DYNAMIC PILE MONITORING
A Continuing Research Effort

GEORGE GOBLE

The author is Principal, Goble Rausche Likins and Associates, Boulder, Colorado.

Driven pile foundations were constructed in antiquity. At first, they consisted of timbers driven into soft ground with small hammers that were lifted and dropped by crews of people or by draft animals. Of course, this system could not drive piles very hard, but successful foundations were constructed more than 4,000 years ago.

During the industrial revolution, mechanized winches powered by steam came into use, and mechanical hammers were later developed that were powered directly by steam. As the machine age advanced, pile driving hammers became bigger, and pile sizes and capacities increased. During the middle of the 19th century, scientific methods began to be applied to pile driving to measure and predict the load-carrying capacity of driven piles. Static load tests were performed for this purpose. Yet static tests were costly and time-consuming, and simpler methods were therefore sought.

It was logical for engineers to turn to energy concepts for predicting pile capacity. The potential energy of the pile driving hammer at the top of the stroke could be equated to the work done in penetrating the pile. The pile penetration could be observed so the force resisting penetration could be calculated. However, many questionable assumptions were made in deriving the equation, so the results did not agree very well with those of static load tests. Thus the formulas were adjusted and corrected to achieve better agreement with the results of static load tests, and a large number of new formulas were developed. More than 400 formulas resulted, and while their use has always been viewed with suspicion, their simplicity has made them attractive in practice. These formulas have become known as *dynamic* formulas since they use data obtained during the dynamic driving operation.

20th-Century Developments

In the early part of the 20th century, the results of dynamic penetrometers were used for predicting pile driveability. In the 1920s, soil mechanics emerged as an engineering science, and methods for predicting pile capacity on the basis of information derived from subsurface investigations were developed. Again a large number of methods were developed. Although these methods have generally been even less reliable than the dynamic formulas, they have the advantage that they can be used before pile driving begins, and for that reason their use is essential. The static analysis makes it possible to predict the pile length before going to the field so that estimated quantities can be given to the contractor.

In the 1950s, E. A. L. Smith of the Raymond Company proposed a discrete dynamic model of the total pile driving system, including the soil, for analysis by electronic digital computers. In the analysis, the analytical model of the pile driving ram was dropped on the top of the pile and driving system model, and the predicted penetration of the pile into the soil was obtained by dynamic analysis. This method of computer analysis, known as the *wave equation,* is in general use today. This program may have been the first civilian engineering application of electronic digital computers.

In 1960 the Michigan Highway Commission performed a study of pile driving hammer performance. Extensive measurements of force and acceleration were made at the pile top to determine the energy transmitted to the pile by several different hammers. This research project was concerned primarily with hammer performance, and for the first time acceleration was measured during pile driving. Strain and hence force measurements had already been made in 1938 at the British Building Research Station. The Michigan effort was a realistic field study that produced many useful results that helped advance the state of the art.

At first, the idea of routinely using force and acceleration measured at the pile top during driving for determination of pile capacity was viewed as unrealistic, if not impossible, because of the problems associated with making those measurements under the difficult conditions existing at a

FIGURE 1 Dynamic pile monitoring with pile driving analyzer at job site, Cleveland, Ohio.

pile driving construction site. Today the use of dynamic monitoring of pile driving has become routine (see Figure 1). The equipment used for the purpose is employed in 40 countries around the world, including almost all of the major industrial nations. Use of the equipment is covered by several of the world's standard specifications. When difficulties are encountered in pile driving, it has become standard practice to use dynamic monitoring to diagnose the problem and seek a solution.

In 1958, dynamic tests were performed in a laboratory at Case Institute of Technology (now Case Western Reserve University) on a steel rod that had been driven into a container of sand. Acceleration was measured during driving, and after completion a static load test was performed on the rod. The axial load-bearing capacities predicted by an analysis of the dynamic measurements showed general agreement with the statically measured values.

Ohio Project on Dynamic Measurement

In 1964, Ohio Department of Transportation funded a project at Case Institute aimed at developing the capability to make dynamic measurements in the field and use those measurements to predict pile axial load-carrying capacity. For this project to succeed, the equipment necessary to measure force and acceleration at the pile top on a routine basis had to be assembled, tested, and proven. At the time, the idea of making routine dynamic measurements under the pile driving hammer was considered altogether unrealistic, first because such measurements were difficult, and second because the field construction environment was so unfriendly to scientific measurements. This effort continued for about 8 years, during which time the project benefited from continual advances in electronics. It was also necessary to perform analytical research to develop and improve methods for predicting the static pile capacity from the dynamic measurements.

ODOT performed a large number of static load tests during the normal bridge construction process. It was suggested that these load test piles be tested dynamically to collect full-scale field data for correlation of dynamically predicted capacity with static test results. Even though such early use of field measurements was deemed unwise by the researchers, this approach was required by the sponsor. Obtaining the full-scale field data proved highly useful in the long run and instrumental to the success of the project.

The equipment needed to make the necessary measurements was assembled. At that time, instrumentation-quality magnetic tape recorders were all analog with half-inch tape. Their cost and size made them unsuitable for the project. Thus at the beginning of the project, all recording of measurements was done with a high-speed oscillograph. This device limited the amount of data that could be recorded in an uninterrupted sequence to about a dozen hammer blows. The recording was made on light-sensitive paper at a speed of 80 inches per second. The measurements were then digitized manually to produce data that could be processed automatically.

A procedure for organizing and scheduling field testing was developed in cooperation with ODOT. At that time, closed-end pipe piles were normally used for sites that required friction piles, and they were frequently load tested statically. The test loads were applied to soil failure or three times the design load. On piles that failed at less than three times the design load, the pile was again driven with a few blows by the piling hammer, and dynamic measurements were made. Thus, measurements could be recorded on piles that had been statically load tested to failure. Effects of strength changes that occurred between the end of driving and the time of the static load testing were covered by this procedure. Nearly 100 sets of field data were collected in this way on ODOT projects.

In the initial stages of the project, force measurements at the pile top were made by attaching foil resistance strain gages to the pipe pile walls near the pile top. This method provided reliable measurements, but the gage installation was difficult and time-consuming. A great deal of effort was therefore devoted to developing a simple, accurate, easily attached strain-measurement transducer. The resulting device solved many of the problems involved in making routine force measurements. This transducer, which can be attached easily and quickly, has provided excellent results. Since initial successful tests in 1970, a number of improvements have been made to the device. Today it is being used for strain measurement applications other than pile driving, including bridge testing.

Acceleration was measured using commercial accelerometers that were attached to the pile with a special mount. Early in the project, accelerometer problems sometimes occurred as a result of the high accelerations encountered during hammer impact and the high frequency of the motion when measurements were made on steel piles with steel-to-steel impact in the driving system. The latter problem continued to occur for several years. Accelerometers were continually improved by their manufacturers, with the result that problems became much less frequent. Figure 2 shows an accelerometer and strain transducer mounted on a steel H-pile. To account for bending that may be induced inadvertently during driving, a second set of instruments is attached to the opposite side of the pile.

By 1969, the availability of a portable, modestly priced, instrumentation-grade tape recorder made it possible to perform dynamic pile driving measurements easily and store the analog data on ¼-inch magnetic tape. The data were then processed automatically using a minicomputer to digitize the measurements and store them in digital form. Large volumes of data could be processed automatically, and a variety of analytical computational procedures could be tested. A large volume of full-scale field data was then collected.

From the beginning of the project, analytical work was undertaken on two fronts. First, the simplified method of capacity prediction was expanded and given a firmer analytical basis, and assumptions were eliminated. The dynamically predicted capacity from the full-scale field data was tested against measured static load test results. This effort was carried out throughout the life of the project and has continued. It was possible to develop simplified capacity-prediction methods that were based on one-dimensional wave propagation theory. This approach is still in use and is known as the Case Method since all the research, development, and proving of the method was done at Case Institute of Technology.

Experience, both analytical and experimental, from the first 4 years of the project made it possible to formulate the goal of seeking a more reliable method for capacity prediction based on a discrete rigorous, time-domain analysis. Given a measurement of force and motion (acceleration) at the pile top, could the resistance forces acting on the pile be determined? The pile is represented by discrete elements, and the soil resistance is divided into the same types of static and dynamic components as in the wave equation development. If the measured

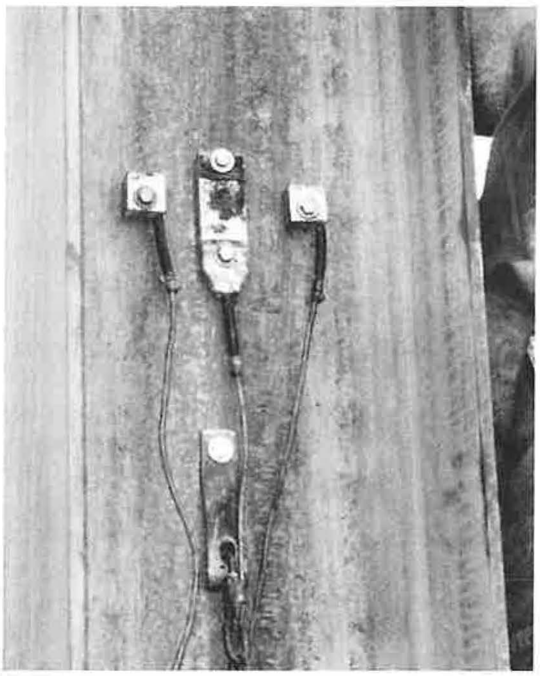

FIGURE 2 Accelerometer and strain transducer attached to H-pile.

motion is input at the pile top and the soil resistances are assumed, it is possible to calculate the force required to generate the input motion. Then the calculated and measured forces are compared, and the resistances are changed to improve the match between the two forces. This process is performed iteratively until the match can no longer be improved.

As a result of these efforts, software called the Case Pile Wave Analysis Program (CAPWAP) was developed. CAPWAP has been modified during the past 25 years to simplify the process of selecting improved resistances. The soil models have been enhanced, and portions of the matching process have been automated. Analysis with CAPWAP provides a much-improved pile capacity prediction. In addition, the static soil resistance distribution is predicted along the length of the pile, and with the static soil model, a predicted static load test curve can be obtained. Use of this analysis reveals a great deal about pile behavior in addition to pile capacity.

With both the Case Method and CAPWAP available for capacity prediction, a study was undertaken to correlate the results of those analyses with the capacity measured in static load tests. Project personnel believed that for the results of the dynamic capacity prediction to be credible, they had to be correlated with those of static load tests. The Case Method requires the input of a parameter determined by soil type. This quantity was studied so that specific values could be recommended on the basis of the results of the correlation study. The CAPWAP analysis produces results that are based only on the analysis, and these results were compared with the statically measured values.

One of the goals stated in the original research proposal was the development of some means of processing the measurements in the field. In 1966 work began at Case Institute on developing a field computational device to take and process the measurements and provide a capacity prediction. All of this had to be done in real time to be of use to field construction engineers. It was necessary to use analog computational methods to obtain the results at the speed of typical pile driving hammers of about one hammer blow per second. In the 1960s, digital computation was much too slow and expensive to use for this application. Development of a successful device called a *pile driving analyzer* was completed in 1970. While this device was rather crude, it clearly showed the potential of the capability, and it was used by ODOT jointly with research project personnel.

At this stage it was necessary to make advances on all aspects of the project. Transducers and measurement equipment were improved as a result of advances in electronic devices. More field correlation data were assembled and the load tests compared with dynamically predicted capacity so the prediction methods and measurement equipment could be enhanced.

Improved pile driving analyzers were developed. Since force and acceleration measurements were available, it was possible to calculate additional quantities that could be of use in understanding and controlling the operation of pile driving systems. Energy transferred to the pile could be calculated for each hammer blow, maximum driving stress could be observed and displayed, and maximum reflected tension stresses could be estimated and displayed. As a clearer understanding of the important aspects of one-dimensional wave mechanics developed, measured parameters could be displayed that would be useful in evaluating the correctness and accuracy of the measurements. With all of this information, the pile driving analyzer became useful in evaluating hammer operation and determining the source of problems on the job site.

An important aspect of the Ohio research project was the role of the ODOT and Federal Highway Administration project supervisors. In the 1960s and 1970s, this function was performed by engineers whose primary duties were in the areas of design or construction. Since all of these engineers were involved in foundation design and construction, they were able to evaluate the research on a continuing basis. They frequently suggested directions that were not obvious to the researchers. Those engineers who were concerned primarily with design and construction work could contribute their broader, more applied view.

Project Outcomes and Applications

The results of the Ohio project were demonstrated during the Geotechnical Specialty Conference on Field Testing at Purdue University in 1972. An H-pile was driven and tested dynamically, and the capacity was predicted by the Case Method with a pile driving analyzer. A static load test was then performed with less than a 1-hour delay after completion of driving. The capacity prediction agreed very well with the statically measured value. Also in 1972, FHWA decided it would be desirable to acquire the latest version of the pile driving analyzer for its own testing and evaluation.

Thus 1972 represented a milestone in the evaluation of dynamic monitoring. The basic development of the concept was complete. No patents had been obtained, and all the results had been published in reports and papers in the public domain. From this point, the task was one of improving existing methods and capabilities. The economic usefulness of the capability had been proven. Commercial testing opportunities began to emerge, and this work paid for further development of the capability. Additional data collected as part of these commercial testing projects also supported improvements in the analytical methods and equipment.

The first commercial test was performed in St. Paul, Minnesota. The test was successful, as verified by a static load test. Use of the pile driving analyzer spread rapidly in the upper Midwest.

One of the earliest transportation organizations to use dynamic pile monitoring outside of Ohio was New York State DOT. The agency supported the collection of data and in 1974 purchased a pile driving analyzer for its own use. Implementation of the capability is more problematic for smaller DOTs because of their limited resources.

To encourage the implementation of dynamic pile-testing technology, FHWA started Demonstration Project No. 66 (DP66), Design and Construction of Driven Pile Foundations. This project had the overall objective of incorporating modern methods of driven pile practice, including dynamic pile testing, into state transportation projects. The project was active from 1982 to 1992 and involved making visits to all state transportation agencies at least once.

The DP66 project offered a range of services, including classroom and field training, technical assistance on all phases of construction project development, and field demonstrations of both dynamic testing and conventional axial and lateral load tests. Approximately 100 static and several hundred dynamic tests were performed as part of the project.

A comprehensive driven pile design and construction manual was developed under DP66. This manual served as a training document, as well as FHWA's national recommended practice for driven piles. The manual, along with the associated training materials, is now available through FHWA's National Highway Institute. A key aspect of DP66 was the local delivery of not only technical training, but also demonstration of how modern driven pile methods could be integrated into each state's practice. By implementing these methods on real construction projects, state and federal engineers learned how to achieve both cost savings and improved quality.

Recent Developments

Considerable research on the dynamics of pile driving had been done in Sweden by the Swedish Pile Commission, and those engineers were particularly able to appreciate and understand the work that had been done under the Case Institute project. In 1977 they acquired a pile driving analyzer and were successful in bringing it into practice in Sweden. Within a few years, dynamic pile testing was being used almost universally in Sweden.

FIGURE 3 Pile driving analyzer.

At present, dynamic pile testing equipment is being used in 40 countries. About 550 pile driving analyzers (see Figure 3) are in use, more than 150 of them in the United States. In 1999 it was estimated that the device was being used on more than 6,000 projects annually worldwide. It is difficult to determine cost savings as a result of the use of dynamic testing, but in general, it has been estimated that pile lengths could be reduced by 15 percent. In Sweden, a major factor was less controversy on jobs and therefore less time spent on resolving differences regarding possible pile damage during driving.

Another major change in practice is currently being implemented. The capability to transmit signals to and from the field pile driving analyzer by cellular telephone has been developed. Thus, the field testing can be conducted from the office, and required travel can be greatly decreased. During the next few years, the unit cost of dynamic testing is expected to be considerably reduced.

The Case Institute project represents an important application of high-tech capabilities in the construction industry. Progress was made possible by dramatic advances in electronics and digital computers and associated cost reductions that took place during the past three decades. As such this effort is probably representative of future developments that can be expected to change the construction industry.