# New Techniques for Reliable Pile Installation and Pile Behavior Design and Analysis

MELVIN ENGLAND

Recent advances in rig-mounted computer-controlled monitoring and recording of pile-installation processes have allowed reliable and high-quality control to be developed. An automatic method for assessing the quality of continuous-flight-auger (CFA) pile-installation data, recorded during construction, is now well proven and most successful as both a management tool and as part of internal quality control of Cementation Piling & Foundations Limited in the United Kingdom. The data contain all the pertinent control parameters that when analyzed can identify important imperfections in the pile construction. The impact of these anomalies on the foundation behavior may then be assessed and any additional pile testing or corrective action prescribed if appropriate. Computers have also found their way into the practice of static load-testing for which they may be employed to monitor the pile-head displacement and the load applied by using electronic sensors. In addition, they can be made to control directly the load applied with regularity and accuracy that are unsurpassed. The quality of data returned from such test equipment has promoted the development of pile-behavioral models that have demonstrated remarkable accuracy in characterizing the measured pile behavior. The advances in this field are significant to soil mechanics generally, not just to pile behavior. The technique for modeling pile behavior under load has been developed into an important foundation-design tool that also allows the introduction of a sensible partial-factoring system that can be applied according to specific design conditions.

Since the development of the microprocessor, information technology has expanded to become a major growth industry. The collection, transmission, and analysis of data have become an everyday activity for almost all enterprises, and the piling and ground-engineering industry is no exception. Cementation Piling & Foundations Limited developed its own computer systems specifically for installation on piling rigs to monitor the processes of pile construction and to automate the labor-intensive task of performing static pile load-tests.

The on-board rig computers provide immediate display of information from various sensors on the rig as an aid to the operator. The data for each pile are stored and can be reproduced in graphical form and inspected from an in-cab printer or office-based computer, in many different formats.

Specific analysis software was developed to check automatically every pile installation and reduce the voluminous data produced by the fleet of rigs. This summarized data can be used as the basis for comprehensive statistical reports. Such analysis supplies a very important method for increasing the control of many aspects of a piling operation and can be very rewarding both technically and financially.

Cementation Piling & Foundations Limited, Maple Cross House, Denham Way, Rickmansworth, Hertfordshire, United Kingdom, WD3 2SW.

The introduction of microprocessors to static load testing provides a cost-effective, safer testing method, with a minimum of on-site staff. In addition, the automation of the load application has revealed significant aspects of soil behavior that hitherto have not been identified clearly. Specific pile behavioral models have been developed to study soil interaction with the pile and have greatly enhanced our understanding of pile behavior and provided the industry with new tools for the interpretation and design of foundation performance.

Time, load, and deformation may be regarded as the three dimensions of soil behavior. These components are interdependent, and if their interaction is not addressed the deformation/time and load/settlement diagrams may suffer distortion. On the other hand, if the load is held truly constant, the displacement/time function becomes hyperbolic for each particular element of the behavior, shaft friction and end bearing, and may be modeled mathematically and extrapolated to infinite time. This modeling in turn allows the long-term (fully drained) deformations to be calculated. These are also accurately represented by hyperbolic functions in terms of load.

## PILE INSTALLATION MONITORING

### Overview

Rapid development of computers over the last decade has enabled small, powerful systems to be used in the cabs of construction equipment. This, together with the advent of the personal computer, has created opportunity to gather and process large amounts of data.

By 1986, continuous-flight-auger (CFA) piling was becoming well established in the United Kingdom, and it was soon realized that, due to the nature of the process, monitoring CFA production was essential. Consequently, a system was developed to incorporate the measurement of concrete flow and concrete pressure as well as auger depth and revolutions. An in-cab printer provided the first major step forward, as the rig operators were required to produce these data for every pile, as unequivocal evidence and assurance of each pile's correct installation. A removable storage module incorporated in the system allows the data to be displayed and reviewed by computer at a head office.

Data retrieval and analysis enabled us to identify some specific innovations that would assist the operators and improve their performance and ability to follow the instrument display.

This commitment to monitor, process, and control site operations led to the Cemcomputer, a completely programmable, robust instrument. It incorporates up-to-date hardware and requires only minor software adaption to suit various applications.

The first operation to benefit from this rig-mounted system was the CFA operation. The instrumentation of the rigs has optimized the technique and minimized its cost without adversely affecting the piles themselves.

Operators' reluctance to be the "spy in the cab" soon disappeared as the value of the instruments became recognized and the benefits, even for the drivers or operators, became apparent.

A similar system is now installed on many pile-driving rigs for precast concrete and wet-shaft piles, to monitor depth, number of blows, and actual set per blow—providing complete driving records for every pile installed automatically.

## CFA Instrumentation

As illustrated in Figure 1, a concrete flow meter and pressure transducer, plus auger-depth and rotation sensors, send their respective measurements to the host display system for processing and storage. The rig operator uses the display for immediate control of the pile installation.

All the displayed information, together with other pertinent data, are stored in a nonvolatile storage module. It is then returned to the head office regularly for analysis by a specifically written software program that polices the data, to ensure that all piles have been constructed correctly. If any anomalous pile installations are detected when the many checks are performed, these are highlighted for inspection by the relevant site engineer or project manager.

The most important aspects of CFA production are to control the auger penetration rate, to make optimum use of the soil/pile friction that can be developed, and to fully and consistently fill the shaft with concrete throughout its length as the auger is withdrawn. Specific attention to the technique employed to initiate the concrete phase of the operation is also needed so that maximum end-bearing results. The data collected are specifically important when installing piles in loose sands or in alternating strata of cohesive and non-cohesive soil.

The amount of data that may accrue from the continuous operation of several instrumented rigs is considerable, and the task of checking every pile record individually prohibitively time consuming and expensive if performed manually.

Policing requirements were developed in consultation with internal piling specialists. The standards contain several different checking levels for the data and produce a printed summary automatically, indicating whether a particular pile has passed or failed each of these criteria—at a rate of approximately 100 piles per min. Should a particular pile fail, the engineering staff can be informed and an assessment is made as to whether any further action is necessary, such as a nondestructive test. The numerous, unexceptional results are documented and filed.

Comprehensive statistical assessments of all the significant aspects of the piling process can be compiled and analyzed, from the number of piles installed by each driver to actual production rates. This additional information provides a satisfactory assessment of the overall operation; it allows areas of poor performance to be identified and highlights options for reducing operating costs.

For instance, statistical analysis may be carried out for specific contracts to reveal actual production rates. Alternatively, analyses can be performed to provide a global picture for all rigs, all contracts, or all drivers and to display actual concrete consumption.

To date, the data base of the CFA operation monitored in this way contains more than 100,000 instrumented pile installations. Histograms are produced automatically for each rig at regular intervals for 36 different parameters. Histograms are employed so that the picture conveyed is not distorted by any atypical data. Therefore, the plots illustrate the general trends instead of the mean values.

Numerous combinations of statistics can be produced. Figure 2 shows the amount of concrete consumed. The dotted line (100 percent) represents the nominal bore of the hole, that is, the calculated volume from the auger diameter. The 125 percent marker indicates the selected target overconsumption that should be achieved.

Figure 3 shows maximum auger travel where the volume of concrete supplied fails to meet the volume of the bore removed by the auger, plus an inset limit. Rig number CM48/2 shows a poor performance for the period, which would warrant investigation.

The habits of a particular crew can be analyzed by examining the start times for each pile. The example shown in Figure 4 illustrates that a crew may have set break times irrespective of other site influences.

## Management Tool

The preceding examples illustrate some of the information that can be presented to a management team to help control overall operation, as the system illustrates clearly the performance, technique, equipment and concrete usage, and efficiency of the overall operation.

Concrete-consumption and boring-rate statistics for each rig allow particular operators to be made aware of any poor results and how they may have incurred additional costs or taken risks that could be avoided. Operators who need further training can be identified.

Poor auger-lifting control together with auger boring rates are major concerns. Potentially these problems have very expensive repercussions; now they are specifically identified. Again, more training can be required and a close watch kept on policing results and data analyses to ensure that appropriate corrective action is taken.

Pile-depth and auger-size analyses also provide a picture of trends in the market. Such information is an important aid when purchasing new equipment, as the type and size of rig most able to meet production demand can be selected.

The automated system's benefits are also seen when estimating for new jobs. Actual production rates are available for particular rigs and crews for different requirements and site conditions. The information can be used to schedule jobs and assign particular rigs or crews in order to achieve specific production rates.

Both CFA and driven-pile instrumentation continue to develop. Additional features are regularly incorporated, for example, mast inclinometers, which can be installed readily on the basic system, reducing set-up time.

## Conclusions

CFA piles nearly always are constructed in the United Kingdom with the benefit of computerized instrumentation and the require-

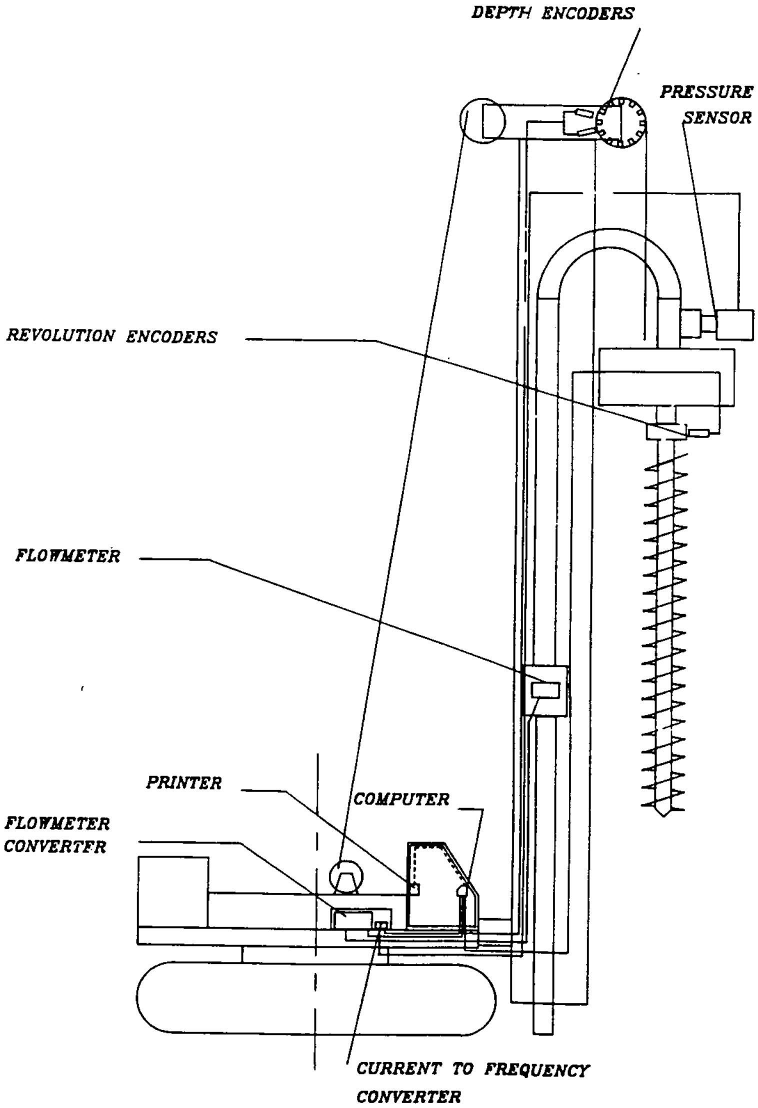


**FIGURE 1 CFA instrumentation system diagram.**

ment of on-site cab printouts for each pile. If an operator's performance cannot be relied on, client representatives on site may be the first to identify operator deficiencies and demand costly interruptions and remedial works during the piling program.

The policing system provides not only a comprehensive quality-control tool but ensures a high level of operator reliability and a standard of excellence for pile installation. The best reason to use such a system is the opportunity it affords to control the operation.

Analysis of the results of concrete consumption and auger lifting reveals some performance deficiencies. Of course, unless such problems can be identified and corrective action taken, potentially defective piles will continue to be installed.

To control the auger-lifting rate on the basis of concrete delivery can be a demanding task for rig operators, yet the ability to withdraw the auger at a steady rate based on concrete flow is critical. Withdrawal of the auger under computer control may soon be a standard requirement unless quality control methods, such as the self-policing system we describe, are used.

## INNOVATIONS IN STATIC LOAD TESTING AND ANALYSIS

### Overview

Although the recorded test results from a static load test may be a factual record of the pile displacement during the test, it is not the pile's definitive, long-term behavior that has been measured. Testing a partially drained pile does not allow for the total creep that may ltaer result.

Every pile, at the time of testing, has a single and unique behavior that can be determined by carefully controlled load-application and pile-displacement monitoring. The method we will describe is based on Terzaghi's definition of ultimate bearing capacity (*1*). Definition of the term is unequivocal and may be expressed mathematically as the asymptote of the load/settlement curve.

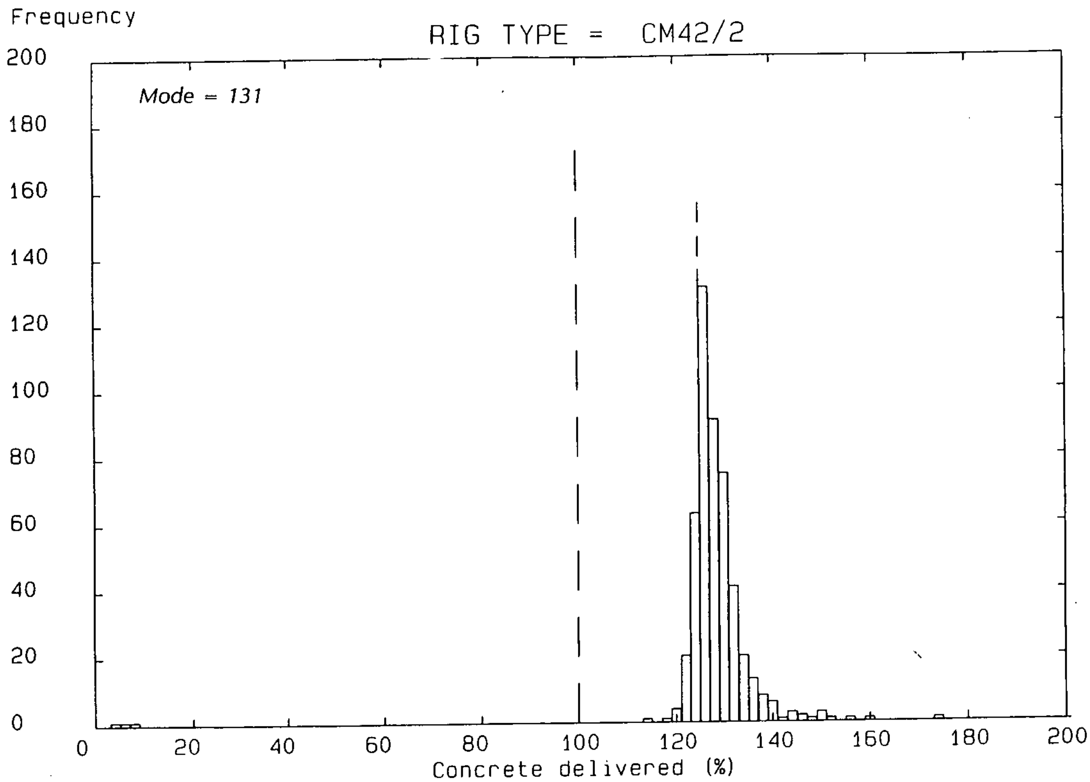


**FIGURE 2 Concrete consumption during installation.**

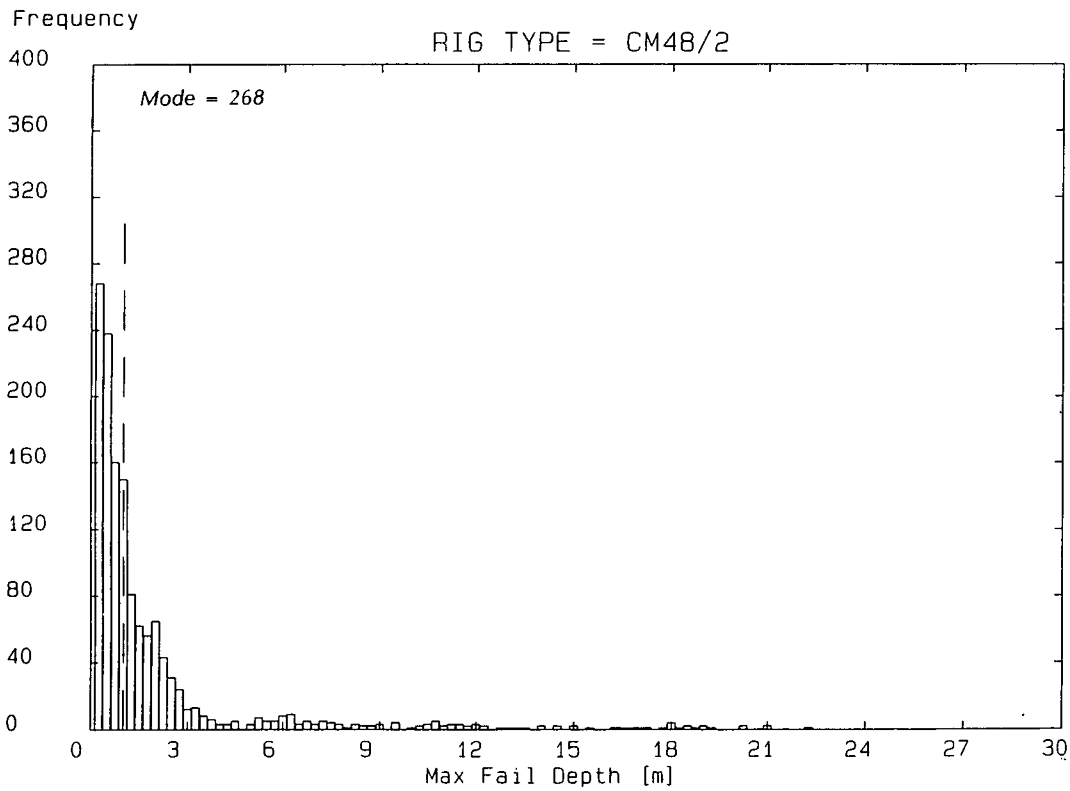


**FIGURE 3 Fail depth.**

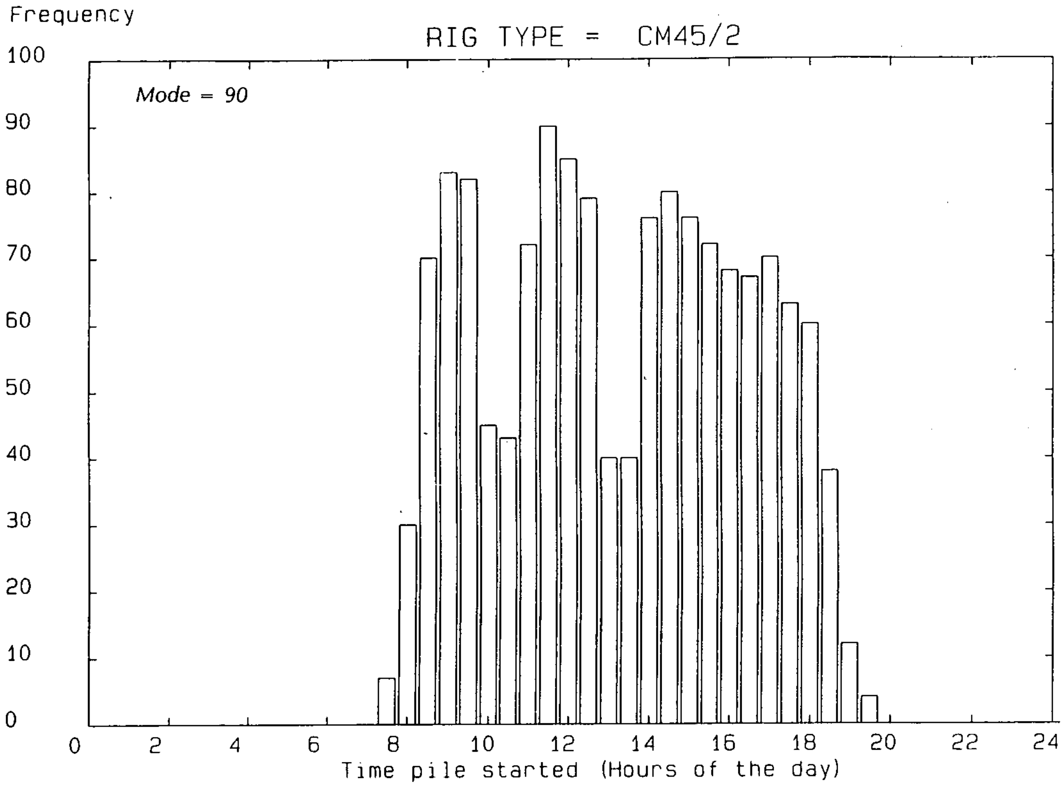


**FIGURE 4 Pile start time.**

Because the behavioral characteristic of a pile under load is unique, interpretation of results becomes necessary to remove the effects of the test method, the sequence in which and the time and the data are taken. Sometimes accurate evaluation of the pile behavior may be impossible.

Although a considerable amount of test data has been recorded in the past, complete analysis of these data has been difficult because, in general, the conditions under which the data were recorded impede analysis.

The test equipment we describe is basically a computer-controlled loading and pile-head displacement measuring system. Analysis involves a time-displacement model that accurately characterizes the development of both end bearing and shaft friction to derive the final settlements under each load. These settlements can then be used to determine the unique load/settlement behavior and the distribution of load between the shaft and base.

The method employs the major elements that control pile behavior. Soil stiffness and strength, together with changes to them in time, are vital to understanding pile performance. The techniques appear to be applicable to most foundation types for which deformation assessment is significant.

## Type of Test

Foundations generally are required to carry axial static loads for a long period of time. During most construction, civil engineers find that the loads applied to the foundation system are gradually increased as work progresses to some final value. The best foundation test that could be employed would be one that replicates the interim and final conditions as closely as possible. However, for practical reasons it is desirable to carry out these tests expeditiously to minimize any external influences and allow construction to progress without interruption.

If a pile test were carried out by long-term application of load, over a range of loads, during which the force applied is constant and the displacement ceases completely at each load stage, then the unique load behavior of the pile would be discovered.

All pile-test methods have to compare with this standard. On the other hand, if the duration of the test is reduced, its effect should be taken into account separately to ensure correct interpretation. For example, the continuous rate of penetration test, which involves pushing the pile into the ground at a constant rate, was not designed to produce the unique pile characteristic. Despite its declared aim, determining the ultimate capacity, a number of authors (*2*) confirm that it generally overestimates pile capacity.

Quick maintained load tests and all impulse or dynamic load-testing systems, present the same problem; they do not reveal unique long-term pile behavior or a pile's ultimate capacity.

The behavior of a correctly constructed pile is controlled by its interaction with surrounding soils. It is fundamental that soil properties are taken into consideration, especially the primary ones governing pile: behavior strength, stiffness, and time.

The time-dependent effects of soil surrounding a pile are generally not addressed in short duration tests, and consequently pile performance is usually overestimated. However, once these effects are correctly assessed, the load/settlement behavior of any pile is unique and independent of the test duration.

Most British engineers use conventional maintained-load testing and it is the basis of the developments we describe here.

### Computer-Controlled Load-Test Equipment

Basic computer-controlled load-test equipment consists of several displacement transducers to monitor the pile head movement with respect to a datum, and electronic load-measuring equipment; all are linked to a data logging system. These are the basic components required for any pile-load test. The microprocessor, which regulates all the functions, also checks the load applied to the pile at intervals of a few seconds and effects any changes required by controlling the hydraulic pressure feeding the loading jack, as illustrated in Figure 5. The equipment has been refined to minimize any external influences that might affect the measured pile behavior.

Some of the immediate advantages of employing this equipment are as follows:

- Simultaneous readings of all transducers are made selectively at intervals of between 2 sec and 10 min.
- Printing and plotting of all data are possible directly from the computer, minimizing clerical effort for producing reports.
- Current readings can be displayed remotely, enhancing the safety aspects of the test. Automatic system control allows for unattended operation if required. This feature is particularly suitable for overnight tests, although a security person may need to be in attendance.
- Data are already compatible with a suite of programs for back analysis, allowing accurate and reliable interpretation of the results and characterisation of the dominant materials that surround the pile.

Whereas the measurement of actual elastic properties of the pile and separate base-load sensors are desirable, these are unnecessary when using the analysis techniques developed; therefore, deployment of costly sensors within the pile can be avoided.

### Models that Characterize Pile Behavior

Any pile/soil modeling technique or mathematical model must:

1. Characterize accurately the pile behavior both in time and under load.
2. Be able to model the displacement/time behavior accurately so that, with sensible load-holding periods, the final settlement at infinite time under a given load can be determined precisely.
3. Follow load/settlement behavior at each and every load stage up to the ultimate load-bearing capacity, determining the maximum settlement at any load.
4. Encompass the nonlinear behavior of the soil, including parameters relating to strength and stiffness along the pile shaft and beneath the pile base as well as related time constants.
5. Be suited for both pile design and back-analysis of test data.
6. Employ typical pile-head displacement data so that they can be used to back analyze commonly available information from well carried out tests, enabling the evidence and validity of the models to be determined.

Mathematical models now exist that are based on hyperbolic functions and fully satisfy the preceding requirements. One component of a model deals with shaft friction development, and a second component with the behavior of the pile base. Analysis has been performed on many hundreds of test results with out-

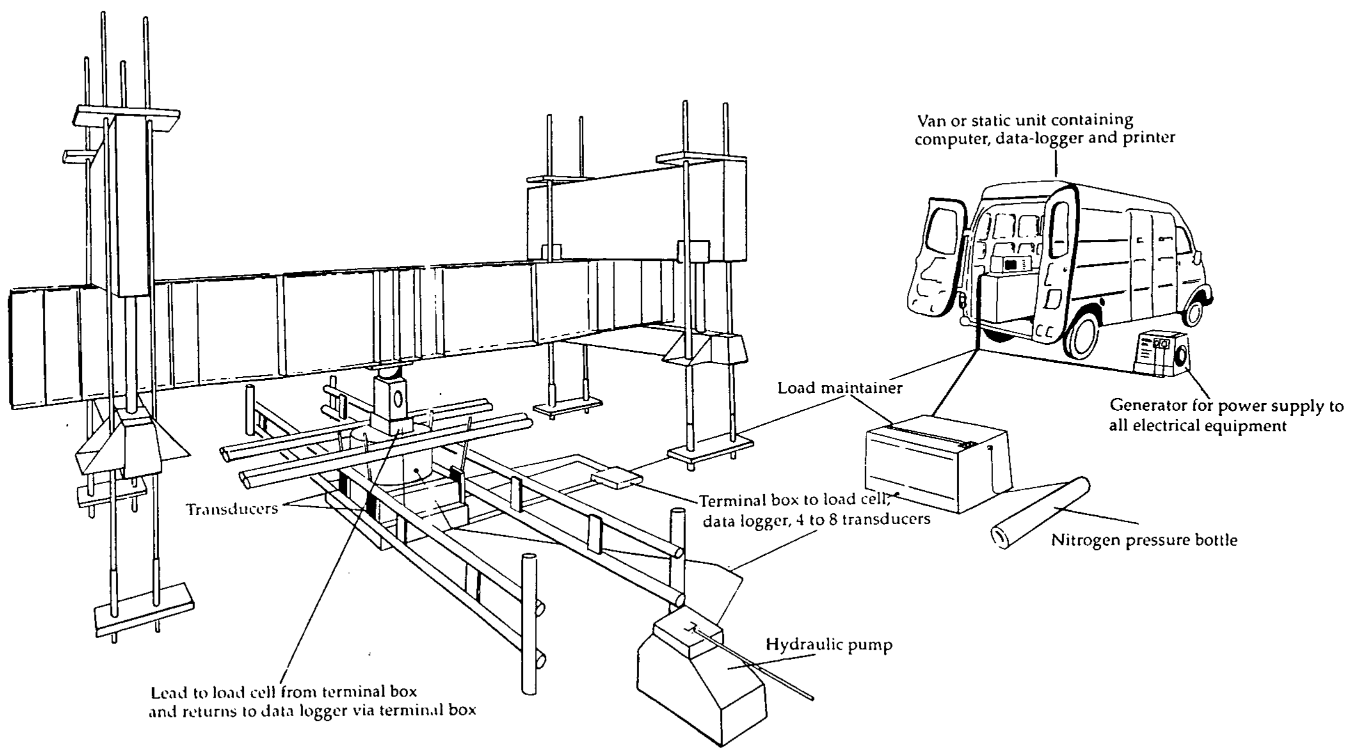


**FIGURE 5 Computer controlled static load test equipment.**

standing success. One of the features of the technique is its simplicity, as it requires only two parameters to fully characterize the displacement of each element under load. Following is the total parameter set required for the complete model of pile behavior.

- *Ds* = equivalent diameter of the pile shaft,
- *Db* = equivalent diameter of the pile base,
- *Us* = ultimate shaft friction load,
- *Ub* = ultimate pile base load,
- *Ws* = asymptote of shaft development at given load,
- *Wb* = asymptote of base development at given load,
- *Lo* = upper length of pile carrying little or no load by friction,
- *Lf* = length of pile transferring load to the soil by friction,
- *Ms* = flexibility factor representing movement of the pile relative to the soil through friction,
- *Eb* = deformation secant modulus for soil beneath the pile base at 25 percent of ultimate stress,
- *Ts* = shaft material time constant to reach 50 percent of final settlement for a given load,
- *Tb* = base material time constant to reach 50 percent of final settlement for a given load,
- *Ec* = Young's modulus of elasticity of the pile material, and
- *Ke* = factor positioning the effective centroid of the friction transfer diagram.

## Assessment of Pile Behavior Against Time

The final pile settlement at a given load is clearly that which would occur at infinite time, when the settlement rate is zero—the asymptote of the displacement/time characteristic. This value is representative of the working condition of the pile.

Until recently, the preferred assessment methods were based on plotting the slope of pile settlement against time on either a semi-logarithmic or time-displacement scale. The second of these techniques, proposed by Chin (*3*), has been the most popular, but it allows only the shaft and base settlements to be accurately distinguished when one or the other is insignificant—a rare occurrence unless each load application were held for durations greater than 6 hrs. In effect, accurate assessments of final pile behavior under a given load were seldom achieved.

Now, an algorithm that accurately characterizes both the base- and shaft-time elements has been developed and is contained within a new computer program, (TIMESET), which can track field results with remarkable accuracy provided sufficient data have been recorded. This algorithm, based on hyperbolic functions, allows the displacement behavior of the element to be calculated for points outside the test data; indeed, it can determine the asymptotic value for any load stage. A feature of this form of time analysis is that normalized time constants can be obtained. This allows the total duration of the test specification to be minimized as the normalized time constant for the base behavior remains unchanged by the different loads applied.

An example of a pile-test result, obtained using high-grade monitoring and control equipment, is illustrated in Figure 6. The application of each load was held constant for durations between 30 min and 6 hr, and the measured load/displacement is plotted as a continuous line. The final settlements calculated for each load are indicated as separate points.

This method of analysis allows unambiguous interpretation and is particularly suited to cases in which the load applied effectively has been maintained constant within each load step.

The development of this method of analysis of displacement/time data only has been possible since the advent of fully computer-controlled static load tests, in which the data recorded are more accurate and considerably more frequent than before, and the load applied can be maintained at a constant rate.

The extrapolation of the displacement/time behavior represents a fully drained condition and is unaffected by any previous loads applied to the pile before the one under consideration. However, if the previously applied load were higher, factors such as plastic deformation and the history of the soil may preclude accurately predicting a compatible load-settlement characteristic.

The displacement/time model illustrates why pile-testing methods of short duration reveal pile behavior in an undrained or partially drained state and offers an explanation for the widely recognized over-prediction of pile performance; it also explains why base performance is so often underestimated.

Figure 7 shows displacement/time data recorded with a computer-controlled testing system for one specific load hold period, together with the results from the analysis. The separate components of the time relationships for the shaft and base are obtained by mathematical optimization and are illustrated as broken lines on the figure. The pile displacement/time model is the sum of the two components *Ws* and *Wb*.

The data points, which are plotted continuously, are virtually indistinguishable from the results obtained from the mathematical model. The quality of modeling has been consistently good for all soils we have analyzed to date. Note that this displacement behavior is apparent in cohesive and non-cohesive materials and is therefore not solely due to excess pore-water pressure dissipation.

## Assessment of Pile Behavior Under Load

The interpretation of pile settlement/load relationships has been a matter of some controversy. Many empirical rules have been developed in this field, perhaps as a result of differing ground conditions in various parts of the world and favored pile types.

One of the best interpretative methods employs a technique developed by Chin (*4*) in which, when settlement is plotted against settlement divided by load, the slope of the latter part of the data is taken as a good indicator of a pile shaft's ultimate capacity.

Two things have militated against Chin's proposed method. First, because its means of plotting implies a single hyperbolic function, the method fails to give a good result in cases where there are really two strong hyperbolic functions present, one for the shaft and one for the base. Second, the method's definition of "ultimate" pile capacity (*5*) does not suit everyone's structural requirements.

Under these conditions, "serviceability" states should be defined. True "ultimate" states cannot be defined arbitrarily or be based on mechanical dimensions of the pile alone. From a mathematical point of view, the correct definition for foundations has to be the asymptote of the settlement/load relationship. From this asymptotic definition most other definitions of "pile failure" can be derived.

The CEMSET method of prediction (*6*) and the program CEMSOLVE, specifically developed for back-analysis of single-pile behavior under load, overcome the limitations encountered with Chin's method by identifying the fundamental hyperbolic functions that characterize the shaft friction and end bearing

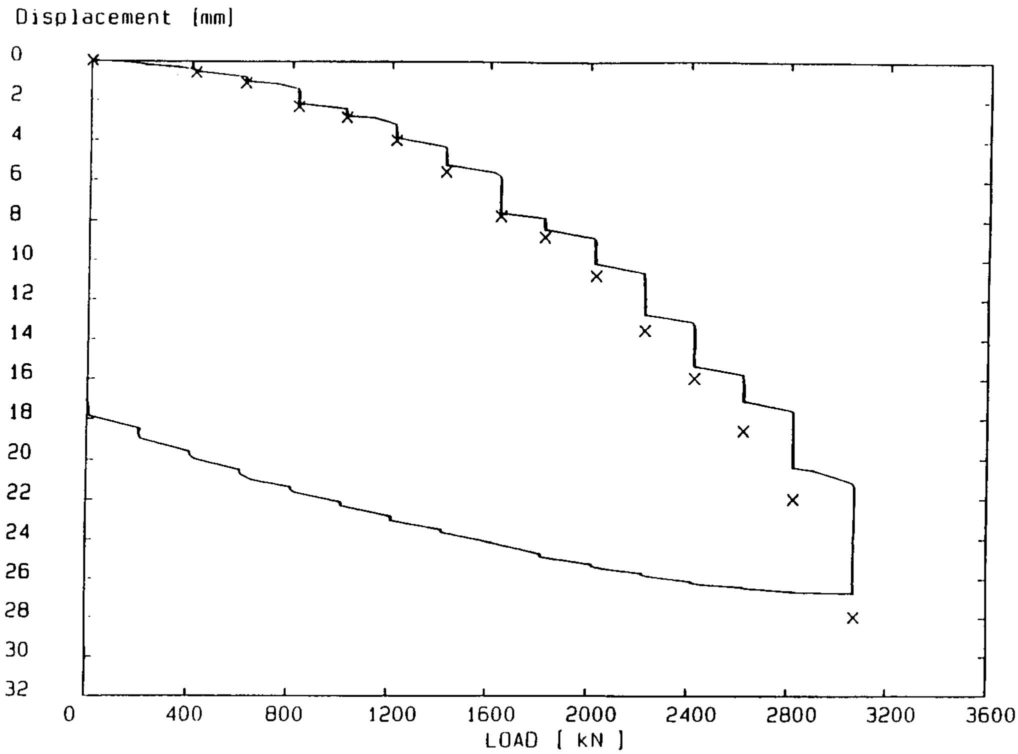


**FIGURE 6 Load/displacement diagram.**

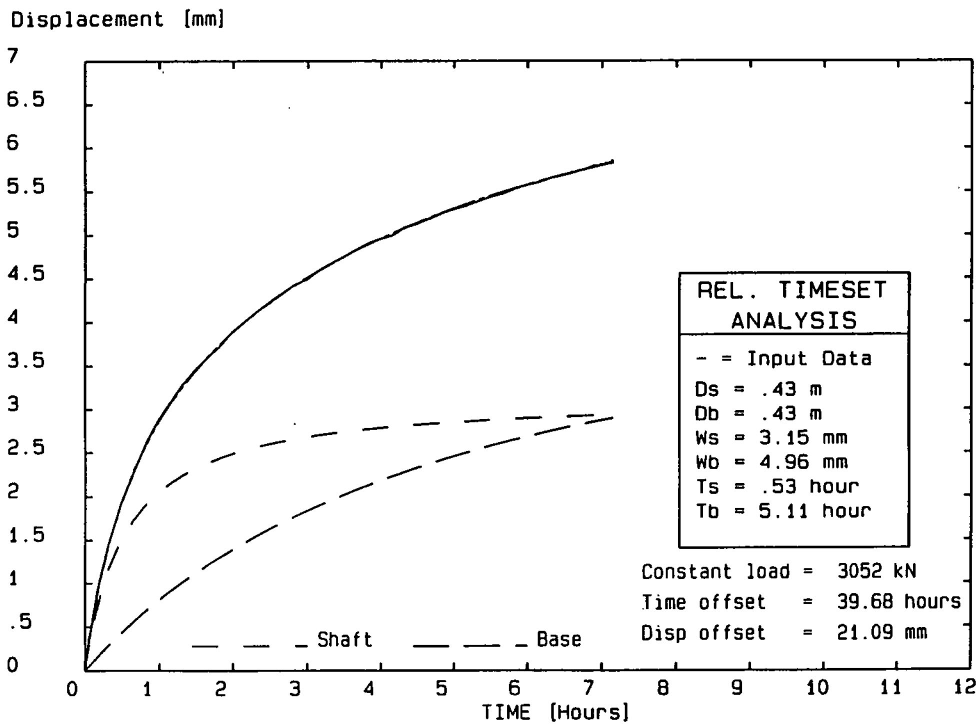


**FIGURE 7 Displacement/time diagram.**

separately. CEMSET and CEMSOLVE define asymptotes for the ultimate capacities and then include a basic, but sensible, elastic shortening model of the pile material.

Illustrated in Figure 8 is the back-analysis of the data shown in Figure 6. The correlation between total settlement at each load and the line generated from the numerical model is excellent and typical of the results that can be obtained from a computer-controlled load test.

The models return a high level of accuracy in the wide range of ground conditions encountered, provided the settlement and applied load have been well recorded and sufficient data are available. Results from static Maintained Load tests are compared with the model solutions in the program CEMSOLVE and show correlation coefficients that are superior to those obtained by earlier forms of analysis. More than 800 pile-load tests have been analyzed in this way with outstanding success. No case has yet been found in which the mathematical models do not represent with high accuracy the measured pile behavior.

Piles in the same ground conditions but of differing diameters have also been studied. The behavior of soils around piles of differing diameters can be readily characterized. For load/settlement analysis, the potential for installing smaller-diameter test piles to confirm the pile design and obtain all the relevant soil parameters is now a reality.

So accurate are the modeling techniques that they have been extended to characterize the behavior of surface foundations as well as piles. Similarly, unloading and reloading can be tracked and modeled.

**Limitations**

If a test pile is not moved sufficiently, few of its pertinent characteristics can be accurately defined. But provided the piles mobilize a significant part of their base capacity and overcome skin friction, back analysis using these models can reveal significant characteristics of pile/soil behavior and the distribution between skin friction and end-bearing capacity, although not their location on the pile. This analysis allows contractors to either confirm that the design is good or diagnose how the design is deficient or over conservative with respect to the pile geometry, type, and installation technique.

Back analysis is not intended to provide an accurate measure of the elastic shortening of a test-pile result. It does however, allow for a first approximation by employing one of several models that allow for differing soil-strength distributions along the pile length. There are better and more suitable methods of determining this parameter, such as extensometers within the pile body.

Any results obtained from a static load test are pertinent to the conditions prevailing when the pile was tested, and any subsequent soil (structural) changes cannot readily be identified. For example, a single isolated pile may be tested, but the installation of additional adjacent piles can significantly affect the original pile's performance. Also, if the mechanical properties of the materials or time characteristics of the pile or soils change—either with time or because of moisture content or general consolidation—these may not be assessed.

Note that the TIMESET model is most suitable for use if the pile test load has been maintained constant and sufficient data

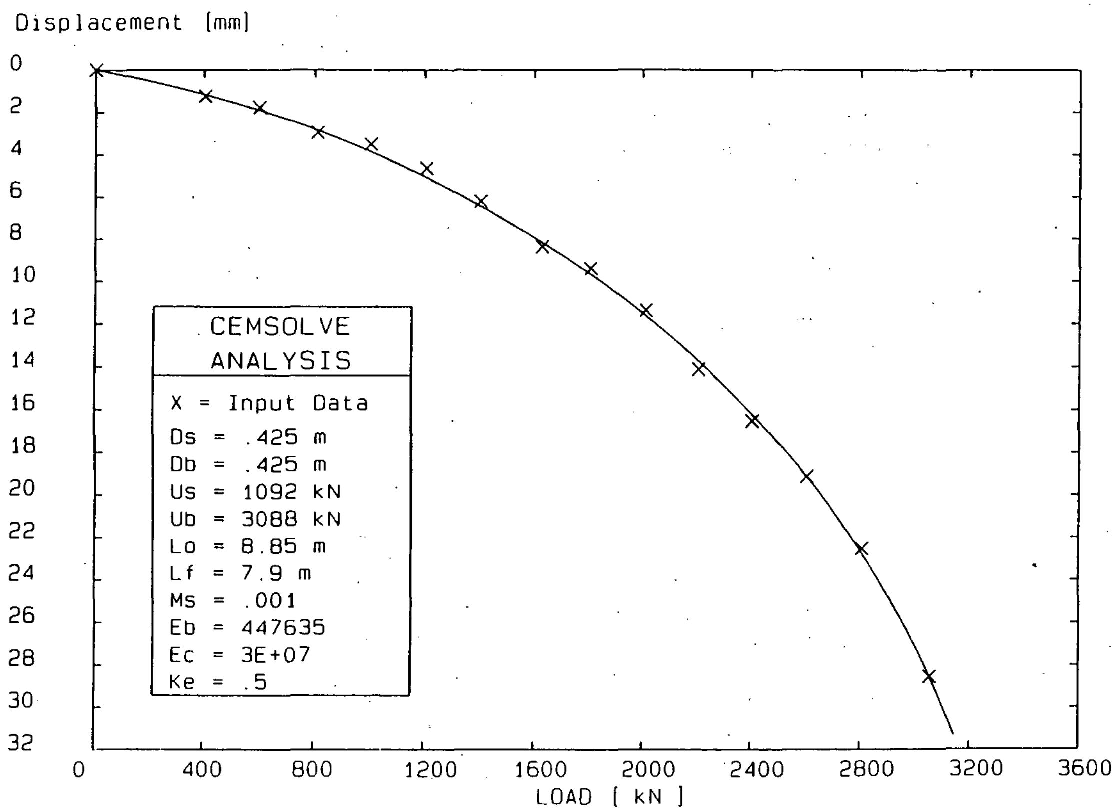


**FIGURE 8 Load/settlement diagram.**

points have been recorded in order to allow the model to determine the best fit to the data mathematically and calculate uniquely the separation of the components. Similarly, the shaft and base characteristics under load must be sufficiently different for their separation to be possible. Fortuitously this is generally the case.

## PILE SETTLEMENT PREDICTION

### Overview

To model the displacement over time, hyperbolic relationships are introduced first, then the functions for characterizing the settlement/load. The origin of this approach was the development of a new design technique based on hyperbolic functions linked to soil parameters, which model the behavior of the end bearing and skin friction individually to allow pile-settlement prediction (*6*).

Proving this design method could be applied in many other scenarios required the development of a behavior-analysis technique and appropriate test equipment. The pile behavioral model employed for design is the one we previously described for the analysis of load-settlement.

Some engineers are keen to link this technique to Chin's method and to recognize that it is just an extension of the single hyperbolic function; others are more interested in noting that the stiffness of soils is now recognized as a significant element-controlling pile-settlement behavior, or that it can be considered an extension of the *p-y* technique for characterizing soil behavior.

In this work it is evident that soil stiffness is defined in relation to its in situ value and linked directly to its ultimate capacity. This strength and stiffness relationship thus provides the framework for characterizing the behavior that may result after preloading or reloading.

Currently most information from soil investigations do not indicate the stiffness values directly; therefore, these need to be established by direct experience. The CEMSOLVE analysis method allows for assessment of the resulting soil parameters after pile installation, thereby allowing the designer to take into account the merits of different pile-installation methods. Certain types of soils exhibit marked boundaries and the limiting values, strength and stiffness, are generally well recognized.

The ability to arrive at pile-reaction parameters on a much broader basis than before means that, for example, bearing-capacity coefficients and frictional factors may be derived from real rather than theoretical considerations and that the use of this system as a design tool is not necessarily limited to a specific range of data, soil conditions, or foundation types.

### Partial Factors

The parameters used in the CEMSET model for pile behavior allow each of the governing components to be assessed individually. The method also takes into account the likely variation of parameters that could occur, depending upon the method of design or interpretation of soil data. The method suitably applies a sensible, partial factoring system (*7*). The parameters can be assessed independently to determine the degree of confidence in the expected results, so it is no longer necessary to address the problem of how to combine factors on parameters that are interdependent, as it is necessary for some design methods.

The factoring method can also be used during back analysis to review the likely worst-case pile behavior at a particular site. The factors used reduce as the system gathers more detailed and more accurate installation records. In some instances, the installation records can be used directly to determine the worst pile or worst soil conditions on a site.

## CONCLUSIONS

The diagnostic value of a single-pile test depends on whether the selected pile is representative of those installed at a particular site. The instrumentation method we have described does provide documented evidence of the quality and reliability of each pile installation.

The pile-behavior analysis system is suitable for use with practically any test specification; it also allows the most effective test specification to be selected. Many engineers now recognize the hyperbolic relationship and realize that there will be one such characteristic for each element of the system being studied.

Test equipment has been developed that maximizes, in a cost-effective way, the information that can be retrieved from a load test and allows the minimum test specification duration to be determined. The new techniques require measurement of only the pile-head displacement under load for complete analysis. No sensors are required within the pile.

The time- and load-settlement modeling performed using the TIMESET and CEMSET/CEMSOLVE algorithms indicates that this method of pile behavior analysis is reliable and superior to any existing method.

Although it is often implicit that specified test methods or testing practices reveal "useful information," it is apparent that the methods described herein extend well beyond normal expectations in this respect, as soil parameters can be deduced from the results.

From a designer's viewpoint, the methods allow the most cost-effective piling system to be identified, to comply with specific settlement requirements, for example. From preliminary test-pile results, the pile parameters can be optimized for both minimum cost and maximum performance. Therefore, its use potentially extends into the field of piling equipment design.

Because unique pile behavior under load can be determined using the method, it is an invaluable tool for design, analysis, and diagnosis. The method is simple to use and greatly improves understanding of pile and soil behavior.

## REFERENCES

1. von Terzaghi, K. *Theoretical Soil Mechanics*, 2nd ed., John Wiley and Sons, Inc., New York, May 1944, p. 118.
2. Twine, D., and W. Grose. *Proc., International Chalk Symposium*, Brighton, Thomas Telford, London, England, Sept. 1989, p. 417.
3. Chin, F. K. The Seepage Theory of Primary and Secondary Consolidation, *Proc., of the 4th Southeast Asian Conference on Soil Engineering*, April 1975, pp. 3/54–3/61.
4. Chin, F. K. The Inverse Slope as a Prediction of Ultimate Bearing Capacity of Piles, *Proc., 3rd Southeast Asian Conference on Soil Engineering*, Hong Kong, 1972, pp. 83–91.
5. Fellinius, B. The Analysis of Results from Routine Pile Tests, *Ground Engineering*, Vol. 6, Sept. 1980, pp. 19–31.
6. Fleming, W. G. K. A New Method of Single Pile Settlement Prediction and Analysis, *Geotechnique*, Vol. 42, No. 3, Sept. 1992, pp. 411–425.
7. Fleming, W. G. K. Limit States and Partial Factors in Foundation Design, *Proc., Institution of Civil Engineers*, London, England, Nov. 1992, pp. 185–191.