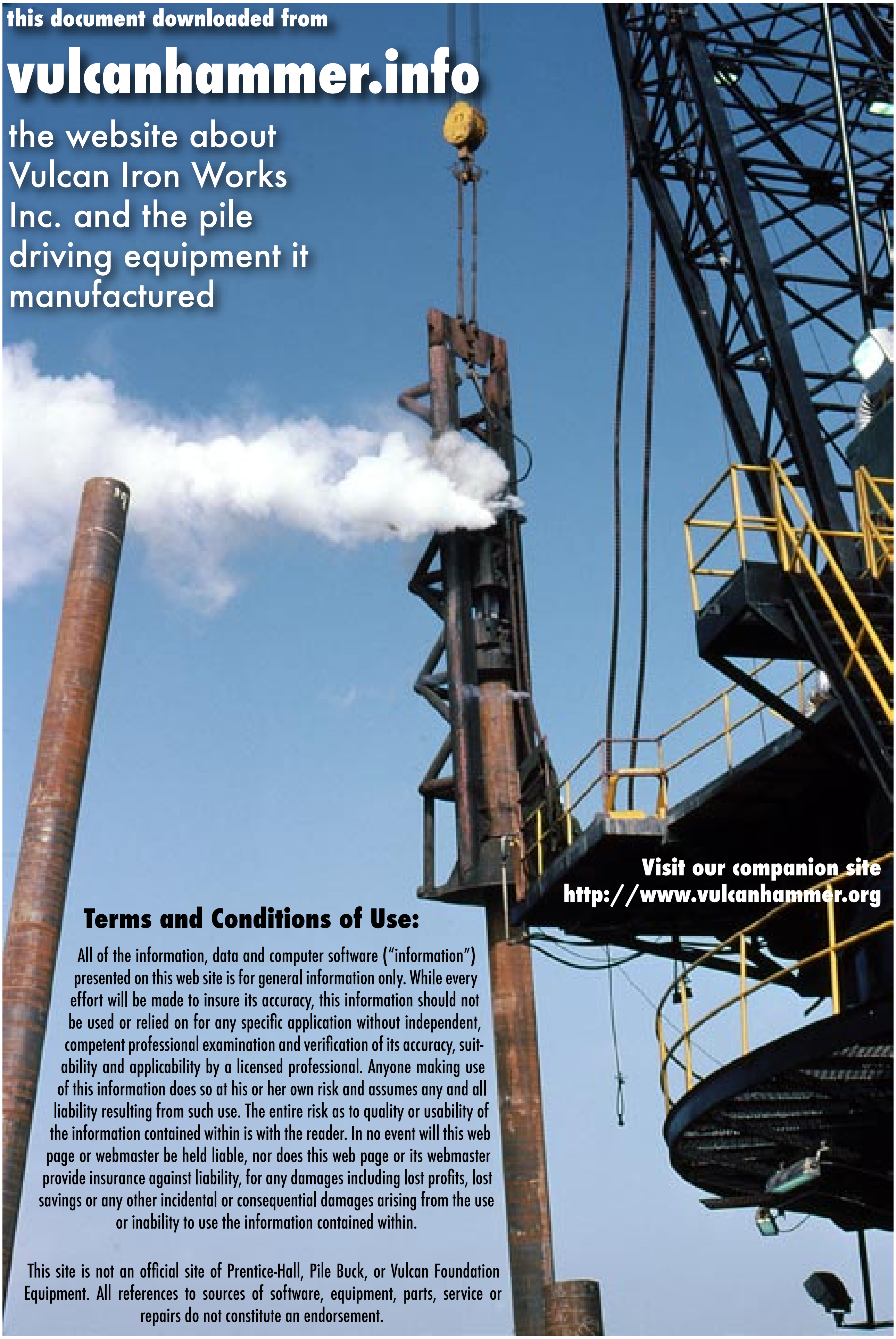

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THE ANALYSIS OF PILE DRIVING

A STATE-OF-THE-ART

By G. G. Goble[1], Frank Rausche[2] and G. E. Likins, Jr.[3]

INTRODUCTION

During recent years wave analyses, or analyses of the elastic pile, were utilized with increasing frequency for both pile design and construction control. These methods range from purely analytical to experimental. They were developed to answer one or more of the following questions:

(1) What is the static bearing capacity of the pile given observations taken during pile driving?

(2) Can the pile be driven given a complete description of pile, soil and hammer properties (driveability)?

(3) Is the pile structurally sound (pile integrity)?

(4) What are the stresses in the pile during driving?

(5) What is the efficiency of the driving system?

The following discussion presents a review of available analytical methods and gives examples both of equipment used for measurements and of results obtained.

ANALYTICAL METHODS

The first analysis of one dimensional wave propagation applicable to pile driving was presented by St. Venant (39). He found the differential

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[1] Chairman, Dept. of Civil and Architectural Engineering, University of Colorado, Boulder, Colorado 80309, USA.

[2] President, Goble & Associates, Inc., 12434 Cedar Rd., Cleveland Heights, Ohio 44106, USA.

[3] President, Pile Dynamics, Inc., 12434 Cedar Rd., Cleveland Heights, Ohio 44106, USA

equation governing one dimensional wave propagation in an elastic rod and also its solution. This work presented the analysis of some limited cases of boundary conditions but more importantly gave the basis for insight into wave propagation. Further work in this direction was presented by Isaacs (19) and Fox (7). Their work is interesting since it was specifically for the analysis of pile driving. These closed form solution efforts had only limited success because of difficulties in describing a real hammer-pile-soil system. A widely used method for pile driving was never developed.

With the advent of the digital computer, discrete solutions of the wave equation became practical. Smith (34) developed the original model. His work is of general interest since it was one of the very first applications of the digital computer in the solution of mechanics problems. A generally usable program was prepared by researchers at Texas A & M University (4) as a direct outgrowth of Smith's work.

Computer programs used for this analysis became known as "Wave Equations" in the United States. They were originally used for bearing capacity and pile stress predictions. With increased need, particularly in offshore construction, the programs were later also applied to the driveability problem.

Regarding bearing capacity predictions by the wave equation, the group at Texas A & M University performed extensive correlation studies (21), (31). Static load test results were matched with wave equation predictions at an observed blow count to obtain recommendations for the necessary constants required in the analysis.

Among the many case study papers published involving the wave equation, two contrasting ones may be mentioned. Rempe (31) showed that very good bearing capacity predictions (better than 10%) agreement may be obtained while Tavenas and Audibert (37) found no correlation at all between wave equation results and actual production pile performance. The difference between the two observations is probably a result of different construction control; on the one hand, well controlled tests; on the other hand, normally supervised pile driving.

Today, a number of programs are in general use in the United States. Among them are the TTI (22) and WEAP (12) programs which were written under the sponsorship of the U.S. Department of Transportation. The TTI (Texas Transportation Institute) program is a modernized and updated version of the Texas A & M program with expanded and improved documentation. The WEAP program was developed to improve the analysis of diesel driving systems. In addition, for the first time, extensive correlations were performed between the calculated force and velocity-time records and available field measurements.

In Europe the solution of the wave equation has been obtained in a pseudo-closed form manner. De Juhasz (3) presented this method and Fischer (6), Cerclet (1), Laine (21) and others utilized it in their studies. It is believed that this method produces results equivalent to those from the wave equation and that the pile is modeled in either case with sufficient accuracy. Work needs to be done to compare the results from the two methods.

Finally, a few extensions of the wave equation approach should be referenced. Holloway (17) showed that residual stresses remaining in the pile and soil at the end of a hammer blow can be included in the analysis and may be important. Matlock and Foo (24) presented a discrete algorithm that may be used for either static or dynamic predictions and included Holloway's residual stress analysis. The wave analysis techniques were further advanced by including more elaborate hammer models, e.g. Goble and Rausche (12) and

Rempe and Davisson (32). Also improvements in the soil and pile splice tension models were made and tested (37). Recently, Parker (25) succeeded in developing tables necessary for tension stress analysis of concrete piles in easy driving, thereby avoiding the need for a new computer execution for each problem.

MEASUREMENT TECHNIQUES

Apparently the first attempt to make dynamic stress measurements in pile driving was made by Glanville et al(9). Strain measurements were made using piezoelectric force transducers on concrete piles and recorded on an oscilloscope. In about 1960 a large research project was performed by the Michigan Department of Highways (18). They used a specially designed force transducer to measure the force at the pile top and also added a strain gage accelerometer on the transducer. The primary purpose of the tests was to evaluate hammer performance. Data was recorded on a high speed oscillograph.

The results of the force measurements were controversial and were finally explained by Rausche and Goble (29) in a paper that also gave insight into the design procedure for transducers. The Michigan researchers used their dynamic measurements primarily for calculating hammer energy delivered to the pile (ENTHRU). The problems with their force measuring system did not prevent the measurements from producing correct energy data. While the Michigan project did not produce a large volume of useful data, it was remarkable that measurements were made successfully at that time.

The most extensive program of stress wave measurement began at Case Institute of Technology (now Case Western Reserve University) in 1964 and was continuously active for 12 years. During this time, measurement techniques and equipment were developed and theoretical studies were performed.

A large volume of literature was produced. A summary of the work is contained in References (10), (13), (14) and (15).

At the beginning of the Case project, strain measurements were made by mounting resistance strain gages directly on the wall of steel pipe piles (the most common pile type in the early part of the project). The resulting signal was amplified by an AC amplifier and recorded on a high speed oscillograph (2 m/s). Acceleration measurements were made using high impedance quartz crystal accelerometers. This first system produced satisfactory measurements in the field but it was difficult and time consuming to use. As developments occurred in electronics, the improvements were included in the equipment.

Force transducers were developed and tested for use on pipe piles. These devices are ideal where a transducer of some weight can practically be brought to the job site. Lightweight, reusable bolt-on strain transducers were developed for use with any type of pile. New developments in signal conditioners and amplifiers produced DC instruments of satisfactory accuracy that were much easier to use than the AC amplifiers. Low output impedance quartz crystal accelerometers were developed and relatively inexpensive portable instrumentation tape recorders became generally available in about 1970. The system is summarized by the schematic shown in Figure 1.

One of the important advantages of the record on analog magnetic tape is that the event can be recreated in the laboratory. It can then be processed automatically by converting the analog signal to digital form and then storing only the important part of the record. Further analysis and plotting can be easily accomplished using a minicomputer and a variety of peripheral devices. The processing system is shown schematically in Figure 2 and a sample of plotted force and velocity records are shown in Figure 3.

The system has been used to test thousands of piles in the past 10 years. Its flexibility and ease of use have been well proven in this application.

A variation of the Case approach was introduced by TNO (40). Displacement measurements were made using an optical system and then were differentiated to obtain velocity. Velocity was initially interpreted as force which is, however, only correct for a short time during impact. Improvements of this method were introduced when strain measurements were also included and described by Smoltczyk et al (35). The TNO system includes, besides analog signal conditioning and recording equipment, a minicomputer which performs the necessary calculations.

ANALYTICAL METHODS FOR INTERPRETATION OF PILE TOP RECORDS

Bearing Capacity

In general the bearing capacity of a pile can only be determined from top measurements if <u>both</u> the force <u>and</u> a motion quantity are available. This fact was recognized early by the Case project. The methods and techniques at Case evolved over a period of several years. Initially the soil resistance, R, was computed from the rigid body equation

$$R = F(t) - m\,a(t) \tag{1}$$

where F(t) and a(t) are the pile top force and acceleration measured as functions of time and m is the pile mass. Later studies of the elastic (27) pile produced the following relation

$$R = \tfrac{1}{2}\{F(t_1) + F(t_2)\} + \frac{mc}{2L}\{v(t_1) - v(t_2)\} \tag{2}$$

where $t_2 = t_1 + 2L/c$ and t_1 is some selected time during the blow. The pile length below the point of measurement is L; v is the particle velocity at the pile top obtained from the acceleration by integration; c is the velocity of wave propagation. Note that mc/L is often referred to as the pile impedance. Usually the time associated with the first relative maximum in the force and velocity is used for t_1.

The penetration resistance, R, is assumed as in the discrete wave equation analysis to consist of two parts: a static component, S, and a velocity dependent portion, D. Thus the R found by Equation 2 has to be reduced to yield the static pile bearing capacity

$$S = R - D$$

It is now assumed that D is proportional to the pile bottom velocity, v_{toe}, thus

$$D = J\ v_{toe}$$

where J is the damping constant. A simple closed form wave analysis leads to v_{toe} given v(t) and R. Thus,

$$v_{toe} = 2v(t_1) - \frac{L}{mc} R$$

J is used in dimensionless form by division by mc/L (then referred to as j_c). Of course, j_c is dependent on soil type. Substituting for R, D and v_{toe} using Equations 2, 4 and 5 in Equation 3 yields the Case Method bearing capacity, S.

Concurrently with the development of the Case Method, the Case Pile Wave Analysis Program (CAPWAP) was conceived and tested (30). This analysis technique also makes use of the measurements of force and acceleration. A brief description of this digital computation method is appropriate.

Either pile top force or pile top velocity (integrated from the measured acceleration) can be used in a dynamic analysis as a boundary value. The dynamic analysis can be performed either in closed form or in the wave analysis procedure common to "Wave Equation" programs (discrete form). Soil resistance forces must be described.

The soil forces are passive and in CAPWAP, as in the Smith type wave equation analyses, they are expressed as a function of pile motion only. Thus, three soil constants must be known for each pile element in the embedded portion: static resistance, R_u; quake, q; and damping, j.

In the computation, a reasonable assumption is made regarding the soil parameters, and then the motion of the pile is input using the measured top acceleration as the boundary value. Output results are not only all pile element motions and soil resistance forces, but also the computed pile element forces, all as functions of time.

The computed and measured pile top forces will in general not agree in all time. The agreement can be improved iteratively by changing the assumed soil resistance parameters. When a computed pile top force is obtained that gives an agreement with the measured force which cannot be improved, the associated soil parameters are considered to be the best estimate values. Static computations can be used to predict the static load test curve the pile. In Figure 4, three successive comparisons of calculated and measured force are shown as the agreement is improved on repeated analyses. The different soil assumptions for these curves are presented in Table 2. Table 3 then presents the calculated force time histories during impact for several other locations in the pile.

The original application of the technique in 1970 produced a computer program that was fully automated (27). This program produced satisfactory solutions for piles which were not more than 25 meters in length. For longer piles computation times became excessive. A recent program performs the computations iteratively in a man-machine interactive mode. The engineer inputs a set of assumed resistance parameters and the machine then displays the associated force comparison curves. The engineer then inputs a new set of resistances based on his analysis of the results. The cycle is repeated until further improvement cannot be achieved. In this application, a minicomputer with 32K words of core memory is used and the results are displayed on a drum plotter.

The bearing capacity prediction by the TNO method is different from both Case Method and CAPWAP. The basic assumption is that the impact force is a test load and the ensuing pile set is measured. Choosing larger and larger loads (increasing the impact velocity of the test ram) and plotting pile sets, a load deformation curve is obtained. Obviously this method was developed for use with special impact test equipment while the Case Method evaluates impact data from any type of pile driving equipment.

The TNO method also includes the prediction of skin friction. First the pile displacement time relation is differentiated and a pile velocity is obtained. The difference between force and velocity, just before the impact wave returns after reflection at the pile bottom, is interpreted as skin friction. This approach is only correct for short rise time impacts and ideal plastic soil behavior.

Integrity

The records of force and velocity are proportional before stress wave reflections arrive at the pile top from resistance effects or pile cross sectional changes. Resistance effects cause the force to increase relative to the velocity. A cross sectional reduction causes the opposite effect.

Defining the pile impedance (for uniform piles) as

$$I = \frac{mc}{L} = \frac{EA}{c} \qquad (6$$

where E is Young's modulus and A is the pile's cross sectional area, then

$$F(t) = v(t)I \qquad (7)$$

before any upwards traveling waves arrive at the pile top.

If the pile changes its impedance from I_1 to I_2, then an impact wave having force F_i will generate an upwards traveling wave with force

$$F_u = F_i \frac{I_2 - I_1}{I_2 + I_1} \qquad (8)$$

The corresponding velocity is

$$v_u = F_u/I_1 \qquad (9)$$

Given F_u and v_u through measurement, one may also determine the lower cross section or impedance from

$$I_2 = I_1 \frac{F_i + F_u}{F_i - F_u} \qquad (10)$$

Usually F_u is superimposed on other waves so it can only be determined by comparison with the velocity record. Further details and refinements of this method are discussed by Rausche and Goble (28).

Stresses

See also p. 14

During pile driving, stresses in the pile at locations other than the point of measurement may be critical. Compression stresses are dangerous either if pile top stresses are high or if the resistance is concentrated. In the first case, the measurements can be used directly. In the latter case, the larger of the measurements or Equation 2 gives a good estimate of the maximum pile stress.

For concrete piles the maximum tension stresses may be more detrimental than the compression forces. Their magnitude and location of occurrence depends greatly on the distribution of skin friction. Utilizing again the measurements of force and velocity, the tension stresses, occurring at a distance x below the point of measurement, is given by

$$T(x) = \tfrac{1}{2}\{I\ v(t_2) - F(t_2) - I\ v(t_3) - F(t_3)\} \qquad (11)$$

where time t_2 is as in Equation 2 and $t_3 = t_1 + 2\frac{L - x}{c}$

Driving System Performance

Any analytical pile analysis depends primarily on a realistic prediction of hammer and driving system performance. An efficiency, i.e. the ratio of actual to rated hammer kinetic energy, is used in the wave equation approach to account for a variety of losses.

Using measurements of force and acceleration, the energy transferred to the point of measurement can be determined by using

$$E(t) = \int_0^t F(\tau)v(\tau)\ d\tau \qquad (12)$$

where $v(\tau)$ is the integrated acceleration. The maximum of the E(t) function occurs just before pile rebound starts. It is the maximum that was referred to as ENTHRU by the Michigan researchers. A new efficiency value can be defined as the ratio of ENTHRU to rated hammer energies. This efficiency may be as low as 10% and reaches as much as 85% under favorable conditions.

APPLICATIONS

Stress wave theory and measurements are meeting rapidly increasing applications in practice. Actually, the use in practice is moving much faster than is the reporting of these applications. In this Section, applications, both in common use and proposed, will be reviewed.

Prediction of Bearing Capacity

The use of Wave Equation analyses for bearing capacity prediction is well established in the United States. While dynamic formulas are still in use, they are being replaced and it is entirely possible that the use of the formulas will have completely disappeared in a few years. The examples presented in the literature are much too numerous to review here. Six programs are in use:

1. The Raymond Company program (proprietary)
2. The TTI program which is similar to 1 and is not much different from Smith's original program.
3. The WEAP program which contains an accurate diesel hammer model.
4. DIESEL-1 by Rempe (proprietary).
5. DUKFOR, a program that is similar to the TTI program but it contains a residual pile and soil stress analysis (proprietary).
6. SWEAP, a combination of 3 and 5 (proprietary).

Other programs exist but are seldom referenced. In any of these programs, the process of bearing capacity determination is the following.

A mass-spring model of both hammer and pile is constructed (see Figure 5) and the following soil constants are selected at each embedded element: R_u, the ultimate resistance; q, the elastic displacement of the static soil resistance (quake); j, the damping constant. The most commonly employed values of J and q are also given in Figure 5. A dynamic analysis is then performed by giving the ram mass element an initial velocity. At the end of the analysis the displacement (set) is calculated. Successive analyses are performed by giving the individual R_u values proportional increases and each time determining the associated set. The sum of all of the resistances is then plotted as a function of set giving a relationship generally known as a bearing graph. An example is illustrated in Figure 6. Usually stress maximum and stroke are also plotted together with bearing capacity. With the bearing graph available, pile capacity is predicted when blow count is known or driving resistance can be estimated for a given driving system and assumed soil resistances.

A reliable Wave Equation bearing capacity analysis depends on the availability of accurate soil data and reliable driving system performance. Recommendations are given in References (12) and (22). If soil parameters are correctly selected and hammer performance is as assumed, accurate capacity predictions can be expected for the assumed conditions during driving (or restriking). If the capacity changes due to setup or relaxation prior to load testing or if the driving system behaves differently than assumed, the wave equation prediction cannot be expected to agree with the static measurement.

The Case Method avoids the Wave Equation problems with hammer performance and to some extent with soil parameter selection. Since measurements are made at the pile top, the model used in deriving the equations excludes the driving system. The only assumption then contained in the method is the soil damping constant used. It is possible to evaluate the sensitivity of the results to the damping constant selection. Setup or relaxation effects are easily considered.

Results of bearing capacity are given in Table 1 for the sample data set. This pile had previously been driven into a cohesive soil. Measurements were made during restrike after soil setup had occurred. The first 10 blows show a distinct decrease in capacity as setup is destroyed. The second set of data, after approximately 300 additional blows, shows even more capacity reduction. Conditons during this set were then similar to those on other piles on that site which were tested at the end of initial driving.

Recommended values for j_c were reported in Reference (10). If these recommendations are used, the correlation between the static capacity as obtained in a static load test evaluated by Davisson's procedure (26) and the Case Method is given in Figure 7 for 102 sets of available data. Similar correlations have been obtained by Fellenius et al (5) using the Case Method measuring system.

Since the Case Method is computationally simple, it can be accomplished in real time in the field. Special purpose instruments, known as Pile Driving Analyzers, have been developed to calculate and display the results.

The CAPWAP method avoids all assumptions and provides a direct estimate of bearing capacity and resistance distribution. No soil constants need to be assumed in order to make the analysis. Experience has proven the method to be reliable. A correlation plot for 79 data sets is shown in Figure 8. For the same sample data set and the demonstrated pile top force matches of Figure 4, resistance vs depth plots are shown in Figure 9. The predicted capacity was also entered in Table 1.

Applications of the Case Method and CAPWAP approach have been discussed by LaFond (20) and Gilbert et al (8).

Driveability

The driveability problem is the inverse of the bearing capacity question: If all hammer-pile-soil parameters are given, what will be the driving behavior? Of course, only a purely analytical method is of interest. The problem is particularly difficult due to the nonlinear character of the bearing graph. If blow counts that are relatively high are predicted (over 120 blows per foot or 400 blows per meter) then a small error in the capacity estimate will produce a large change in the predicted blow count. Figure 6 (line 2) indicates the predicted blow count, pile stresses and hammer stroke for an ultimate capacity value that was determined by static analyses.

An interesting approach to the driveability question has been proposed for the offshore application by Goble and Rausche (11). Dynamic measurements are made during the driving of conductor pipes for exploratory wells. The CAPWAP analysis is then used to determine the soil constants. If a producing platform is to be constructed, the CAPWAP soil constants can be used in a Wave Equation driveability analysis. The concept was tested with good results at one site in the Gulf of Mexico.

Control of Integrity

The most common approach to pile integrity testing is the use of a low mass impact or a low strain, steady state excitation. Reflections coming from cross section changes or discontinuities are then evaluated. This method has been extensively tested. One of the most interesting test programs was performed by Steinbach and Vey (36) and it is strongly recommended that this paper be reviewed by anyone attempting the use of this general approach.

The Case Method measurements can be used to test integrity (28) and this approach is now well proven. The derivation was discussed above and an example is now given. Measurements were obtained during the driving of a concrete pile. Damage and breakage occurred while the measurements were being made. In Figure 3B the pile is still sound in the early records. Successive hammer blows damage and finally completely break the pile. Table 1 gives a β integrity factor which is the ratio of the reduced area at the point of damage to the uniform section area (see Eq. 10). The location of damage is indicated in Figure 3B to be 18 meters below the top of this 22.5 meter pile. This same approach has been used with some success on cast-in-place piles.

The above approach is effective if a pile breaks some place along its length. It is less satisfactory for cases where damage occurs at the pile tip since it would be detected by an earlier arrival of the tip reflection. Accuracy considerations make it impractical to detect small amounts of tip damage. An approach to this problem was presented by Teferra (38). In this solution, parametric relations for force and displacement with respect to time can be obtained if the shaft resistance is known. Thus, a force displacement relationship can be obtained for the pile tip. A sharp reduction of the stiffness is an indication of damage.

Driving Stresses

Dynamically induced stresses must be kept within the limits required by material properties. This means that compression stresses must be limited in all materials and tension stresses must be controlled for concrete. The limits that should be placed on these parameters are materials questions not within the scope of this paper. Pile driving stresses are obtained in Wave Equation analyses and included in the bearing graph (see Figure 6). However, these predictions are sensitive to changes in the driving system parameters and skin friction distribution. Furthermore, different Wave Equation programs can give substantially different stresses for a particular set of parameters. The WEAP program is the only one for which any substantial number of correlations were made with measured stresses (12) and, therefore, it can be expected to produce the most reliable stress predictions. However, these predictions must be compared with measured stresses rather than with a mere evidence of failure which could be due to system misalignment or other unpredictable problems. In many cases, the fact that piles have been successfully driven where other Wave Equation programs had predicted very high stresses should not be used as evidence of pile material strength. Probably the high stresses were not present.

Field measurements give an accurate assessment of the stresses present at the location of measurement. It was shown in Table 1 that measured force and velocity records allow for the determination of stress maxima and their location. The same table indicates how tension stresses increase as compression stresses and bearing capacity decrease. Again the Pile Driving Analyzer provides the necessary data in the field. Before going in the field, wave equation analyses, and after taking data, CAPWAP, provide a complete pile stress history (see also Table 3).

Driving System Performance

The most direct approach to the determination of driving system performance is the use of the Pile Driving Analyzer. As described above, it determines and displays maximum force and energy delivered to the pile top. Usually the system is used to display force and velocity records on an oscilloscope and this visual display can also be used for system performance control. For instance, preignition of diesel hammers can be easily detected by examining the force record. Table 1 lists maxima of both pile top force and energy from consecutive blows. They would be printed by the Analyzer in the field in a similar fashion. The use of the Analyzer in evaluating driving system performance where problems had been encountered has been discussed by Chen et al (2).

Another approach to driving system control has been used by Hirsch et al (16) in offshore applications. In this case, a series of Wave Equation analyses are made prior to going to the field, and force time records are plotted for various assumptions of driving system performance. Force measurements are made in the field and are compared with the various computed values. The system performance parameters are then obtained indirectly. In the offshore case, rams are relatively light compared to the pile mass and, therefore, the input force has largely decayed prior to the return of the stress wave from the pile tip. For land applications where piles are shorter and the pile-ram weight is larger, the input wave is not so nicely separated from the reflected wave. Thus the approach is then less accurate.

A still lower level of control is available for open end diesel hammers. The WEAP program provides ram stroke as an output. If the system is performing as assumed in the Wave Equation analysis, the calculated and measured stroke can be expected to be about the same. A device measuring stroke of open end diesel hammers, called SAXIMETER, has been developed and is in routine usage on construction sites in the USA.

CONCLUSIONS

The current state-of-the-art of the analysis of pile driving has been summarized. Techniques are available to solve most piling design and installation control problems using dynamic analyses and measurements. These techniques are now coming into engineering practice.

Table 1: Sample Results from Case Method

Blow[1] No.	Maximum Force Measured MN	 Tension[2] MN	 Compr[3] MN	Maximum[4] Energy kJ	Bearing Capacity Case Method[5] MN	 CAPWAP[6] MN	Integrity[7] Factor β
1	2.16		2.56	10.6	1.8		1.00
2	2.52		2.80	15.6	1.8	1.8	1.00
3	2.79		2.99	17.1	1.9		1.00
4	2.83		2.91	17.5	1.7		1.00
5	2.99		3.02	20.0	1.7		1.00
6	2.99	.23	2.99	20.0	1.6		1.00
7	2.93	.18	2.93	19.5	1.5		1.00
8	2.93	.31	2.93	18.6	1.4		1.00
9	2.93	.23	2.93	18.9	1.4		1.00
10	2.99	.32	2.99	19.3	1.3		1.00
4	2.82	.45	2.82	18.2	.5		1.00
5	2.72	.27	2.72	17.7	.5		.96
6	2.88			19.0			.81
7	2.83			19.0			.74
8	2.74			18.5			.68
9	2.86			19.6			.58
10	2.83			19.0			.51
11	2.71			18.5			.44
12	2.70			18.0			.40
13	2.80			18.5			.38

[1] Blow numbers correspond to identifications in Figure 3. Second set of blows occurred approximately 300 blows after first set.

[2] From Equation 11, negligible tension in first five records; no tension computation possible after damage occurred.

[3] From the greater of Equation 2 or maximum measured force; no results for damaged pile.

[4] From Equation 12, rated hammer energy = 75 kJ.

[5] Using J = .45, no results for damaged pile.

[6] Result corresponds to Final Match of Figure 4.

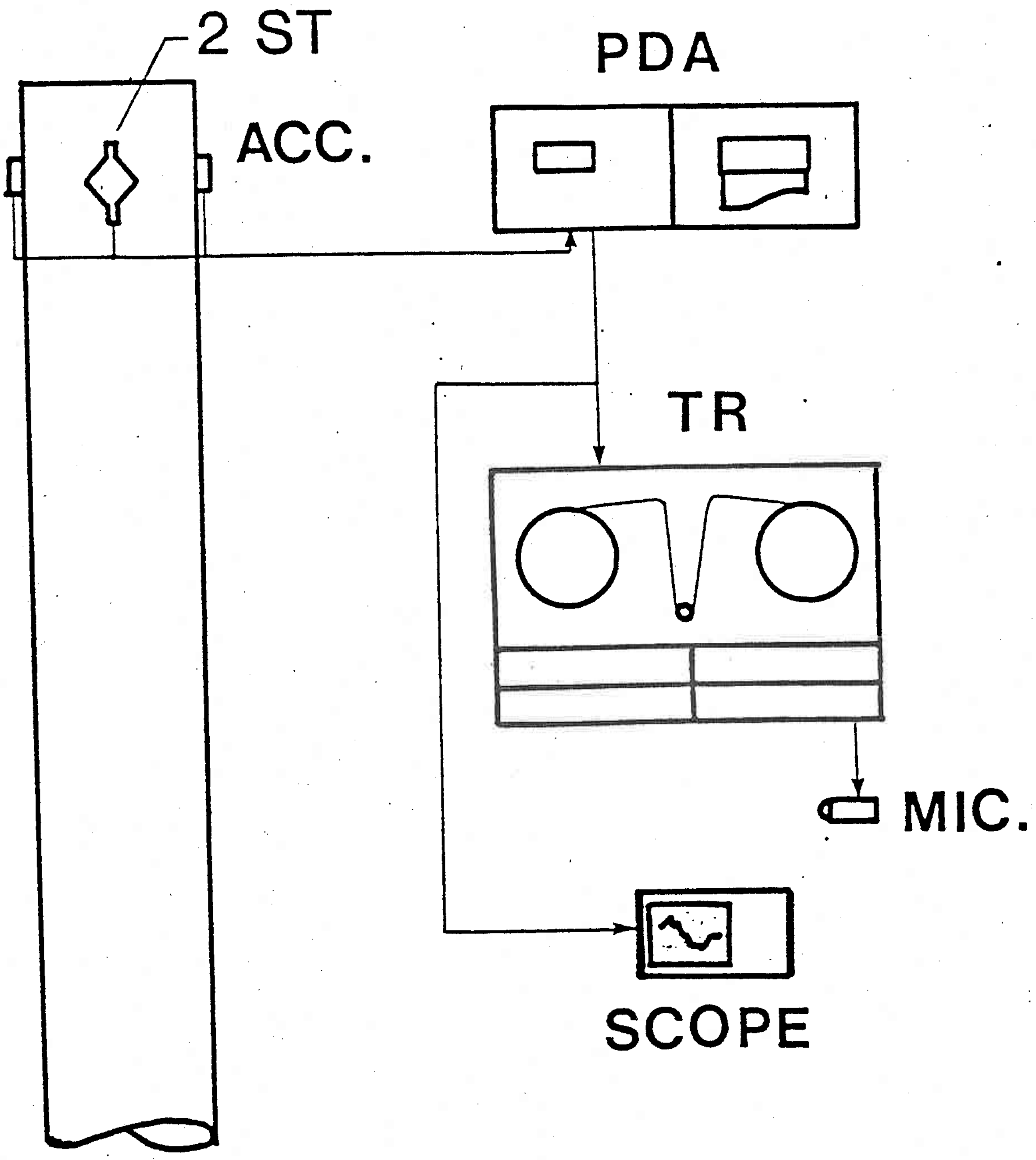
[7] [illegible] for complete break

Table 2: CAPWAP Trial Run Parameters

Run Identif.	Ultimate Capacity Skin MN	Toe MN	Total MN	Case Damping Skin	Toe	Quake Skin mm	Toe mm
Low Damping	1.36	.42	1.78	.35	.10	3.6	4.1
High Static	1.72	.53	2.25	.55	.20	3.6	4.1
High Skin	1.65	.13	1.78	.55	.20	3.6	4.1
Final	1.36	.42	1.78	.55	.20	3.6	4.1

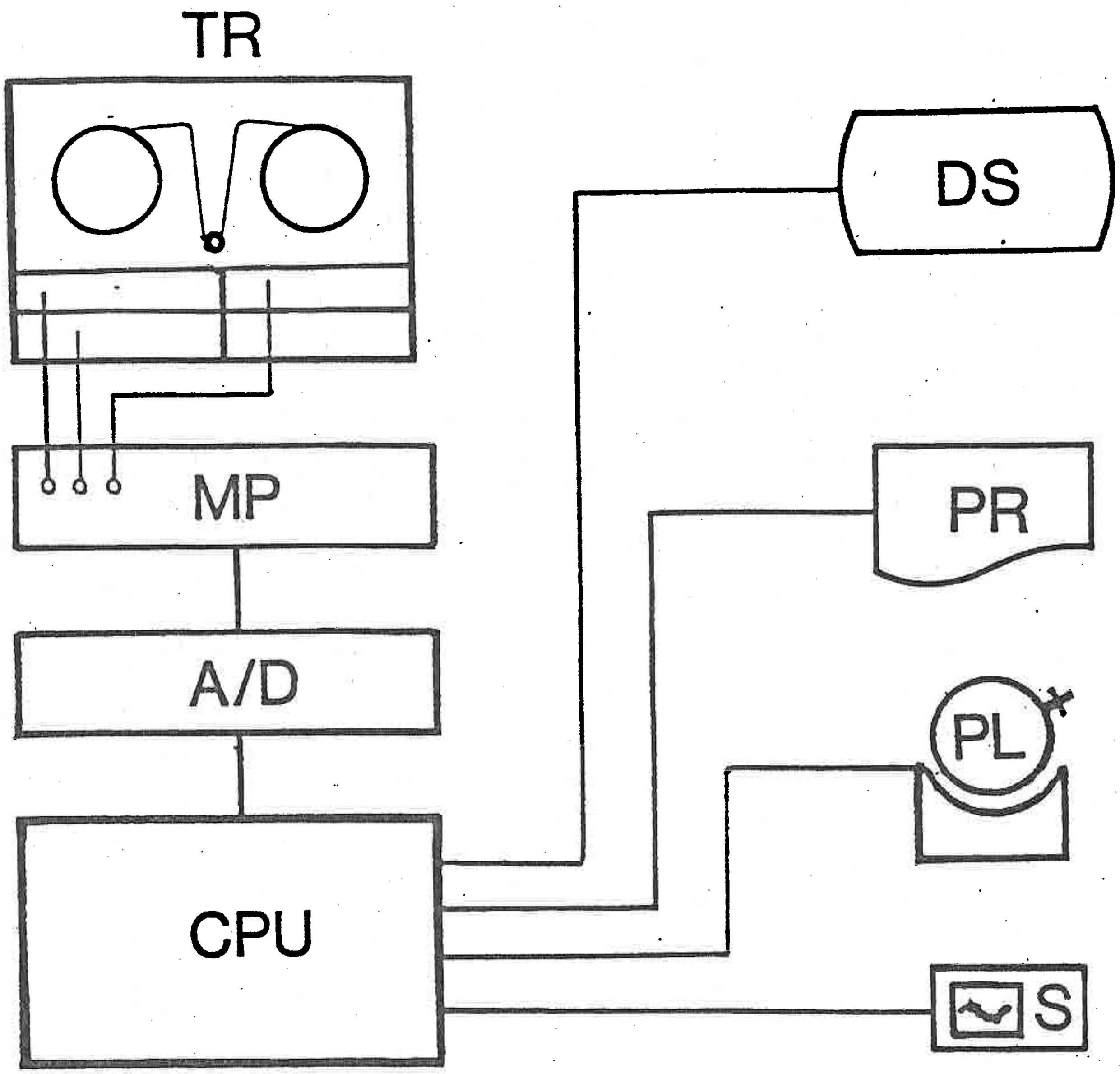
Table 3: Pile Forces vs Time From CAPWAP

	Pile Forces at Locations Below Top					
Time Ms	0.0 m MN	4.5 m MN	9.0 m MN	13.5 m MN	18.0 m MN	22.5 m MN
0	.00	.00	.00	.00	.00	.00
1	.03	.00	.00	.00	.00	.00
2	.33	.06	.00	.00	.00	.00
3	.58	.45	.05	.00	.00	.00
4	1.27	.66	.38	.05	.00	.00
5	1.98	1.46	.66	.32	.06	.01
6	2.23	2.10	1.40	.69	.26	.03
7	2.32	2.27	2.09	1.29	.59	.17
8	2.36	2.38	2.41	2.03	1.00	.40
9	2.28	2.46	2.57	2.46	1.69	.54
10	1.90	2.33	2.68	2.55	1.90	1.08
11	1.40	1.92	2.59	2.54	1.85	.98
12	1.06	1.47	2.11	2.46	1.64	.93
13	.87	1.08	1.57	1.86	1.60	1.06
14	.74	.84	1.01	1.26	1.31	1.03
15	.64	.63	.66	.85	.84	.74
16	.46	.38	.57	.64	.44	.48
17	.37	.47	.50	.46	.28	.36
18	.30	.42	.43	.39	.34	.31
19	.33	.27	.42	.54	.44	.31
20	.37	.34	.49	.69	.50	.29
21	.38	.56	.63	.60	.54	.26
22	.37	.59	.77	.60	.39	.29
23	.42	.49	.65	.66	.39	.14
24	.49	.45	.44	.54	.39	.20
25	.57	.45	.34	.30	.35	.22
26	.56	.48	.27	.18	.18	.16
27	.53	.44	.32	.15	.02	.03
28	.41	.39	.35	.18	.00	-.00
29	.32	.34	.25	.18	.14	.05
30	.25	.17	.14	.20	.21	.09
31	.19	.11	.12	.18	.17	.10
32	.15	.15	.10	.11	.11	.07
33	.09	.15	.11	-.00	.02	.05
34	.04	.03	.06	-.00	-.00	.00
35	.00	-.00	-.00	-.00	-.00	-.00



ST.... STRAIN TRANSDUCER
ACC... ACCELEROMETER
PDA... PILE DRIVING ANALYZER
TR.... TAPE RECORDER (ANALOG, 4-CHANNEL)

FIGURE 1: SCHEMATIC OF INSTRUMENTATION



TR.....	TAPE RECORDER SYSTEM
MP.....	MULTIPLEXER
A/D....	ANALOG-TO-DIGITAL CONVERTER
CPU....	32 K WORD MINICOMPUTER
DS.....	DISC STORAGE
PR.....	PRINTER
PL.....	PLOTTER
S......	SCOPE

FIGURE 2: SCHEMATIC OF LABORATORY PROCESSING SYSTEM

A - Early Records of Retapping

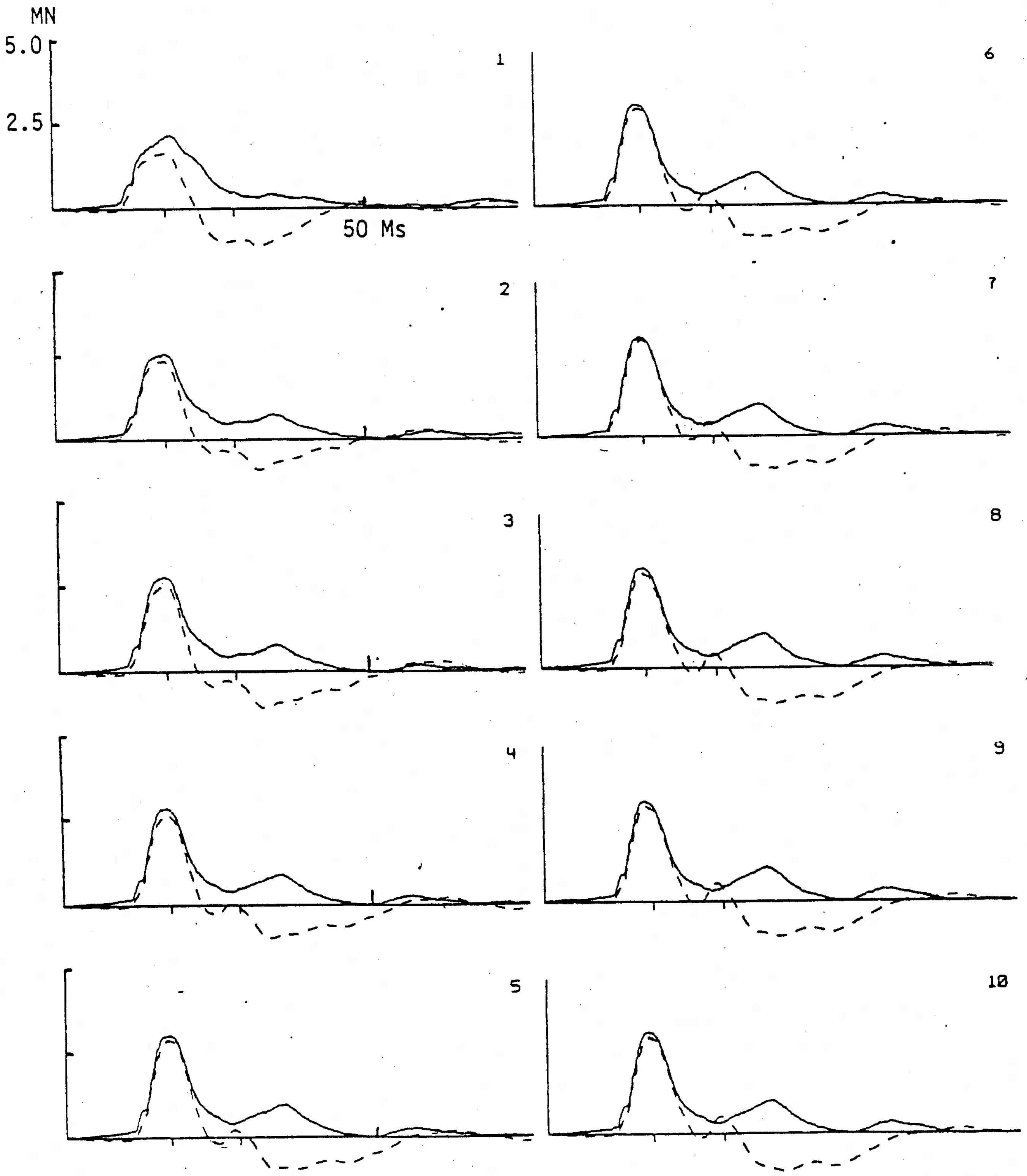


Figure 3: Example of Processed Data Plots, Solid line is Force,
Dashed line is Velocity (multiplied by EA/c).

Pile: 46 cm square prestressed concrete.
Wave Speed c = 3.87 m/Ms
Length L = 22.5 m; 2L/c = 11.6 Ms (Time between Tick Marks)

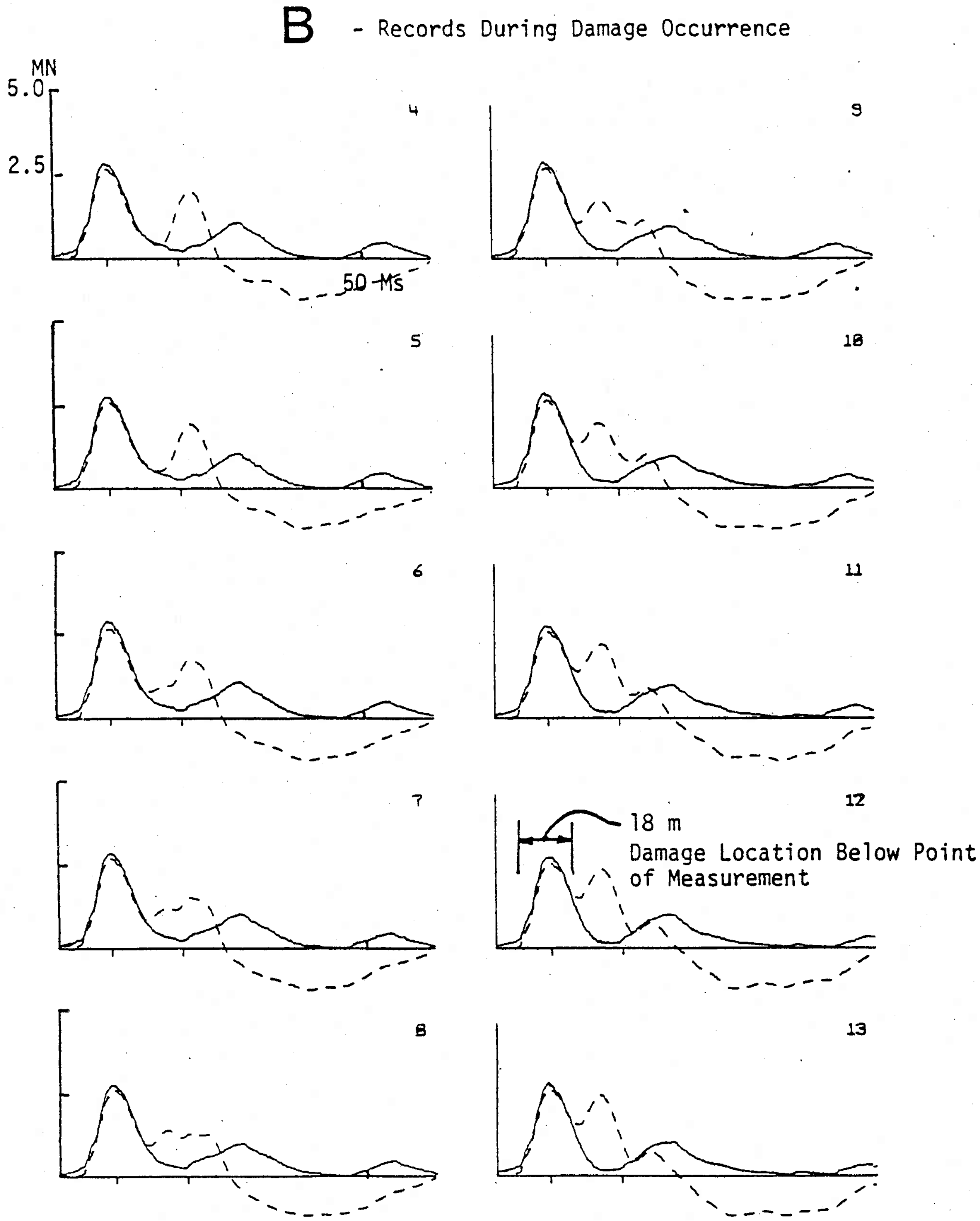
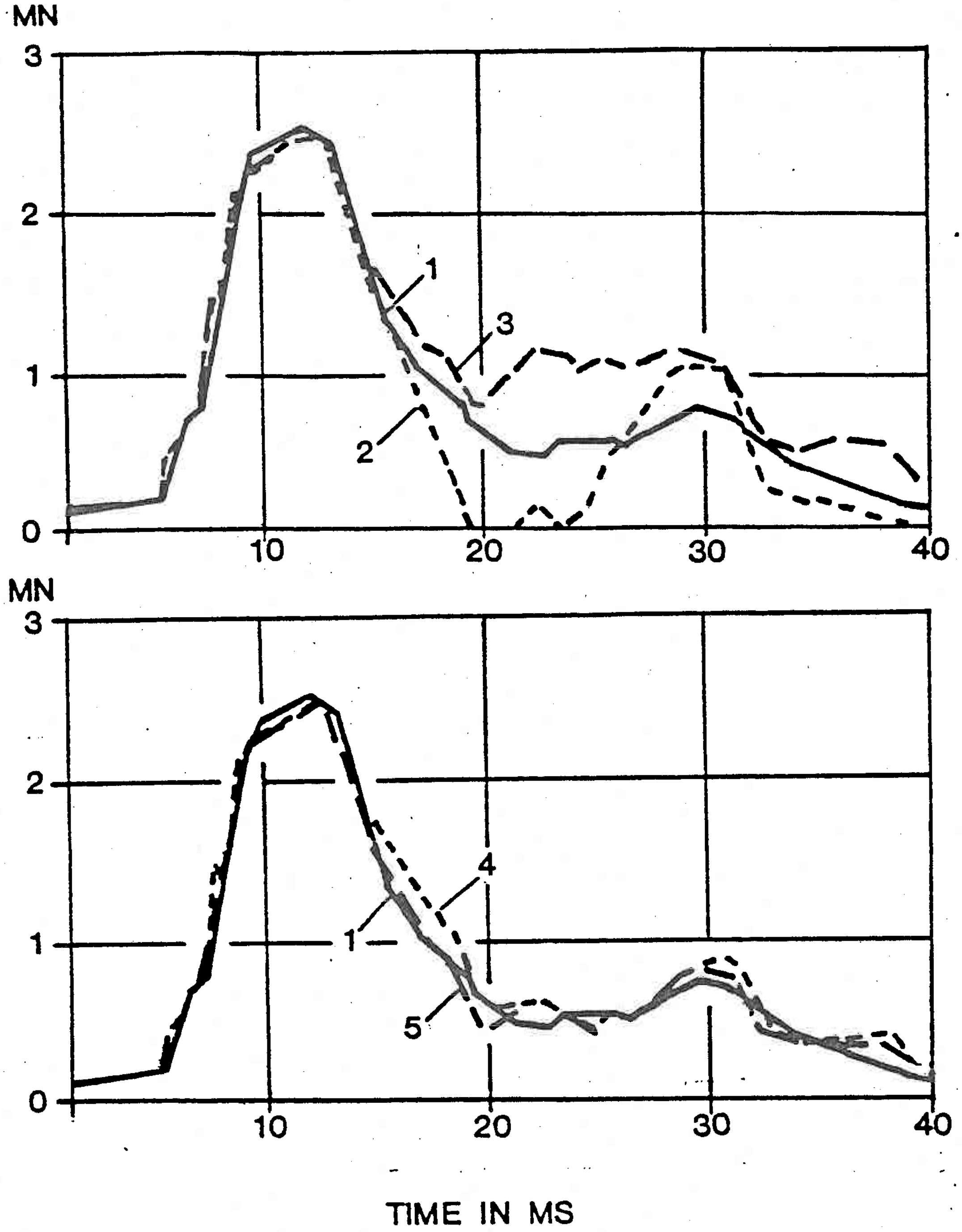


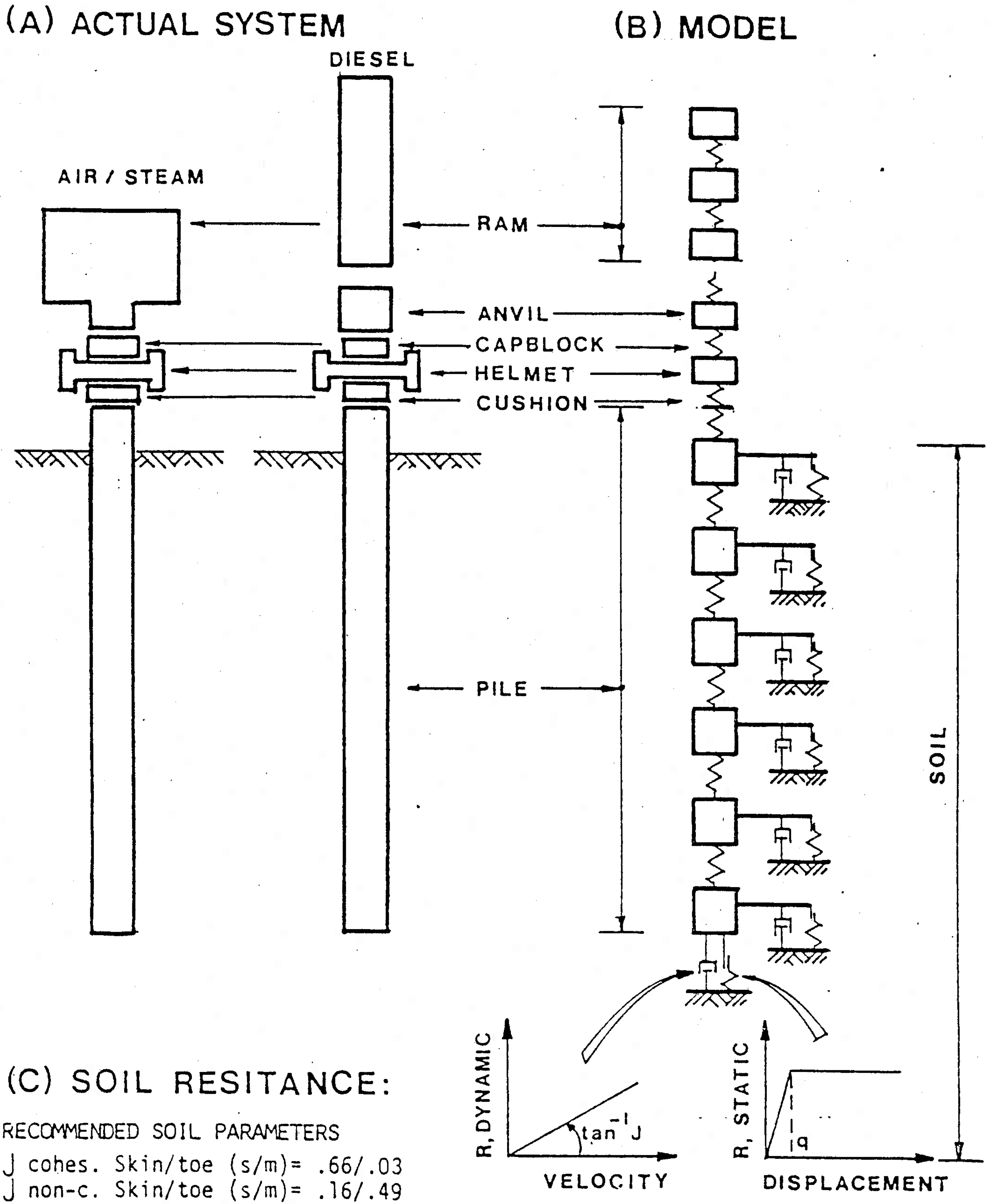
Figure 3: Continued

First graph (4): no damage; Second graph (5): slight damage; last graph (13): pile broken. All graphs are from consecutive blows.



1: MEASURED FORCE CURVE
2: LOW DAMPING
3: HIGH STATIC RESISTANCE
4: HIGH SKIN FRICTION, LOW END BEARING
5: FINAL SOLUTION

FIGURE 4: PILE TOP FORCE MATCHES FOR FOUR DIFFERENT SETS OF SOIL RESISTANCE PARAMETERS. FOR FURTHER DETAILS SEE TABLE 2.


(A) ACTUAL SYSTEM

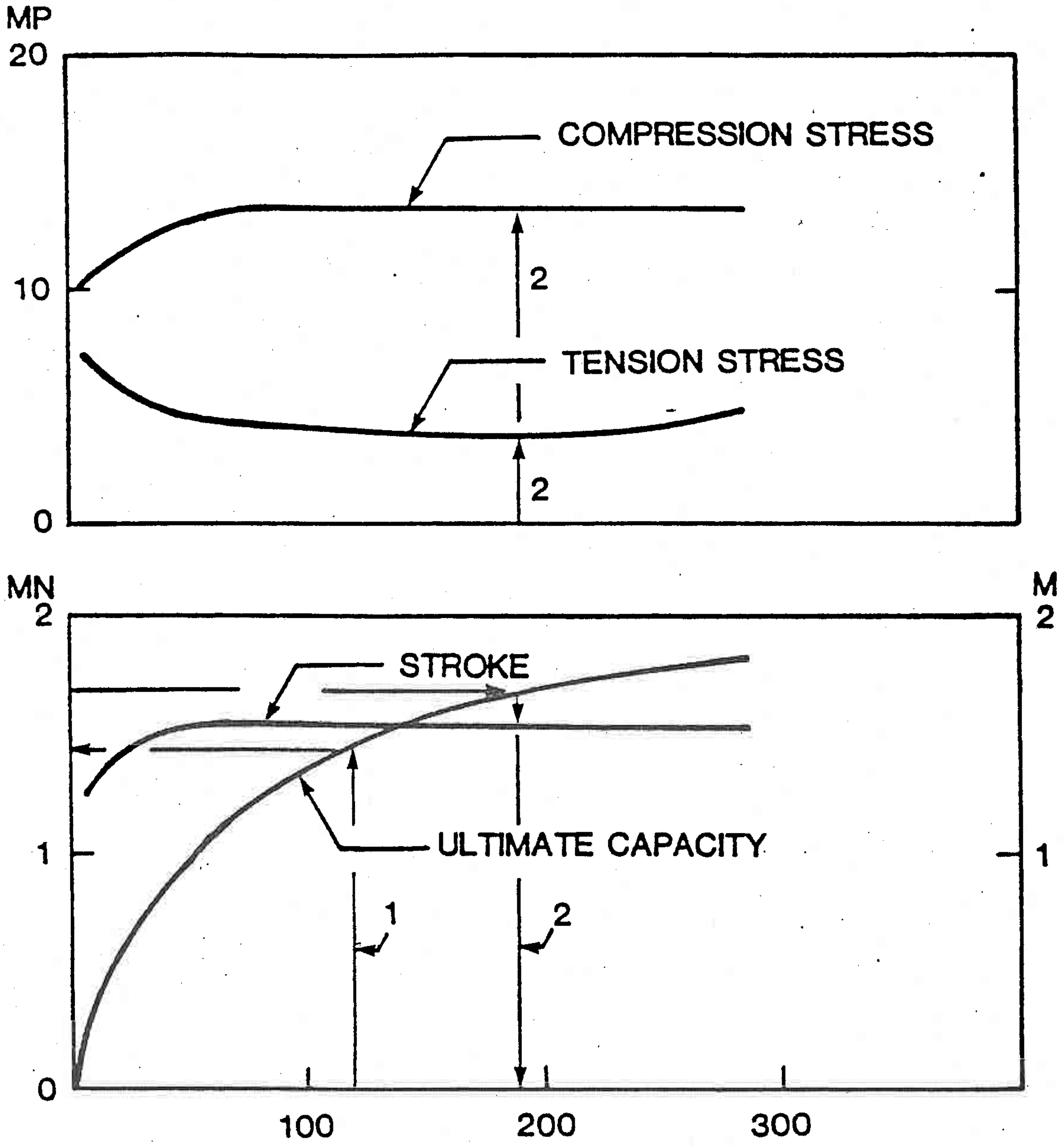
(B) MODEL

(C) SOIL RESITANCE:

RECOMMENDED SOIL PARAMETERS

J cohes. Skin/toe (s/m)= .66/.03
J non-c. Skin/toe (s/m)= .16/.49
q always (mm) = 2.5

Figure 5: Hammer-Pile-Soil Model of Wave Equation



1: WITH MEASURED BLOW COUNT FIND PREDICTED BEARING CAPACITY STRESSES AND STROKE.

2: WITH BEARING CAPACITY FROM STATIC ANALYSIS FIND PREDICTED BLOW COUNT.

FIGURE 6: BEARING GRAPH INCLUDING STRESS AND HAMMER STROKE VS BLOW COUNT RELATION

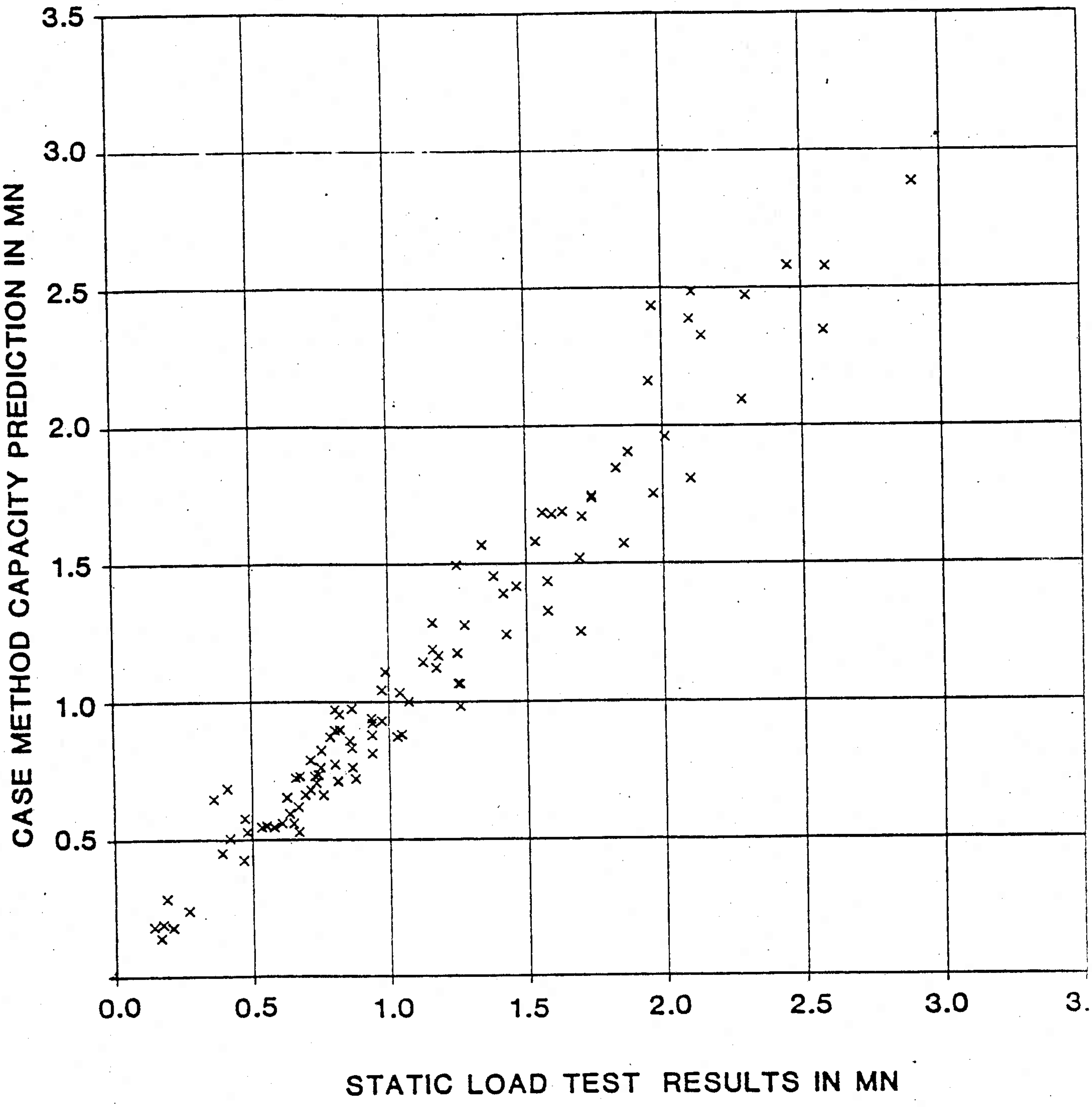


FIGURE 7: CASE METHOD AND STATIC LOAD TEST CAPACITY CORRELATION.

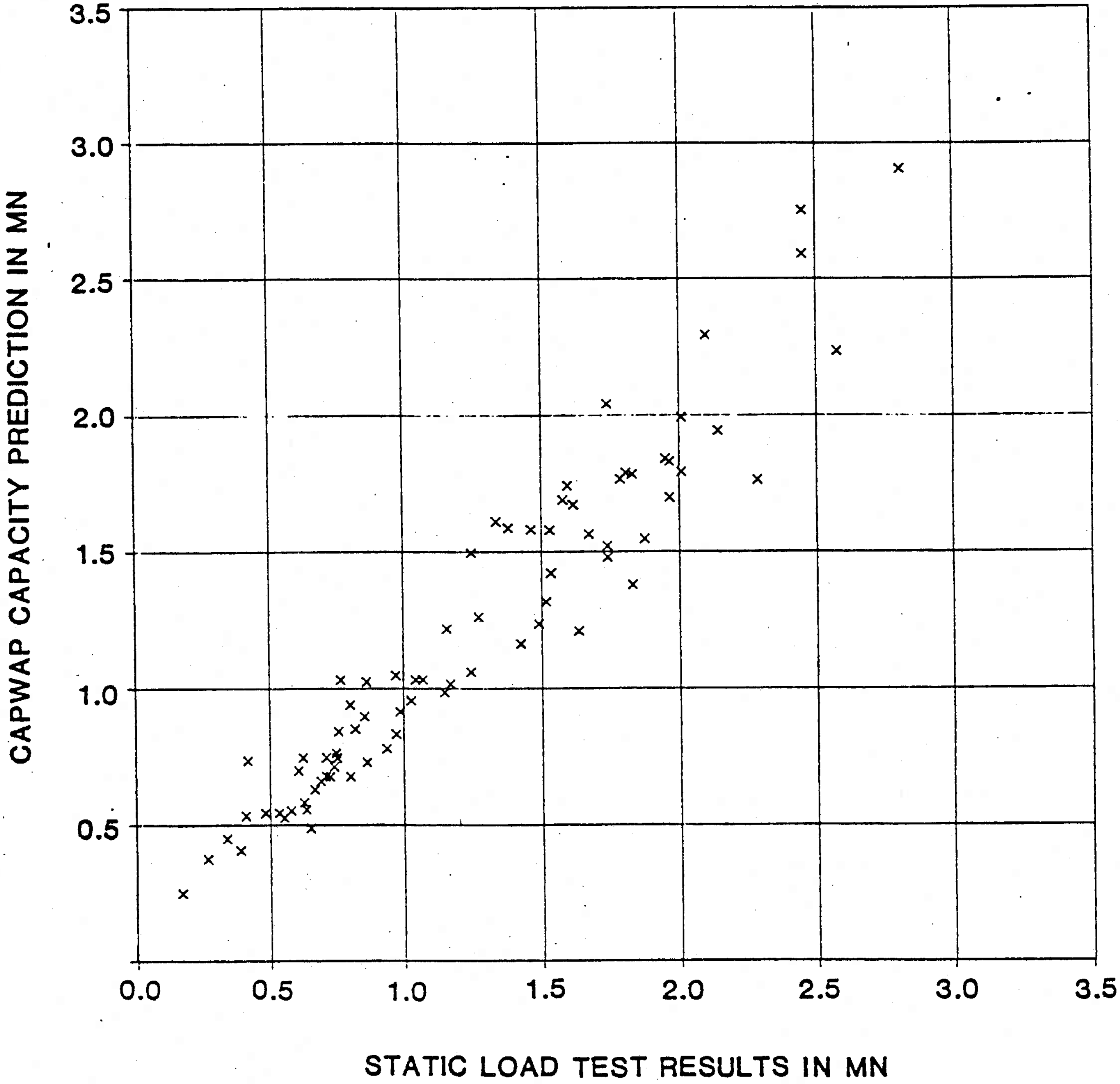


FIGURE 8: CAPWAP AND STATIC LOAD TEST CAPACITY CORRELATION

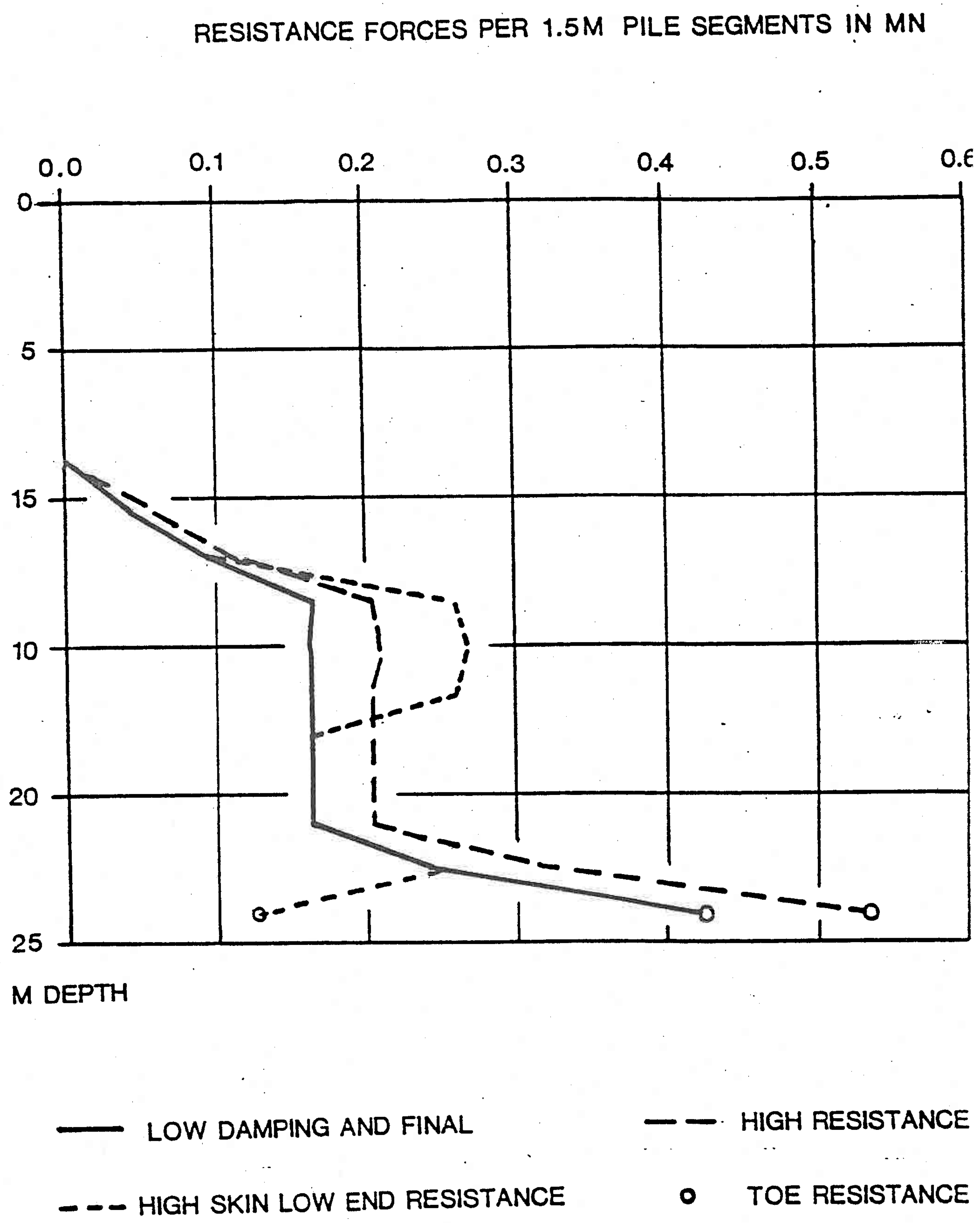


FIGURE 9: SKIN FRICTION DISTRIBUTION AND END BEARING FORCES FROM CAPWAP ITERATIONS OF FIGURE 4

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