Development of Nondestructive Small-Strain Methods for Testing Deep Foundations: A Review

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The first small-strain integrity tests applied to drilled shafts were made in France in 1964. Early tests were limited by the size, slowness, and cost of the available electronics, as well as the variety of geotechnical conditions and construction methods encountered. The various methods and their progress during the past 25 years are reviewed, and their strengths and weaknesses are outlined as an aid to selecting the most appropriate technique for a given set of circumstances. In addition, ideas are proposed for test development and integration in the U.S. market for the near future.

Nearly a quarter of a century has elapsed since the first practical attempts were made using nondestructive test (NDT) methods to assess the quality of piles, drilled shafts, and slurry trench walls after installation.

Discussed here are the origins and development of the techniques commonly used today, as well as how they were influenced by their local engineering environment. Also presented are views of the trends appearing in 1990 in the development of existing and new methods, and improvements in analysis and in the integration of these techniques in contractual matters.

HISTORICAL REVIEW

Progress was made in the 1960s in developing ultrasonic pulse velocity equipment for testing concrete quality. The basic principle is that the velocity of an ultrasonic pulse through concrete is directly proportional to the Young's modulus and density of the concrete (which happen to be interactive variables). Research demonstrated that increasing pulse frequency tended to reduce the effective pulse path length through the concrete.

Nearly all NDT small-strain pile-testing methods in use today apply the principle of the transmission of ultrasonic pulses or acoustic (sonic) waves through pile materials such as concrete, wood, and steel. An exception is nuclear gamma ray transmission, or back scattering, which receives limited application.

Three main techniques form the basis of all the methods developed since 1965: ultrasonic pulse transmission, acoustic wave reflection, and impedance/mobility measurement.

The first two techniques rely on the measurement of wave velocity, whereas the third requires the added measurement of force needed to generate the wave velocity. These methods are described using different names and are categorized respectively by technique: sonic or ultrasonic logging, sonic coring; echo, seismic, sonic or acoustic wave; and vibration, impedance, shock, transient dynamic response, mobility. The three base techniques are referred to here as sonic logging, echo, and impedance.

The development of NDT techniques 25 years ago was influenced in different countries by the nature of the piling market in each country and the limitations of existing electronics technology.

For example, early French workers in this field (*1*,*2*) were influenced by the high proportion of drilled shafts constructed in their country, as opposed to driven precast piles. Paquet (*1*) considered the echo method as a possibility, but suggested that (in 1968) it was not as informative as the impedance test for drilled shafts because of their often irregular profiles.

Briard (*2*) continues this reasoning by describing the application in France of sonic logging and impedance testing only, with limited reference to echo testing.

On the other hand, the prevalence of precast concrete driven piles in Holland meant that the echo tests could be used and developed with greater confidence because of the straight-sided shafts (*3*). Development of this method was emphasized by the Dutch during the 1970s.

The United Kingdom followed the early work in France by applying both sonic logging and impedance testing (*4–9*) to drilled shafts, driven cast-in-place piles, and slurry trench walls. This culminated in an important document for the United Kingdom piling industry in which available NDT methods were described (*10*).

Because of this early work in France, Holland, and the United Kingdom, type specifications began to appear that defined procedures for using these tests as quality control tools for new piling construction, as opposed to "pathological" studies of problems noticed during or after construction.

Currently, more than 95 percent of integrity tests on drilled shafts and piles in the United Kingdom and France are performed for quality control. The number of piles tested in this way is still growing, with present annual test rates in the United Kingdom alone at more than 20,000.

Many developments have occurred in electronics during the last 25 years, with more versatile and compact testing equipment as a result and a corresponding increase in the testing

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rate. A good example is the evolution of impedance testing equipment; the original method using a pile head vibrator (*7*) needed unrealistic pile head preparation, weighed up to 1,000 lb (450 kg), and was powered by generator or main feed electricity. The arrival of small microprocessors 15 years ago enabled Paquet's theory (*1*) of the application of Fast Fourier Transform to a single blow to become feasible, with more compact equipment as a result (*11*).

Present day impedance testing equipment, such as the MIMP 15 from France, weighs as little as 33 lb (15 kg), is battery powered, fully portable, and can store all data on floppy disk (Figure 1). Instead of 10 to 12 piles per day, testing rates in excess of 100 piles per day can be achieved.

Despite these developments in Europe and the availability of various NDT methods in North America, use of NDT by the piling industry in the United States is still at the exploratory/case study stage. Specifying NDT at the design stage is rare in the United States, and it is pertinent to examine the reasons why.

NORTH AMERICAN CONTEXT

North America is a vast area with a diverse piling market. Many pile and drilled shaft construction methods are used, with sizes ranging from 6-in. diameter micropiles to caissons with diameters greater than 10 ft. Regional preferences for different pile types and construction methods are prevalent, often controlled by local soil conditions, engineering experience, and building codes developed over the years in different regional centers.

FIGURE 1 MIMP 15 integrity testing equipment with transducers shown on pile.

As a result, quality control practice often varies slightly from region to region, but usually is based on close visual inspection during the construction phase and on concrete strengths. No general type specifications are approved by regulatory bodies for quality control with the aid of NDT techniques, although such specifications have been included by engineers in specific contracts.

This pragmatic, deductive approach means that nearly all practicing engineers and regulatory bodies remain to be convinced that NDT methods as currently offered will contribute efficiently to the quality control process, without adding a significant extra cost burden. The fact that these methods are now used regularly in Europe for this purpose is not sufficient in itself.

One major reason for this reticence is the lack of Class A studies to prove the claims made by proponents of the different NDT methods. A Class A study would require construction of deep foundations with carefully controlled defects whose position and size are unknown to the testing teams, followed by assessment of the test results and conclusions by an independent authority.

The only real documented Class A study is reported by Levy (*4*) on behalf of the Greater London Council, England. Drilled shafts with controlled defects were built to test the capability of the sonic logging method.

Other full-scale tests have been performed, but none have reached the stringent control requirements of Class A studies. Examples are the construction of 26 drilled shafts near Newcastle, England (*12*), with preformed faults; the nature and position of the defects and pile lengths were known to participants before testing. Similarly, a series of tests organized by FHWA in San Jose (*13*) allowed knowledge of fault-position and pile length to the testing groups.

One other study with careful control was carried out in Ghent, Belgium (*14*), where shafts contained no defects but shaft length was not given to participants before testing.

Confidence in these methods can only be obtained by (a) a good understanding of the principles and the limitations of the method, (b) an ensuing belief that the test results can be used contractually to help in the acceptance or otherwise of pile foundations, and (c) the elimination of as much subjective test interpretation as possible.

NEW TESTING TRENDS

A clear distinction is emerging between tests that use cross-hole techniques, such as sonic logging, and methods that excite the pile at the head only, such as acoustic wave reflection and impedance testing.

The former is considered to be the most suitable for measurement of the concrete integrity of the total length of large diameter drilled shafts because signal damping problems do not occur as they can in the head-excitation methods.

Present-day equipment allows continuous readings to be obtained of the total pile shaft, regardless of length, and shafts up to 90-m (300-ft) long have been tested. Figure 2 shows results from a sound shaft and a defective shaft with an anomaly at 18 m (59 ft.) below shaft head, approximately 8-in.

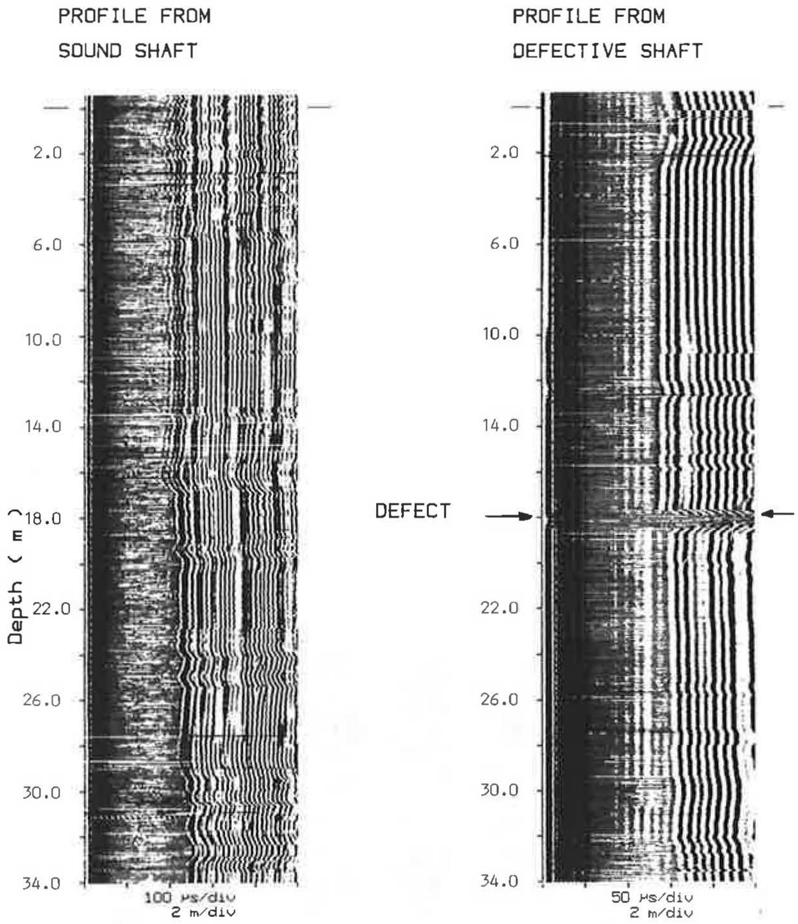

FIGURE 2 Example of sonic logging trace.

(200-mm) thick. This indicates the presence of an inclusion or necking in the pulse path between the two tubes. Bulges outside the normal pile shaft perimeter cannot be detected by this method.

A trend is appearing now for a combination of the two methods when conditions are suitable for acoustic wave reflection and impedance methods. This is made possible by recent developments in data sampling, acquisition, and storage, as well as improved filtering techniques. New equipment can sample both wave reflection and impedance properties of tested shafts.

Measurements of force and velocity response are stored as time base data, with a wide band pass filter and rapid sampling. Resolution of both weak and strong response levels are thus favored.

The time-base response, referred to as a reflectogram, can be amplified exponentially to compensate for damping of the signal toward the shaft base.

The impedance (frequency domain) analysis gives the shaft dynamic stiffness and characteristic mobility, and confirms shaft length. In addition, simulation of the shaft and its surrounding soil can be carried out most efficiently in the frequency domain (*7*). Figure 3 shows a typical reflectogram record with the corresponding real pile data. The reflectogram and the characteristic mobility of the shaft can then be combined to produce a trace referred to as the impedance log (Figure 4).

The output of this analysis is in the form of a vertical section through the shaft, giving a calculated visual representation of the pile shape. The accuracy of this pictorial display is influenced by the signal quality obtained, which in turn is influenced by the quality of the striking surface (hard concrete with no cracking) and operator technique, as well as occasional problems like reinforcement bar "ringing." However, with correct pile head preparation and operator training, the impedance log method can form the basis of a greatly improved shaft-head response method, with the added advantage of a direct visual image of the pile shaft, which is helpful to lay engineers responsible for decisions in pile quality control.

FUTURE DEVELOPMENT

A most important development is understanding the potential of integrity testing as a quality control tool instead of a last resort to assess known problems.

A noticeable effect of integrity testing in Europe has been improvement in construction methods and practices as certain types of problems have been encountered repeatedly. Several large engineering and contracting groups regularly use the methods, not only for in-house quality control, but as research tools to develop more efficient or reliable construction systems.

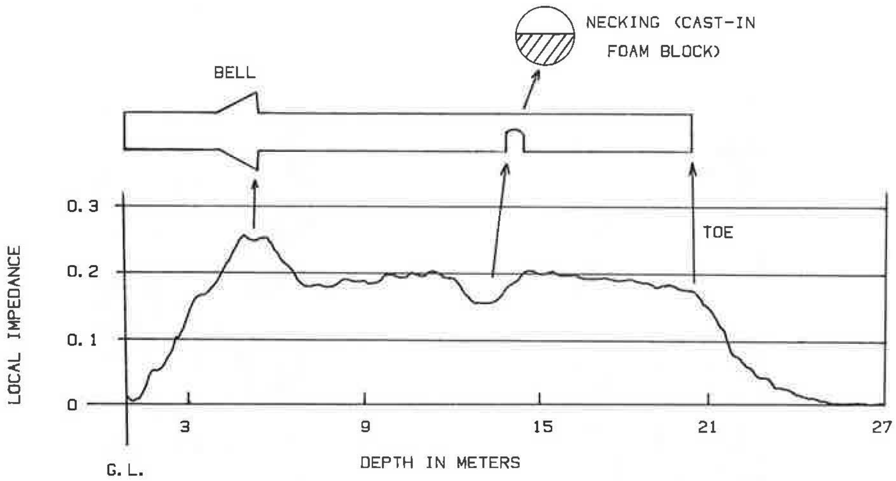

FIGURE 3 Example of reflectogram (for Shaft D, San Jose) and real pile shape.

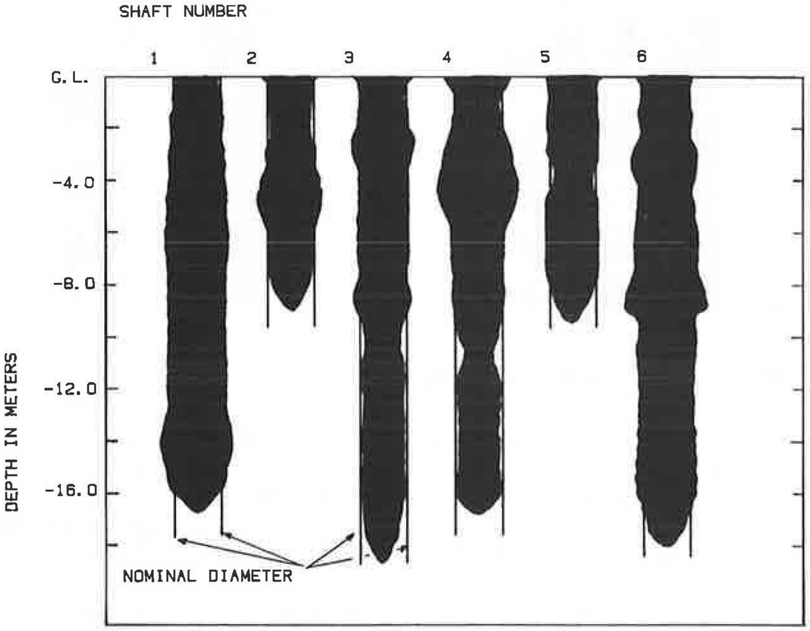

FIGURE 4 Examples of impedance log results.

This is starting to become the case in the United States. However, many engineers and contractors still do not accept the methods as reliable or are awaiting some form of specification from regulatory bodies. They are therefore reluctant to use integrity testing.

For the industry to benefit from the results of integrity testing, it is important that organizations such as FHWA, ASTM, and the Deep Foundations Institute assess and evaluate the methods and endorse those that they find to be effective and reliable or instigate research on those that show promise of fulfilling a quality assurance need.

Impedance Tests

Although the theory of analysis for impedance response curves is well established and confirmed by extensive site experience, there is still room for subjective error, particularly on complex, multiple resonances. Research is continuing in this area, with the ultimate aim of achieving an analysis that will automate the interpretation of data and thus eliminate any subjective error.

The impedance log analysis, previously mentioned, combines the advantages of the impact/echo and impedance methods. Its incorporation into the existing impedance system will greatly simplify automation of the analysis and provide the engineer with a pictorial interpretation of the shaft cross section.

Sonic Logging Tests

The continuous-flight augered (CFA) shaft has gained popularity and acceptance in Europe, particularly since the development of systems for using concrete instead of grout. The main advantages of this method are low cost, rapid construction, and minimum environmental disturbance from noise or vibration. The method has become popular for urban redevelopment, where noise and vibration are key concerns. Two drawbacks of the system, however, are the difficulty of placing reinforcing steel, and the irregular cross section that can result from pumping concrete into soft soils.

Concerns with CFA first centered on the difficulty of placing the reinforcing steel, then later the inconclusive nature of low-strain integrity test results caused by the irregular section. Researchers are looking at improved methods of steel placement, including the incorporation of access tubes for sonic logging, which will be able to confirm the integrity of the main body of the shaft, regardless of external shape or oversize sections.

The development of more comprehensively instrumented construction rigs, use of concrete, larger diameters, and a reliable integrity test will help the CFA method of construction gain wider acceptance in the United States, particularly for sensitive inner-city redevelopment work.

Load Testing

The European experience has been that if large numbers of test results for a given soil type in a particular geographic location are correlated with static load test data, it is possible to derive a correlation factor, and by applying this to dynamic stiffness measurements, predict caisson behavior under load from low-strain integrity test results (*9,15*). These correlations are so well established that in many European cities, engineers will reduce the number of load tests required if integrity test results fall within certain predefined limits. In London, for example, sites tend to be small and congested. It is common for the borough surveyor to accept caissons with no load tests if integrity test results fit within the now established range for caissons in London clay.

As more test data become available for American cities, similar correlations may be established, and the need for expensive, time-consuming load tests be significantly reduced.

In addition, most foundation calculations include a safety factor to allow for certain potential defects. As integrity testing becomes more widespread, designers may be able to reduce safety factors, in the knowledge that all shafts meet a certain minimum standard, thus making more efficient use of time and materials. This has been accepted practice in France for some years now.

Specification

All forms of integrity testing require a certain amount of preplanning or preparation, some much more than others. For the tests to gain wide acceptance and bring maximum benefit to the industry, it is important that the type of test is selected and allowed for at the design stage. This may help avoid the current Dutch Auction situation, in which the job is often let to the lowest bidder regardless of the bidder's actual capability or experience with the method. Integrity testing should be part of the quality assurance program to avoid choosing the wrong method because of economic pressures.

For this to be done effectively, engineers must be aware of the abilities and limitations of each method and decide what kind of integrity test data they will need for complete assurance of a quality product. This choice will be dictated by construction method, soil conditions, access, and type of loading on the finished caisson. Only when armed with this knowledge can the engineer select the appropriate method and avoid having to make judgments based on inconclusive results.

Miniaturization

Several recent attempts have been made to reduce testing costs by using small portable data recorders and taking results away for later analysis. Two significant arguments against this approach are as follows: (a) if the data are invalid, the test either is void or must be repeated, causing both expense and delay; and (b) time is often at a premium in construction programs, and the delay between testing and analysis can be expensive.

Because of these problems, it is important that data are visualized on site so that a qualified operator can not only judge the validity of the result, but also instantly recognize and report any potential problems or defects. Future development will take advantage of miniaturization, battery-operated systems, and improvements in transducer design, but the ability to visualize data on site at the time of testing must be retained.

CONCLUSION

A wealth of experience already exists overseas with non-destructive small-strain test techniques covering more than 26 years of development and application to deep foundations.

By drawing on this experience and setting up more evaluation programs to take account of regional requirements, the foundation construction industry in the United States can capitalize on the latest developments in this field to establish an acceptable set of techniques that will further enhance quality assurance methods for the industry.

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