Dynamic testing in sensitive & difficult soil conditions

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ABSTRACT: Dynamic testing of piles has proven to be a cost effective and reliable method of determining capacity for both driven piles and drilled shafts. For driven piles, dynamic testing can be performed during initial driving to evaluate hammer performance, pile driving stresses, integrity and pile capacity. However, the long term capacity can differ from that computed at the end of initial driving due to time dependent soil strength changes such as soil set-up (increase in capacity). To obtain a better estimate of the long term capacity, restrike testing should be performed after an appropriate waiting time period to identify soil strength changes.

Soil set-up is most often attributed to water pore pressure dissipation and is more profound in fine grained soils. In some cases, results from testing during initial driving may greatly under-predict the long term capacity, and in some cases, testing results indicate very low computed capacities at relatively high driving resistances (blow count) and high peak force input and transferred energy. This paper presents example data from dynamic testing of piles driven into these highly sensitive and difficult soils. Through signal matching analysis by CAPWAP® of data measured at both end of initial driving and restrike, possible causes of the unusually low computed capacity during initial driving will be discussed. Based on these findings the benefits and shortcomings for improved predictions of long-term capacity based on end-of-drive information will be investigated.

1 INTRODUCTION

After four decades of research, development and field testing experience, high strain dynamic testing is the test of choice for evaluating hammer, soil and pile performance from pile driving operations. Dynamic testing can be performed on both off-shore and on-shore environments on driven piles (steel, concrete or timber), in-situ piles (drilled shafts, auger-cast, etc.), micro-piles and also on sheet piles. The test method has been standardized by the American Society for Testing and Materials (ASTM, D 4945-00). Detailed derivations of the Case Method have been presented in a variety of publications including Rausche et al (1985).

While dynamic testing is only performed during pile driving, when real-time measurements are collected in the field, the complete dynamic testing process consists of three components. These components include 1) wave equation analysis, 2) field testing utilizing specialized equipment such as the Pile Driving Analyzer™ and 3) refined wave matching techniques such as CAPWAP™ analysis (CAPWAP manual, 2006) which, among other information leads to soil resistance and pile stress distribution. These three elements of testing and analysis lead to the most comprehensive evaluation of hammer performance, pile drivability and pile capacity determination (Likins, Rausche, Goble, 2000).

Dynamic testing provides the engineer essential information on hammer, pile, and soil performance. For driven piles, testing can be performed during initial driving or during restrike testing. Testing during initial driving is normally performed to evaluate hammer performance, driving stresses, pile integrity and capacity at time of testing. Restrike testing, performed after an appropriate waiting period, is essential to evaluate time dependent soil strength changes. These soil strength changes can occur from changes in pore water pressure or soil remolding once initial drive operations are stopped.

2 BACKGROUND

2.1 Soil changes during driving

Depending on the soil density and the soil's reaction to disturbance during initial driving, pore water pressure can either increase or decrease with time. In loose to medium dense sands and sandy silts, the pore pressure typically increases during pile driving operations due to soil densification. An increase in pore pressure leads to a decrease in effective stresses which consequently reduces the soil strength. In wet, silty clay and clay soil, disturbance or remolding of the soil adjacent to the pile can occur which, in addition to an increase in pore water pressure, can greatly reduce the strength during initial pile driving operations. After pile driving ceases for an extended period of time, dissipation of pore water pressure and soil remolding results in increased soil strength. This phenomenon, or increased soil strength is widely referred to as soil ''set-up'' or soil ''freeze''.

When driving into dense to very dense sands and sandy silts, the driving may disturb the tight particle structure increasing the pore volume (normally referred to as dilation). During this process, water may not infiltrate sufficiently fast to equalize the pore pressure and therefore a reduction in pore pressure occurs for a short time period. This reduction in pore pressure increases the effective stresses which, in turn, increase the soil strength. However, this increased soil strength is temporary and only occurs during soil shearing. After pile driving is stopped, the pore pressures equalize typically in a relatively short time period resulting in reduced soil strength. This phenomenon is widely referred to as soil ''relaxation''. When relaxation occurs, a lower capacity is computed during restrike testing relative to the end of drive capacity. Soil relaxation can occur along the pile side surface (loss in friction) and/or at the pile toe (loss in end bearing).

To identify the set-up or relaxation potential, dynamic testing is generally performed both during initial driving and during restrike after an appropriate waiting time period. During the restrike test, close attention is given to the results of the first few hammer impacts since relaxation or set-up may be evident only during these few early impacts. If these soil property changes are not evaluated properly, or dynamic testing is performed only during initial driving, the long term capacity may either be under-predicted when set-up occurs or be over-predicted if soil relaxation occurs.

2.2 Radiation Damping

Dynamic testing experience has shown that if soil strength changes from pile driving are not evaluated properly, the estimate of the long term pile capacity may not be adequate. In some cases, results from dynamic testing, especially when testing during initial driving, have indicated very low computed capacities at relatively high driving resistances (blow count) and relatively high measured peak force and hammer energy transfer when compared to wave equation analysis and static testing. For these cases, difficulties may also have been experienced in modeling the soil by CAPWAP analysis using the traditional standard Smith model and have resulted in unusually high Smith skin damping values. In these cases, using the Radiation damping model in CAPWAP has resulted in satisfactory correlations with static testing (Likings, Rausche, DiMaggio, Teferra, 1992 and Likins, Rausche, Thendean, Svinkin, 1996)). In cases where both dynamic testing and CAPWAP analysis compute a much lower pile capacity compared to wave equation analysis, and very high Smith damping values are computed by CAPWAP, the force and velocity response may have characteristics similar to the curves shown in Fig. 1. Normally, these measured force and velocity records can be divided into four phases: 1) pre-impact, which is typically zero for air or hydraulic hammers and slightly positive for diesel hammers (as shown in Fig. 1), 2) impact, which normally contains most of the soil response from friction, 3) toe loading, which contains the response from the toe and the total capacity and 4) unloading/reloading of the pile. These same phases also apply to the wave-up curve (which is computed from force and velocity) as shown in Fig. 1. Using the radiation damping model in CAPWAP has been useful when dynamic testing has resulted in measured curves which characteristically show a relatively large wave-up reflection just before time 2 L/c, which would normally signify relatively high friction, followed by a low measured curve after 2 L/c, which normally signifies relatively low total pile capacity. Therefore, using the standard Smith damping model in CAPWAP generally results in very high Smith damping (in order to match the measured curve from time zero up to time 2 L/c) and a relatively low total capacity in order to match the response just after 2 L/c. Since the Case Method capacity computation looks at the magnitude of the measured curve just after time 2 L/c, a low measured wave-up curve also results in a relatively low computed capacity with the Case Method prediction.

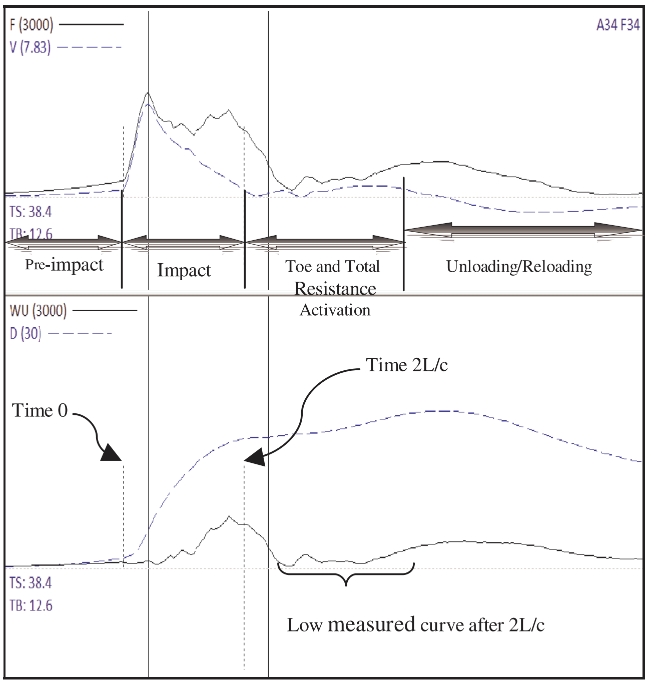

Figure 1. Force, velocity and wave-up records which show characteristically low measured response after 2 L/c.

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3 CASE HISTORY

3.1 Project details

The pile foundations, designed to support a bridge pier, consisted of 20 m long, 400 mm O.D. closed-ended pipe piles with a wall thickness of 7.5 mm. The required ultimate capacity was 980 kN. The soils were highly variable although they consisted mostly of sandy to clayey silt. The piles were driven with an ICE I19 single-acting diesel hammer. This model has a ram weight of 18 kN and a maximum rated energy of 58.8 kN-m. Throughout the testing sequences, the hammer was typically operated at fuel setting 3 (setting 4 is maximum).

Dynamic testing was performed on a pile during initial driving. A restrike test was performed the next day since the required capacity could not be achieved at end of initial driving. The observed blow count, hammer performance, driving compressive stress and mobilized capacity are summarized in Table 1. The pile was stopped at a blow count of 18 blows/0.1 m at which point a Case method capacity of 670 kN was mobilized. The restrike test a day later showed the capacity had approximately doubled to 1360 kN apparently due to soil set-up surprisingly with only a marginal blow count increase to 24 blows/0.1 m (only a 33% gain).

Wave equation analysis using GRLWEAP™ was performed using the program's standard input values of damping and quakes and modeling a 20 m long steel pipe and the ICE I19 diesel hammer. Adjustments to the model were made in order to best match the field measured hammer performance. The analysis was performed for both the end of initial drive (EOID) and beginning of restrike (BOR) conditions. The results of the analyses are summarized in Table 2. The EOID analysis indicates an ultimate capacity of approximately 1000 kN at the observed blow count of 18 blows/1 m. Note that the Case Method capacity of 670 kN at EOID is only 0.67 that of the capacity predicted by wave equation analysis. For the restrike condition, the Case Method mobilized capacity of 1360 kN correlated much better and was 1.13 times the wave equation prediction of 1200 kN. The unsatisfactory correlation between Case method and wave equation analysis for the EOID static capacity estimates was unexpected and unusual.

As an additional independent verification of capacity, the generally more reliable CAPWAP analysis was performed on data representative of the EOID and BOR conditions first without using the radiation damping model. The capacities from CAPWAP analysis (along with the corresponding computed Smith damping values shown in parenthesis) are given in Table 3 along with the capacities computed from the Case Method and wave equation analysis. As shown in Table 3, the computed capacities from CAPWAP using the standard Smith model (without using radiation damping) were even less than the Case Method predictions. Compared to wave equation analysis, the CAPWAP capacity at EOID was only 0.58 times that of the wave equation prediction. For the BOR condition, the CAPWAP capacity correlated better and was 0.85 times the wave equation prediction. In addition, as indicated in Table 3, unusually high Smith shaft damping of 1.71 and 1.41 s/m were computed for the EOID and BOR, respectively. Although the correlation between the three methods is adequate (within ±15%) for the

Table 1. Summary of Case Method Results

Blow Count (blows/dec)	Average hammer Stroke (m)	Average Transf'd Energy (kN-m)	Max. Compressive Force (kN)	Max. Compressive Stress (MPa)	CASE Mobilized Capacity (kN)	Notes
18	2,2	18,9	1740	183	670	EOID
24	2,4	20,4	1870	197	1360	BOR

Table 2. GRLWEAP Capacity Estimates

Ultimate Capacity (kN)	Maximum Compression Stress (MPa)	Blow Count (blows/.10m)	Stroke (m)	Energy (kN-m)
End of Initial Drive				
200	122,02	1,7	1,55	24,19
450	156,51	4,9	1,95	20,47
650	169,36	8,9	2,13	19,29
900	177,97	14,6	2,26	19,20
1000	181,34	18,0	2,31	19,45
1100	184,49	22,4	2,36	19,70
1200	187,21	28,7	2,40	19,85
1300	188,27	38,5	2,42	19,76
1400	189,93	53,4	2,44	19,82
1500	191,62	79,2	2,47	19,92
Beginning of Restrike				
Ultimate Capacity (kN)	Maximum Compression Stress (MPa)	Blow Count (blows/.10m)	Stroke (m)	Energy (kN-m)
200	128,35	1,6	1,56	25,73
450	164,15	4,7	1,97	22,22
650	177,81	8,3	2,17	21,07
900	186,94	13,3	2,30	20,99
1000	190,56	16,2	2,35	21,29
1100	193,71	19,9	2,41	21,51
1200	196,50	24,9	2,45	21,75
1300	197,62	32,4	2,47	21,65
1400	199,86	42,6	2,50	21,88
1500	201,20	59,9	2,52	21,90

Table 3. Summary of Capacity Estimates

	Wave Equation (kN)	Case Method (kN)	CAPWAP without Radiation Damping (kN) (*s/m*)	CAPWAP with Radiation Damping (kN) (*s/m*)
EOID	1000	670	578 *(1.71)*	914 *(0.80)*
BOR	1200	1360	1023 *(1.41)*	1202 *(1.28)*

values in parenthesis denote shaft damping values

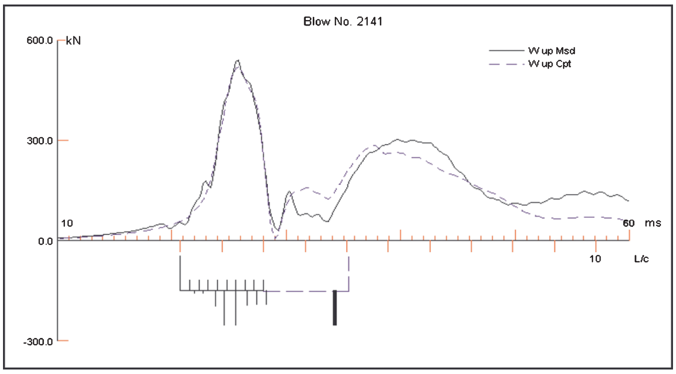

Figure 2(a). Final wave-up match plot using the standard Smith model (match quality of 3.94).

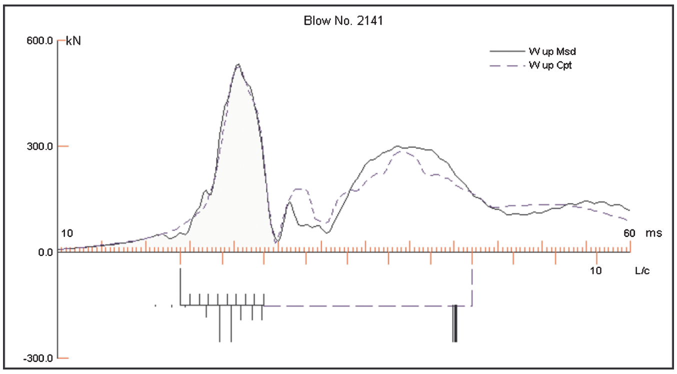

Figure 2(b). Final wave-up match plot using the radiation damping model (match quality of 2.89).

BOR condition, the correlation was not adequate for the EOID condition.

Since very high Smith damping values were computed in CAPWAP when using the standard Smith damping model and since the wave-up curve exhibited the characteristically low response after time 2 L/c (see Fig. 1), CAPWAP analysis was performed again but with the radiation damping model. As indicated in Table 3, the capacities computed by CAPWAP using radiation damping resulted in higher capacities (and lower, more realistic Smith damping values). In addition, the computed capacities correlated very well to the wave equation predictions for both EOID and BOR conditions (within 10% for the EOID condition and within 1% for the BOR condition). The final wave-up match plots for the EOID condition are shown in Figs. 2(a) and 2(b) for the standard Smith model and the radiation damping model solutions, respectively. In comparison, the match quality of 2.89 computed from the solution using radiation damping is significantly better than the match quality of 3.94 computed from the solution using the standard Smith model (the match quality number is a measure of the relative difference between the measured curve and the computed curve).

4 CONCLUSIONS

Dynamic testing was performed on a steel pipe pile during initial driving. The Case method capacity mobilized at end of initial driving (EOID) was unusually low when considering the observed blow count and measured peak force and transferred energy. Wave equation analysis with the GRLWEAP program using standard input parameters indicated a more reasonable and significantly higher capacity for the blow count observed in the field. CAPWAP analysis performed on data representative of EOID using the standard Smith model indicated even lower capacity as compared to the Case Method with unusually high Smith skin damping.

Table 3 summarizes the computed capacities for all three methods. The comparison shows that both the Case method and CAPWAP analysis using the standard Smith model at EOID greatly under-predicted the capacity relative to wave equation analysis. The results from restrike testing, which resulted in a much higher mobilized capacity due to set-up, showed a much better correlation between the three methods.

In cases where the Case Method capacity prediction is considered low relative to the applied force, transferred energy and observed blow count (especially if capacity is significantly lower than the wave equation analysis prediction), recent experience has shown that using the radiation damping model in CAPWAP, when the standard Smith model results in Smith damping values above approximately 1.3 s/m, has resulted in satisfactory correlations with static testing. In addition, this case study also demonstrates the importance of performing restrike testing to better estimate the long term capacity.

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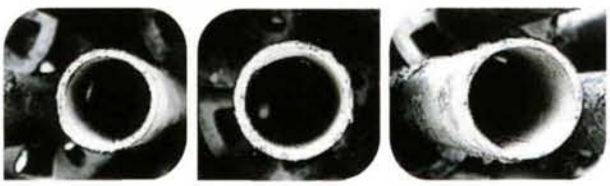

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