Using the Pile Driving Analyzer

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The advent of the wave equation analysis in the mid-seventies was a quantum leap in foundation engineering. For the first time, a design could consider the entire pile driving system, such as wave propagation characteristics, velocity dependent aspects (damping), soil deformation characteristics, soil resistance (total as well as the distribution of resistance along the pile shaft and between the pile shaft and the pile toe), hammer behavior, and hammer and pile cushion parameters.

The full power of the wave equation analysis is first realized when combined with dynamic monitoring of the pile during driving, that is, the recording and analysis of strain and acceleration induced in the pile by the hammer impact. It was developed in the USA in the late 1960's and early 1970's by Drs. G. G. Goble and F. Rausche, and co-workers at Case Western University. It has since evolved further and, as of the early 1980's, it is accepted all over the world as a viable and valuable tool in geotechnical engineering practice.

As is the case for so much in engineering design and analysis, the last few decades have produced immense gains in the understanding of "how things are and how they behave". Thus, the complexity of pile driving in combination with the complexity of the transfer of the loads from the structure to a pile can now be addressed by rational analysis. In the past, analysis of pile driving was simply a matter of applying a so-called pile driving formula to combine "blow count" and capacity[1)]. Several hundred such formulae exist. They are all fundamentally flawed and lack proper empirical support. Their continued use is strongly discouraged.

When Capacity is the Issue

Pile driving consists of forcing a pile to penetrate into the ground by means of a series of short duration impacts. The impact force has to be greater than the static soil resistance, because a portion of the force is needed to overcome the dynamic resistance to the pile penetration (the dynamic resistance is a function of

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1) In the past, when an engineer applied a "proven" formula — "proven" by the engineer through years of well-thought-through experience from the actual pile type and geology of the experience — the use of a dynamic formula could be defended. It did not matter what particular formula the engineer preferred to use, as it was the engineer's experience, knowledge, and good judgment that controlled. That solid experience is vital is of course true also when applying modern methods. The engineers of today, however, can lessen the learning pain and save much trouble and costs by relating their experience to the modern methods. Sadly, despite all the advances, dynamic formulae are still in use. For example, some Transportation Authorities and their engineers even include nomograms of the Hiley formulae in the contract specifications, refusing to take notice of the advances in technology and practice! Well, each generation has its share of die hards. Centuries or so ago, they, or their counterpart of the days, claimed that the Earth was flat, that ships made of iron could not float, that the future could be predicted by looking at the color of the innards of a freshly killed bird, etc., refusing all evidence to the contrary. Let's make it absolutely clear, basing a pile design today on a dynamic formula shows unacceptable ignorance and demonstrates incompetence. However, one must not forget that even the most sophisticated computer programs do not necessarily produce good results unless linked with experience and good judgment.

the velocity of the pile). Mass of the ram (hammer), ram impact velocity, specifics of the pile helmet and of cushioning element such as hammer and pile cushions, as well as cross section of the ram, and cross section and length of the pile are all important factors to consider in an analysis of a specific pile driving situation. Of course, also the soil parameters, such as strength, shaft resistance including its distribution along the pile, toe resistance, and dynamic soil parameters, must be included in the analysis. It is obvious that an analysis to be relevant requires that information used as input to the analysis correctly represents the conditions at the site. Unfortunately, the persons doing the WEAP is not always furnished with the required information.

The soil resistance acting against a pile that is forced down by the hammer is approximately the same as the resistance developed from an excessive static load on the pile. Both resistances are governed by the effective stress in the soil. Therefore, to estimate in the design stage how a pile will behave during driving at a specific site requires reliable information on the soil conditions including the location of the groundwater table and the pore pressure distribution.

The design of piles for support of a structure is directed toward the site conditions prevailing during the life of the structure. However, the conditions during the pile installation can differ substantially from those of the service situation—invariably and considerably. The installation may be represented by the initial driving conditions, while the service situation may be represented by the restrike conditions.

Numerous tests performed by a large number of persons all over the world show indisputably that the static resistance determined from a CAPWAP analysis of the recorded values strain and acceleration is representative for the static capacity of a the pile. That is, were we able to perform a static test **immediately** before or after recording a blow, the capacity determined in the CAPWAP analysis of the blow records and the capacity shown in a static test will be equal (within reasons—different definitions of pile capacity applied to the results of a static loading test may give very different values of capacity).

The PDA takes a snapshot of a situation. The facts are there and they can be subjected to unbiased analysis and assessment of the pile capacity. Much like examining a photograph of a truck being loaded with dirt at a site enables one to assess if the truck was full, next to full, or barely full on the occasion of the "photo session". From the snapshot, one can also estimate if the loader (also shown, say) would be able to continue to fill the truck or only be able to fill it to a certain limit (governed by the size and reach of the loader). Of course, a correct statement as to what amount of dirt the truck will finally take away means that one must apply a bit of experience and a portion of common sense—engineering judgment. Lacking that, well. . . In any case, it is easier to assert the final amount of dirt in the truck from examining a snapshot taken when the loading of the truck is finished. Similarly, taking "the PDA snapshot" when the conditions are more representative for the long-term service conditions is preferable to when conditions are not so representative. That is, if we are concerned primarily with bearing capacity in the long-term, the analysis should be made on a restrike blow rather than a blow from the initial driving.

In restriking, the pore pressure distribution, and, therefore, the resistance distribution is very different to that during the initial driving. For this reason, a pile construction project requiring verification of capacity normally involves testing piles at restrike. Usually, the restrike observation indicates that a useful amount of set-up has occurred. (Notice, it is not possible to quantify the amount of soil set-up unless the hammer is able to move the pile). Sometimes, the restrike will show that relaxation, i. e., diminishing capacity, the opposite to soil set-up, may have occurred.

However, foundation engineers should be concerned with the conditions at **both** initial driving and restrike, that is both at construction and in service. Information of importance at the outset of the pile driving are the site conditions, including soil profile and details such as the following**:** will the piles be driven in an excavation or from the existing ground surface, is there a fill on the ground near the piles, and where is the groundwater table and what is the pore pressure distribution. Additional important information is**:** will the soils be much remolded by the driving and develop large and excess pore pressures that will take long time to dissipate? Is there a risk for the opposite, that is, dilating conditions, which may impart a false resistance? Could the soils become densified during the continued pile installation and cause the conditions to change as the pile driving progresses?

The best value of the dynamic test data is obtained when information and answers to questions such as these are combined with the measurements and analyses. The PDA must not be looked upon as the only tool to use at a site. It cannot work in a vacuum.

There are those who will happily extrapolate the results of a static loading test, where the reaction load fell short, saying that it is so obvious that "failure" was not reached and therefore the capacity must be at least a 100 kips larger than the maximum test load. One must be grateful for the fact that a similar benightedness rarely occurs amongst CAPWAPpers in the parallel case of a pile driving hammer not being able to move the pile. If the hammer is too small or too light, then, the CAPWAP determined capacity only reflects the resistance Nature needed to mobilize to resist the driving and this may be short of the ultimate resistance. The first rule of dynamic testing is that the pile driving hammer must be strong enough to mobilize the pile ultimate resistance. Far too many still believe that the CAPWAP value at all times is equal to the ultimate resistance of the pile. Notice, one always gets a value from a calculation. It behooves the engineer to assess the relevance of the value.

On occasions, the hammer is quite able to drive the piles to a depth where after set-up the piles have the desired capacity, but the hammer is unable to mobilize the final capacity in a restrike. This does neither mean that the hammer is not good enough for the job, nor that the PDA is no good (because the restrike CAPWAP would probably be smaller than the actual capacity). There are many ways the PDA and CAPWAP can be used in this situation to positively assure the long-term pile capacity.

The routine static loading test cannot provide more than a minimum of information on the distribution of resistance along the pile. How much is along the shaft and how much at the pile toe? In contrast, the CAPWAP analysis does provide information on the resistance distribution. Having the choice between one static loading test on the one hand and on the other a couple of CAPWAP analyses on PDA records from initial driving and restrike of three or four piles, I'd choose the PDA and CAPWAP every time. Not just because I would save costs and time, but also and primarily because I would know more, have more confidence in the design, do a better job for my client, and worry less about my liability for the job.

Performing a static loading test can still be very useful for a piling project. By all means, the static loading test is not made redundant by the dynamic test. However, the one-night stand, "standard method" gargoyle of a test is pointless. Not so, however, a static loading test where strain gages have been placed in the pile and the test designed eyeing the specific geotechnical questions needing answer at the site. The static loading test becomes particularly useful and worthwhile if supplemented by dynamic testing of piles at the site at initial driving and restrike.

Let me reiterate, the capacity determined in a CAPWAP analysis and the capacity evaluated from the load-movement curve of a static loading test—properly performed, analyzed, associated in time, and associated in conditions with the dynamic test—will be the same! The "same" means that the capacity values are within about 15 % to 20 % of one another. The "*properly . . . associated in time*" is a very important. The restrike one hour after the initial driving and the static loading test one week later may or may not be a proper association. Nota bene, "non-association" testing is not useless by any means, as long as it is understood to be a bit of an apple and a bit of an orange. Equally important is the "*properly . . . associated in conditions*". Such conditions are that material changes should not have occurred to the pile between the two testing occasions due to time—of course—but also due to adding fills, excavating, draining or charging the groundwater, etc. Many, some very ambitious studies of correlation between static and dynamic tests are nothing more than attempts to cook a witches brew spiced up with a "*new, improved, coefficient or correlation factor*", or other "whitening agent".

From my more than twenty years of continual practice with the PDA, I have numerous examples of good agreement between capacity determined from dynamic and static tests. On quite a few occasions, I have also met with situations where the static and dynamic (CAPWAP) did not agree. Where **reliable** information on details the static test and conditions was available (a minority of the cases,), on all but one case, the static loading test was in error, not the CAPWAP analysis. The one case where the results of the static test were properly obtained and yet the capacities differed between the methods was with a pile driven in a collapsible, uniform fine silt, one of the most difficult materials for a geotechnical engineer to work with. And, which of the two capacity values was the correct, if any? Actually, pile foundation design for this case should not and was not let to be governed by the here overly simple capacity approach.

When Capacity is not the Issue

Obviously, the PDA records are useful also for other purposes than determining pile capacity. Hammer assessment is generally the first that comes to mind. As important as the value of transferred energy is the consistency of the value. One should not just use the value of transferred energy, EMX, to assess a hammer as adequate or not adequate. The EMX value can be low because the hammer is oversize in relation to the pile, or the pile is unloading early (velocity becomes negative well before 2L/c). Impact force is always a necessary corroborating value. Notice, no such assessment must be made on values from a single blow, but assess a hammer on its consistency of performance. Monitor the entire driving and present the results in a diagram along with soil layering and borehole results. Engineering judgment is based on information. If we limit the information, to where do we relegate the judgment?

Does anyone believe that a hammer that has seen many years of service at construction sites in all weathers, been given minimal maintenance and cleaning, etc. will provide the same energy and impact force as one more of less fresh out of the factory? The PDA records will tell the difference between hammers. Notice, a hammer that has low "test values" might still do the job it is set to do. Many specs require a hammer that is stronger than necessary.

Does the System Still Need Development?

The current state of analysis of PDA records is good, but more can be done. As the foundation design practice slowly is improving beyond the ungainly SPT-and-factor-of-safety approach and advancing toward design for deformation—for serviceability—we need to have better means of estimating pile toe-deformation under load. The old quake concept (elastic-plastic soil behavior) is too crude. Reality is more complex and more advanced models are necessary so that the results can be used in movement analysis. We need to get a better way to separate shaft and toe resistances. As of now, the effect of residual load blurs the picture too much.

However, it is necessary that the persons using the PDA results (whether they are those taking the records or those using them afterward) must understand that they have to incorporate information on the soil layering and soil characteristics, the groundwater and pore pressures, and other geotechnical matters and bring this information to par in quality with the dynamic records. This does not need research and development, but it does take education and willingness to learn. I think it is too important a subject to be left to the academic community. I think that the PDCA is a very suitable body to undertake a series of two-day courses to educate members as well as clients about the design and construction, advantages and limitations, and testing and performance verification of the driven pile?

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