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COMBINING STATIC AND DYNAMIC LOADING TEST RESULTS OF PILES

Frank Rausche, Ph.D, P.E., D.GE, Pile Dynamics, Inc., Cleveland, OH 44139; e-mail: frausche@pile.com

Abstract

Dynamic load testing is the most economical means of estimating deep foundation behavior under static loads. Unfortunately, this relatively quick and inexpensive test method has limitations: incomplete assessment of time dependent soil resistance changes, incomplete resistance mobilization, failure criteria which differ from those for static tests, different failure modes in open end profiles and sensitivity to high loading rates. Because of their economy, dynamic loading tests can be done on numerous piles at a site while static loading tests must be limited to one or only a few piles. Modern codes such as AASHTO (American Association of State Highway and Transportation Officials) specifications allow for increased resistance factors, equivalent to reduced factors of safety, when several dynamic tests are performed at a site. Even greater reductions of factors of safety are acceptable when the dynamic test is calibrated by comparison with static loading tests, performed at the same site or at least under similar pile, soil and hammer conditions. Exactly how to do such a calibration and how to combine the results of both types of tests is rarely discussed or specified and is, therefore, made the subject of this paper. The calibration procedure is not a simple matter, because it has to take into account the reasons for the differences between the two test types. The paper describes how to set up and perform effective test programs. Differences between the static and dynamic tests are explained and classified so that rational and specific recommendations for the test calibration process can be developed.

Key words: driven piles; static loading tests; dynamic loading tests; signal matching; failure criteria; incomplete resistance activation; rate effects; soil setup; soil relaxation; superposition

Introduction

The static top loading test is considered the most reliable predictor of long term pile performance. If all piles of a foundation would be subjected to this test and if these tests were properly executed, i.e., at the right time with accurate instrumentation and adequate loading equipment, then that would provide the foundation professional with optimal information about the deep foundation's ability to support structural loads at tolerable settlements. Yet even this expensive and time consuming static testing program would not preclude failures due to long term effects on the soil such as negative shaft resistance, corrosion, changes in water table elevation and related variations in the state of effective soil stresses or uncertainties associated with group behavior among others. Like all tests, static load testing may suffer from inaccuracies of measurement systems or improper execution [1]. Therefore, in the language of the Load and Resistance Factor Design (LRFD) approach, the nominal or characteristic resistance value established by such a thorough and extensive testing program, still must be reduced by either a resistance factor (United States terminology) or a partial safety factor.

Analytical or empirical design methods based on soil investigations are generally considered less accurate and require higher factors of safety than methods that include load testing. Higher factors of safety in turn lead to more conservatism and foundation cost. Static load testing, is economical, both from a financial and construction time point of view, if performed on only one or a few selected test piles. However, variability of site geotechnical conditions, potential structural damage issues of individual piles, unpredictable behavior of installation equipment and other problems require additional quality assurance and control measures. Such measures include thorough construction monitoring plus complementary dynamic loading tests.

While static and dynamic tests usually agree quite well with each other [2], dynamic loading tests do not and cannot provide the exact same information that static testing provides. For example, data collected during pile driving may be affected by elevated pore water pressures or soil structural changes. Even waiting long enough with restrike dynamic testing after installation effects on the soil resistance have dissipated may not avoid having to deal with quickly changing soil properties due to the dynamic loading test itself. Another concern is associated with rate dependent soil strength changes which may or may not be accounted for by analysis of the dynamic records [3, 4]. Furthermore, non-displacement piles may not plug during driving, but experience full end bearing during static load applications. The most frequently encountered problem is an insufficient pile testing energy which will not produce the necessary pile penetrations into the soil to provide full resistance activation. Finally, every loading cycle, either static or dynamic, affects the stiffness and nominal resistance of the foundation element. For that reason it cannot be expected that these test are completely reproducible.

Modern codes require reductions of the dynamic test capacity values if no static test is performed. That is reasonable considering that statistical analysis of the ratio of static to dynamic nominal resistance (NR) values shows some variability and a bias factor not equal to 1.0 [5]. Exactly how much the dynamic nominal resistance from a dynamic test should be reduced is a point of contention. Obviously, severe reductions of the NR can be uneconomical and thus not desirable when the soil, pile and test conditions are such that they will definitely produce underestimations. For that reason, individual US State Highway Departments have studied dynamic testing results in their specific geotechnical environment and generally have come up with less severe capacity reductions than the AASHTO [6] recommendations.

In order to be able to define more economical overall factors of safety, one or at most a few static test are sometimes required to "calibrate" the dynamic test. For example, in Section 2.5.3 the EC 7 [7] states: *"Dynamic load tests may be used to estimate the compressive resistance provided an adequate site investigation has been carried out and the method has been calibrated against* *static load tests on the same type of pile, of similar length and cross-section, and in comparable soil conditions."* AASHTO [6] similarly comments: *"Dynamic Testing requires signal matching and best estimates of nominal resistance are made from restrike tests. Dynamic tests are calibrated to the static test where available."* Again, the calibration process is not a straight forward and will be discussed paper. Comprehensive background information on test types, analysis methods and driving criteria formulation may be found in the Manual for the Design and Construction of Driven Piles, Hannigan et al., [8].

About the terminology in this paper

To avoid confusion, in this paper the term "Nominal Resistance" or NR will be used in lieu of "Ultimate Resistance", "Capacity", "Ultimate Capacity", "Characteristic Resistance", or other expression for what is a typical "Failure Load" achieved by a particular testing or analysis method. The term NR recognizes that each testing method produces a specific or characteristic resistance value.

Since the specifications referenced in this paper deal primarily with driven piles and because driven piles undergo changes of soil resistance with time, distinction has to be made between tests performed at the end of driving and at the beginning or end of restrike testing; these tests are, respectively, named EOD, BOR and EOR. While the examples and also the testing requirements mentioned in this paper deal primarily with driven piles, similar situations are encountered when dynamic and static tests are performed on cast-in-situ piles. In that case, the dynamic testing would correspond to the BOR condition.

Static load testing is a term commonly associated with top loading. This common static test type can be dangerous, because it may require very high reaction loads or elastic reaction systems which can shift and/or collapse. Plotting the top load vs. top displacement curve is evaluated for an NR value according to a specified failure load criterion. An alternative static test called Bi-directional or Osterberg test [9] applies the load some distance below the pile top so that the upper pile section's shaft resistance reacts against shaft resistance and end bearing in the lower portion of the pile. An analysis then provides an equivalent pile top loading curve that can be evaluated as for the standard static test. The advantage of the bidirectional is a much safer test and one that can be reasonably efficiently done with much higher loads than the top loading test. The Bi-Directional test is not very easily done on driven piles. Both top loading and bi-directional testing will be referred to as static loading tests in this paper.

Dynamic loading tests require measurement and digital processing of pile force and velocity occurring while the pile is loaded with an impact of a pile driving hammer or drop weight. Most commonly, measurements are taken by surface mounted, reusable sensors; these accelerometers and strain transducer are installed on the pile on the construction site prior to pile testing. The dynamic measurements may be taken by a Pile Driving Analyzer® (PDA) system, although several other systems also exist. The test records are then analyzed by signal matching, most commonly by the CAPWAP® approach [10]. The dynamic analysis results in a simulated equivalent static load-displacement curve which can be interpreted using a failure criterion like for the equivalent statically determined curve. Besides CAPWAP a few different computer programs exist and the abbreviation CW will be used in the following to refer to a general signal matching approach.

Embedded sensors are an alternative solution for the dynamic testing of concrete piles. The method has been studied and described by McVay and Wasman [11]. In that case, the sensors are installed already in the casting yard. A proprietary system then collects, analyzes and displays the results which are generally not subjected to signal matching. Results from both embedded and surface mounted sensors are referred to as dynamic test results in this paper.

The preferred pile testing and installation procedure

Depending on the size of the job, the type of deep foundation or the geotechnical conditions encountered (friction piles, piles driven to hard layers) different quality assurance approaches may be chosen. The following discusses three common types of test programs as they may be designed when several piles support individual structural elements (in contrast to a single large, high capacity element). The first scenario is a relatively large job, probably with more than 200 piles; the second one a smaller job with less than 200 piles, but perhaps more than 50 piles and the last one a smaller job yet. In all cases, due to uncertainties with pile and soil behavior, a static test is specified in addition to several dynamic test piles and a certain percentage of dynamic tests on production piles.

(a) Large jobs – friction piles

It is assumed that the project is large enough to justify an initial test program which is performed as a project separate from production pile driving. The objective of the test program may not only be the development of installation criteria and a production pile testing program but, often more importantly, the selection of optimal pile types and assignment of possible and required nominal resistances and associated pile lengths. Moreover, the test program may be designed for the determination of necessary waiting times to achieve optimal NR gains through soil setup which is further discussed below. During the initial test program one static test is performed (for each site condition if the site is very large or highly variable) plus dynamic tests on the static test pile and on several dynamic test piles. Additionally, during the production pile installation a certain number of the production piles would be tested to verify that hammer and soil performance continue to match those observed during the test program. The total number of test piles should conform to the applicable specifications. For example, AASHTO [6] requires 2% and 100% dynamic testing for respective resistance factors of 0.65 and 0.80 while EC 7 [7] specifies an absolute number of test piles.

Dynamic tests must be performed on the static test pile and should be done on additional dynamic test piles at EOD, 15 minutes after installation (BOR1), one day after the installation (BOR2) and then again after the static loading test (BOR3). The static test pile and the additional dynamic test piles are driven to a criterion that has been based on static geotechnical analysis plus wave equation analysis, the latter with the estimated static resistance to driving, SRD, i.e. the long term resistance minus losses of soil resistance due to pile driving. During the installation these initial soil resistance and driveability estimates are verified and possibly modified based on PDA monitoring results. For example, there is no point driving the pile to an excessive resistance or the later tests will not be able to mobilize the NR either due to a lack of reaction capacity of the static test setup or insufficient hammer energy in the dynamic test.

The time between installation and static loading should be at least one week for piles in granular soils or piles driven into a moderately hard rock and 4 weeks for cohesive/plastic soil types. After the initial test program has been completed and the report issued, the production piles are installed to a driving criterion developed based on the test results and the required NR. Shorter waiting times for production restrike tests are acceptable. No pile driving activity should take place during the waiting period(s) near the static and the dynamic test piles. The required minimum distance depends on soil type, pile size and pile driving equipment. For example, Hussein et al. [11] report that vibrating reaction piles according to generally recommended distances of 5 pile diameters or at least 2.5 m [7] caused loss of soil resistance in a test pile.

(b) Large Jobs – piles driven to hard layer

When driving into hard rock static testing is usually unnecessary and all testing can be done dynamically. In this case pile toe damage is the most relevant concern and it can be determined or better prevented by dynamic monitoring. Note that EOD tests are usually more effective in determining pile toe damage when shaft resistance is low and does not mask the damage reflections.

When driving piles into very dense sand or moderately hard rock, both soil resistance and pile toe damage concerns have to be addressed. For that reason at least one static test and the associated EOD and BOR tests plus several additional groups of EOD and BOR tests have to be conducted in the initial test program. Waiting times are at least 1 week, but if shaft setup is deemed important, longer waiting times may be necessary as discussed in (a).

Static and dynamic restrike testing has to be done to assess the bearing layer's potential for relaxation which is further discussed below. If the static and restrike tests indicate that relaxation is not a problem, and if soil setup is not considered important, then EOD testing is sufficient for the production piles. If relaxation is a potential problem, then the piles have to be driven to an increased NR at EOD so that the required NR can be confirmed at BOR. The required, increased EOD resistance has to be determined during the initial test program.

Heave also may reduce the end bearing when other piles driven nearby cause soil displacement upwards. This problem occurs often on displacement piles in cohesive soils. When reseating production piles, dynamic testing of a certain percentage of piles should confirm that no pile toe damage occurs.

(c) Smaller jobs

Smaller jobs usually do not justify mobilizing equipment for both an initial test program and later production driving. If the foundation relies on slowly developing soil setup and the cost per pile is high or if soil relaxation (see below), not compensated for by soil setup along the shaft, is a possibility, it may be reasonable to have a separate initial pile test program as for larger jobs.

Unless high capacity piles are installed it may not be cost effective to wait for full soil setup to take place which means that some soil resistance gains with time have to be sacrificed for the sake of an improved construction schedule. The testing can then possibly be done at EOD, 15 minutes or 1 hour (BOR1) and 24 hours (BOR2) after driving.

The static loading test can be done after 1 week and an additional restrike test is then performed (BOR3). During the preparation time for the static test it may be possible to drive some production piles based on preliminary dynamic test information, but not in the vicinity of the test pile(s). The driving sequence has to be selected in a way that makes it possible to get back on those piles in case additional driving and/or pile reseating becomes necessary. A 5% or higher dynamic verification testing of the production piles may either be done during the installation (EOD testing) or by 1-day restrike testing; EOD testing may be sufficient if setup gains or relaxation losses are either negligible or predictable from the initial test program.

(d) Small jobs

If only a few piles with moderate NRs are needed on a job then it is best to merely test dynamically the production piles as they are installed, perform a 1-day restrike and base the driving criterion on the restrike and installation nominal resistances. The overall factor of safety is then the one for dynamic testing only. However, static testing should be considered, if in plastic soils, no significant increase in nominal resistance is indicated by the restrike test and, therefore, the possibility of a rate effect related overestimation of the NR by the dynamic test exists [3, 4].

REASONS FOR STATIC-DYNAMIC TEST DIFFERENCES AND RECOMMENDATIONS FOR MITIGATION

Different failure criteria

In the late 1960s when the Ohio DOT prepared for implementing the dynamic load testing method, their standard static test was a maintained load test which lasted more than one day. It was evaluated by a yield criterion (failure was reached when the displacement exceeded 0.51 mm (0.02 in) for a load increase of 8.9 kN (1 ton). The Case researchers instead used a so-called constant rate of penetration test (CRP) which was typically finished within at most two hours and, therefore, included lower creep displacements. The dynamic test matched the CRP test results quite well, but on the average the CRP failure load exceeded the ML results by approximately 10%.

The CRP and dynamic tests were “calibrated” to the reference ML test by requiring that piles tested with either one of those two methods should exhibit a 10% higher capacity than specified. The yield criterion was eventually abandoned and replaced by the Davisson criterion. The higher CRP capacities were attributed to the faster loading speed which increased the plunging failure of piles in cohesive soils. Today a Quick test is the preferred static loading method [8]; its rate of loading is and its effect on NR lies somewhere between the ML and CRP tests and is usually ignored.

Failure according to Davisson occurs when the static test displacement of the pile top, subjected to a load Q, exceeds d_{Dav}.

$$d_{Dav} = 3.8 + B/120 + QL/EA \text{ [mm]} \qquad (1a)$$

where B is the pile toe diameter or width and L, E and A are the length, elastic modulus and cross sectional area of the pile. Originally, this criterion has been used for dynamic/static test comparisons for all driven piles, regardless of size. Today AASHTO [6] requires that Davisson's criterion only be used for pile sizes up to 610 mm and that a modified criterion is used for piles sizes greater than 914 mm; the latter criterion replaces the B/120 term with B/30. Thus,

$$d_{AAS} = 3.8 + B/30 + QL/EA \text{ [mm]} \qquad (1b)$$

For pile sizes between 610 and 914 mm a linear interpolation between the two criteria is used. While Davisson and AASHTO are commonly used failure criteria for driven piles in the US transportation industry, other failure criteria, referenced frequently in the building and cast-in-situ pile industry [12], include the following.

- A fixed displacement may be specified; for example the California transportation department defines failure at 12.7 mm pile top displacement; this criterion makes sense if it is to be based on structural considerations.
- The Butler-Hoy criterion, frequently used in the US building industry, defines failure as the intersection of a tangent on the origin and a tangent at the maximum load of a load-displacement curve.
- For cast-in-place piles and internationally also for driven piles a 5 or 10% of pile diameter criterion is often referenced.
- The Chin criterion extrapolates the load-displacement curve of a static loading load test.

The latter two criteria usually indicate failure loads at much higher load levels than achievable by dynamic tests and also at levels which are potentially inconsistent with structural requirements.

It is well known that these very different criteria, depending on soil and pile type, can define significantly different pile capacity values. Consider Figure 1, left, which shows data that has been discussed by Hussein et al. [13]. Both static and dynamic tests suggest a so-called plunging failure, i.e., one where no resistance is gained with increasing displacements. In this case most criteria would provide the same result except a careless extrapolation of the static test, had it not been carried to failure. The static and dynamic loading tests were conducted on a 914 mm square concrete pile of 29.3 m length. The dynamic BOR test was performed one day after the static test. In this case the EOD indicated a surprisingly high resistance and it was later found that the vibratory driving of reaction piles, after the test pile was installed, most probably caused losses of resistance and the unusual plunging behavior of this displacement pile in a sand.

Quite different is the situation depicted in Figure 1, right. It shows a few of the results from the demonstration tests described by Rausche et al. [14]. The three load-displacement curves were obtained from an end-of-drive (EOD) dynamic test, a static load test, conducted one day after pile installation, and then the first blow of a restrike test, performed within only a few hours after the static test. The pile was a 325 mm diameter, 6.2 mm wall thickness, closed ended pipe driven through a clay crust and then 12 m of soft silts and clays to a sand layer which was under artesian pressure. There was less than a one day waiting time between pile installation and static testing. Figure 1 shows the loads applied vs. the cumulative displacements beginning with a zero displacement for a CW analyzed EOD blow.

In this example the Davisson criterion indicates NR values of EOD, static test and BOR of 725, 500 kN and 800 kN, respectively. Applied to the static test, the 12.7 mm (½ inch) criterion would yield almost the same result as the Davisson criterion (500 kN) while the 10% of diameter criterion would indicate an 840 kN capacity and match the dynamic tests very well. It is rare that the 10% diameter criterion yields as good an agreement with the dynamic test as it does in this case; the reason is an unusually soft static behavior of a pile with a rather small diameter. Later testing at the same site yielded static and dynamic NR values which agreed well according to Davisson; they were in the neighborhood of 1000 kN.

The point of this discussion is (a) that the dynamic and static tests have to be evaluated by comparable criteria and not necessarily the same criteria and (b) that both static and dynamic tests have to be carefully executed and after adequate waiting times or either test would indicate false NR values.

Soil setup after pile installation

Soil setup has been observed to take place in both cohesive and non-cohesive soils. In cohesive soils it is generally thought that the pile driving process generates increased pore water pressures, particle alignment changes in the soil fabric and soil fatigue among other causes for loss of shaft resistance during driving. In non-cohesive soils pile driving also causes pore water pressure changes, though rather short lived, and in dense soils perhaps an arching effect around the pile with lower effective stresses in the immediate neighborhood of the pile wall and hence relatively low shaft resistance forces. In most instances it can be expected that these reductions of resistance are reversible and that the shaft resistance forces increase with time after pile installation. Soil setup not only occurs in driven piles but also on cast-in-situ foundations due to disturbances in the soil by the drilling process.

The generally accepted theory on soil setup has been formulated by Skov and Denver [15] and was further evaluated by Bullock et al. [16]. According to this accepted theory the pile capacity, R, at a waiting time, t_{wait}, can be calculated from

$$R(t_{wait}) = R_o[1 + A \log (t_{wait}/t_o)] \qquad (2)$$

The parameter A in Eq. 1 indicates a relative gain of resistance and R_o and t_o are, respectively, a reference capacity and associated waiting time. As a reference R_o, t_o from an early restrike rather than from EOD should be used since t_o is not well defined for EOD and the associated soil resistance not in the typical consolidation process. According to Eq. 2 it is expected that the NR increases by the same amount with every additional 10 times greater waiting time. This formula is often applied to the total resistance of a pile, although soil setup is generally assumed to occur primarily at the shaft and not at the pile toe.

Neither static nor dynamic tests can be performed after very long waiting times to assess full setup capacity. However, longer waiting periods are both necessary and reasonable for static tests than for dynamic tests. Thus, to avoid underestimation problems by the dynamic tests an appropriate testing schedule should be adopted as discussed earlier.

Soil setup is not limited to cohesive soils. Examples of high losses of resistances can be found in the literature. For example, Seidel and Kalinowski [17] show that in very dense sands the driving resistance was little more than a quarter of the expected and much later verified long term resistance. Recouping the full expected long term resistance lost in very dense materials take much longer, like several weeks, than porewater pressure effects which in sands may dissipate within a few hours.

Relaxation

Relaxation is a reduction of end bearing with time after pile installation. Fortunately, this problem is relatively rare. It has been observed in shales, chalk, weathered rock, glacial till, very dense fine sands. Reasons for soil relaxation are varied and not particularly well understood. An example of relaxation in shales has been described by Morgano and White [18]. Without dynamic testing relaxation may not be recognized, because the EOD resistance would not be known. Merely comparing blow counts from end of driving and redriving may lead to erroneous conclusions. For example, a high EOD driving resistance, compared to the restrike blow count, may have been caused by a low EOD hammer energy, e.g., due to hammer overheating. In that case, the comparably low restrike blow count would not be the result of end bearing relaxation.

If restrike testing is done too early, when the relaxation has not fully developed, or if a late rather than a very early restrike blow is analyzed so that an artificially high toe resistance has been regenerated, then it must be expected that the dynamic test indicates a capacity higher than the later static test. To avoid an overestimation of NR for relaxing piles it is, therefore, important to execute an adequate testing schedule and to do the dynamic analysis carefully.

Quality assurance based on EOD dynamic testing results has to be cognizant of the high toe resistance and thus NR at EOD has to be higher than the required long term NR. The ratio of static test to EOD NR would be the calibration factor; of course, a calibrated restrike test could be similarly calibrated, however, care must be taken in that case to specify which restrike blow should be used for the NR assessment if the first restrike blow is one of low energy.

Rate effects

Dynamic tests on piles in plastic soils may indicate higher soil resistances than static tests. Such overestimations can occur both on shaft and toe due to loading rate effects as experienced on many materials when they are tested at high loading velocities. Although the velocity related resistance is modeled in a signal matching analysis the full rate effect may not be accounted for in a highly plastic soil [3, 4]. CW results may have to be reduced by up to 30% in order to match static test results for driven or cast in situ piles in plastic soils with high Liquid Limits. Frequently in plastic soils, load testing has to be done after sufficiently long waiting times in order to include soil setup gains. If testing is done too early then unaccounted for additional soil setup may mask the rate effect. Ideally soil exploration programs would evaluate the liquid limit of plastic soils so that the required correction or calibration can be anticipated.

Example of calibration procedure of a soil with setup and rate effects

The calibration procedure for a pile driven into clay is demonstrated by test results which have been discussed as an example of simultaneous setup and rate effects by Rausche, Hannigan and Alvarez [3]. The construction project involved a 610 mmm square prestressed concrete pile of 39 m length, driven to a depth of 20.4 m. Plasticity indices were typically between 30 and 80. A static test was scheduled approximately 5 weeks after pile installation. Let us assume that the engineer decided that the NR occurring 30 days after pile installation would be accepted for design purposes.

Dynamic tests were conducted during driving and at 15 minute, 1 day and 39 day waiting periods. A static load test was performed 37 days after the end of installation. Table 1 shows the dynamic and static test results which were also plotted in Figure 2. Using the 15 minute test as a reference (t_o = 0.01 days and R_o = 740 kN) and with R(39d) = 3410 kN the setup resistance gain occurring during 3.59 cycles of waiting time (log(39/0.01) = 3.59) is 3410-740 = 2670 kN; the parameter A of Eq. 2 then becomes (2670/3.59)/740 = 1.01 and Eq. 2 can be written as

$$R(t_{wait}) = 740[1 + 1.01 \log(t_{wait}/0.01)] \qquad (3a)$$

With this formula the 30 and 37 day dynamic resistance values were calculated and entered together with the other test results in Table 1.

After a waiting time of 37 days, the static loading reached a peak load of 2340 kN; this load was held for 28 minutes. When it was then tried to add more load, the pile plunged and even lost resistance and then held only a residual load in the range of 1220 to 1620 kN. It could be argued, that once a critical displacement or load was exceeded the pile lost progressively more and more of the setup resistance and plunged. Using this argument, the nominal static test resistance at 37 days would be 2340 kN. Obviously the static NR is lower than the dynamic NR at 37 days which is attributed to rate effects. The calibration factor would then be the ratio of the static nominal resistance to the dynamic value at the same time. Thus, $f_{cal} = R_{static}/R(37d)$ = 2340/3410 = 0.686. Applying this factor to all dynamic test results yields a new setup relationship:

$$R_{cal}(t_{wait}) = 0.686\ (740)[1+1.01\log(t_{wait}/0.01)] \qquad (3b)$$

Substituting 30 days for t_{wait} yields a calculated, calibrated 30-day nominal resistance of 2290 kN (this would be expected in a static test).

Commented [xx1]: I found this after revision: it was hours instead of days

Now let us assume that a 1 day restrike test is performed on a dynamic test or production pile whose signal matching analysis indicates a dynamic NR of R_{test} = 2500 kN (210 kN more than the test pile capacity at 1 day). The calibrated 1-day test capacity is then 0.686(2500) = 1715 kN and the 30-day calibrated nominal dynamic resistance becomes, simply by ratio, 2290(1715/1570) = 2500 kN. This 30-day NR, being equal to the dynamic test result at 1 day, is a coincidence, but it points out that the 1-day dynamic test result can be equated to the calibrated 30-day NR in this particular case.

This example does not address the question of an installation criterion. In the example given here, the piles most likely will be driven to a certain depth, because of the large difference between the EOD and the setup nominal resistance values which makes an EOD blow count driving criterion somewhat unreliable. However, NR verification should be done by 1 day restrike tests. Furthermore, if the soil deposits are uniform, the calculated setup and calibration factors can be used to test piles for different pile lengths and required nominal resistance values.

Incomplete resistance activation

General Remarks

Probably the most common reason for differences between static and dynamic test results is incomplete resistance activation. While sometimes static test setups do not reach the specified failure criterion due to insufficient reaction load or hydraulic jack capacity, more frequent is an underestimation of NR by the dynamic test due to insufficient hammer energy. The problem occurs more frequently with end bearing piles in granular soils and friction piles with high soil setup.

In general it is agreed that a 2.5 mm set per test blow is sufficient to meet the requirement of the Davisson criterion in a dynamic test. However, it is also important that the pile toe achieves a sufficiently large total dynamic displacement (temporary compression plus permanent penetration), because large displacement piles with significant resistance at the pile toe require a large elastic movement before they reach and thus activate the ultimate resistance.

Static test did not reach failure

If the static test has failed to reach a top displacement required by the failure criterion and an extrapolation of the load-displacement curve is reasonably possible, then the static test can be accepted with the extrapolated nominal resistance as if it had been reaching the failure criterion. However, it is not recommended to use an extrapolation method such as Chin’s [12] unless there is a clear indication of an onset of failure. Otherwise an excessively optimistic failure load could be estimated.

Consider the following example of a 21 m long, 610 mm square concrete pile with internal void driven through clay and an interbedded sand layer to a depth of approximately 12 m. The pile was dynamically tested at the end of driving, indicating an NR of 2600 kN, and after waiting times of 1 and 15 days with respective NR values of 4270 and 4530 kN. Fourteen days after installation the static test was taken to a maximum load of slightly less than 3200 kN where it reached a pile top displacement of less than 5 mm.

Using an extrapolation of a form similar to Chin's extrapolation method, i.e.,

$$R_{ext}(d_{top}) = 1/(\alpha + \beta/d_{top}) \qquad (4)$$

where R_{ext} is the extrapolated resistance and d_{top} is the pile top displacement and picking two points along the static load-displacement curve to determine the constants α and β, the extrapolated static curve of Figure 3 was achieved suggesting a failure load of almost 5000 kN according to Davisson. The two point approach was chosen here, because it can also be reasonably well adopted to the CW simulated load-displacement curves.

A word of caution concerning extrapolation

A word of caution should be added. Relying on a static test for an improved factor of safety requires great caution when extrapolating the static load-displacement curve. Extrapolating a dynamic test to match a carefully executed and interpreted static loading test is much less controversial. In the case shown in Figure 3, the soils were plastic (PI 20 to 40) except for a sand layer which was penetrated and did not provide end bearing. The failure mode of this pile would most likely be of the plunging type while the extrapolation applied here is of the type normally associated with high end bearing in a granular soil. Also the soil setup occurring between the 1-day and the 15-day setup tests was quite low and by day 100 at best another 250 kN should be expected to materialize which would yield a 100-day dynamic nominal resistance of around 4800 kN. Because of the plasticity of the soil (see rate effects above), and since the static load test did not indicate a higher capacity it would be prudent to reduce the 100-day dynamic NR to 70% or to 3360 kN, not far above the maximum load of the static test. In this example, the recommended calibration factor for the 1-day restrike would, therefore, be 3360/4270 = 0.79. The close agreement between the 15-day restrike simulated load-displacement curve and the extrapolated static curve should be considered a coincidence and not evidence of a valid extrapolation.

Incomplete resistance activation by dynamic tests – Mitigation possible

If the dynamic loading generates less permanent pile set per blow than 2.5 mm, all of the static soil resistance may not be activated and included in the dynamic test results. This condition is relatively common for driven piles, because pile driving hammers are usually only designed to drive the pile and not for restrike testing when a much higher than the installation resistance is present due to soil setup. For cast-in-situ piles with high end bearing it is sometimes unpractical to mobilize the impact mass necessary for full end bearing activation.

When lack of dynamic energy is responsible for low dynamic test resistance values then the simplest means of improved testing would be with a more powerful hammer. It could be a simple drop hammer dedicated to dynamic testing which would allow the contractor to continue with the production pile installation activities while dynamic testing is done. An example is discussed by Teferra et al. [19].

Alternatively the method of superposition should be tried to combine EOD and BOR results for a more realistic overall resistance distribution and total nominal resistance. Superposition uses the fact that during an early restrike at least the soil resistance along the upper pile portion is activated while EOD blows are more likely to activate the full toe resistance; additionally EOR blows activate additional setup resistance above the pile toe. The method has been described, for example, by Hussein, et al. [1]. Three somewhat different superposition methods can been used.

1. End bearing from EOD and shaft resistance from BOR. This is the simplest and most common approach.
2. Upper shaft resistance from BOR, lower shaft resistance and end bearing from EOR; this method would be used where EOD records are either not available or not reliable for end bearing calculations.
3. An envelope of all resistance values vs. depth calculated from EOD and several BOR records. This method is particularly helpful for piles with deep penetrations where loss of resistance and thus activation of lower resistance is gradual. Care has to be taken that, for the different records analyzed, resistance from individual soil layers are not shifted relative to each other or severe overestimation of total shaft resistance could result.

Of course, superposition methods 2 and 3 require that sufficiently many blows are applied during the dynamic test so that the upper resistance degraded to the point that allowed for improved resistance activation in the lower part of the pile.

Incomplete resistance activation by dynamic tests – Mitigation not possible

It may be too difficult or expensive to bring a bigger hammer to site and the superposition may not work because the incomplete resistance activation is, for example, the result of a high end bearing and not the result of soil setup. In those cases an optimal utilization of all available soil resistance may be difficult to achieve. In the case of the high end bearing, the dynamic stresses during testing may become unsafe. For the dynamic test piles, those that are not statically tested, a number of different scenarios are conceivable.

a) The dynamic test pile is loaded with higher energy than the static test pile and the set per blow is less than or equal to that measured for the static test pile. The NR of the dynamic test pile is then most likely greater than that of the static test pile. It is then reasonable to extrapolate the dynamic test of the static test pile and apply the same extrapolation (practically a calibration factor) to the simulated load-displacement curve of the dynamic test pile. The specified failure criterion can be applied to the calibrated/extrapolated curve.

   An example of the simplest possible extrapolation method (another method would be Eq. 4) is given in Figure 4; it is really a factoring by simple multiplication of the dynamic load; in this case a factor f_{cal} = 1.2 made for a nice matching of the static test curve. This case involved a 610x16 mm closed ended pipe pile with 41 m penetration in cohesive soil. While end of driving was relatively easy (7.6 mm set per blow at 50% transfer energy ratio of the air hammer) the restrike set per blow was only 0.12 mm at a transferred energy ratio of 39%. In this case, if the energy of a restrike blow on a production or dynamic test pile were greater than 39% with the same hammer and the set per blow less than or equal to 0.12 mm, then the same extrapolation factor of 1.2 could be used on the simulated load-displacement curve calculated from the dynamic tests with good confidence.

b) The dynamic test pile test is tested with a lesser energy than the pile statically tested and the set per blow is less than or equal to that measured for the static test pile. The same procedure as in (a) can be applied, but with the calibration adjusted by the ratios of transferred test energy values.

$$f_{cal\text{-}adj} = f_{cal}\,(E_{t,dyn}/E_{t,stat}) \qquad (5)$$

where $E_{t,dyn}$ and $E_{t,stat}$ are the transferred energy values measured during the testing of the dynamic and static test piles, respectively. In our example, a restrike energy ratio of 35% and a set per blow less than 0.12 mm would allow for a calibration factor of 1.2 (35/39) = 1.11. Of course, the reduced calibration factor should not be lower than 1.0.

c) The dynamic test pile receives less energy yet achieves a greater set per blow than measured during the dynamic test of the static test pile. In this case it would be unwise and non-conservative to make an extrapolation. The dynamic test result should be accepted as is for the NR calculation or the test repeated with a greater energy.

Different failure modes in open profiles

General remarks

Open ended pipe piles and H-piles, particularly large cross sections, tend to exhibit a different plugging behavior in static and dynamic load applications due to a potentially high inertia of the soil mass inside the pipe or between the pile flanges. Owing to the greater soil mass of the plug, inertia forces are higher for larger pile sizes. They are also higher for lightly cushioned impacts compared to heavily cushioned tests with g-levels reaching more than 1000 g's in the former case and less than 100 g's in the latter case. Pipe piles with diameters greater than 762 mm are infrequently plugging and very large piles (diameters greater than 1500 mm) are rarely expected to plug during pile driving although partial plugging may occur. Brown and Thompson [20] summarized current testing practice in the United States and in offshore construction. Different owners, engineers or testing agencies came to different conclusions and practices according to a survey conducted by the authors. While conclusive studies are lacking, it is reasonable to distinguish two different situations.

(a) Cohesive soils: The soil plug slips relative to the pile wall and causes internal friction in the pile during dynamic loading. During static loading the pile plugs, but the end bearing is lower than the internal friction experienced during the dynamic loading. Overestimation of soil resistance is then possible and potentially aggravated by rate effects. As long as pile lengths and diameters are comparable, reducing the dynamic NR can be reduced by the ratio of static over dynamic resistance should be acceptable.

(b) Cohesionless soils or moderately hard rock: The soil pile plug slips and produces moderately high internal friction. End bearing in the dynamic case, therefore, acts only against the steel or concrete of the pipe pile or H-pile. In the static test a high end bearing develops against the soil plug; arching or an inverse silo effect inside the pile or between the flanges prevent the soil plug from slipping. The total resistance of the plugged pile is then underestimated by the dynamic test.

In practice, however, conditions are generally more complex. It is not always assured that an arching mechanism develops during static load applications. Furthermore, during the dynamic event, the plug may only slip during the time of high pile acceleration and that would lead to partial plugging.

Both static and dynamic analyses are therefore difficult and fraught with uncertainty. As far as signal matching is concerned, Likins et al. [21] concluded that on the average the radiation damping model provides for a better agreement between static and dynamic test results. This method yields, in general, higher static resistance values which is more realistic in the cohesionless case (b) above, but which may lead to overestimations in cohesive soils. However, when a static test is used for comparison and calibration, the radiation damping method can always be used with good confidence and may help in the case of open ended pipe piles in granular soils or when driven to a moderately hard rock. This analysis method was also helpful when analyzing dynamic records obtained on pipe piles with an internal plate [20].

An example of open ended pipe pile test results

Figure 5 shows load-displacement curves from static tests performed on a 762 mm diameter, open ended pipe pile with 19 mm wall thickness. The pile penetration was approximately 20.4 m. The soil profile consisted of sand, clay and silt layers overlying moderately hard claystone. The pile had been driven and tested two weeks prior to the static test by an 8 ton Diesel hammer.

The static test reached a peak load of 7,380 kN, but exhibited some creep which caused a slight reduction of resistance with time and settlement. Extending the static test curve, the AASHTO criterion yielded an NR of 7,250 kN. The test was also evaluated by a 12.7 mm pile top displacement criterion indicating an NR of 6,000 kN. Based on a static uplift test it was concluded that the shaft resistance was approximately 4000 kN and the maximum end bearing and/or internal friction was therefore 3380 kN. Since no toe measurements were taken it is not certain that the pile actually plugged in the static case.

Unfortunately, dynamic testing was only done at the end of driving. The calculated maximum resistance as well as failure according to Davisson applied to the simulated static load-displacement curve was 5780 kN with a shaft resistance of 4980 kN and an end bearing of 800 kN. Under the assumption of no soil setup it can be concluded that the claystone plug slipped during pile driving thereby causing some internal friction and a low end bearing. Of course, setup can also be responsible for some of the difference between static and dynamic test results. Using the radiation damping model the CW resulted in a calculated NR of 6850 kN, with 6270 kN on the shaft and 580 kN at the toe (presumably acting against the steel toe). Since the uplift capacity was 4000 kN, it could be argued that 6270 – 4000 = 2270 kN occurred as internal friction which would be a reasonable percentage of 57% of the outside friction. It is not expected that the CW analysis identifies end bearing against the soil as toe resistance if the plug slips and causes internal friction. Only if there is a strong arching effect which concentrates the internal friction near the toe would it be expected that the CW analysis identifies the end bearing against the soil as such. The load-displacement curves from both dynamic analyses are shown in Figure 5 together with the static, extrapolated curve.

If the static test were evaluated by the AASHTO or other large displacement criteria, then the differences between static and dynamic tests would be either 7,280 vs. 5,780 kN (21%) for the standard CW or 7,280 vs. 6,850 kN (6%) for the radiation damping approach. For such moderate underestimations it is acceptable to apply a simple calibration factor to the calculated dynamic load.

SUMMARY

The calibration of a dynamic test is not a straight forward application of a calibration factor. The reason for the differences between the calibrating static and the calibrated dynamic test have to be investigated and the proper approach selected. The following reasons for differences and possible mitigations, given available static load testing results, were discussed and recommended.

- Different failure criteria may be applied to static and dynamic tests with the dynamic result agreeing most likely with the generally somewhat conservative Davisson criterion applied to the static load-displacement curve. The same criterion or one that matches better the static criterion has to be applied to the load-displacement curve from the dynamic test.
- In case of soil setup, static and dynamic tests of the static load test pile should be performed at the same waiting times. Calculating the soil setup vs. time relationship can then serve as a basis for dynamic testing at an earlier time to accelerate construction.
- In case of rate effects a reduction of the dynamic result may be necessary [3, 4].
- If static tests do not reach the failure criterion the load-displacement curve can be extrapolated. Caution has to be exercised in cohesive soils where plunging failure has to be expected.
- Where insufficient dynamic energy is the reason for low dynamic results it should be checked if either the method of superposition or a better test hammer can help. If not,

calibration may or may not be possible depending on the transferred energy and pile sets per blow observed during the static and dynamic tests.

- In case of open profiles producing different failure modes it is important to understand the failure mechanisms. Obviously, a well thought out test program with either instrumentation or uplift testing to determine the shaft resistance is of great help. For underestimations, most likely occurring in cohesionless soils, either the radiation damping model should be used and/or a simple calibration factor. For overestimations (most likely in cohesive soils) a reduction factor can be applied

While this paper discussed calibration of the dynamic testing when static tests are performed, the information contained in this paper may also be useful in cases without accompanying static testing or where no experience in similar conditions exists. In those cases the overall factor of safety should be higher and the economy of the foundation solution may be negatively affected. Even though a higher overall safety factor is then specified, it would be wise to apply the experience with dynamic test results in various soil types to reduce the likelihood of unsafe overestimates of resistance by the dynamic test or uneconomical underestimates of the nominal resistance.

It should be added that dynamic testing of cast-in-situ piles also may benefit from some of the methods discussed in this paper. For example, rate effects may require reductions of the nominal resistance, partial activation of resistance may allow for extrapolation and applying the radiation damping approach should also be helpful for deep foundations in granular soils.

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Table 1: Test results and calibrated resistance values

Waiting time	Dynamic Test	Static Test	Calibrated Dynamic Test
	kN	kN	kN
End of Drive	530		360
15 minute test	740		510
1 day - test	2290		1570
30 day - calculated	3340		2300
37 day – calculated/test	3400	2340	2340
39 day - test	3410		2340

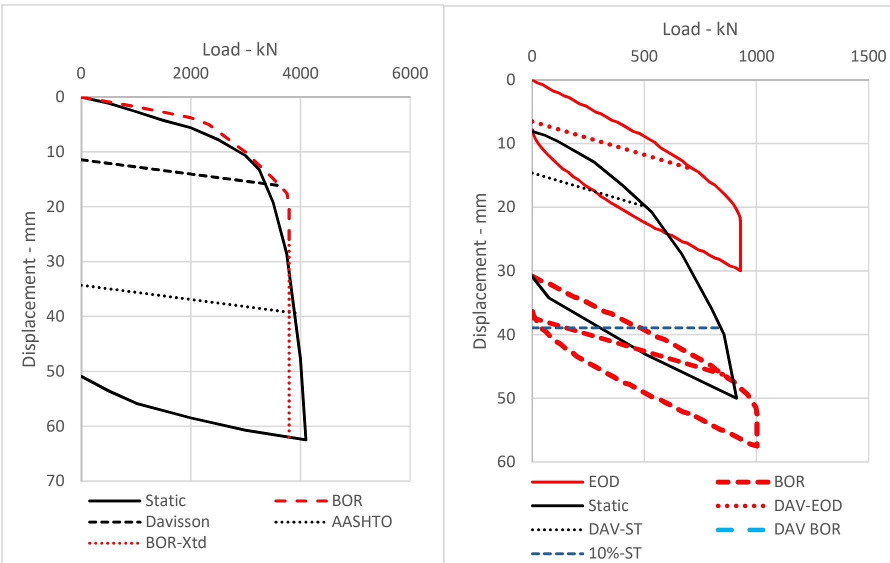

Figure 1, Left: close agreement between beginning of restrike (BOR) dynamic and static load-displacement curves for a 935 mm square concrete pile after Hussein et al., 2012. Right: EOD, Static and BOR load vs. cumulative displacement for a 325 mm diameter closed ended pipe pile after Rausche et al., 2014.

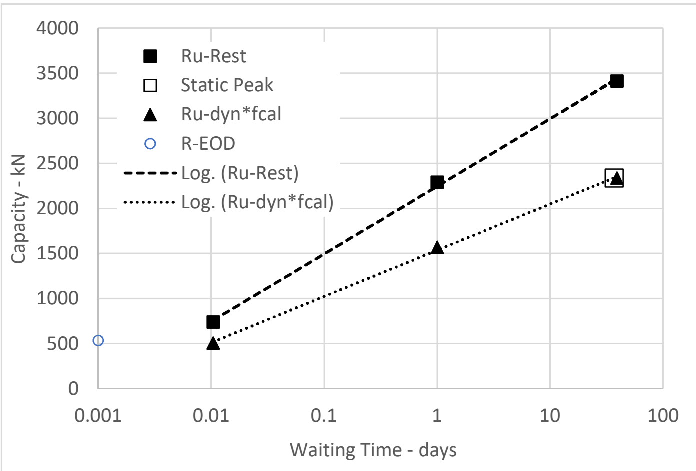

Figure 2: Semi-logarithmic plot of dynamic and static test results vs. waiting times

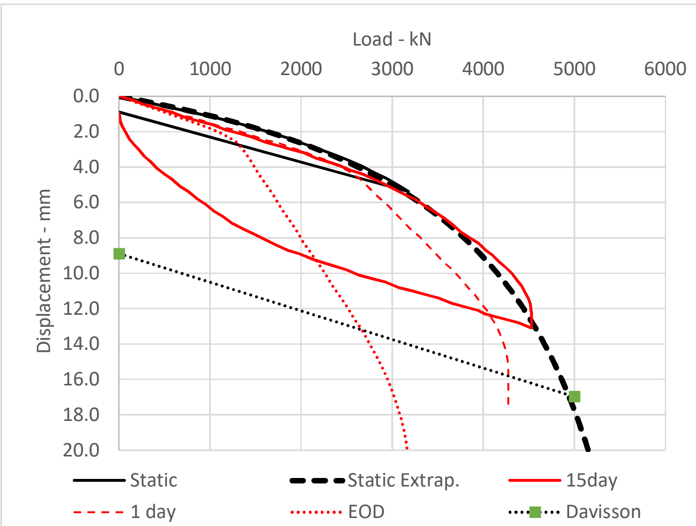

Figure 3: Extrapolation of a static load-displacement curve together with results from EOD, 1-day and 15-day restrikes. This extrapolation is not valid for cohesive soils!

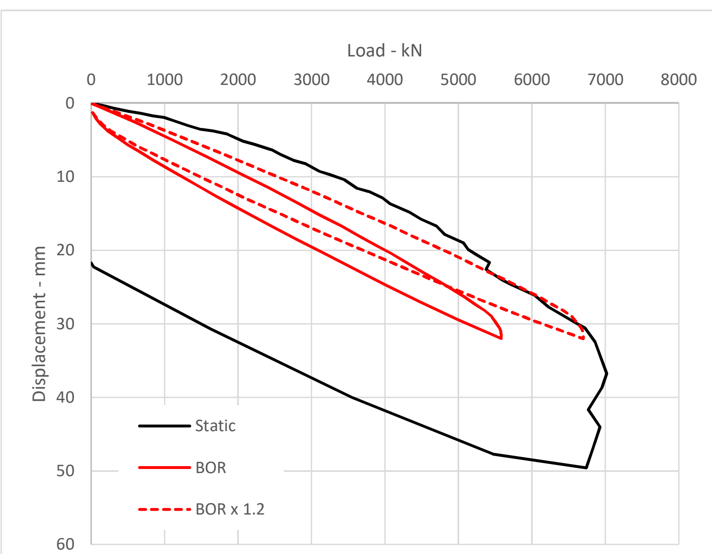

Figure 4: Example of a static load-displacement curve and of a BOR test result with insufficient energy and the same BOR curve matched to the static test with a 1.2 calibration factor applied to the load.

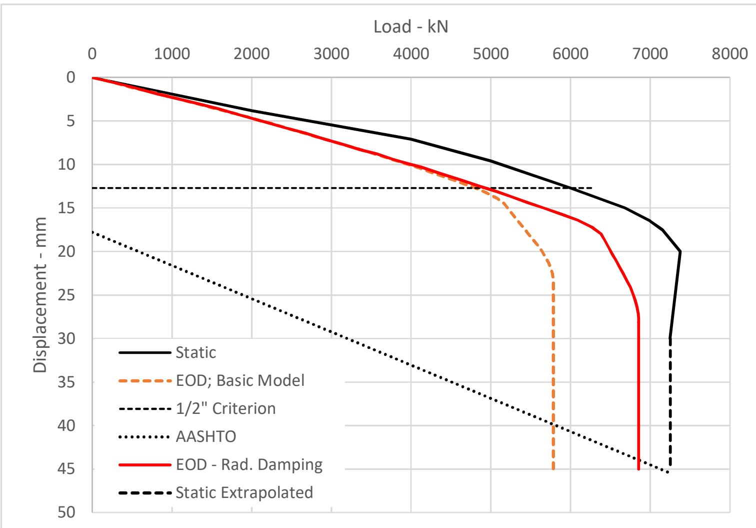

Figure 5: Static and Dynamic (EOD) load-displacement curves for a 762 mm diameter, open ended pipe pile driven into weathered and moderately hard claystone.