ADVANCES IN THE EVALUATION OF PILE AND SHAFT QUALITY

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Abstract

For the past half century, great efforts have been made and progress has been achieved in developing a variety of electronic testing methods for the quality control and quality assurance of deep foundations. These developments took advantage of major advances in ever more accurate and sensitive sensor manufacturing and faster and more powerful computers. The dynamic pile testing methods were the primary beneficiaries of these R&D efforts and its application has been expanded from bearing capacity assessment of driven piles to drilled shafts, micro piles and even penetrometers. In addition to soil resistance, results from construction monitoring now provide information about stresses along the pile, pile integrity and occasionally soil vibrations. Dynamic pile testing methods also include non-destructive techniques involving sonic and ultra sonic signals. Much of the recent developments involved not only ruggedizing hardware and preparation of more user friendly software, but also deriving reliable calculation procedures and presenting results in a way which is easy for the report recipient to understand. Additionally, experiences from construction sites showed that an immediate assessment of the foundation characteristics is imperative. This requirement lead to the need for easily used simulation software and workshops. Today such training events are frequently performed over the internet. This presentation summarizes several recent hardware and software developments and shows a few typical results.

Introduction

Four different types of deep foundation quality evaluations will be examined. They include:

(a) Construction monitoring,
(b) Post construction evaluation of the pile or shaft bearing capacity,
(c) Post construction evaluation of the pile or shaft structural integrity,
(d) Length and quality evaluation of foundations under existing structures.

Main emphasis in this paper will be placed on driven pile monitoring. Monitoring of driven piles by the Pile Driving Analyze® (PDA) and the related Dynamic Pile Load Testing (DLT) with analysis by CAPWAP® (Likins et al., 2008), Pulse Echo Testing (or Pile Integrity Testing, PIT) and Cross Hole Sonic Logging (CSL) are generally referred to as "Dynamic Pile Testing Methods". They rely on motion measurements to determine wave speeds and/or the response of the deep foundation to an impact. Except for the Cross Hole Method, dynamic testing methods also require or make use of force measurements. Most convenient is, of course, that measurements are taken at the pile top, however, embedded sensors have also are occasionally employed as another means of determining concrete quality or pile toe response.

The fourth task, evaluating foundation type and length under existing structures, often is completed by PIT, however, parallel borehole methods are also available. For concrete piles a stress wave is introduced in the pile and sensed in the borehole and for steel piles, an inductive device senses the proximity of a conductor. These methods have been described elsewhere (Rausche, 2004) and will not be further discussed in this presentation.

Additional background information on these methods will be included in the following summary. A few examples will demonstrate those methods which are of primary interest to the geophysicist with an emphasis on recently improved or developed technologies.

Description of Methods

1. ***Pile Driving Monitoring***

This is the most important and most frequently used dynamic pile testing method. Strain (or force) and acceleration measurements of an impact driven pile during installation are the basis for the calculations. Typical strain and acceleration ranges are between 100 and 2000 $\mu\varepsilon$ and 50 to 2000 g's, respectively. The method has been standardized in ASTM D4945-08. Analysis is done in closed form by the so-called Case Method which solves the one-dimensional wave equation and which has been programmed in a PDA. Taking advantage of the fact that force and velocity at a point can be transformed into the force and velocity components of the upward and downward traveling wave, bearing capacity, pile stresses and pile integrity can be calculated from the upward traveling wave (Likins et al., 2008). Additionally, hammer performance can be evaluated as energy transferred to the pile top together with calculated hammer stroke for open end diesel hammers.

To satisfy the LRFD requirements now demanded by several codes (e.g., AASHTO, 2009), 2 to 5% of the piles on a site are often monitored by the PDA. For reasons of safety, testing speed and convenience, the sensors are now sending signals wirelessly to the PDA. An even greater time and money savings can be achieved by remote monitoring, which allows the experienced test engineers to view the data in real time on their office computer while field personnel installs the sensors and connects the PDA to the internet via broadband devices. The advantage of this method is the ease of test scheduling for the contractor and the reduced travel time and travel cost expense.

Vibrations near a pile driving operation may be considered destructive or at best annoying and certain limits of ground motions have been published (Woods, 1997). More and more frequently it is therefore required to measure surface vibrations in the neighborhood of a pile driving operation. Using commercially available geophones or accelerometers, the PDA accepts, saves and evaluates up to six ground motion signals. This makes possible, direct correlation with energy transferred from the hammer to the pile, pile velocities, or resistances on a blow by blow basis. Furthermore, because the pile impact measurement provides for a distinct trigger signal, accurate timing of the arrival of the compressive wave at the geophone allows for soil wave speed measurements as a function of pile tip penetration (Figure 1). A PDA record of pile top velocity, obtained when a 3 Mg (3.3 ton) ram impacted the 450 mm (18 inch) diameter, augered cast-in-place pile is shown in Figure 2. The pile was 9 m (30 ft) in total length and had a penetration of 8.1 m into the silty, clay soils. Figure 2 also shows vertical particle velocities of the ground surface at a horizontal distance of 6 m (20 ft) and 12 m (40 ft) away from the pile. In this case the compressive wave speeds in the partially saturated soil with slightly frozen top surface was between 975 m/s (3200 ft/s) and 1070 m/s (3500 ft/s). In the future, additional measurements can and should include the horizontal motion components for an assessment of the total, geometric peak particle velocity (PPV).

Combining assessment of ground surface PPV values with pile measurements also can lead to interesting relationships. Figure 3 shows for the site of Figures 1 and 2, the energy transferred to the pile top and the PPV values measured at a 6 m (20 ft) distance from the pile. The transferred energy, calculated as the time integral of the product of pile top force and velocity, was variable because the 3.3 ton ram was dropped from heights between 0.3 (1 ft) and 1.2 m (4 ft).

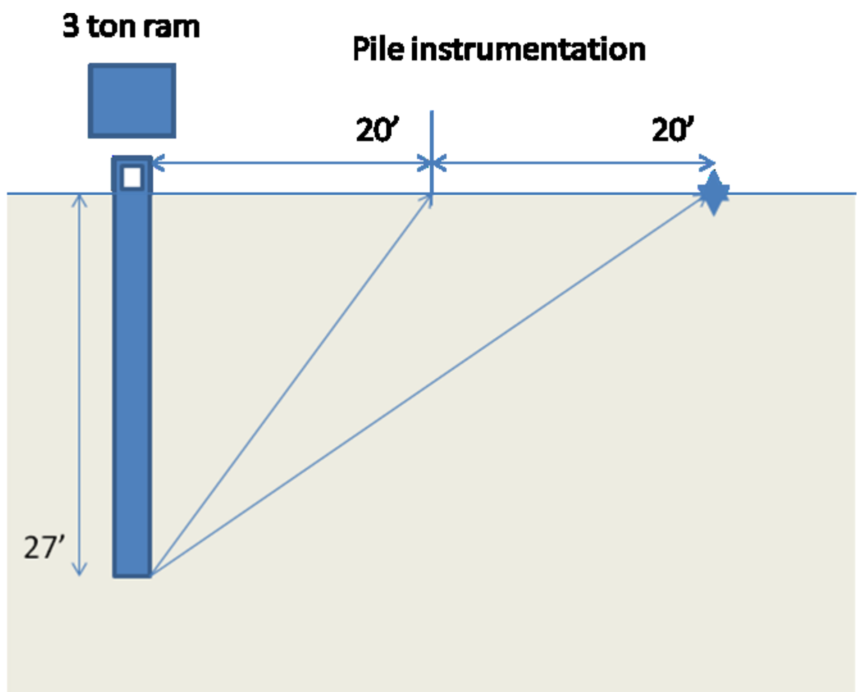

Figure 1: PDA test setup with ground surface velocity measurements.

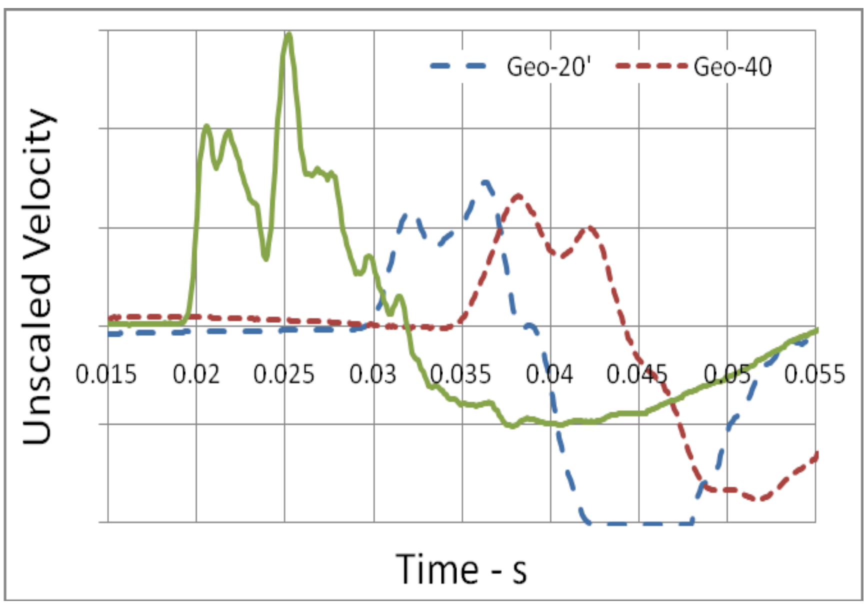

Figure 2: Results from PDA measurements of ground surface and pile top velocity

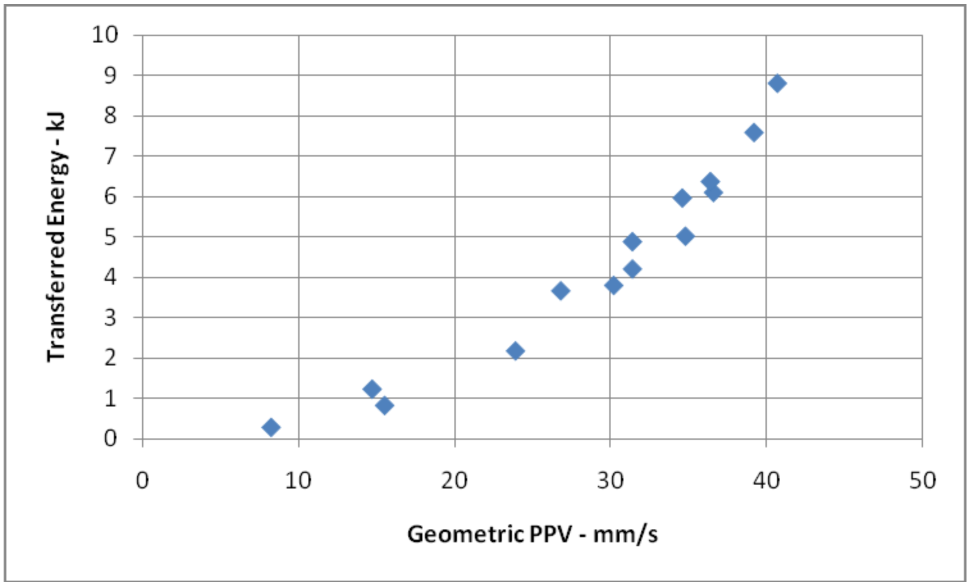

Figure 3: Transferred energy in pile and ground surface PPV at a distance of 6 m (20 ft) from pile

A more extensive study was performed by Robinson, 2006. As shown in Figure 4, he combined ground motion measurements of peak particle velocities (PPV) for consecutive hammer impacts measured at a large construction site in Wisconsin with PDA pile velocity measurements. The PDA monitoring was primarily utilized to determine bearing capacity of the 300 mm (12 inch) to 400 mm (16 inch) diameter, closed ended pipe piles, both at the end of driving and during restrike testing. Using these measurement results, Robinson showed that this information can also be used to develop a wave equation based prediction of PPV at some distance from the pile driving site, based on the GRLWEAP (Pile Dynamics, 2005) hammer-pile-soil model and wave propagation theory.

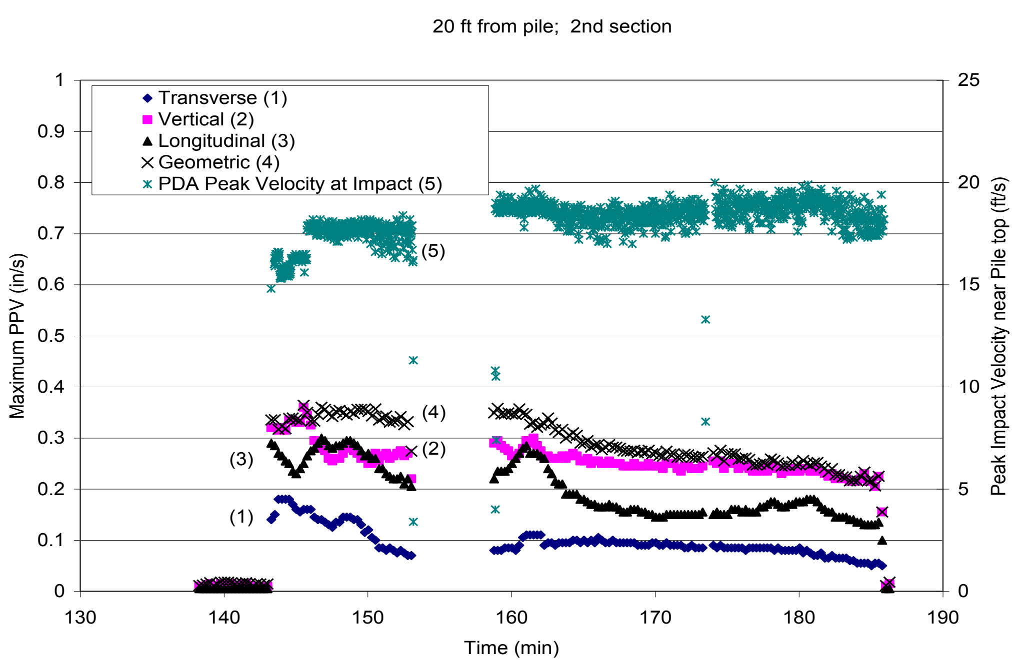

Figure 4: pile top and ground surface PPV values (Robinson 2006)

2. *Dynamic Pile Load Testing*

Performing strain and acceleration measurements at the pile top under a high strain impact according to ASTM D4945-08 yields the necessary measurements for a Dynamic Load Test. The data is analyzed with the numerical CAPWAP approach yielding the load-set curve of a very quick load test. This method is a natural extension of the pile driving monitoring but it has been expanded to very large drilled shafts and to smaller micro piles or ACIP piles (Hussein, et al., 2008; Gomez et al., 2004). In many instances, even for driven piles, a special impact device has to be brought to the site. The so-called APPLE system allows for the measurement of the ram deceleration and, therefore, a pile strain independent determination of pile top force. A pile top transducer is an additional recent development.

Rausche et al., (2007), have described dynamic load test results and their most recent recommendation for the selection of the appropriate record. This is not necessarily trivial, since normally a number of impacts are applied in a dynamic load test and both hammer energy and soil resistance parameters change from blow to blow. Results from a test obtained with a 54 Mg (60 ton) ram on a 1.8 m (6 ft) diameter pile can be seen in Figure 5. In this case, four consecutive hammer blows were evaluated by the CAPWAP program and their simulated load-set curves plotted versus accumulated penetrations.

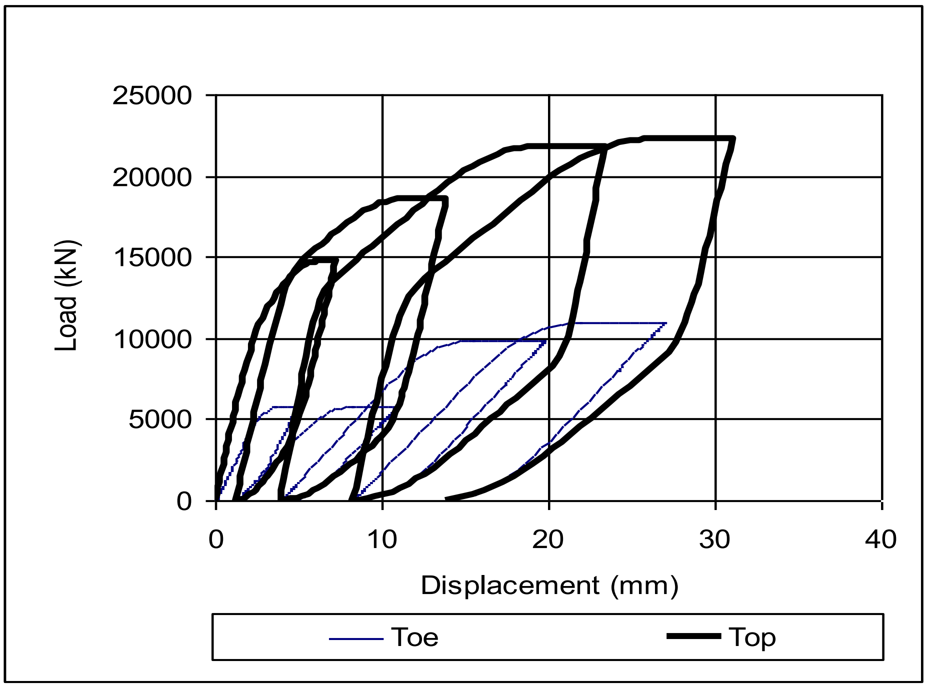

Figure 5: CAPWAP calculated load cycles for 1.8 m diameter drilled shaft (Rausche et al., 2007)

The dynamic load test requires a ram weight between 1 and 2% of the test load. However, it can also take the form of a Rapid Load Test. In this case a very heavy ram, typically 5 to 10% of the required test load, impacts the pile top on a rather soft cushioning. This produces a longer force pulse than the dynamic load test and potentially reduced tension stresses. A recent development, the Hybridnamic device, has a ram weight of up to 80 Mg or 88 tons.

3. *Automatic Blow Count and Hammer Energy Monitoring*

Another, less thorough monitoring of hammer and pile has become necessary because of the variety of pile driving hammers which are being developed and implemented. These hammers offer different features and performance characteristics. For example, open end diesel hammers are now being built with ram weights of up to 25 Mg (28 tons), while hydraulic hammers offer even higher ram weights and associated driving energies. The working and rating principles of these hammer types differ substantially and require occasional monitoring for energy performance verification. Kinetic energy measurements (that is the energy which the ram has immediately prior to impact) can now be made with the E-Saximeter™. Essentially, the measurements determine ram position and timing information for each hammer blow and these results can be converted to ram impact velocity and therefore the hammer's kinetic energy. For diesel hammers the hammer stroke can also be calculated together with stroke. The relative position between hammer and leads (and thus the pile penetration and blow count) can additionally be measured by digital encoder on a cable fastened to hammer and leads, or by laser, radar or other devices. The measured data can be transmitted to a data collector either wirelessly or through cables. This method of pile installation monitoring can be fully automated and, therefore, can be applied to every pile on a site yielding an electronic pile driving log which can be downloaded to a computer spread sheet..

4. Pulse Echo Integrity Testing

The Pulse Echo Method, embodied in the PIT equipment, requires a low strain (less than 10 $\mu\varepsilon$) impact with a hand held hammer (Rausche, 2004). The method is standardized by ASTM 5882-07. Instrumentation includes one or two accelerometers and, optionally, an instrumented hammer. The latest developments do that with wireless equipment and a very low weight, high resolution monitoring equipment (Figure 6).

Evaluation of the records is normally done in the time domain and takes advantage of the fact that the force pulse is a simple half sine pulse which is short compared to the wave travel time. The velocity has a proportional impact pulse but then displays the upward traveling wave which provides information about pile and soil characteristics. The analysis can also be done in the form of mobility vs frequency which additionally yields a dynamic stiffness value. A Pile Profile provides an easily understood visual result. Admittedly, this result is somewhat subjective and relies for its accuracy on (a) knowledge of the concrete volume, (b) the actual pile top diameter and (c) a clear reflection from the pile toe.

Figure 7 shows both a pile top force-velocity-time record (time downward positive) and a calculated profile from a Pulse Echo Test measurement taken on a 610 mm (24 inches) diameter pile. Calculation of this profile involves first the definition of a reference line which accounts for the soil resistance effects on the pile top velocity and secondly, an integration over time of the difference between velocity and reference curves. In the present example, the record indicates a reduction of size of concrete quality between approximately 7 (23 ft) and 9 m (30 ft) depth.

Further analysis provides the response of the pile top in the frequency domain. For the example of Figure 7, the force, velocity and mobility (velocity divided by force) curves are shown in Figure 8. The linear increase of mobility at the origin can be interpreted as a characteristic pile stiffness. Frequency intervals between peak mobility peaks indicate pile length and depth to defect. However, these distance values are easier evaluated in the time domain. Similarly, distinguishing between bulges and necks are also more easily determined in the time plots. The reason is that bulges produce a leading negative signal followed by a positive one while necks have the opposite phase information. Because of the missing phase information in the frequency response plot, such timing information is not apparent.

It should be mentioned that it is very instructive to perform a so-called PIT-S simulation of a Pulse Echo Test. The software is freely available on www.pile.com for initial inspection and tryout. It allows for the variation of hammer impact point, measurement location, soil strength and distribution and pile configuration. This software is very versatile and aids in the preparation and interpretation of a PIT test.

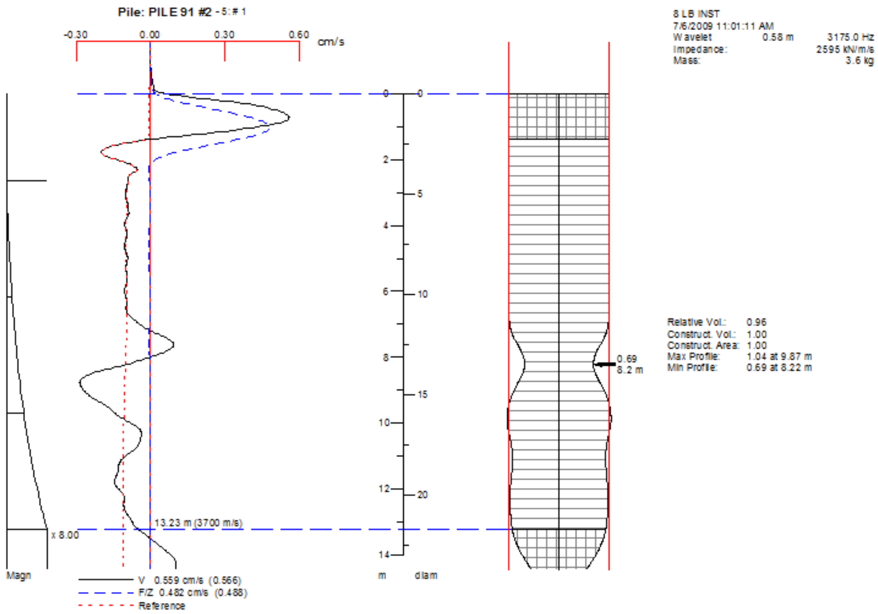

Figure 7: Pile Profile calculated from PIT records for a 610 mm diameter drilled shaft

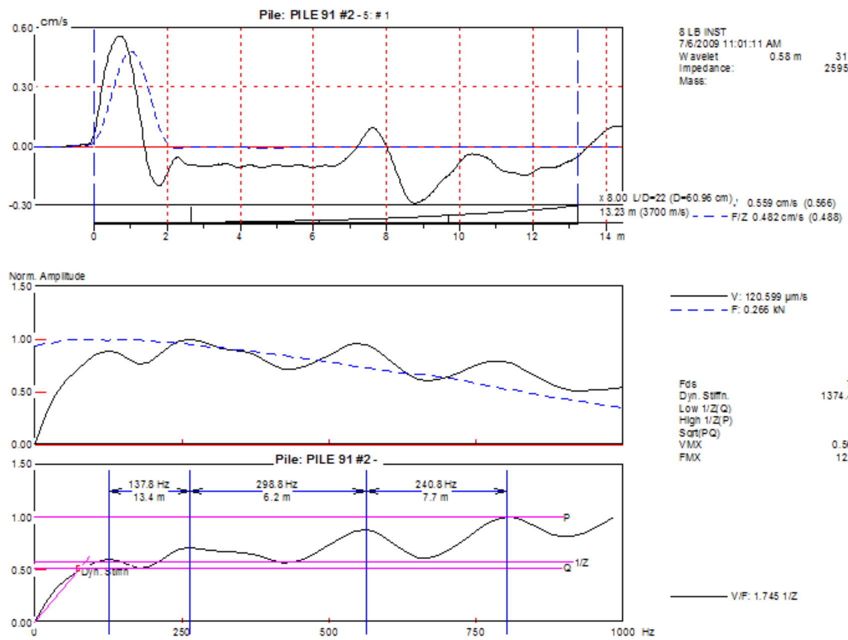

Figure 8: Frequency response of the Figure 7 example

5. Cross Hole Sonic Logging

Cross-Hole Sonic Logging is another dynamic pile testing method which is based on the traveling wave concept. As described by Rausche 2005, the method uses ultra-sonic pulses transmitted horizontally from one vertical inspection tube to another one. Measuring the wave travel time between the inspection tubes yields a detailed concrete quality assessment. The method is standardized by ASTM 6760-08. Recent improvements have been made in the area of sensor sensitivity allowing clear signal arrival detection for distances in excess of 3m (10ft). Also, the work can now be greatly simplified by means of motorized cable drums. The method allows for quality assessments of large piles and/or barrettes. A related method, Single Hole Logging, of either ultrasonic pulses or back scattered gamma radiation, helps identify defects in the concrete cover zone of a drilled shaft. Interpretation is not always simple and further study is warranted.

After a defect has been detected in a shaft by CSL, further quantification is usually desired. This can be achieved with a Tomography analysis which is closely related to geophysical data presentations. The relatively limited information from a CSL test is subjected to an inverse analysis which finds the most likely wave speed distribution in a shaft element grid from the wave speeds measured between inspection tubes. An example is show in Figure 9. This is the image obtained for a 1.5 m diameter shaft of 12 m (40 ft) length with known defects. Measurements were taken between 8 inspection tubes. Zones with concrete wave speeds less than 2100 m/s (7000 ft/s) have been depicted with dark colors as those of potential defects. In the present case these defects were either sheets of Styrofoam or sand filled buckets.

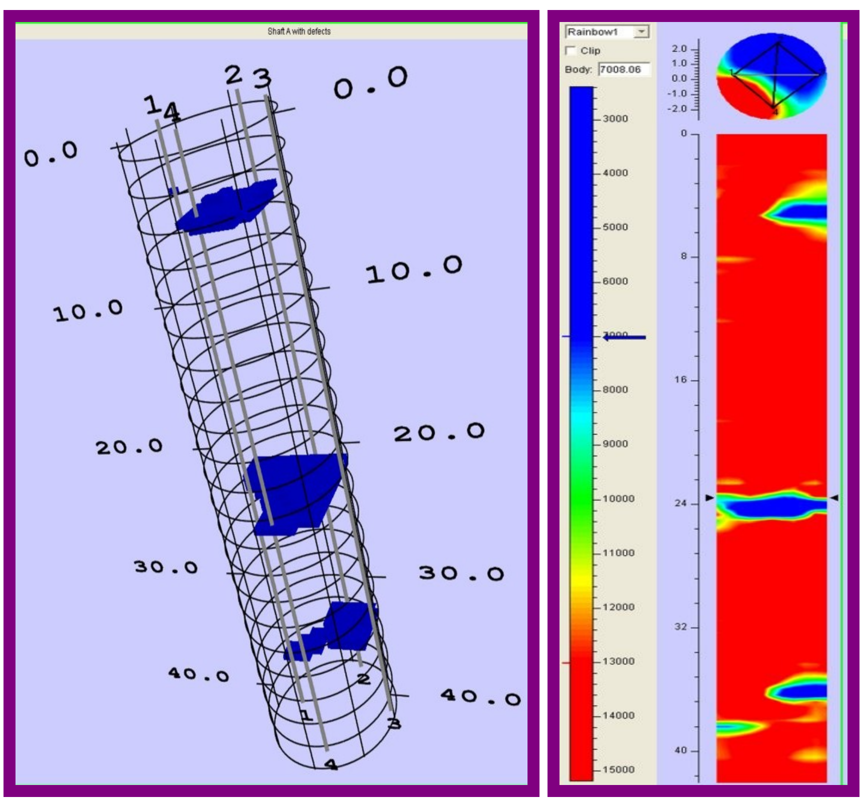

Figure 9: Tomography of a shaft with planned defects.

Summary

Today's deep foundation QA/QC methods take advantage of a number of different dynamic testing methods which are based on motion and force measurements and whose interpretation is based on wave propagation theory. The more powerful methods involve not only motion but also force measurements and provide results of pile capacity, stresses and soil stiffness. Recent developments allow for simultaneous measurements of soil surface motion. In addition, the methods provide for pile material wave speed results which can be interpreted regarding material quality and strength. Advances have been made in the quantity and quality of measurements and in the interpretation techniques. In addition wireless and remote testing technologies help reduce the cost of QA/QC.

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