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Is Capacity Fully Mobilized?

Introduction

Dynamic pile testing is no exception to Life's general rule: what we achieve depends on the resources at our disposal. Occasionally, for example, pile resistance determined from analysis of dynamic test data is smaller than the actual capacity of the pile, because the pile driving hammer is not always able to mobilize the full soil resistance - move the pile against the soil. Normally, confidence in that full soil resistance is mobilized is expressed when the net pile penetration for the impact is larger than about 2 mm/blow (or expressed in terms of penetration resistance: when the blow count is smaller than about 12 blows/25 mm). If the penetration resistance is larger, the full soil resistance is often not mobilized and the capacity value is then an "underpredicted" value.

When taking measurements in the field, it is important to evaluate pile penetration together with the visual message given by the force and velocity traces. For instance, if the pile penetration is very small and the toe reflection is weak despite that the pile toe is in a dense soil, then there is a good chance that the toe resistance is not fully engaged and that the capacity value is an "underpredicted value".

When the industry decides to perform a static test, sufficient resources are provided to achieve the goal, that is, reaction is provided for the intended maximum test load. We have no problem in thinking in terms such as "mobilized capacity", "lower-bound capacity", "at-least capacity". After all, in static testing to "twice the design load", we accept that soil failure is not reached and see no need to increase the test load. Similarly, dynamic testing is limited to the impact provided by the pile driving hammer. The purpose of the hammer is to advance the pile to a capacity at end-of-initial-driving that coupled with soil set-up ensures the final capacity of the pile. A condition called "refusal" may occur at restriking after soil set-up has developed. "Refusal" is characterized by that the penetration for the blow is very small, often corresponding to a penetration resistance (PRES) in excess of 20 blows/25 mm. That is, the soil resistance is greater than what the hammer can overcome.

Capacity is ultimate resistance. Anything smaller is not capacity. Because the resistance mobilized for "refusal" condition is normally smaller than the pile capacity, it is tempting to increase the capacity value by some "judgement" portion. Such an approach is very arbitrary, dangerous, and highly inadvisable. Never indicate that the pile has a **quantified** capacity that is higher than the value determined from the analysis of the test results!

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Sometimes, the dilemma can be resolved by comparing test results obtained at end-of-initial-driving (EOID) with those at restriking (RSTR) and combining the dynamic test data with an analysis of the static load distribution and the transfer of load to the soil. The approach is greatly enhanced if during the initial driving of a special test pile the driving is stopped before the pile reaches the termination criterion specified for the project. The prematurely stopped pile has about the same shaft resistance as the pile driven to the specified criterion, but its toe resistance is smaller. Therefore, in restriking the pile, the hammer will be able to move the pile and fully mobilize its capacity. By subtracting from this RSTR capacity the capacity established at the EOID, the soil set-up is quantified. (The soil set-up at the pile toe is normally small and the capacity increase is mostly made up of soil set-up along the pile shaft). Piles not prematurely stopped but driven at EOID in accordance with the specifications for the particular project have the same magnitude of set-up as the special test pile. Consequently, the final capacity of the regularly driven pile can be taken as the capacity at EOID plus the soil set-up found for the special test pile.

CAPWAP analysis provides additional means of evaluating the soil set-up effect. First, CAPWAP analysis provides a reassured evaluation of capacity. Second, when combined with prolonged restriking, performing CAPWAP analysis on early and late blows provides a rationale for upgrading the computed pile capacity. For the first blows of restriking, fully developed shaft resistance is mobilized along the upper portion of the pile, but not in the lower portion and at the pile toe. For each blow of the continued driving, however, the shaft resistance along the upper portion breaks down and more resistance is progressively mobilized in the lower portion of the pile. The results from CAPWAP analysis on blows from the beginning and from the end of restriking (BOR and EOR) may be combined by adding the shaft resistance values obtained in the upper pile elements of the BOR analysis to the values obtained for the EOR analysis in the lower shaft elements and at the toe element.

Prior to performing dynamic testing, a static analysis of expected shaft resistance should always be performed for both EOID and RSTR driving conditions. The results of the static analyses are then input into a Wave Equation Analysis (WEAP) to produce a Bearing Graph and Drivability Analysis to estimate what to expect in the driving at the site. The WEAP analysis may indicate whether or not the desired capacity can be verified by means of simple routine dynamic measurements or if the hammer is, or might be, unable to mobilize pile capacity to the desired value.

The simple fact is that, if we want to determine capacity in a dynamic test, we need,to provide an impact that fully mobilizes the pile capacity. Sometimes, this necessitates bringing in a larger hammer, but more often than not, it is possible to provide a better "whack" with the ordinary hammer. A higher fuel setting can be used for a diesel hammer, or its performance can be improved by scavenging the hammer by means of connecting an air hose to the air intake. A drop hammer can be raised to a higher height-of-fall. The latter method is the simplest as illustrated in the following case history.

Soil, Site and Pile

Closed-toe, pipe piles were installed for a five-storey office complex in Ottawa south. The soil profile at the site consists of approximately 10 m (30 ft) of silty clay overlying a 15 m (50 ft) thick layer of dense sand that, at a depth of about 25 m (80 ft), is followed by about a 5 to 8 m (15 to 25 ft) thick layer of glacial till deposited on shale bedrock.

The piles were 219 mm (8.625 inch) and 245 mm (9.625 inch) diameter closed-toe steel pipe piles with a wall thickness of 8 mm (0.315 inch) and 9 mm (0.350 inch). The steel yield was specified to 360 MPa (52 ksi) or greater. The design loads for the two pile sizes were 815 KN (92 ton) and 1,030 KN (116 ton), respectively. These loads correspond to a steel stress of 151 MPa (21.9 ksi) and 157 MPa (22.7 ksi), which are high values and presume that soil set-up will occur after the installation driving.

The pile driving was performed with a 41 KN (9.2 kip) drop hammer with height-of-fall specified at 0.9 m and 1.2 m (3 ft and 4 ft). The termination criterion applied to the pile driving was 12 blows/25 mm. The piles were driven into the glacial till and the total embedment lengths varied from 26 m (87 ft) through 31 m (100 ft).

Test Results

Dynamic testing was performed on three nine-inch piles that were restruck 1 day, 8 days, and 11 days, respectively, after EOID. The piles were denoted Piles A, B, and C, respectively.

At first, three to four blows were given with a height-of-fall of 1.2 m (4 ft) (Piles A and B) and 0.9 m (3 ft) (Pile C). Measured maximum stresses were 240 MPa (35 ksi), 225 MPa (33 ksi), and 190 MPa (28 ksi), respectively, and occurred at time 2L/c, that is, when the toe reflection reached the gage location. The high stresses would have been of some concern for mild steel piles, but not for these piles.

No penetration was achieved for the blows. The Case-Method-Estimate of capacity (CMES-RMX), as later confirmed by CAPWAP analysis, indicated mobilized capacities for Piles A and B of 1,600 KN (180 ton) and 1,480 KN (166 ton) for Pile C, which values fell

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up of shaft and toe resistances. Fig. 1 presents transfer curves obtained from the CAPWAP results. The curves show that as the height-of-fall increases, a larger portion of the toe resistance is mobilized. Also, as would be expected, the curves indicate that the shaft resistance increases with depth and in proportion to the increase in effective stress (suggesting the use of the beta-method for static analysis). The steeper the curve, the smaller the shaft resistance, which makes it clear that the largest unit shaft resistance is obtained in the till. The slope of the transfer curves in the clay and the sand (upper 28 m) is steeper for each increase of the height-of-fall, that is, as the number of blows increases. This is an indication that some of the shaft resistance was indeed lost during the restriking and that, therefore, the actual capacity is higher than the one computed.

Summary

This case history discusses the limitations of dynamic analysis as well as presents ways to overcome some of the difficulties. Details are presented on a project involving small diameter pipe piles driven into dense glacial till using a drop hammer. Dynamic testing and CAPWAP analyses indicated inadequate bearing capacity when restriking the piles with the project specified hammer height-of-fall of about 1 m. However, the capacities were "underpredicted" values and the height-of-fall was raised until a noticeable penetration was achieved for a blow. The increased height-of-fall transferred a greater energy to the pile and imparted a larger impact force that overcame the soil resistance. Analysis of the new blow data indicated higher pile capacities and that the pile design and specified pile driving criteria were suitable.

Table I Results From Dynamic Testing and CAPWAP Analysis

BLOW No.	EMAX (KJ)	FMAX (KN)	SMAX (MPa)	FIMP (KN)	SIMP (MPa)	CMES (KN)	CPWP (KN)	HMR (m)	PRES (B1/25 mm)
Pile A (1 day after initial driving)									
1	31	1590	240	1190	180	1700	1605	1.2	N/P
5	45	1840	280	1350	205	1920	1885	1.6	N/P
8	51	1890	285	1480	225	2020	1950	2.1	16
Pile B (8 days after initial driving)									
1	31	1490	225	1150	175	1600	1610	1.2	N/P
5	47	1870	285	1420	215	1960	1910	1.8	16
8	57	2040	310	1580	240	2130	2060	2.1	16
Pile C (11 days after initial driving)									
2	21	1260	190	970	150	1390	1480	0.9	N/P
7	31	1450	220	1170	180	1510	1575	1.5	25
9	45	1760	270	1430	215	1860	1905	2.1	8

BLOW: Sequence number of the hammer blow in restriking the pile
EMAX: Maximum value of the energy transferred into the pile
FMAX: Maximum measured compression
SMAX: Maximum compressive stress
FIMP: Impact force
SIMP: Impact stress
CMES: Maximum Case Method Estimate (RMX) using a J-factor of 0.6
CPWP: Capacity calculated by CAPWAP analysis
HMR: Hammer height-of-fall
PRES: Penetration resistance in blows per 25 mm
N/P: No penetration achieved for the blow