IMPROVED PILE ECONOMICS: HIGH DESIGN STRESSES AND REMOTE PILE TESTING

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Abstract

Tradition has often dictated low design load stresses on piles. Such traditions often developed prior to modern static or dynamic pile testing methods and perhaps result from a few limiting situations. These low stress limits were then broadly applied, even in cases where the piles could carry substantially higher loads. With sufficient testing to prove the design, higher design loads may present significant overall savings to the project owner. The cost of the testing then becomes an insignificant cost compared to the potentially great benefit of increased pile loadings. To confirm higher load possibilities for driven piles, the pile is tested either statically or dynamically. Further savings and increased testing efficiency result from remote dynamic pile testing. This paper presents a project where design stresses were considerably increased as a result of additional testing and use of remote dynamic pile testing equipment.

Load Evaluation

When designing a driven pile foundation system, engineers have a wide range of choices, including the ultimate load per pile and pile size (type, length, and diameter). The required pile capacity depends on the applied loading from the superstructure, the test method for verification of the pile capacity, and the frequency of testing. The ultimate pile capacity must exceed the applied loads by a sufficient margin or else the foundation system will fail due to unacceptable settlements. To reduce the risk and prevent foundation failures, safety factors are assigned to compensate for uncertainties. Logically, less testing performed increases the risk of a failed foundation, while more testing reduces risk. Similarly, more accurate test methods reduce risk, while less accurate methods increase risk. The goal being to have an acceptably low probability of failure at an economic cost.

Deep foundations require adequate quality assurance for a successful service life. A well planned test program allows the design engineer to assure adequate bearing capacity while at the same time minimizing the foundation costs, for example, through reduced factors of safety.

When the ultimate failure load can be determined, loads per pile can be optimized for the same risk and foundation costs can be reduced. For large projects special test programs performed in advance of final design can be quite effective. Fewer piles are required if higher working loads can be proven, or shorter piles can be used. For moderately sized projects, the first production piles are often used as test piles and some adjustment to the driving criteria and therefore cost savings are possible. Production piles are usually driven to the established test pile criteria.

However, it is not practical to statically test every pile because it is time consuming and has high costs, particularly for higher pile loads. Therefore, static testing is usually limited to a very small sample of piles on any site (typically one percent or less on large projects, or often only one pile per job). Prior to 1970, often there was no static testing at all.

Dynamic pile monitoring during pile installation has become an important part of many projects to supplement and in some cases replace static testing. Dynamic pile testing is specified by most major codes including AASHTO, ASCE, ASTM, IBC2000, PDCA, and USCOE. In addition to capacity assessment, it provides otherwise unavailable information on stresses, pile integrity and hammer performance during installation, thus checking the drivability, especially important for piles which are highly loaded. Dynamic load tests at the end of driving and during restrike provide the engineer the necessary information for long term bearing capacity assessment and soil strength changes as they occur with time after pile driving, usually due to soil setup but possibly relaxation in some soils or weak rocks.

Comparative tests of both static and dynamic tests on the same test pile are often used to confirm the correlation between these two test methods. Large databases of correlation cases add assurance as to the reliability of dynamic tests on smaller projects where static testing is not economically justifiable.

Safety Factor Selection

In the extreme case where every pile is tested with a very accurate method (e.g. static load test) with a conservative definition of failure, then the safety factor can be significantly reduced because the uncertainty of pile performance and therefore the risk is reduced. The Davisson offset yield line criteria recommended by the Federal Highway Administration and Pile Driving Contractors Association is among the most conservative of failure criteria and thus justifies use of lower safety factors. For end bearing piles, typically there is often significant reserve strength above the Davisson load, so lower safety factors are appropriate. For piles in sensitive clays, the failure load might be reached suddenly with no reserve strength so safety factors should be selected cautiously.

The minimum safety factors recommended by the PDCA code (PDCA, 2001) depend on the number or percentage of piles tested as shown in Table 1. In this table, D% is the percent of piles statically tested on the job while F.S. is the global factor of safety. Piles are selected so that the site variability is adequately addressed, and adequate hammer performance is periodically verified. With these guidelines, assurance is obtained that all statically tested piles exceed the desired working load times the specified safety factor. Alternately, because the loads are then known and thus uncertainty reduced, a lower safety factor could be used without increasing the risk. This approach, taken by the PDCA code, awards lower safety factors when testing more piles. Lower safety factors might mean the load per pile can be increased, resulting in fewer piles, or that the driving criteria can be relaxed resulting in shorter piles, either way reducing time and costs to the contractor. The cost of the extra testing is often more than compensated by reduced foundation costs for larger projects.

Table 1: PDCA safety factors for static testing only

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D% (% of piles tested)	F.S.
0.5	2.0
1	1.9
2	1.8
3	1.75
5	1.65

After establishing a correlation between dynamic and static tests, dynamic testing with signal matching has been then used to replace additional static load tests on the same site. ("Signal matching" is a process where the pile is modeled, a soil model assumed, and the measured velocity signal is applied as a boundary condition. The complementary force signal is computed and compared with the measured force. The soil model is iteratively adjusted until the computed and measured signals match.) After correlating the static and dynamic tests, the PDCA code allows substitution of three dynamic tests for one static test in determining the quantity of testing for static tests as shown in Table 2. Thus, with at least one successful correlation, then the PDCA suggested testing 5% of the piles statically can be translated into testing 15% of the piles dynamically, and then the result is a suggested reduction in safety factor to 1.65. This is justified because the dynamic testing was proven accurate by the correlation process, and the large number of tests allow site variability and hammer performance consistency to be properly assessed.

Table 2: PDCA safety factors for dynamic testing (with confirming static test)

D% (% of piles tested)	F.S.
1.5	2.0
3	1.9
6	1.8
9	1.75
15	1.65

In many cases, dynamic pile testing has completely replaced static testing. Because no firm correlation on the site has been established, there is slightly higher risk since the correlation depends upon past experience only of the signal matching analysis correlation accuracy from tests on other sites. This extra risk requires an increased safety factor for dynamic testing only compared with safety factors from static testing or static plus correlated dynamic methods. In this case, the safety factor suggested by the PDCA code can vary from 2.1 with only 2% of the piles tested only dynamically down to 1.9 when 10% of the piles are tested only dynamically as shown in Table 3.

Table 3: PDCA safety factors for dynamic testing only (no static testing)

D% (% of piles tested)	F.S.
2	2.1
5	2.0
10	1.9

Remote Dynamic Pile Testing

In the past, dynamic pile testing required a highly specialized test engineer on site, and scheduling the arrival time of the engineer was often difficult. The engineer might arrive a day early to be sure he was present to test the first pile. The first pile testing often was delayed due to weather or in readying the rig for pile driving. Furthermore, travel related costs such as travel time, airline cost or car mileage and living expenses have grown disproportionately compared to the cost of the testing itself. Once on site, the engineer often spent more time waiting than actually monitoring piles. This testing process is therefore not as efficient as it might be.

Most pile driving contractors and engineering consultants are quite familiar with dynamic pile testing. In most traditional dynamic testing with the PDA testing engineer on site, the contractor's field personnel usually attach sensors to the pile.

Fortunately, recent developments in communication technology have made remote dynamic pile testing feasible. The remote testing equipment includes a special type of Pile Driving Analyzer ® (PDA) called the PAL-R which conditions, digitizes, saves and pre-analyzes the signals from the sensors. It has communication capability through cell phones. The remote PDA with cell phone already connected is placed in a cushioned case for protection during shipping. Upon arrival at the site, opening the case and attaching the cable connecting the sensors to the pile gives fast access to the system as shown in Figure 1.

After attaching the sensors to the pile, the site operator (usually a pile crew member or the inspector) connects the phone to the remote PDA and with two quick presses of the touchscreen the PDA automatically dials the office phone number and

Figure 1. Remote PDA system

connects to the office computer. A quick entry of the pile name and length completes the data input. The PDA then acquires the data and sends the data through a cell phone to the test engineer's office. The PDA test engineer in his own office evaluates the pile data as it is being measured. Because cell phones are so readily available, a separate voice communication is usually maintained between the office and the site to help direct the testing, acquire site information like blow counts and penetrations, and take care of and problems that may arise.

Currently the amount of data is too large to send every blow in real time. For restrikes, the PDA spools the data for a limited number of restrike blows. If many blows are expected, as in a 1000 blow driving sequence, then the PDA collects the first blow and then sends it. It then collects several more blows, which are stored for future access. When the first blow sending is complete, the remote PDA sends the next blow triggered (in this way typically every 5th blow is sent, giving a representative sample of the 1000 blow sequence). Following data acquisition, the PDA engineer can remotely request the PDA to retrieve important data like the first ten blow or the last ten blows from the memory card and send only this important data for immediate analysis. For long driving sequences, all data from every blow is available if needed from the memory card, and could be later sent by email. Future improvements in telecommunications are anticipated which should allow faster data transmissions and hence more blows sent in real time.

This process gives the contractor complete control over the testing schedule. With the remote PDA in hand, the contractor can request a test at any time on any pile for any reason. Piles with unusual blow count records or different penetrations can be investigated. When specified, periodic random production testing can be efficiently accomplished. Hammer performance spot checks can be made after any hammer maintenance, or new hammers qualified for service. Variations in soil profile can be addressed as the installation progresses across a large site. Repeat restrikes with varying wait times can be accomplished without multiple visits to a site by the PDA test engineer.

From the PDA engineer's viewpoint, less time is spent traveling and waiting on the jobsite for testing activity. Fewer jobsite trips reduce costs. Less time spent on site creates additional savings. Further, he can test piles from multiple sites on the same day. Thus he becomes more efficient. Increased efficiency and reduced direct costs reduce the cost of pile testing to the client and ultimately to the owner.

Equally important is that the analysis and reporting of results can now be completed within a short time after data has been collected, since there is no more lost time for travel back to the office. The CAPWAP® Signal Matching analysis and summary of the field data can begin immediately after data collection. This results in faster report turnaround, which speeds up the decision-making process.

It should be noted that there are some cases where the engineer's presence on site is still very desirable, such as in large preconstruction test programs to get a better feel for the site. In such large projects, the cost of the engineer's site visit is still a minor consideration. Once criteria are established further production testing could be performed remotely.

To date, Lawrence Construction Company has successfully used the Remote Pile Driving Analyzer on five occasions in the Rocky Mountain Region as an easy and cost effective way of getting their PDA needs accomplished. Lawrence Construction rents the PAL-R, and sends the data to GRL for analysis and the reports. The reasons that Lawrence Construction prefers the remote PDA are numerous. First of all, from a cost standpoint, travel time and expenses for a testing engineer are eliminated. This results in considerable savings because most PDA testing projects are in remote areas. Another advantage for Lawrence Construction is that the PDA testing can be bid on a unit cost basis in their proposals. This reduces the financial risk to the owners and the contractors for the PDA testing items on these projects. Lawrence Construction realizes indirect cost savings by being able to perform the tests when convenient, thus the testing can be done with little interruption to production pile driving.

Case History

One of the five Remote Pal-R projects was for a southern Colorado power plant. The original bid called for 27,000 linear feet of HP 10 x 57 H-pile. The initial design pile capacity was 150 kips, corresponding to 9 ksi on the steel cross sectional area of the pile. This design load is a common value based on tradition and mild steel yield stresses.

Lawrence Construction proposed a test program to the structural engineer consisting of driving one static test pile along with two reaction piles. The static test pile was driven to 10 blows per inch by an APE D19-32 with a 4.2 kip ram and a rated energy of 44.4 kip-ft. The static test pile and both reaction piles were each PDA tested at the end of driving as shown in Figure 2 using the remote PDA. The energy transferred to the pile was 18.6 kip ft (42% of rated; common performance) and the driving stresses were about 30 ksi. A static test performed by the ASTM D1143 quick loading procedure the following day plunged at 360 kips (about 10 percent lower than predicted dynamically) as shown in Figure 3.

Figure 2. Remote PDA on test pile

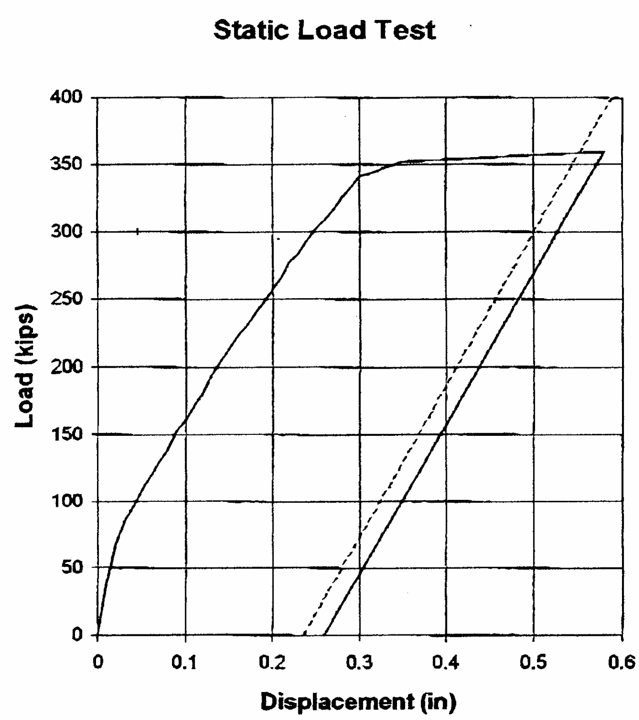

Figure 3. Static load test result

A wave equation analysis study was then made to determine if loads could be increased if a larger hammer was employed. The APE D30-32 with a 6.6 kip ram and a rated energy of 69.9 kip-ft was investigated. Using the D30-32 hammer, the study predicted an ultimate capacity of 600 kips at 10 blows per inch at 33 kip ft estimated transferred energy and 37 ksi driving stresses. From this information, the design capacity was almost doubled to 295 kips, corresponding to 17.5 ksi. To achieve this significant design stress increase and confirm the pile capacity, PDA testing of about 4% of the total piles (25 piles) was then required.

In addition to almost doubling the design stresses, the initial test program and additional PDA test piles enabled the factor of safety to be reduced to 2.0 from an initial value of 2.25. This safety factor agrees favorably with the PDCA recommendations for the tested percentages for correlated tests and dynamic only tests. If a higher percentage of piles were tested, then a still lower safety factor would be justified. In this case, the main savings were due to dramatically increasing the design loads per pile and thus reducing the total number of piles required.

The structural engineer was requested to mark the critical piles (the piles with the maximum loading) on the plans and the PDA testing was then performed on those piles. For the first three production test piles driven by the APE D30-32, the energy measured by the remote PDA was about 40 kip ft and the driving stresses were 40 ksi. Because the hammer performed better than expected, the driving criteria was reduced to only 7 blows per inch. The higher design stress presented no difficulty structurally since the H-pile had a 50 ksi yield strength.

The soil report indicates soft silty clay over weathered claystone. Piles were driven into the claystone. To ensure that relaxation of the claystone was not a problem, the 25 production test piles were driven to 7 blows per inch and a number of restrikes were required. At the very beginning of production pile installation, four initial tests on the first two large pile caps were made along with two restrikes to allow the general contractor a place to start working. The restrikes showed no significant change in blow counts or total capacity determined by the remote PDA, or obvious trends indicating setup on the shaft or relaxation at the toe. Lawrence Construction selected a couple dynamic test piles in the next area, and during one final day of testing finished all the remaining dynamic test piles, including a couple of restrike tests. All subsequent dynamic tests confirmed sufficient capacity. Ultimate capacities for most piles ranged from 599 to 769 kips, with two piles having capacity of about 800 kips (approximately equal to the yield strength of the steel). In all cases, the final dynamic testing CAPWAP results were performed the same day data was received and results transmitted to Lawrence Construction, thus speeding up the decision process. An example remote PDA signal matching result is shown in Figure 4.

By approximately doubling the design stresses and capacities on each pile, the final quantity of piling was reduced from 27,000 linear feet to only 17,700 linear feet, resulting in substantial savings to the owner even after adding the small test program. The production piling installation in progress is shown in Figure 5.

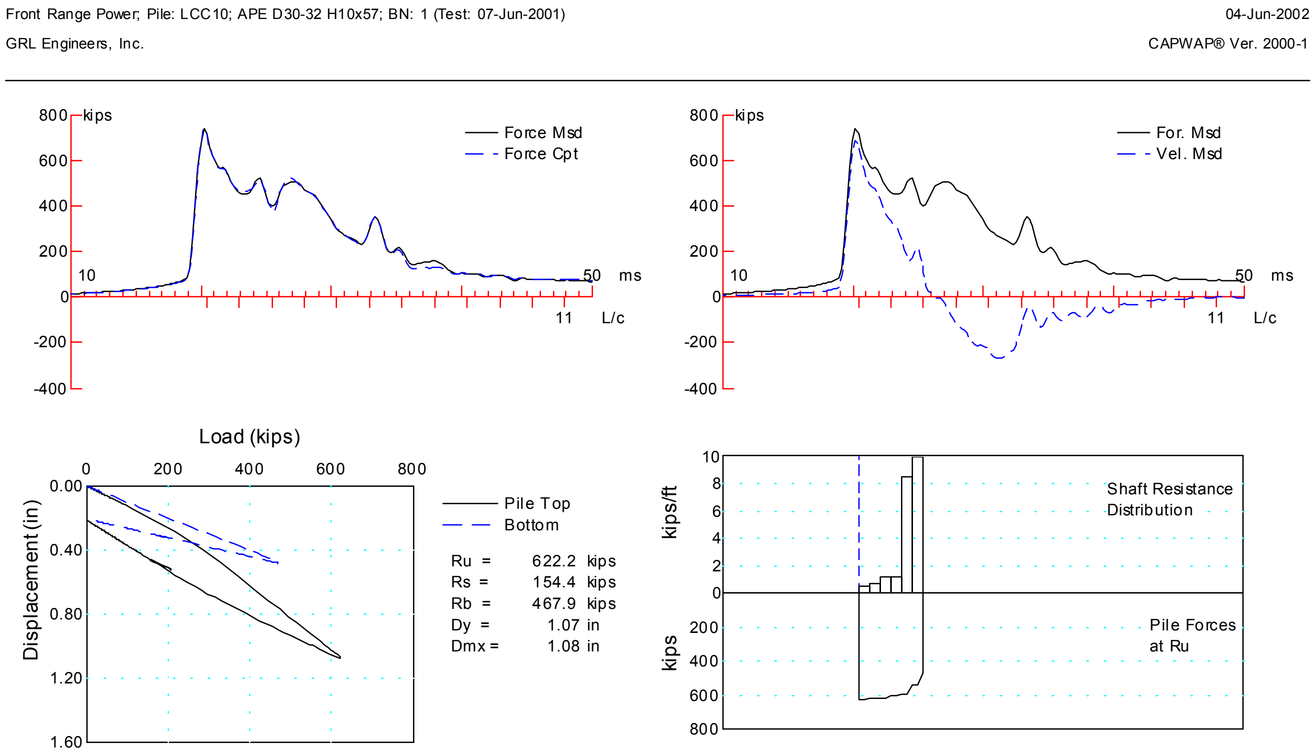

Figure 4. Typical PDA test result for restrike of pile 10

Figure 5. Production piling in progress

Conclusions

As foundation costs increase, innovative technology can result in substantial savings to the total cost of the project. Higher strength steel can support higher applied loads than the traditional 9 ksi design stresses. In fact doubling the design stresses to 18 ksi is possible for 50 ksi steel. Use of traditionally low design stresses is not economical nor is it universally justified in modern practice. If a testing program conclusively proves that higher loads are acceptable, then the design should be modified to benefit the owner. The case history documents proven 35% savings in the foundation costs due to a relatively minor amount of additional testing.

To confirm acceptability of higher design stresses, test programs with both static and dynamic pile testing can be employed. Marking the critical piles on the plans allows for testing of those piles. The cost of the test piles is easily recovered in the savings to the total foundation costs. The safety factor used should relate to the type of confirmation testing and the percentage of piles tested. More tests can result in lower safety factors for exactly the same low probability of failure. The PDCA Design Specifications reflects this logical philosophy.

The remote Pile Driving Analyzer is a viable alternative for dynamic testing. It reduces testing and travel costs and increases testing efficiency for the engineer. It also allows the contractor to schedule testing at his total convenience, allows for a true unit price per test bid, and results in a faster turnaround of report results to speed the decision making process.

References

Recommended Design Specifications for Driven Bearing Piles, 2001, Third Edition, Pile Driving Contractors Association.