What constitutes a good PDA test?

Likins, G.
President, Pile Dynamics Inc., Cleveland Ohio USA

Rausche, F.
President, GRL Engineers Inc., Cleveland Ohio USA

ABSTRACT: High strain dynamic pile testing (HSDPT) is routine practice, and has many benefits that make its use highly attractive. However, it requires careful preparation, attention to detail and testing engineer skill to properly perform these tests.

Depending on his or her experience level, the test engineer may or may not realize when results are valid, or when capacity results may be only a lower bound. It is widely known that the capacity of driven piles may change with time after installation and for that reason restrike tests are generally recommended. It is also generally stated that the set per blow should be at least 2 mm, or otherwise the dynamic test may only yield a lower bound solution. To investigate the validity of these recommendations, GRL's database of dynamic test results is compared with static load tests, and various comparisons are made for both driven and drilled piles. Conclusions from this study and recommendations for practice are drawn.

1 INTRODUCTION

In the several decades since the beginning of research on modern dynamic testing of piles in 1964, much progress has been made in the tools used such as the Pile Driving Analyzer® (PDA) and CAPWAP® (Likins, 2008). High Strain Dynamic Pile Testing (HSDPT) has become an indispensable tool initially for the installation and testing of driven piles, and in recent decades to also assess the capacity of drilled shafts. Many codes recognize the procedures of ASTM D4945 and highlight its value by including mention of this test method. During installation of driven piles, the benefits include providing actual information based on actual measurement of the event to assure a safe and efficient installation at a rather modest cost. As a predictor of ultimate static capacity of the pile or drilled shaft, results from HSDPT have conclusively demonstrated good correlation with results from static load testing (Likins, 2004), and provide substantial cost savings when compared with Static Load Test (SLT) costs. As a result of the good correlation experience, HSDPT is often used to supplement static tests on larger projects, and on smaller projects often to provide some quality assurance that the installation is sufficient by serving as a replacement for static tests. But like any other tool, HSDPT is only beneficial if the test is performed properly. Several considerations go into obtaining a good test.

2 DATA REQUIRED

Dynamic pile testing should follow ASTM D4945 guidelines to obtain the dynamic force and velocity on the pile, often two diameters below the pile top. Usually measurements are made with reusable strain and acceleration sensors. Obtaining the average force requires using strain transducers attached to the pile in diagonally opposite pairs to assess and compensate for bending and obtain the axial response. While at least two accelerometers are also suggested, for good data the velocity signals are practically identical even when bending is severe (e.g. bottom graphs in Fig. 1 each show two velocities). Thus, one well performing accelerometer is the minimum required. The sensors are typically bolted to the pile. Loose attachments must be avoided. While Fig. 1b shows data with good signals, Fig. 1a depicts a strain record where a loose bolt or concrete anchor corrupted one of the strain signals. The loose strain transducer, F2 dashed curve in the middle graph of Fig. 1a, gives a signal similar to an accelerometer since the unrestrained end of the strain transducer acts as a mass responding with inertia to the pile acceleration. A loose bolt on an accelerometer (not shown) would result in two different velocity signals with one being delayed and with different frequency content. In Fig. 1b, the steel pipe pile has bending so that the two strains on opposite sides of the pipe are quite different in magnitude (middle graph of Fig. 1b),

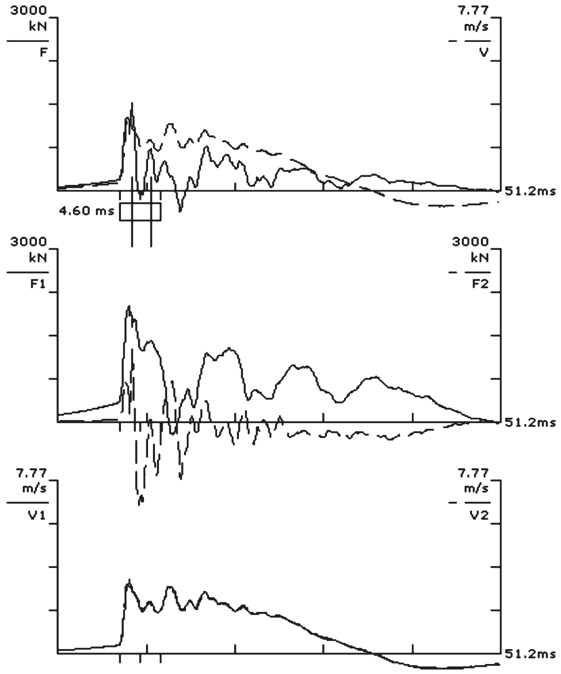

Figure 1a. Data with a loose strain transducer.

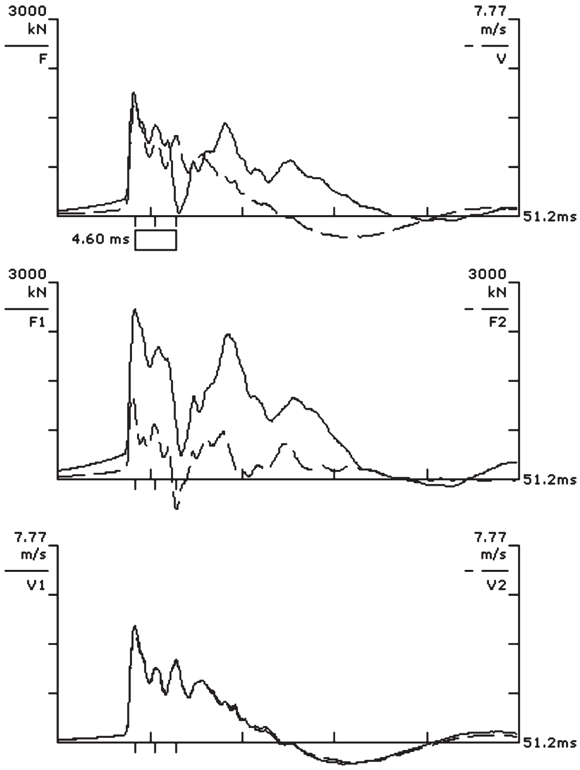

Figure 1b. Good data with tight bolts.

and many times different in shape and magnitude, yet the average force (solid line in top graph 1b) shows good proportionality with the velocity. For a series of blows from a pile driving hammer, good data will be reasonably consistent from blow to blow (if the hammer performs consistently), and the early portion of the force and velocity records (e.g. at first peak input) should be proportional by the pile impedance EA/c.

In the case of HSDPT for drilled or augured piles, because of the non-uniformity of the concrete or grout and the casting conditions and methods, the general recommendation is for 4 strain measurements. The four individual signals, and opposite pairs, can be compared to assess data quality. If one sensor produces poor results, then its signals and those of its opposite mate can be ignored and the signals of the remaining two sensors used. Since the number of blows is usually relatively low when testing drilled or augured piles and because each impact is critical, having backup sensors assures useable data for every applied impact.

The pile properties, such as pile cross sectional area, density, modulus, wave speed, and length, must be known. Modulus is calculated from the pile material density and observed wave speed. If the pile is composite (e.g. concrete filled steel pipe pile), the composite properties are used. If the pile is non-uniform along the length (e.g. area or material changes) then this must be noted.

3 SIGNAL MATCHING ANALYSIS (SMA)

A valid dynamic load test must be evaluated by signal matching (e.g. CAPWAP) analysis. For non-uniform piles (drilled shafts and augercast piles are often non-uniform) such analysis is essential since simplified methods (e.g. the Case Method used by the Pile Driving Analyzer) calculate capacity assuming a uniform pile. The signal matching also develops a soil model for the dynamic event (quakes and damping), and better distinguishes between static and dynamic resistances, without depending on unreliable soil investigation descriptions. Geotechnical engineers sometimes erroneously assume that the SMA should incorporate results from soil borings in its solution. Such a process would totally defeat the purpose of the HSDPT and lead to useless results (a) because the HSDPT should provide additional information, (b) because the results from soil exploration and dynamic testing do not match each other (soil properties at the time of testing and at the strain levels applied are different from those occurring during the soil sampling and/or testing), and, most importantly, (c) often the closest soil boring is not always representative of the soil condition at the tested pile (and frequently does not even extend to the pile toe).

Another advantage of SMA is the simulated static load test graph relating applied load (capacity) to displacement which can then be correlated to static load test results; viewing a series of CAPWAP results for the early restrike blows also provides interesting insights when evaluating the capacity (Rausche, 2008). Other benefits include evaluation of pile integrity and modeling of splices, and, when questions arise, an accurate investigation of tension and compression stresses along the shaft and at the pile toe.

For most situations, the best test is obtained when the pile experiences a net final set (permanent displacement) as a result of the impact. If the pile to be tested is a driven pile, usually the pile driving hammer is used as the impact device. The hammer is often selected using a "wave equation analysis" to determine its adequacy (Hussein, 1996) for pile installation to avoid overstressing or excessive blow counts, i.e. insufficient penetrations per blow.

In cases where the set per blow is anticipated to be very small, e.g. when the soil develops a high soil setup following installation, a larger hammer may be needed during restrike to mobilize and prove the required pile capacity. Fig. 2 shows the relative ratio of predicted CAPWAP solution to SLT as a function of set per blow for the FHWA database reported at the 1996 Stresswave conference (Likins, 1996). The SLT result was evaluated with the Davisson offset procedure. As mentioned earlier, it has long been recommended that for driven piles a net permanent set per blow of at least 2 mm be achieved in order to mobilize the full soil strength. Although this advice does not seem to be confirmed by this database, it is still felt to be good advice and recommended procedure. On the other hand, net sets greater than 8 mm per blow are not desirable either, since they make the analysis more difficult, and more sensitive to errors in dynamic resistance. In Fig. 2, there are few data points above the recommended upper limit of 8 mm set, but generally the correlation is still good with one exception of overprediction by a ratio factor of 1.32. Interestingly, in this one case, a Rapid Load Test (e.g. Statnamic) was conducted between the dynamic restrike and the static load test, pushing the pile an additional net settlement of 0.22 m which according to the closest soil profile easily could have pushed the toe from a sand layer into a clay layer, thus corrupting the correlation. Also interesting in Fig. 2 are the relatively conservative predictions for pile sets between about 2 and 8 mm per blow.

As demonstrated in Fig. 3, very few dynamic test results from CAPWAP have a prediction in excess of

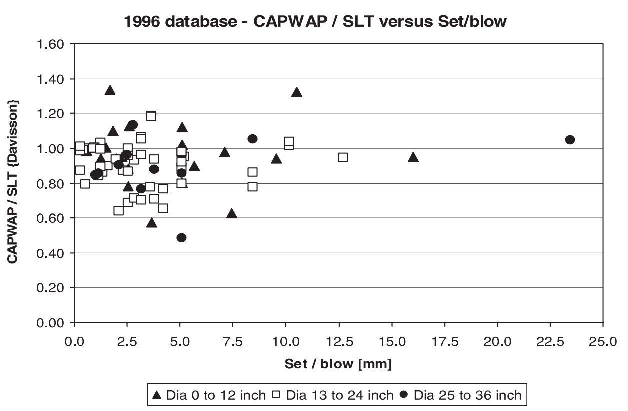

Figure 2. Ratio of CAPWAP to SLT prediction versus permanent set per blow.

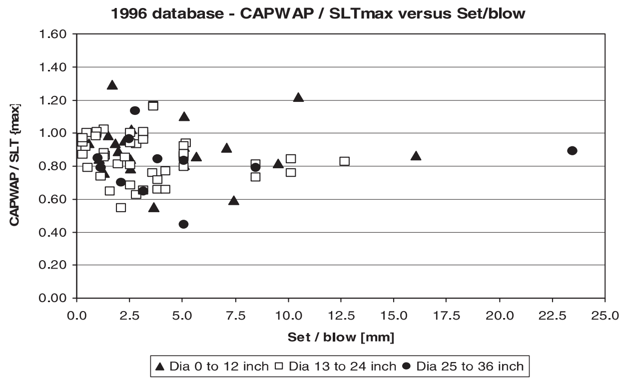

Figure 3. Ratio of CAPWAP to max applied load in SLT vs. set per blow.

the maximum applied load, indicating CAPWAP and even the Davisson criteria to which it is often compared both are generally conservative compared with this reserve strength.

Testing of drilled shafts and augered (CFA) piles requires a minimum drop weight of 1 to 2% of the ultimate test load required (Hussein, 1996). Of course, larger drop weights with lower drop heights are likely to be acceptable too, and are generally preferred whenever practical.

The best data is generated when the pile top and impact device both have flat surfaces which impact uniformly so that local stress concentrations are minimized. For concrete piles or drilled shafts, a cushion of soft material (e.g. usually plywood) is inserted between the impact device and the pile top to smoothen any surface roughness and reduce the peak stress. It is also strongly recommended that the pile top is extended by typically 1 m or at least one diameter length at the time of initial installation and with the same concrete as used for the pile shaft. This pile top extension should include some external reinforcement in the form of a thin walled tube. Forces can also be measured by instrumenting the known drop weight with an accelerometer to measure the deceleration and using Newton's Law ($F = ma$) (Robinson, 2002).

In refusal situations, i.e. when the set per blow is less than 2 mm, a number of steps can be taken to assure meaningful results. First, as described in Rausche et al. (2007), the maximum pile toe displacement should be calculated by SMA. If the pile toe displacement plus the permanent set of prior impacts exceeds D/60 (D being pile width or diameter), it can be concluded that the resistance has been activated. Secondly, if the soil is sensitive and looses capacity as it activates more resistance near the toe during the restrike test, "superposition" may lead to better capacity estimates (Hussein, 2002). Superposition may use soil resistance components from either early and late restrike tests or from end of pile installation and early restriking. Thirdly, in the case of drilled piles whose end bearing is in a relaxed state, the pile may have to be "driven to capacity" with a series of a few blows usually with increasing energy per blow. It then has to be checked, however, whether or not the necessary penetrations to achieve a significant end bearing would be less than allowable movements.

5 TIME OF TESTING

''When the pile is tested'' is closely related to the ''purpose of the pile test''. If the issue is determining dynamic stresses during pile driving to confirm adequate procedures to prevent overstressing and thus damage, to determine alternate installation procedures (e.g. changed cushions, reduced stroke, etc), or monitor the installation efficiency for a pile driving hammer to confirm the driving criteria, then tests during pile driving are appropriate. For a concrete pile where tension stresses in easy driving is a concern, the pile is often tested for the full installation length. For steel piles, testing only the last portion of driving is generally sufficient.

When determination of the long term ultimate capacity is the reason for the test, since soil properties often change with time after installation, both driven piles and drilled piles are usually evaluated during a dynamic test (restrike) following some wait period after installation. While some researchers have suggested using end of drive data with a Measured Energy Approach to estimate long term service capacity of the pile, the premises of this procedure are not correct and the correlation is worse than that of a proper HSDPT test during restrike (Rausche, 2004). For piles with much of their capacity coming from cohesive soils where setup (e.g. a capacity increase) can be very significant, the wait before restrike might be many days or even weeks to simulate the long term service conditions and take maximum economic advantage. Piles driven into weathered shale or dense saturated silts may experience a capacity decrease (e.g. ''relaxation''); testing after a few days is usually sufficient to identify this problem.

The selection of the duration of wait period between end of installation and restrike depends on many factors. Certainly the soil type has a major influence. It is well known that clays can exhibit pore pressure effects causing effective stress changes and should require longer wait periods due to the reduced porosity. While clean coarse sands may drain quickly, often well graded sands, particularly fine sands and silty sands may have sufficient fine content to retain excess pore pressures for longer times. Sands may also experience arching effects as the pile experiences lateral motions during driving that create an oversized hole; with time, the hole diminishes and normal earth pressures reestablish themselves. Calcareous soils require longer times for the soil structure to recrystallize.

Most Static Load Tests are performed at least 7 days after installation. In fact, in the 1996 database, only 6 piles had 3 or fewer days wait before the SLT. Fig. 4

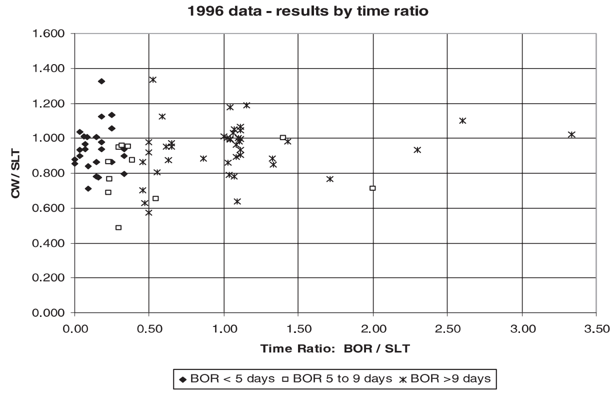

Figure 4. Time of dynamic test.

presents the dynamic CAPWAP (CW) result to SLT result plotted as a function of ''time ratio'' (time ratio is the ratio of days for the restrike (BOR) after the installation, to the number of days for the SLT after installation). A time ratio of 1.0 would then be represent having the restrike and SLT on the same day. Fig. 5 shows the same data designated by soil type (key labels ''toe, shaft'': where SA is sand, SI is silt, and CL is clay). Admittedly the classification is subjective, particularly for shafts in a layered soil; fine grained sands were classified as silt in this study since their drainage appears to behave similarly).

It is interesting to review Figs. 4 and 5. Looking at the data where BOR was less than 5 days, they all have time ratios of less than 0.4 meaning the SLT was run considerably later in time than the restrike. Most data was in sand, or silt, with the silt cases generally yielding low capacity ratios, likely because the full setup had not yet been developed by the time of the relatively early PDA restrike test. The highest point is the aforementioned controversial data point with the intervening Rapid Load Test.

For BOR data of 5 to 9 days, although the wait time was longer, the time for the SLT was delayed even more so that the time ratios were generally 0.25 to 0.55 and since most of the cases are in silts where continued setup is expected, it is not surprising that the CAPWAP to SLT ratio are usually less than unity, particularly for the lowest time ratio cases.

For the data where the restrike was 10 or more days after installation, most cases were also in finer grained silt or clay soils as might be expected from the longer wait times. For the data with time ratio of about 0.5,

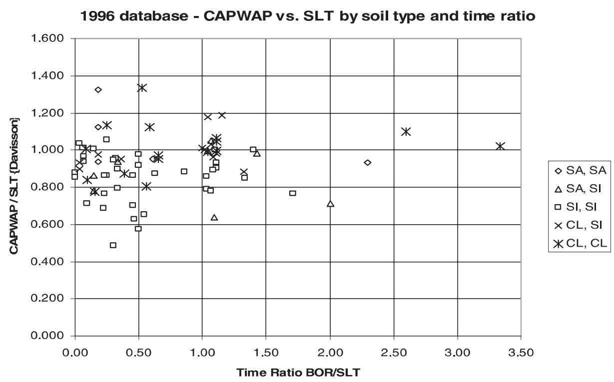

Figure 5. CAPWAP vs SLT by soil type and time ratio.

most CAPWAP data result in underprediction of SLT Davisson result due to incomplete setup in silt or clay soils. The notable exception with capacity ratio 1.335 is for an open profile H pile in clay where the end bearing was likely overestimated; caution is therefore warranted when CAPWAP would suggest high end bearing for H piles where the soils are known to be clay. Most cases with a time ratio of greater than unity have a CAPWAP prediction within 10% of the SLT Davisson value.

Results from this investigation suggest that for finer grained soils, or soils with porosity that behave as finer grained soils, waiting longer for the dynamic test is beneficial to the dynamic capacity prediction by CAPWAP, while piles in clean sands might be tested relatively early with good results. These findings confirm long held beliefs and suggestions about the time of testing.

Testing at end of driving and during restrike, or multiple restrikes for special test piles at different wait times (and evaluated by extrapolation for longer waiting times on a log time scale for cohesive soils), can be useful in determining a proper driving criteria and assure sufficient capacity (using short term restrikes of production piles, provided the piles display the same capacity gain trend line). Drilled shafts and augercast (CFA) piles naturally require at least a week (and usually longer) wait time after casting concrete prior to the dynamic testing to allow the concrete to harden sufficiently. This time period is then generally adequate for the soils disturbed by the drilling or augering process to regain their pre-drilling strength.

6 CONCLUSIONS

A good dynamic pile test requires certain minimum requirements which can be summarized as follows.

- Measurements must be of good quality or the dynamic test results are meaningless. Sensors must be firmly attached to the pile, and their calibrations known.
- Interpretation of the data for uniform driven piles may be straightforward in the field for stresses induced in the pile, evaluation of damage, or assessing hammer energy transfer to the pile.
- Interpretation of dynamic test data for pile capacity, or analysis of non-uniform piles and drilled shafts, must be made using a signal matching analysis such as CAPWAP.
- To assess ultimate pile capacity, the impact device used must be of sufficient weight to push the pile, at least temporarily, a sufficient distance to activate the passive soil resistance.
- If the dynamic loading device (e.g. pile driving hammer) is of insufficient energy capacity estimates may only be a lower bound if the resulting set per blow is very small. Superposition methods may then be used to project the full bearing capacity.
- Since pile or shaft capacity usually changes with time after installation, and dynamic tests reflect the capacity at the time of the test, sufficient wait time after installation is required for a good dynamic pile test. The wait after installation for coarse grained soils may be short, while the wait for piles installed in fine grained soils should be at least a week or two to gain the maximum economic advantage.

REFERENCES

ASTM D4945 (2000). ''Standard Test Method for High-Strain Dynamic Testing of Piles''.

Hussein, M.H., Likins, G. E. and Rausche, F. (1996). '' Selection of a Hammer for High-Strain Dynamic Testing of Cast-in-Place Shafts''. Fifth International Conference on the Application of Stress-wave Theory to Piles (STRESSWAVE '96): Orlando, FL.

Hussein, M.H., Sharp, M. and Knight, W.F. (2002). ''The Use of Superposition for Evaluating Pile Capacity. Deep Foundations 2002 an International Perspective on Theory, Design, Construction, and Performance'', Geotechnical Special Publication No. 116, O'Neill M. W., and Townsend, F. C. Eds., American Society of Civil Engineers: Orlando.

Likins, G. E., Piscsalko, G., Rausche, F. and Roppel, S. (2008). ''PDA Testing: 2008 State of the Art'' Eighth Int'l Conf. on the Application of Stresswave Theory to Piles, Lisbon.

Likins, G. E. and Rausche, F. (2004). ''Correlation of CAPWAP with Static Load Tests''. Proceedings of the Seventh International Conference on the Application of Stresswave Theory to Piles: Petaling Jaya, Selangor, Malaysia.

Likins, G. E., Rausche, F., Thendean, G. and Svinkin, M. (1996). ''CAPWAP Correlation Studies''. Fifth International Conference on the Application of Stress-wave Theory to Piles (STRESSWAVE '96): Orlando, FL; 447–464.

Rausche, F., Likins, G. E., and Hussein, M. H. (2008). ''Analysis of Post-Installation Dynamic Load Test Data for Capacity Evaluation of Deep Foundations'' ASCE Geotechnical Special Publication ''From Research to Practice in Geotechnical Engineering''–Honoring John Schmertmann. Eds: Jim Laier, David Crapps, and Mohamad Hussein.

Rausche, F., Robinson, B. and Likins, G. E. (2004). ''On the Prediction of Long Term Pile Capacity From End-of-Driving Information. Current Practices and Future Trends in Deep Foundations'', Geotechnical Special Publication No. 125, DiMaggio, J. A., and Hussein, M. H., Eds, American Society of Civil Engineers: Reston, VA.

Robinson, B., Rausche, F., Likins, G. E. and Ealy, C. (2002). ''Dynamic Load Testing of Drilled Shafts at National Geotechnical Experimentation Sites. Deep Foundations 2002'', An International Perspective on Theory, Design, Construction, and Performance, Geotechnical Special Publication No. 116, O'Neill M. W., and Townsend, F. C. Eds., American Society of Civil Engineers: Orlando, FL.

Stress Wave

Lisbon | 2008

The 8th International Conference on the

Application of Stress Wave Theory to Piles

Science, Technology and Practice

J.A. Santos
Editor