SOME UNCERTAINTIES IN HIGH-STRAIN DYNAMIC PILE TESTING

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ABSTRACT: High-strain dynamic pile testing is an important tool for driveability analysis, but the major objective of dynamic testing is determination of pile capacity at the time of testing. This method is a convenient tool in the pile driving industry. However, though high-strain dynamic pile testing has been used in practice for years, the actual accuracy and the area of application of this method, and also understanding the results of dynamic pile testing are vague. The paper presents discrepancies in high-strain dynamic pile testing, some uncertainty in the CAPWAP signal matching, negligible effects of soil properties on the CAPWAP results, incorrect interpretation and misleading use of testing results. It is shown the necessity to use engineering principles for verification of high-strain dynamic pile testing.

INTRODUCTION

Dynamic methods have been used in practice for about one hundred fifty years. These methods have certain advantages and some uncertainties in their application.

Determination of pile capacity by dynamic formulas is the oldest and frequently used method. There are a great number of dynamic formulas available with different degrees of reliability. Dynamic formulas have been criticized in many publications for unreliable determining pile capacity, for example, Hannigan et al. (1996).

Contemporary dynamic methods are founded on the application of the stress wave theory to piles. There are two different techniques of the use of wave equation analysis for determining pile capacity: computation of pile capacity without dynamic measurements on driven piles and a signal matching technique for computed and measured force and velocity records at the pile head.

The main goal in using wave equation analysis is to provide a better prediction of the pile capacity, as a function of pile penetration resistance, than can be obtained from

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classical dynamic formulas. The wave equation method is used for prediction of pile capacity prior to the beginning of pile driving and before restrikes. However, in most cases, computed pile capacity differs substantially from results of both static and dynamic load tests. The use of the variable damping coefficient considerably increases reliability of pile capacity predicted and gives an opportunity to compute the time-dependent pile capacity by wave equation method (Svinkin 1997; Svinkin and Woods 1998; Svinkin 2002a).

High-strain dynamic pile testing (HSDPT) includes measurements of force and velocity at the upper end of the pile during pile installation followed by a signal matching procedure. The application of the HSDPT method to driven piles has advantages in assessment of the hammer-pile-soil system and in data acquisition during pile driving and restrikes. This method provides verification of hammer performance and energy transferred to a pile, and also evaluation of driving stresses and pile integrity. HSDPT is a significant tool for driveability analysis.

Nevertheless, determination of pile capacity at the time of testing is the major objective of high-strain dynamic pile testing. This area of the HSDPT application has some uncertainties and discrepancies.

Because dynamic testing is often used to replace the static loading test (SLT), it is necessary to ascertain the adequacy of both static and dynamic tests. The paper gives insight into discrepancies of HSDPT, negligible influence of soil properties on the CAPWAP outcomes, and misapplication of the HSDPT results. Various problems such as misuse of the specified signal matching software, the soil consolidation effect in determining pile capacity by HSDPT, comparison of static and dynamic tests, impossibility of pile capacity prediction by HSDPT, overestimated capabilities of signal matching technique, incorrect use of HSDPT results and others are discussed. It is shown that HSDPT has to be used with the proper engineering basis.

DISCREPANCIES IN HIGH-STRAIN DYNAMIC PILE TESTING

HSDPT is a convenient tool in the pile driving industry and during more than thirty years, this method has become an integral part of pile capacity determination for numerous projects. The HSDPT method is based on the application of specified hardware and software. In the medium of geotechnical engineers involved in dynamic testing and analysis, there is a belief that hardware and software themselves can solve geotechnical problems of piling. Indeed, hardware and software are great tools but only tools, and these tools cannot replace engineering understanding of pile capacity determination. Formal implementation of the signal matching procedure is a common approach in dynamic pile testing, Svinkin (2002a).

HSDPT has been used in practice for years. During the past decade, about a few thousands dynamic testing were made each year around the world. However, actual accuracy of pile capacity determined by this method and areas of application of HSDPT are unknown. High-strain dynamic pile testing has good hardware and software support but obviously lacks the engineering foundation. The following are obvious discrepancies of high-strain dynamic pile testing.

First, Fellenius (1999; 2001) asserted that routine pile static loading test with measurement of only the load-movement of the pile head is meaningless and such a test is a waste of money. It is necessary to point out that dynamic testing also uses the load-movement of the pile head measured at the time of impact on the pile head. For dynamic testing, we have the same problems that we meet in static loading test. Besides, there are additional limitations because the long-term behavior can be represented only approximately over short time dynamic testing is carried out.

Second, HSDPT provides *direct* measurement of data on strain (force) and acceleration (also velocity and/or displacement) at the pile head undergone a hammer impact force. These data are utilized for *indirect* determination of pile capacity using signal matching procedure.

Third, there are several methods for interpretation of the load-movement of the pile head measured *directly* from SLT. However, there is only one way for verification of pile capacity determined *indirectly* from dynamic pile testing. This capacity is compared with the result of a static loading test found in accordance with the Davisson's criterion, Davisson (1972). The adequacy of static loading test and HSDPT has to be confirmed by proper correlation of dynamic testing results. Published data demonstrate comparison of SLT and HSDPT results without taking into account the time between tests compared, e.g. Hannigan (1990), Paikowsky and Chernauskas (1996), and others. Such a comparison is incorrect. A statistical approach for comparison of SLT and HSDPT is also unacceptable because this approach demonstrates correlation of setup factors rather than correlation of dynamic testing.

Fourth, there are cases of failure of pile foundations dynamically tested.

Fifth, ASTM D 4945 (1989) states that this test method (dynamic) is not intended to replace Test Method D 1143 (static loading test). However, in practice, high-strain dynamic pile testing replaces static loading test in violation of ASTM D 4945. It is imperative to ask a question: what is a legitimate engineering basis for determination of pile capacity by high-strain dynamic pile testing?

SIGNAL MATCHING TECHNIQUE

The CAPWAP computer program (GRL and Associates, Inc. 1995) is used for a signal matching procedure in pile driving analysis. This program is widely distributed among users of the Pile Driving Analyzer. The CAPWAP program provides determination of the boundary conditions through a trial and error process of signal matching. The boundary conditions include the pile capacity, the soil resistance distribution, and soil damping and quake factors, Hannigan (1990).

The Smith model of the hammer-pile-soil system was used as the basis for the CAPWAP program, but this model was expended in order to receive good matches over a period of time that includes the rebound portion of the force and velocity records. The following model parameters were added: the unloading quakes, the unloading limit for the negative pile capacity, the toe gap, the toe plug, and the soil dashpot at the toe, Rausche (1986).

The match quality is evaluated by summing the absolute values of the relative differences between the computed and measured pile top variables. For the purpose of match quality determination, the total analyzed time period of variables considered is subdivided into four intervals. There are the overlaps of intervals 2, 3, and 4. Therefore, values of the pile capacity affect the overall match quality number more than other soil resistance parameters, Rausche (1986).

The signal matching is a specific approximation process. It is necessary to point out that the time intervals were assigned very conditionally and two questions of the general problem of approximation have not been answered: 1) does the best approximation of a measured curve exist? and 2) is the best approximation determined uniquely? Furthermore, feedback of the pile capacity to the match quality number is an evidence of some uncertainty in determination of pile capacity by signal matching.

It is necessary to underline that in any case the pile capacity determined by HSDPT cannot be more accurate than the result of SLT. However, the pile capacity from SLT depends strongly on a method of interpretation of the load-deformation curve.

COMPARISON OF SLT AND HSDPT

According to the traditional approach, the main criterion for assessment of the pile capacity determination based on dynamic measurements is a ratio of capacities obtained by dynamic and static tests or vice versa. It is necessary to point out that the ratio of HSDPT/SLT or vice versa, taken for arbitrary time between compared tests, is not a verification of dynamic testing results. It is well known that HSDPT yields the real static capacity of piles at the time of testing, Rausche (1985). Besides, the static capacity from SLT is considered as a unique standard for assessment of dynamic testing results. Unfortunately, that is a major error. As a matter of fact, pile capacity from Static Loading Tests is a function of time and the so-called actual static capacity from SLT is not a constant value, Svinkin (1997; 2002a).

For the general case of assessment of the HSDPT reliability, the ratio of restrikes to static loading test results has been considered for various pile types, soil conditions and time of testing lumped together. Such mixture has no real meaning. It is not a verification of dynamic testing at restrikes and it is not an assessment of real set-up factor because everything is lumped together without taking into account the time between different tests. Such a comparison of the pile capacities from static loading test and dynamic testing is invalid for piles driven in soils with time-dependent properties because the soil properties at the time of dynamic testing do not correspond to the soil properties at the time of static loading test, i.e. soil consolidation between two compared tests is taken into account for the latter test and not considered for the former test. As a matter of fact such a comparison uses pile capacity values which are incompatible from the point of verification of dynamic testing (Svinkin and Woods 1998; Svinkin 2002a).

DYNAMIC TESTING RESULTS AND SOIL PROPERTIES

In addition to pile capacity, outcomes of the CAPWAP analysis are the soil resistance distribution, and the soil damping and quake factors.

Soil Damping and Quake

The Case damping coefficient is dependent on soil type in pre-driving classical wave equation analysis. The damping coefficient in sandy soil is substantially less than the same in clayey soils, but the latter is close to the damping coefficient in saturated sandy soils (sands with high damping), Svinkin (1996; 2002b). Also, the damping coefficient is a function of time after pile installation. For post-driving analyses, additional parameters such as toe gap and plug, radiation damping, etc. are used to describe the soil behavior. In CAPWAP analyses the damping coefficients are used together with other soil parameters to receive the best match of measured and computed velocity or force curves. If several parameters are arbitrarily changed in order to obtain the best match of two curves, it is difficult to find a relationship between the damping coefficients and a soil type. As a result of signal matching procedure, the damping coefficients do not reflect soil damping in CAPWAP analyses.

A similar situation is observed on a quake. Authier and Fellenius (1981) stated that the actual quake value used is not important when the purpose of the CAPWAP analysis is to determine the mobilized static capacity of the pile, and even if the hammer energy is not sufficient to mobilize the full ultimate soil resistance. It is a mystery of the CAPWAP wave equation.

Soil Resistance Distribution

There is an attempt to identify the side-friction properties of shafts by correlating HSDPT information with static loading test data, Hertlein (2003). This approach is wrong and can yield false results because of several reasons.

First, it is sensible to use information from dynamic testing and the CAPWAP analysis if the pile capacity determined by HSDPT is correct. Otherwise it does not make sense to use any data from HSDPT. Unfortunately, accuracy of dynamic pile testing is unknown and at present there is no condition for compiling side-friction data from SLT/HSDPT comparison.

Second, suppose we have a good coincidence of static and dynamic test results. The next step should be verification of the soil resistance distributed along a pile shaft. For such verification, it is necessary to have telltale and strain gage data from the static loading test. Otherwise assessment of side-friction data cannot be made.

Third, it is important to point out that the soil resistance distribution along the pile shaft is not so much the soil resistance but it is the result of the application of signal matching technique to measured and calculated curves. This situation is similar to assessment of the damping coefficients from the CAPWAP analysis. It is not clear how the soil resistance distribution obtained from the CAPWAP analysis can represent the actual soil resistance distribution along the pile shaft.

INCORRECT INTERPRETATION AND USE OF HSDPT RESULTS

There are phrases in some publications and advertisements such as "Evaluating static pile capacity by dynamic testing has become routine procedure in contemporary foundation engineering practice worldwide" or "High strain dynamic pile testing is well-established and accepted foundation testing technique in use around the world". These statements are incorrect and they confuse the readers. The application of hardware and software is established, but determination of pile capacity is not established at all because the accuracy and the area of application of HSDPT are unknown though

HSDPT is used in practice more than thirty years. There is the principle difference between the accuracy of the high-strain dynamic testing and the accuracy of determining pile capacity based on the results of dynamic testing. It is necessary to point out that any interpretation of the HSDPT results cannot replace unknown accuracy of pile capacity determined by HSDPT. This discrepancy has demonstrated a unique dangerous situation in the pile driving industry.

Furthermore, there are examples of incorrect and misleading interpretation and use of the HSDPT results.

Overestimated CAPWAP Capabilities

Superposition of dynamic testing results from the end of initial driving (EOID) and beginning of restrike (BOR) is used for determination of pile capacity when the hammer energy is insufficient to fully mobilize the soil resistance at restrike (Hussein et al. 2002). A tested 762 mm square prestressed concrete pile with 457 mm circular void and 1.2 m solid ends was driven in fine to coarse sand underlain by weathered limestone in which a lower part of the pile was embedded. Groundwater was encountered at the top of a sandy layer. The pile capacity at BOR was estimated by compounding the resistance distribution from two different HSDPT using the highest values of the pile end bearing resistance from EOID and the shaft resistance from BOR. It seems that such a procedure overestimates capabilities of signal matching technique.

Table 1. Pile capacity at EOID and first restrikes

Pile			Static Capacity from CAPWAP						Decrease of Toe Capacity %
			EOID			BOR			
No.	Size (mm)	Embdt (m)	Total (kN)	Skin (kN)	Toe (kN)	Total (kN)	Skin (kN)	Toe (kN)	
1 (12)	457	19.7	913	334	579	1145	668	477	18
2 (13)	457	22.9	1907	757	1140	2176	1528	650	43
3 (14)	610	19.5	1513	695	811	1368	1230	138	83
4 (15)	610	22.9	1986	566	1421	2691	1457	1234	11
5 (16)	915	22.3	2949	1310	1639	4210	2807	1403	14

It is necessary to point out that the pile-soil system has various soil stiffness, damping and soil mass involved in vibrations at EOID and BOR. The pile end bearing resistance at BOR can be less, equal or more than the appropriate resistance at EOID. Also, it is known that identical tested piles at the same site can have completely different shaft/bearing resistance at EOID and BOR. Superposition of dynamic testing results has no engineering confirmation. By way of illustration, results of dynamic testing of five prestressed concrete piles are shown in Table 1: two 457 mm square piles, two 610 mm square piles with 267 mm circular void and solid ends, and one 915 mm square pile with 570 mm circular void and solid ends, Svinkin et al. (1994). Pile number in parentheses is taken from FHWA database. These piles were driven on a site with predominantly silty sands. The water table was at a depth of 0.6 m from ground surface. It can be seen in Table 1 that the end bearing resistance for all five piles at BOR was less than similar resistance at EOID in the 11-83 % range. Furthermore, regarding the pile described by Hussein et al. (2002), it is necessary to point out that the end bearing resistance of a pile embedded in weathered limestone usually substantially decreases after pile installation.

Incorrect Comparison of Dynamic and Static Tests

A ratio of HSDPT/SLT or vice versa, taken for arbitrary time between compared tests, is considered as verification of dynamic testing results. However, such comparison is nonsense, Svinkin and Woods (1998), Svinkin (1998, 2002a). In the case of several SLTs made on one pile, it is not clear what SLT should be taken for comparison. As a matter of fact such an approach can yield whatever results. Unfortunately, this incorrect and misleading approach was used as the basis of rewriting AASHTO Deep Foundation Specifications (Paikowsky and Stenersen 2000; Paikowsky 2003). It seems these authors missed the forest for the trees. The authors' erroneous assessment of pile capacity is dangerous for design and construction of pile foundations.

Misleading Prediction of Pile Capacity

In some publications, dynamic testing is used for a capacity prediction without prior knowledge of the static loading test, *e.g.* Goble (2000), Holeyman et al. (2000), Zhang et al. (2001) and others. This is a misleading interpretation of HSDPT which does not have any connection with Class A type prediction defined by Lambe (1973). No in-situ pile test can predict pile capacity as a function of time after pile installation. Only static analysis and wave equation analysis without pile testing are truly predictive methods.

Zhang et al. (2001) evaluated the reliability of axially loaded driven pile groups considering pile capacities determined with HSDPT as predicted values. As a matter of fact the authors made wrong interpretation of pile testing results. If database is wrong it is impossible to prove a new authors' method.

VERIFICATION OF HIGH-STRAIN DYNAMIC PILE TESTING

There is the only way for verification of the pile capacity determined by high-strain dynamic pile testing - a comparison of results obtained from SLT and HSDPT. Criteria should be established for correct comparison of in-situ tests made at different times after EOID. An attempt to establish new criteria for comparison of SLT and HSDPT was made by Svinkin (2002a).

The adequacy of SLT and HSDPT has to be confirmed by proper correlation of the HSDPT method. Due to the consolidation phenomenon in soils, comparison of SLT and HSDPT can be made only for tests performed immediately one after another. In practice, it is sometimes difficult to make two immediately successive tests, but nonetheless the time difference between both comparable tests should not exceed 1-2 days during which soil setup changes only slightly.

It is necessary to point out that a study of data used for comparison of SLT and HSDPT (Svinkin 2002a) has revealed the major role of the elapsed time after pile installation and the set-up rate per day in affecting the results of compared tests. The effect of a time between two compared tests depends on these factors. During soil consolidation around a pile, SLT and HSDPT should be made in short succession. However, after completion of soil consolidation process, the time factor is no longer important for comparison purposes.

Verification of pile capacity determined by HSDPT was made for 39 different piles in various soil conditions. The time differences between static and dynamic tests were 1-2 days for all considered piles, but the time elapsed after EOID was diverse. An acceptable margin of error was determined in accordance with the set-up rate. Compared capacities had a good agreement within the acceptable margin of error for 28 piles. Calculated capacities for five piles had errors from 20 % to 25 %. The worst results were obtained in the CAPWAP analysis of six piles, which were analyzed with errors between 30-54 %.

Analysis of 39 cases revealed substantial errors in determination of the pile capacity for 6 piles that is about 15 % of the total number of considered piles. However, it is important to recognize such cases in advance. Besides formal implementation of signal matching procedure, it is necessary to have knowledge about the accuracy and the area of application of HSDPT.

A comparison of static and dynamic test results is a complicated problem because results of HSDPT depend on a number of various factors such as the time between compared tests, the time after pile installation, the set-up rate, the sequence of tests, the pile type, the blow count, the type of signal matching technique, the quality of dynamic records and the soil conditions (Svinkin 2002a). Effects of various factors on the HSDPT results are big areas for future research.

It is necessary to demystify dynamic testing methods and their applications in foundation design and construction, Holloway (2001). The HSDPT method deserves to be explicitly determined and properly used.

CONCLUSIONS

Dynamic measurements of force and velocity at the upper end of the pile during pile driving, followed by a signal matching procedure, is the most common method for dynamic determination of pile capacity. HSDPT is a convenient tool in the pile driving industry. However, though HSDPT has been used in practice for years, accuracy and application of HSDPT have some uncertainties and discrepancies.

HSDPT provides indirect determination of pile capacity under limitations because the long-term behavior can be represented only approximately over short time dynamic testing is carried out. Moreover, a legitimate engineering basis for determination of pile capacity by HSDPT is vague.

The CAPWAP analysis, as a signal matching procedure, has no answer regarding existing and uniqueness of the best approximation of a measured curve. Feedback of the pile capacity to the match quality number is an evidence of some uncertainty in determination of pile capacity by signal matching.

For the general case of comparison of static and dynamic test results, soil consolidation between two compared tests is taken into account for the latter test and not considered for the former test. As a matter of fact, such a comparison uses pile capacity values which are incompatible from the point of verification of HSDPT.

Soil damping and quake and also the soil resistance distribution along the pile shaft are not so much soil properties determined in the CAPWAP analysis, but they are the results of the application of signal matching technique to measured and calculated curves. Thus, the actual quake value used is not important when the purpose of the CAPWAP analysis is to determine the mobilized static capacity of the pile

There are numerous examples of incorrect interpretation and misleading use of HSDPT results.

An attempt was made to establish new criteria for comparison of SLT and HSDPT. A comparison of static and dynamic test results is a complicated problem because results of HSDPT depend on a number of various factors such as the time between compared tests, the time after pile installation, the set-up rate, the sequence of tests, the pile type, the blow counts, the type of signal matching technique, the quality of dynamic records and the soil conditions.

The main objective of this study is to bring attention to the engineering basis of dynamic testing in order to demystify HSDPT. It is imperative to clarify the accuracy and the area of application of HSDPT for engineers involved in dynamic testing and for a number of geotechnical engineers who do not recognize the pile capacity determined by HSDPT.

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