MODERN PROCEDURES FOR THE DESIGN OF DRIVEN PILE FOUNDATIONS

Significant progress has been made in the past three decades in determining the load bearing capacity of pile foundations. Developments in the means of prediction of pile capacity as limited by soil strength have been substantial, particularly in the use of dynamic methods. The use of currently available equipment, analytical procedures, and practices in the field, will often produce material economies on a job by allowing increased loads with proven factors of safety. This approach justifies the minimum number of piles required for a safe foundation in a wide range of job sizes and soil conditions.

To avoid exposing the reader to excessive detail in the body of this paper, technical topics have been covered more thoroughly in several appendices.

Wave Equation Analysis of Piles	Appendix A
Dynamic Monitoring and the Pile Driving Analyzer	Appendix B
Case Method Capacity Calculation	Appendix C
Case Pile Wave Analysis Program	Appendix D

1 The General Design Problem

In designing driven foundations, there must be a close relationship between design, construction control procedures, driving practices, and the size of the job. Small commercial buildings or residences involving loads that are only a small fraction of the pile capacities do not justify the expense of detailed design processes or elaborate construction controls. Nevertheless, some preliminary analysis of the job requirements and a limited subsurface investigation must be made to understand existing conditions and the possible foundation solutions. It is necessary to determine that driven piling is the best overall choice of foundation.

Several different levels of design and construction control are appropriate depending on the size of the job and the difficulty of the subsurface conditions. Dynamic methods offer the opportunity to reduce the cost of pile foundations and can be combined in a variety of ways. In the case of a small job with a few low capacity piles for a small structure, very limited design and construction control procedures would be appropriate. Some limited subsurface investigation would be required to assist in the selection of the proper foundation type and then for a pile foundation to estimate the required pile length. Prior to beginning pile driving a Wave Equation analysis would be performed to determine that the piles can be driven at a reasonable blow count with driving stresses that are not excessive. The required blow count to achieve the necessary capacity would be determined in the same analysis. During pile driving the usual inspection procedures would be followed and the piles would be driven to the blow count determined in the Wave Equation analysis. To make sure that relaxation is not present, one pile would be restruck with the longest possible wait time consistent with the job conditions.

As the job becomes larger it is desirable to increase pile capacity. This can be accomplished by driving to higher capacities and by reducing the safety factor. Safety factor reduction is justified by improving the accuracy of capacity determination and by tightening quality control. Capacity determination was accomplished by Wave Equation analysis and blow count observation in the simple case described above. The next level of capacity determination is based on the use of dynamic monitoring with Case Method and CAPWAP. Finally, a static load test can be performed. These procedures can be combined in a variety of ways, both for capacity determination and for quality control. Each of these dynamic methods will now be described in greater detail.

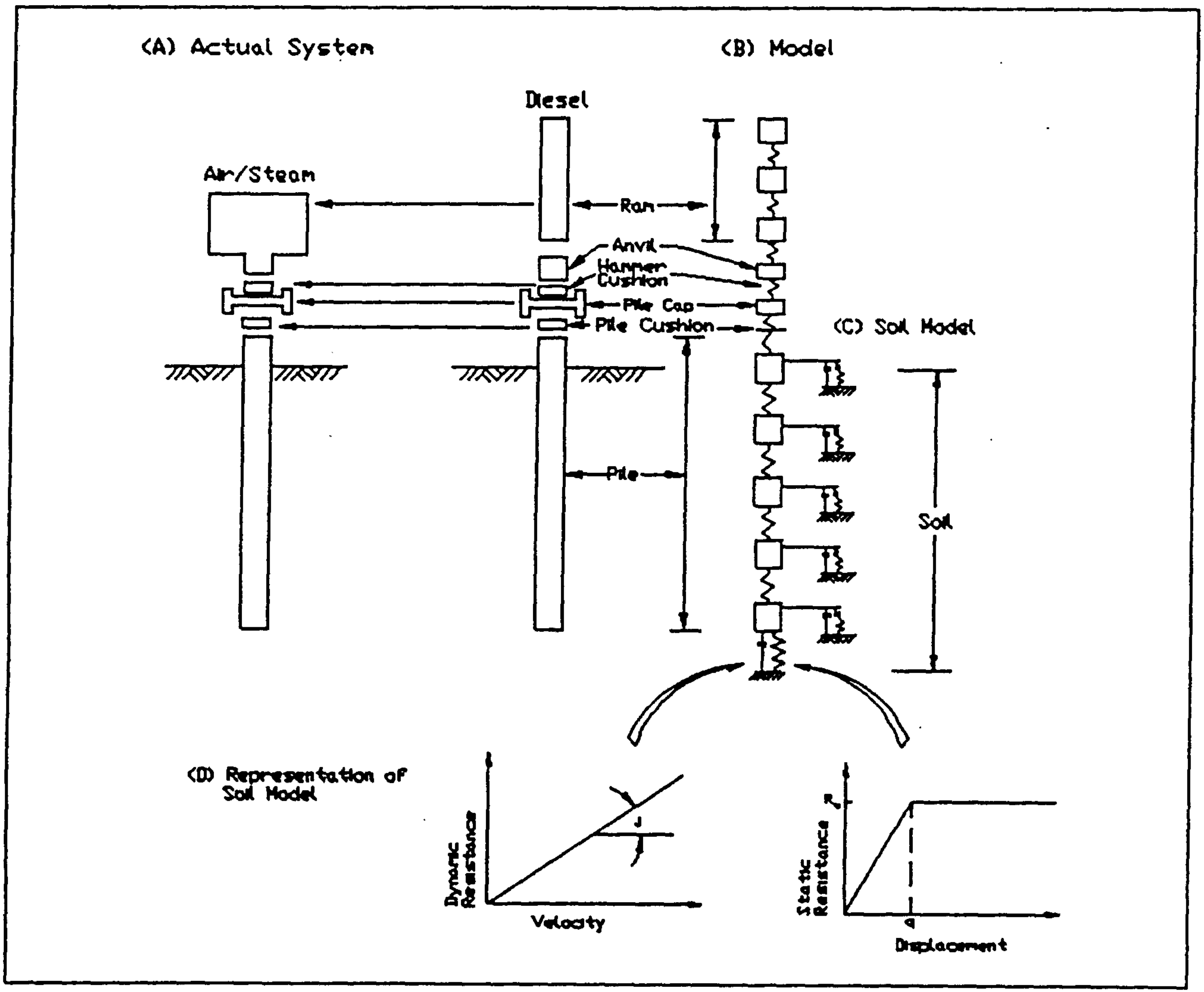

Figure 1: Representation of Driving System and Pile for Wave Equation Analysis

2 Available Dynamic Pile Design and Construction Control Tests

2.1 Wave Equation Analysis

A computational tool for the analysis of pile driving, known as the Wave Equation, has been available for more than three decades. Several versions are now readily accessible to the foundation designer. One of the most widely used programs, called WEAP (Wave Equation Analysis of Piles), was written by Goble & Associates, Inc. (now Goble Rausche Likins and Associates, Inc. or GRL) under contract with the Federal Highway Administration. The most recent version of this program, GRLWEAP is maintained and regularly updated by GRL and is commercially available.

Wave Equation analysis is performed by representing the pile and the driving system as a series of masses and springs. The size of the individual mass elements and the stiffness of the springs depend on the mass and stiffness of the real system. In general, it is possible to create, in the computer, very realistic representations of the hammer and the driving system. The soil is represented by a series of elastic-plastic springs and linear dashpots. The computer representation of the entire system is shown in Figure 1.

Wave Equation analysis is performed by entering into the computer the appropriate values that represent the soil. The ultimate resistance, R_u, of the elastic-plastic soil spring at each element represents the static soil resistance over the equivalent length of pile. The total of all the ultimate elastic-plastic soil springs is the ultimate pile capacity, R_{ut}. After the pile, driving system, and soil have been properly represented the ram elements are given a velocity equal to the hammer impact velocity and a dynamic analysis is performed to determine the motion of all of the mass elements. The permanent set of the soil springs can be obtained from this analysis. This value is, of course, related to the particular static soil resistance used. Usually the permanent set is inverted to obtain a blow count rather than a penetration.

If a series of static capacities is analyzed, the results can be represented as shown in Figure 2. Here a curve is plotted through the series of points for capacity and related blow count. This curve is known as a bearing graph. For any capacity of interest the related blow count can be determined. Similarly, a field observation of blow count can be used with the curve to estimate pile capacity. Experience has shown that the bearing capacity can be estimated with a much greater degree of accuracy with a Wave Equation generated Bearing Graph than with a dynamic formula.

The blow count obtained in the field is related to the capacity of the pile at the time the data was taken. Frequently, the capacity will change after driving has stopped. Fortunately, this change is usually an increase since pore water pressures usually build up during the driving operation reducing the effective stress in the soil and hence the shear strength. In coarse grained soils, pore pressures may decay so rapidly at the end of a hammer blow that the resistance recorded at the end of driving is a realistic measure of the pile strength. In some soils, a brief wait is sufficient for the pile to gain its final strength while in some clays, the pile may still be gaining strength after months or even years. Strength changes that occur with time will not always produce increased pile strength, and infrequently, the strength will decay. Both of these problems can be detected by restriking the pile after a waiting period, and carefully observing the blow count at the *beginning* of the restrike.

The use of Wave Equation analysis avoids many, but not all of the problems associated with the dynamic formula. The most important difficulty arises from the assumptions that must be made about hammer performance. The impact velocity is an input quantity in the Wave Equation analysis. Impact velocity will depend on hammer operating characteristics and performance and cannot be determined in the field by simple visual observation.

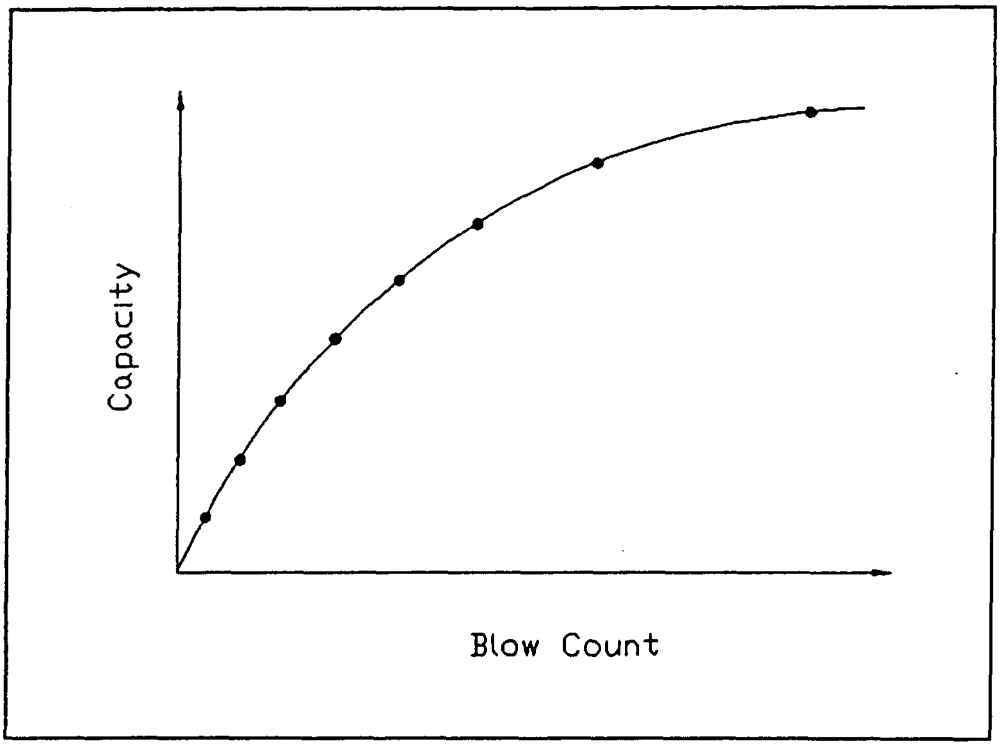

Figure 2: Example Bearing Graph

Some of the soil parameters that must be entered for Wave Equation analysis also are not easily determined from subsurface investigation information, and inaccurate information can produce differences in the results. However, Wave Equation analysis is certainly the most accurate and reliable tool available to predict pile driving performance prior to beginning pile driving.

More Details on Wave Equation analysis is given in Appendix A.

2.2 Dynamic Monitoring

Apparatus is available to eliminate, by field measurements, the unknowns in the Wave Equation analysis discussed above. Radar-type devices are being used to monitor ram impact velocity for hammers where the ram is exposed. These measurements are of primary use in construction control. In some cases, the maximum velocity may not be the impact velocity, so the device must be used with care. (The primary difficulty can occur in cases of pre-admission for air/steam hammers or pre-ignition for diesels.) More details on Wave Equation analysis are given in Appendix A.

The most thorough approach for routine field application is to make force and acceleration measurements on the pile. These measurements can be made with strain transducers that attach directly to the pile surface at some point above the ground. Force is obtained from the strain measurements using the material modulus and the pile area. Accelerometers can also be easily attached to the pile. A photograph of a typical field installation is shown in Figure 3.

The most useful motion parameter is the pile particle velocity, and it can be obtained by integration of the measured acceleration. The records of force and velocity are then processed to obtain useful quantities for pile design or installation control. Processing is accomplished using a Pile Driving Analyzer™ (PDA). The PDA provides signal conditioning and amplification for the transducers, processing and storing of the driving parameters, display of the measured signal, and storage of a digital record of the measurements. The total system for making and processing measurements is shown in Figure 4.

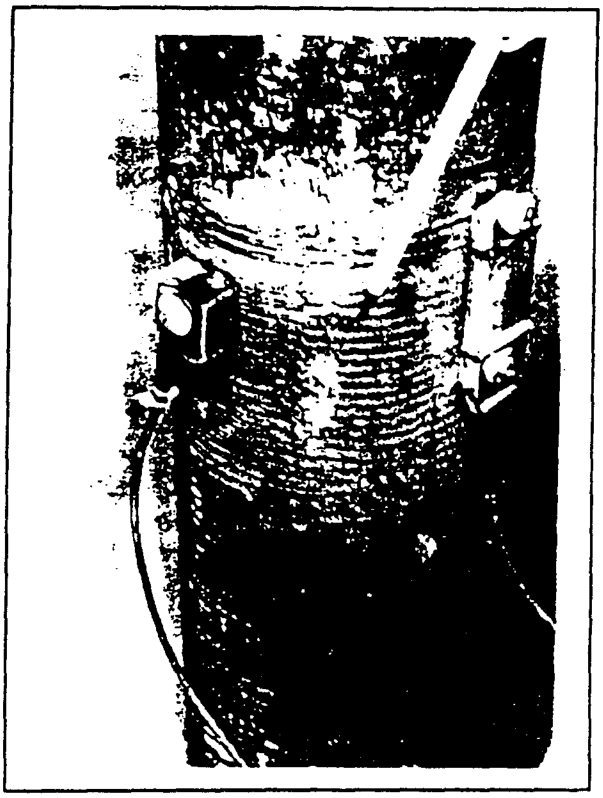

Figure 3: Transducer Installation

The PDA can calculate, display, and store nine quantities for each hammer blow. They can be selected from a large number available and they can be examined and plotted later as a function of depth or blow count. Among the available quantities are.

- Maximum force or stress at the location of the transducers.
- Maximum particle velocity at the location of the transducers.
- Maximum energy delivered to the pile.
- Case Method axial pile capacity.
- Maximum pile axial displacement during the hammer blow.
- Warning of potential pile damage below the ground surface.
- Maximum tension force or stress in the pile.
- Speed of hammer operation in blows per minute.

Several other quantities that supply information to the PDA operator for checking the validity and the accuracy of the measurements are also available for display.

The quantities obtained from the PDA provide all of the information needed for field decisions on pile design and construction control. They can be used to evaluate hammer performance and to determine pile capacity and they can also be used to evaluate pile integrity by observing the wave form of the displayed force and velocity records. More details on dynamic monitoring are given in Appendix B.

2.3 Case Method for Pile Capacity Determination

The Case Method for pile capacity determination was developed at Case Institute of Technology (now Case Western Reserve University) in a research project funded by the Ohio Department of Transportation and the Federal Highway Administration, and directed by Professor G. G. Goble. The Case Method uses an equation obtained from the mechanics of one dimensional wave propagation to calculate the forces acting on the pile to resist penetration. These forces arise in response to very rapid motions, and therefore, are larger than they would be if penetration were slow, as in the case of a static test. To accommodate this influence, the resisting forces are reduced by a

Figure 4: PDA and Associated Equipment Set-up

dynamic force that is assumed to be proportional to the maximum velocity at the pile toe. The toe velocity can be calculated from the measurements using one dimensional wave mechanics. It is multiplied by an empirically determined quantity called a damping constant. This constant was determined from a correlation study that compared the Case Method capacity with the results of static load tests made at over 120 sites. The agreement is quite good. The Case Method is described in more detail in Appendix C.

Since the Case Method computation is quite simple, it can be made for every hammer blow in real time by the PDA during the pile driving operation. The PDA requires the input of the damping constant. This constant was determined empirically to be dependent on soil grain size. Recommendations for damping constant values related to soil classification were made by the Case research project.

2.4 Case Pile Wave Analysis Program (CAPWAP)

The CAPWAP analysis uses field measurements of force and velocity in an elastic dynamic analysis to extract Wave Equation soil constants. In this procedure, the pile is represented in the same way as in the Wave Equation analysis except that the hammer, the driving system, and the pile above the point where the gages are attached are not included. During the analysis, values are assumed for the Wave Equation soil constants, and the measured acceleration is imposed on the element where the measurements were made. A dynamic analysis is performed to obtain the force required at the point of measurement to generate the imposed acceleration. The soil constants are successively changed in an effort to cause the calculated top force to match the measured force as closely as possible. This analysis requires substantial computational effort, and cannot be done in real time. Usually the CAPWAP analysis is performed in the office after returning from a field test site. However, current lap top personal computers can be used in the field to give an immediate result.

Wave Equation soil constants are obtained from the CAPWAP analysis. This gives an estimate of pile capacity that contains no empirical assumptions. In addition, the distribution of the resistance forces along the pile is determined and the actual damping constant that should be used in the Case Method analysis is verified. As increased computational speed has become available CAPWAP usage has increased. Since it does not require the input of soils information it has made Case Method capacity determination less important. The CAPWAP analysis is described in more detail in Appendix D.

3 Application of the New Technology in Design

Several hypothetical examples will be used to illustrate the use of the pile design and construction control tools that have been described above. In general, these examples will progress from simple to more complex cases.

3.1 Example One

About 30 piles are to be driven to support a small modification to an industrial plant. The limited available subsurface investigation indicates a bearing layer of silty sand overlain by soft normally consolidated clay. The water table is near the surface. Other previously driven piles on the site have not been driven into this particular bearing layer.

A static analysis is made using the information from the subsurface investigation, and the pile length is selected. Using the results of the static analysis, the selected pile cross section and length, and the driving system that the contractor will use to drive the piles, a Wave Equation analysis is performed and a preliminary driving criteria is selected. The ultimate pile capacity is selected from the working load using a safety factor of 2.5 to 3.0. Due to the potential for large down drag loads arising from the consolidation of the clay care must be used to prevent any permanent loads from being applied directly to the ground surface.

The driving of the first pile is carefully monitored. Driving is stopped at a somewhat lower blow count than the specified one. After a one hour delay, the blow count at the beginning of restriking is carefully checked. It is observed to have increased sufficiently to meet the criteria determined in the Wave Equation analysis. The remaining production piles are driven to the blow count used for the test pile.

3.2 Example Two

Approximately 200 piles are to be driven to support a four-story office building. The subsurface investigation shows a loose sand of increasing density with depth. The water table is near the surface.

A static analysis is performed using the subsurface investigation information and the pile length is estimated. The ultimate load, used in selecting the pile length, is determined from the working load using a factor of safety of 2.0 to 2.5. With the results of the static analysis, the pile length and cross section selected, and the driving system to be used by the contractor, a Wave Equation analysis is performed and a driving criteria selected. The appropriateness of the selected driving system is evaluated and changes are made if necessary.

Near the end of driving of the first pile, PDA monitoring is started and continued until satisfactory Case Method capacity is achieved. Hammer performance is compared with that assumed in the Wave Equation analysis. After a 15-minute interruption in driving, the pile is restruck with dynamic monitoring and a careful blow count. In this soil, there may have been little or no strength change. If there has been an increase in the capacity determined by the PDA, then it may be desirable to repeat and lengthen the wait time. A CAPWAP analysis is performed on one or two hammer blows after returning to the office. This analysis will verify the field-determined capacity and the damping constant. Based on all of the information obtained, driving criteria are established and the production piles are driven. If a low safety factor is used, it is desirable to test an additional ten to twelve production piles with the PDA. Usually the piles selected for quality control testing would be those that had relatively low blow counts. It is also desirable that they be scattered across the site if they can still be accessed.

3.3 Example Three

Several hundred piles are to be driven for the foundation of a grain elevator. The subsurface investigation indicates that a pile foundation will be required due to the presence of a considerable depth of weak material overlaying the proposed bearing layer consisting of medium dense to dense clayey sand. The water table is near the surface.

The pile length and cross section are selected based on a static analysis of the data obtained from the subsurface investigation. The ultimate load used in selecting the pile is obtained from the working load using a factor of safety of 1.8 to 2.0. An attempt should be made to estimate the setup that will develop in the bearing layer after the end of driving. Wave Equation driveability studies are performed using the results of the static analysis and the selected pile together with some candidate driving systems. The purpose of the study is to verify that it is possible to drive the pile as designed. If strength change can be estimated, then end of driving and restrike blow counts should be determined from the Wave Equation analysis.

At the beginning of the job one pile is tested statically to failure. Dynamic monitoring is performed on that pile with a PDA during the latter part of driving. After completion of the static load test, the pile is restruck and PDA data is taken. CAPWAP analyses are performed on selected hammer blows from both the end of driving and the beginning of restrike. From all of these data, the driving criteria can be set with a good understanding of the magnitude and rate of setup. Thus, during the dynamic testing of production piles, the required capacity will be well defined. About five percent of the production piles are tested by the PDA, as well as any piles with driving records that raise questions.

3.4 Example Four

Several thousand piles are to be driven for the foundations of a large industrial plant. An extensive subsurface investigation shows considerable variability across the site, indicating that the piles will vary in length and the driving may be difficult in some areas. It is not clear what pile type will be most economical in this application. The water table is near the surface.

A pre-design test program is undertaken to better evaluate the site. Based on the subsurface investigation, test piles of different types are driven at several critical locations. Dynamic monitoring is performed during driving, and for selected piles, restrike data are taken after a variety of different wait times. Two piles are selected for static testing to failure. Several hammer blows are analyzed by CAPWAP. Based on this information, pile type and ultimate capacity are selected using a factor of safety between 1.7 and 2.0. Pile lengths are estimated across the site and the Wave Equation soil constants are made available to all bidding contractors. It may prove desirable to offer pile type and ultimate capacity options for bidding but care must be used since footing design may fix the pile capacity, limiting the choices available.

About five percent of the production piles are tested by the PDA during driving, in addition to any piles about which the driving record raises questions.

5 Conclusions

Several new methods for pile design and construction control have been summarized. This presentation is necessarily superficial, emphasizing the things that can be done rather than how they are done. More detail is presented in the Appendices. A hypothetical example is also presented to illustrate the use of Wave Equation analysis in practice. Other combinations of the procedures could be used. While the examples are very general, they provide useful guidelines for the practitioner.

APPENDIX A: WAVE EQUATION ANALYSIS OF PILES

Elastic dynamic analysis of pile driving was first suggested by E. A. L. Smith (1951, 1957, 1960), then an employee of the Raymond Company. He not only created the original concept but also, produced the first working computer program for its execution. It may be that this program was the first application of electronic digital computers in non-military engineering work. In what follows, the basic concepts of this analysis will be described and illustrated.

The analysis of one dimensional wave propagation began over 100 years ago. A differential equation describing the wave propagation process was derived and solved. This equation, commonly known as the "Wave Equation", can be written in the form

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2}$$

where x defines a position on the rod, t is time, u is the displacement of the rod at point x, E is the elastic modulus of the material in the rod, and ρ is its mass density. Solutions of the Wave Equation have been applied to the analysis of pile driving and they are very useful in visualizing the process. However, they are of limited value in obtaining quantitative results since they are difficult to apply to the real boundary conditions typical of pile driving.

The analysis developed by Smith was based on a discrete representation of the total hammer-pile-soil system. He used this capability for pile driving analysis in a framework that produced useful results for both the selection of pile driving systems and the prediction of axial pile capacity. He called the resulting computer program the "Wave Equation" and this name has been generally adopted. In what follows, the term "Wave Equation" will always refer to a computer program used for the analysis of pile driving rather than the second order, partial differential equation.

Many other wave equation programs have since been written. The one most widely used today is a program called WEAP, developed by Rausche and Goble (1976) under contract with the Federal Highway Administration. This program is in the public domain and operates on a wide variety of computers, including the IBM PC and compatibles. The current version of the program, known as GRLWEAP, has been improved and expanded and is maintained by Goble Rausche Likins and Associates, Inc.

The Wave Equation representation of the total pile driving system is shown in Figure A1. The pile driving hammer, hammer cushion, pile cap and pile are represented by a series of masses and springs. The size of each of the masses is determined from the weight of the piece of the system represented. For example, if the pile is divided into discrete lengths of one meter, then the equivalent mass element would have the same mass as one meter of pile. Similarly, the discrete spring would have the same stiffness as one meter of pile. Some of the elements of the system are naturally discrete. For

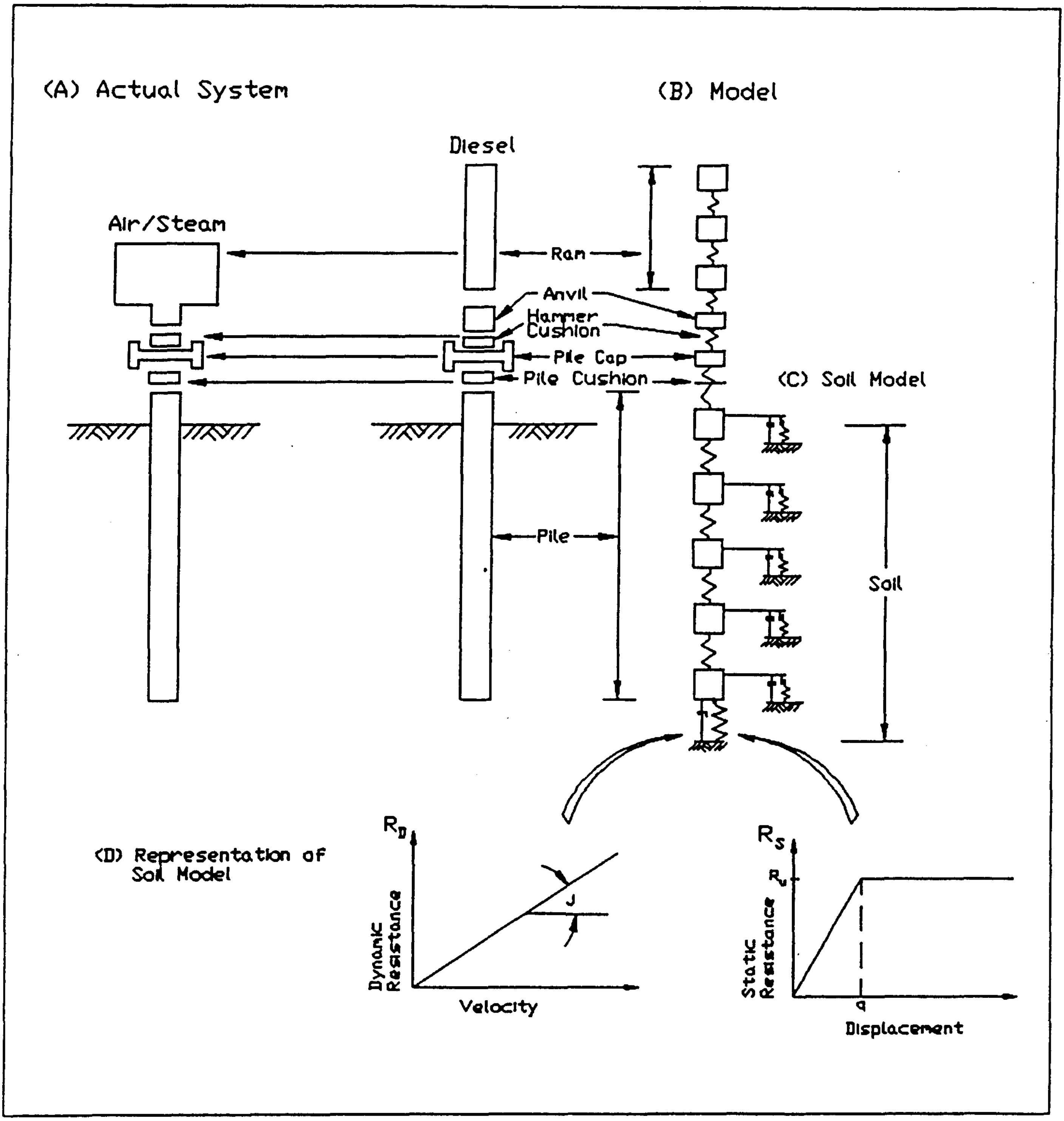

Figure A1: Wave Equation Model

effect of the impact on the ram and protect it from damage. It can be easily represented by a spring in the computer model. The pile cap is a very compact element that contributes little or no flexibility to the system, so it can be treated as only a mass element.

The hammer must be represented in as realistic a manner as possible. For the usual air/steam or hydraulic hammers the representation is quite straight-forward. However, for diesel hammers where the stroke can vary by a significant amount and the forces in the combustion chamber can have an important effect, the computer representation must be carefully constructed to represent what really happens during pile driving operations. For purposes of calibration, the performance of the WEAP program was extensively compared with force and acceleration measurements made at the pile top during production pile driving.

The commonly used soil model is also shown in Figure A1. More complex representations have been made, but since they usually require more extensive, difficult-to-determine input information, they are not frequently used. As a result, soil resistance to pile penetration is represented by a displacement dependent part and a velocity dependent part. The displacement dependent part, illustrated in Figure A1(D), can be thought of as an elastic-plastic spring. The force at which plastic displacement starts, R_u, is the ultimate static soil resistance acting on that piece of the pile represented by the mass element. This quantity is obtained from a geotechnical analysis of the subsurface soil investigation information. The displacement at which the soil spring becomes plastic is denoted by q in Figure A1(D), and was named the quake by Smith.

The velocity dependent portion of the resistance is also illustrated in Figure A1(D). Usually the relationship between resistance force and velocity is assumed to be linear, with a slope, J. A more complex treatment could be used if information were available on the performance of various soil types. Again, as in the case of the displacement dependent part, the analysis capabilities exceed our ability to obtain soil properties.

Three constants, R_u q, and J are required at each element to represent the soil according to this model. The value of R_u can be determined from a geotechnical analysis of the subsurface investigation information. A value of 2.5 millimeters has been used for the quake, q, since the original work of Smith. It has been shown that in some cases a much larger value is appropriate for the pile toe (Likins, 1983). The toe quake is usually dependent on the size of the pile toe but in a small number of cases may also depend on the soil and these conditions usually cannot be foreseen from the subsurface investigation. The velocity dependent portion of the resistance, known as the damping, is defined as a function of the static resistance. Thus,

$$R_D = jR_s v$$

where v is the velocity of a point on the pile. The product jR_s is equal to the value J used above. The quantity j is usually known as the damping constant and R_s is the current value of the static resistance. This treatment of velocity dependent resistance is not the only one, but it is certainly the most commonly used today. As with the quake term, it is difficult to establish the proper value for damping. Usually it is taken to be a function of the soil profile. Recommendations have been made by Smith and others but a clear, rational, accurate means of determining damping remains to be established.

The analysis proceeds after all of the physical parameters have been defined. To begin, the ram elements are given a downward velocity equal to the impact velocity, and the subsequent motion of all of the masses is calculated. This computational process can be illustrated by a typical mass taken from someplace within the string during the dynamic event. It is shown as a free body in Figure A2. Due to the motion of the individual masses of the element string, the springs are deformed inducing forces as shown. Also, the displacement of the element has induced static soil resistance forces and the velocity dependent dynamic soil resistances. In Figure A2 the sum of the static and dynamic soil resistances is R_{so}. This set of conditions exists at some specific instant in time. Now Newton's Second Law is applied to determine the instantaneous acceleration:

$$a = \frac{F_t - F_b - R_s}{M}$$

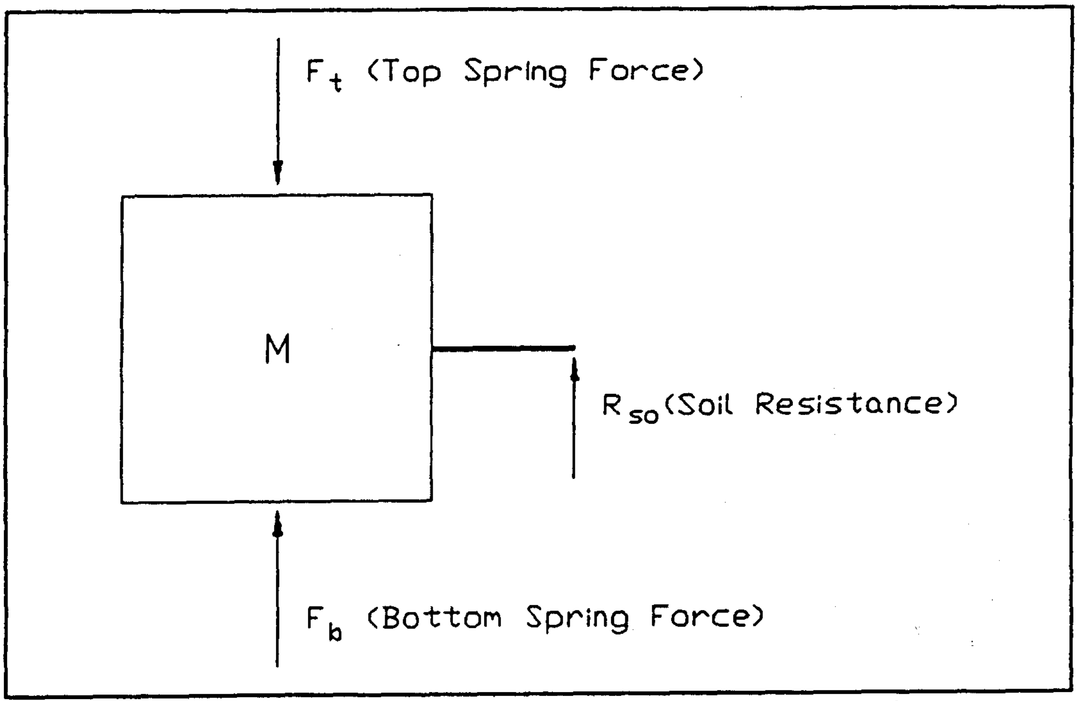

Figure A2: Wave Equation Analysis - Free Body

where the variables are defined as shown in Figure A2. A similar expression can be written for each mass element at this instant so all of the instantaneous element accelerations can be determined. From the accelerations, the change in velocity occurring over a short time interval can be calculated by multiplying the accelerations by the time interval, Δt. If the velocity change is added to the velocity at the beginning of the time interval, the velocity at the end of the time interval is found. This same computational procedure can be applied to the velocities to determine new displacements. Now, new spring deformations and hence, forces can be determined from the new displacements. The process is repeated for successive time intervals. The computational algorithms that are actually used in available software are more complex than the simple procedure described above. But, for the purpose of a general understanding of the procedure, this description is adequate. As a result of the analysis the motion of all of the masses together with the forces in all of the springs are determined for the duration of the impact event.

It is more important to understand the way in which this computational tool is used to analyze the pile driving operation than to understand the numerical analysis process. Given the above analysis capability, how can it be used to analyze pile driving? The analysis gives the motion of all points on the system during the dynamic event. The total permanent set of the pile is therefore known since the "slip" of each of the soil springs is determined from the mass displacements. This quantity is usually defined by the inverse of the permanent set, the blow count. If the resistance force is gradually increased for each analysis, then the blow count is also increased. This result is usually represented by plotting ultimate resistance against blow count producing a curve known as a bearing graph. An example is shown in Figure A3. With this curve, the required blow count for a desired capacity can be determined, or for a given observed blow count, the expected capacity can be predicted. Driving stresses can also be determined from the spring forces that are calculated in the dynamic analysis and they can also be plotted as a function of blow count.

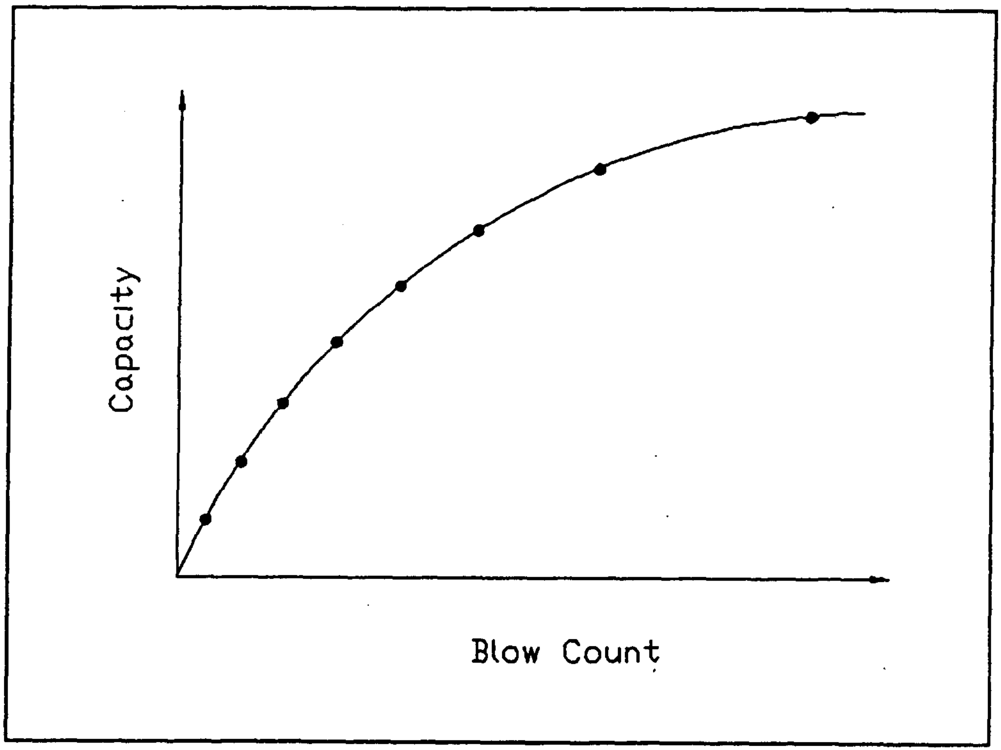

Figure A3: Example Bearing Graph

To illustrate the use of Wave Equation analysis, a specific example will be investigated. A subsurface investigation at a proposed construction site produced the soil profile shown in Figure A4. As is frequently the case, the only information beyond the profile was SPT blow counts. The decision was made to prestressed concrete piles. A working load design design capacity of 800 kN will be sought. A geotechnical analysis was performed, and after some trials it was determined that an 300 mm square pile is sufficient to meet the requirements. It is estimated that a pile penetration of 15 meters will be required to achieve adequate capacity. The load transfer analysis is shown in Figure A5. Note that the resistance in the upper 5 meters is included in the load transfer analysis and also in the Wave Equation analysis. That soil resistance is neglected when evaluating the pile capacity and stresses under

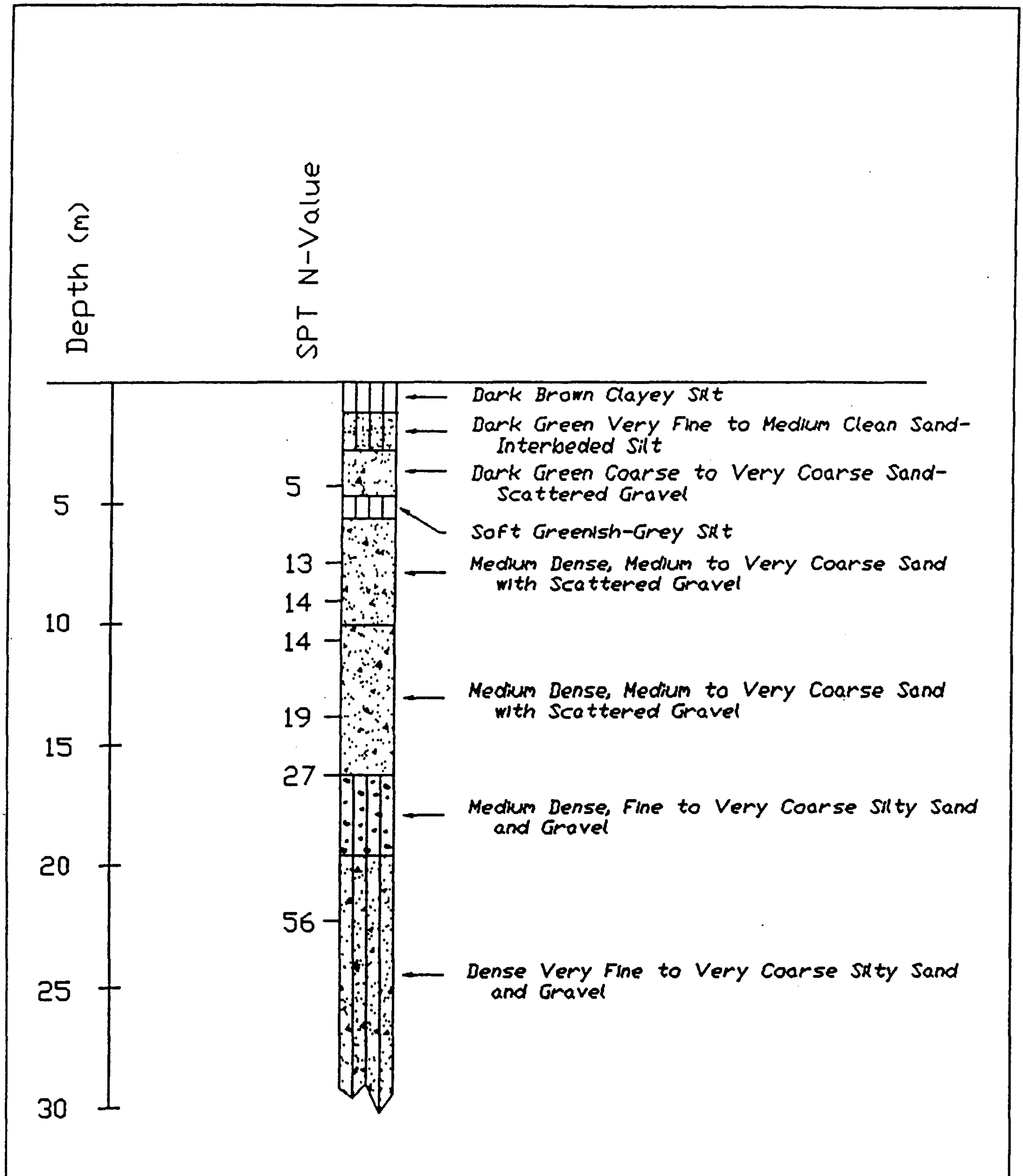

Figure A4: Example Problem - Boring Log

Pile Dimensions

Pile Diameter . . . . 300 mm
Pile Circumference . . . . . 1.20 m

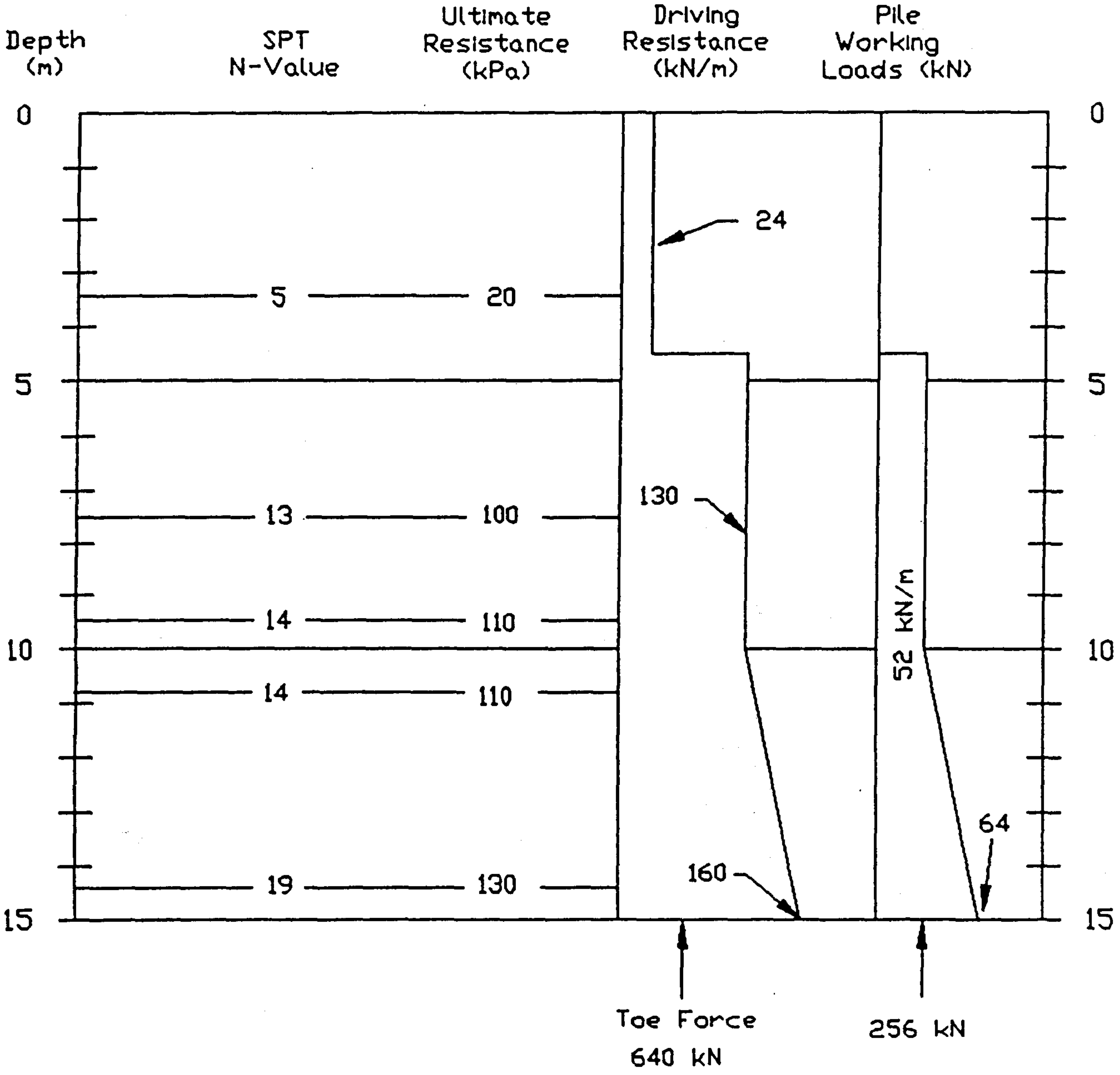

Figure A5: Pile Design Calculations

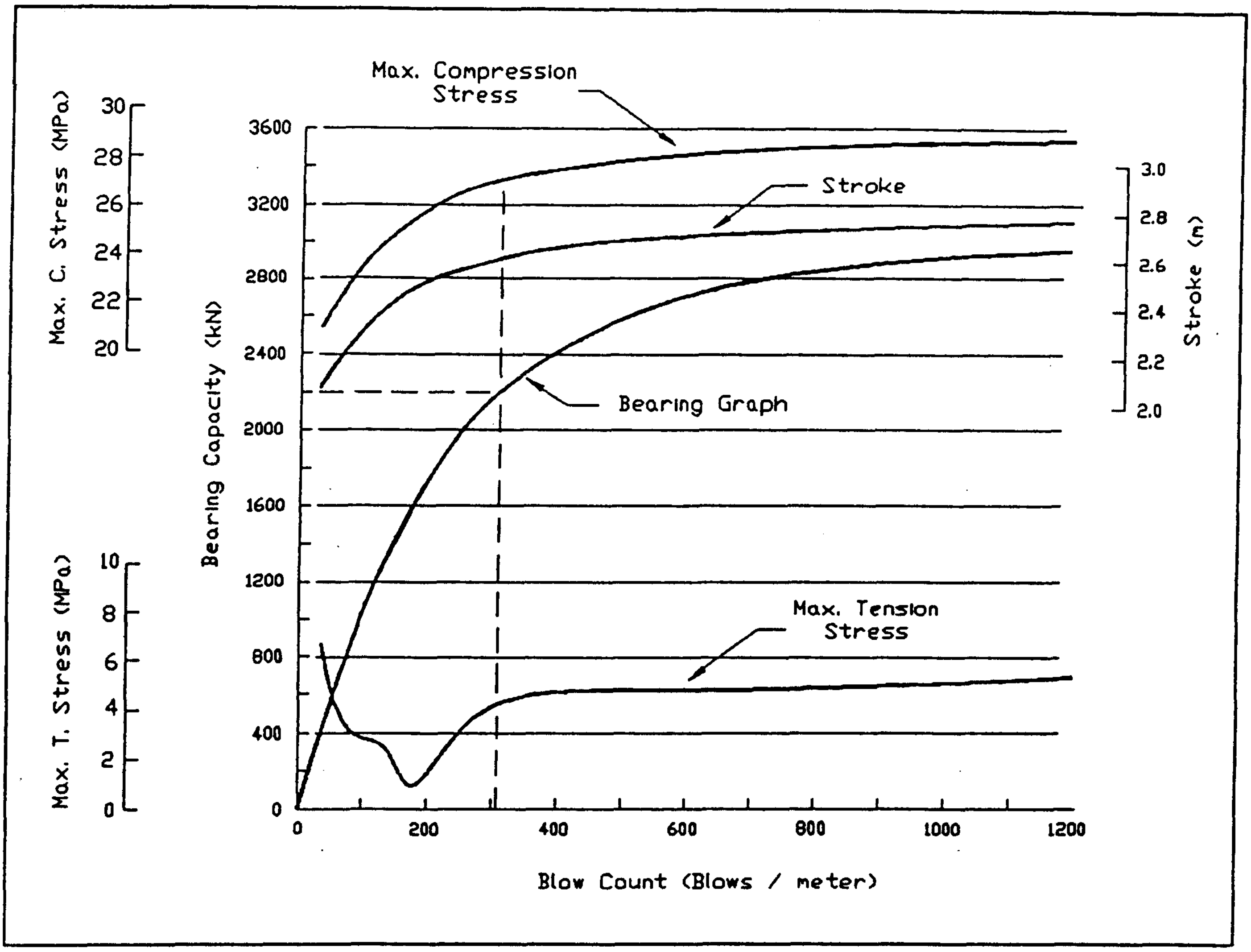

Figure A6: Design Example Bearing Graph

working loads. It is assumed that, due to the possible compressibility of these soils, they cannot be relied on for carrying long term loads.

This design assumes that the only field design and control techniques used will be the Wave Equation applied to the field measured blow count. Therefore, a factor of safety of 2.5 is applied to the soil capacity. The factor of safety could be reduced if higher level engineering design and construction control procedures were used. For example, if a static load test were included, a factor of safety of 2.0 may be appropriate. A design load of 1000 kN then could be safely applied to the soil resistance, and the pile design stresses at 11.1 MPa would still be quite satisfactory.

Because high design loads are being used, a relatively large hammer will be required. This case is analyzed for the Delmag D16-32, a diesel hammer with an energy rating of 53.23 kJ. The resulting bearing graph is shown in Figure A6.

Even though the geotechnical analysis showed an ultimate static capacity of 2200 kN, points on the bearing graph were calculated at a wide range of capacities. For all values of static capacity, the distribution of resistance was assumed to be the same.

Hammer stroke and maximum pile compression stress is also shown on the bearing graph. In order to achieve an ultimate capacity of 2200 kN, the pile must be driven toa blow count of about 310 blows per meter. At this level the hammer stroke will be 2.6 meters and a stress of about 27 MPa will be induced. Tension stresses will be in the range of the prestress. Driving must be performed carefully at these stresses to prevent damage.

At the beginning of the job the first pile should be driven to a somewhat lower blow count (about 250 blows per meter) and a waiting period allowed to elapse. In this soil a 15 minute wait should be adequate. The pile should then be restruck for 10 hammer blows and the penetration measured. The restrike blow count would be used on the bearing graph to determine capacity, and it would have to be at least the equivalent of 310 blows per meter (35 mm for 10 blows). Thus, the final driving criteria could be reduce if set-up is noted. In this way, damaged problems may be reduced.

In the design example presented here, fairly large design loads have been used for this prestressed concrete pile. Because only Wave Equation control was used, a factor of safety of 2.5 was used on the capacity limited by the soil. At rather high driving stresses, the required pile ultimate capacity can be achieved. These capacities include an allowance for the resistance to driving in the surface soils. This resistance is not included in the permanent capacity.

APPENDIX A REFERENCES

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APPENDIX B: DYNAMIC MONITORING AND THE PILE DRIVING ANALYZER

The use of dynamic monitoring of pile driving was developed in a research project at Case Institute of Technology (now Case Western Reserve University). Sponsorship for this project came primarily from the Ohio Department of Transportation and the Federal Highway Administration. Some support was also supplied by other state highway departments, contractors, and equipment manufacturers. A large volume of data was obtained by dynamically testing piles, previously tested statically, by restriking with a pile driving hammer. The Case project produced both equipment that can be used routinely and the methods for processing those measurements.

In 1973, the Case Project had progressed to the stage where the development of dynamic monitoring equipment could be continued on a commercial basis. The Case researchers founded Pile Dynamics, Inc. for this purpose and equipment development has continued on a private basis.

Experience has shown that the most useful and convenient quantities for measurement are force and acceleration at the pile top. Force can be measured using a top transducer or, more commonly, strain transducers attached to the pile above the ground. These instruments use resistance strain gages attached to an axially flexible device that can be mounted on the side of the pile. As the transducer is deformed by the passing stress wave, signals proportional to the strain magnitude are generated. Acceleration measurements can be made using commercially available accelerometers modified to be easily attached to the pile. Piezoelectric accelerometers were used in the Case project due to their high natural frequency and ease of usage. More recently experience has shown that in a few applications piezoresistive accelerometers give better results. In the basic operation, measurements are made at or near the pile top. The transducers are shown attached to a steel pipe in Figure B1.

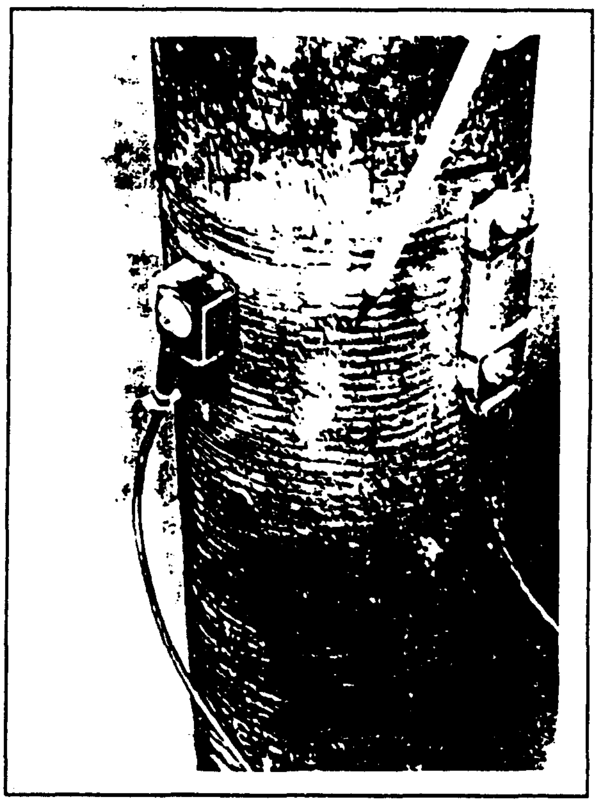


Figure B1: Transducers

It is convenient to attach the transducers to the exposed part of the pile so that they do not need to be protected from the earth during driving. Two transducers of each type are attached to the pile, one on each side to cancel bending effects (or to sense the presence of bending). Usually the two acceleration signals are integrated to obtain a pair of velocity records. Both the velocity and strain signals are then averaged to cancel bending effects. The results of the measurement activity are matching records of force and velocity on the pile at the measurement location. These two quantities are particularly useful in the application of one dimensional wave mechanics to the analysis of pile driving. In addition, since force and velocity are known to be proportional so long as wave propagation is in one direction only, a check of this proportionality provides an excellent verification of the correctness of the two independent measurements.

An example of the measurements for a single hammer blow on a pile is shown in Figure B2. The velocity record has been multiplied by the force-velocity proportionality constant, the pile impedance, and plotted on the same time axis as the force. The first part of the record exhibits good proportionality between force and velocity, so it can be concluded that the measurements are correct. Later in the record, proportionality does not hold when stress wave reflections are generated by resistance forces. Dynamic records of this type must be analyzed to evaluate the pile driving operation.

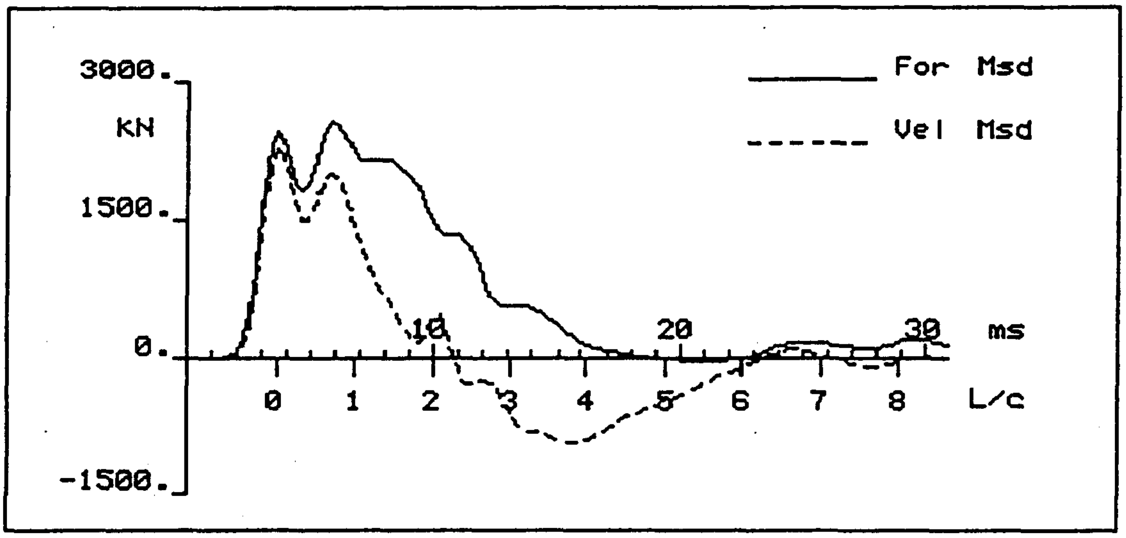


Figure B2: Measurements for a Single Hammer Blow on a Pile

The Pile Driving Analyzer™ (PDA) was developed to acquire the above measurements and perform the analysis in a manner that can be easily used on a routine basis in the field. This is particularly challenging due to the very difficult conditions commonly encountered at pile driving sites. The current PDA is the eighth of a series of designs that have been used during the course of the development. The first three instruments were developed by the research project and single units only were built for concept testing. The private development produced a commercial device and the device sales paid the cost of further development. The first five designs used all analog circuitry to perform the computation and the remaining three designs have operated with digital equipment.

Figure B3 shows the total testing system with the current version PDA, Model PAK. Earlier versions of the PDA required several different instruments, oscilloscope, tape recorder, etc. to perform all of the required tasks. The current version accomplishes everything required in a single unit. The system consists of a set of strain transducers and accelerometers, a "splitter cable", and a main cable. This will bring the signal to the PDA where the main cable connects directly. The PDA is briefcase size. It is powered by 12 volt dc which can be supplied by a automobile battery or by an ac

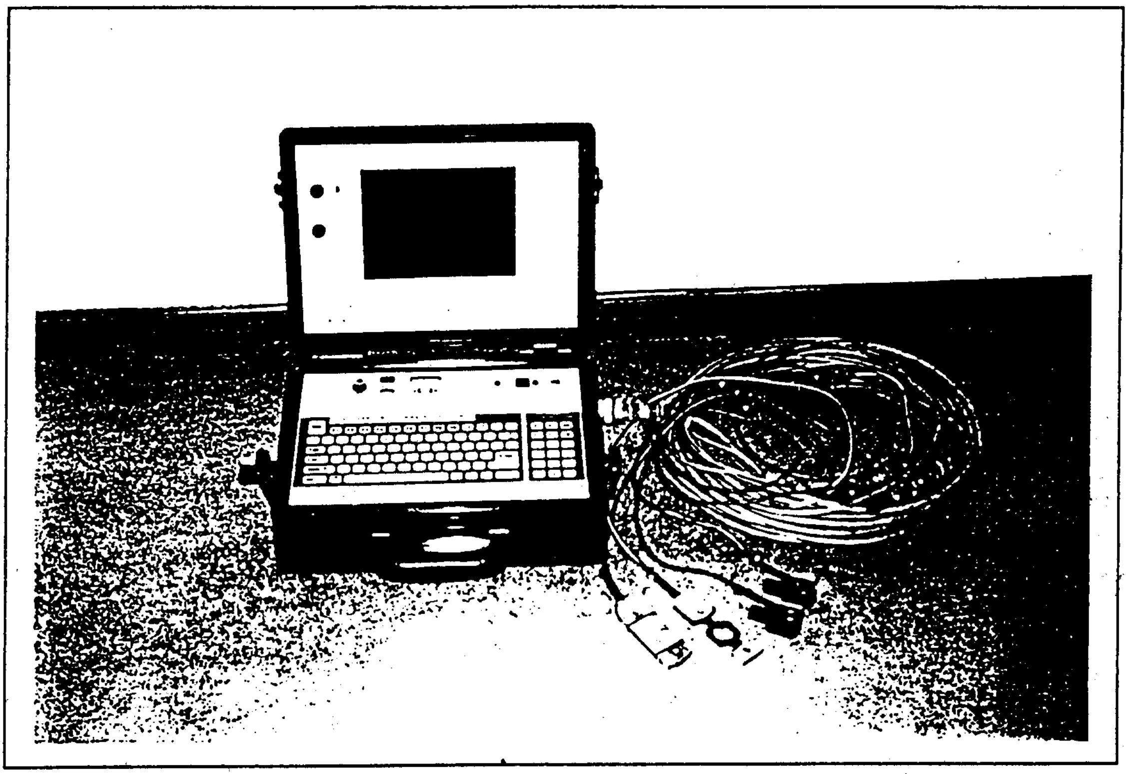
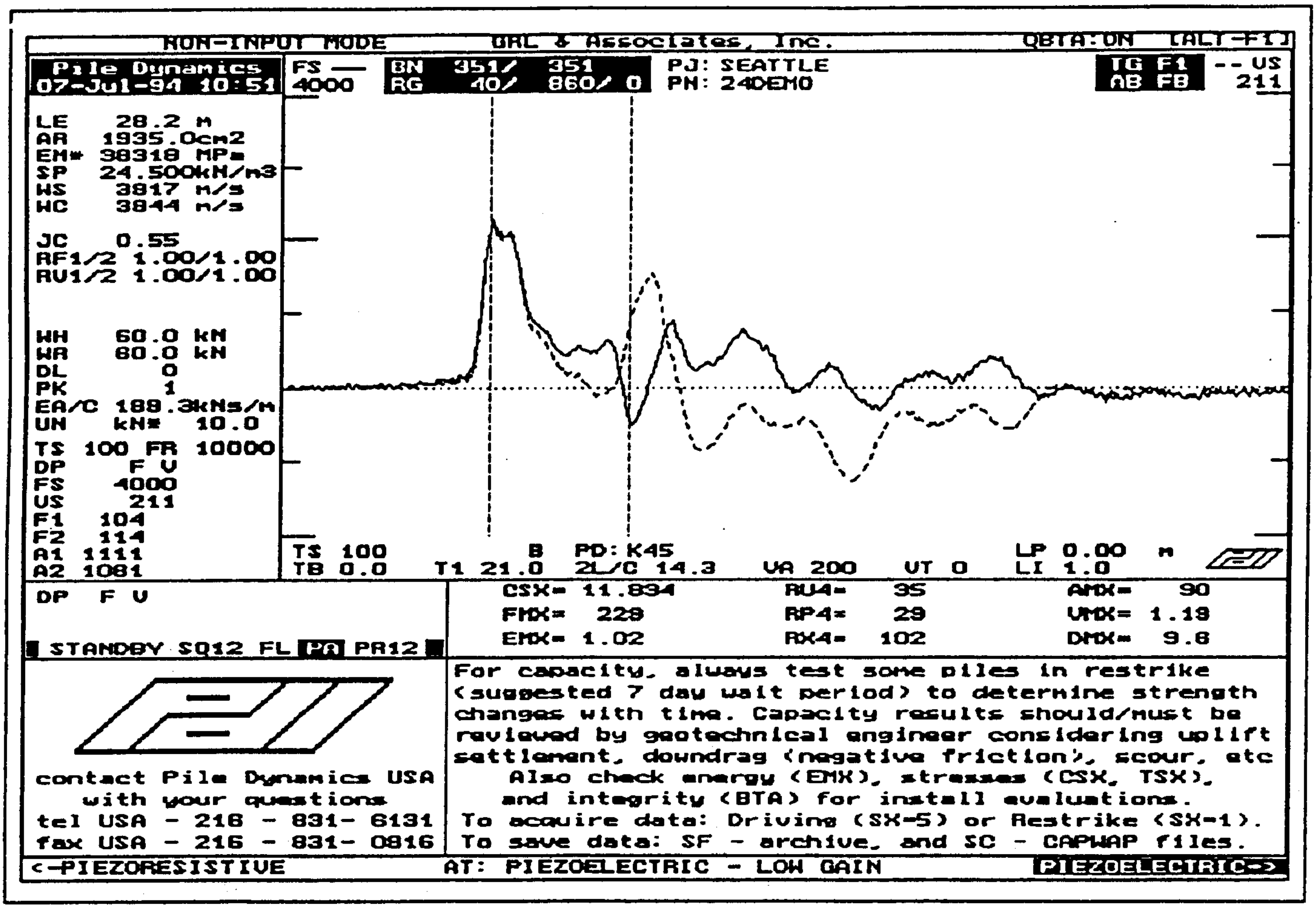


Figure B3: Testing System

driven 12 volt dc power supply. All of the transducer signal conditioning and processing equipment is contained in the PDA for up to four strain transducers and four accelerometers. The PDA will condition either piezoelectric or piezoresistive accelerometers.

In operation, the analog signals from the strain transducers and accelerometers are powered and conditioned by circuitry contained in the PDA. They are then converted to digital form and stored on an internal hard disk. All subsequent processing is done in digital form using a single board IBM compatible Personal Computer also contained in the PDA. The hard disk can store a large volume of data so analog data storage is no longer necessary. Permanent archiving of data is done on floppy disks.

The PDA display screen can be seen in Figure B3. An example of the screen is shown in Figure B4. The various parts of the screen will be reviewed briefly as a introduction to PDA capabilities. The upper part of the block of information on the left side directly under the "Pile Dynamics" heading is input information that describes the pile being tested. For example, LE denotes the pile length, in this case 28.2 meters. It can be entered from the keyboard with the keystrokes displayed in the next lower block. (In this example, the block shows DP F V.) Other pile quantities that must be entered are pile area, modulus, and unit weight. The other important material parameters are calculated from these basic values. The next group of data includes J_c the Case Damping Constant and also constants for adjustment of recorded data when it is replayed. The parameters on down the list have the function of scaling the display, controlling the digitizing process and also include the transducer calibrations. All of these quantities are basic parameter input data.



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        RUN-INPUT MODE           GRL & Associates, Inc.           QBTA:ON   [ALT-F1]
Pile Dynamics       FS ---  BN  351/  351     PJ: SEATTLE                TG F1  -- US
07-Jul-94 10:51     4000    RG   40/  860/ 0  PN: 24DEMO                 AB F8    211

LE    28.2 m
AR   1935.0cm2
EM*  38318 MPa
SP   24.500kN/m3
WS    3817 m/s
WC    3844 m/s

JC    0.55
RF1/2 1.00/1.00
RU1/2 1.00/1.00


WH    60.0 kN
WR    80.0 kN
DL       0
PK       1
EA/C 188.3kNs/m
UN    kN*   10.0
TS  100 FR  10000
DP     F V
FS    4000
US     211
F1   104
F2   114
A1  1111            TS 100             B   PD: K45                        LP 0.00   m
A2  1081            TB 0.0     T1 21.0   2L/C 14.3    VA 200     VT  0    LI 1.0
DP   F V                     CSX= 11.834         RU4=    35          AMX=    90
                             FMX=  228           RP4=    29          VMX=  1.19
 STANDBY SQ12 FL PA PR12     EMX= 1.02           RX4=   102          DMX=   9.8
                           For capacity, always test some piles in restrike
                           (suggested 7 day wait period) to determine strength
                           changes with time. Capacity results should/must be
                           reviewed by geotechnical engineer considering uplift
                           settlement, downdrag (negative friction), scour, etc
contact Pile Dynamics USA     Also check energy (EMX), stresses (CSX, TSX),
   with your questions        and integrity (BTA) for install evaluations.
tel USA - 216 - 831- 6131  To acquire data: Driving (SX-5) or Restrike (SX-1).
fax USA - 216 - 831- 0816  To save data: SF - archive, and SC - CAPWAP files.
<-PIEZORESISTIVE           AT: PIEZOELECTRIC - LOW GAIN         PIEZOELECTRIC->
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Figure B4: Example of Display Screen

The information across the top of the main display gives the scales of the displayed record, the status of the hard disk, a project title (PJ), a pile number (PN), the signal trigger information, and the selection of the transducer to be displayed. A total of 860 hammer blows can be recorded in a single data set and this data set can be readily filed on the hard disk. The hard disk also makes it possible quickly recall previously recorded data for re-examination.

The measurements that are shown in the main display in Figure B4 are of a force and velocity measurement that was made during the driving of a prestressed concrete pile. The force is the solid line and the velocity, the dashed line. Other time dependent quantities can be selected by the PDA operator. For instance the upward and downward traveling waves, the dynamic displacement and the delivered energy, the measured bending forces and a number of other selections can be shown. The two vertical lines show the point of first relative maximum in the force record and the time 2L/c later (2L/c is the time required for the wave to travel the length of the pile and return) when the peak force is reflected from the toe of the pile. In this record, it can be seen that force and velocity show excellent proportionality at impact. (For the purpose of the display, the velocity scale is selected so that it will plot on the force if it is proportional.) There is evidence of shaft friction indicated by the deviation of the velocity beginning in reflections from about one-third of the depth of the pile. The toe reflection, with a large increase in the velocity and a decrease in the force, indicates that the toe resistance is fairly small. A visual examination of the record by an experienced operator can give considerable information on measurement quality and an understanding of the pile driving.

The quantities at the bottom of the main display are values such as display time scale, hammer type, velocity adjustment characteristics, and other similar values.

Up to nine sampled or calculated quantities of specific values are given in the box directly under the measurement display. These quantities are user selected from an extensive list to meet the needs of the particular job. Some of the most important of these values are:

- Maximum force at the transducer
- Maximum velocity at the measurement location
- Total force resisting penetration
- Predicted static pile capacity by Case Method
- Maximum energy transmitted to the pile
- Maximum computed tension stress in the pile
- Pile integrity evaluation
- Hammer operating rate in blows per minute
- Maximum displacement at the transducer
- Maximum acceleration at the transducer

A large number of additional parameters are available for selection by the PDA operator. These values can also be stored for later display on the PDA screen or for printing. Supplementary software is also available to provide plots of the stored data.

The use of the PDA must be under the control of an engineer with sufficient background and training to immediately evaluate the results and make recommendations. Special training in PDA operation is required and this must include sufficient background in one dimensional wave mechanics to understand the information that the PDA supplies.

About 350 Pile Driving Analyzers are now in use around the world (1994). Of these, approximately 300 are of the most recent model available described here.

APPENDIX C: CASE METHOD

In 1964, when the Case Institute of Technology pile project began the announced goal was develop methods to predict the axial capacity of a driven pile using dynamic measurements. Earlier work of a preliminary nature had been done at Case in the late 50's (Eiber, 1958) which produced results that gave a strong reason for optimism. The Case project proceeded in three directions. First, small scale piles driven and tested both statically and dynamically. Second, dynamic measurements were made on piles driven by the Ohio Department of Transportation for static load test. In the third activity, analytical studies were performed to try to understand the impact wave propagation problem and relate it to capacity determination.

The model pile study produced little of permanent use to engineering practice. Probably the most important result was the extensive testing of dynamic measurements systems. In a model pile driving environment, devoid of the pressure to make measurements quickly to avoid delaying the pile driving contractor, it was possible to test new equipment and to make improvements on the existing system. During this time great developments were taking place in electronics from which the Case project benefitted. In fact, the success of the project was substantially dependent on these developments.

Of major value to the project, was the large volume of data obtained in the second activity, the Ohio full scale tests. In the practice of Ohio D.O.T., static load tests were frequently specified. These tests were run to failure or three times the design load, whichever came first. In those cases where the static load reached failure, the research project made dynamic measurements of strain and acceleration on the pile at a point near the top. It was a fairly simple matter to restrike the pile with the pile driving hammer. In almost all cases the dynamic measurements were made after completion of the static load test. Thus, the results of the measurements included the effects of pore pressure decay and were relevant to the conditions at the time of the load test. This volume of data growing to about 70 different piles was a major factor in the success of the project.

The general goal of third activity, the analytical work, was to develop a means of predicting static pile capacity. The research project was committed to the development of a method that could be applied in the field and produce immediate results. This work had a long development period, and several methods were produced successively that gave improving agreement with the static load test results. Each of these methods was correlated with he data bank of full scale test measurements. As the work progressed the methods became more soundly based in fundamental wave mechanics. At the same time, improved correlations with the full test results were obtained. The purpose of this Appendix is to describe the end result of this work.

The Case Method assumes the measurements of axial force and acceleration are available on a pile at a point above the ground surface. It can be shown (Rausche et al, 1985) that, at time t, the sum of all the forces resisting the penetration of a pile being driven into the ground are given by the expression

$$R(t)=\frac{1}{2}[F(t)+F(t+\frac{2L}{c})]+\frac{Mc}{2L}v(t)-v(t+\frac{2L}{c}) \qquad (C1)$$

where

F(t) = the force at the point of measurement given at time t
L = the length of the pile
c = the velocity of wave propagation in the pile
E = the elastic modulus of the pile material
M = the mass of the pile
v(t) = the partial velocity at the point of measurement given at the time t.

This equation was derived based on the assumption of linear elasticity and one dimensional wave propagation; therefore, it is quite fundamental. The resistance force that is obtained from it is a function of time. The problem that must now be solved is the selection of the proper time for definition of the static capacity and the relationship of the penetration resistance to the static capacity. An example of measurements of force and velocity Figure C1. In most cases, the value used for capacity is taken at the time of the first peak in the force and velocity curves. There are cases where other times are used, but they will not be discussed in this brief presentation (Rausche et al 1985).

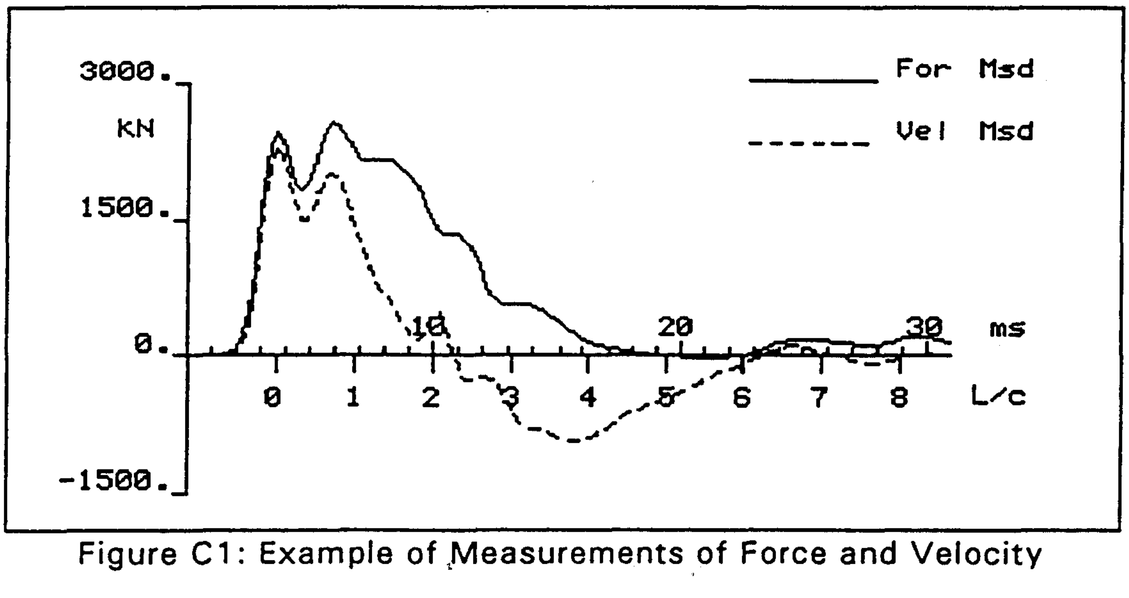

Figure C1: Example of Measurements of Force and Velocity

There are many reasons for the difference between the dynamically measured resistance to penetration and the static capacity. This problem is further complicated by the fact that the performance of a static load test is not standardized nor is the method used to evaluate it. In the Case project, a particular load test evaluation procedure, the Davisson Method, was adopted. Empirical methods were developed to obtain, from the resistance to penetration, a prediction of static capacity that agreed with the statically measured value.

Assume that the resistance to penetration can be divided into two parts according to the relation.

$$R = R_u + R_d \tag{C2}$$

where R_u is the ultimate static capacity, R_d is the dynamic portion of the resistance to penetration, R, given in Equation (C1) above. This division of the resistance into two parts could be considered arbitrary. Such an approach is commonly used in wave equation analysis. Since R is known, if R_d can be estimated, then R_u, the desired quantity, can be calculated.

The dynamic portion of the resistance to penetration is assumed to be related to pile tip velocity by the equation

$$R_d = Jv_b \tag{C3}$$

where v_b is the velocity of the pile tip and J is a constant. This equation assumes that a viscous damping component is contained in the pile resistance and is concentrated at the pile tip. The assumption that the resistance is concentrated at the tip is supported by extensive experience with CAPWAP analysis. The tip velocity can be determined from one dimensional wave mechanics, and with some manipulation it can be shown that (Rausche et al, 1985).

$$R_d = j_c[2F - R] \tag{C4}$$

There is a proportionality between force and velocity (as can be seen in the first part of the measurements shown in Figure C1), so it is convenient to represent all quantities in terms of force. Finally substituting back into Equation (C2), the static capacity can be determined from

$$R_u = R - j_c[2F - R] \tag{C5}$$

In Equation (C5) all of the terms on the right side are known except j_c, the damping constant. It should be noted that this constant is related to J by

$$J = j_c \frac{EA}{c} \tag{C6}$$

Since a large volume of both static and dynamic data were available and, thus, all of the quantities in Equation (C4) except j_c were known it was determined by correlation. The constant j_c was assumed to be a soil parameter. It generally becomes larger as the soil becomes more fine grained. Recommended values of j_c related to the soil profile were determined in the correlation study. The agreement between Case Method and statically measured capacity for 120 different test piles is shown in Figure C2. Several other methods of capacity prediction based on Equation (1) have since been developed. All of these methods are founded on extensive experience and are related to specific pile and soil types.

Case Method capacity predictions have proven to be quite accurate. Given the availability of force and velocity measurements, the necessary computations are quite simple. It has the advantage of giving (with the aid of a Pile Driving Analyzer) an immediate result in the field.

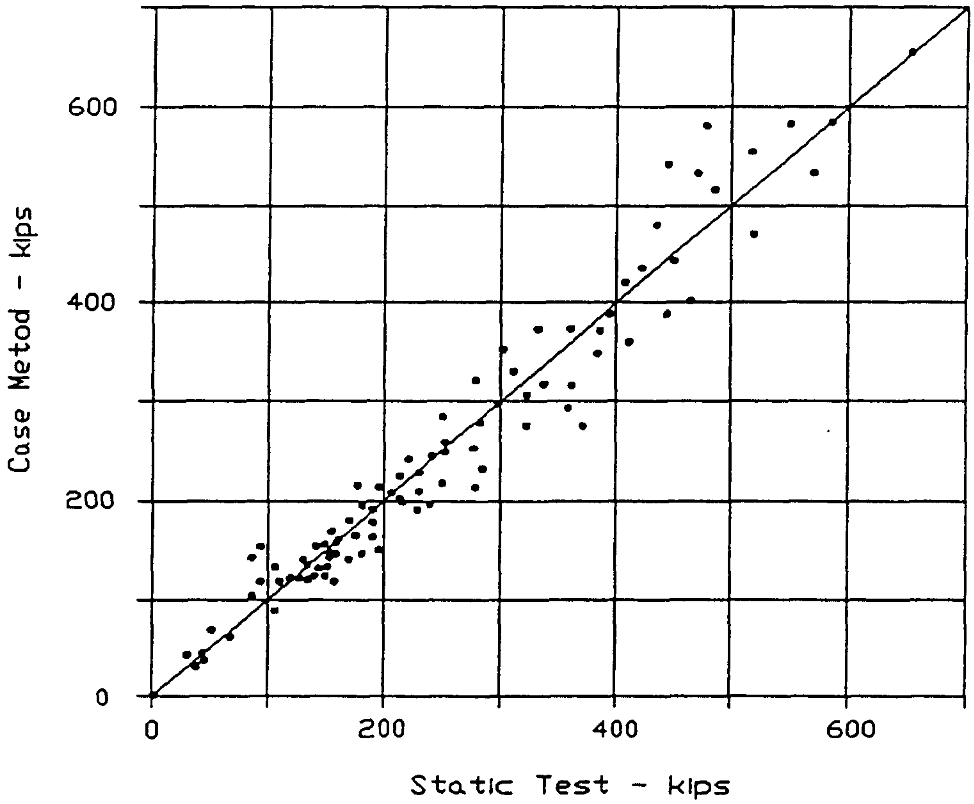

Figure C2: Agreement Between Case Method and Statically Measured Capacity for 120 Different Test Piles

APPENDIX C REFERENCES

Eiber, R. J., 1958. "A Preliminary Laboratory Investigation of the Prediction of Static Pile Resistances in Sand." Masters Thesis, Department of Civil Engineering, Case Institute of Technology.

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APPENDIX D: CAPWAP

The CAPWAP analysis was developed at Case Institute of Technology during the Case Piling Project. The acronym CAPWAP refers to the Case Pile Wave Analysis Program. The analytical concepts and their first computer realization was done by Rausche as a part of his doctoral dissertation (Rausche, 1970) The purpose of the program is to determine the distribution and magnitude of the soil resistance forces along the pile and to separate them into static and dynamic parts.

This program depends on the availability of force and motion measurements at the pile top during impact by a pile driving hammer. The quantities that are usually measured are strain and acceleration. These are selected because well developed transducers are available for their measurement. (The general topic of dynamic monitoring is discussed in Appendix B.) The measured record from the impact event is most conveniently processed by converting it to digital form. It can then be stored in the computer and operated on by the appropriate processing software. Due to the relationship between force and particle velocity, these two quantities are used in the analysis. In the following discussion it will be assumed that these two records from a hammer blow are available for the analysis.

The original CAPWAP analysis used the same mathematical model of the pile and the soil as is used in Wave Equation programs. However, in this case the model does not include the hammer and driving system, but only that portion of the pile below the location of the gages. In Figure D1, the mathematical model is shown. Since the original development the computational system has been changed to use a "discrete continuous" model. However, for the purpose of this discussion the differences in computational procedures are unimportant. The purpose of CAPWAP is to extract the values of R_u, q, and j from the measured data.

At the beginning of the analysis process, the digital representation of force and velocity, as well as the basic dynamic analysis procedure, are available in the computer. A complete set of Wave Equation soil constants is estimated and entered by the engineer-operator. Judgement regarding the selection of these quantities comes from a clear understanding of one dimensional wave propagation and past experience with CAPWAP analysis. It is interesting to note that the earliest version of this program used a fully automated system requiring no user interaction. When mini and micro computers became available and it was possible to use man-machine interaction easily, the program efficiency was greatly improved by the use of an interactive program.

A dynamic analysis is performed with the measured velocity imposed as an input at the top element. This analysis determines the top force necessary to induce the imposed element velocity. The measured and calculated top forces are plotted as a function of time. If the correct resistances have been input the two curves should match. These two records are examined by the engineer, the resistance description is adjusted, and the analysis is repeated.

The process is illustrated in Figure D2. Three successive resistance distributions used in the process of generating the match produced the calculated force records shown plotted with the measured record. In some cases agreement is quickly reached, while in others a large number of iterations may be necessary. Theoretical analysis has shown that the resistance distribution obtained is unique (Rausche et al, 1985). The primary problem with the CAPWAP analysis is the fact that the soil model used does not necessarily always represent the soil. When these differences are great, it is sometimes impossible to get good agreement.

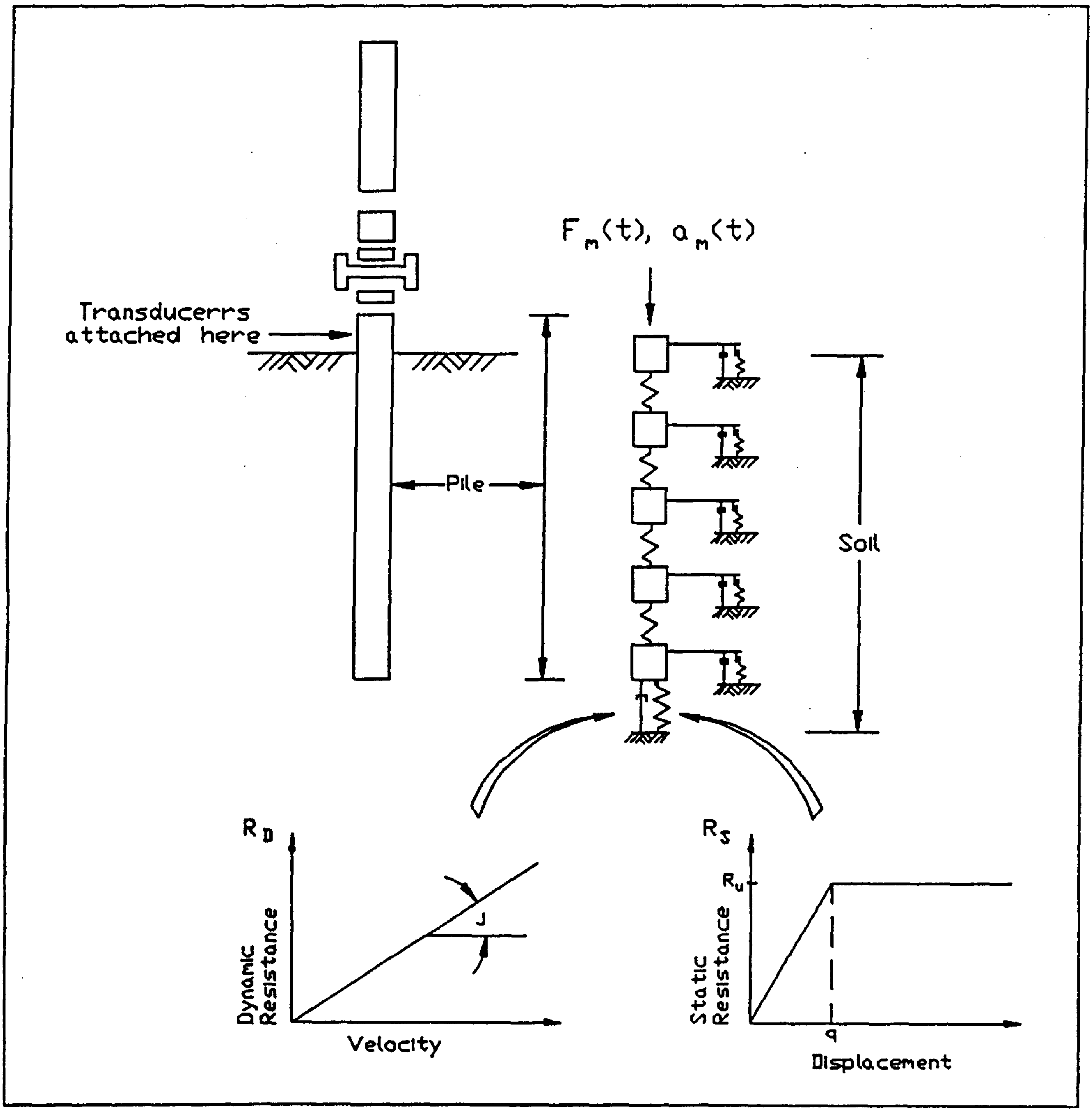

Figure D1: CAPWAP Model

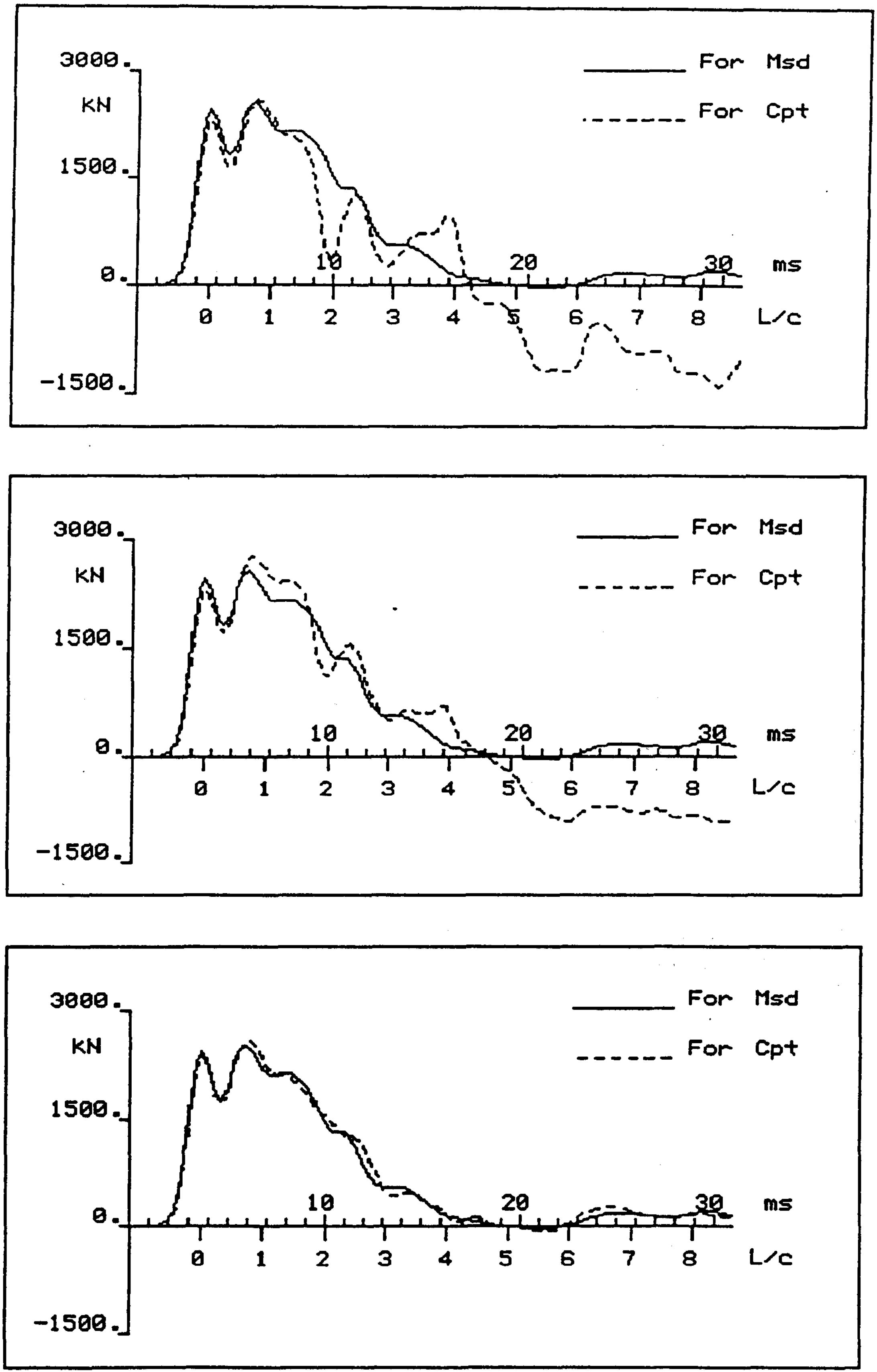

Figure D2: Three Trial Matches Showing Poor, Fair and Good Match **Between Measured (solid) and Computed (dashed) Pile Top Force**

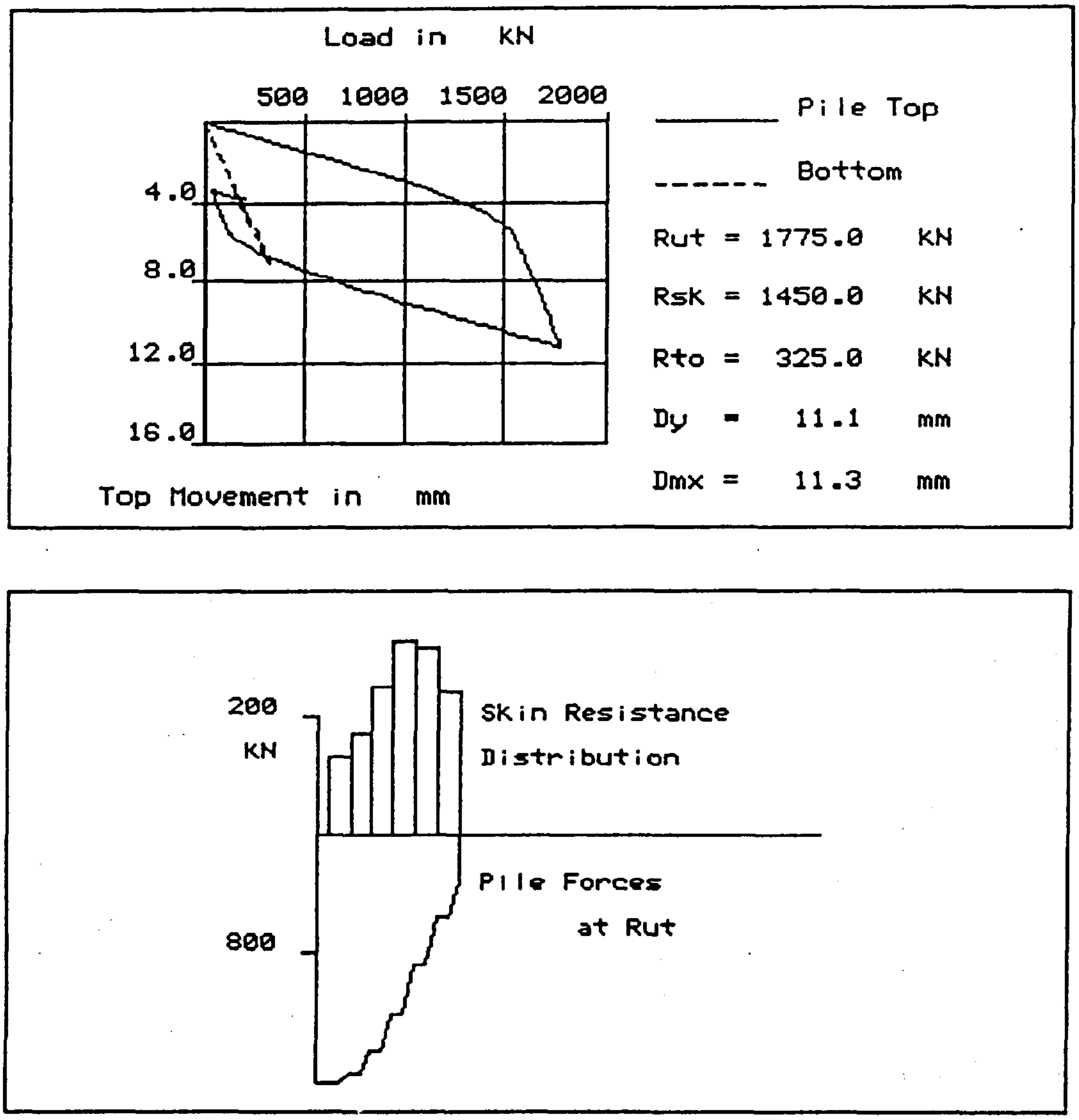

Figure D3: Static Resistance Distribution Matching Length of Pile and Time Scale

When the best possible agreement has been achieved, the resistance has been divided into a static and a dynamic portion and the characteristics of the static portion have been defined. Now a static load test can be simulated in the computer with the representation of the pile and the soil. Figure D3 shows the distribution of the static resistance and the CAPWAP load deflection curve for the top of the pile.

The CAPWAP analysis produces a complete representation of the pile and the soil behavior under load. There is no need to make assumptions like those used in the Case Method analysis. With the knowledge of the force displacement characteristics at each element, the pile ultimate capacity is defined. The soil parameters obtained can be used in Wave Equation analyses for evaluation of modified driving systems. The j-values used in the Case Method can be obtained from the damping constants of the CAPWAP method. Thus, this tool closes the circle in dynamic pile analysis.

With successive improvement in the CAPWAP model occurring over 25 years of use it has been possible to achieve progressively better matches. The current version (1994) has an automated matching capability that will run in a reasonable amount of time and achieve quite a good match. Comparisons between CAPWAP predicted capacities and statically measured values have shown good agreement with the CAPWAP value with a possible trend toward results that are somewhat low (or conservative). It has become possible to obtain this analysis with much less engineering effort and with the availability of the laptop computer the result is available in the field. Therefore, it is not necessary to depend so heavily on Case Method capacity.

APPENDIX D REFERENCES

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