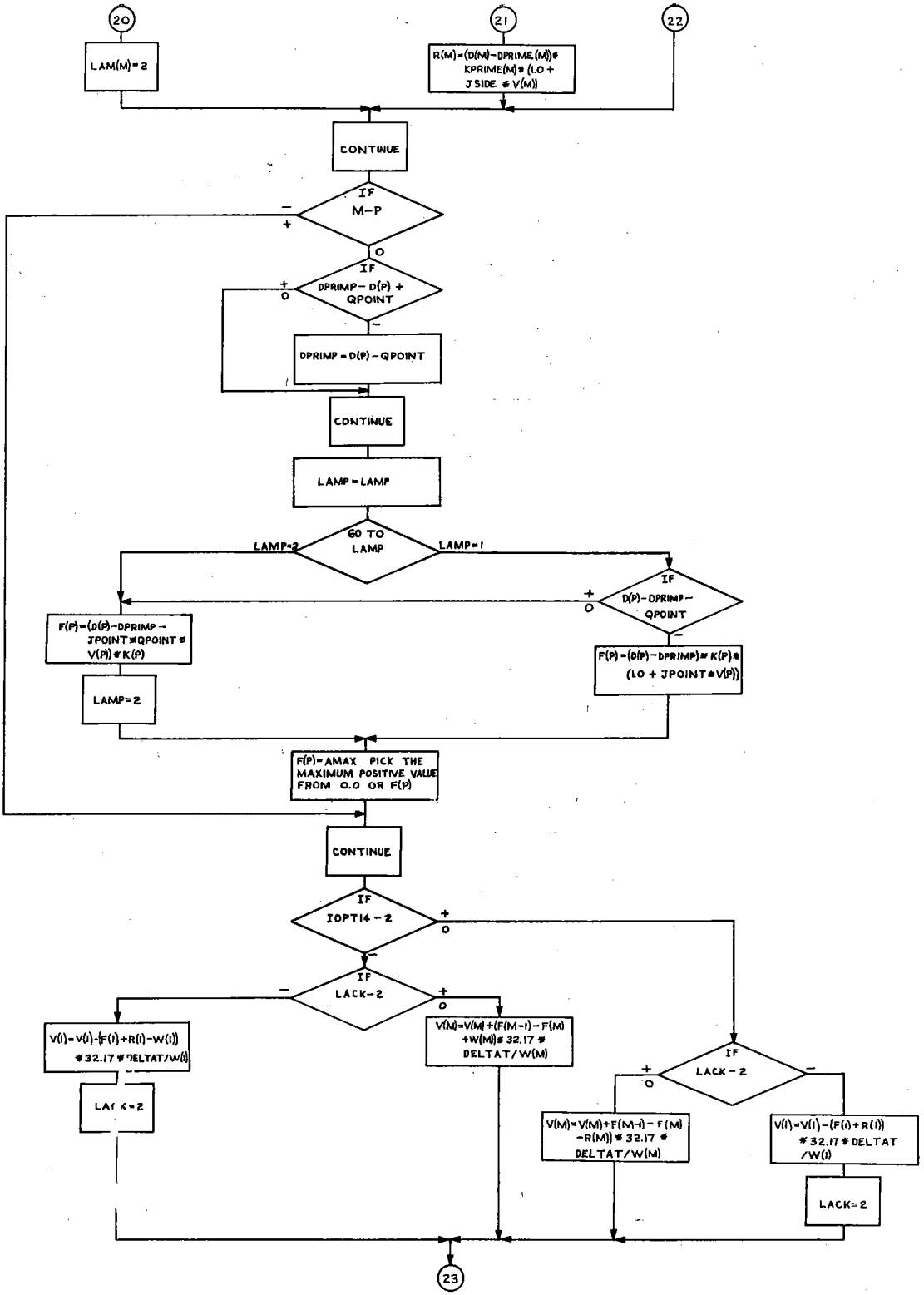

8
9
RU(M) = 0.0
IF M = MO
NO
YES
RUPINT = (PERCENT / 100.) * RUTOTL
IF IOPT12 - 2
+
0
-
TOTAL=0.0
M=1
TOTAL= TOTAL + RULIST(M)
IF M = PPLUS1
NO
YES
IF (ABS(TOTAL-100.) -2.0)
+
-
0
WRITE CASE, PROB, TOTAL
7
M=1
RU(M) = (RULIST(M)/100.) * RUTOTL
IF M = PPLUS1
NO
YES
M=MO
RU(M) = (RUTOTL-RUPINT) /FLOAT(P-MO+1)
IF M=P
NO
YES
RU(PPLUS1)= RUPINT
M=MO
RU(M)=(2.0*(RUTOTL - RUPINT)*FLOAT(M-MO +.5)/(FLOAT(P-MO+1)) **2
IF M=P
NO
YES
RU(PPLUS1) = RUPINT
VI = VSTART
M=2
V(M)=0.0
IF M=P
NO
YES
V(PPLUS1) = 0.0
K(P)=RU(PPLUS1)/QPOINT
LT = LT +1
10

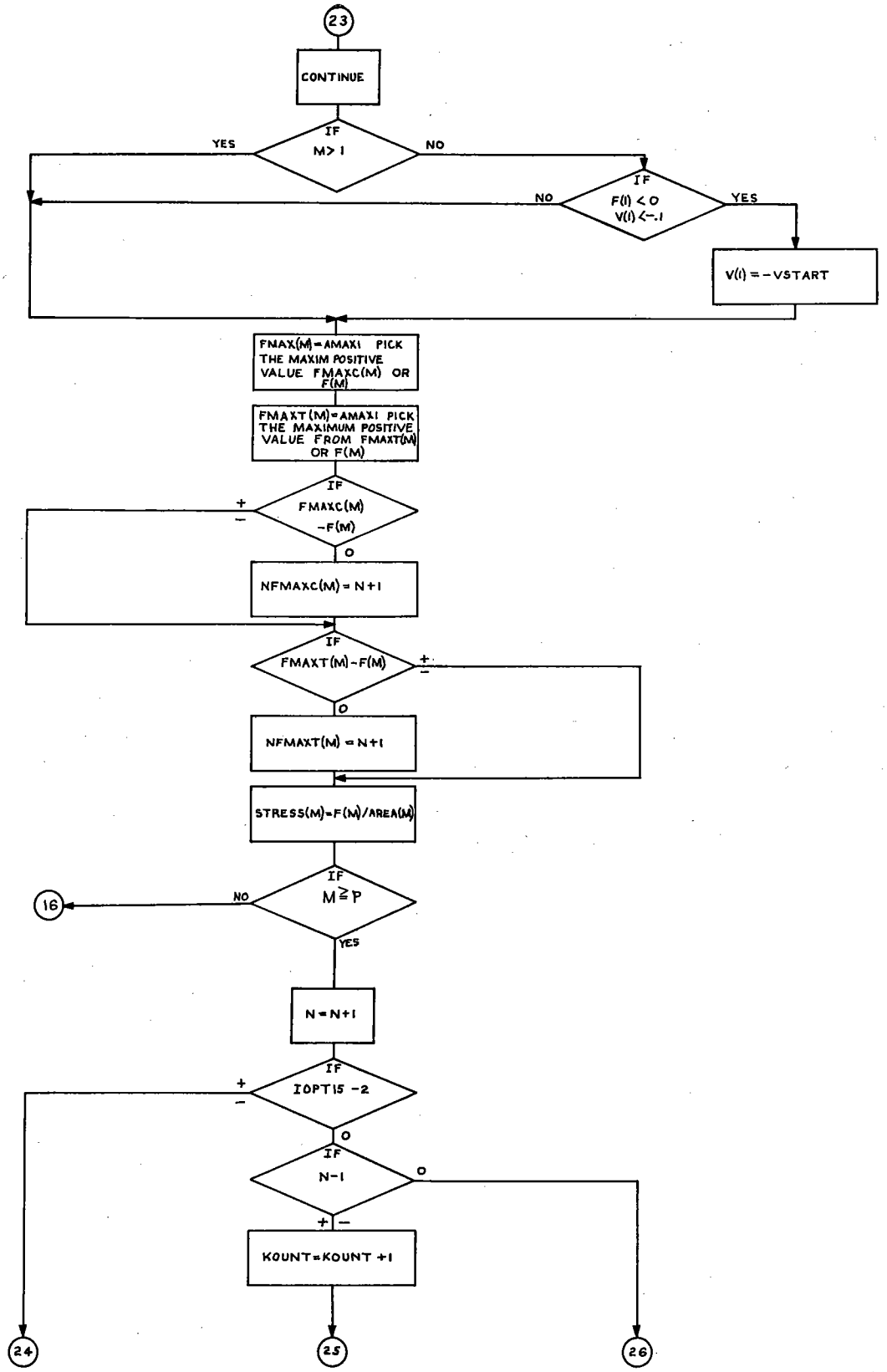

10
CALL SUBROUTINE DELTCK(NPASS,P,W,K,TTDELT,TDELTA,DELTAT,N2
M=1
KPRIME(M)=RU(M)/QSIDE
C(M)=0.0 NFMAXC(M)=0
F(M)=0.0 NFMAXT(M)=0
CMAX(M)=0.0 DMAX(M)=0.
LAM(M)=1 NDMAX(M)=0
D(M)=0.0 FMAXC(M)=0
R(M)=0.0 FMAXT(M)=0.
DPRIME(M)=0.0
IF M=P
NO
YES
KPRIME(PPLUS1)=0.0
DPRIME(P)=0.0
LAMP=1
WRITE CASE, PROB, PROBS
WRITE TDELTA, P, IOPT1, IOPT2, IOPT3, IOPT4, IOPT11, IOPT12, IOPT13 IOPT14, IOPT15, FEXP
WRITE RUTOTAL, MO, PERCENT, QPOINT, QSIDE, JPOINT, JSIDE, NPASS, N2
WRITE M, W(M), K(M), V(M), AREA(M), RU(M), SLACK(M), ERES(M), KPRIME, FROM M=1 TO PPLUS1
IF IOPT14-2
WTOTAL=0
RTOTAL=0
JT=2
WTOTAL=WTOTAL+W(JT)
RTOTAL=RTOTAL+RU(JT)
IF JT≥PPLUS1
JT=2
R(JT)=(RU(JT)*WTOTAL)/RTOTAL
F(JT)=F(JT-1)+W(JT)-R(JT)
IF JT≥PLESS1
IF K(P)
IF KPRIME
D(P)=(F(PLESS1)+W(P))/(KPRIME(P)+K(P))
11
12
13
MAKE REAL K, NPASS
MAKE INTERGER P, PLESS1
DIMENSION VARIABLES
PLESS1=P-1
N=2*P-1
SUM=0.
TMIN=1.
TDELTA=TTDELT
DELTAT=1./TDELTA
M=1
DELTI(M)=SQRT(W(M+1))/K(M)/19.648
NN=PLESS1+1
DELTI(NN)=SQRT(W(M)/K(M))/19.648
IF M≥PLESS1
IF K(P)>0
DELTI(N)=1.0
DELTI(N)=SQRT(W(P)/K(P))/19.648
M=1
TMIN=AMIN PICK A MINIMUM VALUE FROM TMIN OR DELTI(M)
IF M=N
IF TMIN/2.-DELTAT
DELTAT=TMIN/2.
DELTA=1.0/DELTAT
M=1
SUM=SUM+DELTI(M)
IF M≥N
14

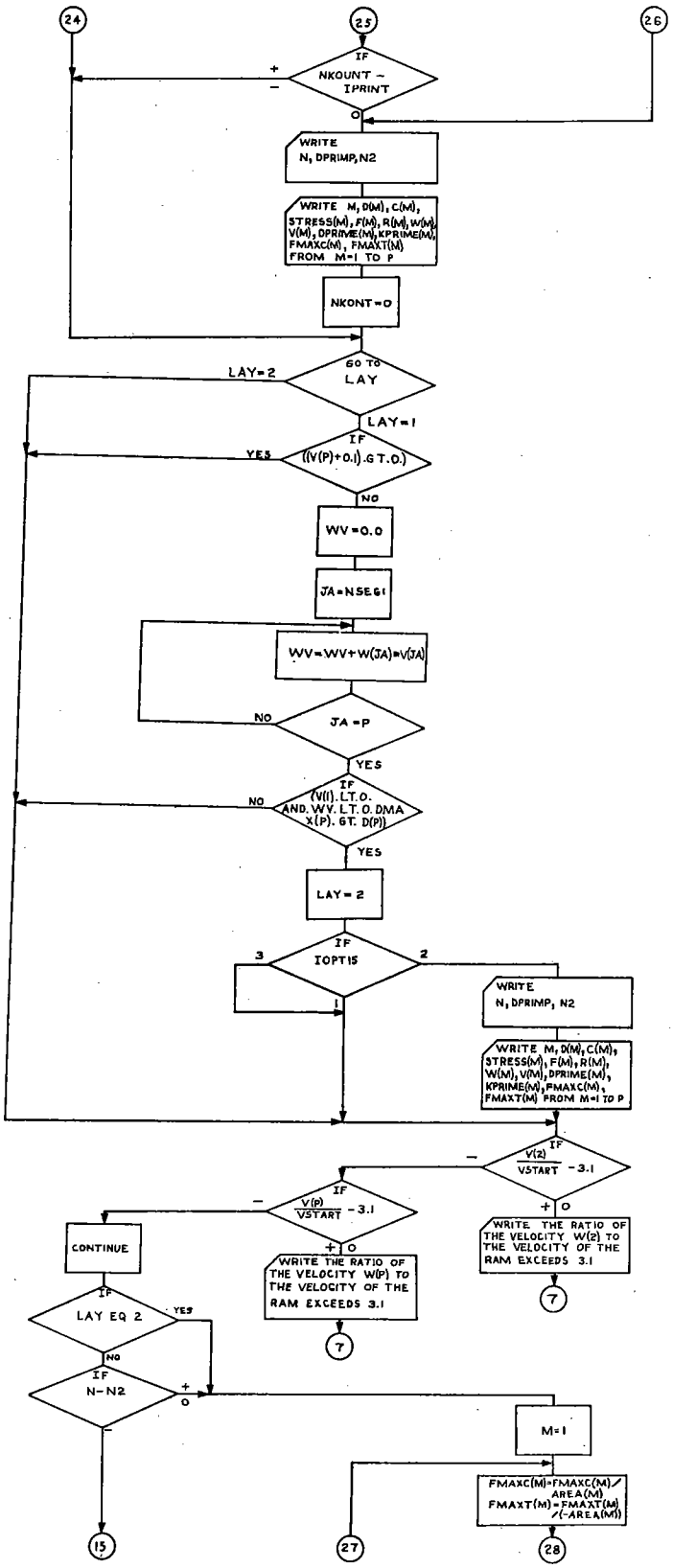

13
IF
QSIDE - D(P)
-
+
0
R(P) = RU(P)
F(P) = F(PLESS1) + W(P)
-R(P)
D(P) = F(P) / K(P)
R(P) = D(P) * KPRIME(P)
F(P) = D(P) * K(P)
12
CONTINUE
JT = 1
JTM = P - JT
C(JTM) = F(JTM) / K(JTM)
D(JTM) = D(JTM+1) + C(JTM)
DPRIME(JTM) = D(JTM) - WTOTAL * QSIDE / RTOTAL
IF
JT ≥ PLESS1
NO
YES
CONTINUE
M = 1
STRESS(M) = F(M) / AREA(M)
IF
M ≥ P
NO
YES
11
N = 0
LAY = 1
IF
IOPTIS - 2
+
-
0
WRITE
N, DPRIME, N2
WRITE M, D(M), C(M), STRESS(M), F(M), R(M), W(M), V(M), DPRIME(M), KPRIME(M), FMAXC(M), FMAXT(M), FROM M=1 TO P
NKONT=0
15
LACK=1
M = 1
16
D(M) = D(M) + V(M) * 12.0 * DELTAT
17
14
N2 = 4.0 * SUM / (2.0 * DELTAT)
RETURN
END

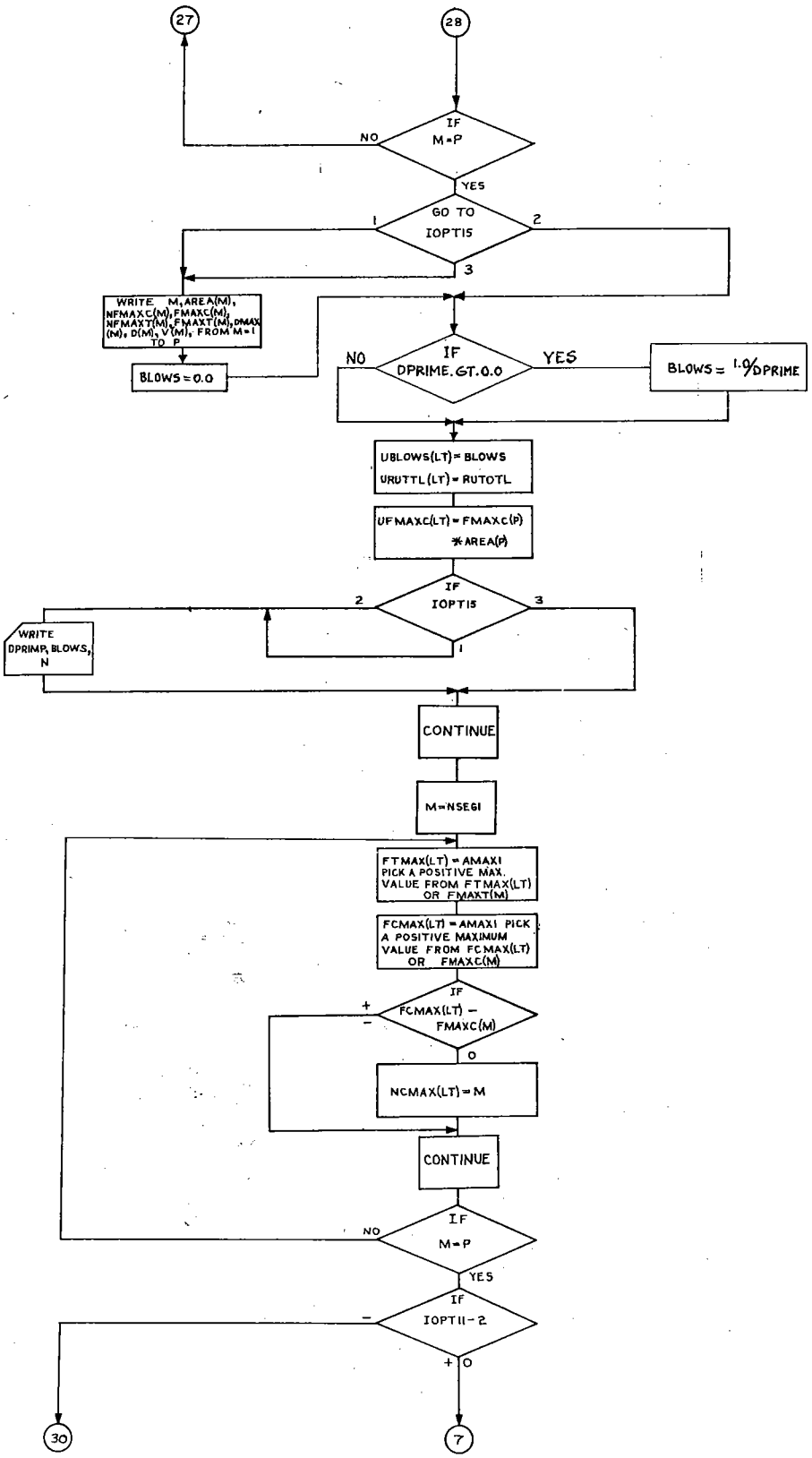

17
IF DMAX(M) −D(M)
DMAX(M) = D(M)
NDMAX(M) = N+1
CX(M)=CM
IF M−P
18
C(M) = D(M) − D(M+1) − V(M+1) *12.0* DELTAT
IF C(M)
IF ABS(C(M)) − SLACK(M)
C(M)=C(M)+SLACK(M)
C(M)=0.0
FX(M)=F(M)
IF IOPT4 − 2
IF ABS(ERES(M) − 1.0) −.00001
IF C(M) − CX(M)
IF ERES(M) − 1.0
F(M)=C(M)* K(M)
F(M)=FX(M)+((C(M)− CX(M))* K(M))
F(M)=FX(M)+((C(M)− CX(M))* K(M) / ERES(M)**2)
F(M)=AMAX PICK THE MAXIMUM POSITIVE VALUE FROM 0.0 OR F(M)
F(M)=C(M)* K(M)
IF C(M)
F(M)=0.0
IF C(M) − CMAX(M)
F(M)=(K(M)/ERES(M)**2)*C(M)−(1/ERES(M)**2−1)*K(M)* CMAX(M)
F(M)=AMAX PICK THE MAXIMUM POSITIVE VALUE FROM 0.0 OR F(M)
CMAX(M) = C(M)
F(M)=C(M)* K(M)
18
19

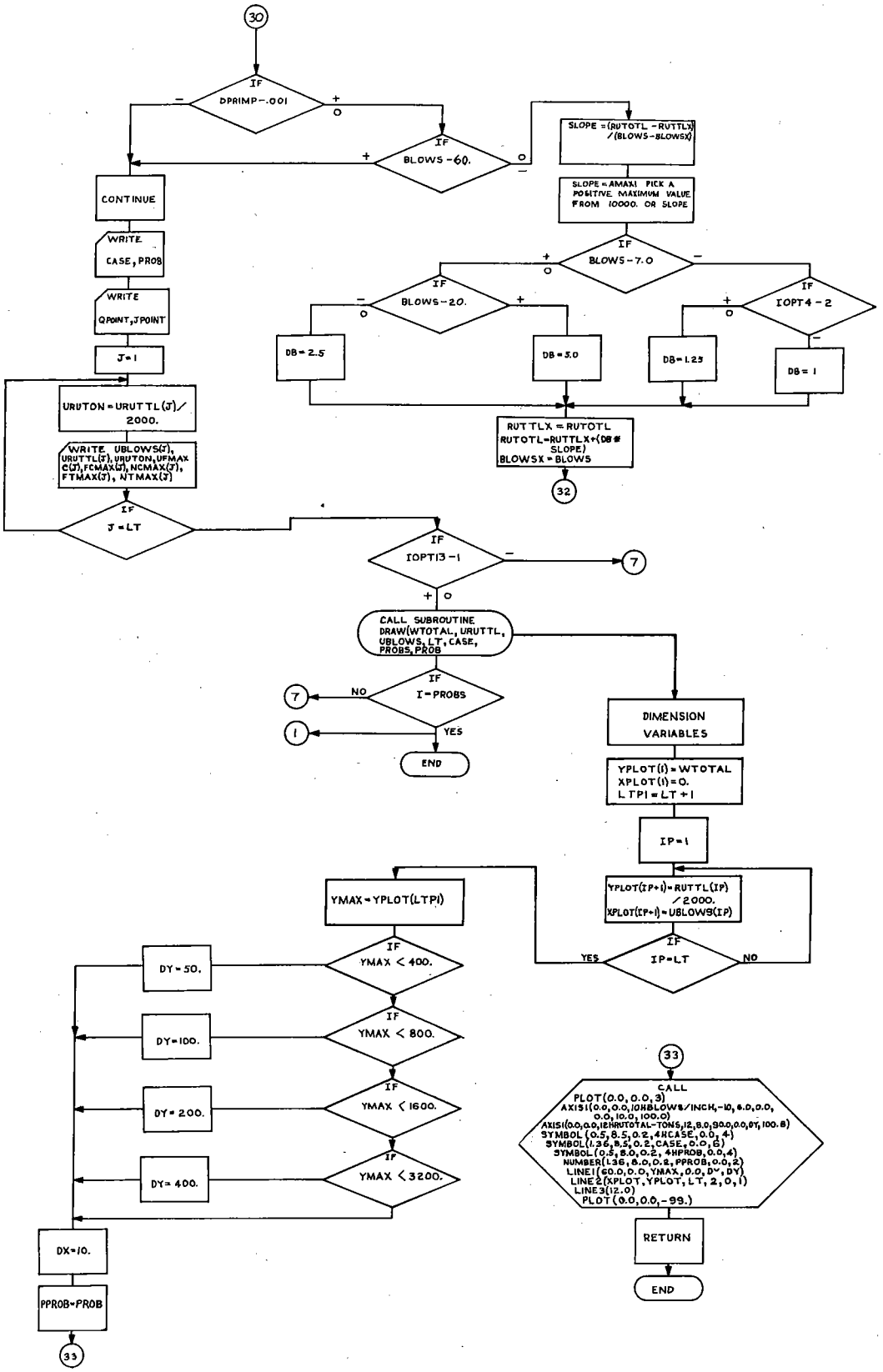

19
IF M>1
YES
NO
IF FEXP<0
YES
NO
NPI=N+1
IF NPI > .0125/DELTAT
YES
NO
IF NPI - .01/DELTAT
+
F(I)=AMAXI PICK A MAX. POSITIVE VALUE BETWEEN 0.0 AND FEXP*((1.0-(DELTAT*(NPI-.01/DELTAT)/.0025)))
-
0
IF F(I)-FX(I)
+
0
-
F(I)=AMAXI PICK A MAXIMUM POSITIVE VALUE BETWEEN F(I), FEXP AND 0.0
IF KPRIME(M)
0
-
+
IF DPRIME(M)-D(M)+QSIDE
0
+
-
DPRIME(M)=D(M)-QSIDE
CONTINUE
IF DPRIME(M)-D(M)-QSIDE
-
0
+
DPRIME(M)=D(M)+QSIDE
CONTINUE
LAP=LAM(M)
GO TO LAP
LAP=2
LAP=1
IF D(M)-DPRIME(M)-QSIDE
+
0
-
R(M)=D(M)-DPRIME(M)+JSIDE*QSIDE*V(M)*KPRIME(M)
20
21
22


20
21
22
LAM(M)=2
R(M)=(D(M)-DPRIME(M))*KPRIME(M)*(LO+JSIDE*V(M))
CONTINUE
IF M-P
IF DPRIMP-D(P)+QPOINT
DPRIMP=D(P)-QPOINT
CONTINUE
LAMP=LAMP
GO TO LAMP
LAMP=2
LAMP=1
IF D(P)-DPRIMP-QPOINT
F(P)=(D(P)-DPRIMP-JPOINT*QPOINT*V(P))*K(P)
F(P)=(D(P)-DPRIMP)*K(P)*(LO+JPOINT*V(P))
LAMP=2
F(P)=AMAX PICK THE MAXIMUM POSITIVE VALUE FROM 0.0 OR F(P)
CONTINUE
IF IOPTI4-2
IF LACK-2
V(I)=V(I)-(F(I)+R(I)-W(I))*32.17*DELTAT/W(I)
LACK=2
V(M)=V(M)+(F(M-1)-F(M)+W(M))*32.17*DELTAT/W(M)
IF LACK-2
V(M)=V(M)+F(M-1)-F(M)-R(M))*32.17*DELTAT/W(M)
V(I)=V(I)-(F(I)+R(I))*32.17*DELTAT/W(I)
LACK=2
23


23
CONTINUE
IF
M>1
YES
NO
IF
F(I) < 0
V(I) <-.1
NO
YES
V(I) = -VSTART
FMAX(M)=AMAX1 PICK THE MAXIM POSITIVE VALUE FMAXC(M) OR F(M)
FMAXT(M)=AMAX1 PICK THE MAXIMUM POSITIVE VALUE FROM FMAXT(M) OR F(M)
IF
FMAXC(M) -F(M)
+
-
0
NFMAXC(M) = N+1
IF
FMAXT(M)-F(M)
+
-
0
NFMAXT(M) = N+1
STRESS(M)=F(M)/AREA(M)
IF
M ≥ P
NO
16
YES
N=N+1
IF
IOPT15 -2
+
-
0
IF
N-1
0
+
-
KOUNT=KOUNT +1
24
25
26


24
25
26
IF NKOUNT − IPRINT
+
−
0
WRITE N, DPRIMP, N2
WRITE M, D(M), C(M), STRESS(M), F(M), R(M), W(M), V(M), DPRIME(M), KPRIME(M), FMAXC(M), FMAXT(M) FROM M=1 TO P
NKONT=0
GO TO LAY
LAY=2
LAY=1
IF ((V(P)+0.1).GT.0.)
YES
NO
WV=0.0
JA=NSEG1
WV=WV+W(JA)*V(JA)
JA=P
NO
YES
IF (V(1).LT.0. AND. WV.LT.0. AND. X(P).GT. D(P))
NO
YES
LAY=2
IF IOPTIS
3
2
1
WRITE N, DPRIMP, N2
WRITE M, D(M), C(M), STRESS(M), F(M), R(M), W(M), V(M), DPRIME(M), KPRIME(M), FMAXC(M), FMAXT(M) FROM M=1 TO P
IF V(2)/V5TART − 3.1
−
+
0
IF V(P)/V5TART − 3.1
−
+
0
CONTINUE
WRITE THE RATIO OF THE VELOCITY W(2) TO THE VELOCITY OF THE RAM EXCEEDS 3.1
WRITE THE RATIO OF THE VELOCITY W(P) TO THE VELOCITY OF THE RAM EXCEEDS 3.1
7
7
IF LAY EQ 2
YES
NO
IF N−N2
+
0
−
M=1
FMAXC(M)=FMAXC(M)/AREA(M)
FMAXT(M)=FMAXT(M)/(−AREA(M))
15
27
28


27
28
IF M=P
NO
YES
GO TO IOPTIS
1
2
3
WRITE M, AREA(M), NFMAXC(M), FMAXC(M), NFMAXT(M), FMAXT(M), DMAX(M), D(M), V(M), FROM M=1 TO P
BLOWS=0.0
NO
IF DPRIME.GT.0.0
YES
BLOWS = 1.0/DPRIME
UBLOWS(LT)=BLOWS
URUTTL(LT)=RUTOTL
UFMAXC(LT)=FMAXC(P) *AREA(P)
IF IOPTIS
2
3
1
WRITE DPRIMP, BLOWS, N
CONTINUE
M=NSEGI
FTMAX(LT)=AMAXI PICK A POSITIVE MAX. VALUE FROM FTMAX(LT) OR FMAXT(M)
FCMAX(LT)=AMAXI PICK A POSITIVE MAXIMUM VALUE FROM FCMAX(LT) OR FMAXC(M)
IF FCMAX(LT) - FMAXC(M)
+
-
0
NCMAX(LT)=M
CONTINUE
IF M=P
NO
YES
IF IOPTII-2
-
+
0
30
7


30
IF DPRIMP-.001
CONTINUE
WRITE CASE, PROB
WRITE QPOINT, JPOINT
J=1
URUTON=URUTTL(J)/2000.
WRITE UBLOWS(J), URUTTL(J), URUTON, UFMAX C(J), FCMAX(J), NCMAX(J), FTMAX(J), NTMAX(J)
IF J=LT
IF BLOWS-60.
SLOPE=(RUTOTL-RUTTLX)/(BLOWS-BLOWSX)
SLOPE=AMAX1 PICK A POSITIVE MAXIMUM VALUE FROM 10000. OR SLOPE
IF BLOWS-7.0
IF BLOWS-20.
DB=2.5
DB=3.0
IF IOPT4-2
DB=1.25
DB=1
RUTTLX=RUTOTL
RUTOTL=RUTTLX+(DB*SLOPE)
BLOWSX=BLOWS
32
IF IOPT13-1
7
CALL SUBROUTINE DRAW(WTOTAL, URUTTL, UBLOWS, LT, CASE, PROBS, PROB
IF I=PROBS
NO
YES
END
DIMENSION VARIABLES
YPLOT(1)=WTOTAL
XPLOT(1)=0.
LTP1=LT+1
IP=1
YPLOT(IP+1)=RUTTL(IP)/2000.
XPLOT(IP+1)=UBLOWS(IP)
IF IP=LT
YES
NO
YMAX=YPLOT(LTP1)
IF YMAX < 400.
DY=50.
IF YMAX < 800.
DY=100.
IF YMAX < 1600.
DY=200.
IF YMAX < 3200.
DY=400.
DX=10.
PPROB=PROB
33
33
CALL
PLOT(0.0, 0.0, 3)
AXIS1(0.0, 0.0, 10HBLOWS/INCH, -10, 6.0, 0.0, 0.0, 10.0, 100.0)
AXIS(0.0, 0.0, 16HRUTOTAL-TONS, 12, 8.0, 90.0, 0.0, DY, 100.8)
SYMBOL(0.5, 8.5, 0.2, 4HCASE, 0.0, 4)
SYMBOL(1.36, 8.5, 0.2, CASE, 0.0, 5)
SYMBOL(0.5, 8.0, 0.2, 4HPROB, 0.0, 4)
NUMBER(1.36, 8.0, 0.2, PPROB, 0.0, 2)
LINE1(60.0, 0.0, YMAX, 0.0, DY, DY)
LINE2(XPLOT, YPLOT, LT, 2, 0, 1)
LINE3(12.0)
PLOT(0.0, 0.0, -99.)
RETURN
END

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