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STATE OF THE ART DYNAMIC LOAD TESTING OF ACIP PILES IN THE AMERICAS.

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ABSTRACT

Augered Cast-in-Place (ACIP) piles have seen a rapid increase in demand. Factors such as high shaft resistance to volume-of-concrete ratio and fast, vibration-free installation with low noise, makes the ACIP pile a desirable deep foundation alternative. A variety of pile installation techniques exist that range from the typical hollow-stem augered ACIP pile to partial or full displacement pile. However, ACIP piles present challenges associated with as-built shape, structural integrity and relatively high load bearing capacity demands. Therefore, load testing techniques that increase reliability of load capacity determination are critical. In this paper, advances in the dynamic load testing techniques as applied to ACIP piles are presented. New techniques include the use of top transducers, the use of embedded instrumentation and testing recommendations specifically for ACIP piles. Top transducers speed up and facilitate load testing and increase the accuracy of top force measurement readings. Embedded instrumentation, particularly near the pile toe, helps improve the accuracy of pile wave speed assessment and calculated resistance distribution. Testing recommendations include the necessary hammer energy for optimal permanent penetrations per blow, which completely activate pile resistance while limiting over-prediction of ACIP bearing capacity in plastic soils. Additionally, a correlation between dynamic load test and static load test results recently performed on 47 ACIP piles tested in North and South America ranging from 16 to 30 inches in diameter is presented. Finally, supplemental testing and analysis techniques for further improvement of testing reliability and performance of ACIP piles are proposed, such as thermal integrity profiling and signal matching of the data from embedded sensors when available.

Key Words: Pile load testing; dynamic pile testing; ACIP Piles; Augered Cast in Place Piles; CAPWAP; Correlation.

INTRODUCTION

Deep foundations are frequently used in our construction world as the requirements to control settlements and carry high loads increase. Among the multiple foundation types available, the Augered Cast-in-Place (ACIP) pile has rapidly increased in popularity. The high soil resistance relative to concrete volume of ACIP piles allows these foundation elements to be a cost effective solution in a wide variety of geotechnical conditions. Relatively low machine noise and vibration free construction makes the ACIP pile a feasible solution for densely populated areas as well. Multiple techniques of ACIP pile construction have been developed during recent years; particularly the common hollow stem auger type and the partial or full displacement techniques that can minimize soil spoils while generating more soil confinement are today common practice in the foundation construction industry. Some challenges that arise with an ACIP acceptance during construction include the uncertain as-built shape and performance of these deep foundation elements. High strength grout and concrete mixes have allowed ACIP piles to reach high levels of structural loads, but with these structural improvements, geotechnical performance conditions need to be verified. Load testing therefore becomes a crucial tool for pile load verification or even more importantly in pile load design as long as testing is implemented in early stages of the construction process. Static load testing and dynamic load testing, or the combination of both, are the most common capacity verification methods in the ACIP industry. Improving and understanding static and dynamic testing, and understanding their differences and limitations becomes a necessity for safety and economy in today’s construction world.

Studlein et al. [1] discuss the challenges associated with the determination of “capacity” or “failure load” from static load tests. The authors argue that the most significant source of differences in the interpreted capacity from static load tests stems from the number of methods available for the interpretation of the static load test data. They mention a spread of 40 to 100% between the lowest and the highest failure loads from the available failure criteria for the same load-displacement curve, discourage the use of the Davisson’s Offset Limit method for ACIP piles and recommend the use of the Butler-Hoy criterion. Reese and O’Neill [2] recommend that the ultimate bearing capacity for drilled shafts, and thus perhaps also ACIP piles, is defined at a top displacement equal to 5% of the diameter of the shaft. AASHTO [3], Brown et al. [4] and other ACIP studies propose a similar failure criterion for ACIP piles and for that reason, the 5% criterion is also used in this paper.

Challenges associated with applying the dynamic load test, which was originally developed for driven piles, to ACIP piles include the accuracy of top force measurements, pile wave speed assessment and a reasonable estimation of the as-built shape or pile size. These complications are addressed in this paper.

THE USE OF LOAD TRANSDUCERS DURING DYNAMIC LOAD TESTING

Determination of the load, applied to a pile during a dynamic load test, requires the installation of strain gages to obtain unit deformation readings. This measured unit deformation, multiplied by the area of the pile and its elastic modulus, yields the measured pile force. For a steel pile, the elastic modulus is well known, but for concrete piles the elastic modulus may vary from mix to mix. For driven concrete piles, the elastic modulus can be calculated based on two conditions: (a) the arrival time of the impact stress wave at the pile top after reflection at the pile toe, as well as the proportionality of strain and velocity during a short loading period with the wave speed being the proportionality factor. Calculating then the wave speed from arrival time and/or proportionality yields the dynamic elastic modulus, E, ($E=c^2\rho$, where c is the wave speed and ρ is the mass density). For an augered pile, obtaining a clear toe response may not be that simple due to the potentially high levels of side friction and it also may prevent getting a clear indication of proportionality. Assuming a wave speed value or calculating it based on concrete/grout strength and/or age is not very accurate. Fortunately, however, these errors would not be excessive since concrete/grout wave speeds generally differ by not more than 10%. However, using a top load transducer, also called a load cell, avoids the use of a concrete elastic modulus for pile top force determination and, therefore, minimizes the effect of an inaccurate wave speed assessment on the dynamic test results and therefore reducing the force calculation inaccuracy.

A second advantage of using a top transducer is that an expensive pile top extension or pile top excavation for sensor attachment becomes unnecessary. Figure 1 shows a test where a top transducer was placed on an ACIP pile with a short extension necessary to provide for a horizontal and smooth top surface. Onsite test preparations will be much quicker, because it becomes unnecessary to anchoring the strain gages to a smooth pile concrete surface of good quality. It is important to understand, that although the transducer accurately measures the force, the motion of the pile must be measured with accelerometers on the pile; however, these sensors only need to be placed a few inches from the pile top and are much less sensitive to local concrete quality and surface properties. It is recommended to place the top transducer on a very thin cushion to avoid an unevenness of the pile top surface causing stress concentrations. The main cushioning should be placed on top of the transducer. Differences between the force measured in the transducer and the force of the pile top, which is used for the data analysis, can only be due to transducer inertia. Because of the need for cushioning, that effect is of a small magnitude and limited to a very short time period during which the acceleration is high. While this small force effect can generally be ignored, it can also be accounted for by acceleration measurements on the transducer. As high loads will be applied to the pile, a thin shell pile buildup is recommended for the pile top. If during the initial construction process a smooth surface at the top of the pile is not achieved, leveling the surface with a self-consolidating grout/concrete can be done as shown in Figure 2.

EMBEDDED INSTRUMENTATION

While the pile top force can be correctly measured by the top transducer without reliance on an assumed pile top wave speed or elastic modulus, it is a dynamic quantity requiring further analysis. This is most conveniently done by the signal matching program CAPWAP®, which was developed at Case Western Reserve University [5]. This program allows for the identification of not only the side friction distribution and end bearing, but also additional dynamic and static resistance parameters such as soil damping and soil stiffness. For the calculation of the distance of the resistance forces from the pile top, i.e., the calculated resistance distribution and thus the percentage of shaft resistance and end bearing, signal matching depends on a good estimate of the overall wave speed in the pile. If a clear toe response is observed from the measurements, the wave speed is readily known. In the absence of a clear toe response, the use of embedded instrumentation, particularly near the pile toe yields an accurate wave speed.

Embedding instrumentation in an ACIP pile can be done by attachment of resistance strain gages to either a center bar or reinforcement cage using instrumented sister bars as shown in Figure 3. With distance from top to sensors known and with the time between impact and wave speed arrival at the sensors determined from the measurements the wave speed of grout or concrete, is readily calculated. Figure 4 presents an example of a top force measurement, and an embedded bottom strain gage. For this particular pile, the known distance of 23.5 m (77 ft) between sensors and the time between rise times of each signal yield a calculated wave speed of 3,230 m/s (10,600 ft/s). A correct wave speed interpretation allows for a more accurate determination of not only the side friction distribution, but also the pile and soil resistance stiffness. This is important when calculating the simulated static load-displacement curve from the dynamic test results. With today's multichannel data acquisition systems and declining cost of embedded instrumentation, these improvements in measurement and analysis procedures become feasible and cost effective and therefore can become standard practice.

Even without measuring the forces at points below the pile top, numerical modeling via signal matching allows for estimating the forces at different pile elevations. Limitations are similar to those known for embedded static pile instrumentation were changes in the pile section area and uncertain local elastic modulus (uncertainty on pile impedance) values may generate errors in estimated pile forces. However, quality assurance during ACIP installation by measuring grout or concrete volumes with flowmeters helps greatly improve the pile modeling of the signal matching process. In essence the volumes installed and measured as a function of depth are equated to the cross sectional area, A, which in turn is related to the pile impedance $Z = A\,(E\,\rho)^{1/2}$. Alternatively, thermal integrity profiling (TIP) is a powerful tool to determine the ACIP pile shape and, therefore, also pile integrity. A correlation test, performed at the University of South Florida, was reported by Mullins and Johnson [6]; the authors demonstrate the accuracy of thermal integrity profiling by comparing the TIP predicted pile shape with an exhumed ACIP pile. Figure 5 presents another comparison of an 18.9 m (62 ft) long pile which was extracted; its measured diameter vs. length values were then compared with the interpreted TIP measurements. Having available for the signal matching analysis a known pile shape will considerably improve the estimated skin friction distribution.

Data from strain gages installed along the pile, with a known accurate pile cross sectional area as described above, can be used as well in the signal matching procedure to assess the localized embedded forces. Alvarez et al., [7] describe the use of strain gages and accelerometers installed near the pile toe to improve side friction estimations. It is important to realize that signal matching of internal forces is a time consuming and complicated procedure, as any change in assumption during the signal matching process will generate changes in several measured and compared records. Figure 6 presents the signal matching results of a dynamic test on an ACIP pile [7], where force and velocity near top and toe were measured. Signal matching of the toe data allows for improved accuracy of the end bearing calculation while also helping to improve shaft resistance distribution based on the measured wave speed as previously described.

DROP WEIGHT AND CUSHION SELECTION

For ACIP piles the general recommendations for bored piles as presented by Robinson et al. [8] should be used. The ram weight, W_r, must be chosen depending on the magnitude of the required pile bearing capacity, Q, following the guidelines below:

$W_r/Q \geq 1\%$ for piles embedded in hard cohesive soils or bearing on rock
$W_r/Q \geq 1.5\%$ for friction piles in general
$W_r/Q \geq 2\%$ for drilled shafts with end bearing in coarse grained soils

Wave Equation Analyses can be used to select the drop heights and cushioning based on the selected drop weight, allowable dynamic stresses and required capacity. Larger drop weights have the advantage of allowing lower drop heights which in turn generate lower compression and tension stresses in the ACIP piles for a similar applied energy and hence pile displacements and resistance activation. If stresses exceed allowable values then more cushioning has to be used which smoothens the force vs. time record. Cushions, placed on top of the transducer if used, are normally made of plywood. A minimum thickness of 40 mm (1.5 inches) is advisable, but thicker cushions are sometimes needed to reduce impact and reflection stresses. The smoothing of the impact force in the pile associated with heavy cushioning is a disadvantage for the signal matching analysis where a sharper response helps determine a more accurate skin friction determination.

Allowable compression and tension stress limits should follow AASHTO [3] recommendations for regularly reinforced precast concrete piles, i.e., respectively, 85% of the concrete or grout compressive strength, *f'c*, and 70% of the steel yield strength, *fy*, times the degree of reinforcement (reinforcement cross sectional area divided by pile cross sectional area).

PERMANENT PILE DISPLACEMENT

CAPWAP signal matching analyses provide a simulated load-displacement curve comparable to the static load test result. Following the procedure normally used, dynamic load testing is performed by applying ram drops from lower to greater heights until a cumulative displacement of *D*/60 has been achieved [9]. Depending on the geotechnical conditions at the pile toe, larger cumulative sets may be desirable when the pile is tipped in a sand layer where greater displacements allow for a higher end-bearing activation. On the other hand, if the ACIP pile is installed in a plastic clay formation, high displacements could possibly generate undesired dynamic resistance effects creating a potential for overestimation of the static pile resistance. It is recommended that, if testing is performed in highly plastic clay (mostly at the pile toe), sets per blow not exceed *D*/90. In summary, it is recommended to adhere to the following procedure for testing ACIP piles.

1. From installation records or TIP measurements obtain information about pile shape and concrete/grout quality including unit weight which is different for concrete and grout.
2. Determine concrete strength from laboratory tests and wait until enough strength has developed to allow for testing.
3. From concrete strength and reinforcement schedule determine allowable compressive and tensile stresses.
4. Unless experience exists already for a certain pile type and size and the associated required static soil resistance, a wave equation analysis should be performed to determine adequate ram weights, drop heights and cushion properties.
5. Once the concrete has achieved sufficient strength, apply ram drops of increasing energy until either the allowable pile stresses are reached or the desired soil resistance is activated.
6. If the applied impacts cause a cumulative pile set of *D*/60, combined simulated load-displacement curves can be used to estimate pile failure. If this desired displacement has not been achieved, then most probably the full load-displacement curve has not been obtained; the calculated soil resistance would then reflect only a lower limit of the available static soil resistance, depending on the failure criterion specified for the job.
7. For piles with substantial toe resistance in sands, it may be necessary to generate a larger cumulative set to activate the potentially high end bearing developing with increasing pile

penetrations. Again, it is important to carefully monitor both compressive and tensile stresses.

8. If high plastic clays make up the bearing layers of the foundation, it is recommended to not exceed a permanent set per blow of *D*/90.

This procedure is independent of certain specified failure criteria. As mentioned earlier, different failure criteria of the static loading tests are specified by different owners and/or engineers and they may produce substantially different failure loads. For that reason, the above mentioned drop weights and cushion thicknesses may have to be modified to meet those criteria, but following the above recommendations a reliable cumulative load-displacement curve can be derived for failure load assessment.

COMPARISON OF STATIC AND DYNAMIC STATIC RESISTANCE RESULTS

A correlation between results of dynamic and static load tests, performed on 47 piles, is presented below. The piles ranged from 406 to 762 mm (16 to 30 inches) in diameter, and included conventional ACIP, partial and full displacement ACIP piles. The load displacement curve was obtained via multiple blow analyses based on the cumulative set as previously described. The failure criterion of 5% of pile diameter recommended by Reese and O'Neill [2] was applied. In those cases where the pile top displacement of the static test did not exceed the 5% criterion, the comparison was performed at the maximum applied load. This happened when the reaction frame's capacity was exceeded. If the simulated load-displacement curve from the dynamic test yielded before the 5% top displacement was reached, the highest signal matching capacity was considered the failure load. Since a dynamic load test cannot maintain the load so as to generate creep displacements as happens in a static load test, it is best to compare dynamic with static load-displacement curves obtained from procedure A of ASTM 1143 [10], i.e., to perform a Quick Load Test. In cases where the procedure B, Maintained Load Test, was used, the measured static load-displacement curve was modified to remove the additional creep (if any) obtained during hold times. Impedance variations mostly followed the flowmeter installation records from the piles; thermal profiling was used in two of the correlated piles.

The static and dynamic test results are presented below in tabular and plotted form. Table 1 presents the analyzed ACIP pile type and length; for the conventional ACIP piles the acronym used in the table is CFA, for the full displacement piles the acronym DP was assigned, and for the partial displacement piles the acronym PDP was used. The table also presents the predominant soil type reported near the pile tip as either FGS for fine-grained soil (mostly silts or clays) or CGS for course grained soils (sands of any density). As shown in Table 1, the mean of the ratio of dynamic to static tests is 1.04 which implies only a slight overestimation of the static load test capacity by the dynamic tests. The ratios of dynamic over static test results ranged between 0.75

and 1.28, but were mostly much closer to unity. As a result the coefficient of variation, COV, was only 11% which is actually better than what can be achieved with driven piles [11] whose performance is affected by time effects (setup and relaxation) in the soil, a great variety of pile types and hammer types, including different failure modes in the dynamic and static cases for open ended profiles (plugging and/or internal friction). ACIP piles, on the other hand, are more uniform and are not affected by these parameters. The COV of the 47 cases presented herein is similar to the one obtained when comparing Quick Load Test results with those from Maintained Load Tests. For those two test types, soil creep and loading rates cause a different load-displacement behavior. It is important to understand that a perfect correlation with no variation between static and dynamic tests is not to be expected. Not only are the loading rates quite different, even the preloading history, i.e., each test loading, makes for a modified stiffness and capacity of a pile. Furthermore, a static load test setup (reaction piles and/or dead load) disturbs and/or preloads the soil surrounding the test pile; this does not happen for the dynamic test.

The highest DLT/SLT ratios were generally obtained on tests in plastic soils with sets per blow exceeding *D*/90. These results were not corrected as per the recommendations by Rodriguez et al. [12] or Rausche et al. [13]. Adjusting the pile bearing capacity values from dynamic tests in highly plastic soils, for example, a reduction of the dynamically determined capacity values of 15%, would further improve the correlation.

To better understand such rate effects in highly plastic soils, based on the geotechnical reports for each job, a separation between piles that were tipped into high plasticity soils were separated from those that were not. Figure 8 differentiates between these results with the piles in plastic soils. Not unexpectedly, plastic soils create a greater bias towards overestimation of the static resistance as evidenced by a mean of the ratio of dynamic to static tests of 1.14 vs. 1.01 for piles in non-plastic soils which have a reduced coefficient of variance of 10%. It must be emphasized that it is important to follow the above presented testing recommendations for piles in plastic soils, in particular, to avoid excessive dynamic displacements. Figure 9 shows the frequency distribution of capacity ratios from DLT over SLT for the 47 piles presented for this correlation study.

CONCLUSIONS

Comparison of the static and dynamic loading test results of 47 ACIP piles was presented. The mean of the ratio of dynamic to static tests was 1.04 which implies a slight overestimation of static load test capacity by the dynamic tests, and a coefficient of variation of 11%. These results should give the profession increased confidence on the use of dynamic load testing on ACIP piles as the uncertainty introduced by these moderate variations are well within the margins covered by standard safety factors.

Although the statistical correlation derived in this paper between static and dynamic load tests, based on a displacement of 5% of the pile diameter, was very satisfactory, it is felt that it is more important to be able to assess the load-displacement behavior of a pile rather than compare arbitrarily selected capacity values. After all, it is the superstructure settlement calculation which is the reason for the load testing effort. Given reliable and sufficiently frequent load testing on a site to assess site variability, the structural and geotechnical engineers can determine the correct failure or acceptance criterion for their project's structural requirements. Therefore, load testing procedures were proposed in this paper to adequately prepare and perform a dynamic load tests on ACIP piles, analyze the measurements and interpret the simulated static load-displacement curve.

The use of load transducers improves testing reliability and accuracy, and in combination with embedded instrumentation and techniques such as thermal profiling and/or grout flowmeter readings improves the calculated shaft resistance distribution, making the dynamic loading test on ACIP piles a versatile design and construction control tool.

Dynamic testing in high plasticity soils sometimes overestimates static capacity values and, for that reason, care must be exercised when dynamically testing in such geotechnical conditions. Following the testing recommendations of this paper and applying a 15% reduction of dynamic test capacities of piles not statically tested will reduce the potential for overestimated static resistance values while avoiding significant underestimations of capacities. This is only necessary when the safety concept does not cover this uncertainty in its resistance or safety factors. Emphasis is made on following the recommended procedures presented in this document in plastic soils; applying an excessive displacement to an ACIP pile tipped and embedded in fine grained soils could generate complex rate effects that could introduce additional dynamic resistance effects and thus a higher overprediction in compared to the static load.

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Table 1. Compilation of static and dynamic test results for 47 ACIP test piles (1 kip = 4.45 kN).

Pile Diameter cm	Pile Type	Soil Type	Pile Length m	SLT 5% or max kips	DLT 5% or SLT max kips	DLT/SLT	Difference %
46	CFA	CGS	18	2443	2243	0.92	-8.2
46	CFA	CGS	17	2865	2865	1.00	0.0
46	CFA	CGS	17	2043	1599	0.78	-21.7
46	CFA	CGS	18	2488	2265	0.91	-8.9
46	CFA	CGS	20	2043	1821	0.89	-10.9
41	DP	CGS	16	2177	2465	1.13	13.3
41	DP	CGS	17	2177	2199	1.01	1.0
41	DP	CGS	17	2265	2310	1.02	2.0
41	CFA	CGS	14	3798	3909	1.03	2.9
41	CFA	CGS	9	3376	3465	1.03	2.6
46	CFA	CGS	7	2088	1999	0.96	-4.3
46	CFA	CGS	10	3554	3287	0.93	-7.5
41	CFA	CGS	12	2665	2710	1.02	1.7
41	DP	CGS	14	3309	3398	1.03	2.7
61	CFA	CGS	44	6974	6796	0.97	-2.5
41	DP	CGS	16	2790	2932	1.05	5.1
41	DP	CGS	17	2665	2665	1.00	0.0
41	PDP	FGS	18	3021	3509	1.16	16.2
46	DP	CGS	34	4131	4131	1.00	0.0
46	DP	CGS	34	4353	3953	0.91	-9.2
41	DP	CGS	12	1963	2132	1.09	8.6
41	DP	FGS	11	2132	2443	1.15	14.6
46	CFA	CGS	23	2954	3176	1.08	7.5
46	CFA	CGS	26	4420	4442	1.01	0.5
46	CFA	CGS	21	3665	3665	1.00	0.0
46	CFA	CGS	19	3598	3598	1.00	0.0
46	CFA	CGS	18	2887	3554	1.23	23.1
46	CFA	FGS	6	800	1022	1.28	27.8
41	DP	CGS	17	3909	4042	1.03	3.4
41	DP	CGS	18	3820	3354	0.88	-12.2
41	CFA	CGS	24	3998	4531	1.13	13.3
41	CFA	CGS	24	3998	4522	1.13	13.1
41	CFA	CGS	24	3976	4553	1.15	14.5
41	CFA	CGS	23	3953	4287	1.08	8.4
41	CFA	CGS	24	2665	2532	0.95	-5.0

Pile Diameter mm	Pile Type	Soil Type	Pile Length (m)	SLT 5% or max Kips	DLT 5% or SLT MAX kips	DLT/SLT	Difference %
41	CFA	CGS	24	2665	2532	0.95	-5.0
76	CFA	CGS	14	2421	1821	0.75	-24.8
46	CFA	CGS	21	3220	3434	1.07	6.6
41	CFA	CGS	20	1199	1510	1.26	25.9
41	CFA	CGS	24	2887	2887	1.00	0.0
41	DP	FGS	24	2132	2532	1.19	17.3
41	DP	FGS	24	2088	2265	1.09	7.0
41	DP	FGS	24	1866	2177	1.17	15.2
41	DP	FGS	12	1111	1288	1.16	14.5
41	DP	FGS	12	1177	1399	1.19	17.4
41	DP	FGS	12	1155	1111	0.96	-5.3
46	PDP	FGS	38	2821	3132	1.11	9.5