Performance of a lifetime

The Stress Wave 2000 conference is being held in São Paulo, Brazil this month. Frank Rausche kicks off *GE's* special focus on dynamic pile testing, charting the history of techniques and examining the latest developments.

Over the past three or four decades, foundation engineers have designed piles with ever-increasing lengths and cross-sections for higher and higher loads. Today, we may see steel piles up to 500m long or 4m in diameter, and concrete driven piles can be handled in unspliced lengths of 50m with 1.5m width or diameter.

High strength materials and better quality assurance measures have allowed for a more economical use of pile material. Engineers have been able to justify higher and higher allowable loads for the same cross-sectional properties.

This progress in piling technology was only made possible by prudent application of a variety of new or improved monitoring and testing procedures. The foundation designer now not only considers the strength of soil and pile but also how to construct the foundation and how to assure its performance. Even though the majority of engineers still use an allowable load design approach, they generally agree that the global factor of safety can be reduced when a greater effort is made to verify both integrity and geotechnical performance of the foundation element. In several countries this approach has been formalised in building codes, based on the factored load and resistance approach.

Quality assurance of deep foundations is achieved with more frequent testing using a variety of new or improved methods. Static load tests now employ more accurate measuring tools – instrumentation along the pile length and feedback controls to maintain precise loading rates. Static loading at the pile toe with the shaft resistance as a reaction force (for example the Osterberg cell) allows combined test loads in excess of 100MN. Slow dynamic tests (eg the Statnamic method) have generated pile-top load-set curves both as a replacement for static tests at a reduced cost and to simulate seismic events. Most importantly, modern stress wave-based methods help with job preparation and installation of driven piles and also with load and integrity testing of all deep foundations at low cost and with little delay.

Because of their speed and economy, stress wave methods have penetrated practice to such a degree that the Swedish Geotechnical Institute organised the first International Stress Wave conference in Stockholm in 1980. The event brought together a wide range of researchers, testers, contractors and geotechnical engineers. It has since been held every four years, and this year it is in São Paulo, Brazil, where dynamic pile testing methods have enjoyed general acceptance over the last 20 years.

A variety of stress wave-based testing methods are available. These include:

- the wave equation analysis for pile design and equipment selection during job preparation
- dynamic pile monitoring during installation of impact driven piles
- dynamic pile load testing for driven piles and drilled shafts
- pulse echo and transient response integrity tests
- cross-hole sonic logging for drilled shafts.

By the 18th century, mathematicians were studying dynamic pile stresses using a solution of the one-dimensional linear wave equation. For rational equipment selection, even the effect of ram to pile weight ratio on pile driveability was investigated for relatively simple situations. Today, computer simulations of pile driving, based on a discrete numerical solution of the wave equation, provide more realistic results for complex hammer-pile-soil systems.

The most popular software is based on the approach developed by EAL Smith of Raymond International shortly after the Second World War. Smith provided an algorithm and an analysis procedure complete with recommendations for the required model parameters, primarily to solve stress problems in non-uniform piles. The wave equation approach is particularly popular among contractors for equipment selection during the bidding process and for job preparation.

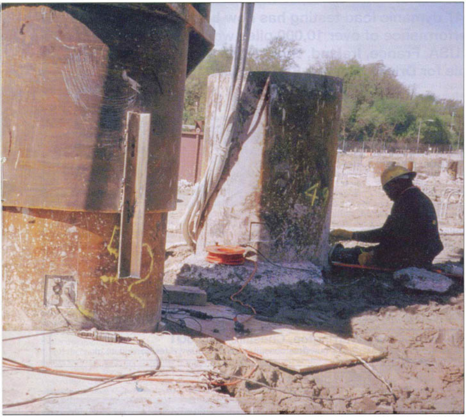
If it were possible to accurately predict both the stresses in the pile and the pile set during a hammer blow, then pile damage or unexpected pile driving behaviour would never occur on site. However, hammers, driving systems (eg packing) and soils often behave unexpectedly. The best means of both avoiding pile damage due to overstressing and assuring that driving equipment and the soil behave as anticipated is to measure during installation.

Electronic stress measurements were being carried out in the UK in the late 1920s, but routine measurements only became feasible in the 1960s. At the time, the Case method was developed in the US and incorporated in the so-called Pile Driving Analyzer (PDA). The Case method is also called a high-strain method and requires the measurement of pile-top force and velocity during hammer impact. Closed form solutions to the wave equation applied to the measurements allow calculation of pile stresses, pile integrity and hammer performance for each hammer blow during pile driving. Most notably, the universally accepted Case method formula calculates the static soil resistance at the time of testing. Typically, when monitoring a driven pile, various results are calculated for each hammer blow and then plotted as a function of depth. In real time, the experienced PDA engineer checks the PDA output and its agreement with installation specifications.

PDA testing on a steel pile.

Dynamically determining pile bearing capacity has always been attempted by the pile driving profession. Developed in the 19th century, the dynamic formula considered the hammer energy and the set of the pile per blow (or an average set) to find bearing capacity. Although often modified for improved correlation with static load test results, formula results were frequently too conservative and occasionally unsafe.

Replacing the formula with Smith's wave equation approach produced a more accurate relationship between pile set per blow and bearing capacity. However, engineers quickly realised that this more accurate method determined the bearing capacity at the time of testing which was not necessarily equal



PDA instrumentation on a 1,200mm diameter drilled shaft in preparation for a test with a 25 tonne ram with 2,000 tonne test load.

to the pile's long-term capacity, because of time-dependent soil strength changes. Restrike testing, some time after pile installation, was found to be the only accurate solution, short of guessing what the soil set-up effect would be.

As dynamic load testing became more and more accepted, so did restrike testing with PDA instrumentation to avoid the uncertainties associated with observed hammer energy and assumed dynamic soil behaviour. Since 1970, signal matching has replaced the simpler Case method for calculating bearing capacity from force and velocity records. For example, the CAPWAP software package calculates the resistance distribution and a dynamically determined pile-top load-set curve.

With a special ram, dynamic load testing carried out some time after pile installation can be applied on a drilled shaft as well as a driven pile. Test loads reaching 30MN have been generated in this manner.

In an attempt to simplify the dynamic loading apparatus for drilled shafts, a Canadian-Dutch co-operation developed a system in the 1980s in which a reaction mass is lifted by the forces of a rapidly combusting material while loading the pile. Since the combustion is five to ten times slower than the impact duration of a falling ram, this test is considered a nearly static dynamic test – a "Statnamic" test. A stress wave analysis of its measurements is not very meaningful because of the slow loading rate and a simple dynamic analysis is generally used to calculate the load-set curve.

Non-destructive evaluation methods have found their way into the piling industry since the early 1970s when research and development efforts in France, the Netherlands and the UK established a basis for both the low-strain methods of pile testing and the cross-hole sonic logging method. These are generally only useful for concrete piles, either drilled or driven. The low-strain method involves tapping the pile with a light, hand-held hammer and the resulting pile-top motion is recorded and then interpreted in either time (pulse echo method) or frequency domain using stress wave theory.

The challenge is to correctly identify pile discontinuities such as bulbs or necks from wave reflections appearing in the pile-top records. Another variation, the parallel seismic method, can be used to determine foundation depth. A borehole is sunk near the foundation and is filled with water. When a foundation is hit with a hammer, a stress wave travels quickly through the foundation but slowly through the soil. Thus, the arrival time of the wave in the borehole, measured with a hydrophone, identifies foundation depth.

In the cross-hole sonic logging method, typically 50mm diameter steel or plastic tubes are installed in the pile. After the concrete has hardened, an ultrasonic transducer emits a signal in one tube and a receiver measures its arrival in a neighbouring one. The calculated stress wave speed is an indirect and relative indicator of concrete quality. A variation of this involves a transmitter and receiver both placed in the same hole and gamma radiation instead of ultrasonic sound pulses as the signal source. The single hole method is often used on smaller piles such as continuous flight auger piles, sometimes even when the concrete is still wet. Using gamma rays tests a wider path between the tubes, allowing a check of the cover of the reinforcement.

There are, of course, limitations to all of these methods. Dynamic load tests have to be evaluated with great care to separate dynamic from static resistance components and to assess the time effects on the soil, unless long waiting times can be allowed between pile installation and test. Pile damage assessment during pile monitoring is limited to effects that reduce the axial stiffness of the pile. The low-strain method can neither test very long piles nor those with high soil resistance or complex geometries. The cross-hole test may break down if the tubes separate from the concrete due to shrinkage. An inconclusive result and detection of a defect may cause tempers to flare on a construction project. However, most serious disagreements between testing firm, contractor, engineer and client can and should be avoided by establishing a clear understanding of the resolution of negative test outcomes, before testing begins.

Stress wave-based measurements for both integrity and dynamic load testing have been standardised in several Asian and European countries, Australia, Brazil and the US. Construction codes in several countries, including Australia, Brazil and China, specify the required number of dynamic load tests and the required factors of safety. Various construction specifications in the US contain similar provisions.

Digital technology has made operation of stress wave-based pile testing equipment reliable and relatively simple. However, data interpretation is complex and frequently requires experts on site. This leads to problems with scheduling and excessive travel of senior engineers.

Developments are therefore needed in two different areas: interpretation based on expert systems or artificial intelligence and automated analysis procedures; and remote monitoring using direct telephone hook-ups or internet-based communication from sensor to the expert.

There is still a lot of work to be done and the Stress Wave 2000 conference in São Paulo is one important step in this development.

Frank Rausche is president of Goble Rausche Likins and Associates and was one of the pioneers of the modern application of stress wave theory to foundation integrity testing.