

HIGHWAY RESEARCH RECORD

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Pile Foundations

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Pile Load Test by Impact Driving

G. G. GOBLE and FRANK RAUSCHE, Case Western Reserve University

The use of measurements made during impact driving to predict static pile capacity is a widely used concept. The results are sometimes not satisfactory because of a lack of knowledge of hammer energy, poor estimates of losses in cushions, inaccurate set measurements, substantial strength change after the end of driving, and other factors. A method having a different basis has been proposed for predicting static capacity from dynamic measurements made by impact driving. By applying this method to measurements made after a setup period, the difficulties mentioned are avoided. This method has been applied to 25 piles that were also statically load-tested. The average difference between the static capacity obtained from a constant rate of penetration test and that predicted from dynamic measurements was 10 percent. A wide variety of soil conditions and hammer types is represented in the data. All piles were of hollow steel pipes. The use of this system for routine measurements is not feasible if reliance must be placed on the analysis of records taken on high-speed oscillographs because a substantial time lag occurs between data acquisition and analysis. In addition, equipment of this type is hardly satisfactory for routine field use by personnel having modest backgrounds in electronics. To avoid these problems, a special purpose computer was designed and constructed to perform the necessary computations in the field and to display the results. With this device, the necessary calculations for capacity prediction are made in real time and the results are displayed. Thus, a number of consecutive blows can be recorded to improve the accuracy of the prediction. This device should improve the reliability of pile test data because it is realistic to obtain load test data by driving a number of "test" piles and obtaining dynamic predictions from all of them.

•THE USE OF MEASUREMENTS made during impact driving to predict static pile strength is a widely used concept. Many pile-driving formulas use energy considerations to predict bearing capacity. The results are sometimes not satisfactory because of a lack of knowledge of hammer energy, poor estimates of losses in cushions, inaccurate set measurements, substantial strength change after driving, assumption of a resistance that is constant during the blow, and other factors. A method having a different basis has been proposed for predicting static capacity from dynamic measurements made during impact driving (1, 2, 3). By applying this method to measurements made after a setup period, the difficulties mentioned are avoided. This procedure has been applied to 25 piles that were also statically load-tested. The difference between the static capacity obtained from a constant rate of penetration test and that predicted from dynamic measurements is much smaller than that commonly observed by using pile formulas. A wide variety of soil conditions and hammer types are represented.

A special purpose, electronic computer has been designed and constructed to automatically perform the necessary computations in the field and display the results. With this device, a predicted capacity is displayed within 2 milliseconds after the end of the hammer blow. Thus, a number of consecutive blows can be recorded to improve the

accuracy of the prediction. This device should increase the reliability of pile test data because it is realistic to obtain test data by driving a number of "test" piles and obtaining dynamic predictions from all of them.

Procedures are now being developed jointly with the Ohio Department of Highways and the researchers at Case Western Reserve University to begin implementing these methods and equipment into Ohio construction practice. It is anticipated that the researchers will gradually decrease their involvement with the routine application of the technique.

DATA ACQUISITION, EVALUATION, AND CORRELATION

A simple force-balance method has been proposed to relate dynamic measurements to static capacity. The pile is assumed to be a rigid body struck by a time-varying hammer force. Motion of the pile is resisted by a force, R , given by the expression

$$R(t) = R_0 + R_1v + R_2v^2 + R_3v^3 + \dots \quad (1)$$

where v is the velocity of the pile, and R_0, R_1, R_2, \dots are constants. Thus, R_0 represent the static capacity. Under the action of these forces at the instant of zero velocity and by use of Newton's Second Law, the resistance is found to be

$$R_0 = F(t_0) - ma(t_0) \quad (2)$$

where m is the mass of the pile, $a(t_0)$ is the acceleration at time, t_0 , when the velocity is zero, and $F(t_0)$ is the force at the top of the pile at the same time.

Subsequent studies have shown that the reliability of the capacity predictions can be improved by averaging the acceleration over some time increment around the zero velocity time to avoid extreme acceleration values arising from elastic waves in the pile. In the following discussion, Eq. 2 will be referred to as the Phase I method and the same equation containing an averaged acceleration will be referred to as the Phase II method. Theoretical studies, recently completed but not yet reported, have shown why these simple approaches provide such good results and have given some indication of the limitations to be expected. These simple methods will be less reliable for application in highly cohesive soils and for very short piles. A Phase III method has been developed that shows promise in providing good capacity predictions for all soil types. It will not be discussed here.

The application of Eq. 2 requires the measurement of force and acceleration at the top of the pile. Velocity can be obtained by integration of the acceleration record. Developments in electronic instrumentation and transducers in the past few years make it possible to obtain these measurements on a routine basis. Equipment for making the measurements was assembled and extensively tested. A high reliability was attained for obtaining successful records under the normal rather difficult field conditions. Force measurements were made during the early project phases by using resistance strain gages attached to the pile and later with transducers either on top of the pile or attached to the pile. Accelerations were measured with piezoelectric accelerometers attached to the pile a short distance below its top. Force and acceleration were recorded continuously on a high-speed oscillograph.

Data were obtained from full-scale piles driven for static load testing on highway bridge projects. After completion of the usual Ohio Highway Department load test, project personnel performed an additional load test by using a constant rate of penetration. In this test, the goal was to reach ultimate bearing capacity, as a basis of correlation with dynamic results. The load test was then removed, and dynamic measurements were made during several hammer blows sufficient to obtain a permanent set of the pile. This procedure has become quite routine. At present, the instrumentation is assembled, and all readings are taken by only 2 people from the research project. For the past 3 years, successful records have been obtained from every attempt. It should be noted that in all cases the contractors have donated the time and services required to redrive the pile. Thus, the data have been obtained at a very low cost.

The data were analyzed by manually transforming them to digital form on punched cards. The computations outlined earlier were made by a digital computer, and drawings of the results were obtained automatically from a computer-controlled plotter. A sample result is shown in Figure 1.

The dynamic prediction is expected to correlate with ultimate capacity, and for this reason the constant penetration load test was performed because the standard Ohio Department of Highways load test does not go to ultimate load.

A comparison of dynamic predictions with static measurements is given in Table 1. Additional results have been obtained that are not reported because the procedures outlined were not followed exactly. These results are reported in another paper (3). Some comments are appropriate. Piles 10 through 15 and 20 through 23 were special test piles driven under research project control and having additional special instrumentation. Static load tests were performed, and the dynamic predictions make use of only the usual measurements.

Substantial differences between static measurements and the Phase II predictions exist only for 2 piles, 22 and 24. Pile 22 had a very low capacity so that a 21-ton difference results in a large percentage. Furthermore, studies conducted on small-scale piles and recent analytical studies have raised questions about the Phase II method on piles in highly cohesive soils. An application of the preliminary Phase III procedure showed better correlation for the piles driven in fine-grained soils. The agreement on pile 24 was substantially better, and it was almost exact on pile 22. However, it should be emphasized that this was only a very early application of Phase III, and considerable further study is required.

Piles 4 through 9 were driven into a material having a static behavior that does not exhibit a sharp break in the load-set curve. Considerable "strain hardening" appears at large set values. The current analytical studies show promise in providing a solution to this difficulty.

Pile 5 was a steel pipe pile that had been filled with concrete prior to making dynamic measurements. Thus, it had a large mass typical of all precast concrete piles. It is interesting to note that the agreement with static test results was good. These were the only data obtained from "high mass" piles.

The average difference between the static ultimate strength and the dynamic prediction was 29 percent for Phase I and 17 percent for Phase II. If piles 22 and 24 are dropped, the differences are 22 and 10 percent for Phase I and Phase II respectively.

SPECIAL PURPOSE COMPUTER

The instrumentation system outlined earlier is satisfactory for use by experienced personnel. However, it hardly represents an acceptable system for routine use by engineers whose primary concerns are with other activities. Effort has been devoted, therefore, to the design and development of a special electronic computer and the necessary associated transducers.

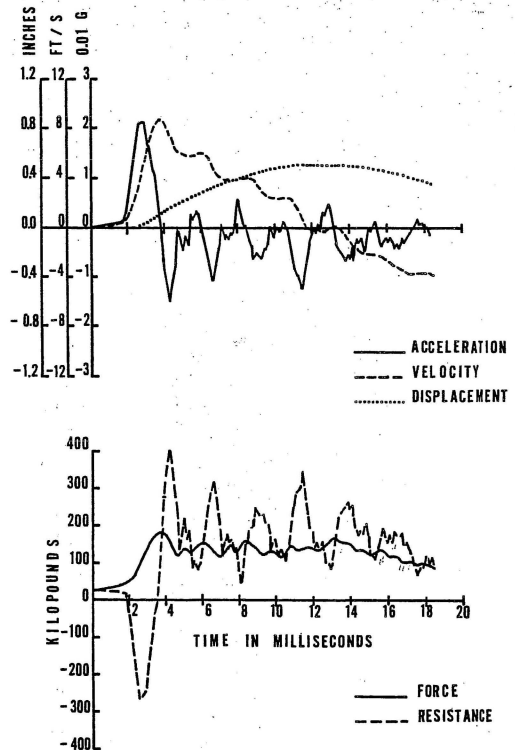


Figure 1. Dynamic results of pile 12.

TABLE 1
COMPARISON OF STATIC ULTIMATE CAPACITY WITH PHASE I
AND PHASE II DYNAMIC PREDICTIONS

Pile	Length (ft)	Soil	Static Resistance (tons)	Phase I Dynamic Prediction (tons)	Difference (percent)	Phase II Dynamic Prediction (tons)	Difference (percent)
1	76.5	Gray silt and clay	126	139	+13	131	+4
2	74.0	Medium coarse sand	148	200	+26	174	+18
3	78.0	Sand silt and clay	122	141	+14	139	+14
4	59.0	Gravelly sand	96	95	-1	94	-2
5	76.0	Gravelly sand	106	110	+4	106	0
6	71.0	Gravelly sand	95	87	-12	91	-4
7	71.0	Gravelly sand	100	72	-28	73	-27
8	77.0	Gravelly sand	99	92	-7	92	-7
9	84.0	Gravelly sand	125	101	-20	105	-16
10	31.5	Silt and sand	52	61	+17	60	+15
11	31.5	Silt and sand	57	58	+2	63	+11
12	50.0	Silt and sand	112	139	+24	97	+13
13	50.0	Silt and sand	119	142	+19	113	-5
14	59.0	Silt and sand	102	144	+41	109	+7
15	59.0	Silt and sand	121	164	+36	111	-8
16	71.0	Coarse gravel	95	126	+33	95	0
17	58.0	Gravelly sand	113	138	+22	114	+1
18	41.0	Gravel and sand	105	158	+52	101	-4
19	52.0	Clayey silt	111	164	+48	130	+17
20	50.0	Gray silt and clay	35	33	-6	47	+34
21	50.0	Gray silt and clay	48	37	+23	53	+10
22	60.0	Gray silt and clay	22	43	+96	43	+96
23	60.0	Gray silt and clay	43	50	+16	47	+9
24	56.0	Gray silt and clay	47	100	+113	88	+87
25	78.0	Gray silt and clay	88	135	+54	78	-11

The piezoelectric accelerometers used during most of the project were quite satisfactory except for one problem. The signal coming from the accelerometer requires considerable amplification before it can be recorded. Therefore, there is a problem with lead wire noise. Recently, accelerometers of this type with an amplifier built into the transducer have become available. Their output signal is large enough so that long lead wires can be used without difficulty. These devices have made the acceleration measurements much easier. The accelerometers were attached directly to a small steel block in a semi-permanent fashion. This total system was attached directly to the pile wall by drilling and tapping a hole in the pile wall and bolting the steel base directly to the wall. This setup is shown in Figure 2.

During most of the time that the project has been active, force measurements were obtained by attaching resistance strain gages to the pile near the top. The Ohio Department of Highways usually uses steel pipes for friction piles. Two strain gages were attached to the exterior pile walls on a diameter to cancel out gross bending of the pile. Force was then determined by using the nominal area. This system gives very reliable force measurements but is unsatisfactory for routine application because it requires the attachment of at least 2 resistance strain gages to the pile under field conditions. The use of Eastman 910 contact cement results in a gage attachment that can be used immediately. However, the process of attachment is, at best, a tedious process and unsatisfactory in routine application.

Two transducers were developed for force measurement. One system uses a piece of pipe of the same diameter as the pile with strain gages attached to the pipe. One of these devices is shown in Figure 3. A plate is then welded to the top of the pile, and the transducer is bolted to the plate. An adapter attached to the top of the transducer accepts the driving system in the same manner as does the pile. The second transducer

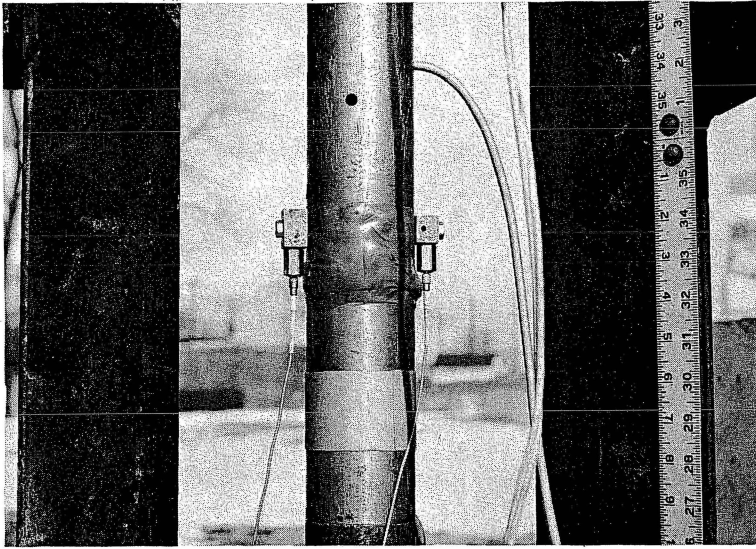


Figure 2. Accelerometer attachment.

could best be described as a strain transducer. A small curved strap was designed to be quite flexible in the longitudinal direction. Strain gages were attached to the strap in points of stress concentration to provide a large strain output from the transducer. This bears a linear relationship to the strain in the material to which it is attached and can be calibrated. The transducer is shown in Figure 4 attached to a 3-inch diameter pipe. On the left is the transducer, and on the right is the transducer with the template used for supporting it during the attachment operation. In actual use, 2 transducers are applied, one on each side of the pile. A typical setup of the instrumentation attached to the pile is shown in Figure 5.

Both transducers provided satisfactory records for this application. The first device has the advantage of providing an output that has been calibrated to force. It is, however, heavier and bulkier than the second device, and, because it has substantial mass, the dynamic behavior is affected to some degree. The second device is light and easily attached, but, because it is calibrated on strain and thus dependent on a knowledge of pile area, it will not be as accurate as the first device.

The strain and acceleration signals, after appropriate conditioning, were recorded on a high-speed oscillograph. The resulting records were then examined and digitized manually for subsequent automatic analysis. A more rapid, simpler data processing system is necessary. Therefore, a special purpose electronic computer was constructed to perform the computations of Eq. 2 and provide a readout in real time. It is shown in Figure 6. In use, the device is calibrated to a particular pile by the operator. (The accelerometer and force transducer calibrations and the pile mass

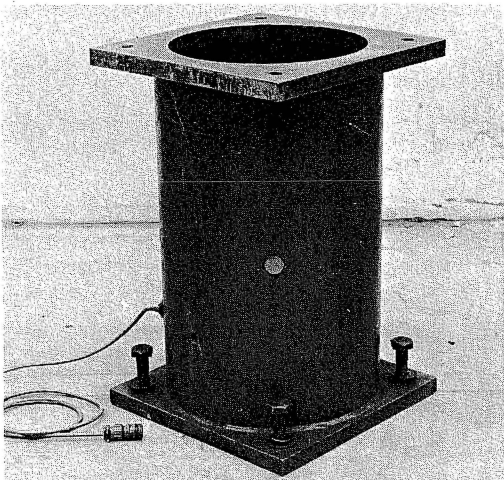


Figure 3. Force transducer.

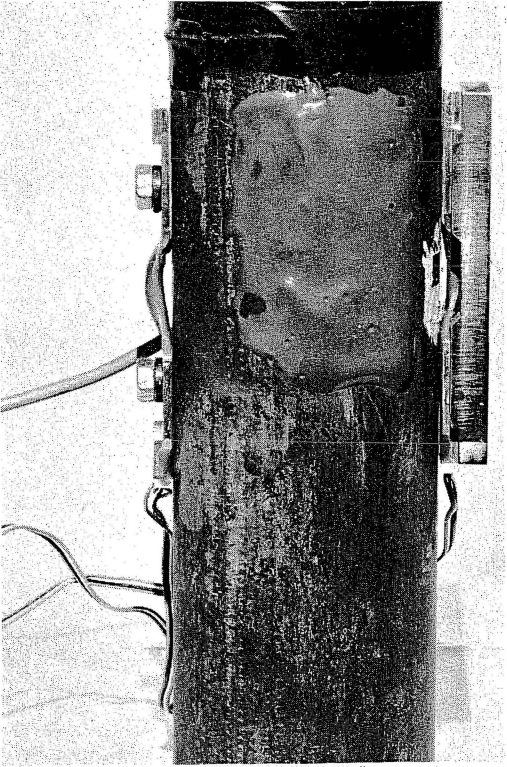


Figure 4. Strain transducer.

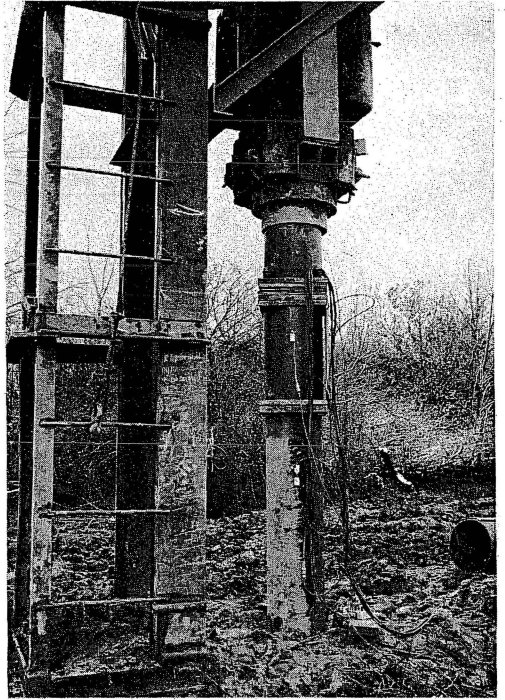


Figure 5. Force transducer and accelerometer in driving system.

must be introduced.) The computer then provides a visual output of 3 digits on a nixie tube display. All blows or selected blows can be recorded.

The operational characteristics of this system of computer and transducer indicate that it could be used by the construction engineer with only brief training.

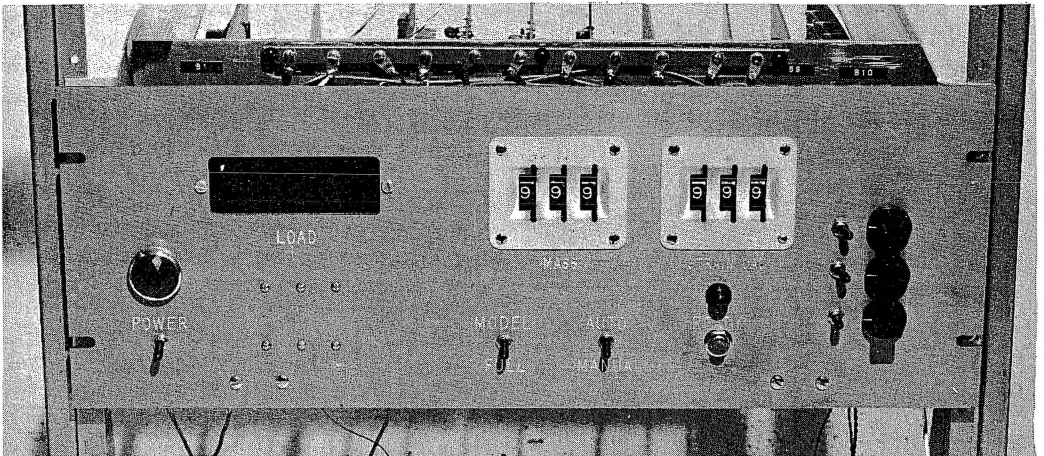


Figure 6. Operator control panel of special purpose computer.

PLANNED APPLICATION IN FOUNDATION CONSTRUCTION CONTROL

It is unrealistic to expect that a drastic change in pile-driving control, such as the system outlined, can be introduced without an extended period of trial. In the first place, only a limited amount of correlation with static load tests has been obtained. Furthermore, all data to date have been gathered by research project personnel. The first step toward routine use will be to make the Phase I computer available to the Ohio Department of Highways. Department personnel plan to use it for continued correlation with static test piles and the driving formula. If correlation is poor, project personnel will be available to obtain dynamic records for more thorough study. In many smaller jobs, the requirement of a load test pile is not considered economical. Thus, occasionally, if engineers are surprised by the pile lengths obtained from a driving formula, the computer would be used to provide further information on which to base a decision.

A Phase II computer will also be constructed, tested, and introduced into use as with Phase I. Present data indicate that this device should be satisfactory for all conditions except perhaps in uniform highly cohesive soil deposits. A totally different system may be necessary for application of the Phase III procedure.

It is hoped that it will be possible to obtain substantial reductions in foundation costs as a result of the use of this method. Static load tests will be less frequently necessary, but probably more important will be the use of the additional information to reduce the rather large margins between indicated bearing and capacity required by design. The economic use of multiple test piles will further add to the reliability of test results.

Additional data and study are required for piles having a large mass and for piles driven in highly cohesive soils.

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