ECONOMY, BENEFITS AND LIMITATIONS OF NDT FOR AUGERED-CAST-IN-PLACE-PILES

Abstract. Since the early 1970s, more and more test methods have been devised and employed as a check on the geotechnical and structural quality of deep foundation elements. Several of these methods are useful for augered cast-in-place (ACIP) piles. These foundation elements are long and slender, and therefore of particular interest as far as structural integrity. During the last decade electronic logging of the installation process has become an important additional quality assurance tool.

This paper presents a description of several tests, which have frequently been employed for construction monitoring and post-construction testing for bearing capacity and structural integrity. An estimate of their relative costs is also included, an effort that can at best lead to orders of magnitude of cost rather than exact numbers, first because the testing firms charge differently and second because additional cost incurred by the contractor or owner are even more difficult to assess.

The paper also includes a proposal for an installation and testing procedure that considers the possibility of occasionally discovering a defective pile and suggests the quickest and most economical corrective action.

ECONOMY, BENEFITS AND LIMITATIONS OF NDT FOR AUGERED-CAST-IN-PLACE-PILES

INTRODUCTION

The project owner expects a new structure to be sufficiently safe under defined extreme loading conditions. If deep foundations are required, they must have sufficient bearing capacity and should not settle significantly under design loads. Excessive quality demands are expensive and waste resources, while insufficient quality assurance could result in a project whose value may prematurely depreciate.

An optimum is achieved if the cost of the constructed foundation itself plus the cost of quality assurance is a minimum. Modern design methods achieve this premise by lowering the required factor of safety for an increased quality assurance effort. In many countries, design codes already incorporate this approach; they may be developed based on statistical studies or experience values. For example, a recent study in Florida (*1*) for driven piles investigated the influence of the type and number of pile tests on the total cost of a project, considering the required load and resistance factors which are used to limit the risk of failure. In that study, the authors describe the method of statistical development of resistance factors based on the evaluation of information contained in a data bank and adds an interesting cost analysis for a drilled shaft foundation in Florida.

Unfortunately, the total cost of testing is often not just the cost of test preparation, test engineering, testing equipment, data interpretation and report. Additional cost occurs when a problem is discovered, such as a real or perceived defect in the pile. Then, time delays, repairs or replacements and additional tests add greatly to the project's total cost. However, the cost of a foundation failure due to an undetected defective pile is far higher still.

Augered cast-in-place (ACIP) piles are installed by drilling a hole with a continuous flight auger. As the auger is withdrawn, at least as much grout volume should be injected under pressure through its hollow stem as is vacated by the withdrawn auger. Certain special procedures have to be followed on the construction site to achieve a quality product. The construction procedure and the minimum construction requirements are described in Ref. (*2*).

WHY QUALITY ASSURANCE OF ACIP PILES?

ACIP piles can and are constructed with large slenderness ratios [length over diameter, for example 60 ft (18 m) long piles with 12 to 16 inch (300 to 400 mm) diameters are common]. Because of their relatively high unit shaft resistance, the piles can achieve ultimate capacities in the neighborhood of the structural strength of the grout, which is typically only 3 to 4 ksi (20 to 28 MPa). The pile can be rapidly installed and is therefore a very competitive solution with a typical cost of $20 per foot for smaller diameter piles. Reinforcement is inserted into the wet grout after completion of the grouting and therefore is generally limited to a single full length bar or a short small cage. High torque modern machines can install ACIP piles with diameters up to 36 inches with design loads reaching or exceeding 500 tons.

Adequate inspection of the ACIP installation process by only manual or visual methods is difficult or impossible. The contractor is often just trusted to provide a flawless pile. A single mistake while withdrawing the auger, primarily withdrawing the auger too quickly or erratically, can render a pile with a structural flaw resulting in low or no bearing capacity.

Common practice requires that in an initial test program one or more static tests check both the adequacy of pile structure and soil strata and thereby also the installation procedure. The problem with this procedure are the assumptions that the production piles are constructed with as much care as the load test piles and that there is little variation of the geotechnical conditions over the site. It is therefore not a luxury when observations during construction are complemented with post construction pile integrity tests.

MONITORING METHODS FOR ACIP PILES

In the past, the construction foreman monitored the pile installation by counting the number of strokes of the grout pump and controlling the rate of auger withdrawal. This process is fraught with errors: the grout pump may deliver an insufficient amount of grout per pump stroke. The upward speed of the auger may be difficult to control, because coordination between foreman and crane operator is difficult. Volume and depth are important measurements that can improve an error-prone state of the art.

Measurement of grout volume alone may not prevent occasional faulty piles, for example when cavities exist underground. In that case, the grout pressure at the auger bottom would be expected to sharply decrease. Accurate measurement of auger pressure at the auger bottom, however, is difficult under construction site conditions. Grout pressure measurements on top of the auger or at other points along the grout hose are easier to conduct, but, because grout pressure is not a constant but peaks with every pump stroke, pressure measurement taken somewhere between pump and auger bottom may not provide the necessary information.

Auger torque may be a valuable indicator of soil resistance and provide information comparable to blow count of an impact driven pile. It could be a tool for the designer to assure geotechnical pile quality; however, there are no currently accepted methods to calculate design parameters such as skin friction or end bearing from auger torque.

An up-to-date ACIP installation requires as a minimum that auger depth and grout volume are measured. Automated monitoring systems are available (*3*), and additional measurements such as torque or pressure can be easily incorporated in the network system. The measured quantities are numerically and/or graphically displayed in the central processing and recording unit, which is installed in the crane cabin to guide the crane operator during the critical grouting phase. The unit saves the data, which can be printed following completion of the pile. The crane driver has immediate feed-back on the progress of the installation, and can therefore take immediate remedial action should, for example, the display show insufficient grout volume for any incremental depth.

The measurement system can be built into the drill rig by the rig's manufacturer, or it can be subsequently installed as a stand-alone system. Since the electronic measurement systems can be used for many thousands of piles, its initial cost is relatively insignificant. If a special installation is made for a particular project then approximately $1000 per project must be added, and an equal amount should be considered for maintenance per job. Depending on the size of a project and whether or not the system is already installed, the cost per pile may therefore be between $2 and $20 per pile.

Important advantages of this monitoring method can be summarized as follows:

- No construction time is lost due to the monitoring effort.
- If an error is detected, immediate corrective action is possible at little incurred cost.
- Only the necessary grout is installed which avoids waste.
- A permanent, objective log is generated and can become part of the as-built documentation.

Disadvantages are:

- Electronics require careful operation and some maintenance
- Not all possible defects can be eliminated

In summary, since monitoring cannot avoid some pile defects additional integrity tests have to be performed.

TEST METHODS FOR THE INSTALLED ACIP PILES

As discussed, both the geotechnical capacity and the structural quality of the pile must be assured. The two requirements are linked: a pile that has been constructed with a severe localized reduction in cross section will have neither sufficient capacity nor the required structural integrity. Similarly a pile shorter than required would also have a lack of both capacity and integrity. Integrity tests will generally provide little information about bearing capacity while load tests give only marginal information about pile structural integrity. Load tests may, however, be conducted as an acceptance test of a pile with questionable integrity. The following test methods are commonly used for ACIP pile integrity testing:

For integrity, non-destructively:

- Low strain tests
- High strain tests
- Cross Hole Sonic Logging
- Single Hole Sonic Logging

For integrity, destructively:

- Drilling and core drilling

For bearing capacity:

- Static load tests
- Dynamic load tests

Before conducting these tests, a waiting time between installation and testing has to elapse for the concrete to attain at least 75% of the design concrete strength. For load tests the concrete strength should be at least 125% of the desired test load and, for sufficient setup of the material in the pile/soil interface, a waiting time of at least 7 days is recommended.

Low Strain Tests

This test method is probably most commonly employed on ACIP piles. It can be applied to any concrete pile of moderate length to diameter ratio, typically less than 30 (although the method has been successfully applied to piles with L/D ratios of 60 using special low noise electronics with high A/D resolution). The pile top is lightly tapped with a hand held hammer and the ensuing pile top motion is measured by an accelerometer. Reflections of the impact induced stress wave from major changes in pile size or concrete quality are observed in the pile top motion records. Generally, a lack of a major reflection prior to the time of the reflection from the pile toe plus a clear reflection from the pile toe is considered evidence of an acceptable pile.

Advantages of this method include its simplicity and speed (after the pile top has been cleaned and any contaminated grout removed, testing takes less than 5 minutes per pile) and its general applicability (no need for special construction procedures or preparations). The fact that the method only detects major defects can also be considered an advantage.

Disadvantages are (a) only minor defects (say less than 20% of the cross section) can be clearly identified; (b) more than two major pile property changes often lead to complex records with inconclusive results; (c) shrinkage cracks in unreinforced piles generate clear reflections thereby hiding the condition of the lower part of the tested pile; (d) the length to diameter ratio must be below certain limits depending on the ratio of concrete elastic modulus to soil (or rock) modulus or clear reflectioins from the bottom part of the pile are not received. Furthermore, while the test is simple, data interpretation can be difficult and requires experience. Thus, for clients unfamiliar with the method, judging the value of the report can be difficult or impossible. To avoid confusion it is recommended that the test report classifies the piles/records as follows (*4*)

1. Pile has no obvious defects, clear toe signal indicates an intact pile.
2. Pile is clearly defective.
3. Pile has a defect, but the presence of a toe signal suggests that the pile is continuous.
4. Record is complex or has no toe signal and assessment of pile integrity is only possible to a limited depth.

Recognizing the method limitations is important at the time the specifications are being formulated. For example, it could be stipulated that for every uninterpretable record, one additional pile is tested. Alternatively, replacement of an occasional pile with an, at best, questionable record, may be the most economical solution. Corrective action for such a "false negative" may be considered an additional cost of the overall quality assurance program.

Low strain testing costs strongly depend on the number of piles available for testing in one day. Additionally, the proximity to a testing firm is important. Figure 1 shows a trendline of test cost per pile as a function of total number of piles tested and total cost of testing. For example, if only a single pile is tested, then this single test could cost $1,700. The testing cost per pile reduces to $37.50 if 200 piles are tested, conservatively assuming up to 40 piles can be tested in one day. The total testing cost would increase from $1,700 for one pile to $7,500 for 200 test piles, including a professional interpretation of the records. Since data interpretation is more reliable when several piles are tested on the same site, and incremental costs are low, there is no reason why only single piles should be tested.

High-Strain Test

This test is useful for both structural and geotechnical quality assessment. A relatively heavy mass is dropped onto the cushioned pile top and then pile top force and velocity are measured. As for the low strain test, the impact creates a stress wave, which will be reflected from major impedance changes of the pile or at the pile toe. Because of its greater pulse length, the high strain test does not show as good a resolution as the low strain test, and because of its much higher cost, it will rarely be used only as an integrity test. Its value as a combined capacity and integrity test is much greater than a mere integrity test and is therefore discussed below in more detail.

Cross Hole Sonic Logging

Cross Hole Sonic Logging (CSL), originally developed for drilled shaft quality assurance testing, requires that two or more tubes are attached to the reinforcement cage and installed in the pile. The inspection tubes are usually 1.5 to 2 inches (38 to 50 mm) in diameter and water filled. A transmitter and a receiver are simultaneously lowered in the pile into separate tubes and then again simultaneously raised as sonic pulses are emitted and received at regular time or distance intervals. If a strong signal is received at an early time corresponding to a high stress wave speed in the concrete, then it can be concluded that the concrete between the tubes is of good quality. However, if the signal is delayed or very weak then a defect is present.

Figure 2 shows a cross-hole record obtained on a 24 inch (600 mm) diameter pile in the form of the classical waterfall diagram (i.e. signal versus time, horizontal, and depth, vertical, on the right hand side of the figure). Evaluated for wave speed (left curve) and relative signal strength (center curve) by a Cross Hole Analyzer (CHA), clear variations in wave speed are apparent. There was no reinforcement cage and the cross-hole tubes were therefore unsupported over most of their length. Because the wave speed variations are gradual, they probably should be attributed to non-parallel tubes in the pile rather than a defect in the pile. Obviously, difficulties with perfectly aligning the test tubes make the interpretation of the CSL results difficult. This would be particularly true for smaller ACIP pile diameters, where small changes in tube distance can cause large changes in the apparent wave speed. Attaching the tubes to a stable reinforcement cage would reduce these problems. For CSL testing it is generally agreed that areas smaller than 15% of the pile cross section cannot be detected. On the other hand, the vertical resolution of the test is typically 1 to 2 inches (25 to 50 mm). Cost of CSL/SHSL testing is again heavily dependent on the number of tests that can be performed in one day.

A single CSL scan of up to 100 ft (30 m) depth can be performed in 15 minutes. Thus, if only one or two tubes are available for testing, roughly 30 piles can be tested in one day by CSL at a cost of about $70 per pile. For three tubes (piles of more than 24 inch or 600 mm diameter), the productivity decreases to 10 piles per day and the cost increases to roughly $200 per pile. While these tests are still infrequently used for ACIP piles, it is expected that their popularity will increase as more ACIP piles of diameters in excess of 24 inches (600 mm) are constructed, particularly if full length reinforcement cages are installed so that parallel, full length access tubes can be more easily installed.

Single Hole Sonic Logging

For small diameter piles only single access tubes can be reasonably installed. Then the transmitter and receiver are lowered in the same tube at a fixed separation distance (e.g. 20 inches or 500 mm). The signal received from this single hole sonic logging (SHSL) scans the concrete surrounding the single tube. Unfortunately, it is currently not clear how much of the concrete cross section is involved in the test. Furthermore, the concrete at or near the pile toe is not well tested. With only one tube installed and one scan per pile, the cost of this test is less than or equal a two-tube CSL test.

Drilling and Core Drilling

If an integrity test suggests that a defect exists, either drilling into the concrete or core drilling and extracting a sample is sometimes used to confirm the defect or remove any doubts about the pile integrity. A combination of both methods is also possible. Down-hole percussion drilling can be very rapid and generally half as expensive as core drilling and may yield some concrete quality information by the rate of drilling progress. Bore holes also allow for concrete quality inspection by video camera (concretoscopy) and may be used for repairs (washing out of inclusions, insertion and grouting of high strength reinforcement bars.) Combining drilling to a suspected defect and then core drilling the defect zone may be a more economical alternative to pure core drilling.

Unfortunately, for small diameter piles it is nearly impossible to guarantee that the bore hole remains within the cross section of the pile and, for a large pile, it is not assured that the hole bore will actually penetrate through a zone of low quality concrete that affects only a portion of the cross section.

The cost of core drilling is typically in the range of $30 to $50 per foot ($100 to $165 per meter) for a 4-inch (100 mm) diameter bore hole. For a typical 60 ft (18 m) pile, coring would therefore roughly cost $1800 to $3000 and for percussion drilling one half of that cost may be anticipated. However, site accessibility and quantity of drilling will strongly affect cost.

Static Load Tests

Static testing requires reaction piles, anchors or a dead load. Alternatively, an Osterberg test could be performed, which requires a hydraulic jack at the bottom of the pile so that shaft resistance provides the reaction for the end bearing, thereby testing both resistance components. Since it is not a simple task to install an O-Cell in an ACIP pile, traditional top load is more frequently done. Conducted as quick tests lasting at most a few hours or as maintained load tests lasting several days, these tests provide little information about consolidation or creep related settlement effects. Obviously, unexpectedly low capacities may either be caused by structural or geotechnical deficiencies. A static test would generally not indicate the cause for pile failure, since for ACIP piles, instrumentation along the pile length is difficult to install and resistance distribution is, therefore, usually not determined. Because of their high cost, which may be estimated at $50 per ton, load tests are almost never conducted to investigate the quality of suspect production piles. On the other hand, static tests are best suited to assess the quality of the bearing layer(s) for load transfer. If an unexpectedly low failure occurs, additional NDT methods are needed to assess the true reason for that failure, and it is therefore reasonable to specify such tests as part of the load test program.

Dynamic Load Tests

Using the measurements of the High Strain Method and subjecting it to a signal matching analysis, soil resistance parameters and a simulated static test result can be obtained. This result represents the soil resistance mobilized during the test. The recommended drop weight should be 1% to 2% of the desired test load, depending on soil type. The higher drop weights are necessary in cases of end bearing piles in granular materials. The 1% drop weight may be sufficient when the piles are socketed into rock, since rock requires little movement, and therefore energy, for resistance activation. If the drop weight is not sufficiently heavy or if it is not dropped from a sufficient height, then only a proof load will be established. In general, however, it is not desirable to use very high drop heights on ACIP piles with a low degree of reinforcement because of the associated high stresses. To activate higher capacities, heavier ram weights rather than higher drop heights should be used. If the upper two diameters of the pile are cast into a steel shell, pile top damage during testing will be prevented and the high strain testing instrumentation will be quicker and easier to install. The cost of the dynamic load test is heavily dependent on the number of tests performed at a site and, of course, on the load to be mobilized, as shown by the estimated trend lines in Figure 3.

EXAMPLE: MONITORING, INTEGRITY AND LOAD TESTING ON THE SAME PILE

As an example of the value of installation recording, static load test and low strain integrity test, consider the following case of an ACIP installation. Installation recordings were performed during installation of the load test pile; however, the technology was "imposed" on the construction personnel. The pile was 18 inches (450 mm) in diameter, 44 ft (13.5 m) long and was augered into medium dense to dense sand. The load test pile suddenly failed structurally under a relatively low load (Figure 4) corresponding to a compressive stress on the cross section of only 1.9 ksi (13 MPa). The PIT result (Figure 5), obtained after the failure, indicated a defect in the lower third of the pile (28 ft or 9.5 m). Belatedly investigating the automated monitoring record (Figure 6) indeed revealed a greatly reduced grout volume between 20 and 28 ft depth.

In this example, the static test cost was probably in the neighborhood of $10,000, the PIT test, because it was only done on the preliminary load test pile, cost approximately $1,200 while the automated monitoring was nearly free for that pile (it had to be used on all other piles of that foundation). In this case, the monitoring would have been the most valuable method, had its results been utilized by the contractor. Convinced by the static test failure, the contractor relied on the automated monitoring equipment for installation guidance for subsequent ACIP piles installed at this site.

PROPOSED TESTING PROCEDURE

For a reliably installed ACIP foundation, the following proposed procedure takes advantage of the available test methods and assures both structural and geotechnical quality and avoids unnecessary costs due to pile and/or testing failures.

1. Enough soil borings should be drilled, and static design methods should be employed to clearly assess site variability and available pile bearing capacity.
2. For geotechnical suitability, prior to production ACIP pile installation, four piles, or 1% of the production piles (whichever is greater), reasonably distributed over the site, shall be constructed. At least one of these load test piles shall be subjected to both static and dynamic load testing to establish a correlation. The remaining piles are subjected only to dynamic load testing. These piles must be automatically monitored during construction and their integrity must be tested prior to performing the load tests. For piles with modest length-to-diameter ratios (say less than 30) the low strain test is adequate, but can also be tried on other piles. For piles with less than 24 inches (600 mm) diameter the SHSL may be used and for larger piles CSL is recommended. The

initial integrity tests will not only check the pile quality, but also the adequacy of the proposed integrity tests for production pile checking.

3. Piles with questionable integrity shall not be statically tested, for the static test must clearly identify the geotechnical capabilities of the site conditions, while dynamic load tests can be used to check both bearing capacity and integrity.

4. If load testing indicates that bearing capacities are insufficient, the design can be changed by increasing the number of piles (each with lower capacities than planned in step 1) or by increasing the pile properties (length and/or diameter). Similarly, adjustments of the design parameters may reasonably be made if excessive capacities are available (reducing the number of piles or decreasing the pile length or diameter).

5. If the test piles meet the load requirements, production piling can be started with depths established by the static and dynamic test program.

6. During production piling, all piles shall be automatically monitored for grout volume versus depth. Any pile that does not meet the relative incremental volume requirements established in the pile test program, shall either be immediately redrilled or replaced.

7. Spot checking of 20% of piles shall be done by the integrity test method that has been qualified during the initial test program. All piles with questionable installation logs shall be among the piles to be tested.

8. If the integrity test of a pile does not allow for a clear interpretation, then another nearby pile shall be tested instead. If an integrity test indicates a clearly defective pile, the following action may be chosen:

i. Replace pile and repeat the integrity test on the replacement pile;

ii. Drill and/or core drill pile (if feasible), inspect and repair or replace;

iii. Dynamically load test pile; if test result is satisfactory after careful structural reanalysis, no further action is needed; if not, replace the pile.

iv. If the defect is near the pile top, excavate and repair the problem.

The above testing procedure should qualify for a 10 to 20% safety factor reduction. Note that this proposal requires that the pile installation equipment be available until satisfactory quality has been demonstrated for all test piles.

SUMMARY

Deep foundations have a significant impact on the total cost of a structure and their quality is essential for maintaining the long term value of a structure. ACIP foundations can be a cost effective solution, but their installation requires experience and also accurate grout volume versus depth measurements.

Additional quality assurance testing can be minimized if automatic monitoring of installed grout versus depth is performed. This is also the lowest cost method to improve the quality assurance for ACIP piles. However, even these installation measurements cannot prevent occasional defects and additional integrity and load testing methods are therefore needed.

The cost of the necessary testing is lowest if the specifications are clear as to how many piles to test, and what measures are to be taken when defects are detected or when the tests are inconclusive. Having to test a few piles when unplanned questions arise is nearly as expensive as conducting a fairly comprehensive, planned testing program.

In many instances the immediate replacement of suspect piles would generate the lowest expense. In cases where the defect is near the pile top, excavation and repair of the defect is cost effective. Core drilling, if possible, is another alternative allowing for both inspection and repair of a defective pile; however, this is not always possible, sometimes because access may be difficult or, at other times, when the pile diameter is too small or the pile length too great. Finally, dynamic load testing provides a means of checking both the structural and the geotechnical quality of any suspect piles.

It was shown that both ACIP installation procedures and testing methods have limitations. For that reason, the test procedures should allow for initial checking of the adequacy of the methods and point out ways to proceed in the case of inconclusive results. Both integrity and load testing methods, described in this paper, must be performed and reported by qualified and experienced personnel.

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List of Figures:

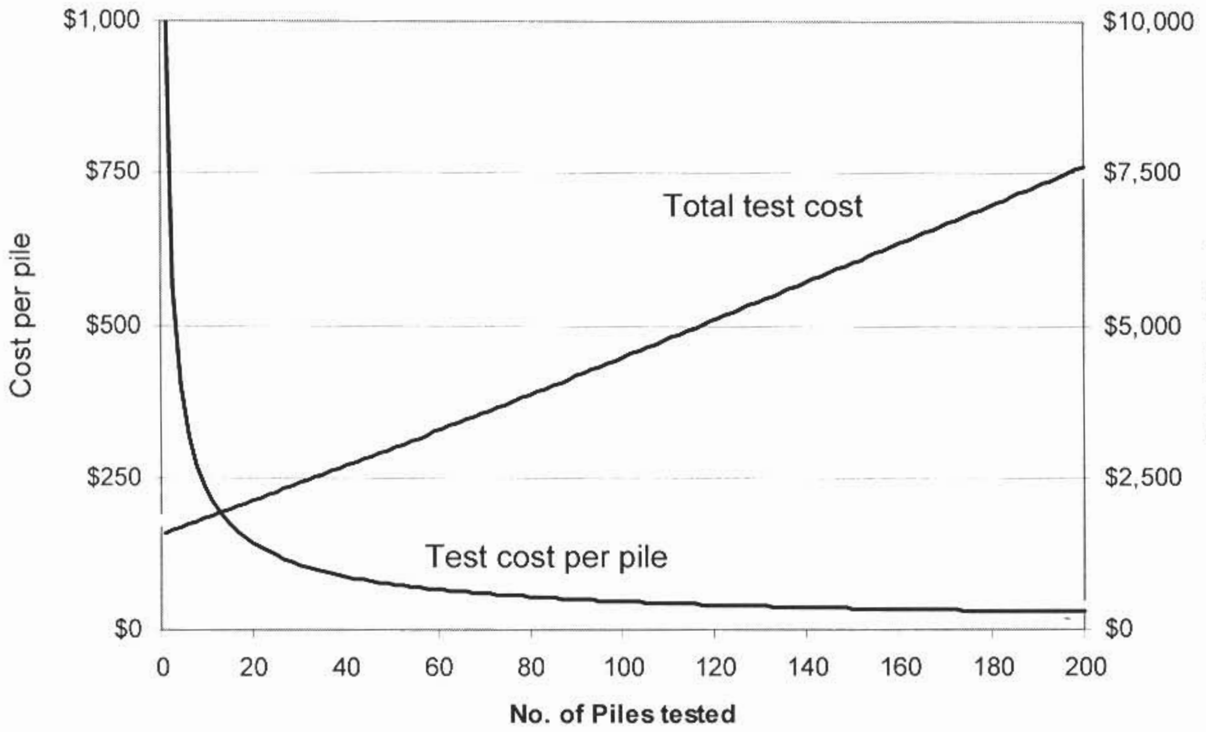

FIGURE 1 Cost of low strain testing.

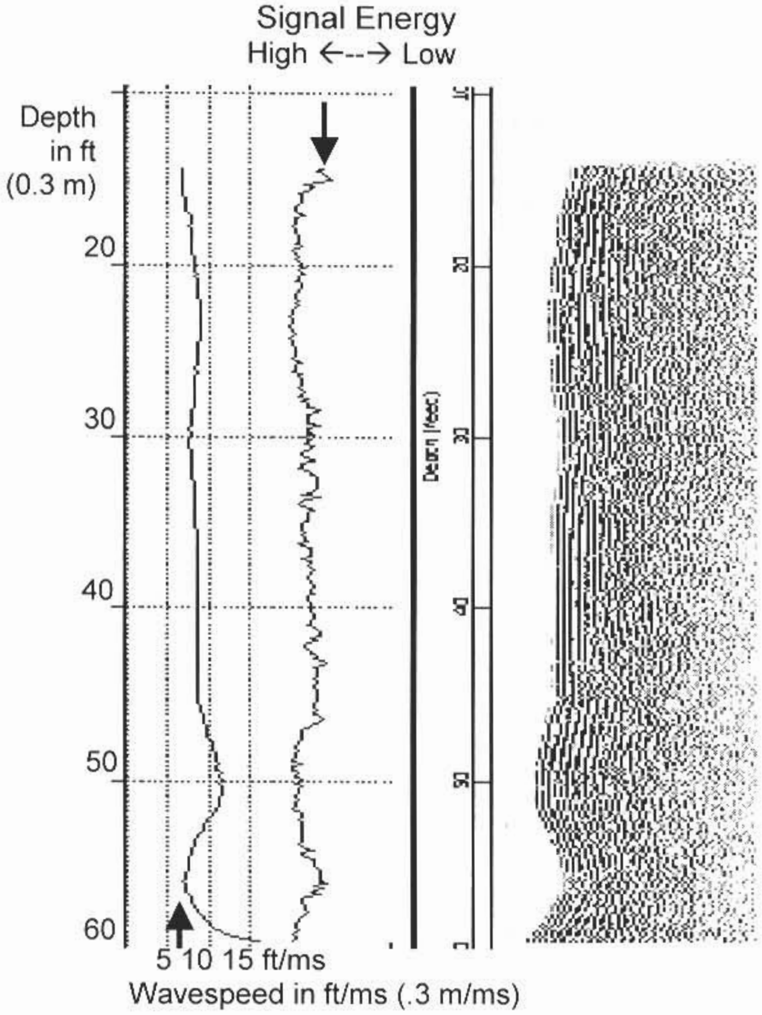

FIGURE 2 Cross Hole Sonic Logging record from 24 inch dia. ACIP pile.

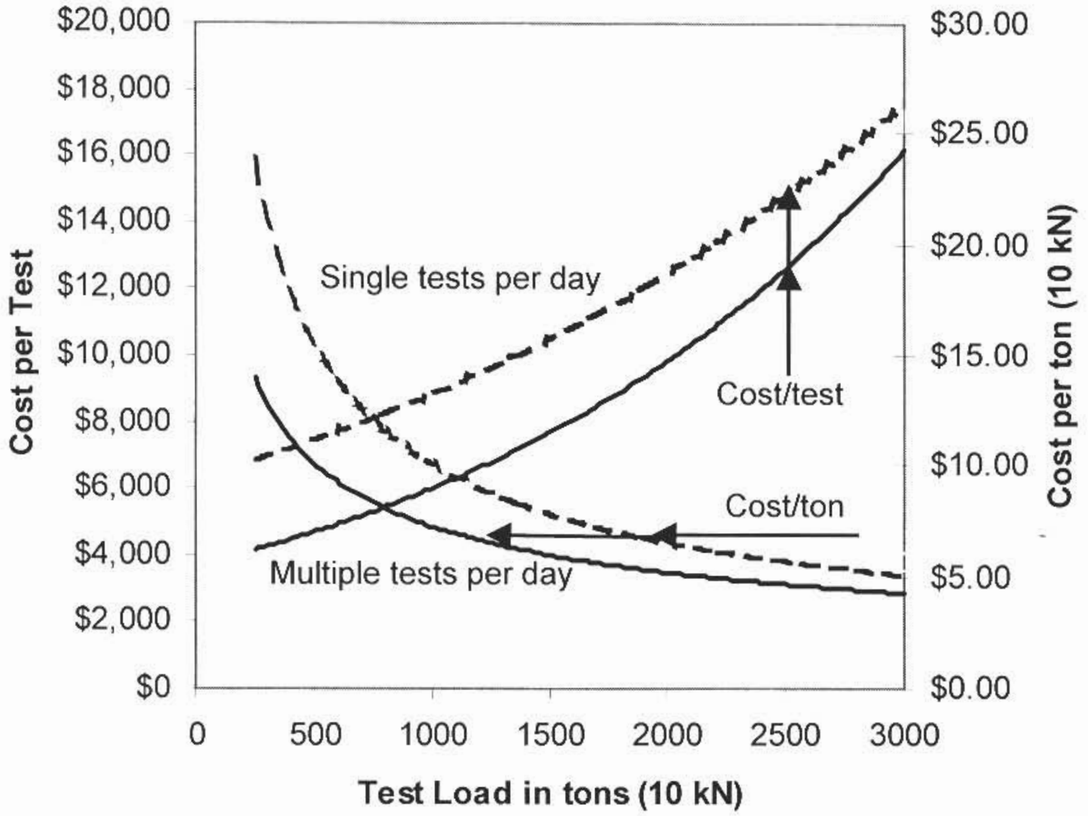

FIGURE 3 Cost of dynamic load testing.

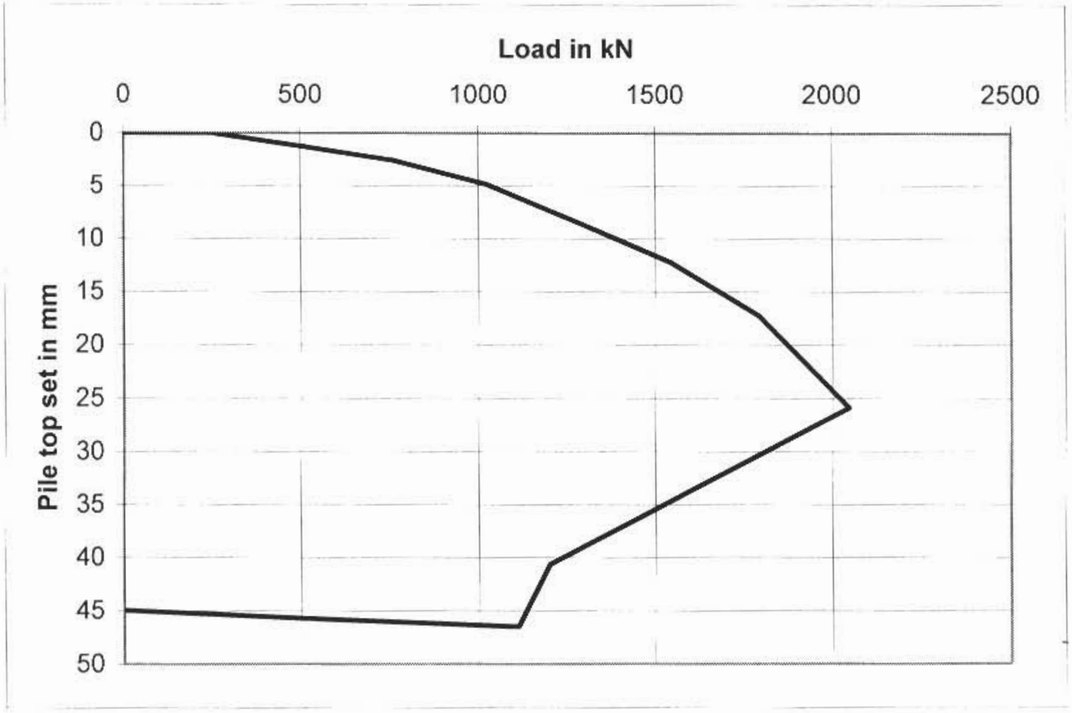

FIGURE 4 Load-settlement curve.

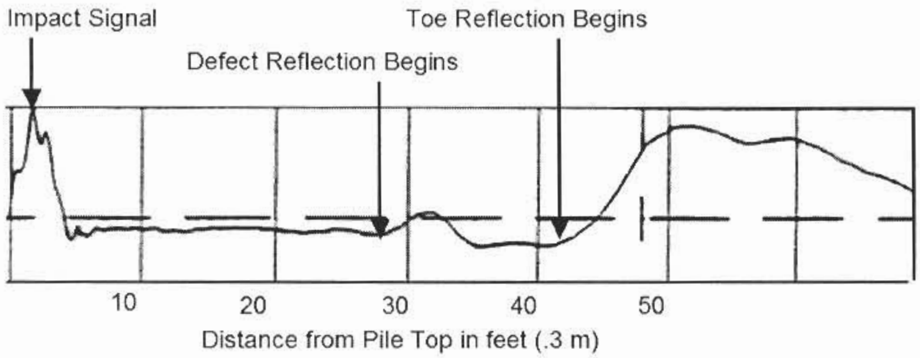

FIGURE 5 PIT results showing an impedance reduction below 28 ft (8.5 m) depth.

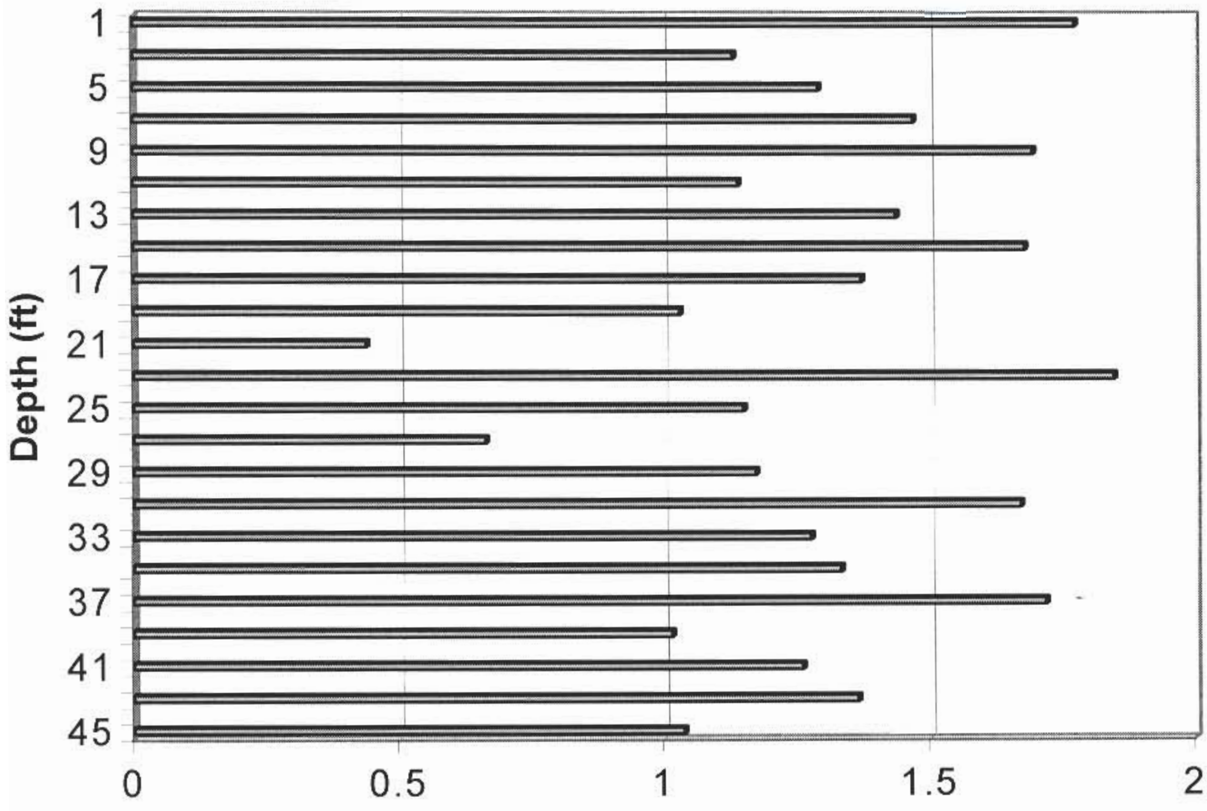

FIGURE 6 Results from Installation Recorder: measured/nominal grout volume.