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A New Testing Procedure for Axial Pile Strength

By

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ABSTRACT

A dynamic pile test method has been developed to accurately predict axial pile bearing capacity. The method requires acceleration and force data measured at the pile top under a hammer blow. The pile can be restruck a few days after driving to include strength changes of the pile-soil interface during set up.

A portable data recording system has been assembled making use of light weight, reuseable strain transducers and piezoelectric accelerometers which are bolted to the pile wall. Recordings are made on a four channel magnetic tape recorder.

The data are digitized automatically with an analog-to-digital conversion system. Punched paper tape, thus obtained, can be immediately fed into a high speed digital computer for processing.

A computer program has been prepared that uses both force and acceleration records to predict location and magnitude of soil resistance forces. Damping resistance forces are separated such that a static pile bearing capacity can be predicted. One dimensional stress wave considerations have been used as a theoretical basis. Other results that can be directly derived from the measurements are the magnitude of pile stresses and the hammer energy delivered to the pile.

Results from dynamic pile tests performed under various pile, hammer and soil conditions showed good correlation with results of static load tests. As a further check on the prediction scheme stresses along the pile and velocities at the pile point have been measured. Analytical predictions and measurements were found to be in good agreement.

References and illustrations at end of paper.

INTRODUCTION

Important and useful information on the static behavior of piles can be extracted from dynamic measurements made at the pile top during impact driving. Developments in electronics technology make it possible to obtain these measurements on a routine basis at modest cost. A continuing research activity at Case Western Reserve University has produced instrumentation and methods for predicting pile static capacity which are now coming into routine application with the Ohio Department of

Highways (1,2). The purpose of this paper is to present portions of the results of the research project which show potential for application in off-shore construction.

Instrumentation has been assembled and developed which makes possible the measurement of force and acceleration at the pile top during impact driving. An important requirement placed on this measurement equipment is that it be so compact and portable that it can easily be carried on board a commercial airplane. The processing of the resulting analog data has been fully automated. Thus, large numbers of hammer blow records can be analyzed in a short time.

Using the above system and an earlier one a substantial amount of data has been collected on piles which were also load tested statically. Analysis techniques have been developed for predicting the static resistance capacity of the pile and the distribution of this resistance from the dynamic measurements made at the pile top. Also, the dynamic portion of the resistance (damping) is determined. A correlation and evaluation of these results are presented.

DATA RECORDING AND PROCESSING SYSTEM

The pile analysis method presented here requires the measurement of both axial acceleration and force at the same pile cross section anywhere above grade. A data recording system has been developed which accurately measures these two high frequency phenomena and does not interfere with the hammer-pile system. In addition, this system was designed to have the lightest possible weight and be independent of line power such that piles in inaccessible locations can be tested. This has also the advantage that, on short notice, the measuring equipment can be carried on board commercial airplanes for tests at distant sites.

Accelerometers

Piezoelectric accelerometers have been used successfully during six years of pile dynamics research. Their high natural frequency and wide amplitude range makes possible the reliable pickup of the acceleration signal of an impact driven pile. Recently a new version of the piezoelectric accelerometer featuring an amplifier built into the transducer became commercially available. This transducer requires a simple battery powered coupler (Figure 1) for operation. It then provides a signal that can be recorded on a magnetic tape recorder without further amplification.

Two accelerometers were always used at opposite sides of the pile for cancelling gross bending effects in the pile. The transducers were mounted to the pile using a small aluminum block and self tapping 1/4 inch bolts for steel piles or anchors and bolts of the same size in the case of concrete piles. These attachments are shown in Figures 2(a) and 2(b). The inertia of accelerometers and attachment blocks was small so that separation between pile and instrument never occurred.

Strain Transducers and Strain Signal Conditioning

The most common method of obtaining force measurements on a pile during impact is to insert a force transducer into the driving system. This provides a very accurate system if the elastic and density properties of the transducer are not very different from those of the pile. However, force transducers are heavy and hard to transport although they could and should be built much lighter than reported in the literature (4). Transducers of this kind are therefore not usable in the present system.

For these reasons another type of transducer was developed which is bolted to the pile in a fashion similar to the accelerometer attachment. This device was designed very flexible and light and is calibrated to strain. Figure 3 shows one of these so-called "Clip-On" transducers and an accelerometer bolted to a concrete pile. Strain gages are attached to the aluminum transducer at points of deliberate stress concentration. The strains in the transducer bear a linear relation to the strains in the pile. Thus, the device can be calibrated to strain in the laboratory. Two of these strain transducers are always attached to the pile at opposite sides, again, as in the case of accelerometers, to cancel gross bending effects. Their signals can be recorded either individually or as an average by connecting corresponding strain gages in parallel. A DC instrument is used for bridge power and amplification. Such a balancing and amplifying unit has a frequency response higher than FM instruments and also has a size advantage.

Recorder

During the first six years of this project an oscillograph was used to record force and acceleration of impact driven piles. Such recorders are advantageous in that they produce a record that can be checked immediately for malfunction in the signal pick up system. However, there are several reasons why a magnetic tape recorder is superior for the current application:

1. An analog-to-digital data conversion can be done automatically thus allowing complete data reduction in short time.

2. The vast storage capability of a magnetic tape allows the "waste" of recording space, thus, making possible a complete record of a driving operation. Due to a late start or due to limited paper length oscillograph recordings may miss important record portions.

3. A sound track helps both to eliminate possible loss of information and to synchronize information with particular records.

4. The high input inpedance of magnetic tape recorders allows the recording of acceleration signals without further amplification.

A portable four channel tape recorder was successfully employed. Three tape speeds of 15, 3-3/4 and 15/16 inches per second allow a time base expansion of 16 for replay. At maximum speed a total of 20 minutes can be recorded without tape exchange.

Automatic Analog-to-Digital Data Conversion

A system for automatic A/D conversion already in use for several years at Case Western Reserve University was expanded. The system now accepts three data channels which are multiplexed to form one input into the A/D [illegible] osen at 1000, 2000 and 4000 cycles per second. Thus, under a time base expansion of 16, samples are taken at actual time increments of 1/16, 1/32 and 1/64 millisecond, respectively. The slowest of these sampling frequencies is sufficient for commonly encountered records. All three channels are filtered for cancellation of components having one half or more of the sampling frequency. The length of the converted record is dependent upon the memory capacity of the computer which stores the digitized data. The existing system accepts 2560 numbers per channel which corresponds to a record length of 160 milliseconds at the slowest sampling rate with a time base expansion of 16. The data stored in the computer can then be checked on an oscilloscope through digital-to-analog conversion. For further processing on larger and faster digital computers the data is then transferred to eight channel punched paper tape.

Figure 4 shows two traces of acceleration taken on opposite sides of a pipe pile and a trace of an averaged force. The record was replayed from magnetic tape into a Visicorder (Figure 4(a)) and automatically digitized and then plotted utilizing a digital computer controlled plotter. A comparison of the two results shows that the filter employed in the process of D/A conversion smoothed the acceleration records. However, high components lost this way are of no value to the dynamic analysis and predictions.

DYNAMIC PILE ANALYSIS

Generally, a pile can be treated as a slender rod whose dynamic behavior is described by the one-dimensional linear wave equation. A problem as important as the impact driven pile has attracted the attention of many investigators. For example, Fox and Isaacs (5,6) followed St. Venant's example to obtain solutions by superimposing properly chosen stress waves. Other investigators (7,8) divided the piles into a number of masses and found quite realistic solutions of the pile driving problem. While the stress wave solution provided an understanding of pile motion the lumped mass analysis allowed the realistic modeling of soil resistance forces. Both methods, however, assumed a perfect impact at the pile top which is hard to obtain even under carefully controlled laboratory conditions.

The method, presented here, considers only the pile not the hammer-pile system and replaces the action of the hammer by using force and acceleration records, continuous over time, that are recorded in the field. In addition to this improvement over conventional ways of treating pile dynamics both of the above outlined methods of analysis are utilized.

Either of the two records, force or acceleration, would suffice as an input to a realistic pile analysis assuming a knowledge of soil resistance forces. For example, the force can be chosen as an input and as the result of an analysis, an acceleration curve can be obtained which can be compared to the measured acceleration. The analysis could then be repeated with different soil resistance forces in order to obtain a better match*.

Assumptions about soil resistance laws such as an elasto-plastic spring in connection with a viscous damper will always be necessary as a basis for analysis. In the work presented here a soil description similar to Reference 7 was used. Even though such a law simplifies the problem there are still countless possibilities of choosing locations of forces and magnitudes of parameters. A pure trial and error procedure such as in Reference 9 to determine these unknowns would therefore be very tedious at best. A better and more economical approach is to find out what effects a certain resistance force has on the pile top variables. Once this is found the process is reversed and from pile top measurements conclusions are drawn on actually present resistance forces. As described in Reference 2 stress wave considerations allow such an analysis. Essential results

*This wad done by Tomko (9) using a modal analysis.

taken from 2 are summarized as follows:

1. Hammer impact produces a stress wave that travels pile downwards without changing its magnitude.

2. A change in pile cross section or a resistance force acting somewhere above the pile bottom produce two equal stress waves that travel in opposite directions.

3. The pile end produces a tensile reflection wave.

4. A resistance force acting at the pile bottom produces a stress wave traveling upwards.

5. The soil resistance force is activated by the impact wave. Thus, it acts only after the impact stress wave arrived at the location of resistance and its effect can be felt at the pile top only after arrival of the upwards traveling resistance wave.

6. The pile top velocity is proportional to the pile top force as long as no upwards traveling waves arrive (e.g. due to effects described under 2, 3, and 4).

Examples

Consider Figure 5 where pile forces are plotted as a function of both pile length and time. The plot was obtained from four measurements on a special load test pile. Interpolation between the measured curves was used to obtain a surface. The pile was driven into clayey silt that offered little driving resistance (the static load test result was 46 kips at ultimate). The pile tip force increases only slightly at a time L/c after impact where L is the length of the pile (here 50 feet) and c is the speed of the stress wave (17 feet/millisecond for steel). After the impact stress wave reaches the pile tip a tensile reflection wave is propagated pile upwards that reduces the effect of further compression stresses due to the hammer action. It can be observed that the stresses in the pile become small as the reflection wave travels towards the pile top.

Another example of stress wave propagation is given in Figure 6. In this case the pile tip reached a hard soil layer. Again as in Figure 5 it can be observed that the stress wave reaches the pile point at a time L/c after impact. This time, however, the force at the pile tip increases to values even larger than the impact force at the pile top. This large resistance force, therefore, produces a stress wave traveling upwards that exceeds the magnitude of the tensile reflection wave. On arrival at the top (time 2L/c after impact) the resistance wave produces an increase in force.

This theoretically derived and experimentally confirmed stress wave behavior makes possible the determination of soil resistance forces from pile top measurements using the following procedure:

1. A lumped mass analysis is performed that uses the measured acceleration record as an input at the pile top. Zero soil resistance forces are used in this first analysis. The analysis output is a force vs. time curve for the pile top. This force curve is subtracted from the measured force curve. The difference is the force effect of the soil resistance forces at the pile top.

2. The difference curve thus obtained is investigated and resistance forces are predicted according to the above stated stress wave criteria.

3. As a check a lumped mass analysis is performed again using the measured acceleration as an input but this time having the predicted soil resistance forces placed at the proper elements. The analysis output is again a force vs. time relation for the pile top that can be compared with the measured force curve.

4. Errors made in the predicted resistance forces can now be evaluated using the difference between predicted and measured pile top force.

5. Steps 3 and 4 are repeated until a satisfactory match between measured and predicted pile top force is found or until the match cannot be improved further.

It was found that the above procedure leads to good agreement with static measurements in the case of noncohesive soils. For cohesive soils some difficulties are encountered due to the relatively poor modeling of the damping properties of cohesive soils.

RESULTS

Dynamic records of 21 piles were available for analysis. Several of the dynamic tests were performed immediately after driving the pile; in most cases, however, the pile was restruck after a set-up period. All dynamic data were obtained within a few hours before or after a static load test was performed. Thus, effects of set up are included in the dynamic method.

In 14 of the 21 tests forces in the pile were recorded during the static load test on several locations below grade 1 and at the pile top. This way it was possible to compare predicted with measured static soil resistance distribution and to correlate total static bearing capacity.

As an example the case of a 59 foot long 12 inch diameter pipe pile that was driven by a Link Belt 440 hammer into silty, sandy soil is considered. Figure 7 shows the plot of the measured force and the measured velocity multiplied by the proportionality constant EA/c (E is the Young's modulus, A is the cross sectional area and again c is the wave speed. All three quantities pertain to the pile top properties). Figure 7 clearly indicates the above mentioned initial proportionality between velocity and force. It also shows the pile top force which was obtained as the best possible match. The agreement between the measured and computed curve is good.

The predicted static soil parameters were then used to perform a static pile analysis which leads to a theoretical load vs. penetration curve. This curve is plotted in Figure 8 together with the result from a constant rate of penetration test. The agreement between the predicted and measured load test curve is good. It should be noted that the dynamic test constitutes a very rapid load test which does not allow any creep as experienced under a static load test. This explains in part the steeper initial portion of the theoretical curve. Also shown in Figure 8 is the predicted force distribution in the pile together with results from force measurements during the static load test.

The method of correlation requires further discussion. Many load vs. penetration curves obtained on piles in granular material show considerable strength gains under large penetrations such that an ultimate or "plunging load", R_u, is not sharply defined. On the other hand, it cannot be expected that a pile reaches such large resistance values during driving where the pile penetrations are usually small. Consequently, the largest possible static resistance encountered during driving is associated with the largest pile displacement obtained under the hammer blow. (The displacement can be obtained by twice integrating the acceleration record). A reasonable correlation scheme is then to compare the predicted static capacity, R_o, with that load, R_d, obtained in the static load test at a penetration equal to the maximum dynamic deflection. Figure 8 shows a dotted line (at 0.62 inch) that indicates the load to be correlated (R_d = 174 kips). The prediction (R_o = 198 kips) is somewhat high for this correlation scheme. For the correlation of force distribution in Figure 8 the same reasoning was applied i.e. measured force values were taken from the static load test at maximum dynamic deflection. Both prediction and measurements indicate a relatively large resistance at the pile point.

Table 1 is a summary of all 21 records analyzed. In most of the cases more than one blow was used for analysis and an average taken. Both the measured static resistance at maximum dynamic deflection, R_d, and at ultimate, R_u, are listed for comparison with R_o, the predicted static capacity. The last column lists the sum of the maximum damping forces predicted.

The poorest correlation (66% difference) was obtained for pile W-56 (No. 15). This pile was driven into a highly cohesive soil which offered a large viscous driving resistance. Note that the predicted maximum damping was 87% of the predicted static capacity indicating the cohesiveness of the pile. All other predictions give good agreement.

FURTHER DEVELOPMENTS AND APPLICATIONS

Measurements and analysis discussed in the previous sections can be successfully used to find static and dynamic portions of soil resistance. Further results that can be obtained from the measurements of force and acceleration include the energy that was delivered to the pile and the driving stresses in the pile.

The energy computation can be used as a check on hammer performance, but, in the light of the much more revealing analysis results, it is of minor importance. It should be mentioned at this point that the authors found energy results similar to those of the Michigan investigators (4).

The stresses at the pile top are directly available from measurement. Other stresses along the pile can be obtained by performing a lumped mass analysis using the predicted soil parameters. In this way stresses can be determined very accurately. To prove the analysis stress measurements taken at the pile bottom are compared with the predicted forces. Figure 9 shows the comparison. The data was obtained on a pile having a large toe resistance. The phase shift between analysis result and measurement is explained in part by the finite size element which shifts the force action upwards by one element length (5.8 feet in the case considered). The difference in magnitude between the two stress maxima is 10% and arises from inaccuracies in the prediction analysis.

The accelerometer with built-in amplifier used in this project (Section 2) makes possible measurements of pile tip accelerations without having cable noise problems. As a check on the prediction scheme the velocity of the bottom element in the lumped mass analysis was compared with the result from acceleration measurements. Figure 10 shows a plot of both curves for a pile with low point resistance (No. 18 of Table 1). The agreement is good. It should be noted, however, that such a comparison is very sensitive to small zero shifts in acceleration curves obtained from measurements. This introduces errors in velocity which increase linearly with time due to integration. This explains, at least in part, the increasing difference between measured and predicted pile top velocity in the later portion of the record.

The measurements of both acceleration and force at the pile toe have an important application in finding a proper soil model. It was mentioned earlier that the assumed soil resistance law was the same as proposed by Smith (7). The analysis showed that this model provides sufficient accuracy for coarse grained soils with typically small damping effects. However, comparison of force curves for piles in cohesive soil often showed large differences after a time 2L/c after impact. This lack of agreement between theory and measurement can be explained from pile toe measurements.

Example

Figure 11 shows the velocity and displacement as obtained by integrating the acceleration that was measured directly at the bottom plate of a pipe pile (No. 19 of Table 1). Also shown is a plot of the measured pile toe force, $R_m(t)$.

The soil model proposed by Smith - used in the present method - relates u(t) to the static resistance force, S(t), as follows:

$$S(t) = (S_o/q)u(t)$$
$$S(t) \leq S_o \qquad (1)$$

where S_o is the ultimate static resistance and q is the quake (7). Equation 1 is valid as long as the velocity v(t) is greater than zero. Unloading will not be considered in this example. The soil model includes dynamic resistance effects with a damping force, D(t), that is given by

$$D(t) = (c_d)v(t) \qquad (2)$$

where c_d is a damping constant. Therefore, the total resistance force according to the chosen model is

$$R(t) = S_o/q\ u(t) + (c_d)v(t) \qquad (3,a)$$

or if

$$u(t) > q_o$$

then

$$R(t) = S_o + (c_d)v(t) \qquad (3,b)$$

Equations 3a,b contain three unknown parameters: S_o, q and c_d. These three numbers can be chosen so that agreement exists at least at three points between the measured and theoretical resistance force curves. In the example at hand, q was chosen to be the displacement at the time of maximum velocity, and S_o was taken as the measured resistance force value at the time of zero velocity. The damping coefficient, c_d, was then determined such that the maxima of $R_m(t)$ and R(t) would agree. Since these maxima of v(t) and $R_u(t)$ occur at the same instant (which is also the time where the maximum static resistance is reached) one finds

$$c_d = \frac{\max R_m(t) - S_o}{\max v(t)} \qquad (4)$$

S(t) and R(t) can now be plotted. Comparing the two resistance force curves it is found that the agreement is good in the very beginning and in the later portion of the plot and that the largest difference occurs where $R_M(t)$ reaches the first minimum. Certainly another choice of the parameters can improve the match but under the given soil model it is impossible to describe the (as Grasshoff (10)) called it "explosion like" resistance force behavior in the beginning of the record that is typical for cohesive soils. Another soil model that possibly includes inertial behavior has to be found to give a better description of actual resistance forces activated by the pile point in cohesive soils.

It must be emphasized that the accuracy of the prediction scheme (Section 3) depends on the soil model employed. The discrepancies between model response and soil behavior affect the prediction scheme first in that it is only possible to match an average top force behavior. In consequence, the resistance forces which are predicted describe an average soil response, too. The answers are, therefore, usually good. For coarse grained soils the model suffices and both top force match and predictions are accurate.

The successful application of the present pile test method suggests further utilization.

Soil investigations performed prior to construction often include so-called penetrometer or sounding rod tests. Penetrometers can be considered to be very slender piles. Instrumention of these rods at their top, measurement of both acceleration and force under several blows and a prediction analysis would lead to results including an indication of the driving resistance and damping properties of the soil. Also the skin friction to be expected for a full scale pile can be predicted after proper scaling. First results obtained on a 1-1/2 inch diameter rod having a penetration of 48 feet were encouraging.

CONCLUSIONS

The present test method for pile axial strength requires the measurements of acceleration and force at the pile top. These measurements have been taken on a routine basis and do not interfere with the driving system. Thus, the true pile top stress and acceleration is measured. Predictions of bearing capacity based on the measurements of dynamic quantities eliminate errors due to incorrect or inaccurate assumptions of hammer performance and impact losses. In addition, soil strength parameters are determined which have to be assumed in conventional methods. Another advantage is that strength change during set-up is included if the pile is restruck after a waiting period following driving. Thus, no set-up factor needs to be known. Data acquisition and processing is automated so that results are obtained within short time.

The following results can be obtained:

1. Static resistance force distribution
2. Damping constants
3. A prediction of static load vs. pile top penetration
4. Hammer performance
5. Maximum driving stresses

The results were compared with static and dynamic measurements. Correlation was good.

It was shown that it is possible to obtain measurements of forces and accelerations on locations other than the pile top. These measurements can be used not only for correlation purposes but also for dynamic soil model studies. An improved soil model would produce more accurate results for piles in cohesive soils.

Studies on the use of penetrometer tests for predictions from dynamic measurements are under way. It is hoped that this application will yield better design information through dynamic soil investigation.

It is proposed that the described method can be used in construction control by testing dynamically a large number of piles. To include set up effects the piles should be restruck after a time delay after driving. The dynamic test piles either can be part of a foundation or they can be driven for soil investigation purposes only.

ACKNOWLEDGEMENTS

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TABLE 1 - COMPARISON OF 21-LOAD TEST PILE RESULTS WITH WAVE ANALYSIS PREDICTION

						Static Load Test		Wave Analysis	
	Pile Name	Length Feet	X-Section Inch^2	Soil	No. of Blows Analyzed	R_u kips	R_d kips	R_o kips	max D kips
1.	531-76	82	5.81	Grly. Sand	1	198	151	159	15
2.	F-30	32	9.82	Silt, Sand	2	107	97	91	45
3.	F-30A	32	9.82	Silt, Sand	1	112	107	136	24
4.	F-50	50	9.82	Silt, Sand	3	224	172	163	43
5.	F-50A	50	9.82	Silt, Sand	2	238	200	233	48
6.	F-60	59	9.82	Silt, Sand	2	204	176	210	29
7.	F-60A	59	9.82	Silt, Sand	2	242	174	180	51
8.	Cincinnati	69	6.66	Grly. Sand	3	190	137	166	13
9.	To-272	54	6.66	Silt, Sand	1	227	183	204	24
10.	To-50	49	9.82	Silt, Clay	2	69	60	69	55
11.	To-50A	49	9.82	Silt, Clay	1	94	93	119	70
12.	To-60	59	9.82	Silt, Clay	2	43	32	56	69
13.	To-60A	59	9.82	Silt, Clay	2	86	75	122	107
14.	Logan	57	6.66	Grly. Sand	2	220	165	173	55
15.	W-56	55	6.66	Silt, Clay	4	92	90	151	121
16.	W-76	75	6.66	Silt, Clay	1	160	125	151	141
17.	Chillicothe	40	6.66	Grly. Sand	2	207	152	163	56
18.	Ri-50	49	9.31	Silt, Clay	1	46	40	45	88
19.	Ri-50A	49	9.31	Silt, Clay	3	64	64	84	83
20.	Ri-60	61	9.31	Silt over	2	*	176	184	70
21	Ri-60A	57	9.31	Sand, Gravel	2	*	174	187	33

*Load Test Assembly Failed at Loads Exceeding 200 kips.

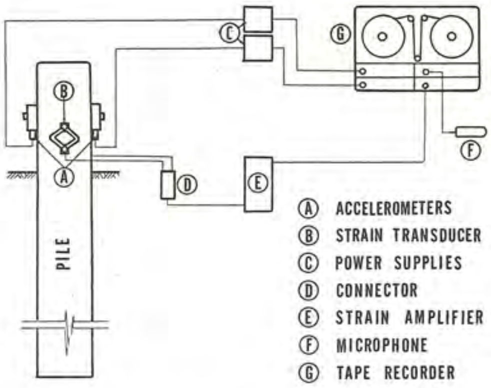

Fig. 1 - Recording system for pile force and acceleration measurements.

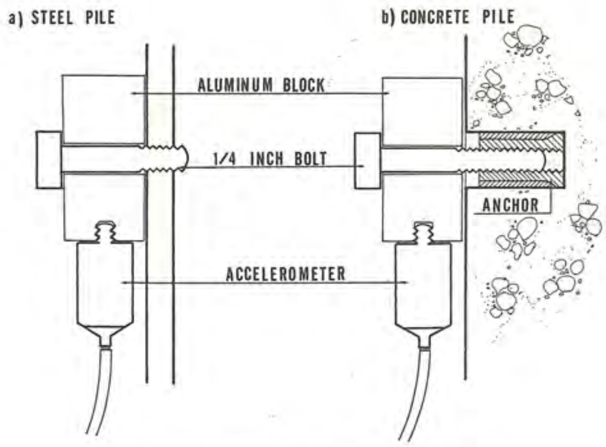

Fig. 2 - Accelerometer attachment (a) for steel pile (b) for concrete pile.

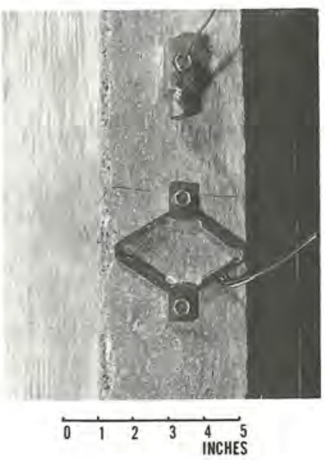

Fig. 3 - Clip-on strain transducer and accelerometer attached to an octagonal concrete pile.

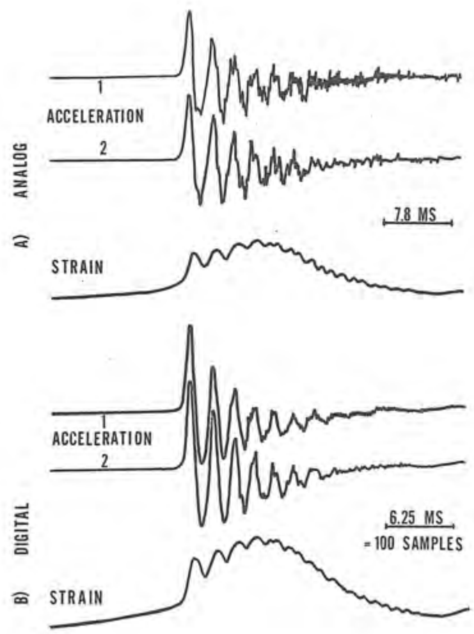

Fig. 4 - Reproduction of portion of dynamic measurements from tape recorder (a) through oscillograph (b) automatically plotted after analog to digital conversion.

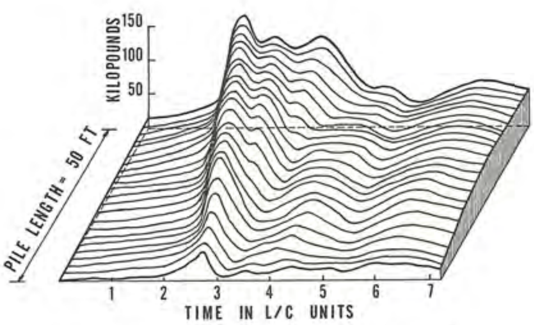

Fig. 5 - Forces in a pile during a hammer blow. Example of a small point resistance (Pile 19, Ri-50A).

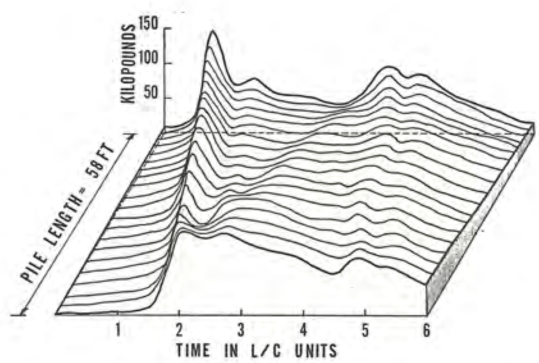

Fig. 6 - Forces in a pile during a hammer blow. Example of a large point resistance (Pile 20, Ri-60).

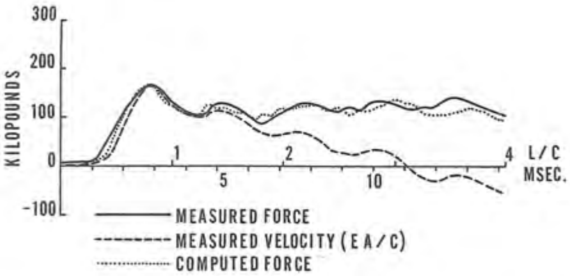

Fig. 7 - Analysis input velocity and comparison of analysis output with measured force curve (Pile 7, F-60A).

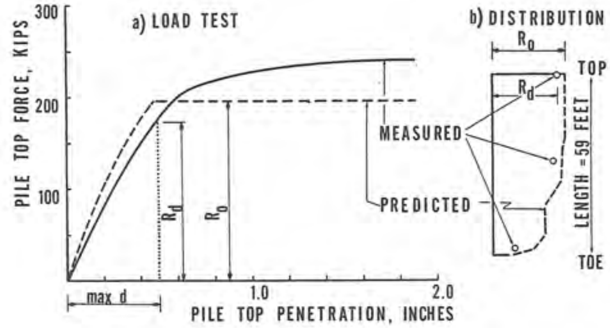

Fig. 8 - Comparison of predictions with measurements (a) load vs penetration curve (b) distribution of forces in pile at predicted ultimate capacity (Pile 7, F-60A).

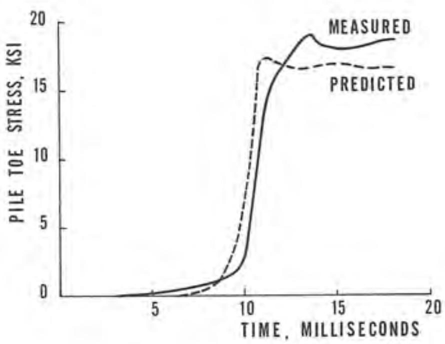

Fig. 9 - Stresses in pile at pile toe as measured 12 in. above bottom plate and as predicted from pile top measurements for bottom element (Pile 21, Ri-60A).

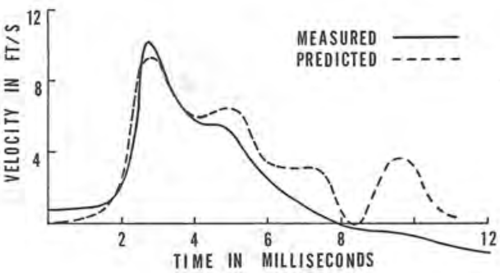

Fig. 10 - Velocities of pile toe as measured by an accelerometer placed directly on bottom plate and as predicted from pile top measurements for bottom element (Pile 18, Ri-50).

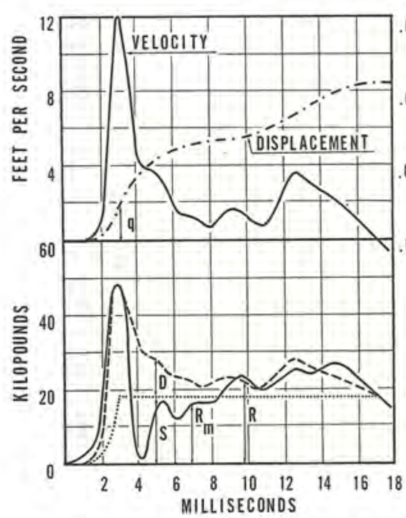

Fig. 11 - Force, velocity and displacement pile from toe measurements and corresponding spring-damper model response.