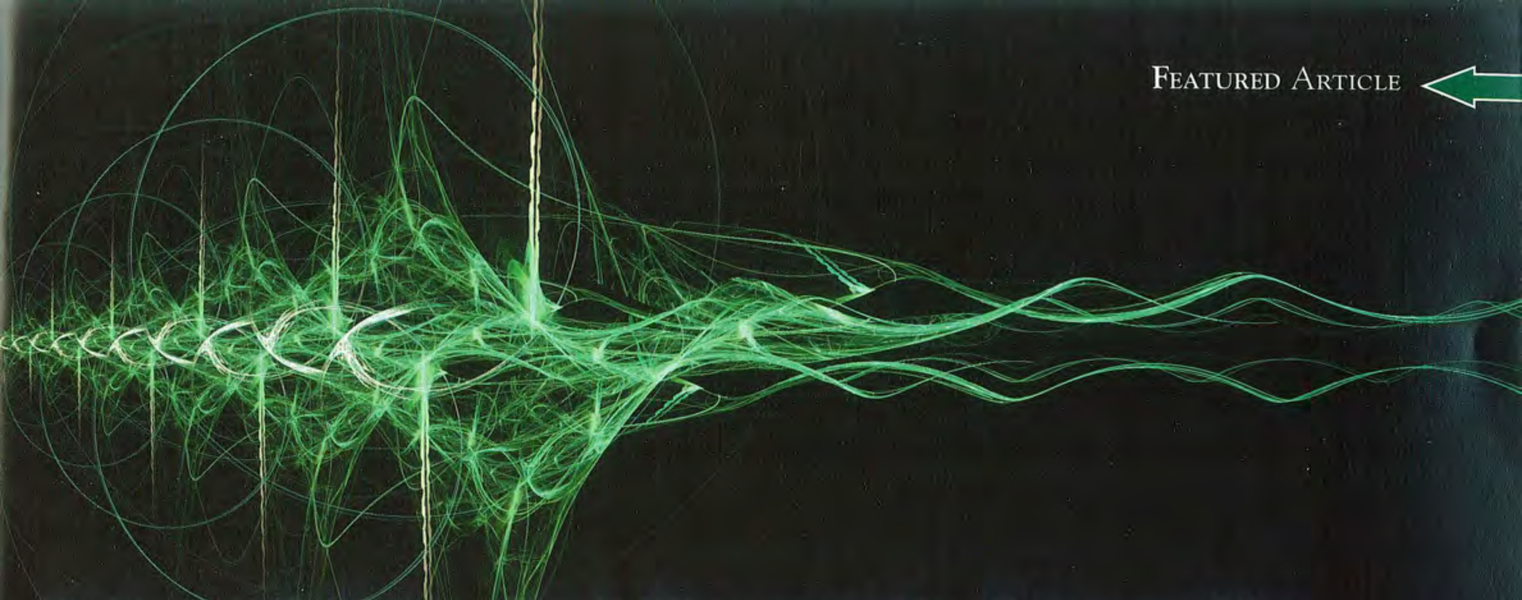

Driveability and Dynamic Capacity Estimation for Vibratory Driven Piles

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Vibratory pile driving often pushes piles in the ground with surprising ease, apparently defeating our traditional methods of soil resistance assessment. Under favorable conditions driving with a vibro hammer is indeed a highly economical pile installation solution posing the question, why this technology did not replace impact pile driving to a much greater degree? Certainly one reason is that the dynamic analysis methods for vibratory pile driving have had little research or application.

The dynamic analyses should answer two questions: (a) prior to pile driving, what equipment will be required to drive the pile to a certain depth (this is the driveability question) and (b) once the pile is installed, what is the pile's bearing capacity.

For many jobs, for example for most sheet pile installations, the second question is immaterial, because there is no bearing requirement. Also in that case the driving resistance is often minimal and simple formulas or previous local experience based on pile size may be sufficient to estimate the required hammer size. Hammer manufacturers can provide the contractor such experience based recommendations. However, actually quantifying the rate of pile penetration is much more difficult and requires three things: a valid numerical analysis, experience based input parameters for the soil, and some luck.

Determining the bearing capacity of the vibro installed pile based on static formulas or dynamic measurements is even more complex. While impact driving often temporarily modifies the soil strength surrounding the pile, a restrike test generally provides reliable information about the long term (LT) soil resistance. A vibratory restrike test moves both pile and soil right from the beginning thereby changing the soil conditions and therefore is not a helpful test.

In four issues of the 2005 *PileDriver* magazine, Kenneth Viking, who in 2003 had completed a doctoral thesis on this subject at the Royal Institute of Technology in Stockholm, Sweden, pointed out some of the complexities of vibratory theory and practice. For the reader, interested in background information on this subject, reading these four articles of referenced material will be very helpful; the present article will not present in-depth background information.

Background information, unfortunately, does not help with estimating installation performance and capacity assessment. Often something has to be immediately done and with rather rudimentary soil information. Fortunately, the wave equation program, GRLWEAP, includes a quick vibratory driveability analysis capability. The program not only provides a large hammer data base, but also a comprehensive set of soil parameter recommendations. Obviously, such recommendations cannot compete with and do not replace actual experience from local case studies. On the other hand such a wave equation analysis should be a good starting value, which can be modified and reanalyzed after a first set of measurements has been acquired.

Driveability by wave equation analysis

A driveability analysis basically involves the following steps:

1. Obtain pile information including: type or profile, length and required depth;
2. Obtain soil profile including strength information (e.g., SPT or CPT or friction angle and undrained shear strength), hammer model to be analyzed, clamp weight.
3. Decide on pile perimeter (for shaft resistance calculations) and toe area (for end bearing calculations). For sheet piles this is relatively easily estimated. For open ended pipe piles the assumption of some internal friction may be reasonable; for H-piles the complete contact area rather than the "box" may be chosen. These assumptions imply that the pile will core (not plug) during vibratory driving and therefore require that the steel cross sectional area is used as the toe area for toe resistance. Plugging may, however, be a possibility in hard or very dense soils.

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4. Perform static soil analysis yielding the long term (LT) friction and end bearing as a function of depth. The GRLWEAP code offers three (four in the Offshore Wave version) different helpful static analysis routines.
5. Choose hammer model (hammer efficiency is usually set to 1) and input clamp weight. If a crowd force can be applied (this seems to be a very effective means for driving the piles faster) then that should be input as a negative line force; if instead the crane maintains some tension (maybe for stability) on the hammer then that force should be entered as a positive line force.
6. Select soil damping and quake (GRLWEAP's HELP suggests different values for vibratory driving than parameters selected for impact driven piles);
7. Select factors relating the Static Resistance to Driving (SRD) to LT (GRLWEAP's Help makes some suggestions). This step requires estimating how much resistance is lost due to the soil vibration. For submerged sands the losses may be as high as 90% while clays may not lose any resistance at all (note this assumption is exactly opposite to those made normally for impact driving.) This is the most important step and unfortunately the one fraught with the greatest uncertainty.
8. Run the program with these input values and plot the calculated penetration speed, calculated SRD and pile stresses as a function of pile penetration (see Figure 1 for an example of the input screen and the driveability result.
9. Run alternative sets of soil resistance parameters to develop a "feel" for the sensitivity of the solution. In other words, run both upper and lower bound solutions.

Obviously, this analysis process involves many estimates and assumptions but anecdotal evidence suggests that at least in granular soils the wave equation results are conservative, i.e., the piles are actually driving easier than anticipated.

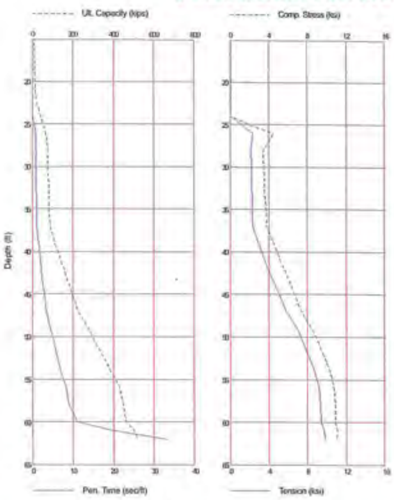

Figure 2: Capacity, Penetration speed, Compressive and Tensile Stress Maxima, all vs. depth.

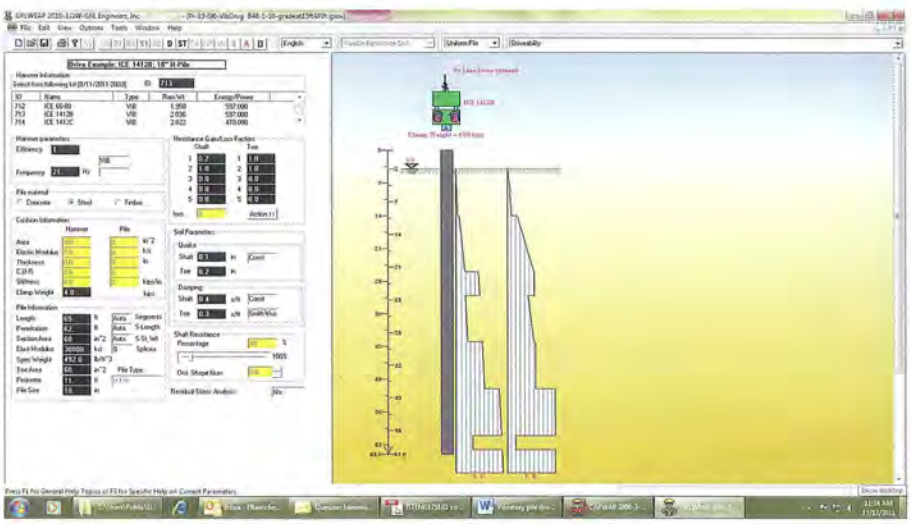

Figure 1: GRLWEAP Input Screen

Bearing Capacity from Wave Equation

While dynamic or static load testing is better, the wave equation analysis is sometimes used to determine bearing capacity of impact driven piles. This process involves calculating a bearing graph (relationship between bearing capacity and driving resistance) and then using the blow count (e.g., blows/ft) observed during pile driving to estimate the associated ultimate pile bearing capacity. An equivalent procedure could be followed for vibratory driven piles where blow count would be replaced by driving resistance in seconds per unit penetration (e.g., s/ft); capacity should be replaced by SRD. Unfortunately, there is no evidence that this process has ever been successfully used as a capacity verification method.

Dynamic Measurements

Using the Pile Driving Analyzer® (PDA), dynamic force and acceleration measurements taken on impact driven piles during installation have become routine during the past 40 years. These two quantities are rarely measured during vibratory pile driving even though engineers and contractors frequently ask how the PDA can help with construction control. Indeed PDA measurements can be as easily taken during vibratory driving as during impact driving. Sensors would be attached near the pile top with sufficient distance from the clamp to avoid non-uniform stresses (Figure 3). In addition, it is suggested that the penetration speed is independently recorded, for example by video camera.

The analysis of vibratory driving data is different from the Case Method analysis of impact data. Pile Dynamics has prepared software which provides the following results:

- Frequency of vibration, because measurements show it is not always the expected value;
- Maximum force which is a function of the relative masses of hammer and pile and the SRD. It can and should be compared to both centrifugal force and the wave equation calculated force to assess the hammer performance;
- Maximum tension and compressive stresses at the gage location; although generally low compared to the strength of the pile material, these values are important for the assessment of fatigue damage and clamping stresses;
- Peak velocity;
- Peak displacement per cycle;
- Power transfer - both peak value during a cycle and average over several cycles;
- Soil resistance to driving according to Case Method (both rigid pile and elastic pile assumptions) and power formula based.

The soil resistance calculation needs an explanation. First of all, it is obvious that only the resistance to driving (SRD) and not an ultimate capacity can be calculated. Developing a relationship between SRD and capacity for various soil types requires additional studies. Secondly, the SRD can be calculated based on a variety of closed form solutions among them a power formula, a simple rigid body formula, or the standard Case Method for impact driven piles. Initial correlations show that damping considerations would unnecessarily complicate the Case Method resistance calculations while do little to improve the accuracy of this simplified approach... Also, the power method, which is analogous to an energy formula for impact driven piles, seems to give reasonable results, however, it requires that both the power and the vibration amplitude be measured with the PDA.

Example

The following example compares various results obtained from GRLWEAP and PDA testing. The project was the I-90 Innerbelt Bridge in Cleveland, Ohio. Walsh Construction Company installed large H-piles to more than 120 ft depth into shale using diesel impact hammers. However, the first 65 ft section of the HP 18x204 was installed by an ICE model 66-80 with 26.7 Hz (1600 rpm) rated frequency and 6,600 lb-inch (749 N-m) eccentric moment which corresponds to a rated centrifugal force of 483 kips (2,150 kN). A generalized soil profile, including SPT N-values and unconfined compressive strength values in tons per square foot is shown in Figure 4.

Measurements taken with the PDA, i.e. force and velocity (integrated from acceleration), for 60 ft penetration are shown in Figure 5, along with the Case Method calculated soil resistance, shown for a time period of approximately half a second. Results pertaining to hammer performance, i.e., actual frequency, pile top force and power transfer are shown in Table 1 together with calculated values for the centrifugal force based on rated and actual frequency and the pile top force range (depending on assumed resistance) from GRLWEAP. The peak power value and the average power, transferred over the analyzed time period, are shown. According to the hammer manufacturer, the required power output of the hydraulic power pack should be almost 600 kW. As such, the peak power transfer was somewhat higher (783 kW) while the sustained value (254 kW) was well below that limit.

Table 2 summarizes a variety of soil resistance and penetration speed (the inverse of the driving resistance) results all pertaining to a pile tip penetration of 60 ft (e.g. depth at the end of the vibratory installation). At that point the observed penetration speed was only 0.29 inches per second. Also for that depth, the N-value based GRLWEAP method calculated a long term soil resistance between 222 (assuming a 6 ft box perimeter) and 387 kips (11 ft complete perimeter). In either case the pile was assumed to core and therefore experience end bearing only against the steel. According to the GRLWEAP recommendations, SRD for vibratory driving should use 20% of the long term shaft resistance in sand and 100% in clay. This leads to an SRD range of 187 to 340 kips for the mixed soil type profile. The SRD values from the dynamic methods from elastic Case Method and measured power formula are 128 and 409 kips, respectively, with the rigid body result between those two values. Obviously this is a wide range and it favors the power approach as the more accurate approach in this particular case.

After the bottom section had been installed by the vibratory hammer to 60 ft, the pile was spliced and then impact driven with a diesel hammer; waiting time were typically more than one day. A neighboring pile was then PDA tested and the 2nd and 3rd blows were analyzed by CAPWAP resulting in 400 and 360 kips capacities, respectively. These values probably include some soil setup resistance although continued driving did not reveal a further distinct loss of resistance. While the CAPWAP

Figure 3: PDA instrumentation on an HP 18x204 and GRL Engineers' Dr. Brent Robinson (left) and Eric Bogen video recording while the PDA Model PAX processes the pile data.

results indicate values close to the upper ranges from static formulas and the power formula, a surprisingly high amount of end bearing (more than 65% of the total capacity) was also determined. It may be theorized that the pile plugged during restrike impact driving but not during vibratory driving (a plugged pile would most probably have refused under the vibratory hammer, however, the unplugged pile would have more shaft resistance).

The GRLWEAP penetration speed values, calculated assuming GRLWEAP recommendations for quake and damping, were much greater than the observed value. The analysis also suggested that the penetration speed calculation is rather sensitive to quake and damping assumptions. Also GRLWEAP would have indicated sudden refusal for not much higher SRD values.

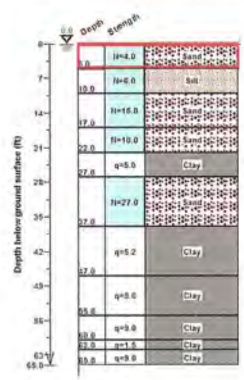

Figure 4: (left) Example soil properties.

Figure 5: (below) Example record showing force and Case Method resistance (top) and velocity (bottom).

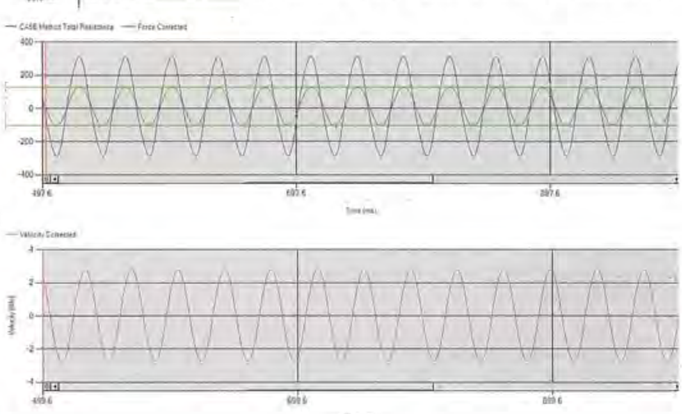

TABLE 1: Hammer and Pile Performance Results at 60'

Eccentric Moment	**(ICE-66-80, rated)**	**inch-kips**	**6.62**
Frequency	Rated	Hz	26.7
	Measured (Actual)	Hz	27.5
Force	Rated Centrifugal	kips	483
	Actual Centrifugal	kips	512
	Measured at sensor location	kips	337
	GRLWEAP at top	kips	286/479
Stress	Measured at sensor location	ksi	5.6
	GRLWEAP stress range	ksi	5.6/8.5
Power	Measured average-transferred	kW	254
	Measured peak-transferred	kW	783

TABLE 2: Capacity and Penetration Speeds at 60'

	Capacity	**Pen.Speed**
	kips	inch/s
Measured Penetration Speed		0.29
GRLWEAP (LT)	222/387	2.42/0.95
GRLWEAP (SRD)	187/340	3.2/1.4
CAPWAP (start of impact driving)	360/400	
SRD range from PDI-Vibro	128/409	

More details on this project are found in the Project Spotlight article "Cleveland's Innerbelt Bridge Project" in this edition of PileDriver magazine.

Recommendations

This review of available methods for preconstruction analysis and pile driving monitoring for vibratory driven piles is very limited, but it shows that both wave equation analysis and Case Method measurements can be employed for vibratory analysis and bearing capacity estimates which, at least in the example, are as good as static formulas.

While the results obtained are not unreasonable and maybe helpful in practice, more experience is needed. Only with experience will we get to the point where capacity and driveability assessments can be made with a higher confidence. The pile driving industry would certainly benefit greatly if the rather economical vibratory installation methods were more widely used and if the prediction of penetration speed and the determination of bearing capacity could be improved. For more precise driveability predictions, this would require preconstruction analyses, penetration speed measurement and PDA monitoring during driving. For soil resistance assessments, as is current practice, instrumented impact restrike testing and CAPWAP analysis must be conducted and the results compared with the SRD values from the end of vibratory installation. ▼