Dynamic pile testing and analysis using expert system methods

G. Likins
Pile Dynamics, Inc., Cleveland, Ohio, U.S.A.

F. Rausche
Goble Rausche Likins and Associates, Inc., Cleveland, Ohio, U.S.A.

David Peterman
Pile Dynamics, Inc., Cleveland, Ohio, U.S.A.

ABSTRACT: Over the last 28 years, dynamic pile testing has evolved from an idea into today's routine testing procedure. Although dynamic testing answers a variety of questions concerning deep foundations, the experience of the engineer often determines the effectiveness of the testing. The need to transmit this acquired experience from experts to the new engineer is obvious as only then can the maximum testing benefit be realized.

The Pile Driving Analyzer™ (PDA) now offers this expert advice in the field to the novice tester. The data is then further evaluated by the rigorous numerical analysis program CAPWAP™ to determine the dynamic soil response and estimate static capacity. While the first CAPWAP program automatically generated solutions for piles of moderate lengths, the current CAPWAP program can automatically produce solutions for most pile lengths based on 25 years experience by the authors.

1 BACKGROUND

Measurements of force and velocity are routinely made on construction sites. Such measurements and their analysis on site in real time situations are known as the Case Method, named after Case Institute of Technology where the original research began in 1964 under the direction of Dr. G.G. Goble. These measurements during driving and/or restrike can present the engineer with a wealth of beneficial factual information on which to base his decisions (Rausche, Likins, Hussein 1988). The compressive and tensile driving stresses can be calculated, and then compared with allowable values to determine if potentially damaging high stresses are present. Pile integrity can be quickly assessed. The hammer performance is further evaluated by comparing the measured energy transferred into the pile with the manufacturer's rated energy. The bearing capacity of the pile at the time of testing can also be calculated.

The equipment and methods have improved considerably over the years due to electronic advancements and continued research on dynamic methods. However, one difficulty that has remained is the education of engineers in the application of the equipment and the interpretation of the results. Unfortunately, dynamic pile testing is generally not included in an engineering graduate's course of study, although many universities now provide instruction in "wave equation analysis" of piling, giving the student at least a brief exposure to the dynamics of pile driving. Over the years, many engineers have been assigned to gather and analyze dynamic pile test data. Although some engineers have been involved in dynamic testing for even decades thus gaining tremendous expertise, there is a continuing need to train new engineers when other experienced engineers accept different career responsibilities, when the testing activity of a company increases, or when new companies or agencies venture to provide the service on an inhouse basis.

The client naturally expects the testing agency to know everything concerning the service it provides, and often is not even aware that different experience levels exist. Since some decisions must be made while the pile is being driven, such as controlling stresses to avoid damage, identifying a poorly performing hammer, or determining when the capacity is satisfactory, experience can in many cases make quite a difference in interpretation. The new engineer, unfortunately lacks an experience base and often may not even understand fully the purpose of the test. Difficult situations may arise and be entirely overlooked because they were not expected.

Nevertheless, application into the real life situation is not without perils. For example, ranges of physical constants are not always well known by a novice engineer. Furthermore, limits for stresses, assessment of hammer performance and particularly capacity determination are not always easily evaluated. Measured values should be compared with established guidelines and data bank information included in the software developed by experts in dynamic testing.

2 EXPERT ADVICE IN THE FIELD

Obviously, it is beneficial to have this experience of experts available on a full time basis. Decision trees, while helpful, are usually checked only after data acquisition has been completed. Since problems occur during driving, such after the fact external "expert system" software is not of optimum benefit since it is not available immediately following each and every hammer blow. This detailed inspection during testing can now be accomplished with the new generation of pile testing equipment. The PDA contains ample advice and warnings to the new engineer such that obvious mistakes can be avoided and the testing completed with a high probability that data quality is good and the piles tested are adequate. The PDA displays essential data collection information continuously, while many information requests, warnings or options are presented in windows which appear when appropriate or as requested in response to user commands.

The expert advice can be grouped into several categories as schematically shown in Figure 1.

1. How to acquire data.
2. How to assure that the data is meaningful.
3. How to interpret results of hammer performance, driving stresses and integrity.
4. How to establish an effective installation criteria to assure sufficient capacity with the lowest acceptable safety factor.

3 DATA ACQUISITION

In acquiring data, the program first asks for project specifics, such as pile type or size, length, and material type (concrete, steel, timber). Data is labeled with pile and project names. The transducer serial numbers are given and the PDA then retrieves their calibration from a data file. After attaching transducers, the PDA automatically self balances and then determines if all transducers are working and if the signal conditioning is balanced and calibrated; malfunctioning transducers and/or cables are identified.

Most importantly, data quality must be evaluated because without good data, all testing results are suspect. Data quality is investigated by first comparing proportionality between force and velocity at impact. A quick check is made for signal noise. Data quality can be further checked automatically for consistency between blows and transducer stability.

Another potential problem area is the determination of wave speed in the pile. For steel piles, the wave speed is known to be 5120 meters per second (16,800 ft/sec). However, for concrete or timber piles, the wave speed can vary from about 3000 to 4500 meters per second. Since the force is computed by multiplying the measured strain with the area and modulus of elasticity (which is a function of the wave speed) the correct determination of wave speed is very important. The PDA can automatically assist in determining the proper wave speed directly from the measurements in many cases.

Another important section of the PDA advice system concerns the frequency of data to be saved. The PDA guides the user into reasonable selections depending on the test situation.

4 DATA INTERPRETATION

As noted earlier, stresses or strains for various pile types should be continuously compared with allowable values which are user supplied or calculated from generally accepted rules. In any case, if higher stresses are detected in either compression or tension, then warnings are given. If high bending stresses are noted, then a message is displayed and suggestions for remedial action are made such as improved hammer and pile alignment or cushion replacement.

High stresses are of course the leading cause of pile damage. The program always investigates the data for indications of pile damage. If detected, an indicator of the suspected damage location is prominently displayed; if the magnitude of damage is serious, a message warns the new engineer.

Poorly performing hammer or driving systems will prematurely cause high blow counts at insufficient capacity. If the hammer model is input, the PDA will find the manufacturer's energy rating from a data file. The energy transferred to the pile is compared with the hammer rating and commonly encountered transfer efficiencies for comparable hammer pile combinations at end of drive. The user may also input a minimum energy requirement, perhaps derived from a wave equation analysis modeling the current job situation.

Determination of pile capacity is by far the most difficult task facing the test engineer. For this reason additional guidance is included as an aid to obtaining the most educated solution. The novice user is asked for design load and safety factor and soil type. Many soils exhibit time dependent effects. For example, fine grain soils such as clays commonly have lower strength during driving due to remolding and pore pressure effects and then gain resistance (soil set-up) with wait time after installation at rates generally dependent upon the porosity. In such cases, the pile can then be driven to a lesser capacity and then obtain the full required resistance due to set-up gains. Other soils exhibit strength losses with time such as piles driven into shales or dense silts. With appropriate consideration of pile and soil type, the PDA calculates expected changes which are then included in the required capacity. The PDA system also provides suggestions as to a recommended restrike program depending on soil type. Ultimately all capacity results should be reviewed by the designing geotechnical engineer.

Bearing capacities above or near the structural strength of the pile may be difficult to activate or produce excessive stresses. For example, a steel pipe pile can be driven in a fine grain soil and later achieve the full capacity due to set-up, or be carefully driven through soft soils to hard rock. However, verification of the bearing capacity may be only possible after the pipe has been first filled with concrete to increase its strength above the bearing capacity. If a larger energy (larger hammer, higher drop height, or less cushion) is necessary to verify capacity then such recommendations would be given to the novice.

Piles which experience high rebound due to large quakes are identified. Similarly low apparent capacity (as compared with the impact force) at high blow counts (small set per blow) perhaps due to soils with high damping characteristics can be noted. Such conditions are made known to the novice with the recommendation for further analysis. This avoids misleading "black box" results which the expert would have treated more cautiously.

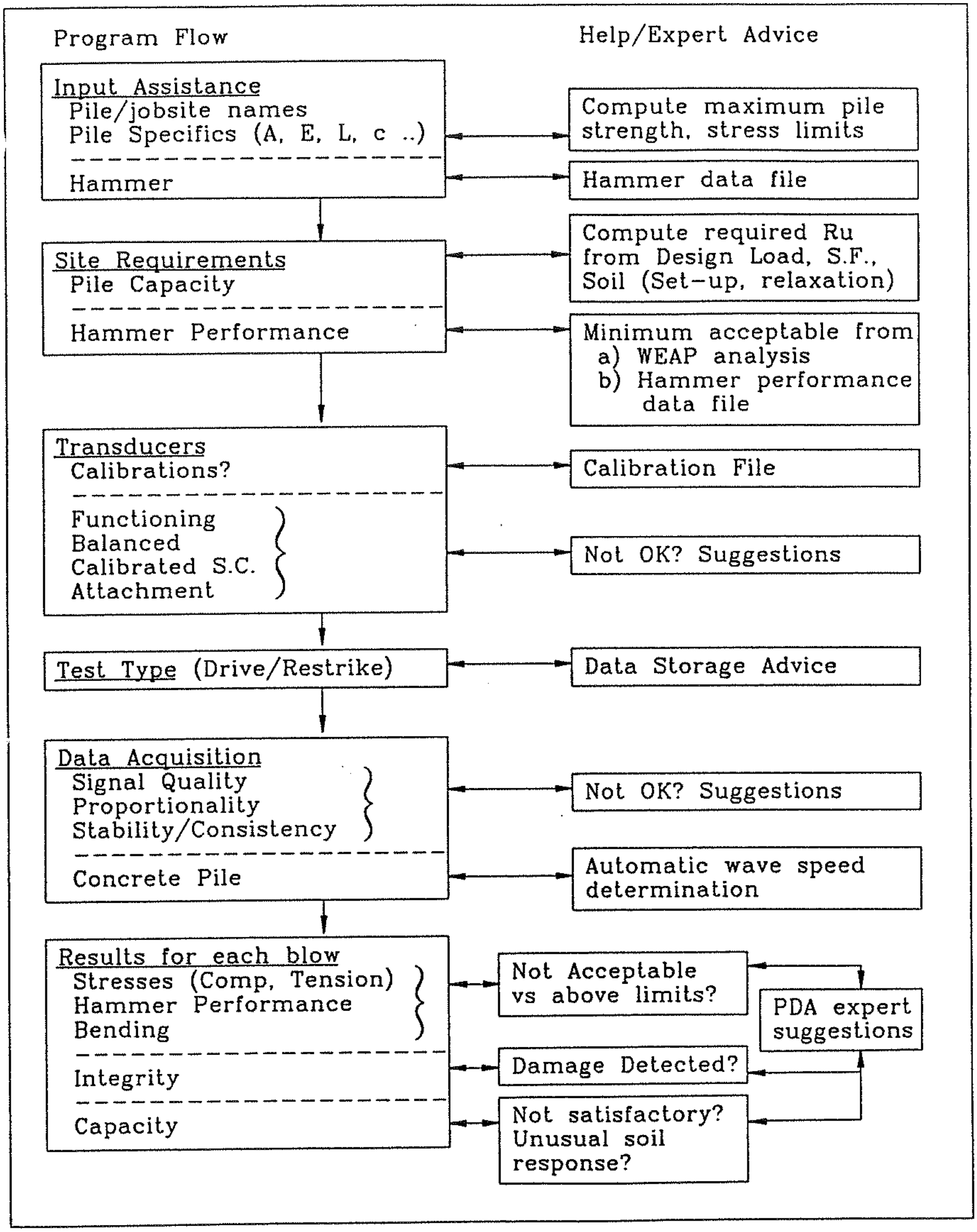

Fig. 1 PDA expert system

5 FURTHER ANALYSIS

The CAPWAP analysis is a rigorous numerical procedure for bearing capacity evaluation (Rausche, Moses, Goble 1972). The pile and soil are modeled in a similar manner as in a wave equation analysis. However, measured pile top quantities eliminate the need to model hammer and driving system. Based on the assumed soil model, the pile response is then calculated and compared with the measured response. Based on differences observed, the soil model is adjusted and the analysis repeated iteratively until the match can no longer be further improved.

Results include the pile's estimated static capacity (and its distribution along shaft and toe) and the pile's dynamic response (damping and stiffness). Finally a static load test simulation can be performed. For properly applied dynamic tests which may include restrikes for fine grained soils, comparisons of predicted results with static load tests are generally very good.

Starting in 1969, this process was done entirely automatically on large main frame computers and results were generally satisfactory for piles of moderate length. Later the process was performed in an interactive mode with the engineer using less powerful computers. During this time, new data occasionally became available from sites where the soil conditions or response were considered unusual and various modifications or extensions to the soil model then became necessary. In general, total capacity results were not overly sensitive to the experience of the engineer, but the match quality and hence reliability of the solution were dependent upon the expertise of the engineer performing the analysis.

The CAPWAP manual contains many "guidelines" which had been formulated by and became second nature to the experienced engineer. Often they are not well understood by the novice. These guidelines have now been included in the current program as suggestions. During the 1980's, more automatic features were added to CAPWAP. For example, the distribution of resistance is quickly calculated from the early portion of the record by CAPWAP. Furthermore, the automatic signal matching process can produce excellent solutions over the entire record which follow all known guidelines. As new challenging situations are encountered, the program is tried on these cases and further experience incorporated into the program as necessary. Now even novice engineers can usually produce reasonable and acceptable solutions by relying only on the program's automatic capability.

6 SUMMARY AND CONCLUSIONS

High strain dynamic pile testing has become a routine procedure with worldwide application. However, the quality and reliability of the collected data and the interpretation of results is dependent upon the experience level of the testing engineer. The most recent testing and analysis software is capable of transferring the experience of the expert to the novice even during the time of testing. Such information transfer should in the future prevent avoidable errors which could result in increased construction cost or time. These new testing tools will assure the client that his money was well spent on testing even if the experts were not on site.

REFERENCES

Rausche, F., Likins, G. and Hussein, M. 1988. Design and testing of pile foundations. Proceedings of the Third International Conference on the Application of Stress Wave Theory to Piles, Ottawa, Canada.

Rausche, F., Moses, F. and Goble, G. G. 1972. Soil resistance predictions from pile dynamics. Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM9, Proc. Paper 9220: 917-937.

Dynamic pile testing and analysis using expert system methods

by

G. Likins, F. Rausche and D. Peterman

Preprint

Proceedings of the Fourth International Conference
on the Application of Stress-Wave Theory to Piles
The Hague, Netherlands
September 21 - 24, 1992