Formalized Procedure for Quality Assessment of Cast-In-Place Shafts Using Sonic Pulse Echo Methods

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Cast-in-place concrete piles are produced by drilling holes in the ground and filling them with concrete. The constructed shape and structural integrity of this pile type is dependent on concrete quality, subsurface conditions, and workmanship. Many engineers are willing to consider this type of piling but require adequate inspection and shaft integrity verification. Dynamic low-strain testing and analysis by the Sonic Pulse Echo Method with equipment such as the Pile Integrity Tester provide a quick and inexpensive means to assess the integrity of all types of concrete piles (where modulus is much higher than surrounding soil) by measuring top motion (and force) under the impact of a small hand-held hammer and then applying one-dimensional wave propagation theories. Data interpretation can be either a simple visual inspection of the dynamic pile records, a rigorous numerical analysis, or a technique that generates an "impedance profile" as a function of length. Testing and data evaluation require experience and engineering judgment. The principles, application, and limitations of the low-strain integrity testing method are presented, and a step-by-step record evaluation and interpretation procedure is proposed. Finally, the value of the record for the quality-assurance process of pile foundations is assessed.

The nondestructive low-strain method of concrete pile testing has become a routine quality-assurance test in several countries. For example, the Institution of Civil Engineers in the United Kingdom has issued a specification for this test type (*1*). Similarly, in Germany the test is recognized through a "recommendation for dynamic pile tests" (*2*). Apparently, engineers in Holland, Belgium, and Austria also routinely use this test type in response to generally mandated quality-assurance requirements. In the United States the test primarily has been performed after difficulties occur during execution of a drilled or driven-pile foundation. Goble Rausche Likins and Associates, Inc. (*3*) has written a specification for the testing procedure that has been used as a guide for agencies contracting for this type of work. For specific projects, other specifications have been proposed. However, there still are considerable differences in opinion as to the proper application and interpretation of the test and exactly how the results should be used in the quality assurance and acceptance process of a pile or shaft.

The method has been employed frequently both in Europe and the United States, particularly on auger-cast (continuous-flight-auger or pressure-grouted) pile projects, in which construction control is difficult because a direct inspection of the drilled hole before grouting is not possible. Correlation tests on auger-cast shafts constructed with planned defects have not been performed, primarily because it is difficult to determine shaft diameter by depth. However, integrity testing and analysis are well supported by contractors' experiences with standard cast-in-place shafts and driven concrete piles. The test methods are generally considered applicable to auger-cast shafts also, and they are used to test auger-cast shafts throughout the United Kingdom.

The nondestructive low-strain method is relatively simple to execute; however, interpretation of the data collected is sometimes difficult. As for other nondestructive test (NDT) methods, the records collected may be divided into four categories:

- Category A—Clear indication of a sound pile shaft;
- Category B—Clear indication of a serious defect;
- Category C—Indication of a possibly defective pile shaft; and
- Category D—Inconclusive data.

The authors briefly discuss records falling into these four categories, drawing examples from actual case histories. Furthermore, because it is desirable to derive quantitative results from records when there's some indication of a defective pile shaft (Category C), the so-called "Pile Impedance Profile" interpretation method will be explained. Finally, recommendations for implementation are made.

LOW-STRAIN METHOD

When a long-driven or cast-in-place pile is struck with a small hammer, a stress wave is generated that travels down the shaft to the bottom where it is reflected. When the reflected stress wave returns to the top, a measurable pile-top motion occurs. If this reflection wave occurs at the correct time, and if no other earlier reflection is observed at the pile top, then the pile shaft is probably free of major defects.

When a lightweight hand-held hammer strikes the pile top, a small pile top motion (velocity) is generated and can be measured. The associated pile strains are of such a low magnitude that this test is known as a "low strain test." However, the force applied by the hammer can be easily measured by instrumenting the hammer itself. Primarily, the velocity record (and to a lesser degree the force record) contains information about the location and magnitude of pile nonuniformities (*4*).

STRESS WAVE PROPAGATION IN A PILE

An impact applied to the pile top generates a momentary compression and particle velocity, v, of the pile-top surface. If the pile

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is made of concrete, the stress-wave travels in the pile at a longitudinal wave speed, c, ranging from 3,000 to 4,500 m/sec, where

$$c = \sqrt{\frac{E}{\rho}} \tag{1}$$

where E is the pile's elastic modulus and ρ is its mass density. Figure 1 shows the path of a stress wave in the pile in the form of a time-depth plot, illustrating that cross-section reductions produce a reflection observable at the pile top. This reflection is of the same sign as the input, and the arrival times of reflection waves at the pile top are related proportionately to the depth of the cross section's change by the wave speed. Soil resistance forces also generate reflection waves, but of opposite sign to the input.

PULSE ECHO METHOD

Figure 2 shows a schematic of low-strain instrumentation using as an example the so-called Pile Integrity Tester (P.I.T.) Collector (*4*). Hardware components also include a hand-held hammer with an integral plastic cushion and an accelerometer. The pile integrity tester or P.I.T. processor provides signal conditioning, digital signal processing and storage, and output on a liquid crystal display screen, graphics printer, or plotter. Various other configurations of this system are possible. For example, the signal conditioning can be combined using a personal computer with analog-to-digital data conversion capability.

The first, and sometimes most important, step for any low-strain test is the preparation of the pile-top surface. In fact, depending on the construction method, it may be necessary to remove the upper section of the concrete if it has been contaminated with soil, bentonite slurry, or other foreign materials during construction. After a clean, hard concrete top surface has been exposed, the accelerometer is attached to a smooth spot prepared on the pile-top surface with a thin layer of a soft, paste-like material, such as vaseline or petro wax. After the accelerometer is attached a hand-held hammer is used to strike the pile top to generate accelerations in the 10- to 100-g range, pile strains less than 10^{-5}, velocities less than 30 mm/sec (0.1 ft/sec), and displacements less than 0.03 mm (0.001 in.). Accelerations produced by several hammer blows are integrated to velocities (usually easier to interpret than accelerations) and displayed on the processor's screen. Consistent records are then averaged, reinforcing the repetitive information from pile or soil effects while reducing effects of random noise.

DATA PROCESSING AND INITIAL INTERPRETATION

Observed time can be converted to a length scale by multiplication with the longitudinal wave speed, c. Since wave speeds of piles installed at the same site normally fluctuate ±5 percent, similar differences in predicted length (or depth to cross-section change) must be tolerated. If there are no reference shafts, and wave speeds are only estimated, then the differences between estimated and actual wave speeds may be as much as ±15 percent. On the other hand, assuming that the accurate pile shaft length is known, the wave speed can be back calculated from the time between impact and pile-toe reflection (when observed).

The test engineer inspects the average velocity signal. The first check concerns the "toe signal". If the reflection from the pile toe is not readily apparent, then the velocity usually is multiplied with an amplification function whose magnitude is unity at impact, which increases exponentially with time until it reaches its

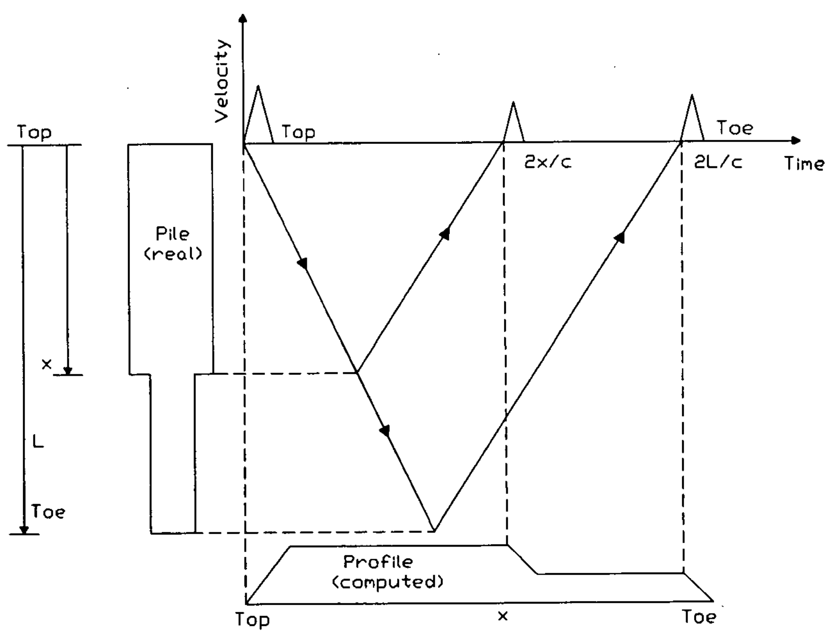

FIGURE 1 Traveling stress waves and the principle of the Pile Profile estimate. Measured velocity at pile top showing input and reflections from cross-section change, and pile-toe and computed-impedance profile.

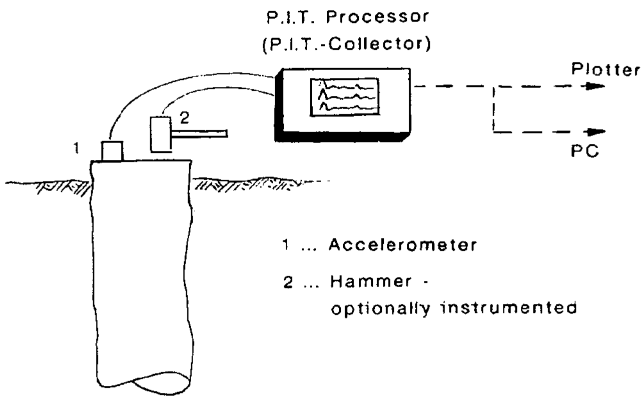

FIGURE 2 Schematic of P.I.T. devices (collector).

maximum intensity at time 2 L/c after impact (Note 2 L/c is the time that the stress wave requires to travel the pile length, L, and return). The amplification may be started at a time after impact that corresponds to the depth at which significant soil resistance in the pile is expected.

Next, the velocity amplitude variations over the first 2 L/c time period are investigated and may be the result of changes in a pile's cross section, the concrete quality, or the degree of soil resistance. For example, increases in relative velocity may result from either a cross-sectional decrease or a soft soil layer. In the absence of soil resistance changes, pile-top variations are caused by pile impedance changes, where impedance is defined as

$$Z = EA/c = A\sqrt{E\rho} = Ac\rho \qquad (2)$$

where A is the pile's cross-sectional area. Thus, an impedance reduction can be caused by a decrease either in area, in the concrete's elastic modulus, or in the concrete's density. Since both modulus and density are related to concrete strength, it is fair to say impedance depends on cross-sectional area and concrete quality.

PILE PROFILE INTERPRETATION METHOD

Based on work done by Paquet (*5*), an estimated Pile Profile may be calculated using the measured pile-top velocity. The basic concept of the Pile Profile calculation is that a step-wise change in impedance causes a pulse-like velocity wave effect at the pile top (Figure 1). The profile can be constructed from the time integral of the velocity wave effects at the pile top. First, the input pulse is integrated (to define maximum profile at "top") and forms the reference for later reflections. Next, the subsequent velocity is integrated (now with opposite sign), such that velocity increases (or cross-section reductions) cause proportionate reductions in the profile, with the final reflection from the pile toe causing the profile to "close" (bringing net integral equal to zero) at the toe. In practice, other procedures must also be considered (*4,5*) to account for the effects of soil resistances along the shaft. The calculated Pile Profile result includes the following:

- Calculated pile impedance plotted versus length. The impedance is normally plotted symmetrically to the pile axis even though actual variations may occur on one pile side.
- Relative volume calculated from the apparent Pile Profile. (This value may be compared with actual construction records.) A relative volume of 1.0 corresponds to the pile-top cross-sectional area times the pile length. (Note that the actual pile top cross-sectional area may be greater than the nominal area; this must be considered when comparing volume records from the construction site.)
- Minimum and maximum impedance values along pile shaft (relative to the pile top).
- Measured velocity (solid line) enhanced by the averaging of several blows, by exponential amplification, and by high-pass and low-pass filtering.
- Calculated velocity (dash) considering a set of assumed soil resistance effects. The difference between the measured and calculated velocity curves is interpreted as reflections from pile impedance variations.

The Pile Profile calculation relies to a very high degree on the judgment of the engineer in the generation of a calculated velocity. The judgment could be removed if the record was strongly filtered to remove all low-frequency effects, implying that only quickly changing (high frequency) pile impedance variations can be detected and that soil resistance effects produce slowly varying wave reflections. Both the engineering judgment and the automated filtering method leave some questions as to the actual soil resistance effects on the pile-top velocity record. For this reason, it is always helpful to establish a typical or reference pile on a site.

The difficulty in interpretation lies primarily in separating soil-resistance from pile-impedance effects. Unfortunately, soil resistance influences the velocity records not only in a uniform manner (as it is tacitly assumed when the exponential amplification is performed) but also with differing intensities at different soil layers. If soil-resistance effects were not properly considered, the calculated Pile Profile would show impedance increases or decreases along the pile where soil resistance increases or decreases.

EXAMPLES OF NDT RECORDS

Category A—Clear Indication of a Sound Pile Shaft

Figure 3 presents velocity and acceleration records of a relatively long auger cast pile (the pile is drawn horizontally between the records with the exponential amplification function superimposed). According to plan, the shaft had a length of 24 m and a diameter of 600 mm. It was installed in loose sands that became more competent with depth. After significant exponential amplification (75 times, at time 2 L/c) a clear toe signal (relative velocity increase begins at 24 m) was apparent. Without exponential amplification, the toe signal was practically invisible. A relatively flat record up to 20 m indicates a uniform shaft; a gradual increase from negative (just after impact) to positive velocity values (in the middle of the record) is interpreted as a slight reduction in soil resistance between the top and the middle of the pile. The soil resistance apparently increased quickly when the shaft entered the bearing layer, a few meters above the pile toe. (The record portion after the 2 L/c time is not of interest in assessing pile integrity.) Without further analysis, this shaft can be considered free of any significant defect.

Category B—Clear Indication of a Serious Defect

Several kinds of defects can be detected by the low-strain test method. However, a number of others cannot be detected with the low-strain method, the following for example:

- Local impedance variations that occur over very short distances such as partial cracks are not detected by long impact pulses. As mentioned earlier, soil-resistance effects often mask reflections from gradual impedance variations, or the two may be indistinguishable from each other.
- More than two strong impedance variations (50 percent or greater) create complex records that are difficult to interpret. Major defects below such impedance variations may not be detectable.
- Any defect below a full crack or mechanical splice cannot be detected. A major crack completely separates upper from lower pile sections that the low-energy stress wave cannot traverse.
- Very gradual deterioration in concrete quality or a cross-sectional area change, occurring over a distance of several impact pulse widths (e.g., 5 m), may not be detected.
- Exact length (compared to the planned length) usually cannot be determined because the wave speed, c, of the material, used to convert time ($2L/c$) to length, L, is at best known within 5 percent.
- A minor defect, for example, one causing less than 20 percent of the pile impedance, may not be detected.
- A major defect at a pile length that is beyond the reach of the stress wave, typically at a depth below grade (dependent upon soil strength) that is greater than about 30 shaft diameters may not be detected. (Figure 3, however, shows a clear toe signal for a depth to diameter ratio of 40).
- A defect within a short distance of the pile toe may not be detected, unless the toe reflection of a typical or reference pile is known.

The soil not only has a resistance effect but inevitably causes unplanned impedance variations. For example, in weak soils the constructed shaft is often enlarged. Alternatively, where the soil changes from weak to firm, the diameter of the shaft decreases back to the nominal diameter. For this reason it often is necessary to establish the ''signature'' of a reference pile at a site to show both the soil resistance effects and the unavoidable impedance variations.

Serious defects that can be detected by the low-strain method include the following:

- Shafts that are constructed more than 5 percent shorter than planned (if records from reference piles are available) and those constructed more than 10 percent shorter than specified (if no reference piles are tested).
- A complete crack that separates the full cross section of the shaft. For example, an opened crack caused by shrinkage in an unreinforced shaft or from the inadvertent impact of construction equipment during excavation would produce a complete wave reflection; however, defects below such a crack cannot be detected.
- An impedance reduction greater than 20 percent, as long as sufficient wave energy is available to produce a toe signal in reference piles. When reference piles are not available or do not indicate a toe signal, a less accurate rule of thumb may be used: that is, that defects to a depth of 30 diameters are detectable.

Figure 4 shows the velocity record and impedance log of a shaft drilled to a depth of 29 m. The apparent length is, however, only about 21 m to 23 m at most; the dashed portion of the profile, equal to the input pulse width, is a zone of uncertainty of impedance. The P.I.T. test clearly indicates the point to which the 1.5-m diameter shaft has been cased (reduction begins at end of casing 8 m below top), a subsequent increase in impedance in the shaft between 9 and 14 m, and then a strong relative positive velocity

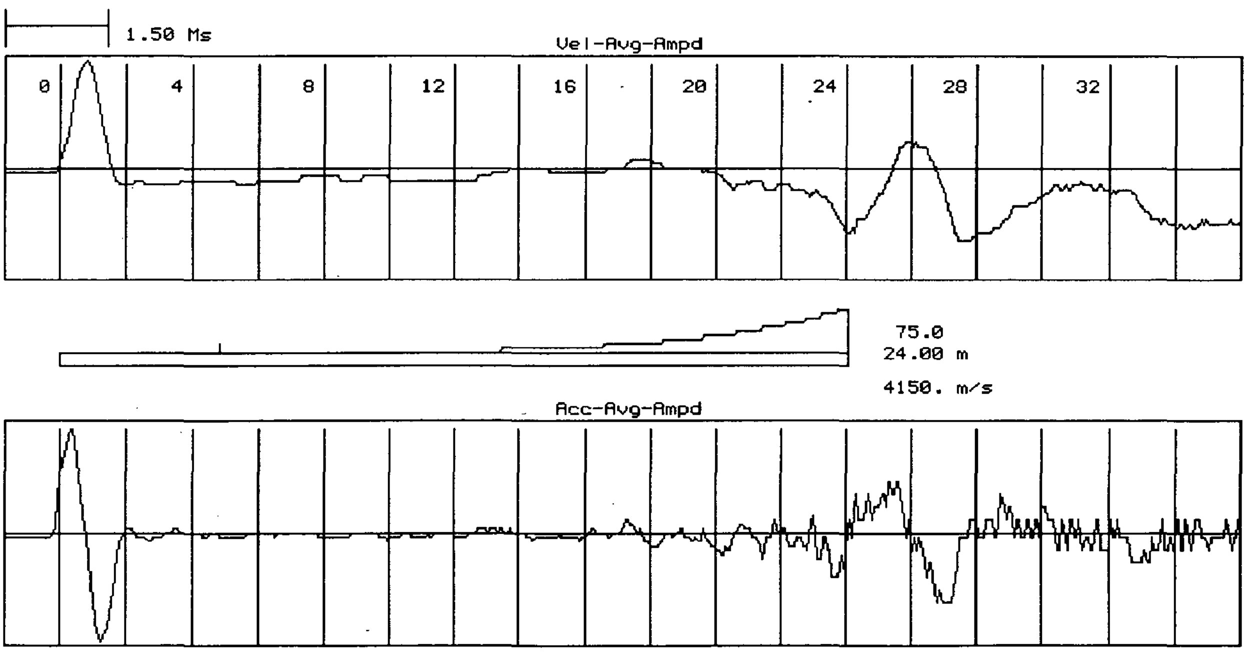

FIGURE 3 Pile-top velocity (*top*) and acceleration (*bottom*) of a 24-m shaft (both with 75 × exponential amplification), with pile model and amplification function (*center*) and a clear toe signal (relative velocity increase) beginning at 24 m.

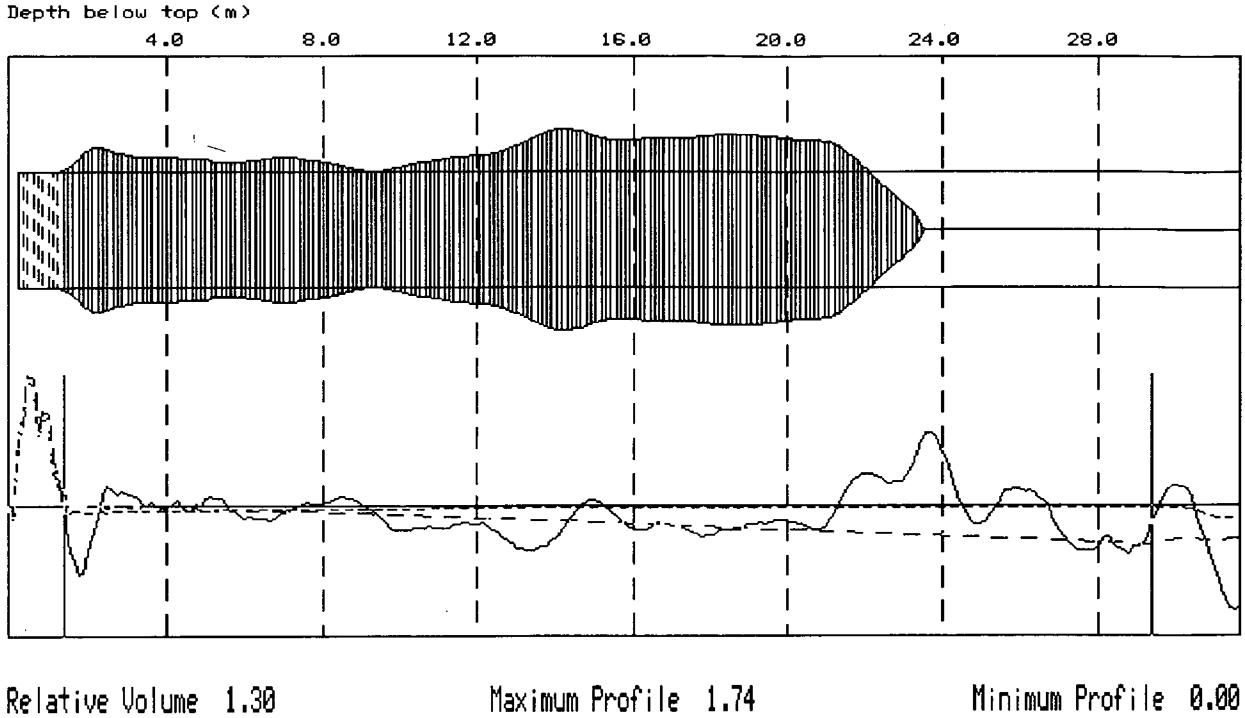

FIGURE 4 Shaft 1.5 m in diameter, and planned length of 29 m, with a casing to 8 m depth, which is oversized below casing and has major defect beginning at 21 m. Impedance profile (*top*) and exponentially amplified velocity (*bottom*).

increase beginning at 21 m. Although it might be argued that a toe reflection (relative velocity increase) is apparent in the velocity record, the earlier reflection is so strong that it must be attributed to a major defect (impedance reduction) that gives the shaft an apparent or effective length of only about 21 m, instead of the design length of 29 m.

Category C—Indication of a Possibly Defective Pile Shaft

Figure 5 shows a record with a positive reflection at a location approximately 3 to 4 m (uncertainty due to input pulse width zone) below the shaft top (*6*). The impedance log shows an increased shaft size shortly below the top, and that cross section may alternatively be used as a reference impedance. Relative to this 12 percent-higher impedance value (maximum profile 1.12), the reduction (minimum profile 0.73, or a 27 percent decrease) appears to be 12 + 27 = 39 percent. Actually, the shaft had been constructed with a planned length of 10.4 m and a planned built-in defect of 50 percent at a depth of about 3 m. A shaft-toe reflection is apparent, and it can be concluded that otherwise the shaft is continuous to its toe.

Quantitative evaluations of impedance (or cross-sectional area reductions) are probably limited to an accuracy of 20 percent of the nominal shaft impedance. Statistically meaningful data currently does not exist to support a stronger statement. This means that a defect of less than 20 percent probably cannot be detected with certainty.

Category D—Inconclusive Data

When the pile top quality is poor, low-strain test results are often inconclusive. For example, Figures 6 and 7 show records from the same shaft, both before and after the pile top had been cleaned off and loose or contaminated concrete removed. A mortar layer for shaft-top smoothing may distort the signal in a similar manner. Another reason the data is inconclusive: heavy reinforcement was protruding above the pile top for more than 3 pile diameters. Even driven precast piles occasionally show inconclusive records shortly after they are driven when microscopic cracks diffuse the impact energy.

Figure 6 would not allow for a clear statement about shaft integrity because of the sine-wave shape of the record; however, neither would it allow the conclusion of a defective shaft. Therefore, it is a Category D record. After the shaft top was cleaned off, the records in Figure 7 were conclusive: the shaft was intact, with a small relative impedance reduction (relative velocity increase) beginning at 18 ft (5.5 m) just before strong soil resistance. The small impedance reduction was probably caused by a return of the shaft to its nominal diameter once it entered more competent soil. Above that location, however, the shaft was probably oversized. The record of Figure 7 also contains an observable toe reflection (relative velocity increase) and therefore falls into either Category C or A.

IMPLEMENTATION OF LOW-STRAIN TEST

Before testing a pile shaft, project managers should consider what actions should be taken if test records indicate a lack of quality.

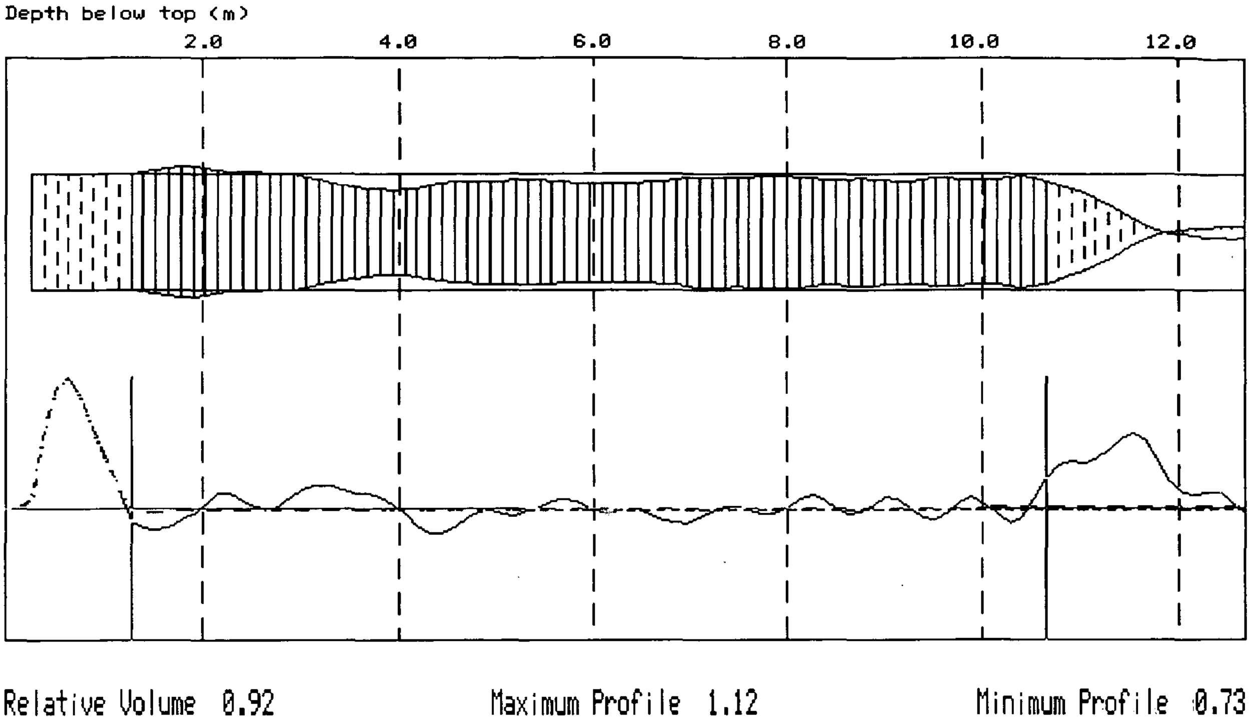

FIGURE 5 Shaft with defect (minimum profile value of 0.73), approximately 3 m to 4 m below top.

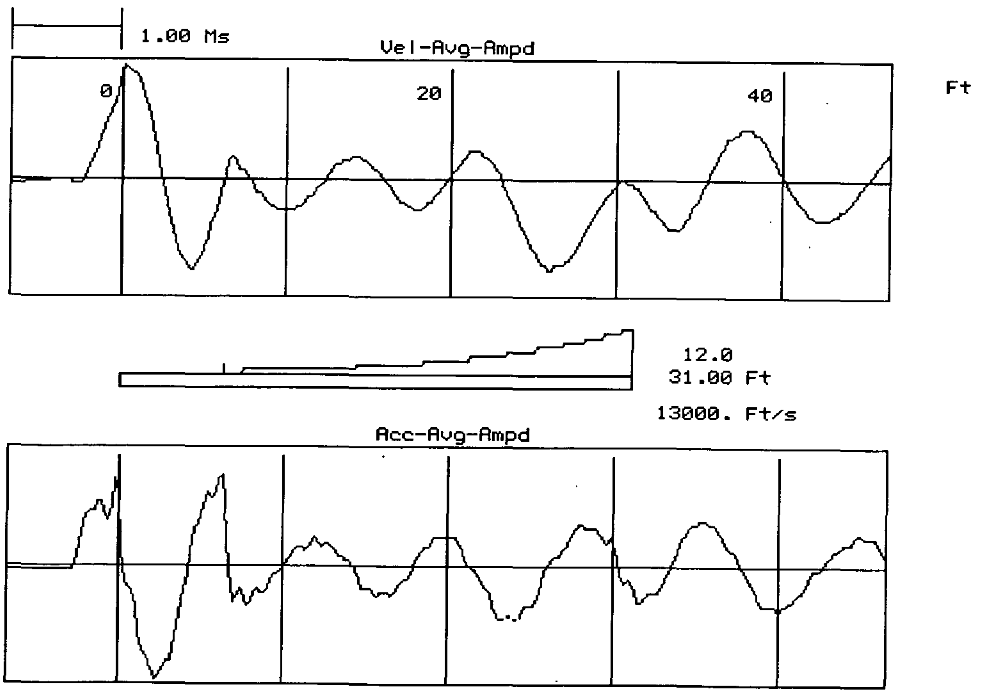

FIGURE 6 Velocity (*top*) and acceleration (*bottom*) records of a shaft before removing contaminated concrete (1 ft = 0.305 m) with pile and amplification function (*center*).

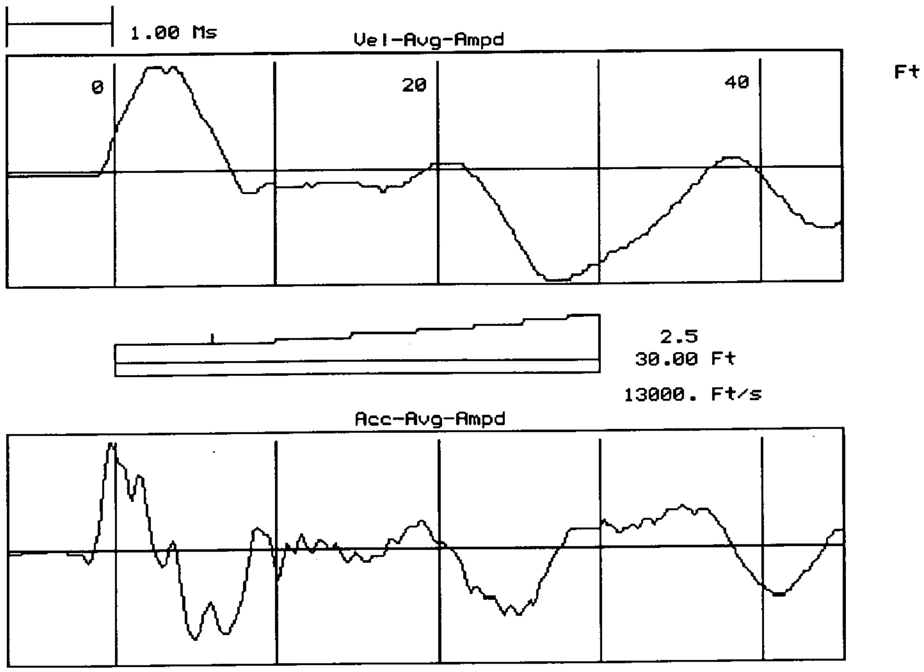

FIGURE 7 Records after removing 1 ft of contaminated concrete from the top of the shaft shown in Figure 6 (1 ft = 0.305 m).

Unless an appropriate "decision tree" is in place for drilled shafts whose P.I.T. records fall under Categories B, C, or D, serious construction delays may result, causing unnecessary work stress for the general and piling contractors, engineers and the testing company. We recommend the following set of actions, according to each record category.

If the test shows a sound pile shaft (Category A) the pile shaft can be immediately accepted whenever its shaft continuity is the only question. If the test reveals a serious defect (Category B), the contractor must assess the foundation's strength either without the defective element or with a reduced element strength. Similarly, if the test indicates the possibility of a defect (Category C), a reduced capacity may be assigned to the defective shaft. In the case of inconclusive records, (Category D) one or more of the following measures may be required:

- Deem a certain percentage of inconclusive records acceptable. Some percentage of records can be accepted as uncertain, particularly, if a very large percentage of piles at a site has been tested. There must be the assurance, however, that Category-B or C piles will not be put into Category D simply to avoid acknowledging defective or possibly defective piles. The acceptable percentage of piles with inconclusive records should be based on the type of structure and the piles' intended use, the redundancies in the foundation (and test results of adjacent piles), the soil type, and the type of pile resistance (for example friction/end bearing).
- Perform the following additional tests or investigations:
  —Excavation or extraction and subsequent inspection of the affected shaft portion; this is useful when the problem appears to occur only a short distance from the pile top.
  —Retesting by the low-strain method after cut-off and cleaning the pile top. This is the most common remedy.
  —Make core borings and make repairs by high pressure grout injection. Unfortunately, this remedy is very expensive, and the boring may or may not move outside the shaft.
  —High-strain dynamic tests using a Pile Driving Analyzer. This test will yield additional information about the shaft's uniformity (7) and about its load-bearing capacity.
  —Static load-testing. A shaft may pass the static load test, however, if the shaft's deficiency is due to contaminated concrete, honey combing, or other concrete deficiencies that leave sufficient structural strength for the static capacity.

STEP-BY-STEP INTERPRETATION

Compile Information

Complete construction records always should be gathered including:

- Size of drilling equipment (diameter and depth);
- Nominal shaft diameter;
- Observed actual diameter at top of shaft;
- Construction procedure;
- Anticipated oversize;
- Planned cross-sectional variations (diameter changes, bulbs), if any;
- Unplanned but expected cross-sectional variations;
- Casing geometry, wall thickness, if any;
- Length as drilled;
- Theoretical volume based on length drilled and anticipated shaft diameter;
- Actual grout volume versus depth;

- Grout pressure variations versus depth;
- Observations of unusual situations or construction interruptions;
- Time of grouting and concreting;
- Anticipated concrete strength at time of testing;
- Reinforcement details (calculate shaft-impedance variations related to reinforcement);
- Soil borings, including details on water table;
- Static test results, if any; and
- Any other test results.

Establish an expected shaft geometry from these records. For example, when going from soft to firm soil, a reduction in cross-sectional area from an oversized to a nominal diameter may be expected; the actual to theoretical grout-volume ratio can be compared with the relative volume computed by the impedance-profile method. Where high resistance soils start, a compressive wave may be expected.

If one or more static tests were conducted successfully, test these shafts to serve as a reference.

Collect Data

Measure force and velocity whenever possible, but at least velocity, from several hammer blows. Only consistent data should be averaged; readings that differ greatly should be excluded from the average. For shafts with diameters in excess of 1 m, several impact and sensing locations should be chosen. Do not average these records; instead present results for all test locations independently. For shafts with large diameters, records should be obtained with both lighter and heavier hammer weights. Where records appear difficult to interpret, attempt to improve the data by

- Removing contaminated pile-top concrete or loose mortar layers.
- Delaying testing until grout/concrete strength has improved.
- Bending away reinforcement that might produce undesirable shaft top vibrations. If bending of reinforcement is impossible, measure force or velocity at points distant from hammer impact and the reinforcement.
- Testing or sensing at several locations. This is particularly important for large-diameter shafts.

Establish Longitudinal Wave Speed

Test Series with No Reference Shafts

If less than 5 comparable shafts are tested at one site, then it is best to assume a wave speed (typically 4,000 m/sec) for the concrete. Experience values from tests in the same general area, with the same concrete specifications and suppliers, may be used if they can reasonably be expected to have relevance to the test project. Shaft-length calculations are then based on the assumed wave speed and, of course, an observable toe signal. Such shaft-length results might be considered accurate within 10 percent.

Test Series with Reference Shafts

If the tests are conducted on at least five comparable shafts, then it may be possible to establish a reference pile or reference record. With clearly apparent toe reflections, a wave speed should be calculated based on the shaft-length values provided by quality construction records. The length of individual shafts can then be back calculated. Again, wave speeds from shafts that indicate greatly differing values should be excluded from the average.

Process Records

Exponentially amplify records to check for a toe signal. Start amplification at grade or where substantial soil effects are expected to begin (often indicated by a clear velocity decrease), but exclude no more than 20 percent of the full shaft-depth of penetration from exponential amplification. Amplification magnitude should be chosen such that the impact signal equals in magnitude the largest reflection amplitude; both the start of amplification and its magnitude should be similar for all records of like shafts at one site; otherwise establishing typical records is virtually impossible. This requirement may necessitate reprocessing records after all records have been collected.

Establish Reference Record

If more than four shafts are tested, attempt to establish a typical record, identifying consistent effects of soil resistance, or planned or unavoidable cross-sectional variations. Load test piles, whenever available, should be chosen for this purpose. Where less than five shafts have been tested, the reference record may be deduced from soil borings and the construction method.

Classify Records

Descriptions of records for Classes I through VIII follow:

- Class I: Clear toe signal indicating a wave speed within 10 percent of average; amplitude variations less than 20 percent of impact signal, or site-typical variations between top and toe. This is a Category-A shaft.
- Class II: Toe signal apparent; unusual records indicating bulbs or other gains in shaft strength. Strength-gain indications are velocity decreases without a prior increase. This is a Category-A shaft.
- Class III: Toe signal indicates wave speed greater than 110 percent of average. This must be interpreted as a potentially short pile (although it could be caused by a particularly high-quality concrete or grout). If a large number of shafts are tested, a statistical method may be used to identify potentially short shafts. Depending on the seriousness of the shortfall, the shaft may be Category B or C. Decision of rejection should be based on geotechnical considerations.
- Class IV: Toe signal indicates wave speed less than 90 percent of average. Conservatively, this must be interpreted as a potentially poor quality shaft (although the late toe signal could be caused by a long pile). It will be either a Category-B or C shaft, depending on the required concrete strength. For this purpose it may be satisfactory to assume that the concrete strength increases by 14 MPa (2,000 psi) for every 300 m/sec (1,000 ft/sec) of wave-speed increase. This approximate and relative strength-wave speed relationship was based on the ultrasonic pulse velocity method

(*8*), which deals with grout and concrete-strength determination based on ultrasonic wave-speed measurements. Differences between ultrasonic and sonic wave speeds were considered small considering the inherent errors in the proposed relationship.

- Class V: Toe signal apparent; major velocity increases greater than 20 percent of input signal indicate impedance loss not balanced by prior velocity decreases. A Category-B or C shaft, depending on the required strength of the shaft.
- Class VI: No toe signal apparent; minor velocity variations, of 20 percent of input signal or less, or site typical variations between top and where toe signal would be expected or velocity decreases indicating impedance gain not following a velocity increase. A Category-C shaft, it may be accepted if depth of apparent stress wave penetration is considered sufficient.
- Class VII: No toe signal apparent; major velocity increases greater than 20 percent of input signal indicate impedance loss that is not balanced by prior velocity decreases. This would be a Category-B shaft and be rejected as defective unless variations could be considered for the typical site, in which case, it would be classified as Category C.
- Class VIII: Unclear records resulting from major reflections near the pile's top or from high frequency components (for example, poor pile-top quality or reinforcement that sticks out at shaft top) or more than two major (greater than 20 percent of impact signal) reflections (impedance increases or decreases). This constitutes a Category-D shaft; additional tests need to be performed.

Analyze If Needed

Using the Pile Profile method or a simulation of the test process, (for example, signal matching, such as in the pile integrity wave analysis program (*9*), records from various categories should be analyzed to prove that the chosen classification is reasonable. These methods are not helpful if soil effects produce stronger reflections than impedance variations, or if cracks cause the reflections.

Prepare Report

The test report may be short. However, it should include soil boring(s), a summary of the construction records, the dates of construction and testing, design diameter and length, pile layout on the site, and records for each tested pile by category.

SUMMARY

The authors have attempted to remove some of the uncertainty "P.I.T." measurement engineers and their clients face in applying and interpreting the Pulse Echo test—and establish circumstances under which a shaft may be accepted or rejected.

The authors are aware that standardization of this test method is very difficult because of the great variety of site conditions, shaft types, construction methods, and even individuals involved in the construction process. Therefore, there may be many circumstances that would prevent a literal application of the guidelines given here. More importantly, these guidelines should not prevent future improvement in testing methods. On the other hand, the guidelines we afford should be expanded or modified to suit new findings or particular site requirements. With time and sufficient input from other experienced users, the guidelines may become a standard.

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