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AUTOMATED INSTALLATION MONITORING FOR AUGERCAST AND DRIVEN PILES

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Automated Installation Monitoring for Augercast and Driven Piles

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ABSTRACT:

Where soil conditions are favorable, augercast piles have significant economic advantages, but they also have some uncertainty due to the in construction methods. To confirm structural integrity, static testing can be performed on a small sample of piles. Other Non-Destructive Evaluation methods like Pulse Echo are frequently specified for a large percentage of the remaining production piles. However, such NDE methods require testing the pile after the grout/concrete has hardened. If problems are found, then the repair or replacement can be relatively expensive. The confidence in the quality of these piles can be improved by automatically monitoring the grout pumped as a function of depth during the grouting phase of installation. If a low grout volume is detected, the pile can be redrilled and regrouted immediately while the piling rig is still in place and the grout still fluid. This considerably reduces remedial costs. To be effective, such installation monitors must accurately determine both grout volume and depth during installation and be rugged simple to operate. Such an equipment can be of great help to the installation crews. The assurance gained may reduce the need for subsequent NDE tests.

The quality of inspection of driven piles depends heavily on the inspection personnel. While inspection is critical in a good installation, it is sometimes assigned a low priority. Inspection personnel in many cases are technicians with little pile experience. They may not understand the project needs or even how the pile driving equipment works. The task is often monotonous and any distraction makes accurate record keeping difficult. In some cases inspection is totally ignored for lack of qualified personnel. Electronic systems can automatically and accurately monitor driven pile installations and include documentation of certain hammer performance parameters.

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This paper describes equipment available and routinely in use for automated monitoring of both augercast and driven piles and demonstrates applications on typical construction sites. The paper also discusses benefits and limitations of the alternative NDE tests.

KEYWORDS: Augercast Piles, Piles, Installation Monitoring, Pulse Echo Method, Integrity Testing

1 INTRODUCTION

The perception of geotechnical engineers is that the quality of augercast piles depends on the skill of the contractor. One of the most critical operations is the control of auger withdrawal during grout placement (Roberts 1998). However, for an inspector, it is difficult to accurately assess grout volume and auger withdrawal rate simultaneously. This shortcoming may be overcome by implementing quality control procedures both during and after installation. Detailed pile installation records, obtained through automated measurement systems, provides information to guide the operator during installation and assure the quality of the inspector's records.

Post construction testing of selected piles verifies the effectiveness of installation control. Most commonly used is the Pulse Echo Method which requires striking the pile top with a small hammer and measuring certain echoes from pile non-uniformities or the pile end. While this method can be applied to any one of the production piles, it requires that the grout or concrete is hardened and it may not be conclusive on very long piles.

For driven piles, the hammer operates as both the installation device and also the inspection tool. Engineers relate observations of blow count or set per blow to pile capacity. Hammer performance affects the installation. Unfortunately many inspectors fail to fully understand the importance of the hammer or are easily distracted during pile installation and may miss important events. Automated monitoring systems can accurately record and print blow count logs and hammer performance parameters as a function of depth for each pile.

2 AUGERED PILES

Visual inspection requires that pump strokes are detected, counted and recorded as a function of estimated auger depth. Since there is a large volume of information to be recorded, there are many possibilities for error in this process. Further it has been shown that pumps do not maintain a uniform volume per pump stroke but rather can be highly variable (Likins et al, 1998).

2.1 Monitoring Augercast Piles

Automated monitoring of augercast piles (Likins et al. 1998) requires electronic acquisition of data on grout volume pumped and auger position. and utilization of this data in real time to aid in proper pile installation. The Pile Installation Recorder for Augercast piles (PIR-A) has the following components:

Depth Indicator. The depth indicator (Figure 1) automatically measures the location of the bottom of the auger as the auger penetrates during drilling and as it is retracted during grouting. A cable from a self-retracting reel is attached to the head of the auger. As the auger advances or withdraws, the depth is measured by a rotary encoder attached to a pulley tracking the cable.

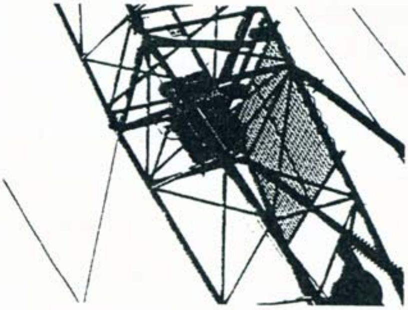

Fig 1: Depth Indicator

Flow Meter. A Flow Meter (Figure 2) accurately measures pumped grout volume. This precise measurement is a marked improvement over the traditional method of counting pump strokes during augercast pile installation, which has proven to be unreliable.

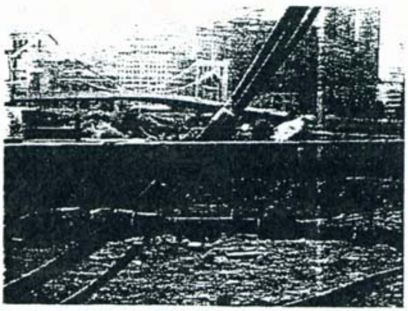

Fig 2: PIR-A Magnetic Flow Meter

Grout Pressure Transducer. This unit is installed in the grout line usually near the Flow Meter but sometimes also at the bottom of the auger. The pressure transducer measures pressure variations in the grout line continuously and therefore can detect minima and maxima of the grout pressure.

Torque Measurement is optionally taken on the motor that generates auger rotation. This parameter may be of interest both from a mechanical and a geotechnical engineering point of view.

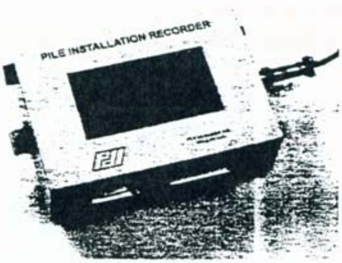

Fig 3: Control Unit Showing Grouting Phase

Data Recording, Storage, and Display Unit - (Control Unit). The data acquisition unit (Figure 3) provides signal conditioning for all sensors, and processes the measured data. The drilling depth, auger torque, and drilling rate are displayed during the drilling phase. During the grouting phase, the nominal pumped grout volume per unit depth is plotted on the screen. The operator observes the volume ratio and is guided to maintain an ideal withdrawal rate. This rate is slow enough to assure a minimum volume per unit depth yet fast enough to avoid grout waste. If a relatively low grout volume (which may be interpreted as a cross sectional reduction) is observed, the operator can immediately auger back down into the hole a second time while the grout is still fluid to repair the deficiency. Data is stored in a removable PCMCIA memory card. Detail and summary results of both auger and grout phases are output to a field printer.

2.2 Application for PIR-A

The schematic in Figure 4 shows the overall configuration of the PIR-A system. In practice, the operator monitors installation on the PIR-A during all phases. After input of the pile name by the operator, the Control Unit handles virtually everything else without further human intervention. The operator will first observe the auger advancement including current depth and torque. Maximizing the torque without stalling the crane minimizes the drilling time which is desirable to minimize installation time and reduce spoils.

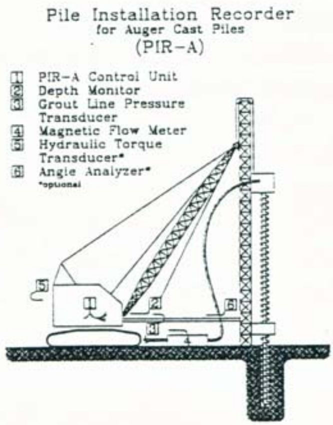

Fig 4: PIR-A Schematic

At the desired depth, the operator initiates auger withdrawal and grout injection. All measured parameters are recorded during this grouting phase and a graphic representation of the grout pumped per desired depth increment is displayed. Numerical values are also shown for reference. If the grout pumped for any increment is less than the desired grout ratio, the pile can be re-augered immediately through this increment and the pile re-grouted. Making corrections in this way while the grout is still fluid greatly reduces the occurrence of defects in the pile, reduces the cost of remedial measures, and improves the engineer's confidence in the shaft quality.

Upon completion of the grouting phase, a printout can be made on-site to document the entire pile installation process. Detailed information including auger time, grout volume and grout pressure for every depth increment are listed. Summary information shows pumped volume for the auger, head, shaft and spill. The total shaft volume is compared with the theoretical volume yielding the listed "grout ratio".

When the monitor device is used and the results observed during installation, the shaft installed should meet any minimum guidelines established by the engineer. In this way the quality assurance of the project is improved since everyone then knows exactly what happened at all times in the installation. By thorough and accurate inspection, the need for further inspection by NDE methods such as low strain Pulse Echo integrity testing may be reduced.

Of course, monitoring during installation does not assure the bearing capacity of the pile. Thus, either additional static testing or high strain dynamic pile testing (Rausche et al. 1985, Hussein et al, 1996) may be needed for confirmation of the pile capacity.

Recording of other construction operations such as grout arrival time on site and collection of grout specimens cannot be done automatically. The construction process also includes other activities such as screening, installation of reinforcement, maintaining adequate waiting times between casting of neighboring shafts, site excavation, etc. which require some human interaction in supervision. If problems are observed in any post grouting phase, the piles can be then subjected to low strain Pulse Echo testing to assure the shaft integrity.

2.3 Pulse Echo Integrity Testing

The Pulse Echo Method (Rausche et al, 1988) uses signals from a hand held hammer impacting the pile top and generating a compressive stress wave in the pile. Figure 5 shows a Pile Integrity Tester (PIT) for the application of the Pulse Echo Method. Stress wave inputs and reflections (from non-uniformities or the pile toe) are measured at the pile top as a function of time by an accelerometer. Its signal, integrated to velocity by PIT, is then interpreted by the test engineer.

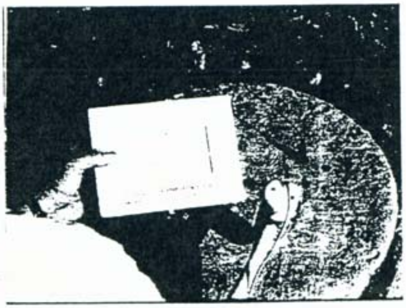

Fig 5: Pile Integrity Tester (PIT) With Hammer and Accelerometer for the Application of the Pulse Echo Method

The first and sometimes most important step for any low strain test is the preparation of the pile top surface which may include removing some upper concrete if it has been contaminated with soil, bentonite slurry or other foreign materials during construction, and finding or making a smooth location. An accelerometer is then attached to the pile top surface with a thin layer of a soft paste like vaseline, petro wax, *etc*. Accelerations produced by several hammer blows are integrated and displayed as velocities. Consistent records are selected, averaged, scaled and then redisplayed. Further data processing includes wavelet analysis and application of an exponentially increasing magnification function. The magnification restores reflection details which are diminished by soil resistance, pile material damping or pile non-uniformities.

Figure 6 shows a standard test output. It includes an exponential magnification (40 times in this case) with the maximum multiplier shown at time of expected reflection from the pile bottom (2L/c, where L is the pile length, 25 meters in this example, and c the stress wave velocity of 4150 m/s). The bottom plot shows a clear signal from the pile bottom together with a steady velocity signal between the impact and pile bottom, indicating a sound pile shaft. The upper plot shows a pronounced velocity increase at about 16 m. Changes such as this may result from reductions in pile cross section or concrete quality.

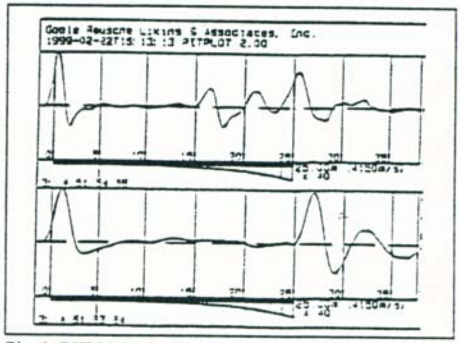

Fig 6: PIT Velocity Records

In general, relatively sharp defined reflections are attributed to impedance changes, slowly changing reflections are usually caused by soil resistance. If the effect of soil resistance is known from reference piles, then unusual shafts can be identified.

An advantage of this method is its simplicity and economy. This makes it practical to test every shaft when questionable conditions occur. It can be applied even after all shafts are installed and requires no advance planning or access tubes.

3 COMPARATIVE RESULTS FOR AUGERCAST PILES

Both Pile Installation Recording for Augered Piles and Pulse Echo testing have been employed on recent construction projects. Records from these methods are compared and interpreted.

3.1 Case History 1 for PIR-A

The 500 mm (20 in) augercast piles range in length from approximately 18 to 20 meters (58 to 66 ft). Following an initial static test failure on this site, the Pile Installation Recorder (PIR-A) was used on the remaining production piles to improve quality assurance. Soil borings generally indicated medium dense sands transitioning into dense sands at a depth of approximately 13.7 to 15 m (45 to 50 ft). The shafts were socketed at least one meter into the bedrock formation.

The Pile Integrity Tester's Pulse Echo Method was applied to several piles. For example, the records of all the shafts in Pier B18 indicated a characteristic decrease of impedance (evident by an increase in velocity) beginning at depths 12 to 15 m (40 to 50 ft). Although the impedance decrease cannot be quantified by PIT it seems likely that the decrease is from a return to nominal diameter in the lower denser soils from a larger shaft diameter in the upper less dense soils.

The PIT velocity record for Pile B18A (Figure 7) indicates a velocity increase or impedance reduction at approximately 14.6 m (48 feet). The PIR-A Summary Printout shows that between 15.2 and 14.6 m (50 and 48 feet) the grout volume per 2 ft increment (0.61 m) decreased from an average of about 0.18 m^3 to 0.13 m^3 (6.5 ft^3 to 4.66 ft^3). The minimum required volume was 0.154 m^3 (5.45 ft^3) per increment.

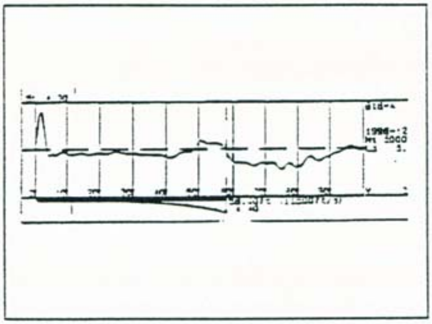
Fig 7: PIT Data (Case 1)

The PIT toe reflection in the rock socket resulted in a negative velocity (compression) at 17.7 m (58 ft). This is typical for shaft sections with either a high soil resistance or an increased pile impedance.

Examination of numerous PIR-A records demonstrated fairly homogeneous grouting rates, and by implication a consistent pile quality. These records indicate piles with no significant problems. In addition, selected piles were tested for integrity after installation. Because no further difficulty was experienced due to adequate quality control by the PIR-A and by pulse echo tests, there was no further static testing.

3.2 Case History 2 for PIR-A

The 450 mm (18 in) diameter augercast piles were about 15 m (50 ft) long. Soils were generally silty clays overlaying silty gravel starting at a depth of about 11 m (36 ft).

Test piles are usually among the first piles installed on any site. Unfortunately grouting procedures are yet to be well established. In this case, the static test pile failed structurally: after a brief hold of the ultimate load, the load dropped to about half as the pile plunged. Although the PIR-A grouting record shows an overall grout factor of 1.53 compared with the theoretical volume (1.25 factor required), a low grout ratio (about 44% of desired) was observed for the depth increment between 8.5 and 7.9 m (28 to 26 ft). Had this low grout for this increment been observed and the pile reaugered and then regrouted to correct this deficiency during the grouting phase, the pile would likely not have failed structurally in the static test. The pile was subsequently tested by PIT for further confirmation. There is an obvious impedance reduction at the 7.9 m (28 ft) depth as shown in Figure 8.

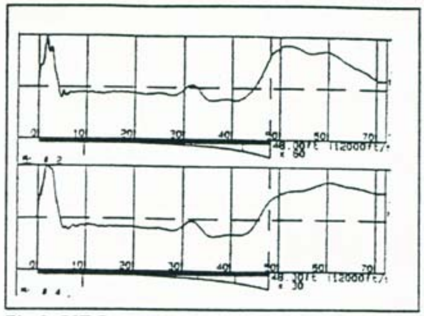

Fig 8: PIT Data (Case 2)

4 MONITORING DRIVEN PILES

Inspecting driven production piles involves as a minimum the counting of blows per unit penetration (e.g. blows per foot). Ideally, information about the hammer's performance is observed and recorded. Unfortunately, the inspection of driven piles is a rather monotonous assignment leading to errors in logs recorded by human inspectors. There are also numerous distractions often resulting in missed information. While inspection is critical in a good installation, it is sometimes assigned a low priority and inspection personnel are often technicians with little experience. They may not understand the project needs or how the hammer works. In some cases inspection is totally absent for lack of available on-site inspection personnel.

4.1 Automated Monitoring - Driven Piles

Automated monitoring systems can accurately monitor driven pile installations and include capability to document hammer performance. The equipment required for the Pile Installation Recorder for Driven Piles (PIR-D) includes the same depth indicator as described above for the PIR-A. The Control Unit is also similar but processes different signals in a custom dedicated software. The following additional components complete the system:

Blow Detector: For any hammer type, a sound recognition can be used to sense the hammer blow due to the relative sound differences created by the impact. The sound sensor also allows the PIR-D to determine the time between blows which can be converted to an equivalent blows per minute (BPM). This operating rate can be used to calculate the stroke for open end diesel hammers from

$$H[m] = 1.22\ (60/BPM)^2 - 0.1$$
$$H[ft] = 4.01\ (60/BPM)^2 - 0.3$$

Hammer Monitor: For air or hydraulic hammers, two proximity switches mounted to the hammer (Figure 9) sense the ram movement just prior to impact. The ram impact velocity can be measured and the kinetic energy therefore computed. If this hammer monitor is used, then it replaces the blow detection by sound sensor.

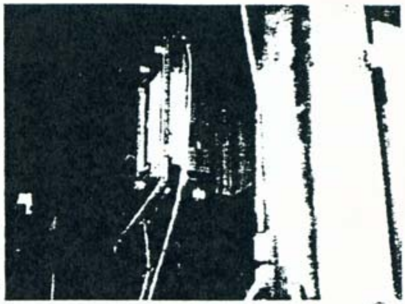

Fig 9: PIR-D Hammer Monitor

Bounce Chamber Pressure: For closed end diesel hammers only, the bounce chamber pressure is monitored with a pressure sensor attached to the bounce chamber pressure hose. This pressure is related to the hammer's potential energy.

These measurements for depth, blow detection or hammer monitor, and bounce chamber pressure (for closed end diesels only) are sent on a network cable to the Control Unit.

4.2 Application of the PIR-D

In practice, the operator enters the pile name and its initial penetration into the PIR-D Control Unit. As the pile is driven, information from the various sensors is sent to the Control Unit for processing. When a blow is detected by either the sound sensor or the hammer monitor, the Control Unit is informed. The current depth is then determined and assigned to this blow. All information is saved into the memory card for each blow. The equivalent blow count is determined and displayed.

The hammer monitoring results are also displayed for every blow; this has proven useful to alert the contractor of potential hammer problems. By maintaining optimal hammer performance the contractor is able to improve productivity.

Various "criteria" developed by the engineer can be entered for minimum depth, minimum blow count (max set per blow), and minimum hammer performance. When all criteria have been achieved, as indicated by the Control Unit, the pile driving can then be terminated. The installation record is then printed for a permanent record. The data is also saved on the memory card in electronic form for permanent documentation.

4.3 Case History 1 for PIR-D

A large project had multiple pile drivers operating simultaneously. On parts of the project, H piles were driven to rock. On other sections, pipe piles were driven to a sand bearing layer. In all cases the piles required splicing and were driven in sections. Four pile driving rigs were equipped with Pile Installation Recorders (PIR-D). Three hammers were closed end diesels, the fourth one was an open end diesel. The project required over one year of pile driving activity.

All PIR-D systems were equipped to detect blows by the sound sensor method. The closed end diesel hammers were instrumented with pressure sensors for monitoring the bounce chamber pressure. Stroke was instead calculated from the open end diesel's blow rate (blows per minute). For one rig, the PIR-D was mounted in the crane cab. For the other three rigs, the PIR-D was mounted outside the rig. In all cases the results from every section were printed in the field for a permanent record (Figure 10.) Data was also recorded electronically on a memory card.

In the initial phases of this monitoring the PIR-D was further improved based on feedback from the job site. During this time many comparisons with visually obtained driving logs were reviewed. A typical comparison is shown in Figure 11. After a three months trial period the system was considered more than sufficiently accurate. The PIR-D units then operated practically continuously with only minor interruptions (e.g. cable accidentally cut occasionally).

Project: FWW SITE #5
Date: 1999-03-04 09:40:07
Filename: 403B

pen (ft)	blows	bpm	psi
section #2			
67.00	19	73.4	15.1
68.00	19	73.4	14.8
69.00	20	73.4	15.5
70.00	21	73.7	16.0
71.00	22	73.4	16.1
72.00	23	73.2	16.6
73.00	25	73.3	16.4
74.00	25	73.2	16.8
75.00	24	73.1	16.7
76.00	25	73.4	16.7
77.00	25	73.3	16.8
78.00	25	73.2	16.9
79.00	25	73.2	16.7
80.00	27	73.2	16.8
81.00	27	73.3	16.9
82.00	27	73.3	17.1
83.00	27	73.3	17.3
84.00	27	73.4	17.7
85.00	28	73.4	17.8
86.00	27	73.4	17.6
87.00	27	73.4	18.1
88.00	30	73.4	17.6
89.00	28	73.4	17.9
90.00	28	73.4	18.1
91.00	29	73.4	17.9
92.00	30	73.4	18.3
93.00	32	73.4	18.4
94.00	34	73.4	18.7
95.00	40	73.4	18.6
96.00	42	74.0	19.2
97.00	48	73.4	19.2
98.00	51	73.4	19.6
99.00	55	73.1	19.9
100.00	58	73.2	19.9
101.00	59	73.2	20.1
102.00	61	73.8	20.2
103.00	80	73.3	20.0
104.00	106	73.7	19.8
105.00	126	73.4	19.9
106.00	126	73.6	19.5
107.00	123	73.8	19.4

finished at 10:18:58
final blowcount: 9.9 bl/in.
(averaged over last 3.00 inches)
set (last 20 blows): 1.91 in.

Fig 10: PIR-D Example Printout

5 CONCLUSIONS

Low strain PIT testing can detect major defects in the pile shaft at low cost and with little effort. Thus, all piles could be economically tested on a site. However, Pulse Echo Tests like PIT are sometimes difficult to interpret and should not be the only means to verify the quality of the foundation. As a minimum, geotechnical borings and field installation observations should be included in the evaluation process of the foundation. For very long piles the method may not provide conclusive evidence of integrity of the whole shaft.

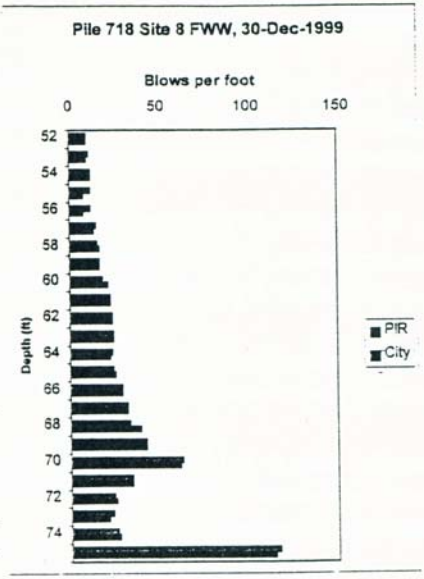

Fig 11: Comparison of PIR-D with Visual Inspector Records

Grout volume and grout pressure records from the Pile Installation Recorder for Augercast Piles (PIR-A) can be used during installation to guide the contractor into installation of quality piles. If these automated installation records of grout versus depth indicate a good shaft, then this may reduce the need for NDE by PIT. Thus, PIT can be restricted to shafts with questionable PIR-A records or shafts with problems observed after installation, during installation of subsequent piles or during excavation. In addition, a small percentage of randomly selected production piles may also be subjected to PIT.

Where the Pile Installation Recorder was installed, it recorded the installation of all piles on a job. The unit performed automatically, requiring only entry of the pile name for each pile installed. The PIR-A records were used to judge pile consistency and acceptance. For job sites where the installation of augercast piles is not closely monitored by such methods as the Pile Installation Recorder (PIR-A), the quality of the foundation is unknown and therefore risky unless there is extensive additional testing.

Similar technology has been used with a PIR-D unit to monitor the installation of driven piles. The PIR-D automatically counts blows, determines depth, monitors hammer performance and records all results. Comparisons of PIR-D blow count driving logs with manually acquired inspector's driving logs have shown the PIR-D to be accurate. Automating this process improves the documentation, and could eventually save labor and inspection costs.

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