Alternate Verification Methods For Augercast Piles

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Abstract

Augercast piles have become increasingly common. Engineers are attracted to this pile type as a way to reduce foundation costs. In addition, the applied design loads have increased as the equipment used by the augercast contractors has increased to both larger diameters and longer lengths, allowing augercast piles to be considered on a wider range of project sites. The performance of this pile type requires a shaft with good integrity and sufficient soil resistance.

However, inspection for this pile type is difficult. The augercast pile is constructed in situ and at no time during the process can the “hole” or injected concrete along the shaft be inspected visually. By contrast, driven piles can be inspected prior to installation. Closed end steel pipes can be visually inspected after driving and prior to concreting. The integrity of driven piles is further indirectly confirmed by driving the pile to the required blow count, and in many cases dynamic pile testing is used to confirm whether or not a pile has suffered damage, even for solid section piles like H piles or square concrete piles. While pile and shaft performance can be verified by static load tests, the cost and time constraints prevent static testing for all but a few augercast piles on even the largest site. For augercast piles, current typical practice with visual inspection does inspect the pile completion process including installation of reinforcement. However, typical inspection during the critical augercast grouting phase in the United States is often limited to counting the total number of pump strokes (and computing a total volume based on that count). This paper describes automated electronic monitoring during construction to assure proper incremental grout volume versus depth for every augercast pile on site. Dynamic integrity inspection after installation and dynamic pile capacity determination for larger percentages of augercast piles on site are discussed. These alternate inspection methods increase the confidence in augercast pile foundations.

Capacity and Integrity Determination of Augercast Piles

For driven piles, the routine counting of blows during driving is in effect an additional inspection. Driving criteria are usually established based on wave equation analysis. Subsequent dynamic pile testing or static load testing is applied to affirm or adjust the initially selected driving criteria. Due to cost, static testing is often limited to one percent of all piles. Dynamic pile testing is often applied to five to ten percent of the piles on site. Codes are coming into practice that relate the applied safety factor to the percentage of piles tested (PDCA, 2001). If a pile is driven to the required blow count, that pile likely has the required capacity. This blow counting procedure generally allows the site variability to be taken into account either directly or indirectly.

For augercast piles, static load testing can be applied. Static tests should be run to failure when at all possible, although they are often run only to a "proof load". In addition, static testing only verifies that the selected test pile can sustain the applied loading. To investigate site variability for an augercast pile project, more static testing is highly desirable since a "blow count criteria" is not applicable. Unfortunately, production piles are not always installed with the same care and to the same high standard as the static test pile. Further, the static test pile is almost never selected at random. Special precautions are made during installation to assure that the test pile will not fail the static test. Nevertheless, occasional failures do occur, sometimes due to failure of the soil and at other times due to structural failure of the pile shaft. Static analysis methods with a very conservative and therefore expensive design and considering the various soil profiles over the entire site would be an alternate method to assure that the design is adequate over the site.

Since each pile is individually constructed in situ, it would be desirable to test each pile for structural integrity. Static testing of every pile is obviously prohibitively expensive. Dynamic pile testing is increasingly applied to augercast piles as an alternative. A more extensive description of this test as applied to augercast piles is found in the references (Hussein et al 1996; Likins et al, 2000b). In some other countries, dynamic testing has been commonly applied for augercast piles for many years. The preferred dynamic pile test system for these piles is a simple drop weight as shown in Figure 1 so that single blows or variable drop heights can be applied. The drop weight should be sized as at least 1 to 2 percent of the desired ultimate load to be tested. The set per blow should be at least 2.5 mm (0.1 inch) to achieve full load activation, or else the test will give a lower bound solution. If the lower bound solution is sufficient for the purpose, this would be equivalent to the "proof" static load test.

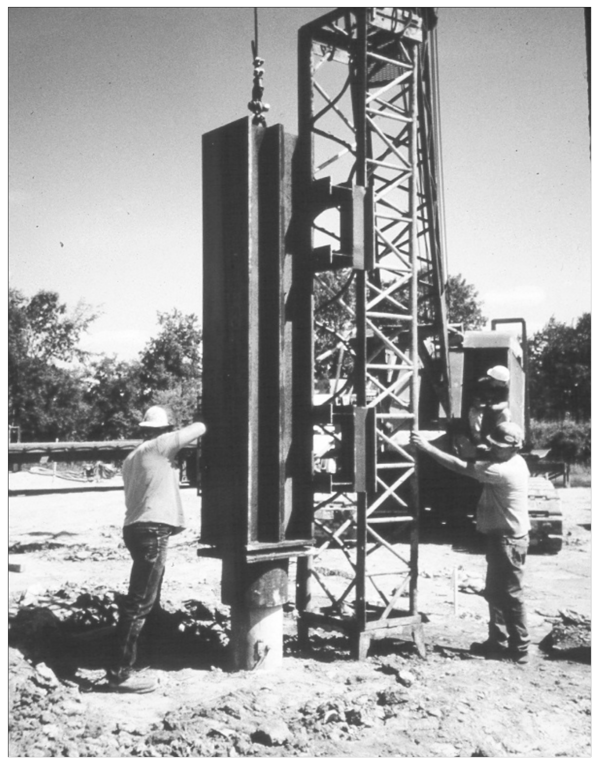

Figure 1: Simple drop weight test on built-up augercast pile

Following minimal guidelines and some pile top preparation, dynamic pile testing can be easily applied to a much larger, statistically significant sample of all piles. This of course allows for investigation of site variability. Since the selection of the dynamic test piles can be made after the piles are installed, it inspires the contractor to exercise the same care for each and every pile. Disadvantages would include the minor extra pile top preparation required, and the delay in time required to allow the piles to cure sufficiently prior to dynamic testing.

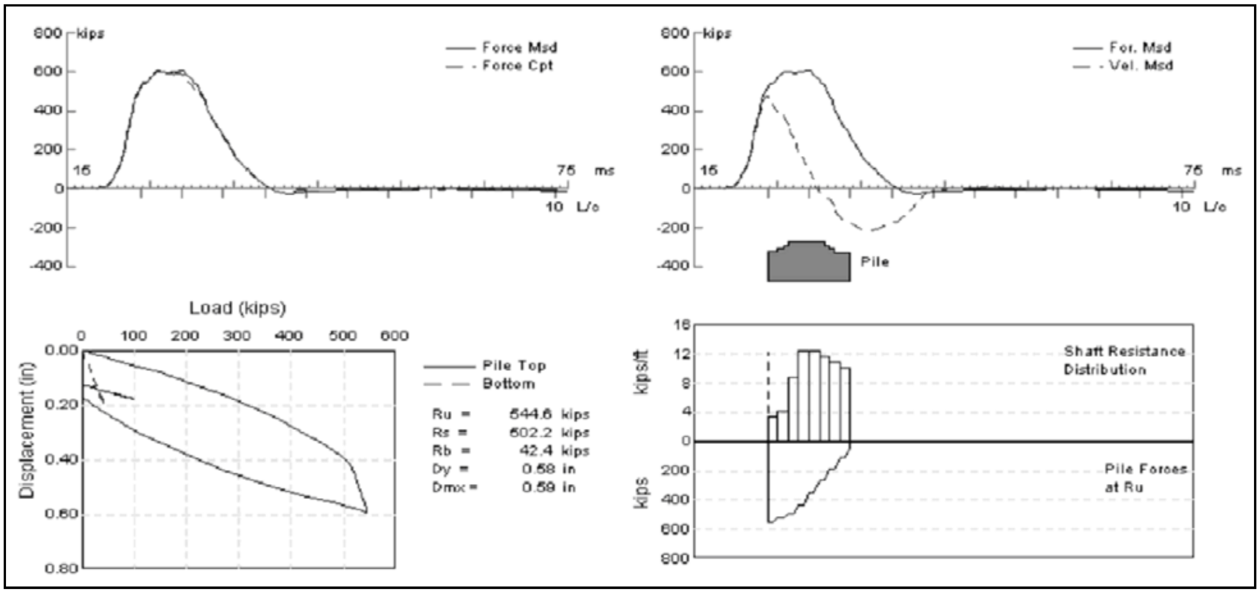

Figure 2: Dynamic test result for an augercast pile
(1 kip = 4.46kN; 1 ft = 0.305 m; 1 inch = 25.4mm)

Figure 2 presents the results of a dynamic test of an augercast pile, including the simulated static test in the lower left. The nonuniform pile model and soil resistance distribution are shown in the right half of the figure. Recent advances in dynamic testing augercast piles and drilled shafts have led to the instrumentation of the ram to measure force independently of instrumenting the pile. This has the advantage of not relying on the conversion of strain using the modulus of elasticity and of simplifying the measurements. However although more piles can be tested dynamically than statically to assess site variability, it still tests only a small percentage of the piles for structural integrity. Since every pile may have a defect, other means must be considered to assure the structural integrity of every pile.

Pile Integrity Testing

Pile integrity testing (Likins et al. 2000b) uses a hand held hammer to impact the pile top and generate a compressive stress wave in the pile as shown in Figure 3. Stress wave inputs and reflections (from non-uniformities or the pile toe) are measured by an accelerometer. This method is frequently applied to augercast piles. The pile top is prepared by removing the upper contaminated concrete, making a smooth location, and attaching an accelerometer with a thin layer of bonding wax. This minimal preparation allows testing

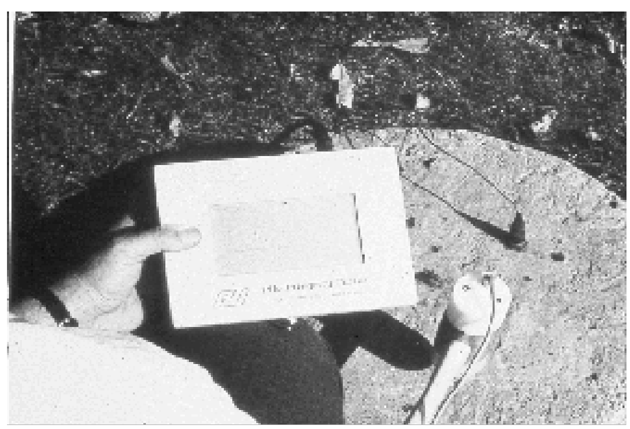

Figure 3. Pile Integrity Tester (PIT) system with hammer and accelerometer (upper right).

any pile, even after construction, provided only that the pile top is accessible. Accelerations from several hammer blows are normalized, integrated, averaged, digitally filtered and displayed as velocities. Further processing applies an exponential magnification function which restores reflection details diminished by soil resistance, pile material damping or pile non-uniformities. The resulting signal is interpreted by the test engineer. This method is limited to solid section concrete piles. It works best on relatively uniform piles in weak soils. Often a 30 Length/Diameter limit is suggested, although more modern equipment with low noise and higher resolution makes testing longer piles now possible.

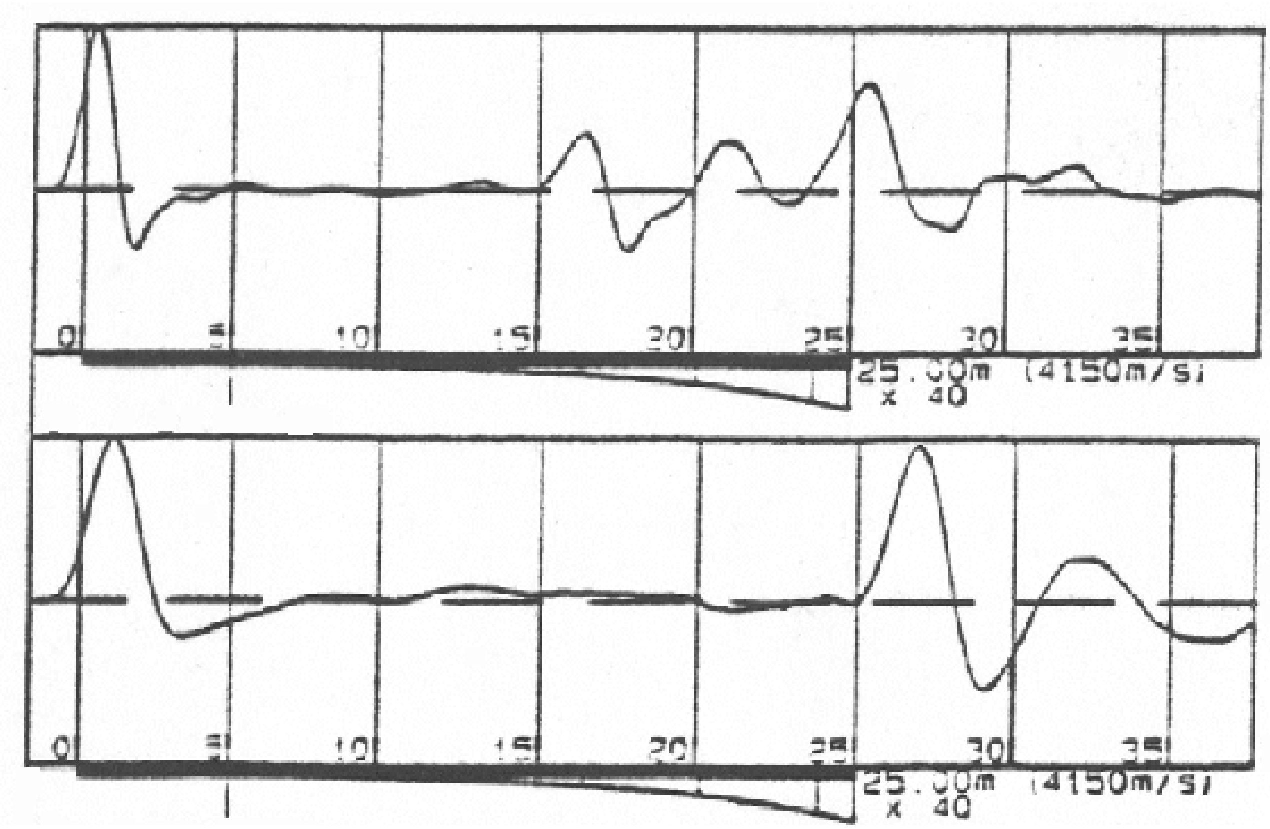

Figure 4. PIT velocity records of deficient pile (top) and normal pile (bottom)

Figure 4 shows an example output for a pile with Length/Diameter ratio of 40. An exponential magnification is applied, increasing from unity value at the left or pile top to a maximum multiplier (40x) at the right for the pile bottom at 25 meters (82 ft). The assumed stress wave velocity is 4150 m/s; 13600 ft/s. The bottom plot shows a clear pile bottom reflection with a relatively steady velocity signal between the impact and pile bottom indicating a good pile shaft. The upper plot for another pile on the same site shows a pronounced velocity increase at about 16 m (52 ft) which indicates a tension reflection from a local reduction in pile cross section or concrete quality. In general, sharply defined changes in the velocity are attributed to impedance changes, while slow changes are usually caused by soil resistance. If soil resistance effects are known from reference piles, then unusual shafts can be identified.

Prevention of Defects by Automated Monitoring During Augercast Installation

In the USA, augercast piles have traditionally been installed on the basis of the experience of the contractor. General guidelines have been developed and documented by the Deep Foundations Institute (1990). This manual recommends that the incremental volume for each 1.5 m (5 ft) of depth is the single most important parameter influencing the quality of the installed pile. In practice, however, this volume versus depth increment is a very difficult measurement to make using manual methods and is usually not recorded. The DFI Manual's second most important observation is that the grout should be observed exiting the hole well before the auger tip reaches the ground surface. This depth, when the grout is first observed coming from the hole, is referred to as the "grout return depth". Usually the quality control is reduced to simply obtaining the total pump stroke count to confirm total volume, and observing that the grout return depth comes sufficiently before the auger tip reaches the surface. In effect, this current state of the practice in the United States relies on the contractor's expertise to distribute the grout along the length properly.

The total volume of grout per pile is then computed from the volume per pump stroke obtained from a "calibration" of counting the pump strokes required to fill a 55 gallon drum. But this "calibration" is done under "ideal conditions" with no confining pressure, and usually only once per project when the grout pump has been recently serviced between projects. During actual installation of production piles, the grout pumped per stroke will vary due to several factors such as grout consistency, hose length, height of the auger gear box above the ground surface, grout pressure generated by the pump, the soil strength and thus passive "confining pressure" exerted against the incoming grout, grout pump speed, valve seating and seals, and general pump maintenance.

Although the augercast piling method was invented in the USA, electronic monitoring in the USA has lagged monitoring development and application in most of the rest of the world. In other countries, depth was recorded with depth sensors usually based on encoders. Initially, volume was measured by electronically counting pump strokes, and coupled with measuring depth allowed for a better definition of volume versus depth. Pump stroke volume variability was eventually recognized as a serious problem by the Institution of Civil Engineers of England (I.C.E., 1994) where they state "In the first instance concrete volume was estimated from the supply pump strokes... Electromagnetic flow meters and accurate measurement of auger depth were introduced to overcome inconsistency of pump stroke volumes...". Magnetic flow meters measure the volume from Faraday's Law by generating a voltage proportional to the flow velocity of a conductive fluid passing through an electromagnetic field encompassing a known cross sectional area of the tube. Wet grout or concrete is more than three orders of magnitude more conductive than the minimum conductivity specifications for accurate measurement (Master Builders, 2000). In England by 1996, automated instrumentation to monitor grout volumes as a function of depth had been developed to the point that "Confidence in the [augercast] method has been significantly improved as a result of reliable, sophisticated computer based instrumentation" such that "automated monitoring is now mandatory" in the 1996 I.C.E. Specification for Piling (Derbyshire et al, 1998; I.C.E., 1996).

A few systems have been imported into the USA which estimate volume by counting pump strokes. To improve the volume accuracy, the Pile Installation Recorder for Augercast piles or "PIR-A" (Likins et al 1998) measures volume to the nearest liter from magnetic flow meters. Depth is typically recorded to the nearest 25 mm (1.0 inch) using a encoder to track the movement of a cable attached to the auger gear box. The system is shown in Figure 5. The information is clearly displayed both graphically and numerically showing the volume pumped for each and every depth increment and is available as the crane operator is grouting the pile. This information guides the operator into a smooth steady withdrawal at a rate slow enough to produce a pile with a grout ratio above the desired minimum grout ratio for each increment, thus producing a good pile. Results are then printed out for the entire pile, showing the distribution of volume pumped.

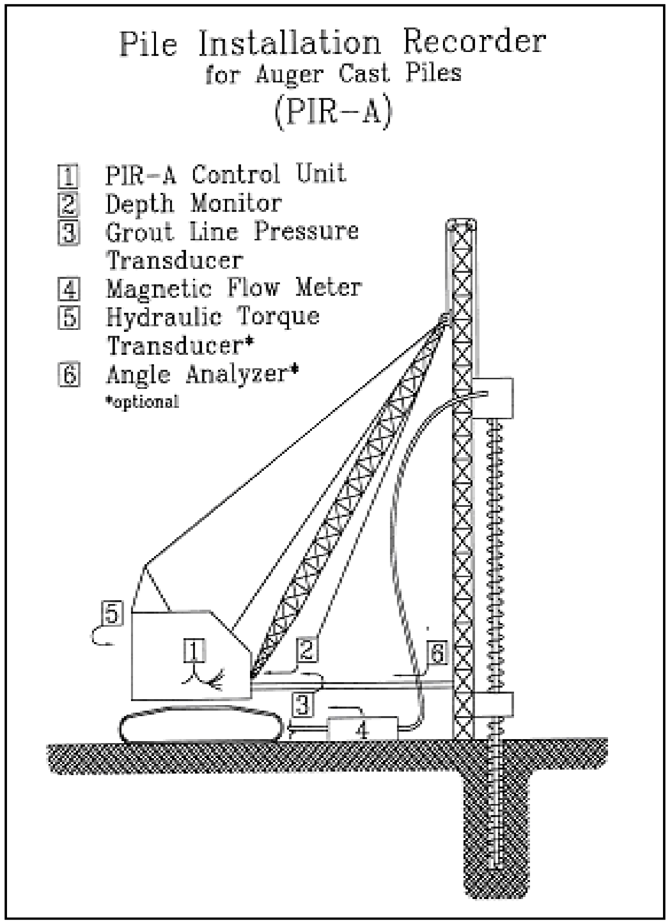

Figure 5: PIR-A schematic

On a recent project, the pile specifications required a 115% grout volume ratio, which is the minimum ratio suggested by the DFI (DFI 1990). This means that at least 15% extra volume was required compared to the nominal volume of the 400 mm (16 inch) diameter auger. For the first six piles installed (reaction piles for static test piles), the total volume recorded by the PIR-A was about 4% lower than that calculated from counting pump strokes (assuming 21.5 liters/stroke; 0.61 ft^3/stroke from a "pump calibration" by filling a drum), and the grout volume ratios recorded by the PIR-A were typically 120% to 130%. These piles started with a 0.75 m (2.5 ft) initial grout head and the "grout return depth" was typically 4.5 m (15 ft), indicating that more grout had been pumped than was required to fill the hole. The grout volumes for each depth increment recorded by the PIR-A were generally fairly uniform and consistent for the entire pile length for all piles.

Two static test piles were installed two days later, both pumped from the same delivery truck. The grout pump however did not perform correctly. When the results differed between counted pump strokes and the PIR-A, the contractor relied on his normal installation procedures. Table 1 summarizes the installation volumes measured by the PIR-A magnetic flow meter for these two piles. The "stem volume" first fills the hollow auger. Next an "initial head volume" is pumped to establish grout on the auger flights before beginning auger withdrawal as recommended by DFI. If the auger is not continuously lifted, but rather redrills a portion of the hole, that volume is listed as "reaugered volume", and this volume is assumed to be wasted (much comes up the auger flights and accounts partially for the earlier grout return depth for pile T3). The actual pile volume pumped is compared with the nominal theoretical volume for the hole to compute the minimum required grout ratio. Spill volume represents the wasted grout pumped after the auger is raised above the ground surface. The total volume pumped is the sum of all the above volumes.

As can be seen in Table 1, the computed volume from assuming a 21.5 liters (0.61 $ft^{3)}$ volume per pump stroke from a "pump calibration" considerably overestimates the PIR-A actual measured volume. The actual grout ratios from the PIR-A for the two piles are 107% and 118%, values which correspond favorably with the volumes recorded for the earlier installed reaction piles installed in the same soils.

Table 1: Summary of PIR-A Results for Two Augercast Test Piles

Description	Pile T3	Pile T4
Length	12.2 m; 40.1 ft	19.9 m; 65.2 ft
Target volume {115% target grout ratio}	2270 L; 64.3 ft^3	3695 L; 104.6 ft^3
PIR-A Stem volume	317 L; 8.97 ft^3	317 L; 8.97 ft^3
PIR-A Initial Head Volume {0.75 m, 2.5ft}	122 L; 3.46 ft^3	122 L: 3.46 ft^3
PIR-A Actual pile volume {equivalent grout ratio}	2114 L 59.9 ft^3 { 107% }	3794 L 107.4 ft^3{ 118% }
PIR-A Reaugered volume	551 L; (6.1 to 7.9m) 15.6 ft^3 (20 to 26 ft)	0.00
PIR-A Spill volume	0.00	61 L; 1.73 ft^3
PIR-A Total volume pumped {sum above}	3104 L; 87.9 ft^3	4294 L; 121.6 ft^3
Observed grout return depth	6.2 m; 20.4 ft	3.3 m; 10.9 ft
Minimum grout ratio {per 0.9 [3 ft] depth incr.}	67% (4.6 to 3.7 m) (15 to 12 ft)	21% (14.6-13.7m) (48 to 45 ft)
Counted pump strokes	204	284
Volume from "calibrated"pump strokes at 21.5 L (.61 ft^3) per stroke {calc grout ratio}	4395 L 124.4 ft^3 { 223% }	6118 L 173.2 ft^3 {190% }
Volume per pump stroke calculated by PIR	15.2 L; 0.431 ft^3	15.1 L; 0.428 ft^3

Because the volume ratio calculated from the pump stroke counts was significantly larger than the required volume ratio, the contractor initially asserted that the PIR-A was not functioning properly. Closer inspection proves otherwise. Combining the total volume for both piles, including an additional 520 L (14.7 ft^3)of grout initially pumped prior to logging these piles to prime the 92 m (300 ft) of grout hose from the pump to the auger, makes the total PIR-A volume 7,918 L (224.2 ft^3) and the calibrated pump stroke volume 11,032 L (312.41 ft^3). However, the volume ordered by the contractor was only 10 cu.yd. (9,535 L; 270 ft^3).

Therefore, the volume calculated from the calibrated pump stroke volume and the counted pump strokes clearly is in error (since that volume could not be even carried by the single grout delivery truck). Dividing the total PIR-A measured volume by the observed number of pump strokes results in a calculated volume per pump stroke of 15.2 L (0.43 ft^3), only 70% of the assumed "calibration". Further, the grout return depth came *later* for the T4 test pile than for the earlier recorded reaction piles, meaning less grout had been pumped (the earlier grout return depth for pile T3 was due to the substantial reaugering for that pile). After making these computations and observations, the contractor was convinced the pump did not perform properly. Had the contractor relied solely on his traditional pump stroke counting methods, these piles would be seriously under grouted and structural failure would be considered very probable.

However, the total volume placed per pile does not tell the full story. The *distribution* of grout placed along the pile can be even more important. The grout pumped per depth increment bears similarity to the volume remaining at that depth. Of course, some extra grout volume injected under pressure

Withdrawal Data [start 14:14]

depth (ft)	pumped volume (ft3)	volume ratio (%)	pump strks	line_pres min (PSI)	line_pres max (PSI)
65.2				(max depth)	
65.1	8.97		21	(stem vol)	
65.1	3.46		7	(head vol)	
63.0	6.92	229	17	0	163
60.0	5.44	130	12	3	163
57.0	4.06**	97	9	2	162
54.0	5.09	121	13	2	163
51.0	3.71**	89	11	3	173
48.0	3.39**	81	11	4	181
45.0	0.88**	21	4	5	186
42.0	3.18**	76	8	4	175
39.0	3.60**	86	10	2	194
36.0	5.69	136	13	2	194
33.0	5.76	137	13	5	200
30.0	5.23	125	13	6	202
27.0	6.07	145	11	9	201
24.0	5.09	121	11	9	201
21.0	5.16	123	10	10	200
18.0	5.19	124	9	8	203
15.0	5.76	137	10	12	207
12.0	6.00	143	12	12	207
10.9	<--- return depth				
9.0	6.25	149	11	18	209
6.0	4.24*	101	11	19	207
3.0	5.76	137	11	21	209
0.0	5.23	125	13	19	216
	1.73		1	(spill vol)	

[stop 14:25 (00:10:26)]

Nominal Inc Vol: 4.19 ft3 (3.0 ft)
Target Inc Vol: 4.82 ft3 (3.0 ft)
Nominal Vol: 90.97 ft3 (16.0 in dia)
Min Target Vol: 104.62 ft3 (115%)
Pile Vol: 107.43 ft3 (118%)
Stem Vol: 8.97 ft3
Head Vol: 3.46 ft3 (2.5 ft)
Reaugered Vol: 0.00 ft3
Spill Vol: 1.73 ft3
Total Vol: 121.59 ft3

* pumped volume < target volume
** pumped volume < nominal volume

Figure 6: copy of PIR-A grouting printout for pile T4

expands the hole in loose or soft soil deposits, and some extra grout is carried up the auger, resulting in an earlier grout return depth than the initial grout head volume would suggest. While DFI suggests a minimum resolution of 1.5 m (5 ft), the PIR-A resolution is typically shown in finer increments. Three ft (0.9 m) depth intervals were used for this project. For these two test piles, the minimum grout ratio for any recorded depth increment is 67% for pile T3 at a relatively shallow depth (which could also affect the lateral pile strength), and 21% for T4 at a deeper depth (as shown in Figure 6 containing the PIR-A grouting summary printout for this pile). Since the grout is still fluid, there is some redistribution of grout between increments during placement. In this case, however, the 21% defect comes in the middle of five consecutive increments of less than 100% grout factors, so there is little extra grout from which to "borrow". Of course, this major "defect" is at a considerable depth below grade and the shaft resistance of the soil above the defect will reduce the effective load applied to this reduced cross section. Had the reduced 21% section of T4 been produced at the defect location of T3, a structural pile failure would have certainly resulted. Similar defects are probably the cause of static load tests with obvious structural failures. In past projects where these deficiencies detected by the PIR-A have been explained to the operator, the operator has then diligently improved his technique and the pile grouting has been subsequently very uniform.

Automated monitoring as shown above provides invaluable assurance of proper installation. However, other visual inspection is still required to inspect grout strength from cube or cylinder samples, for completion or screening operations, to inspect rebar placement, to check for subsequent subsidence, and to observe excavation activities. Should any such phase of installation indicate a problem, the integrity can be further investigated by either ultrasonic single hole or cross hole methods provided access tubes were installed immediately after grouting, or by sonic pulse echo methods such as PIT, or the capacity checked by static or dynamic methods. However, *prevention* of defects using automated installation inspection methods such as PIR-A (or if defects are detected, immediate repair for defects by redrilling and regrouting while the grout is still fluid) are preferable to subsequent detection by ultrasonic or sonic methods after the grout has hardened.

Conclusions

Augercast piles are an increasingly popular foundation solution. A successful installation requires adequate soil capacity and uncompromised pile shaft integrity. The variability of capacity over the site can be effectively investigated using dynamic pile testing techniques. Each pile is individually constructed and the quality of the pile is highly dependent upon the skill of the contractor. Thus each pile must be evaluated for integrity. Pile integrity can be evaluated for every pile on each site using pulse echo methods due to the relatively low cost of this test method and the ability to apply this test after construction is completed. However, finding defects after installation leads to higher cost repairs. It is preferable to monitor the pile shaft incremental volume versus depth during installation with the displayed information being available to guide the operator into a more uniform pile shaft. Defects can be corrected at that time with minimal additional costs. Prevention is preferred to simple after the fact detection. Automated monitoring of grout volume by magnetic flow meters as a function of depth increment has been required in other parts of the world for augercast piles and is now being applied to augercast piles in the United States.

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