# MONITORING QUALITY ASSURANCE FOR DEEP FOUNDATIONS

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**ABSTRACT**: Constructing deep foundations is both an art and a science and their as-built acceptance should be based on evidence of quality confirmed by testing. Early prevention of problems is the most effective means to avoid costly and time consuming construction delays. Recent developments in equipment and methods aid in real-time monitoring of various pile installations.

For driven piles, monitoring of diesel hammers has been done for years using the Saximeter. The measured kinetic energy of any hammer type can now be transmitted by telemetry to the Saximeter unit and stored electronically in an installation log for downloading or computer printout. Traditionally, the Pile Driving Analyzer (PDA) is used by an experienced engineer who collects and interprets measurements on the construction site, and later issues a report after returning to the office. The engineer's travel and availability often dictates the testing schedule and impacts the construction activity. Utilizing wireless cell phones, dynamic pile testing can now be done remotely at the contractor's convenience with substantial cost savings and even more substantial time savings. In the office, the PDA engineer receives and simultaneously views the measured data in real-time, immediately analyzes the data, and summarizes the monitoring results, often issuing the test report within hours of the test. Thus, the foundation installation and quality assurance testing proceed without interruption or delay.

Devices are available for auger cast-in-place pile installations to guide the contractor in real-time to installing a good pile with documented quality so that it can be accepted without doubts or time delays. For drilled shafts, the most common quality assurance tool is cross hole sonic logging (CSL). New 3D tomography analysis of CSL data holds further promise to evaluate the quality of drilled shafts.

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The paper describes these new monitoring devices and illustrative experiences from actual project sites. Recommendations for use and future developments are made.

## INTRODUCTION

Inspection is part of the quality assurance process. Traditional inspection required on-site engineers or inspectors to monitor activities. This was generally limited to visual evaluations of equipment and procedures. Advances over the past 40 years in electronic instrumentation have greatly improved the measurements that can be made. More appropriate, persistent and knowledgeable inspection leads to an increase in reliability and reduction of risk. But often the measurement was taken and the evaluation made days later in the office by the engineer. If the measurements confirmed proper construction, the late evaluation did not cause more problems due to delay the construction. However, if the measurements delayed the progress of construction, or found problems that required correction (often at additional cost due to after-the-fact remediation), then delayed reporting of results was less than ideal. Measurements taken at the convenience of the contractor's schedule, in proper sequence and evaluated almost immediately, are preferred to reduce later problems and remediation costs. Electronics have progressed in the last decade where real-time measurements for deep foundation solutions are made routinely by construction personnel or civil engineers with little electronics knowledge.

Communications have been markedly improved. In previous years, only larger projects had on-site land phone lines. Now, cell phones make practically all sites accessible. Immediate reporting of problems and observations to the engineers in a distant office is routine.

Many measurement instruments acquire data digitally. Results can be saved directly or transferred and stored in computer files. These files can be transmitted electronically by email or over the internet to engineers for immediate analysis and confirmation of quality. But this process may still require manual manipulations of data files. Newer electronic devices can immediately give guidance and/or communicate results to decision-making engineers. Deep foundation installations require inspection, and electronic methods now commonly can provide significant detailed inspections automatically.

## DRIVEN PILES: HAMMER ENERGY AND PILE BLOW COUNT MONITORING

The routine monitoring of every driven pile includes counting hammer blows. However, blow counts without hammer performance information is of limited value and blow counting is a tedious task that is prone to mistakes by the inspector, either because of distractions or boredom. Electronically, the sound of the hammer impact can be used to detect the hammer blows. The time between blows can also be accurately determined and this blow rate converted to an equivalent blows per minute (BPM). The blow rate can be used to calculate the stroke (H) for open-end diesel hammers from the equation:

$$H\ [ft] = 4.02\ (60 / BPM)^2 - 0.3$$

The so-called "Saximeter" hand-held unit has been used to count blows, determine blow rate for any hammer type, and calculate stroke for open-end diesel hammers. The operator presses one key every penetration increment (e.g., every foot, or perhaps inch) and the Saximeter summarizes the average result (blow rate or stroke) with the blow count for that penetration increment, thus compiling a complete driving log automatically. Results are stored in memory and can be downloaded electronically for storage and output. These results can be sent electronically from the site to any location using e-mail.

The hammer performance should be part of any driven pile installation inspection since it has a direct effect on blow counts, and thus assessment of pile quality. Unfortunately, inspectors relying on traditional visual inspection often only focus on just counting blows and then ignore observing the hammer because it is very difficult to focus on more than one parameter.

Hydraulic hammers have a variable stroke which directly affects energy transferred to the pile. Because of this variability, some hydraulic hammers have built in inductive proximity sensors to monitor the impact velocity and hence kinetic energy developed by the hammer. Knowing the kinetic energy aids in evaluation of the pile installation and acceptance. These inductive proximity sensors create an electrical oscillating sensing field that is emitted away from the face of the sensor. When a metallic object such as the hammer ram enters this sensing field, it causes a disturbance in the field that is detected by the sensor. When a pair of sensors are strategically placed at a fixed distance apart axially along the ram travel path and so they are activated just prior to the ram impact, the ram impact velocity can be computed from the time required by the ram to travel the known distance between the sensors (hammers that lack proximity sensors can have proximity sensors attached as an add-on device).

A recent advance in Saximeter technology is the inclusion of proximity sensor inputs for the purpose of measuring hammer kinetic energy just before impact. From a small battery powered electronics package attached to the hammer, the proximity sensor output can be sent by telemetry to the Saximeter to record and produce a real time display of kinetic energy of any hammer equipped with proximity sensors. The use of telemetry avoids a connecting cable which is often in the way and subject to failure. Monitoring hydraulic hammers for kinetic energy is considered an essential part of good inspection practice and to confirm the driving criteria.

The actual kinetic energy at impact and also the energy transferred to the pile are sensitive to the blow rate for all hammers. Even traditional air hammers while thought to have a "constant stroke", in reality have a variable stroke and depend on the pile resistance and air volume and pressure input for their actual performance. For example, the data in Figure 1 shows a strong correlation between blow rate and energy transferred to the pile for a double acting air hammer on a steel pipe pile. Blow rate dependence has also been observed for single acting air hammers. Proximity sensors can be attached to these air hammers to measure actual kinetic energy. Some diesel hammer manufacturers are now equipping their hammers with

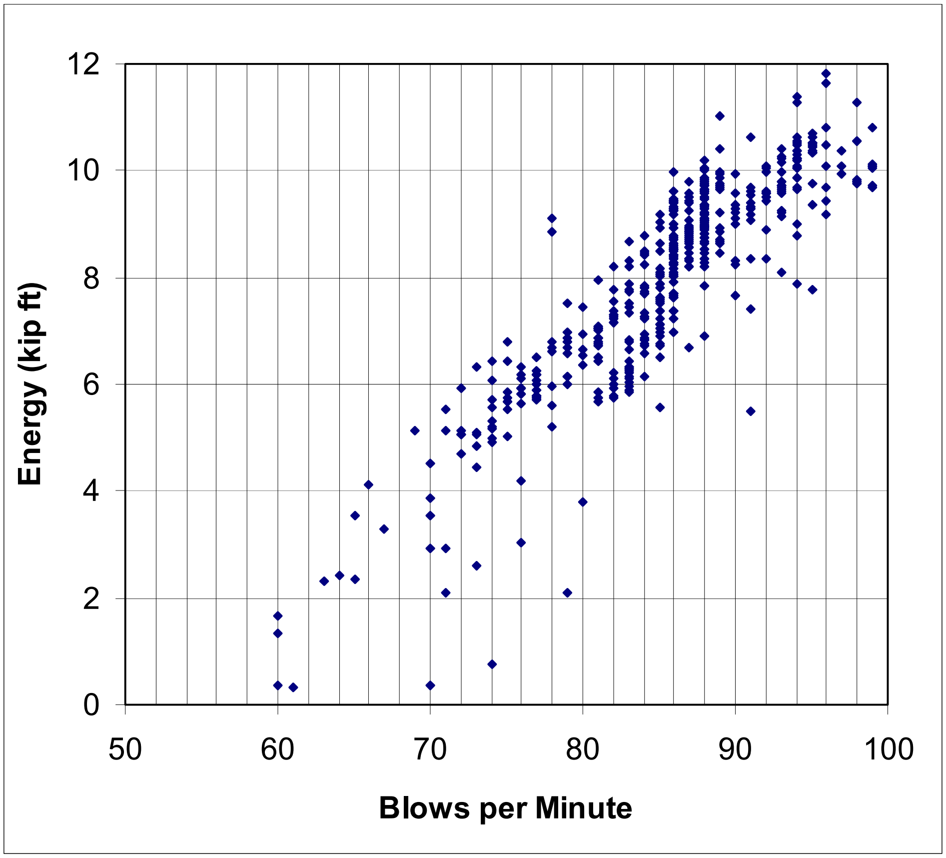


**FIG. 1. Energy Transferred Versus Blows/Minute for Double Acting Air Hammer**

proximity sensors to read out kinetic energy, partly in response to specifications which require such readout for hydraulic hammers. Though not quite as informative as kinetic energy, the stroke of open end diesels, related to both blow rate by the above formula and to pile resistance, correlates well with energy transferred to the pile as shown for a typical case as shown in Figure 2.

## DRIVEN PILES: DYNAMIC PILE TESTING

Dynamic pile testing with a Pile Driving Analyzer® (PDA) was a development sponsored initially by the Ohio Department of Transportation and the Federal Highway Administration (FHWA). It has become routine practice as evidenced by inclusion in many codes and standard specifications in use in the United States, and many other countries. It is often used to supplement static testing, or even replace static testing when the economics do not justify a static test due to project size or rapid construction requirements. PDA tests also monitor energy transferred to the pile and driving stresses to assure proper and efficient hammer performance as assumed by the wave equation analysis usually used to set the initial driving criteria.

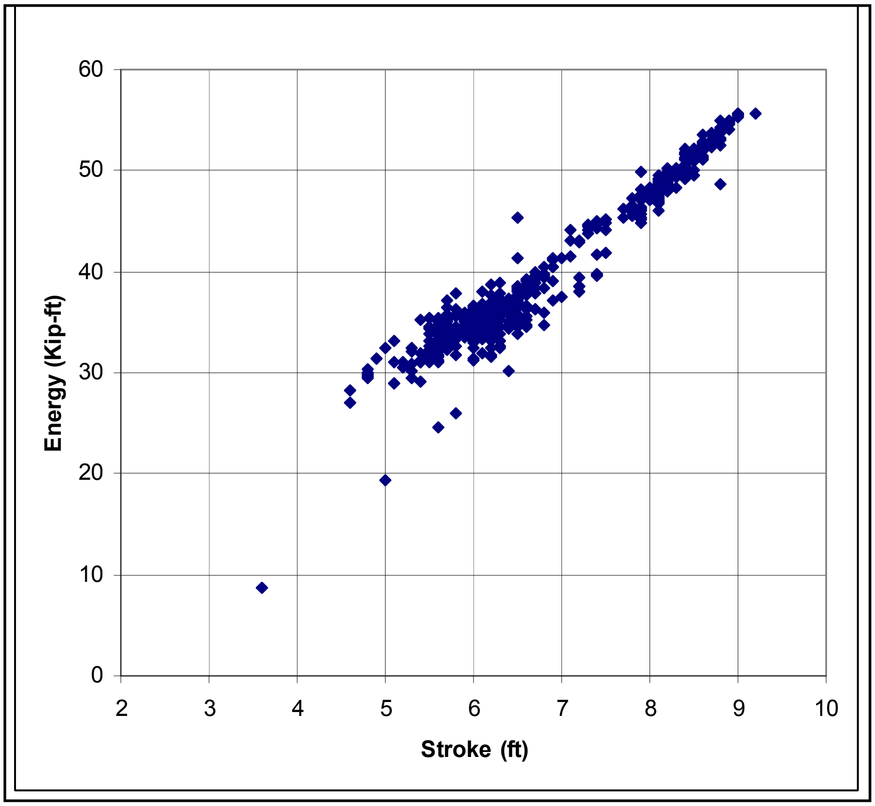


**FIG. 2. Energy Transferred to Pile from a Diesel Hammer**

If stresses are of concern, the hammer stroke or cushion properties can be adjusted to reduce the likelihood of pile damage; again, the effectiveness of such measures should be monitored.

Traditionally, PDA testing was done onsite by the engineer. However, this results in added expense to the project due to travel time and associated costs. In many cases, scheduling conflicts resulted in waiving the testing when the engineer was not available. Because of the large number of bridges simultaneously under construction, it is difficult to monitor all projects with existing personnel, and therefore benefit of the testing is lost on some projects.

A new "remote" PDA called the PAL-R eliminates most of these problems because the engineer is not physically on site. The PAL-R is shipped to the job site prior to the testing. Sensors are attached to the pile by the pile driving crew, normal practice even when the engineer is on site. The contractor presses a button on the PAL-R to connect it with the PDA engineer in the office. The PAL-R collects the data on site and transmits it by cell phone or satellite phone to the engineer's office for processing and analysis. Although the engineer is not physically on site, by voice communication over another cell phone, the engineer is in constant contact with the site during the usual remote test. The site inspector can report any unusual occurrences, and can answer any questions posed by the test engineer. The test engineer sees from the data being received exactly the same information usually obtained on site, and thus can diagnose hammer problems (and observe stroke for diesel hammers, or record blows per minute), evaluate driving stresses, confirm pile integrity, and determine the Case Method pile capacity (Rausche 1985) at the time of testing, and can thus provide advice to the site as the test is in progress.

This revolutionary development has major benefits. Testing in the traditional manner resulted in considerable unproductive time for the test engineer. Unanticipated weather delays or contractor's equipment problems added to costs as did testing a pile both during installation and then a few days later during a restrike, requiring two site visits. Using remote testing, travel by the engineer to the site is eliminated and thus the requirements for test data are not compromised by the calendar. When multiple tests are required the same day, and with only a limited number of engineers qualified for PDA testing, scheduling difficulties often cause the traditional testing to be waived when no engineer is available on site that day, and as a result the quality assurance program is compromised. With the remote PDA testing, one engineer can efficiently handle multiple tests from different site locations in the state (or even from multiple states) in the same day, reducing engineering costs and assuring that testing services for quality assurance are available when needed for all projects. Remote testing can be bid on a fixed "per pile tested" basis, practically eliminating the contractor's test cost uncertainties which should result in lower test prices to the owners. If the testing is done remotely by the highway department, then only the time for the actual test by the contractor is of concern.

The final analysis and reporting of results for a traditional engineer-on-site dynamic pile test occurred after the engineer returned to the office. With innovative remote PDA technology, the engineer doesn't leave the office. Measured data is simultaneously sent by cellphone to the PDA engineer's office computer. Upon completion of the data collection, the engineer can immediately begin the data analysis. This dramatically reduces reporting time delays and speeding up the decision making process.

Thus, dynamic testing using remote technology has several advantages (e.g. lower cost testing, improved scheduling, faster reporting of results) over traditional on-site testing.

There are times when the engineer might go to the field (e.g. at the start of a large project), and the engineer can connect the PAL-R to a laptop computer on site for immediate analysis. However, most subsequent dynamic testing can then be performed remotely, which is particularly helpful for restrike tests after several days to include setup in the evaluation of capacity (a very cost effective procedure). Remote testing then is financially justified and the scheduling of restrikes easily incorporated by the contractor. Remote testing is also valuable for occasional periodic monitoring during construction to assure that the hammer performance is consistent. In contrast, the logistics and costs of the subsequent traditional on site test often prohibit hammer performance monitoring or restrike testing with the preferred wait times.

As an example of use of remote dynamic testing, a 12x74 H- pile was driven as a test pile by an APE D30-32 open-end diesel hammer for the E470 toll road widening at Peoria Street in southeast Denver, Colorado. This relatively small project included 40 additional piles in two abutments and wing walls. The axial design load was 184 kips [820 kN] based on an 8.5 ksi (59 MPa) design stress. The piles were driven to a claystone bearing layer to a final blow count of 10 blows per inch (25 mm). Using the standard AASHTO safety factor of 2.25, the required ultimate capacity was 414 kips (1840 kN). The PAL-R was sent to the contractor two days in advance of the testing. When the test piles were driven, the contractor attached the sensors to the pile and connected the PAL-R via cell phone to a Cleveland engineering office where the PDA engineer acquired the measured (MSD) force and velocity data (Figure 3)versus time (ms is time in milliseconds, L is pile length, and c is material wavespeed) and immediately then performed a CAPWAP® analysis of the PDA data which yielded an ultimate capacity of 830 kips [3690 kN], or about double the required ultimate value. Figure 4 shows the CAPWAP simulated static load test result. The fully analyzed results were transmitted back to the contractor the same day to confirm sufficient pile capacity and hammer performance. Since the pile drove relatively easily and took up relatively quickly, savings in pile length would be relatively minimal in this case and the contractor elected no change in driving criteria. The extra capacity also provided insurance in case of possible relaxation in the claystone although local experience suggests no relaxation.

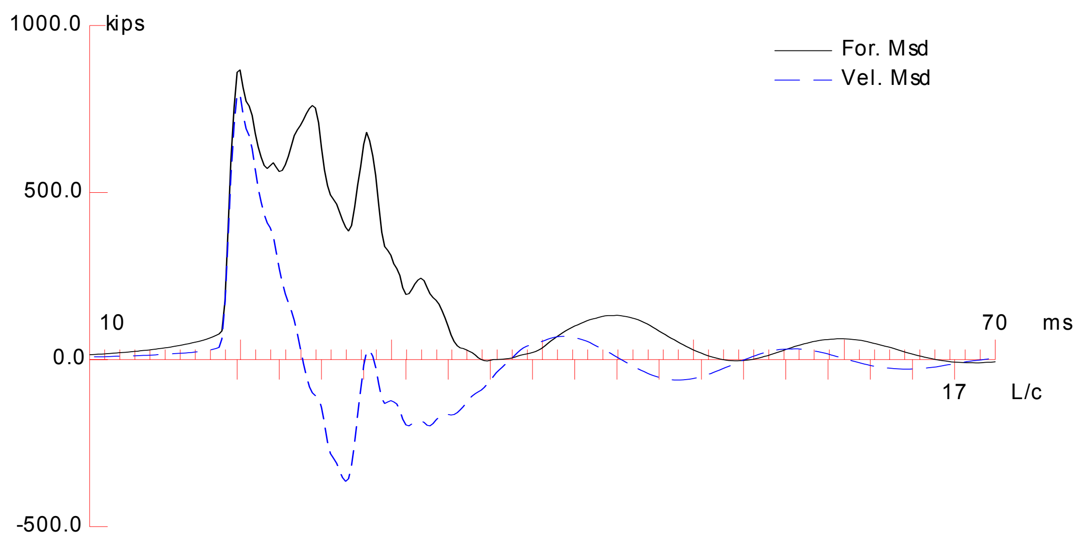


**FIG. 3. PDA Data from Remote PAL-R on E-470 Project**

This same remote PDA testing process was used by the same contractor for a public utility project in Fountain, Colorado with the data again sent to and analyzed in Cleveland. In that case the H pile design stresses of initially 9 ksi [62 MPa] were increased to 18 ksi [124 MPa] at the suggestion of the contractor, and dynamic testing on an indicator pile driven to the claystone rock suggested the piles could be driven to twice the ultimate capacity (with the same safety factor 2.0). A static test was used to confirm the dynamic testing results and the ability to use these higher loads. A safety factor of 2.0 was considered sufficient for the higher loads. Critical piles (those with the highest actual loadings) were marked by the structural engineer and were included in the quality assurance program which included remote dynamic testing on 25 of these critical piles. The test program and higher design stresses resulted in a

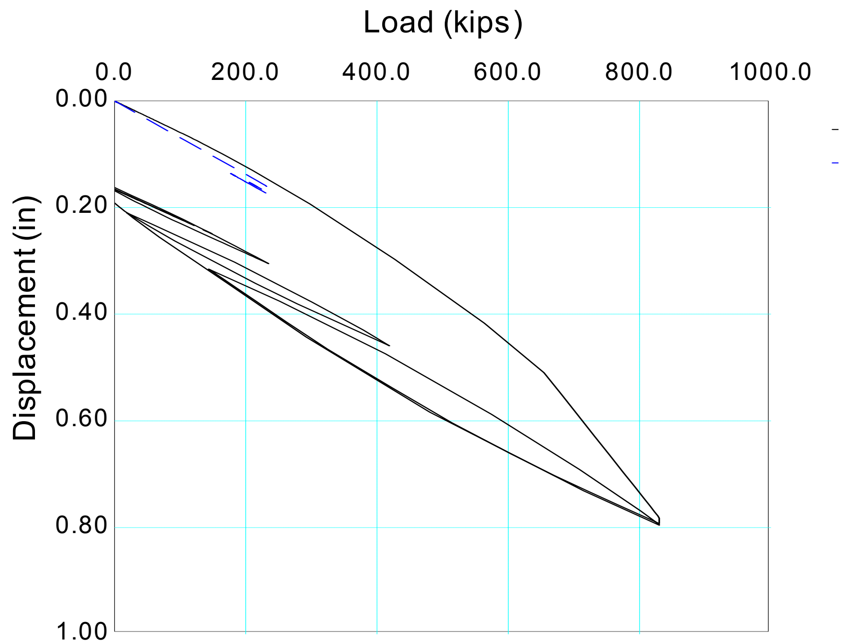


**FIG. 4. CAPWAP Simulated Static Test for E-470 Project**

reduction of number of piles required. Because the piles were driven slightly deeper than for the conventional design, and because all pile locations did not contain an even number of piles, the total pile length was not reduced by 50%. However, actual savings in estimated project pile lengths were 35% and therefore provided substantial savings to the owner (Frazier, 2002).

These two PAL-R test cases show that design stresses for H piles driven to rock can be substantially increased, given adequate testing to prove these higher loads. Because of relatively low remote testing costs, dynamic testing can be used on any size project to give this assurance. Similarly, piles which have substantial setup can also achieve higher design stresses. If the E470 project had a larger scope, the design stresses could have been increased to reduce the foundation costs. The information gained on this E470 project could be used by the highway designers for future projects. If sufficient testing during these small projects seems to always find additional capacity available, then subsequent designs may eventually reflect this through higher stresses and fewer piles. Thus in addition to confirming adequacy of the current designs, potential substantial savings on future projects justify additional testing on these small current projects.

## AUGERCAST PILES

Auger cast-in-place (ACIP) piles are constructed using a continuous flight hollow stem auger. The auger drills into the ground to the design depth. Grout is then pumped through the hollow stem to the bottom of the auger and into the soil as the auger is withdrawn, leaving a column of grout. A reinforcing rod is then usually placed full length in the center of the grout. In some cases, a reinforcing cage (often only partial length) is inserted into the grout.

Traditional inspection of auger cast-in-place piles in the USA is primitive, and unfortunately this inspection is still the norm, although progress has been made in the last few years to a more enlightened approach. Grout volume traditionally was determined by counting pump strokes. Although the guidelines promoted by the Deep Foundations Institute (DFI) for many years recommended obtaining volume in five foot increments (DFI 1990), in practice usually the volume was only recorded for the entire pile, with the actual distribution along the shaft unknown. With such little construction control, many engineers and particularly highway departments were reluctant to accept augercast piles for their foundations.

Instrumentation has been developed to automatically monitor the grout (or concrete) volume injected as a function of depth. Several systems work on a principle of counting pump strokes and using a volume per pump stroke. However, such systems are inherently inaccurate because the pump itself is variable (even missing or making false pump strokes). This deficiency was observed in the United Kingdom many years ago and the Institute of Civil Engineers' current recommendations (ICE 1996) require a magnetic flow meter to measure volume. This is also an essential element of the Pile Installation Recorder (PIR-A) System. Grout volume as a function of depth is obtained by the PIR-A with resolutions of one liter for volume and one inch (25 mm) for depth. Obviously, a one inch depth resolution is too fine for practical use and presentation of results and a two foot (or 500 mm) resolution is usually recommended, as discussed below.

The current DFI guidelines (DFI 2003) suggest optional use of "automated monitoring equipment" (AME) with flowmeters. AME devices can accurately document the drilling phase (time and torque versus depth), and the grouting phase (volume versus depth). There is real time guidance in the grouting phase for the operator. A graphics output displays actual volume versus the target volume (e.g. 115% of theoretical) for each user selected depth increment (usually 2 foot increments). If any incremental volume is lower than desired, then the operator simply re-augers past the deficiency and re-grouts the hole properly. A numeric display also continually shows the percent overage. Because of this more accurate and complete information, the operator can then install piles that are more uniform in volume versus depth, and more importantly can avoid sections of pile which are under grouted. This information is all stored on a memory card and results are also printed on site immediately after pile completion. If a deficiency is flagged by the printout, the engineer or inspector can immediately request the pile be re-drilled and re-grouted while the grout is still fluid to correct the potential problem. The electronic files can be transferred to a computer, and results sent by email in electronic form to the supervising engineer in a distant office. In the future, the results might be sent by cell phone directly from the PIR data acquisition device.

The grout pumped as a function of depth (as determined by an AME system) for a 16 inch diameter auger cast-in-place pile installed with a continuous pull procedure is shown in Figures 5. Of course, while the graph shows the distribution of grout pumped versus depth, there will be some redistribution of grout due to its fluid

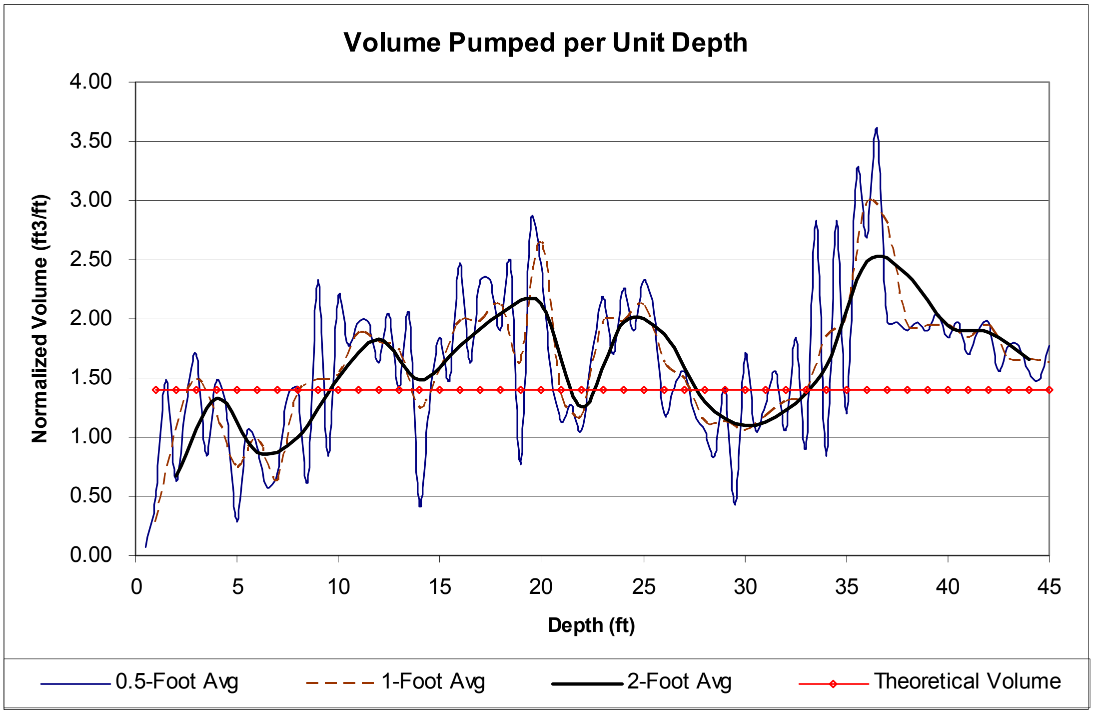


**FIG. 5. Volume Pumped Versus Depth for Augercast Pile**

condition. The required grout ratio (compared to the nominal or theoretical volume of the hole) was 115% for this project. Graphically, Figure 5 presents the PIR-A results recorded in one inch increments and averaged over various depth intervals. The nominal or theoretical volume equivalent to the hole created by the auger diameter is also shown for reference (grout ratio 100%). Because of the pulsing of the pump, it is obvious that reporting at less than 0.5 ft intervals is not practical. At a 1 ft resolution, the data are useful, but not yet consistent. The recommended 2 ft depth increment is smooth enough to be useful, yet yields detailed information where sections may fall below desired levels. It is clear that a section of pile exists at about 30 ft where the grout pumped did not even reach the theoretical volume, and was well below the 115% grout factor ratio required on the project. The volume was also low above 10 ft, which is not surprising as the grout return was observed at 11.1 ft and the contractor chose to withdraw more quickly.

On another project, the PIR-A monitored the installation of 15 inch auger cast-in-place piles with a required 115% grout factor. Figure 6, which demonstrates the installation of pile 209, shows the withdrawal rate of the auger and the pumped volume rate for the grout. Time zero represents the beginning of the auger withdrawal at the maximum depth of 50 ft. After 4.3 minutes, the auger tip reached the ground surface at depth zero. Between times one to two minutes, and also at about 2.5 minutes, the withdrawal rate is relatively slow compared to the rest of the grouting operation. Similarly the pumped volume rate is also relatively low. Because the auger cast-in-place operator followed the guidance of the PIR-A, the

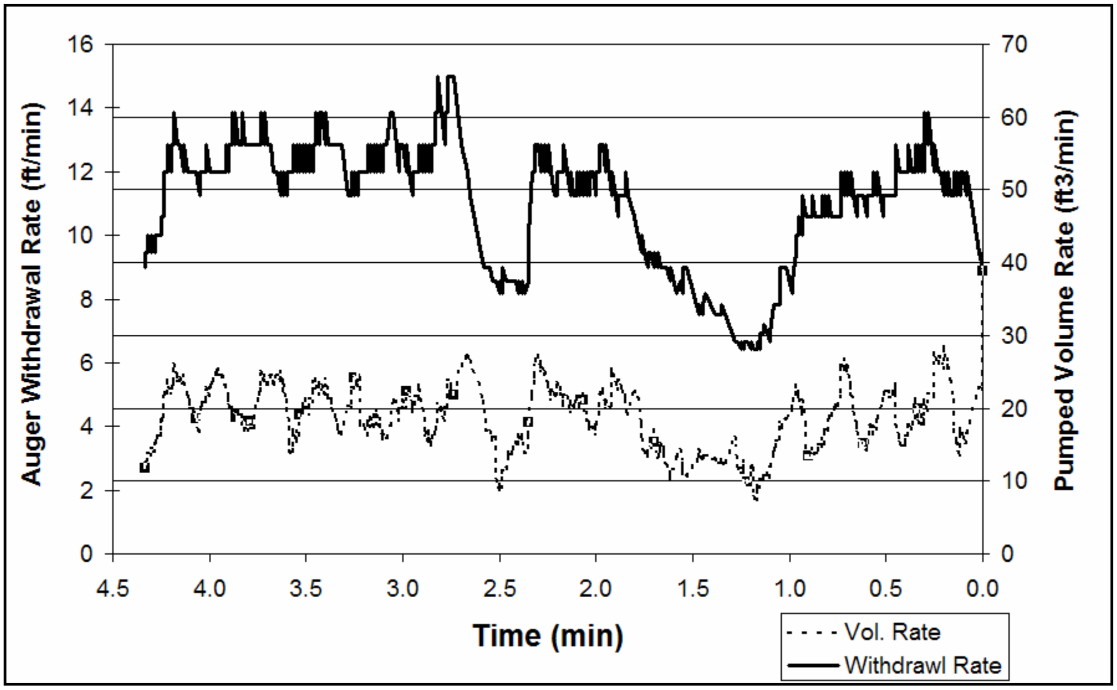


**FIG. 6. Volume Rate and Withdrawal Rate Versus Time**

resulting volume pumped per incremental depth along the shaft is then fortunately reasonably constant, considering the observed variability in the pump and withdrawal process.

The pumped volumes are above the 100% theoretical volume of the hole as shown in Figure 7, even though the withdrawal rate was so variable. Figure 8 compares the measured pressure in the grout line with the pumped volume rate. At the times when the volume rate is low, there is also an obvious disturbance in the grout pressure. During this time, the pump was "operating" and "strokes" were counted, but the ball valves of the pump malfunctioned causing the greatly reduced actual grout volume. There were a small number of other pump malfunctions lasting only one or two strokes in this sequence, such as at about 2.9 minutes and 3.6 minutes. Had the AME equipment not been used, a pile with at least two serious defects would have been the likely result, thus clearly demonstrating the value of real-time monitoring equipment for auger cast-in-place piles.

## DRILLED SHAFTS

Drilled shafts are often required for lateral loading cases or for scour considerations. Drilled shafts are constructed by a variety of methods, often depending on the soil profile for the site. In most cases, a casing is installed to facilitate keeping the hole open during the drilling process. The casing might be almost full length, or in many cases only a partial casing for the very upper section of the pile. The casing may in some cases be left in place, but often it is considered temporary and is removed during installation as the concrete is placed, or at the end

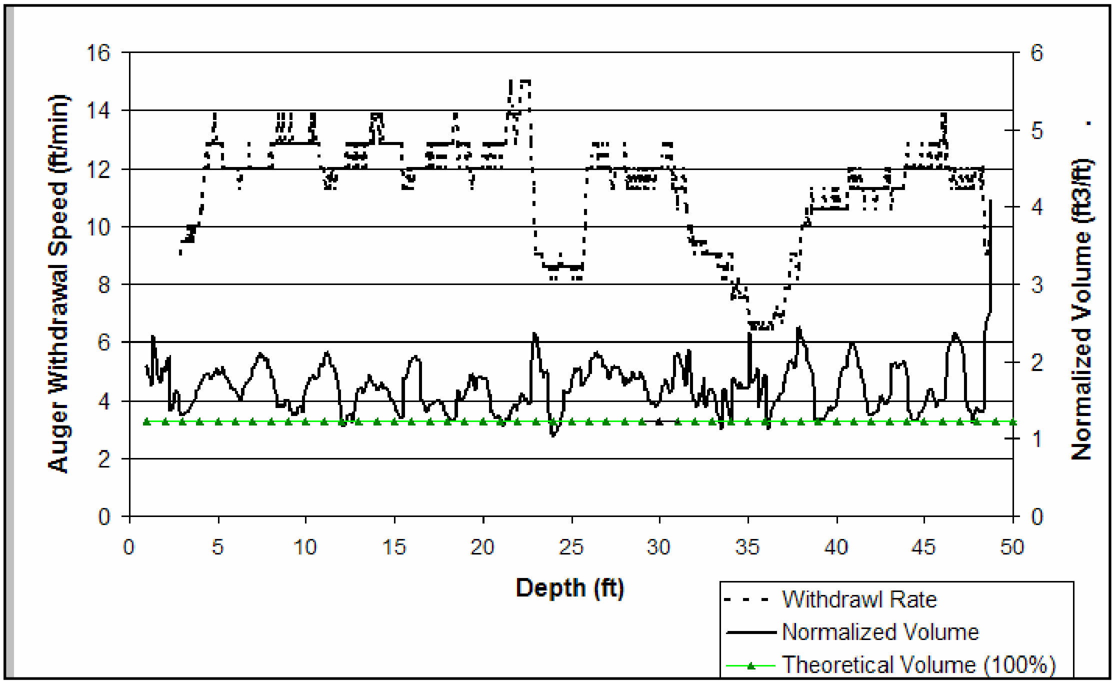


**FIG. 7. Volume and Withdrawal Rate Versus Auger Depth**

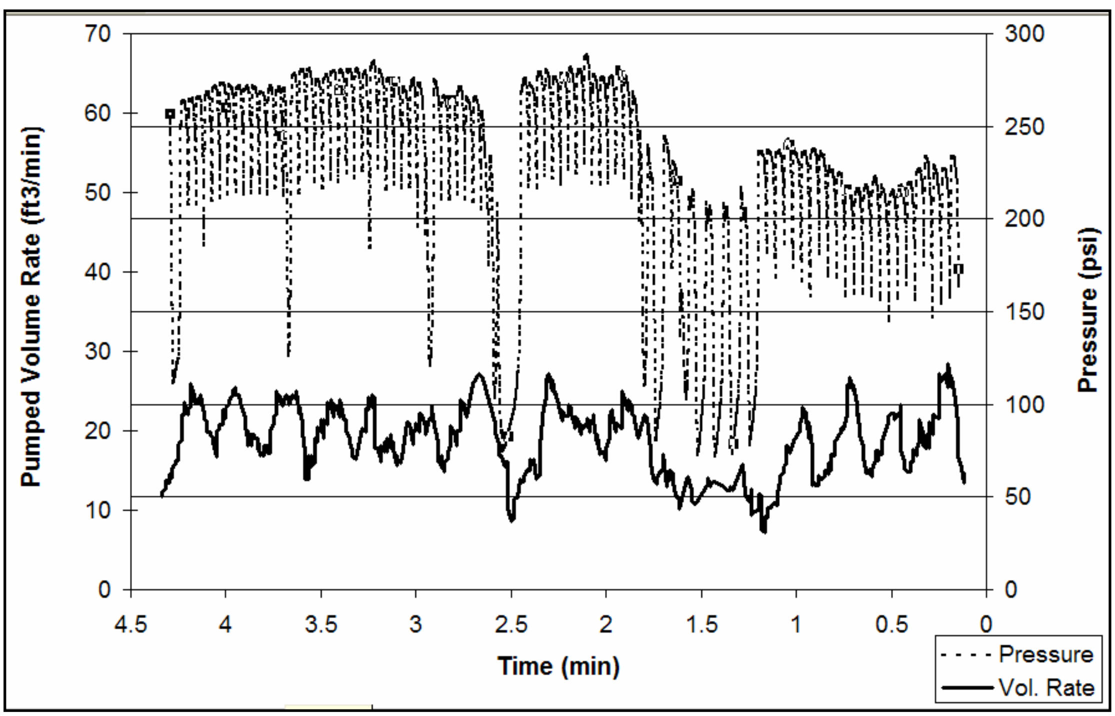


**FIG. 8. Volume Rate and Grout Line Pressure Versus Time**

of the shaft installation. Drilled shafts can be cast in dry conditions if the soils are favorable, but often are cast under wet conditions using a slurry or polymer solution to keep the hole open during drilling and casting of the concrete. Construction under wet conditions makes inspection difficult as a tremie is used and the actual flow of concrete cannot be inspected, nor can the tremie tip be visually observed. Improper management of the tremie usually results in a defect. Even under dry conditions, visual inspection of the shaft is not easy. Removal of the temporary casing can sometimes pull the reinforcing cage when the concrete cures rapidly or the depth of concrete is excessive prior to pulling, or otherwise affect the structural integrity of the shaft. Drilled shafts are also generally the most expensive foundation system, and often due to large diameters have very large loads, and thus relatively few shafts. Because of reduced redundancy of the foundation, the integrity and performance of each drilled shaft becomes more critical.

Inspection during installation is currently limited to primarily visual observations. The current consensus opinion regarding assessing quality of the shaft is that cross hole sonic logging is the generally the best available method. Access tubes are attached to the reinforcing cage and cast into the pile during construction. In general these access tubes extend the full length of the pile. The guideline is that there should be at least 4 tubes and generally at least one tube for each foot of diameter of the shaft, so larger shafts are equipped with more tubes. The tubes are filled with water to provide coupling of the sensors inside the tube with the surrounding concrete. A transmitter is then lowered into one tube and emits an ultrasonic signal that then travels through the concrete and is sensed by a receiver into another tube. ASTM D6760 provides guidance for performing this test. The First Arrival Time (FAT) of the signal at the receiver defines the transit time which is primarily through the concrete between the tubes. From the FAT and the distance between the tubes, a wavespeed in the concrete can be computed. This wavespeed gives a qualitative evaluation of the concrete quality. A section of concrete with a low wavespeed indicates poor quality concrete or a defect. By observing the wavespeed as a function of depth between all possible combinations of tube pairs the concrete homogeneity can be assessed for the entire pile by depth and by quadrant.

Because "debonding" of the tube from the concrete is often cited, the tubes should be filled with water either prior to casting the concrete, or immediately afterwards so that temperature variations are minimized and the bond between the tube and concrete is not compromised by temperature changes. "Debonding" problems have been particularly noted for PVC access tubes, and many have suggested that testing in PVC access tubes is often limited to the first 10 days after casting because of such difficulties. Partly for this reason steel access tubes have been preferred. A drilled shaft with specially constructed defects and both steel and PVC access tubes was installed at Pile Dynamics' facility in Cleveland. Testing of the shaft has been periodically performed over many months. Signals from two different main diagonals of this shaft at almost 7 months after initial installation are shown as a nested "waterfall diagram" in Figure 9. The left edge of the waterfall diagram defines the FAT. The purposely constructed defects can be clearly observed by the white horizontal lines in these diagrams at different depths (most of which were created by wrapping the tube with a thick foam layer). The signals of the PVC tubes (tubes 4-8) have more than double the amplitude and have less "noise" than those from the steel tubes (tubes 2-6), and perhaps more importantly, no evidence of

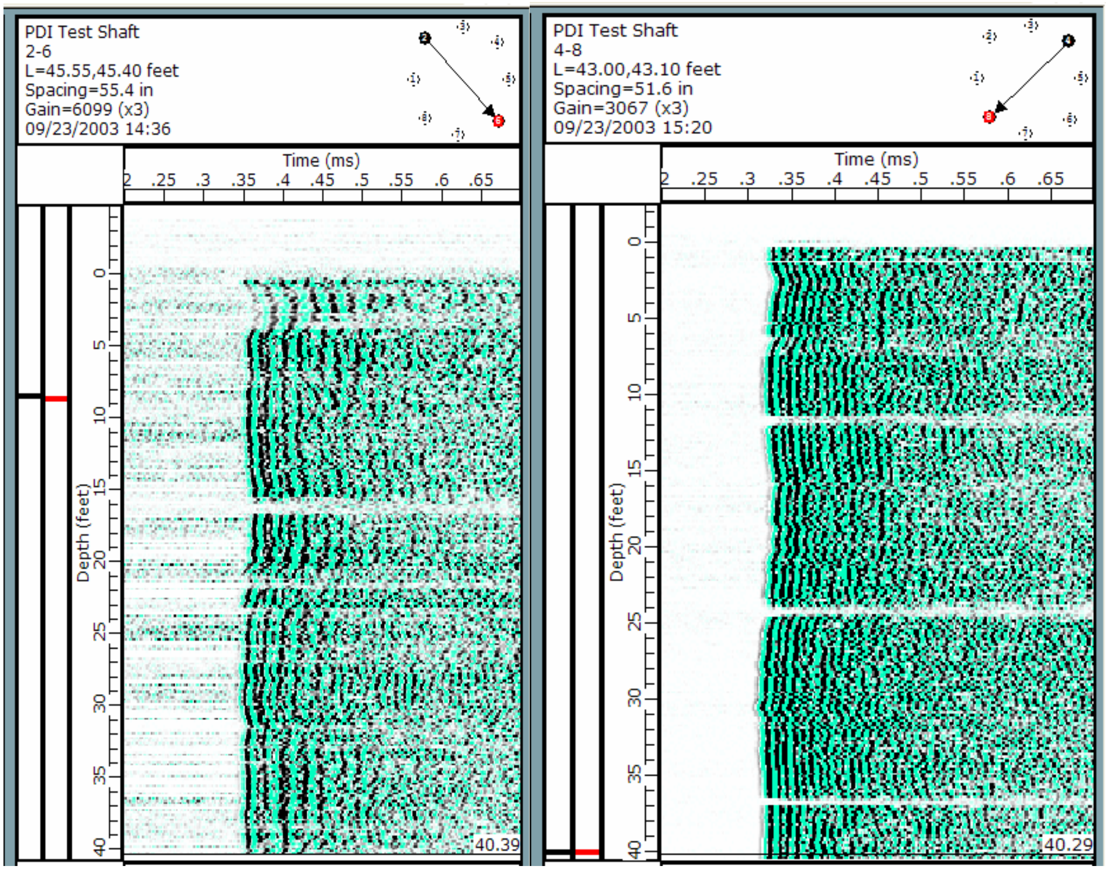


**FIG. 9. CSL Waterfall Diagrams from Steel Tubes (Left) and PVC Tubes (Right)**

"debonding" is noted, even after such an extended time. Because of the cleaner signals, PVC tubes are therefore preferred. In fact, in another deep outside test wall panel constructed almost 10 years ago at Pile Dynamics, signals between PVC tubes still show no evidence of "debonding". In both cases, no special effort was taken to ensure a good bond other than filling the tubes with water immediately after casting the concrete as recommended by ASTM D6760.

In many cases, the shaft has a "full layer defect" as in Figure 10 where all other tube pairs (not shown) show a similar defect in the waterfall diagram at more or less the same depth. The "processed data" is shown as an example of further analysis for the same tube pair at the right in Figure 10. In the processed result, the FAT is shown for this tube pair on the left, and the "relative energy" is shown on the extreme right (low energy to right). Defects have both delayed FAT and a low relative energy (related to signal strength). The energy and signal strength have proven useful in many cases to guide the interpretation of results in detection of defects. In such a case as this shaft where the same defect appears at the same depth in all tube pairs, it is obvious that the defect covers the entire cross section at that depth, and no additional analysis procedures are really necessary. The defective pile can be repaired by coring and pressure grouting, or replaced. However, there are cases

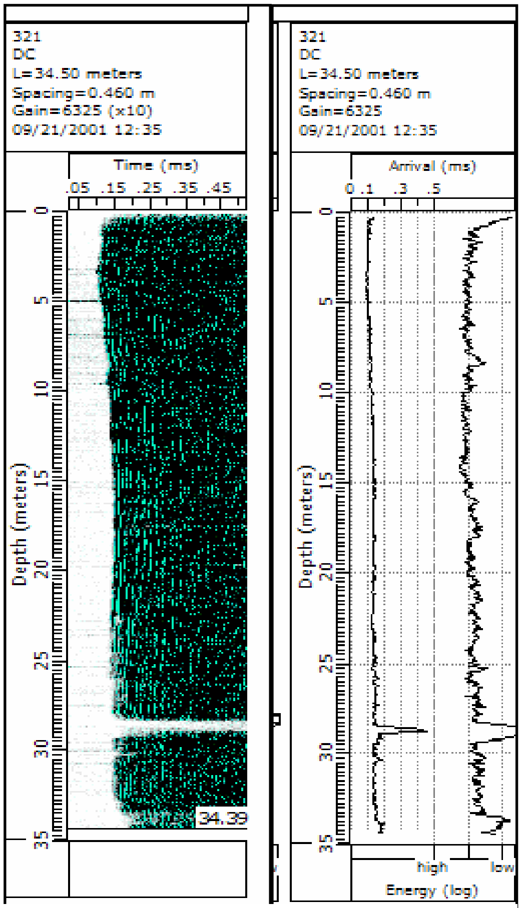


**FIG. 10. Shaft with Full Defect at 28 m**

where the defect is local such as when a defect occurs in only a portion of the cross section. Then it may be helpful to obtain a better grasp of the location and extent of each defect so that the shaft can be evaluated structurally to see if it is satisfactory for the loading conditions or if need remedial action.

Tomography is a mathematical procedure where the shaft is modeled in a grid, each with an assigned wavespeed. An inversion routine is then applied to the data trying to relate the observed arrival times (FAT) of all data points of all tube combinations to the geometry of the probe locations to obtain a least square fit in the wavespeeds at each node which best represents the measured data. Uniform wavespeeds generally produce straight ray travel paths, but variable wavespeeds allow refractions causing curved ray paths. Gradient methods and smoothing allow the wavespeed to be mapped continuously even to node points that are not directly on lines

Such tomography analysis was performed for the test shaft shown in Figure 9 and a resulting sample 3D output is given as an overall “body” image of the entire shaft in the right side of Figure 11. This analysis used only the four odd number tubes, the reasonable number of tubes for this size shaft, and to avoid the foam wrapping placed only on even numbered tubes.

The body sections shown give the locations in the shaft of low wavespeed, corresponding to low concrete strength. The threshold limit for the body view is adjustable. Generally the output is color coded (although Figure 11 is shown only in black and white due to publication limitations), and the user may select various viewing angles, or sections of the shaft, or look at “slices” (either horizontal or vertical), or wrap-around diagrams. Thus the presentation may be as detailed or global as needed to clearly show any potential defect. A horizontal slice of 36 ft depth is shown in the upper left of Figure 11, and a vertical slice between tubes 3 and 5 is shown in the lower left. In all views “black” indicates low wavespeeds and thus defects. These defects were created by installing buckets simulating voids at depths 5 and 36 ft, and a thick Styrofoam layer covering half the cross section (covering tubes 2, 3, 4, 5 and 6) at about the 24 ft depth. The tomography analysis correctly identified the defects and their approximate size and location.

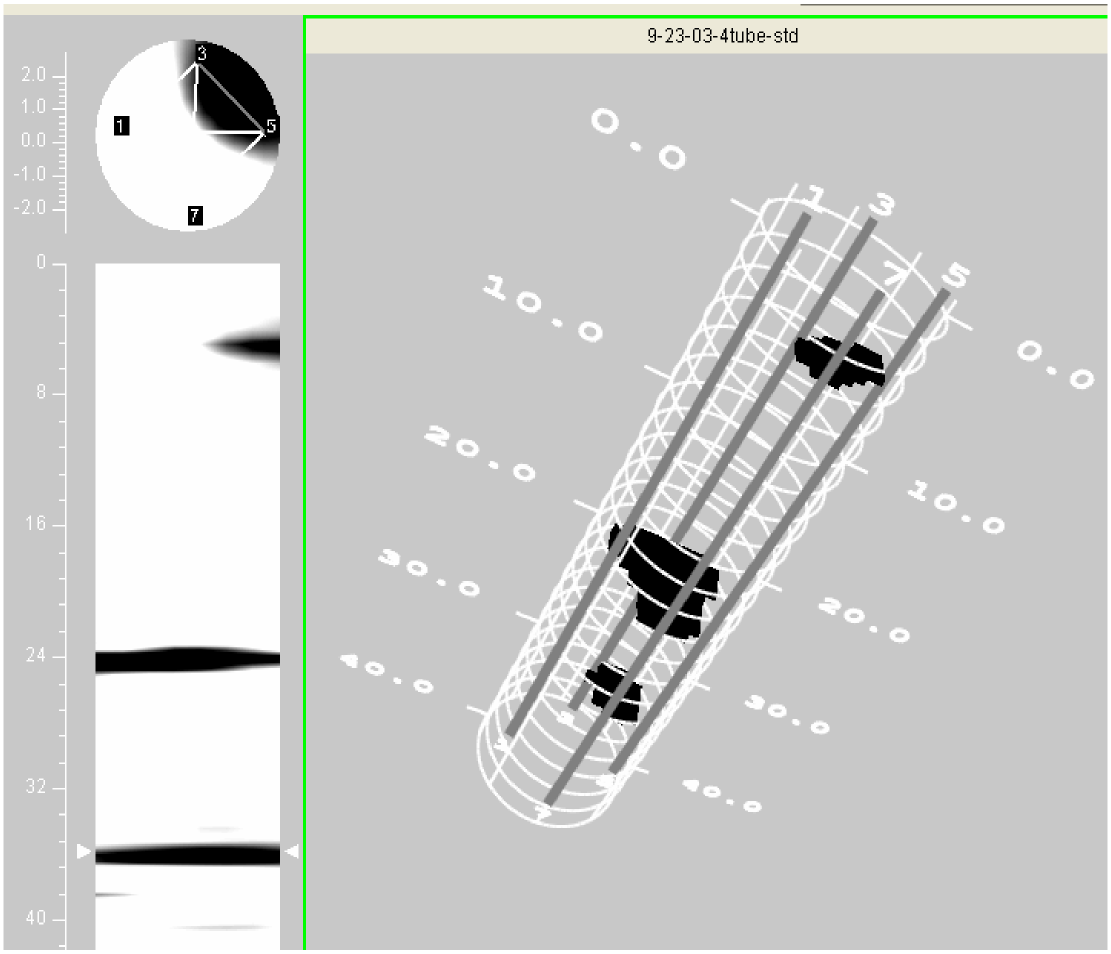


**FIG. 11. Defective Shaft with 3D Tomography "Body View" of Defects on Right**

## SUMMARY

Instrumentation has been recently developed to significantly improve monitoring and testing of deep foundations. For driven piles, hammer performance affects the energy transferred to the pile and thus the blow count for any given depth or capacity. It is therefore important to routinely monitor hammer performance for every pile and for every hammer type (air, diesel or hydraulic). Hammer monitors have been incorporated into many modern hydraulic hammers to obtain kinetic energy just prior to impact, and similar technology is available for installation on any hammer lacking this ability from the manufacturer. The results are sent via telemetry to the Saximeter where a driving log is automatically obtained which includes both blow count and hammer performance. These results are available in electronic form and can be sent to the supervising engineer as soon as they are acquired.

A new remote Pile Driving Analyzer promises to improve the quality and efficiency of dynamic pile testing, and reduce its costs. Data is obtained with a field data collection system, operated by the pile crew, field inspector, or site engineer, with the data transmitted automatically by real-time cell phone technology to the specialist PDA engineers in the office. This reduces scheduling problems allowing testing at the convenience of the contractor, eliminates travel expenses, speeds the analysis and reporting process, improves the efficiency of the PDA engineers, and allows for immediate decision making. By eliminating unknown costs, dynamic pile testing can be bid on a "per pile" basis to reduce costs to the highway departments.

Modern instrumentation of auger cast-in-place pile rigs includes automated monitoring equipment with flowmeters that accurately and without bias determines grout volume versus depth. Real time guidance to the installation operator guides a more uniform installation and that no zones of insufficient volume exist. The engineers and owners are given documented assurance of proper incremental volume for each pile, again allowing for an immediate decision on pile acceptance or rejection. It is obvious that counting pump strokes is not sufficient to monitor the quality of auger cast-in-place piles, and that automated monitoring equipment is essential for evaluation of the installed quality of such piles.

For drilled shafts, CSL testing can determine defects in the shaft by depth and by quadrant. PVC tubes, when properly installed by filling with water immediately after casting the concrete, provide superior data and no evidence of "debonding". Tomography analysis of the data produces 3D images of the shaft wavespeed, which is related to concrete quality, and thus is helpful in assessing defects.

State-of-the-art electronic monitoring technology can now be effectively applied for real-time monitoring and remote testing of driven piles and auger cast-in-place shafts for quality assurance purposes. It is possible, practical, and economically feasible to test every pile of a project in order to reduce the cost of the foundation associated with safety factors that reflect unknowns related to the construction and performance of individual deep foundation elements.

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