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NON-DESTRUCTIVE TESTING OF PILES USING THE LOW STRAIN INTEGRITY METHOD

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ABSTRACT

Non-destructive testing of piles has gained increased acceptance for various purposes, e.g., quality control/quality assurance, verification of existing conditions, and quantification of dimensions. The correct use of this technique can greatly simplify and expedite investigation, and be economical in addressing concerns or questions on pile conditions. Equally, its incorrect use can cause controversies, delays, and/or create adverse reputation for the technology.

This paper presents three case histories on the use of the low strain, pile integrity testing (PIT) for different pile types and for different reasons. In this paper, the term "pile" is used generically and implies all types of deep foundations, e.g., driven or drilled-in, concrete or steel, piles or piers, etc. Initially, a brief overview of the technology along with its capabilities and limitations will be presented, followed by the case histories. The first case is related to the construction of a new power plant at the location of existing pile-supported buildings, necessitating the collection of information on the condition and length of these piles so that they can be used as part of the new foundations for the power plant once the existing buildings were demolished. The second case history is related to the construction of a hotel, involving augered cast-in-place piles. PIT was performed to evaluate the condition of a failing test pile as part of the quality control process. The third case history is related to investigating the quality of several drilled shafts for a retail facility. PIT was performed to obtain an estimate of the shaft lengths and gather information on overall shaft quality.

The case histories will provide details of structures, their foundations, and the PIT application. Along with the PIT results, other relevant information such as subsurface conditions and pile load test results will be presented, where available. The collected PIT data will be compared with pile information available prior to initiating the program to assess the validity and the applicability of the PIT technique.

INTRODUCTION

Deep foundation construction is an inherently "blind" process, i.e., the final product is not readily available for visual inspection. The quality control/quality assurance process for such foundations is almost always through indirect measurement of other parameters, such as performance of the installation equipment, resistance to driving or drilling, examination of drilled cuttings, etc. Therefore, the quality of the final product is often a function of the installer's know-how and the inspector's experience. Even the most experienced foundation contractors acknowledge that there is an initial "learning" period for each project, essentially impacted by ground conditions, equipment utilized, and installation processes. A process whereby confidence in the quality of the installed pile is expeditiously attained is essential to the contractor to confirm the adequacy of the deployed construction methods and vital to the engineer to verify the competence of the foundation installed. The PIT method can be a valuable tool in rapidly making these evaluations as piles are constructed.

Similarly, PIT can be used for obtaining quantitative information on existing deep foundations. In recent years, increased growth in building renovations has necessitated evaluation of the existing building foundations for upgrading or retrofit. In some cases, however, especially in the case of old or historic structures, very little, if any, information may be available of the actual foundations for the structure. In such cases, PIT would be a valuable tool to not only obtain information on the as-built foundation quality but also on length of the piles. Such information will provide the essential parameters to perform an evaluation of the piles to judge the relevance or adequacy of the foundations with respect to the planned construction.

PIT METHOD

PIT is a non-destructive testing technique, sometimes referred to as the sonic pulse echo method. It involves applying low strains to a foundation element using light hammer impacts and evaluating the collected force and velocity records to deduce qualitative and quantitative information for the foundation element. Standards covering PIT performance include ASTM D5882 (ASTM 2003).

Background

Details of the theoretical background and the development of PIT are discussed in various literatures (Rausche and Goble 1979, Reiding et. al. 1984, Davis and Hertlein 1991, Rausche et. al. 1991, and Rausche et. al. 1992). The basics of the concept are highlighted below.

PIT development is based on the theory of wave propagation in media. For a linear elastic pile having a length an order of magnitude greater than its width, stress waves travel in the pile at a wave speed, c, such that

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

where E is the pile material elastic modulus and ρ is its mass density. The applied force, F, imparted by hammer impact and the particle velocity, v, at any point are related such that

$$F = Z\,v \tag{2}$$

Where Z is proportionality constant, also known as impedance; it is a measure of pile resisting change in velocity. Pile impedance for various size piles can be defined as

$$Z = E\,A / c \tag{3}$$

Change in impedance is related to change in pile cross-sectional area, A, as well as pile material quality. Increase in pile impedance or soil resistance forces results in a decrease in measured pile top velocity. Conversely, decrease in pile impedance, results in increased velocity. By observing changes in impedance, pile quality can be assessed and dimensions estimated.

Equipment

The equipment that is in common use for pile foundation evaluation is manufactured by Pile Dynamics, Inc. The PIT equipment is very compact and readily portable, consisting of a hammer, a motion sensor, and a processing unit. The hammer size varies from about 1 to 10 lbs. Sometimes, the hammer is fitted with a pressure sensor or strain gage to measure the applied force. The motion sensor generally consists of an accelerometer. The processor stores and analyzes the recorded signals. Components of the PIT are shown in Fig. 1.

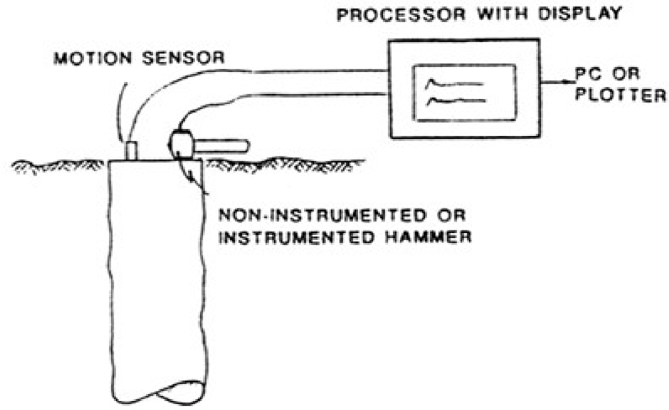

Fig. 1. Components of PIT (Rausche et. al. 1992)

In utilizing PIT, one must recognize the capabilities and limitations of the method. The quality of the PIT results is a direct function of the operator's familiarity with the system and experience with pile foundations, e.g., factors such as pile surface preparation for attachment of the sensors, use of certain hammer weight for certain pile size, data processing, etc., can readily influence the results if their contributions are not recognized. Foundations such as drilled shafts or augered cast-in-place piles with multiple or large variation in cross-sections can result in complex records that are difficult or impossible to analyze (GRL, 1999). Also, generally piles with L/D ratio not exceeding 30 can produce the necessary signals, without excessive damping due to soil resistance or pile material properties, although this rule can sometimes be deviated and piles with greater ratio reasonably tested under special circumstances. PIT does not produce information on pile capacity or pile load transfer mechanisms. PIT is, however, capable of producing information on pile quality, e.g., the presence of defects such as voids or breaks, and on pile length. Even these capabilities are impacted by assumptions that will need to be made during signal processing, e.g., assumptions on the propagation of wave speed based on judging the pile materials. In addition, even under ideal conditions, it is prudent to allow a level of uncertainty in the results although the level of uncertainty is affected by the confidence in available information. It is not uncommon to assume PIT results on pile length to vary by as much as 10%, especially that wave speed variations of 5%± are known to be quite possible due to varying material quality, e.g., concrete.

CASE HISTORIES

Three case histories on the use of the PIT method are presented below for various pile types and projects.

Case History 1: Raymond Step-Taper Pile

A power plant was planned for construction in Bethesda, Maryland. The facility would be constructed at the location of existing buildings after demolition. The existing buildings were constructed in 1950 and were supported on about 1,300 piles; construction of the new power plant required utilizing portions of these piles. Very little information was available on the existing piles. The pile types were not referenced on any of the available drawing. The pile capacity was unknown as well, although drawing notes indicated that the pile caps were designed for 30-ton piles. Reference was available on drawings for pile load tests; however, the results were not available. The available specific information consisted only of few design parameters, namely pile tip diameter of 8 to 10 inches and pile tip elevation (El.) from El. +253 to +267 feet. The lack of adequate information on existing foundations, and the need to utilize these foundations for the new power plant, resulted in undertaking an investigation that consisted of subsurface exploration by test borings, exposing existing piles for visual examination, static load testing of an existing pile, and performing PIT on the test pile.

Geology. The project area is within the eastern Piedmont physiographic province, underlain by the metamorphic rocks of the Whissihickon Formation, consisting of schist and gneiss. Results of a subsurface investigation by test borings including Standard Penetration Tests (SPT) and supplemented by borings taken in 1950 is presented in Fig. 2.

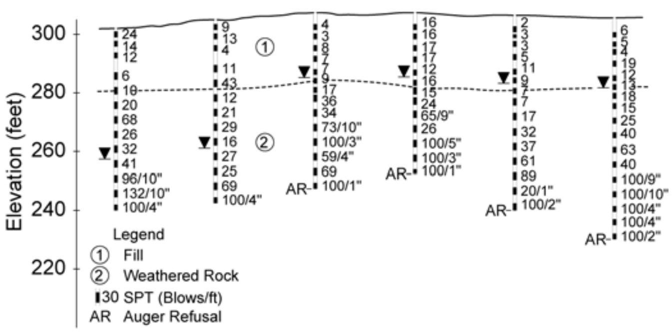

Fig. 2. Subsurface Profile at the Power Plant Site

The results indicated the presence of random fill, underlain by weathered rock and bedrock. The fill varied in thickness from about 20 to 25 feet, consisted of loose to medium dense low plasticity micaceous silt (ML) with varying sand contents, and included debris such as concrete, wood, wire, and cement grout from a previous construction. Weathered rock (residual soils and friable decomposed rock) was present below the fill, extending to depths from 50 to at least 75 feet, and consisted of dense to very dense low plasticity micaceous sand (SM) with silt and gravel. SPT values exceeding 100 blows per foot were common with greater depth, indicating increase in density and a lower degree of decomposition with depth in these materials. Other indices for these soils found in laboratory tests included water content ranging from 10 to 20%, liquid limits of 30 to 40, plasticity index of 7 to 10, and fines content of 30 to 33%. The actual depth to intact rock was not known at the site; however, refusal to SPT sampling, defined as 100 blows per 2 inches or less of penetration, was recorded in some borings at a depth of about 50 feet. Groundwater level at the site was at depths from about 25 to 45 feet, probably influenced by on-going dewatering for nearby construction.

Pile Examination. A test pit was excavated at the location of one of the existing pile caps. The upper portion of 2 of these piles was exposed for visual examination. The piles were observed to be helically corrugated metal, concrete filled, with a top diameter of about 14 inches at the pile cap. A portion of one pile was cut out for further examination and was found to be in reasonably sound condition. A small 5.5-inch long and 2.5-inch deep void, however, was observed in the pile cross-section. No steel reinforcements were observed within the pile. Based on these observations, the pile was identified as a Raymond Step-Taper Pile.

Raymond Step-Taper Piles were developed by Raymond Concrete Pile Company, founded in 1897, and were very common and popular in the mid 1950's. They were essentially discontinued around the mid 1990's. They were typically constructed of steel shells of 12 to 20 gauges in thickness, in basic section lengths of 4, 8, 12, and 16 feet. The shells had nominal diameters ranging from about 8.5 to 18.5 inches. The nominal tip diameters typically ranged from about 8 to 11 inches. The tip of the pile was commonly closed, with a welded flat steel plate. The shells were helically corrugated to withstand lateral ground stresses after installation. Internal reinforcement for these piles was not typically provided unless the piles were designed for uplift, high lateral loads, or for unsupported lengths. The piles were commonly installed by placing a steel mandrel inside the shell, driving the mandrel and shell to the required resistance or elevation, withdrawing the mandrel leaving the shell in place, removing excess shell, and filling the shell with concrete to the required cut-off elevation. The most common pile length was generally in the 50- to 80-foot range with a design compression capacity commonly in the 40- to 100-ton range.

PIT Results. PIT was performed on one of the exposed piles to obtain information on pile quality and pile length. An accelerometer was attached to the pile top and several hammer blows were applied to the pile top to obtain velocity records for the pile. The hammer impact generates transient compression wave that travels down the pile length to its bottom where it is reflected back to the pile top and recorded by the accelerometer. The velocity profiles were recorded and processed. Records were obtained with 3 different hammer weights and a sufficient number of records were obtained with each hammer. Only records containing clear pile features were processed and retained. The processing assumed a wave speed of 13,780 feet/sec, and included amplifying, filtering, and adjusting the records prior to final plotting for presentation of a clear pile toe signal. A typical velocity record for the pile is shown in Fig. 3.

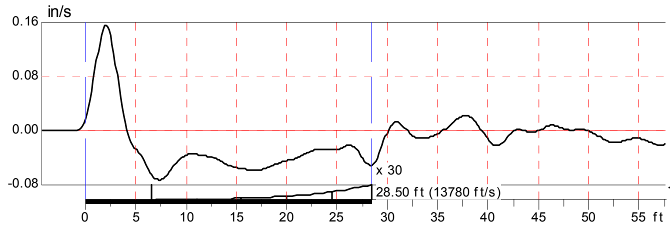

Fig. 3. Typical PIT Record for the Raymond Step-Taper Pile

Although only one record is presented herein, all PIT records indicated strong reflection at a depth of about 28.5 feet (8.7 m) below the impact surface. The reflections reveal the pile toe. Therefore, the test pile is most likely 28.5 feet long, corresponding to a pile tip El. +257 feet. Based on available information from the original pile design, piles in and around the area were noted to have been designed for a tip El. +255 feet which is in close agreement with El. +257 feet indicated by the PIT results, as shown in Fig. 4.

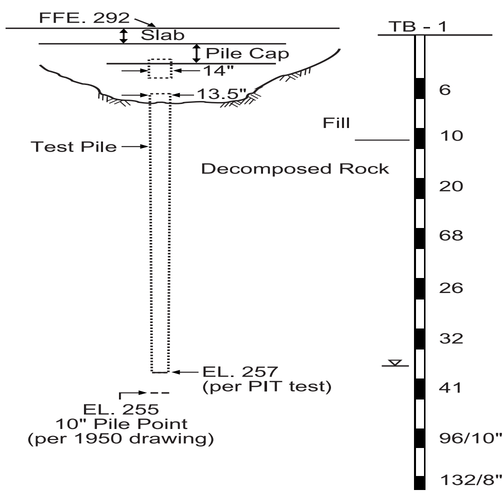

Fig. 4. Comparison of PIT Record with Available Information

Despite lack of records on the actual as-built pile tip, the tip elevations referenced on original drawings appeared plausible for the given piles based on a review of the subsurface soil conditions. Therefore, assuming El. +255 feet as reference per original drawings, the PIT prediction on the pile length was about 7% of that reported on the design drawings. Additionally, the possibility that the actual as-built pile tip is in fact at El. +257 feet, as indicated by PIT, should not be ruled out, in which case the uncertainty in pile length as estimated by PIT would be remarkably minimal.

It should also be noted that the PIT records indicated no measurable defects along the pile length.

<u>Pile Load Testing</u>. Subsequent to performing the PIT, the pile was subjected to a compression "short" load test to evaluate its load-carrying capability, as shown in Fig. 5. A reload cycle was included in the test for the first cycle possibly lacking reliability. The failure load was estimated at about 170 tons. For a factor of safety of 2.0 and 3.0, an allowable compressive capacity for this pile would be about 85 and 55 tons, respectively, which are substantially higher than the 30-ton capacity reported on drawings for the design of the pile caps.

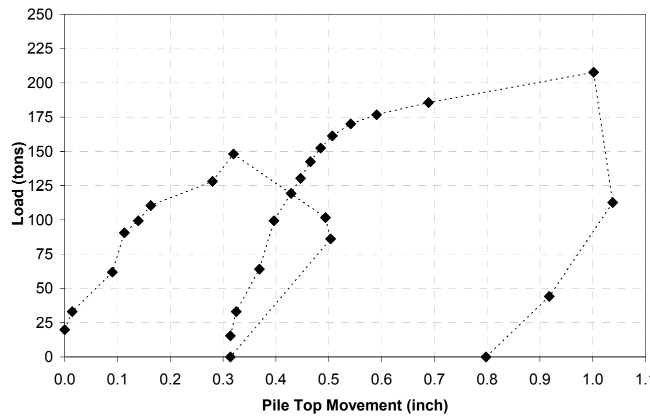

Fig. 5. Compressive Load Test Results on Test Pile

Based on available subsurface information, the ultimate compressive capacity of a single pile was also conservatively estimated using static calculations, calculated as about 60 tons. For a factor of safety of 2.0 and 3.0, the allowable compressive capacity would be about 30 and 20 tons, respectively. The calculated static capacity is in general agreement with the reported design capacity for the pile caps, although it is less than one-half that indicated by the load test result, as shown in Fig. 5.

The results indicated significant variation between available information and the pile capacity as evidenced by the load test result. The exact reasons are not known and would be difficult to determine. However, variations between design and as-built conditions, such as pile size, step taper, length, driving energy, and subsurface conditions, are considered major factors among many others that could cause variations in capacity. Also, the influence of the pile's helical corrugation on its capacity was not accounted for in the calculations, yet is expected to be reflected in load test results as higher failure load. It is also noted that the groundwater level during the load test period was substantially lower than that previously documented, although is not expected to influence the results to the extent that were observed. It is more likely that the higher capacity from the load test, in order of influence, is impacted by key factors such as higher driving energy during pile installation, denser soils near the bottom of the pile, and the pile helical, step taper configuration. Given the variations that could exist in the nearly 1,300 existing piles and that any justifiable increase in pile capacity would have required redesign and retrofit of the existing pile caps, the piles were assigned an allowable compressive capacity of 30 tons each, as reflected on the original drawings for the design of the pile caps.

Case History 2: Augered Cast-in-Place Pile

PIT was performed on a 60-foot long, 14-inch diameter augered cast-in-place (auger-cast) pile installed for a hotel in Ocean City, Maryland. The integrity of the test pile was in doubt after the pile failed at a static load of 83 tons, far short of the anticipated load of 110 tons.

Geology. The soil conditions at the site consisted of sand. Below a depth of 18 feet, the sand was primarily loose.

PIT Results. An accelerometer was mounted on the pile top and several hammer impacts were applied to generate a transient stress wave along the axis of the pile. Acceleration records were collected, automatically integrated over time, and the resulting velocity records were stored. The recorded data was reprocessed in the office, based on an assumed wave speed of 13,000 feet/sec. Several records were obtained; a typical record is shown in Fig. 6.

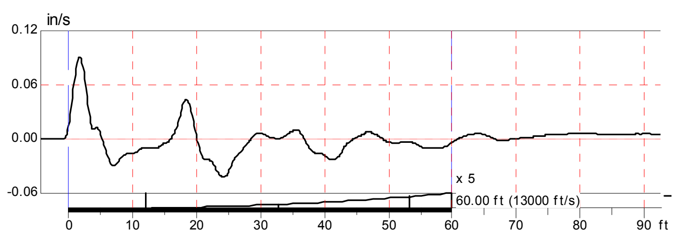

Fig. 6. Typical PIT Record for the Auger-Cast Pile

The records indicated major change in (positive) velocity for the pile at about 15 feet below the top of the pile, with resulting decrease in pile impedance. Such sudden, sharp, positive increase in velocity suggests "necking" of the pile. The pile toe, reported at 60 feet, was not made evident by the records. The observed major impedance reduction at 15-foot is due to a major change in the pile cross-section at that depth, attributed to major discontinuity, which is the likely cause for the pile failing to hold the required static test load. Therefore, PIT successfully provided an answer to the likely reason for the premature failure of the test pile.

Case History 3: Drilled Shaft

A large number of drilled shafts were installed for a retail facility in Round Rock, New Jersey. The shafts were 24 inches in diameter; each shaft was designed for a length of 21 feet. After installation, the actual lengths of the shafts were questioned. PIT was initiated to obtain an estimate of the as-built length of the shaft.

Geology. The subsurface conditions at the site consisted of sand and gravel, sometimes with silt, in the upper 3 to 5 feet followed by silty clay or silty sand to a depth of 9 to 12 feet, and finally glacial till to the boring termination depth of 20.5 feet.

PIT Results. Upon accelerometer installation, impact was applied to the shaft top by different size hammers to generate the stress waves in the shaft. Several records were obtained from each shaft; the records from each shaft were averaged, filtered, and exponentially amplified to enhance record features. Only records with clear indication of shaft features were recorded. Once sufficient data was collected from a shaft, the accelerometer was removed and installed on the next shaft and the testing continued. More than 50 shafts were tested in a 3-day period.

The data was reprocessed in the office, based on a wave speed of 13,000 feet/sec, and plotted. Selected records are shown in Fig. 7.

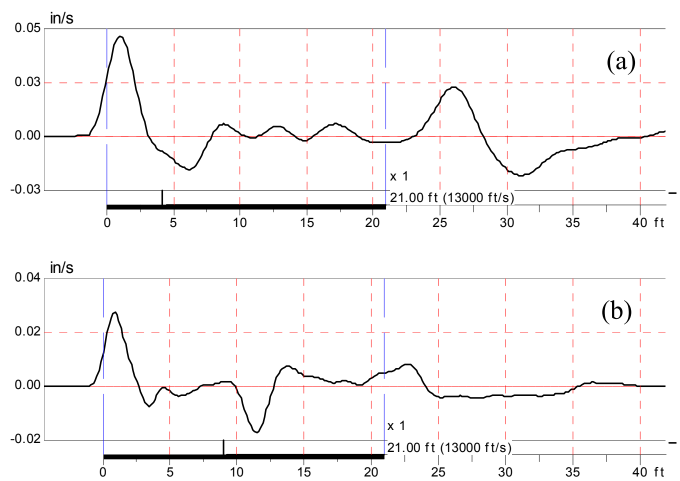

Fig. 7. Selected PIT Records for the Drilled Shaft

As discussed earlier, the velocity response is a function of the soil resistance forces and changes in pile impedance. A slow, mild decrease in velocity over the pile length signifies the effects of soil resistance forces. However, a sudden, sharp decrease indicates a "bulge," i.e., increase in pile diameter, with resulting increase in pile impedance. These features are demonstrated in Fig. 7. Figure 7(a) shows the shaft toe reflection at about 24 feet, indicating the foundation to be about 3 feet longer than the design requirement of 21 feet. In contrast, Fig. 7(b) indicates a sudden, sharp decrease in the velocity response around a depth of about 12 feet, a strong indication of an increase in the pier diameter at that depth. This feature precluded determining the actual foundation length for this particular shaft by preventing adequate energy traveling to the pile toe to obtain a clear reflection from its base. The "reflective" positive velocity at a depth of about 23 feet, as expected from the wave propagation theory, masks any possible toe signal. PIT was successful in supplying information on the as-built condition of more than 50 piers, although in a few cases the results were found inconclusive due to foundation features and the limitations of the method.

CONCLUSIONS

Since the late 1980's, PIT has gained wide acceptability in the foundation engineering and construction community and has become an important tool for verifying pile integrity or pile length. PIT can be successfully used during initial stages of a construction to assist engineers and contractors with quality control/quality assurance needs. It is also a valuable tool to quickly assess as-built foundation features.

The method offers several advantages over other testing methods, including other non-destructive tests, for its rapid deployment, mobility, speed, and cost. A large number of foundations can be tested in a short time using PIT, probably as many as 20 foundations in one day. It is capable of quickly producing information on the possible presence of defects such as voids, breaks, discontinuities, or inclusions, and provides estimates on pile length. The successful application of the technology, however, requires understanding its limitations as well, including operator's familiarity with the system and experience with pile foundations, applications to drilled shafts or auger-cast piles with potentially multiple or large variation in cross-sections, L/D ratio limits, and only where accuracy on pile length within 10%± is tolerable.

Where PIT is found to have limitations, other non-destructive testing methods that can overcome certain PIT limitations may be considered. Obviously, these tests involve a higher level of sophistication, require more time to perform, and are more costly. Discussions on other possible testing techniques are beyond the focus of this document.

ACKNOWLEGEMENT

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