Engineering evaluation of static pile capacity by dynamic methods

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ABSTRACT: During the past three decades, dynamic methods became widespread technique for evaluation of the static pile capacity at the time of testing. High-strain dynamic pile testing and Statnamic tests have a substantial advantage of much lower cost and time. Determination of pile capacity from field testing is the primary application of the dynamic methods, but the accuracy and the area of utilization (soil conditions and pile type) of these methods are vague. Different hardware and software produce substantially diverse pile capacities. Hardware and software cannot resolve themselves the engineering problem of pile capacity determination by dynamic methods. Uncertainties are available in signal matching technique and comparison of the results of static and dynamic tests. Quality of dynamic measurements together with the software features and the engineering factors affect pile capacity obtained by dynamic testing. A simple practical approach is proposed for a proper choice of dynamic pile test at a specified construction site.

1 INTRODUCTION

It is important to know the actual pile capacity for rational design and reliable construction of pile foundations. Static analysis is generally used for prediction of the pile capacity as the long term capacity after soil consolidation around the pile is complete.

A static load test (SLT) is traditionally performed in the field for verification of the real pile capacity. Unfortunately, SLT is expensive and such testing requires much time. Therefore, various projects commonly can afford only one SLT. Evaluation of the static pile capacity in the field by dynamic testing has the advantage in saving of cost and time. It also provides the possibility of testing some piles to obtain more information about variation of pile capacity at a site and verification of pile driveability.

Dynamic in-situ testing or so-called high strain dynamic pile testing (HSDPT) is based on the application of stress wave theory to piles and comprises signal matching technique for computed and measured force and velocity at the pile head. There are three prevalent signal matching programs: CAPWAP, TNOWAVE, and SIMBAT. These computer programs were made by three companies. They use similar dynamic measurements at the pile head, but the programs' procedures employ different approaches in signal matching analysis. These dynamic methods use short-duration impact loads for pile testing. Dynamic loads are also utilized in Statnamic test. According to Justason and Fellenius (2001), Statnamic test is long-duration impulsive test which is different from procedures employed for both static and dynamic load tests. Different dynamic methods are used independently of each others. These methods are not adequate, but all of them are applied without restrictions.

HSDPT and Statnamic tests are frequently used to replace SLT. It is a natural question what the adequacy of dynamic and static testing is because these tests have a different nature. The main criterion for assessment of pile capacity from dynamic testing is the ratio of capacities obtained by dynamic and static tests or vice versa. In assessment of the accuracy of dynamic tests, the ratio of pile capacities from restrikes to SLT has been considered for various pile types and lengths, soil conditions and time intervals between comparable tests lumped together. As a matter of fact such a comparison is not a verification of dynamic pile testing (Svinkin and Woods 1998, Svinkin 2002).

At the time of design and construction of pile foundations, it is important to know what HSDPT or Statnamic test would be appropriate for specified soil conditions and pile types. In spite of good and bad results in determination of pile capacity by dynamic methods, the existing publications recommend the use of HSDPT and Statnamic test at any construction site.

It is very doubtful because any great method has the certain area of applications and some restrictions.

The goal of this paper is the use of the advantages of HSDPT and Statnamic tests in savings of cost and time with no compromising in determination of static pile capacity.

2 COMPARISONS OF DIFFERENT DYNAMIC METHODS

The application of diverse dynamic methods at the same construction site is very seldom. There are only few such publications. Briaud et al. (2000) have presented an interesting study of static capacity assessment by dynamic methods for three bored piles. This study has obvious advantages in comparison between the results of dynamic and static pile testing because the study presented comprehensive research on determining pile capacity of bored piles by dynamic methods and the research study provides a rare opportunity to compare the pile capacities determined for each of three piles by four companies specialized in the application of dynamic methods to piles: GRL and Associates, Inc. (1991), TNO Building and Construction Research (1991), ESSI – Testconsult (1991), and Berminghammer Corporation (1991). Dynamic pile testing was performed without knowledge of the results of SLT. Additional references to static, dynamic and Statnamic pile testing are available in Briaud et al. (2000).

2.1 Site, Soil and Pile Description

The sand and clay sites chosen for pile testing are the two National Geotechnical Experimentation Sites at Texas A&M University. The top layers, 12.5 m at the sand site and 6.5 m at the clay site, are old river deposits, while the hard clay underlying both sites is old marine shale. The sand is medium-dense silty sand, and the clay is very stiff plastic clay. The soil properties at the site can be found in Briaud et al. (2000).

All three piles were planned to be 0.915 m in diameter and varied in length between about 10.7 and 11.7 m. Pile 2 at the sand site was purposely built with defects: mud cake of about 15 mm thick on the side wall, a soft bottom, and a concrete contamination at 5.3 m below the pile head. One more unplanned defect occurred at 5 m below the pile head and resulted in a 45% reduction in area. Pile 4 at the sand site was planned as a pile without defects, but during construction, caving of the side walls created an unplanned bulging defect resulting in a 10% average increase in diameter between 1.2 and 7.5 m below the pile head. Pile 7 at the clay site was planned and constructed as a perfect pile.

The construction schedule and the testing sequence for each pile are presented in Table 1. The piles were constructed by following good drilling and construction practices including desanding of the drilling mud and minimizing slurry stagnation between the end of drilling and the beginning of concreting. Pile 2 at the sand site was an exception. The actual pile shapes are available in Briaud et al. (2000).

2.2 Results of Static, Dynamic and Statnamic Pile Testing

There are various interpretations of defining of the pile capacity from static load tests. In Briaud et al. (2000), pile capacities from the load-deformation curves were defined according to the Davisson criterion ($D/120$ + 3.8 mm + PL/AE), and the $D/10$ criterion ($D/10 + PL/AE$). The designations are as follows: D is the diameter of the pile, 3.8 mm is the compression of the pile, P is the load applied, L is the length of the pile, A is the cross section area of the pile, and E is the modulus of the pile material. The values of pile capacities determined from static load tests are shown in Tables 2 for three piles tested.

After static load tests, Statnamic tests were made in 6 days for pile 2, 5 days for Pile 4, and 4 days for Pile 7. Then after Statnamic tests, drop weight tests were performed in 2 days for Pile 2, 2 days for Pile 4, and 1 day for Pile 7. SLT 2 for Pile 2 was made in 2 days after dynamic testing. Three companies, which performed HSDPT, used similar experimental technique in measurement of force-time signals from the strain gages, acceleration-time signals from the accelerometers, and permanent displacements at the pile head for each hammer blow. However, three companies used significantly different software for signal matching of experimental data to determine at the time of testing, not predict, the static capacity and the load-settlement curve. Other software is used for analysis of the outcomes of Statnamic tests. Load-settlement curves obtained in all static and dynamic tests are presented in Figure 1. An example of a complete load-settlement curve from a static load test is displayed in Figure 2 for Pile 4. The results of dynamic testing and errors in determination of the pile capacity by HSDPT and Statnamic tests are shown in Tables 2 as well.

2.3 Accuracy of Static Pile Capacity Determined by HSDPT and Statnamic Test

It is important to clarify what capacity values should be compared. On the one hand Briaud et al. (2000) have preferred the $D/10$ criterion to the Davisson one because the former yields the pile capacity about 1.4 times higher and an average pile head penetration about 7.8 times higher. On the other hand Fellenius (1980) has stated that the Davisson limit has widespread use in conjunction with the wave equation analysis of driven piles.

It seems that the range between the Davisson and D/10 criteria would be appropriate for correct evaluation of the static pile capacity determined from HSDPT and Statnamic tests. For Pile 2, a comparison was made with the result of SLT 2 because it is obvious that planned and unplanned defects decreased the capacity of Pile 2 at the time of SLT 1. For CAPWAP and TNOWAVE software, determination of pile capacity is based on a single blow, but an average of two blows is sometimes used. SIMBAT software employs a series of blows with varying energy to determine pile capacity. Statnamic test uses one blow for determination of pile capacity.

Table 1. Construction and Testing Schedule. The Table was modified from Briaud et al. (2000).

Pile Number	Soil	Drilling	Concreting	Static Load Test 1	Statnamic test	Drop Weight Test	Static Load Test 2
2	sand	11-16-1990	11-19-1990	11-28-1990	12-4-1990	12-6-1990	12-8-1990
4	sand	11-19-1990	11-19-1990	11-30-1990	12-5-1990	12-7-1990	-
7	clay	11-15-1990	11-15-1990	12-3-1990	12-7-1990	12-8-1990	-

Table 2. Comparison of Static Pile Capacity Determined by Static and Dynamic Tests. The Table was modified from Svinkin (2011).

Pile No.	Pile Capacity Criterion	SLT Static Capacity kN	CAPWAP Static Capacity kN	CAPWAP Error %	TNOWAVE Static Capacity kN	TNOWAVE Error %	SIMBAT Static Capacity kN	SIMBAT Error %	STATNAMIC Static Capacity kN	STATNAMIC Error %
2	*D*/10	1068	1300	+22	4900	+359	2100	+97	3600*	+237
STL 1	Davisson	472	1300	+175	4900	+938	2100	+345	2400**	+408
2	*D*/10	1602	1300	-19	4900	+206	2100	+31	3600*	+125
STL 2	Davisson	1112	1300	+17	4900	+341	2100	+89	2400**	+116
4	*D*/10	4004	2900	-28	5800	+45	2300	-43	4900*	+22
	Davisson	2892	2900	0	5800	+101	2300	-20	4490**	+55
7	*D*/10	3025	4250	+40	2850	-6	2500	-17	3600*	+19
	Davisson	2491	4250	+71	2850	+14	2500	0	3150**	+26

* - Maximum load on static curve determined by Statnamic test

** - Static capacity from the approximate method of Statnamic test interpretation (Justason and Fellenius 2001).

Table 3. Comparison of Static Pile Capacity Determined by HSDPT and Statnamic Tests.

Pile No.	CAPWAP Static Capacity kN	TNOWAVE Static Capacity kN	TNOWAVE Error %	SIMBAT Static Capacity kN	SIMBAT Error %	STATNAMIC Static Capacity kN	STATNAMIC Error %
2	1300	4900	-277	2100	-62	2400	-85
4	2900	5800	-100	2300	+21	4490	-55
7	4250	2850	+33	2500	+41	3150	+26

Similar measurements of force and velocity were made at the pile head for three dynamic methods. Load and displacement were measured during implementation of Statnamic tests. Different software was applied for each method. A comparison between all dynamic tests shows significant discrepancies in outcomes of these methods in Table 3 and Figure 3. The results of three dynamic tests were compared with CAPWAP results, but such comparison can be made with any other test. In comparison with CAPWAP outcomes, HSDPT with TNOWAVE and SIMBAT software and also Statnamic tests yielded variances of pile capacity with errors between -277% and +33%, -62% and +41%, and -85% and +26%, respectively. There is no consistency in the test results.

The accuracy of pile capacity determination in the time of testing by four dynamic methods was evaluated on the basis of their comparison with the results of static load tests (Table 4 and Figure 3). It can be seen that CAPWAP software provided good results in sand for Pile 2 (+17% & -19%) and Pile 4 (0% & -28%) but substantially overestimated capacity in clay for Pile 7 (+71% & +40%), TNOWAVE software largely overestimated capacity in sand for Pile 2 (+341% & +206%) and Pile 4 (+101% & +45%) but provided good results in clay for Pile 7 (+14% & -6%), SIMBAT software substantially overestimated capacity in sand for Pile 2 (+89% & +31%) and substantially underestimated one at the same site for Pile 4 (-20% & -43%) but provided good results in clay for Pile 7 (0% & -17%). Statnamic test substantially overestimated capacity in sand for Pile 2 (+116% & +125%) and overestimated one at the same site for Pile 4 (+55% & +22%) but provided relatively good results in clay for Pile 7 (+19% & +26%). The effect of the time elapsed between compared tests was analyzed by Svinkin (2011).

Table 4. Evaluation of Static Pile Capacity Determined by Dynamic Methods. The Table was modified from Svinkin (2011).

Dynamic Methods	Sand Piles 2 & 4 Error (%)	Clay Pile 7 Error (%)
CAPWAP	Good results between Davisson and D/10 for Pile 2: +17 & -19 for Pile 4: 0 & -28	Overestimation +71 & +40
TNOWAVE	Overestimation for Pile 2: +341 & +206 for Pile 4: +101 & +45	Good results between Davisson and D/10 +14 & -6
SIMBAT	Overestimation for Pile 2: +89 & +31 Underestimation for Pile 4: -20 & -43	Good results between Davisson and D/10 0 & -17
STATNAMIC	Overestimation for Pile 2: +116 & +125 for Pile 4: +55 & +22	Good results +19 and +26

It can be seen that comparative testing and analysis of different dynamic testing technique and software yield the results of the best conditions for application of diverse dynamic methods to piles.

Similar pile tests were accomplished at two sites in California, but static load test results were known to companies which performed HSDPT before dynamic pile testing was made, Baker et al. (1993). A comparison of dynamic and static test results obtained for all of the tests yielded the average value of the three methods as overestimation of 61 % and underestimation of 41 %.

3 COMMENTS ON PILE TESTING BY SHORT AND LONG-DURATION IMPACT LOADS

3.1 High Strain Dynamic Pile Testing

Svinkin (2004) paid attention to the signal matching procedure as a specific approximation process and pointed 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? 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.

A demonstrated case histories show the results of the application of different hardware and software for dynamic testing of the same piles. For the conditions at the particular testing sites, values of the pile capacity in Table 4 were various: CAPWAP yielded good results in sand and substantially overestimated pile capacity in clay, TNOWAVE yielded good results in clay and largely overestimated pile capacity in sand, SIMBAT yielded good results in clay and substantially overestimated and underestimated pile capacity in sand.

It is difficult to give a general preference to any one of three methods. However, for determination of suitable values of the pile capacity, it was reasonable to use HSDPT with CAPWAP at the sand site and apply HSDPT with TNOWAVE and SIMBAT or Statnamic test at the clay site. Nevertheless, it is possible to receive opposite results for different soil stratifications and pile types: dynamic pile testing with CAPWAP may yield good results at clay sites and dynamic pile testing with TNOWAVE and SIMBAT or Statnamic test may yield good results at sand sites.

There are some uncertainties in applications of HSDPT to piles because the complex of essential different qualities is available in dynamic testing in comparison with SLT. Dynamic pile testing at sites with variant soil conditions and pile types could yield the different accuracy in evaluation of the pile capacity.

Poulos (2000) remarketed the pros and cons of dynamic load test. On the one hand a number of comparisons with the results of static load test performed on driven and bored piles have indicated the ability of dynamic pile testing to produce meaningful estimates of the load-settlement behavior of piles under static conditions, specifically at restrikes. On the other hand despite its widespread use, the dynamic pile testing has a number of limitations, including the fact that the load-settlement curve estimated from the test is not unique, but is a best-fit estimate. For over-estimated results, the dynamic testing may give a reasonable assessment of the pile head stiffness at the design load. However, it may be expected to be increasingly inaccurate as the load level approaches the ultimate value.

Svinkin (2004, 2011) demonstrated some uncertainties, problems and pitfalls in high-strain dynamic pile testing. For example, the static load test long-term behaviour can be represented only approximately over short time dynamic testing is carried out; dynamic testing provides indirect determination of pile capacity; only the Davisson criterion is used for verification of the results of dynamic testing; 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 hammer energy, 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, etc. Published data demonstrate comparison of SLT and HSDPT results without taking into account factors mentioned above.

It is necessary to point out that soil parameters are very conditional in the idealized pile-soil system considered for a signal matching procedure. For instance, the coefficient of soil damping in signal matching analysis is not the actual soil damping parameter. This coefficient changes for receiving the best fit of signal marching curves. Even in pre-driving wave equation analysis, the variable damping coefficient obtained for the best fit of predicted and measured pile capacity depends on the ratio of pile capacity to blow count per 0.3 m of pile penetration into the ground (Svinkin 2010).

Research is needed to assess engineering applications of different programs for various soil conditions and pile types. Dynamic methods were initiated long time ago in the middle of sixties of the last century. Substantial research was made for the development of hardware and software, but a little was done for engineering application of these methods.

For the proper use of HSDPT, it is essential to know the values of impact loads applied to piles during dynamic testing. Though HSDPT is used for more than forty years, there are no requirements in existing standards regarding such loads except the common and indistinct condition that the pile capacity be fully mobilized at the time of dynamic pile testing. Wrong results of HSDPT are often explained by insufficient hammer energy. Such a helpless explanation only disgraces dynamic pile testing.

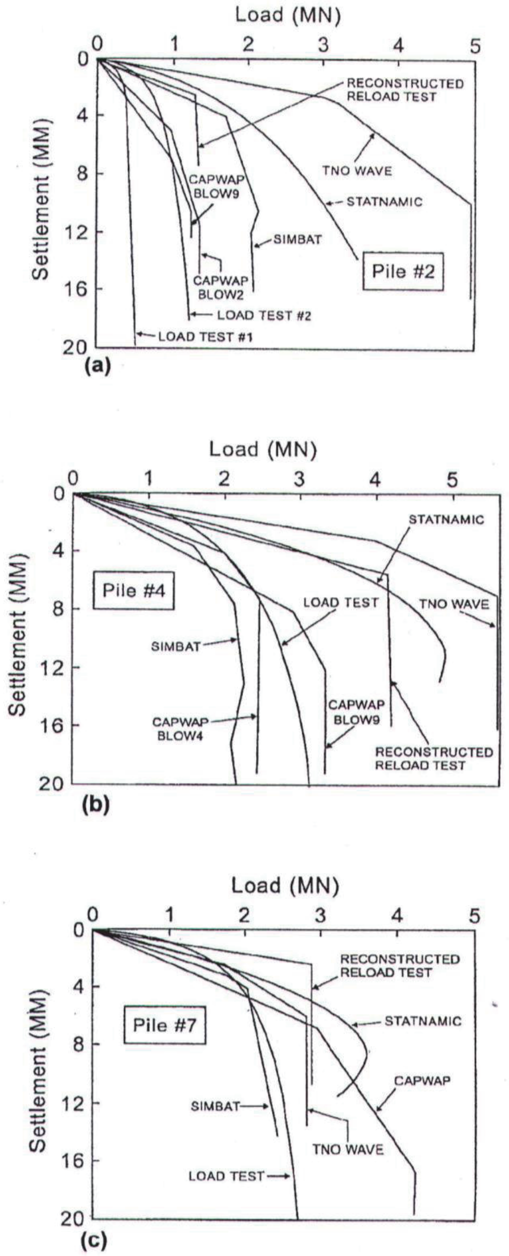

Figure 1. Comparison between measured and determined load-settlement curves: (a) Pile 2; (b) Pile 4; (c) Pile 7. Data were adopted and modified from Briaud et al. (2000).

Because the suitable energy is very important for performance of dynamic testing, it is essential to know the values of impact loads applied to piles during dynamic testing to mobilize the pile capacity.

Svinkin and Woods (2009) proposed a simplified approach to calculate short-duration impact loads for HSDPT. An equation presents the impulse for dynamic pile testing as a function of the pile capacity, P_u, and the dominant circular natural frequency, ω, of the pile-soil system

$$I = \frac{P_u}{\omega} \tag{1}$$

Substituting variables for the dominant frequency of the pile-soil system gives the equation of the impulse for dynamic pile testing

$$I = \frac{P_u L}{k\xi c} \tag{2}$$

where ξ is the adjustment factor (Table 5); η is the pile weight to ram weight ratio (Weaver et al. 1990); c is the velocity of wave propagation in the pile; L is the pile length; k is the coefficient which is equal to 0.4 for concrete piles at the end of driving (EOD), 0.5 for concrete piles at the beginning of restrike (BOR), 0.95 for steel pile at EOD, 1.15 for steel piles at BOR, 0.7 for timber piles at BOR.

It seems that this new procedure is a step toward increasing the engineering understanding of HSDPT.

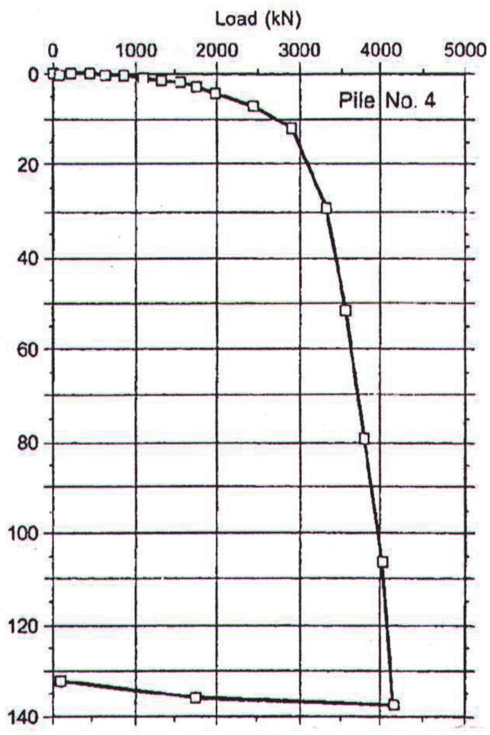

Figure 2. Load-settlement curve for static load test of Pile 4. Data were adopted and modified from Briaud et al. (2000).

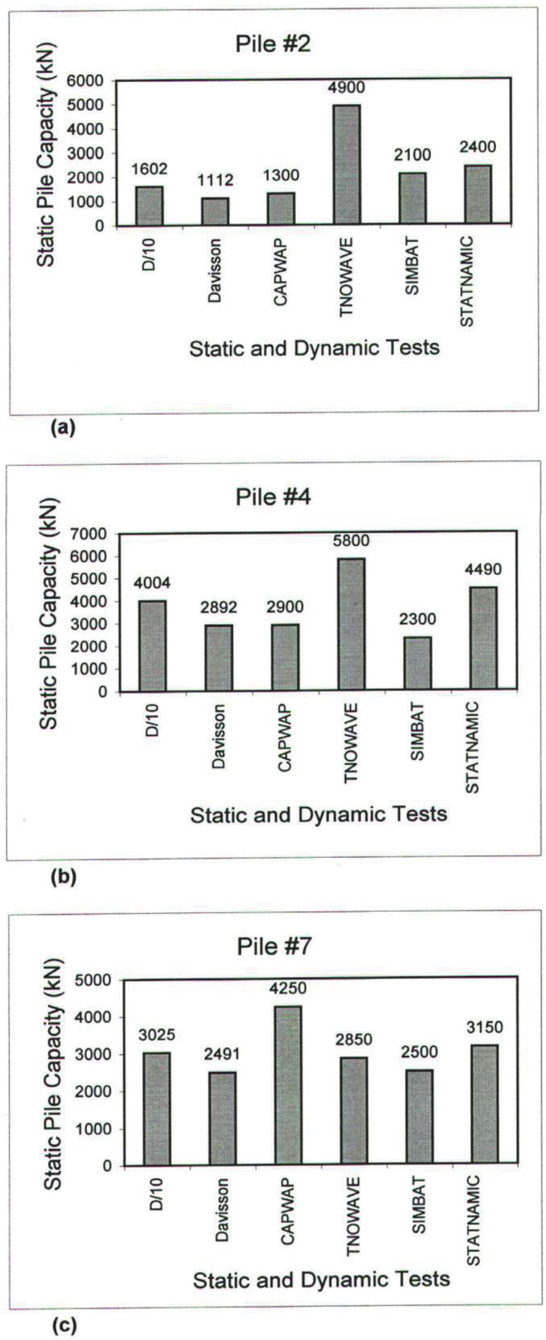

Figure 3. Comparison of static pile capacity determined by static and dynamic tests: (a) Pile 2; (b) Pile 4; (c) Pile 7.

3.2 Statnamic Testing

Demonstrated case histories show the results of application of Statnamic test for determination of pile capacity at the time of testing (Table 4). Statnamic test substantially overestimated capacity in sand for Pile 2 and overestimated one for Pile 4 but provided relatively good results in clay for Pile 7.

Consequently, it was reasonable to use Statnamic test at the clay site. However, Justason et al. (1998) reported the results of Statnamic load testing on a 600 mm square pre-stressed concrete pile installed on a site with the soil comprised medium to dense, poorly graded sand with some silty sand. The Statnamic test produced the correct pile capacity which was slightly less (-14 %) in comparison with the SLT results.

Table 5. Adjustment factor ξ for calculating.

η	ξ	η	ξ
0.01	0.10	2.00	1.08
0.10	0.32	3.00	1.20
0.30	0.52	4.00	1.27
0.50	0.65	5.00	1.32
0.70	0.75	10.00	1.42
0.90	0.82	20.00	1.52
1.00	0.86	100.00	1.57
1.50	0.98	∞	π/2

Poulos (2000) indicated a number of advantages of Statnamic test over other test types: the test is quick; high loading capacity is available; the load is accurately centered; the test is quasi-static and does not overstress the test pile; etc. Potential shortcomings of the test include: certain assumption need to be made in the interpretation of the test; it cannot provide information on time-dependant settlements of movements; etc.

From a practical point, it is unknown in advance the accuracy of determination of pile capacity by Statnamic test.

3.3 A New Rapid Pile Load Test

Matsumoto et al. (2004) developed a new version of dynamic pile testing as a rapid pile load test with the use a falling mass attached with spring and damper. This test has a good perspective of widespread application, but is it necessary to determine the area of test application as well (soil conditions and pile types).

4 A CHOICE OF THE CORRECT DYNAMIC METHOD FOR CONSTRUCTION SITES

Fellenius (1995) stated, "There are many dynamic tests, where the results evaluated from the analysis differ from what was found in the static test. The static test is not always correctly performed and/or interpreted, but when it is and the interpretations yet are too far apart, the reason is more often in inadequate analysis of the dynamic test, rather than that the dynamic test and/or analysis would be in error or not suitable for the situation."

This general suitability confirmation of dynamic pile testing is not applicable for the demonstrated case histories because various dynamic tests were applied for the same piles with high quality of test implementation made by manufactures of hardware and software. Interpretation of the SLT outcomes was the same for all methods. However, the results of dynamic tests were substantially different. It is necessary to point out that the found accuracy of dynamic pile testing is correct only for the presented test sites. Diverse results may be obtained at other sites.

It was shown for considered case histories that determination of the pile capacity by HSDPT with CAPWAP, TNOWAVE, SIMBAT software and Statnamic tests yielded variances of pile capacity with errors in the -277% and +41% range. There is no consistency in the test results. It should be no blames for professional performance of HSDPT and Statnamic tests. The differences in outcomes of these methods can be explained by the application of diverse signal-matching techniques. It is not clear how hardware and software of HSDPT and Statnamic test may affect the signal-matching results depending on soil conditions and pile types. So far, this problem has not been resolved yet.

Each great method has the area of its application and some restrictions. However, dynamic methods are applied for any soil conditions and pile types with no restrictions. Such application of dynamic methods may provide misleading results. Nevertheless, HSDPT and Statnamic tests have the substantial advantage in saving of cost and time that is important for the pile driving industry.

The research study presented in Briaud et al. (2000) demonstrates obvious benefits of pile testing by several dynamic methods. Comparative dynamic pile testing is a reasonable way to find the best fitting dynamic testing technique for the specified soil conditions and pile types. To choose the appropriate dynamic method for a specified construction site with no compromising in determination of the static pile capacity at the time of testing, it is necessary to utilize two or three dynamic methods during carrying out of a pile testing program at the site and compare obtained outcomes with the results of SLT. Such a comparative testing will be a real competition between different dynamic testing techniques.

It seems that the range between the Davisson and D/10 criteria for SLT results would be proper for correct evaluation of the static pile capacity determined from HSDPT and Statnamic tests.

5 CONCLUSIONS

A static load test is traditionally performed in the field for verification of the actual pile capacity. Properly performed conventional static load test can yield the correct pile capacity in certain interpretation. It is well known that there are many substantial differences between static and dynamic tests. Therefore, unlike of static load test, properly performed dynamic testing not necessary bring in correct values of the pile capacity. The found accuracy of dynamic pile testing is correct only for the sites where testing was performed. Dynamic pile testing at other sites with variant soil conditions and pile types could yield other outcomes.

Nevertheless, HSDPT and Statnamic tests have a substantial advantage in saving of cost and time. For practical applications, it is imperative to know in advance the accuracy of HSDPT and Statnamic test depending on the pile type and soil conditions, but there is no procedure for receiving of the answer to such concerns. Therefore, to make a correct choice of the appropriate dynamic method for determination of the pile capacity at a specified construction site, it is necessary to utilize two or three dynamic methods during realization of a pile testing program at the site and compare obtained outcomes with the results of SLT.

The range between the Davisson and D/10 criteria for SLT results would be suitable for correct evaluation of the static pile capacity determined from HSDPT and Statnamic tests.

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