Dynamic Load Testing of Augered Cast-In-Place Piles

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Abstract: High strain PDA testing has become common for verification of capacity of both driven and bored piles. It is equally applicable to Augered-Cast-in-Place (ACIP) Piles. It also evaluates other aspects of the installation such as integrity. The benefit of high strain dynamic test results for the relatively low cost of the tests compared to conventional static testing has resulted in widespread use. The method is described and specific procedures for testing ACIP piles are outlined. Example results demonstrate the application.

Dynamic Pile Testing Methods

As technology changes, the construction industry adapts. Augered Cast-In-Place (ACIP or simply "augercast") piles have been increasingly used in recent years as the technology has improved. To verify both the structural strength and soil bearing capacity of ACIP piles, a few selected piles were statically tested. Unfortunately, static testing is slow and costly and thus applied to only a very small sample of specially prepared piles on a site. In recent years systems have become available for inspection of all piles on site of grout volume versus depth (Likins, 1998). Installation monitoring reduces the need for static testing to prove the structural strength of the ACIP piles. However, it does not estimate pile capacity and additional tests to determine soil strength are still needed.

Fortunately, bearing capacity can also be economically estimated by dynamic pile testing for a larger sample of ACIP piles. Figure 1 shows a conventional hammer or large drop weight is used to dynamically impact piles installed by continuous flight augers. A research program beginning in 1964 at Case Western Reserve University in Cleveland Ohio under the direction of Dr. G.G. Goble (Goble et al 1975, Goble et al 1980) defined the techniques for dynamic pile testing. Dynamic testing requires measurement of force and velocity of the pile during an impact. These quantities are routinely obtained measured by reusable strain transducers and accelerometers with the "Pile Driving Analyzer®" (PDA).

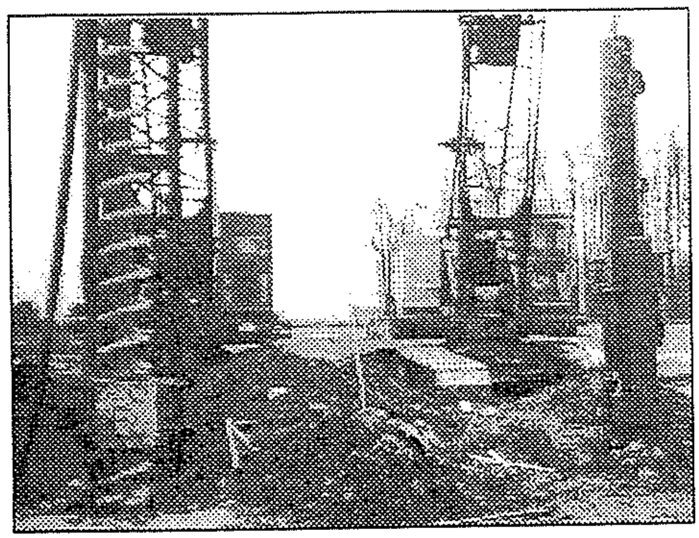

Figure 1: Augered piling rig (left) with system to apply dynamic test impact (right)

The initial goal of the Case research was to measure pile capacity using the pile driving hammer as the loading device. Capacity was evaluated by both closed form solutions called "Case Method" for immediate on-site evaluations and a discrete extensive numerical analysis called "CAPWAP®" for improved accuracy. The CAPWAP signal matching computer algorithm extracts the soil model from the measurements, and provides a simulated static load test result (Goble Rausche

Likins and Associates, 1999) that has been proven to have good agreement with static load test results for driven piles (Likins, 1996).

Dynamic testing of ACIP piles

For capacity evaluation of ACIP piles, dynamic testing data can be collected only after the pile achieves sufficient structural strength. This waiting time also allows the soil to fully bond with the shaft so that the capacity at the time of testing is similar to the long term service load capacity.

If reinforcement protrudes from the pile top, the pile can be built up temporarily above the reinforcement using a thin steel casing as a form. This pile top extension can then be removed after the test to expose the rebar and tie into the permanent structure. Extending the pile top eliminates the need for pile top excavation and allows easier access for attaching the measuring sensors a couple diameters below the pile top (standard practice to avoid end effects and local contact stresses). Ideally, the extension should be cast simultaneously with the shaft so that the grout has the same properties. The steel casing provides additional strength to the pile top.

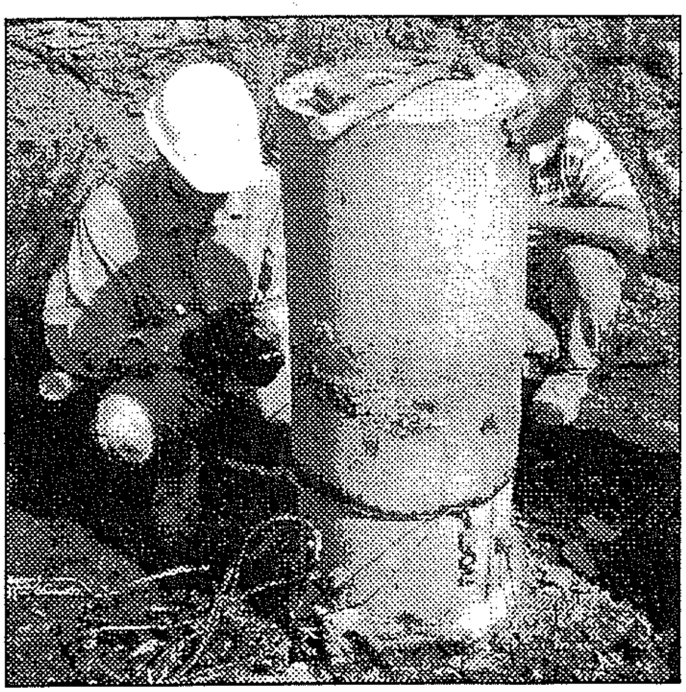

Figure 2: Attaching sensors to ACIP pile top extension after removing forming shell

Figure 2 shows acceleration and strain sensors being attached to an extended ACIP pile. The pile was extended above the ground surface with a thin steel shell. The lower section of the shell was then removed and the sensors attached by bolts to the resulting smooth grout using concrete anchors. As an alternative to measuring strain and converting to force by multiplying the strain by the assumed modulus and measured area , top transducers used in the early research project were sized to the pile dimensions and placed between the hammer and pile to transmit and measure force directly. Top transducers are now being seriously considered again and have significant advantages for ACIP applications, including ease of application to large number of shafts and better force definition.

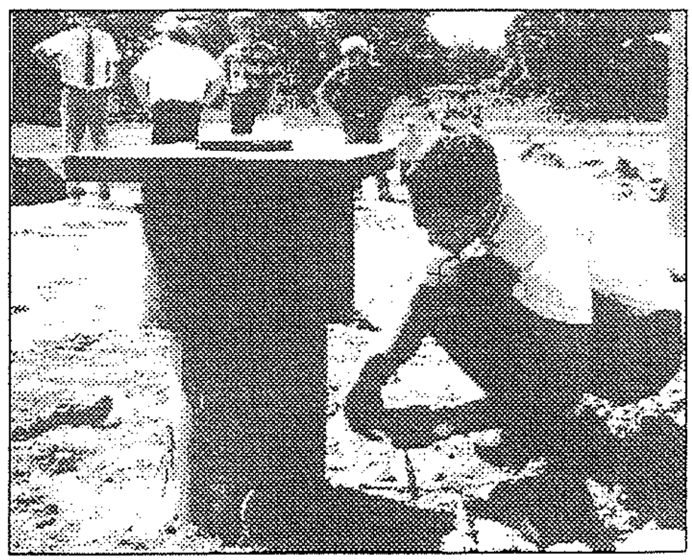

Figure 3: sensor attachment to ACIP with "helmet" in place

The pile top surface should be flat and relatively smooth after casting and only needs some minimal plywood cushion to distribute the impact over the entire top surface. A steel plate or "helmet" is usually placed above the plywood as a striker plate for the impact weight as in Figure 3. A "centering" target is placed concentrically with the pile to assure the hammer imposes the impact over the pile center rather than at the pile edge.

To perform the high strain test, the ACIP pile is then subjected to an impact of an impacting weight. In most cases a simple inexpensive drop weight is preferred. Figure 4 shows a two ton drop weight (four heavy steel H sections welded together) positioned to test an ACIP pile. Generally, the cost of the drop weight is low, and the hammer can be reused many times on similar projects. Other drop weight designs include solid steel cylinders, concrete filled steel pipes or heavily reinforced concrete blocks.

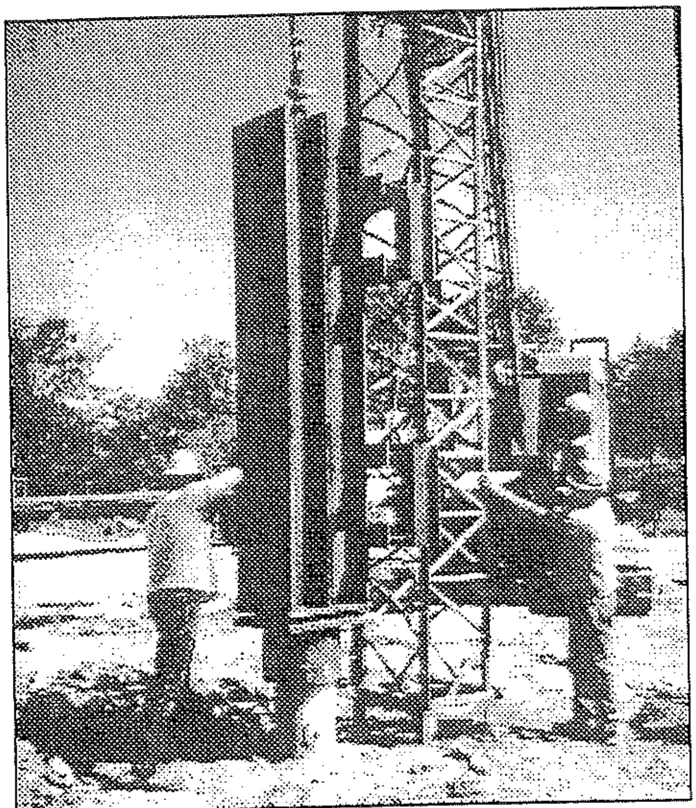

Figure 4: custom 2 ton drop weight made of welded H sections

As a general guide, the weight should be at least 1 to 1.5% of the desired ultimate capacity to be proven (Hussein, 1996) to assure load activation at reasonable stresses. Larger existing weights can be used provided the weight and pile shaft diameters are comparable. Regardless of size, shape or composition, the drop weight is generally guided to provide an axial impact by a short set of leads as in Figure 4. Usually it is raised by cable and dropped by releasing the drum brake. An alternative drop method involves raising and securing the weight and then completely releasing it (e.g. "free drop" by releasing hydraulic jaws, or by tripping a simple mechanical release).

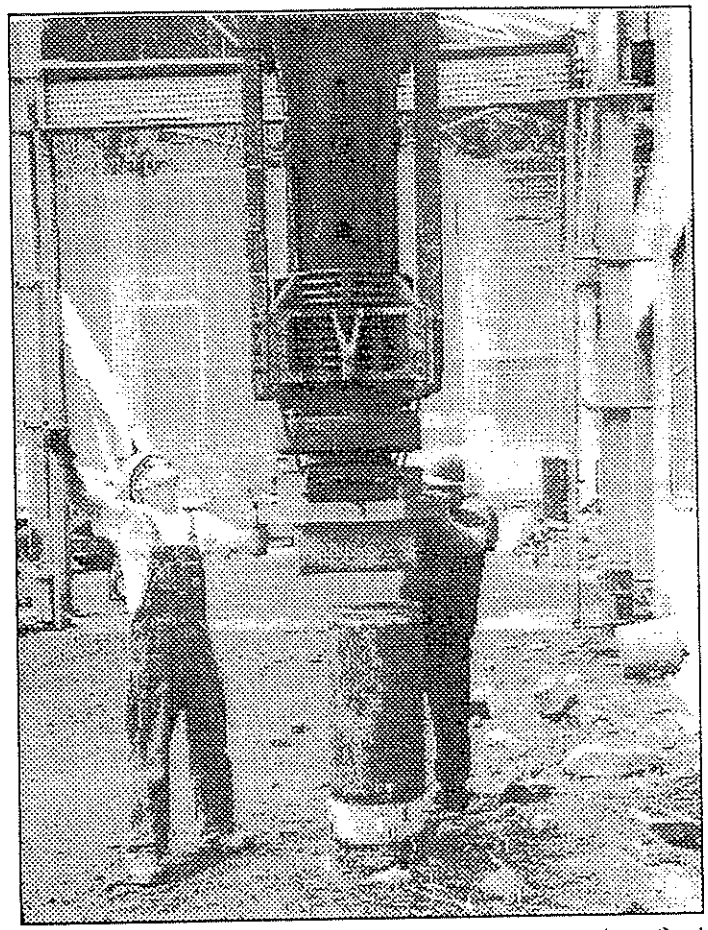

Figure 5: Drop hammer made from removing fuel pump of diesel pile driving hammer

Figure 5 shows a modified diesel pile driving hammer being positioned onto an ACIP pile for dynamic testing. The fuel pump was removed making it effectively a drop hammer. The cylinder acts as the ram guide to maintain alignment. The thin plywood cushion is visible at the pile top. The helmet attached to the bottom of the hammer centers the hammer on the shaft.

The test for ACIP applications usually consists of a few separate impacts. A low drop height is first applied to assess signal quality and alignment of the drop weight with the shaft. Since usually four strain sensors are attached to the ACIP pile and monitored separately, bending and local contact stresses can be assessed and hammer pile alignment improved if necessary. The PDA gives the maximum compressive stress at the sensor location which are compared with the grout strength after each impact. For each blow, the net permanent displacement or "set per blow" is carefully measured to evaluate capacity activation. The test continues with increasing drop heights until either the set per blow exceeds 2.5 mm (a value usually sufficient to insure the full capacity activation), or until the indicated capacity is above the required ultimate capacity, or until the stresses become too large and the risk of pile damage is then too high. Most tests are completed in less than five impacts. If the pile top has been built up to accommodate the dynamic test, the extra top section is removed to facilitate completing the foundation.

Capacity Evaluation

Dynamic load testing indicates the activated or mobilized pile capacity. In the field the capacity is first estimated by the Case Method using the PDA. At very small set per blow (less than 2.5 mm), dynamic test methods tend to produce lower bound capacity estimates as not all resistance is fully activated (particularly at and near the toe). In many cases a lower bound solution is sufficient (this is similar to a static test run to only twice the allowable load as a "proof test" rather than to the ultimate failure load). Many ACIP piles have significantly higher ultimate capacity than required (such as ACIP piles installed to rock which are usually only statically tested to a proof load. Similarly, only a proof load capacity is needed from dynamic testing, rather than loading to ultimate). To activate the full resistance (where required), a higher energy is needed. The higher energy can be generated by application of a higher stroke, or a larger drop weight.

The measured pile top strain and velocity data are analyzed by CAPWAP to independently check the total capacity. If the pile set under the test blow is low, a CAPWAP analysis can be performed in a short time on site after each impact to determine if the activated capacity is sufficient or if another larger impact is required.

In the CAPWAP analysis, the soil model is similar to wave equation soil models (Smith, 1960). The pile and wave transmission are modeled by the method of characteristics (Goble Rausche Likins and Associates, 1999). The wave equation hammer model is replaced by the measured force and velocity as a boundary condition. Since these measurements are redundant, the unknown soil parameters can be directly computed. In practice the soil model is determined by a systematic iterative investigation.

For a measured velocity input, CAPWAP computes the force required to hold the system in dynamic equilibrium for some assumed soil model and subsequently compares it with the measured force. The soil model is adjusted either automatically by the program or manually by the engineer until the computed and measured forces agree. Since the exact shape of the ACIP pile is not known, the pile model is also adjusted as necessary for best agreement with soil investigation and pile installation information. This uncertainty can be minimized for soil conditions likely to yield a uniform pile shape, or where the pile shape is known by direct measurement by installation monitors and can be entered as an input rather than determined by iteration. Fortunately, the total pile capacity (which is the most important result) is not overly sensitive to the pile model, although the resistance distribution is affected. The final soil model (resistance distribution and dynamic and static soil parameters) producing this "best match" then describes the soil behavior during impact. Upon completing the CAPWAP analysis, a simulated static load test is generated from the pile and soil models.

Numerous other factors are usually considered in foundation design. Some of these considerations include additional pile loading from downdrag or negative skin friction, cyclic loading performance, lateral and uplift loading requirements, effective stress changes (due to changes in water table, excavations, fills or other changes in overburden), settlement from underlying weak layers and pile group effects. These factors merit consideration by the geotechnical engineer when designing the pile foundation and applying dynamic testing results.

Implementation Considerations

For small projects with only a few piles, one or two piles may be sufficient. For medium sized projects, the first production piles often serve as dynamic test piles and are distributed over the site to check site variability. For larger projects, dynamic testing allows the amount of static testing to be reduced after establishing a correlation between statically and dynamically tested piles. Additional dynamic tests are added to increase the percentage of piles tested and site coverage. This improves the overall quality assurance while reducing test costs.

Because of the large amount of dynamic testing performed, various codes and specifications are now in place in the USA. In 1986, the D4945 consensus standard was first adopted by ASTM (American Society of Testing and Materials, 1996) for "High Strain Dynamic Testing of Piles." Dynamic testing in the USA follows these guidelines.

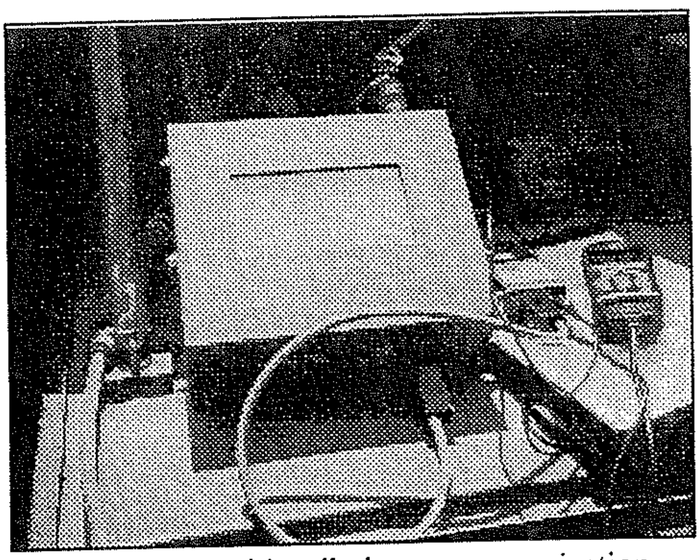

Figure 6: PAL with cell phone communication

The PDA engineer traditionally travels to the job with the equipment, prepares the pile, and attaches the sensors to the pile. The time required to prepare the pile for testing (drill holes and attach sensors) is often only 10 to 20 minutes per pile tested. Interpretation of results is then given by the PDA test engineer as the test proceeds. If periodic tests are required on site, for subsequent tests the latest PDA, called PAL (Figure 6), can be remotely operated by the PDA test engineer in the office to improve field scheduling. The sensors are attached to the pile by either the crew on-site or by a trained technician. Using a cell phone, the PAL connects and sends data to the PDA engineer operating his office PC who then interprets the PAL data, communicates his results back to the site, and can then immediately begin the data analysis and report preparation.

It is conservatively estimated that every year several thousand piling projects require dynamic pile testing on driven piles. The first PDA dynamic testing for ACIP piles in North America was performed in 1977 for a housing project in Charleston, West Virginia. Numerous ACIP piles were tested using a top transducer. Numerous ACIP projects with dynamic testing have been successfully completed since that time, with a growing frequency in the last few years.

Worldwide practice

PDA use outside the USA follows established local practice. Dynamic testing as described above is now routinely applied on ACIP piles and bored piles in many countries in Europe, South America and Asia using drop weights. Foreign contractors often obtain the equipment to perform testing themselves, or partner with independent engineers to provide testing services. In many cases by a "design-build" process, the contractor is encouraged to find better foundation solutions and is fully responsible for the foundation installation. Many contractors have found great benefit in dynamic testing to assure both quality and economy. In some countries the allowable pile capacity has been greatly increased as a result of more dynamic testing. For example, in Sweden the allowable loads for the same identical piles have approximately doubled as a result of codes requiring higher percentages of piles tested by the PDA.

Case History

Several 14 inch nominal diameter (356 mm) ACIP piles were installed at a hotel construction site. The soil investigation showed a 23 ft layer of clay fill over a 15 ft layer of compacted sand fill, over clay to great depth. The SPT N-values in the lower clay ranged from 7 to 15. The piles were designed for a working load of 150 kips (670 kN).

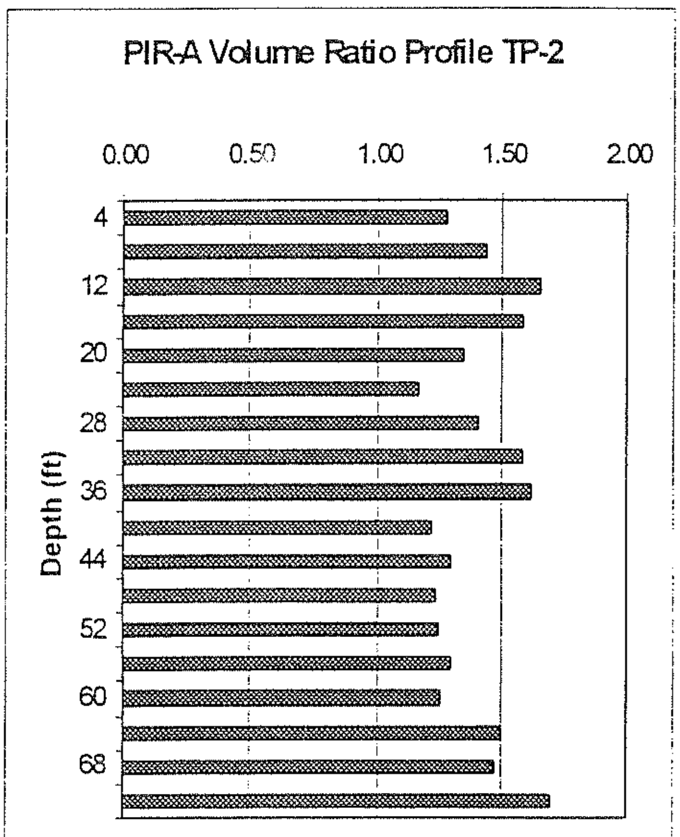

Figure 7: PIR-A Volume profile for TP-2

A Pile Installation Recorder for Augercast piles (PIR-A) was used to monitor the installed grout volume as a function of depth of the test piles. The PIR-A volume profile for test pile 2 (TP-2) installed to a 70 ft (21.3 m) depth is shown in Figure 7. The PIR-A recorded 12.5 minutes drilling time and 4.25 minutes for grouting. The required minimum volume ratio was 120% which was achieved for all depth increments. The overall average volume ratio was 140%. The test piles were unfortunately some of the first piles for the ACIP operator using the PIR-A. However, the data suggests that the piles were installed satisfactorily.

The upper four ft of the pile shaft were cased with a steel shell with the same nominal diameter as the pile in preparation for the dynamic pile tests. Both test piles were dynamically tested eleven days after installation using the 3.3 ton modified diesel/drop hammer depicted in Figure 6. The top of each shaft was protected by a 1.5 inch (40 mm) plywood cushion. The first drop was relatively low and subsequent drops were increased to as high as 5 ft (1.5 m). At most 5 blows were applied to each shaft.

The pile top was excavated and strain and acceleration sensors attached to the shaft below the protective steel casing. The grout below the shell was of similar uniform diameter.

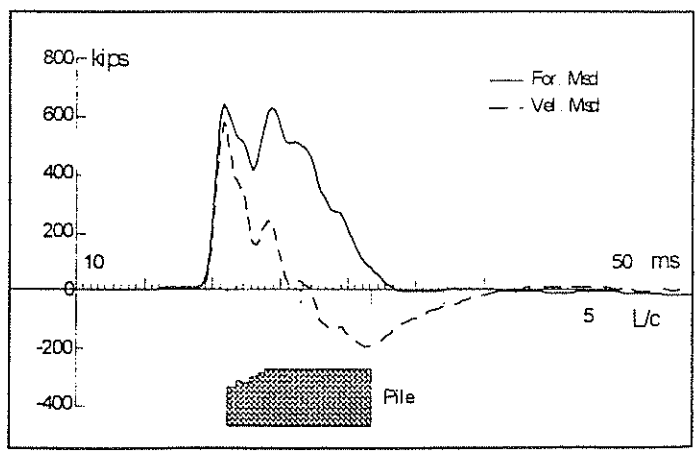

Figure 8: PDA data for TP-2 (1 kip = 4.45 kN)

PDA force and velocity data measured near the pile top is shown in Figure 8. A CAPWAP analysis was performed on this blow. From the CAPWAP analysis producing the final force match shown in

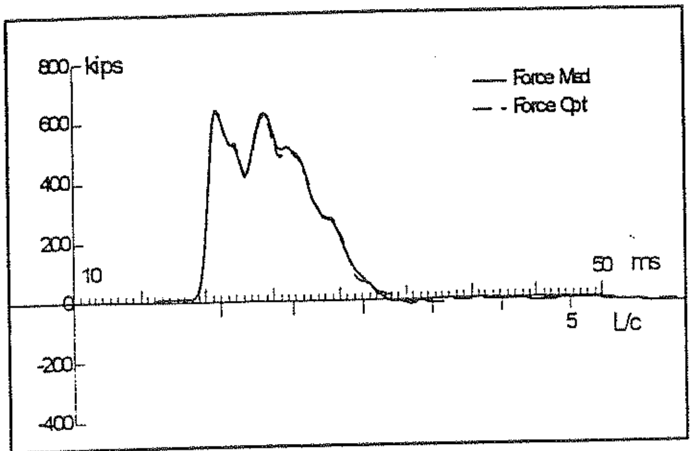

Figure 9: Force Match from CAPWAP

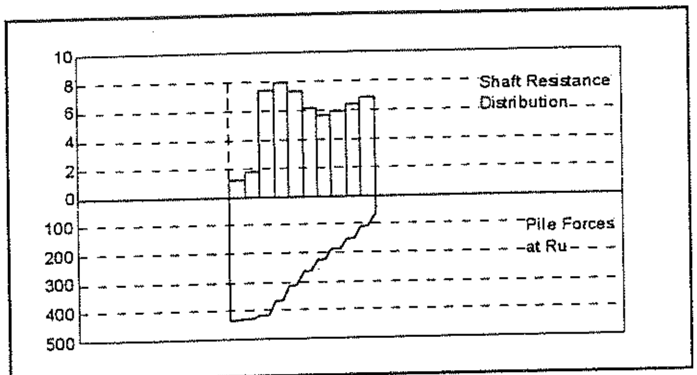

Figure 10: Resistance distribution (top) and Forces in pile at ultimate load (bottom) for 70 ft / 21 m pile (top at left, bottom at right)

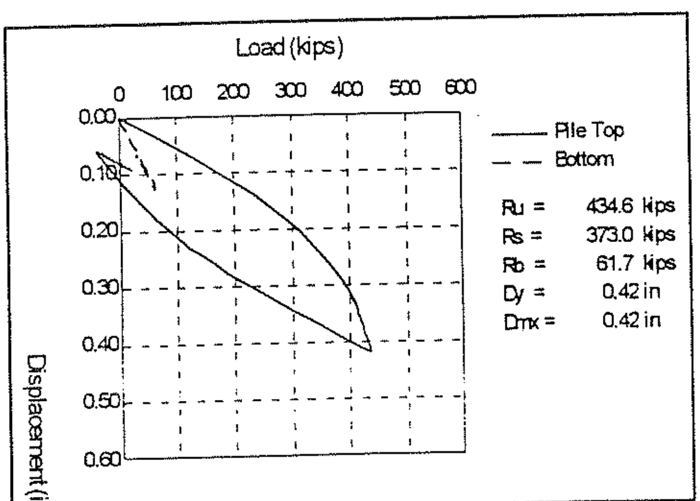

Figure 11: Simulated static load test curve from CAPWAP

Figure 9, the final soil model results show a predicted ultimate capacity of 434 kips (1935 kN) for a safety factor of 2.9 over the design working load. The load was 86% shaft resistance distributed as shown in Figure 10. The upper loose fill exhibited only little resistance while the lower portion of the pile had relatively uniform resistance. Finally the simulated static load test graph produced by CAPWAP is displayed in Figure 11.

The pile model determined from the analysis is also shown graphically in Figure 8. An increased section was found relatively closely below the depth where the grout return was noted. Above this depth the extra grout pumped can relatively easily flow to the ground surface. A uniform shaft with average 44% overage was modeled in the CAPWAP analysis which matches the 140% grout ratio quite well considering the CAPWAP analysis was performed independently of the PIR-A volume records.

Conclusions

Dynamic pile testing with the PDA and subsequent CAPWAP analysis has become a routine practice for engineers and contractors worldwide. On numerous sites, dynamic pile testing has been successfully applied to ACIP piles by applying an impact of a large drop weight. To activate the full soil resistance (and thus correlate best with a static test failure load) for ACIP piles, the energy input must be sufficiently large to produce a 2.5 mm set per blow or more. Numerous codes and specifications now give guidelines for the proper application of dynamic testing. New technology has been introduced to allow the PDA test engineer in the office to remotely monitor dynamic pile tests on site and communicate results with the site engineers.

Capacity of ACIP test piles can be determined by a static load test. However, dynamic pile tests followed by CAPWAP analysis is a quick, and low cost alternative for ACIP piles when minimum installation time is critical or if multiple tests are desirable to evaluate site variability. Dynamic tests on ACIP piles require some pile preparation and a drop weight to apply the impact.

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