Dynamic loads for high-strain dynamic pile testing

Des charges dynamiques pour épreuves de piles dynamiques de haute-tension

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ABSTRACT

The main purpose of high strain dynamic pile testing is the determination of the pile capacity at the time of testing. It is important to know the magnitude of the applied dynamic load in high-strain testing. Nevertheless, there are no widely accepted requirements for producing or measuring the load except that the pile capacity must be fully mobilized during dynamic testing. A simplified procedure to calculate short-duration impact loads is suggested that takes into consideration pile capacity and parameters when performing high-strain dynamic pile tests. Comments are also included regarding the current CAPWAP, TNOWAVE, and SIMBAT methods for determination of pile capacity by high-strain dynamic pile testing.

RÉSUMÉ

Le but principal de l'essai de pieux sous deplacement dynamique eleve est d'obtenir la capacite du pieux au moment de l'essai. Il est important de connaitre la grandeur de la charge dynamique durant cet essai. Neanmoins, it n'y a pas de regles generalement admises pour produire ou meme mesurer une tell charge, sauf que la capacite du pieux doit etre entierement mobilisee pendant l'essai dynamique. On suggere dans cette etude un procede simplifie pour calculer les charges d'impact de courte duree, en utilisant la capacite du pieux et d'autres parameters obtenus durant l'essai a chargement dynamique. Des commentaires sont également inclus relativement à la méthode courante de CAPWAP, TNOWAVE, et SIMBAT pours la détermination de la capacité du pieux.

Keywords : dynamic loads, pile testing, pile capacity, dynamic methods

1 INTRODUCTION

High-strain dynamic pile testing (HSDPT) is the basic dynamic method developed for determination of the capacity of driven piles. This method comprises measurements of force and velocity at the upper end of the pile during pile installation followed by a signal matching procedure. HSDPT has advantages in evaluation of the hammer-pile-soil systems and data acquisition during initial pile driving and restrikes. Therefore, for more than thirty years, this method has become an integral part of pile testing for numerous projects.

The main purpose of HSDPT is the determination of pile capacity at the time of testing. It is a convenient approach for the pile driving industry. However, there are some uncertainties and discrepancies in the results obtained from HSDPT. For example (from Svinkin 2004): • Long-term pile behavior under static loads can be only approximately represented by short time dynamic testing; • The data measured at the pile head are used in an indirect determination of pile capacity through a signal matching procedure which does not provide a unique determination of pile capacity; • There are cases of failure of pile foundations that have been designed based on HSDPT; • The existing standards do not accept HSDPT as a replacement for a static load tests; • Incorrect interpretation and application of HSDPT results.

Dynamic and static pile tests present different ways of determining the pile capacity at various times after pile installation. Nevertheless, the pile capacity from a static loading test (SLT) is commonly accepted as a unique standard for the comparison of the results from dynamic testing. Also, the ratio of HSDPT restrike capacity to STL pile capacities has been compared for various pile types, soil conditions and times of testing lumped together. Such a comparison does not make sense. The validity of any comparison between HSDPT and SLT capacities has to be evaluated only with proper correlation of both tests in time. Due to the consolidation phenomenon in soils, the time difference between both comparable tests should not exceed 1-2 days during which soil set-up changes only slightly for driven piles (Svinkin 1997 and Svinkin & Woods 1998).

To increase viability of HSDPT, it is necessary to improve the engineering basis of the method. Hardware and software used for dynamic testing cannot reflect the effects on pile capacity of many factors such as: values of impact loads applied to piles for dynamic testing; 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 2002).

To properly use HSDPT, it is essential to know the values of impact loads applied to piles during dynamic testing. 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. This paper suggests a simplified approach to calculate short-duration impact loads for HSDPT. The new approach considers impact loads applied to piles as a function of pile capacity and pile parameters.

2 SHORT-DURATION IMPACT LOADS FOR PILE TESTING

The condition of sufficient pile movement to fully mobilize the pile capacity does not provide any specific guidance for determination of the values of dynamic loads applied to piles being dynamically tested. Impact dynamic loads can produce different pile penetration into the ground, i.e. no pile movement, some pile movement or complete pile penetration into the ground. The last case occurs when dynamic loads applied to a pile are substantially higher than the soil resistance. Also, large dynamic loads can damage piles. It is important to have criteria to determine dynamic loads applied to piles for proper implementation of HSDPT.

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A ram of a pile driving hammer creates impulses transferred to a pile. Impulse I is a product of force F and length of time t of force action. The impulse is numerically equal the change in a ram momentum during a hammer blow. According to (Schaum 1961), impulse can be written as

$$Ft = m(v_t - v_0) \qquad (1)$$

where F is an unbalanced hammer force (hammer ram weight) acting for a time t on a ram mass m, v_o is the initial value of a ram velocity (v_o=0), and v_t is the final value of a hammer ram velocity.

To assess whether or not impulse I values are reasonable for high-strain dynamic pile testing, it is necessary to compare the effects of dynamic and static loads applied to the same pile or comparable pile during testing. Assume that the maximum pile displacement should be the same under dynamic and static loads. The maximum vertical pile displacement y under a hammer blow is (Craig 1981)

$$y = \frac{I}{\omega M} \qquad (2)$$

where ω and M are dominant circular natural frequency and mass of the pile-soil system respectively.

The maximum pile displacement for a static load test can be taken as the pile displacement from a static load at the ultimate pile capacity P_u or it can be assessed from a consideration that the ultimate static pile capacity is usually accepted to be twice the design static load. It is known that the pile capacity can be higher than the doubled design load applied to piles tested; nevertheless, if such static loading produces only small pile movements into the ground, the test results are completely satisfied. The maximum vertical pile displacement y under the load P_u is

$$y = \frac{P_u}{K} \qquad (3)$$

where K is stiffness of the pile-soil system.

Equating Equations (2) and (3) and taking into account the following notation

$$K = M\omega^2 \qquad (4)$$

we obtain the impulse for dynamic pile testing as a function of the pile capacity and the dominant circular natural frequency of the pile-soil system

$$I = \frac{P_u}{\omega} \qquad (5)$$

It can be seen that the frequency ω is an important parameter of the pile-soil system. In practice, the application of both static and dynamic loads to the same or comparable pile may result in similar pile penetrations in the ground. An example will be shown below.

Svinkin (1992) considered different pile-soil models and found that the best representation of the pile-soil systems is a rod with one fixed end and a rigid weight (hammer ram) on other end. The dominant frequency of the pile-soil system can be calculated as

$$\omega = k\frac{\xi c}{L} \qquad (6)$$

where ξ is adjustment factor determined in Table 1 where η is pile weight to ram weight ratio (Weaver et al. 1990); c is velocity of wave propagation in pile; L is pile length; k is coefficient which equals 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.

Substituting Equation (6) into Equation (5) gives the expression of the impulse for HSDPT.

$$I = \frac{P_u L}{k\xi c} \qquad (7)$$

Table 1. 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

3 VERIFICATION OF IMPACT LOADS FOR PILE TESTING

A study performed by Briaud et al. (2000) has been chosen to verify calculations of impulses applied to piles during HSDPT. This study was chosen for two reasons: first, this study presented comprehensive research on determining pile capacity of bored piles by dynamic methods, and second, the research provides a rare opportunity to compare the pile capacities determined for each of three piles by three companies specialized in the application of dynamic methods to piles (GRL and Associates, Inc., TNO Building and Construction Research, and ESSI – Testconsult). References to dynamic pile testing reports by these firms are available in Briaud et al. (2000).

3.1 *Site and pile information*

Three bored piles were tested at the two national Geotechnical Experimentation Sites at Texas A&M University. 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 no-defect pile, but during construction, 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. Details of the soil properties at the site and the actual pile shapes are available in Briaud et al. (2000).

3.2 *Results of static and dynamic pile tests*

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 (SLT) are shown in Tables 2, 3 and 4 for three piles tested.

The three companies, which performed dynamic pile testing, used similar experimental techniques 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, the three companies use significantly different software for signal matching of experimental data to determine, not predict, the static capacity and the load-settlement curve. The results of HSDPT, errors in determination of the pile capacity, and the time elapsed after SLT are shown in Tables 2, 3, and 4 as well.

Table 2. Comparison of static capacity determination for Pile 2.

Test	Time after SLT days	Method	Static capacity kN	Error %
SLT 1	-	*D*/10 + *PL/AE*	1068*	-
		Davisson	472**	-
HSDPT	8	CAPWAP	1300	+22* +175**
HSDPT	8	TNOWAVE	4900	+359* +938**
HSDPT	8	SIMBAT	2100	+97* +345**
SLT 2	10	*D*/10 + *PL/AE*	1602***	-
		Davisson	1112****	-
HSDPT	8	CAPWAP	1300	-19*** +17****
HSDPT	8	TNOWAVE	4900	+206*** +341****
HSDPT	8	SIMBAT	2100	+31*** +89****

Table 3. Comparison of static capacity determination for Pile 4.

Test	Time after SLT days	Method	Static capacity kN	Error %
SLT	-	*D*/10 + *PL/AE*	4004*	-
		Davisson	2892**	-
HSDPT	7	CAPWAP	2900	-28* 0**
HSDPT	7	TNOWAVE	5800	+45* +101**
HSDPT	7	SINBAT	2300	-43* -20**

Table 4. Comparison of static capacity determination for Pile 7.

Test	Time After SLT days	Method	Static capacity kN	Error %
SLT	-	*D*/10 + *PL/AE*	3025*	-
		Davisson	2491**	-
HSDPT	5	CAPWAP	4250	+40* +71
HSDPT	5	TNOWAVE	2850	-6* +14**
HSDPT	5	SIMBAT	2500	-17* 0**

3.3 *Comparison of impulses calculated and used for pile testing*

It is necessary 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. Therefore, the static capacity according to the Davisson criterion was not selected for piles tested. 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. Besides, according to Briaud et al. (2000), the Davisson capacity corresponds to an average pile head penetration of 12 mm, and in accordance with Fellenious (2001), the maximum toe movement of 13 mm (pile compression was about 0.1 mm) was obtained in the CAPWAP analysis for Pile 2 under impact blow 2. Obviously, similarities of pile displacements under static and dynamic loads were obtain for three tested piles. It means that Equations (5) or (7) can be used to calculate a dynamic load for HSDPT.

For example, let's calculate impulses for dynamic testing of Pile 4 with the bulging defect and perfect Pile 7 using Equation (5). For pile 4, the pile capacity P_u is 2892 kN, the pile weight is 198.4 kN and the ram weight is 90 kN (Briaud et al, 2000). Now it is necessary to calculate the frequency ω. The pile weight to ram weight ratio η is 198.4 / 90 = 2.2, so ξ = 1.104 (from Table 1) and ω = 0.5 x 1.104 x 4000 m/s / 11.5 m = 192 1/s. The impulse required is 2892 kN / 192 1/s = 15.1 kN-s. For Pile 7, the pile capacity P_u is 2491 kN, the pile weight is 165.6 kN and the ram weight is 90 kN (Briaud et al, 2000). Calculate the frequency ω again. The pile weight to ram weight ratio η is 165.6 / 90 = 1.84, so ξ = 1.042 (from Table 1) and ω = 0.5 x 1.042 x 4000 m/s / 10.7 m = 194.8 1/s. The impulse required is 2491 kN / 194.8 1/s = 12.8 kN-s.

During dynamic pile testing, the falling height was varied from 0.3 to 5 m. Because of the friction in the hammer leads, the actual energy delivered to the pile heads was about 20% of the free fall energy of the ram (Briaud et al, 2000). Therefore, the maximum impulse was (2 x 9.81 m/s^2 x 5 m)$^{1/2}$ x 90 kN / 9.81 m/s^2 x 0.2 = 18.2 kN-s, and the minimum one was (2 x 9.81 m/s^2 x 0.3 m)$^{1/2}$ x 90 kN / 9.81 m/s^2 x 0.2 = 4.5 kN-s. Note that the calculated impulses of 15.1 and 12.8 kN are in the range of 18.2-4.5 kN-s, i.e. the impulses applied in dynamic pile testing. It is an acceptable result showing a practical application of the suggested approach for calculating impulses for HSDPT. Obviously, additional research is needed because these are only two examples.

4 COMMENTS ON PILE CAPACITY DETERMINATION BY HSDPT

First of all it is necessary to emphasize that in principle dynamic pile testing followed by a signal matching technique cannot predict pile capacity. This dynamic method, as well as static load test, provides determination of the pile capacity only at the time of testing (Svinkin 1997, Svinkin & Woods 1998).

4.1 *Accuracy of high-strain dynamic pile testing*

As mentioned above, the accuracy of HSDPT has to be verified by comparison with the Davisson static test criterion. Comparisons of the determination of pile capacity by HSDPT with the Davisson method are shown in Table 5. For Pile 2, a comparison was made with the result of SLT 2 because it is apparent that planned and unplanned defects decreased the capacity of Pile 2 at the time of SLT 1. CAPWAP and TNOWAVE determination of pile capacity is based on a single blow, but an average of two blows is sometimes used. SIMBAT software employs a number of blows with varying energy to determine pile capacity. The accuracy of pile capacity calculations by different software on the basis of similar experimental data measured at the pile head are shown below.

Table 5. Errors in pile capacity by HSDPT compared to Davisson static capacity.

Method	Error % Pile 2	Pile 4	Pile 7
CAPWAP	+17	0	+71
TNOWAVE	+341	+101	+14
SIMBAT	+89	-20	0

It can be seen that comparisons obtained for three HSDPT methods resulted in diverse outcomes. CAPWAP analysis overestimated the pile capacities of Pile 2 by 17 %, which was acceptable, Pile 7 by 71 %, which was an unsatisfactory outcome, but also determined the exact pile capacity of Pile 4.

TNOWAVE analysis overestimated the pile capacity of all three piles. While overestimating Pile 7 by 14% was acceptable, overestimation of 341 % for Pile 2 and 101 % for Pile 4 were unsatisfactory results. SIMBAT software overestimated the pile capacity of Pile 2 by 89 %, which was an unsatisfactory outcome, underestimated pile capacity of Pile 4 by an acceptable 20 %, and determined the exact pile capacity of Pile 7. Thus, there were one good result for Pile 2 and two good results for Piles 4 and 7. Nevertheless, it is difficult to give a preference to any one of three methods.

Similar pile tests were performed in California at two sites (Baker et al. 1993), but the static load test results were known to the companies which performed HSDPT before dynamic pile testing was performed. At the Cupertino site, the soil consisted of about 0.9 m of sandy clay followed by alternating layers of extremely dense, clayey and sandy gravels underlain by extremely dense, silty and clean sands. Five bored piles with 0.9 m in diameter and 28 or 33 m in length were constructed. Four of them had planned defects. At the San Jose site, the soil profile indicated about 0.9 m of stiff, sandy clay followed by about 15.2 m of silty and sandy clays of soft and medium consistency underlain by deposit of stiff silty clay. Six bored piles with 0.9 m in diameter were constructed. A length of two piles was about 10 m, and four piles had a length between 18.3 and 19.5 m. Some of these piles had planned defects.

Pile capacity from high-strain dynamic tests were determined by three methods and compared with capacity from static load tests. A drop hammer weight was 86.7 kN. The Davisson criterion was used. For Piles 2 and 4 at the Cupertino site, CAPWAP analysis underestimated the pile capacities by 8 %, TNOWAVE analysis overestimated the pile capacities] by 12 %, and SIMBAT analysis overestimated the pile capacities by 16 %. The report concluded that such variation is acceptable for engineering purposes. However, a different conclusion was made when a comparison of pile capacities obtained from all of the dynamic and static tests at both sites resulted in the average value of the three methods yielding an overestimation of 61 % and an underestimation of 41 %. This much greater range of variation was less acceptable.

4.2 *Overcoming uncertainties in determination of pile capacity by HSDPT*

Determination of pile capacity by HSDPT can yield good or bad results. Unfortunately, there are no criteria for determination of acceptable pile capacities with an exception of the notorious requirement (without any specifics) that the testing method must mobilize the pile capacity at the time of pile penetration into the ground under a hammer blow. For the use of HSDPT, it is necessary to measure force and velocity at the pile head and apply a signal matching technique to the obtained data, but this procedure does not provide a unique solution of pile capacity determination. Moreover a number of electronic and engineering factors can affect pile capacity (Svinkin 2002, 2004). Taking into account these factors, it is possible to improve the accuracy of pile capacity determination.

It is reasonable to discuss two issues considered in Briaud et al. (2000). First, the pile capacity from the CASE method was presented as a function of the pile permanent set or hammer blows per 300 mm (blow count). The lower Blow Count the higher pile capacity when the pile capacity was mobilized at restrike. However, the same blow count can represent much lower pile capacity during easy driving when the much lower energy applied to a pile. It seems that that pile capacity as a function of the blow count should be connected with energy value applied to the pile. Second, the CASE method used an average of all blows, and SIMBAT also used a series of blows with varying energy to receive the load-deformation curve. In spite of a similarity of using measured data, the results in determination of pile capacity are not the same. For example, the pile capacity of Pile 4 is 2850 kN from CASE method and 2300 kN from SIMBAT. It means that the pile capacity from CASE method is 24% higher that one from SIMBAT. It is apparent that software features of each method can affect the results of pile capacity determination.

Obviously, as any tools dynamic methods for HSDPT have to be calibrated for different pile types and soil conditions to properly determine the pile capacity.

5 CONCLUSIONS

HSDPT is a convenient tool for the pile driving industry, but the actual accuracy, the area of application of this method (type of piles and soil conditions), and the understanding of the results of dynamic pile testing are vague. To fully benefit from this kind of testing, it is necessary to analyze the results of the applied electronic sensors, the software features, and the engineering factors which can affect determination of pile capacity by this method.

Magnitudes of dynamic loads used in dynamic pile testing are important. A simplified procedure incorporating pile capacity and parameters of the pile-soil system is suggested to calculate short-duration impact loads for performance of high-strain dynamic pile testing. This procedure can replace the indistinct condition of the fully mobilized pile capacity at the time of dynamic pile testing.

The writers believe that the new procedure to calculate impulses applied to a pile during dynamic testing is a step toward increasing our engineering understanding of HSDPT.

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