Understanding Dynamic Pile Testing and Driveability

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INTRODUCTION

Traditionally, piles are "static" load tested by loading the pile top with huge blocks of concrete. This is a very costly, but is the most direct approach. In recent years, dynamic pile load test has become widely accepted as an alternative to the static load test due to its advantages of being cheap, simple and fast. The same technology is used to perform pre-installation dynamic pile driveability analysis to assess the driveability and selection of hammer.

It is expected that the dynamic pile testing will gain even wider usage in future due to its economical advantage. However, most practicing engineers do not have access to the background and basics of this method as it is deemed a "specialist's" job. The purpose of this article, therefore, is to present the fundamentals of this method, illustrating what the method is all about and more importantly how to derive correct conclusions from the test results. Some of the associated geotechnical issues are also discussed.

DESCRIPTION OF THE DYNAMIC TEST METHOD

One of the more commonly used dynamic test equipment is from Pile Dynamics Inc.[1], USA. The hardware consists of strain and accelerometer gauges connected to a Pile Driving Analyser® (PDA). The PDA essentially is a computer loaded with software to capture the strains and accelerations measured near the pile top, which then computes a closed-form solution of the pile-soil-hammer system in real time. An illustration of a typical test set-up is shown in Figure 1.

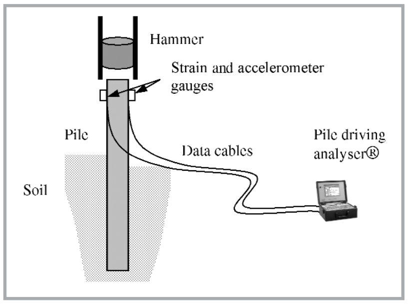

Figure 1: Typical dynamic pile test set-up

Each blow of the hammer creates a stress wave on the pile top, which travels down the pile. The gauges mounted on the pile just below the hammer measure the strains and accelerations as the wave travels down. The pile material and soil surrounding the pile dampen, transmit and reflect the wave as it travels down the pile. At the pile tip, the wave is reflected back to the top. As it reaches the top, the gauges measure the strains and accelerations due to the returning wave. Knowing the stiffness of the pile, the force can be calculated from the strain measurements. Further, the accelerations can be integrated over time to yield the velocity. The force and velocity measurements are the principal data used in the PDA to compute the unknown soil resistance. In most applications, the hammer is not instrumented and only the pile-soil system is considered and analysed.

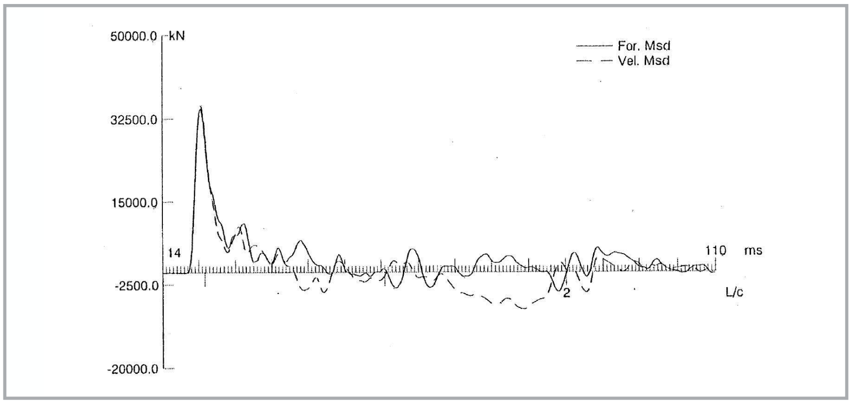

Figure 2: Typical force and velocity trace measured for an offshore steel pipe pile

If the dynamic test is performed during driving, the soil resistance so determined is the soil resistance to driving, commonly referred to as SRD. If the dynamic test is performed shortly after the pile has been installed, it is called a "re-strike" test. If the dynamic test is performed many days after the pile has been installed, it is usually for the purpose of estimating the ultimate static pile capacity. Normally, a wait of at least one week after installation is recommended. In offshore installations, such delay cannot be accommodated. Therefore, the re-strike test is commonly used as a crude "indicator" of the possible long-term capacity.

A typical force and velocity trace for an offshore steel pipe pile installation is shown in Figure 2. By examining the force and velocity trace, a trained engineer will be able to make a diagnosis of the characteristics of the pile-soil-hammer system and detect any abnormalities in the pile driving. Explanation of the characteristics of the force and velocity trace is given in the subsequent sections.

ANALYTICAL FORMULATION OF THE DYNAMIC TEST METHOD

A summary of the historical development of the dynamic test method can be found in the thesis by Wong[2].

Current dynamic test method is based on a one-dimensional wave propagation theory. For a stress wave traveling down a pile due to a hammer impact on the pile top, the compression force and velocity are related by the simple equation;

$$F = Zv \qquad (1)$$

where F = compression force, Z=EA/c, called the impedance, and v is the velocity. E is the Young's modulus, A is the cross-section area, and c is the wave speed. For a given material, E, A and c are constants. As the wave travels down the pile, any change in the pile impedance, such as changes in section area, splices, or defects, will cause the wave to be reflected. The governing equations for the force and velocity transmitted and reflected at points of impedance change are given by;

$$F_t = 2F_i/(1+\beta) \qquad (2)$$

$$F_r = F_i/(1-\beta)/(1+\beta) \qquad (3)$$

$$v_t = v_i 2\beta/(1+\beta) \qquad (4)$$

$$v_r = v_i(\beta-1)/(1+\beta) \qquad (5)$$

where the subscripts i, t and r stand for incident, transmitted and reflected respectively. β is the ratio of impedance before and after the section considered, ie. $\beta = Z_1/Z_2$.

In addition to changes in the pile impedance, the soil resistance along the pile will also affect the wave propagation. Part of the incident wave will be reflected due to the soil resistance. The governing equations for the force and velocity transmitted and reflected due to soil resistance are given by;

$$F_t = -R/2 \qquad (6)$$

$$F_r = R/2 \qquad (7)$$

$$v_t = v_r = -R/(2Z) \qquad (8)$$

where R is the soil resistance.

The force or velocity trace at the pile top due to a hammer blow therefore, can be analytically computed by applying the above equations to a discrete finite element model of the pile-soil-hammer system and solving it in the time domain. The wave input can be either the measured force or velocity. By suitably adjusting the soil model, the computed force or velocity trace can be made to match the actual measured value. Once this is achieved, the soil model is said to represent the actual soil condition. The resulting soil model then provides the required information on the soil resistance and its distribution along the pile length. The pile model usually is a known input, except where it is required to determine unknown "defects" in piles, such as in testing integrity of cast-in-place concrete piles. In this case, the pile model can also be iterated accordingly to produce the appropriate wave matching.

An illustration of a typical pile-soil-hammer system is shown in Figure 3. During actual pile driving, there will not be adequate time to perform the above analysis for each blow as the solution is an iterative process and requires user input to confirm an acceptable match. A simplified closed-form solution therefore is used during driving to estimate the soil resistance and pile stresses. The values obtained are only an estimate and should be confirmed later with a detailed analysis of each blow using the above technique. For pile monitoring, the real time visual examination of the force and velocity trace, such as that shown in Figure 2, will be made instantaneously by the test engineer. A trained engineer will be able to detect anomalies in the pile driving by simply observing the force and velocity trace of each hammer blow.

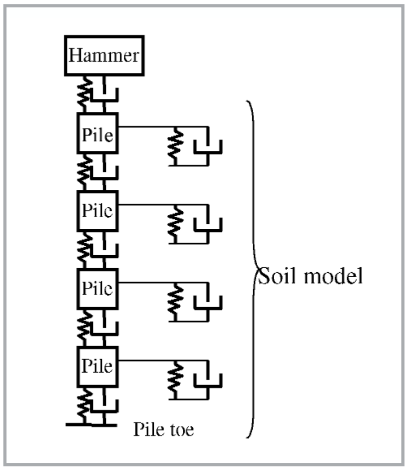

Figure 3: Typical pile-soil-hammer finite element model

BASIC CHARACTERISTICS OF THE FORCE AND VELOCITY TRACE

Equations (2) – (8) form the fundamental tool for the dynamic test method. By applying equations (2) – (8) on special cases of pile-soil boundary conditions, the characteristics of the force and velocity trace can be revealed clearly. Four special cases are shown in Figure 4 for illustration. In Figure 4(a), the pile is a "free rod". The reflected force from the pile tip will be a negative pulse.

The reflected velocity from the tip however, will be a positive pulse. Conversely, for a pile on end bearing as shown in Figure 4(b), the reflected force and velocity from the pile tip will be positive and negative, respectively.

For a more realistic condition where the pile is embedded with distributed soil resistance as shown in Figure 4(c), the force trace will consist of an initial pulse due to the hammer blow, which decreases gradually due to the reflected wave from the distributed soil resistance. At the time 2L/c, where L is the length of the pile, a small upward pulse may be observed due to the returning wave from the pile tip. The velocity trace similarly will consist of an initial pulse due to the hammer blow, which decreases quickly due to the reflected wave from the soil resistance. At time 2L/c, a small downward pulse may be observed due to the returning wave from the pile tip. For the case where there is a discontinuity at distance x from the pile top as shown in Figure 4(d), a downward force pulse will be observed at time 2x/c due to the reflected wave from the discontinuity. At the same time 2x/c, the velocity trace will show an upward pulse due to the same reflected wave. In general, a downward force pulse and an upward velocity pulse before time 2L/c will indicate abnormalities such as a crack, a splice, or "necking". Armed with this understanding, it is possible to detect the condition of piles by simply observing the force and velocity trace during pile driving. This is the basis of the dynamic pile monitoring. Figure 4 can be used as a guide to assess piles in other various situations.

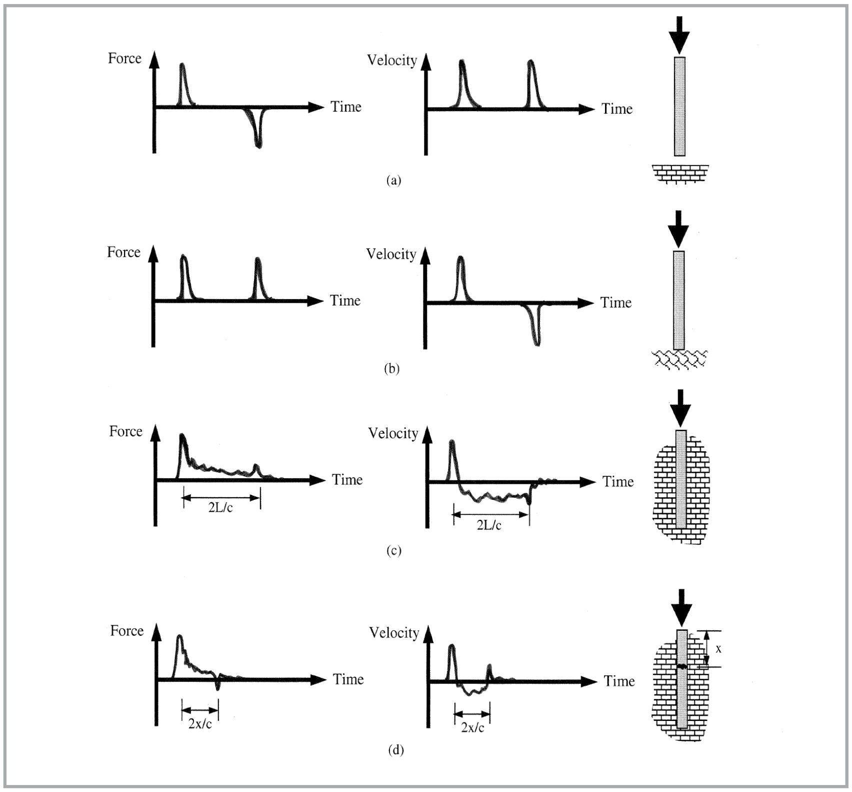

Figure 4: Force and velocity trace for special cases of piles

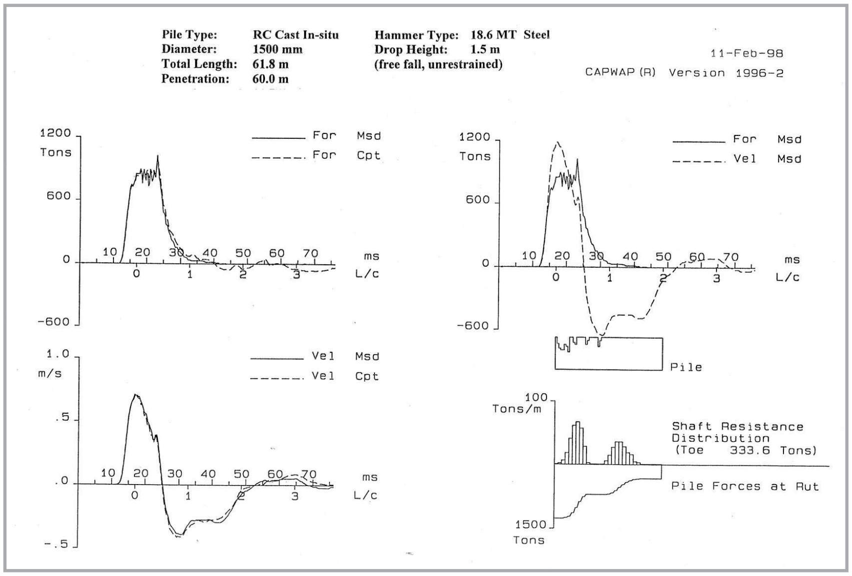

Figure 5: CAPWAP® results for a concrete cast-in-place pile

APPLICATION OF THE DYNAMIC TEST METHOD

The dynamic test method has been codified as a standard test method in ASTM D4945 [3]. In the field, the PDA computes the closed-form solution to determine the soil resistance and pile stresses instantaneously for every blow. The force and velocity time-histories are stored on the computer and retrieved for further analysis in the office.

Back in the office, a software such as CAPWAP® [4] is used to analyse the pile-soil system using the measured force and velocity time-histories. For each hammer blow, the test engineer will assess the quality of the recorded signals and decide whether the force or velocity is to be used as the input wave, and the corresponding velocity or force as the output wave to be matched analytically. The software will iteratively modify the soil model until a "best-fit" match is obtained. The test engineer will then use his knowledge and judgment to manually fine-tune the soil model parameters until he is satisfied that an acceptable and reasonable result is obtained. The resulting soil model then provides the main information required from the test, namely the soil resistance and its distribution along the pile length. The pile stresses and movement due to the test hammer impact are also reported.

An example of an output from a CAPWAP® analysis for a cast-in-place concrete pile test is shown in Figure 5. The set-up for this pile test is similar to that shown in Figure 6, which was performed at a remote site in the Philippines. As shown next to the force and velocity measurements in Figure 5, the illustration of the computed impedances suggested defects near the pile top. After the test, the pile top was excavated and revealed the defects, which was due to mud inclusions.

Each hammer blow produces adequate force and velocity measurements for a complete test. As the soil resistance changes when the pile is driven in the dynamic test, it is crucial NOT to perform more hammer blows to conduct the dynamic load test.

In the construction of offshore platforms, a re-strike test is often specified for the steel pipe piles after 24 hours of installation. In offshore Terengganu and Sarawak waters, a wait of 24 hours is often inadequate for full set-up. Therefore, a re-strike test typically will not show the required design ultimate capacity. The maximum soil resistance measured will be obtained from the initial hammer blow on a re-strike test. Subsequent hammer blows only serve to lower the soil resistance as the pile is being driven once again. This defeats the very purpose of a re-strike test. Unfortunately, re-strike tests are still being specified with up to one meter

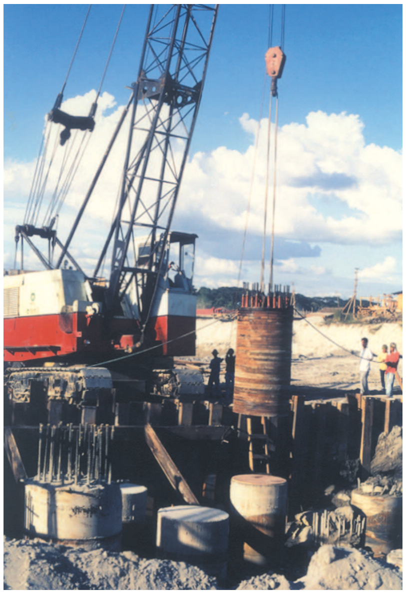

Figure 6: Dynamic pile test for a cast-in-place concrete pile

penetration during re-strike. By doing so, the pile loses its 24 hours set-up capacity and no additional information is gained. A typical steel pipe pile installation in offshore Terengganu is shown in Figure 7.

Figure 7: Typical steel pipe pile installation for offshore platforms

APPLICATION OF WAVE EQUATION FOR PILE DRIVEABILITY ANALYSIS

In the planning for offshore pile installation, it is necessary to perform a pile driveability analysis to determine the appropriate hammer/s to be used. The pile driveability analysis is based on the same wave equation model as used in the dynamic pile test, except that the input wave is analytically generated from the selected hammer instead of being measured. Further, there is no need to perform the wave matching exercise as the soil model is assumed and not iteratively determined. The analysis gives the estimated blow counts at various penetration depths. One commonly used software for performing the driveability analysis is GRLWEAP™ [5].

The accuracy of the driveability analysis is largely dependent on the proper soil model used. The three most important parameters used in the soil model are the resistance values (SRD) and the damping and quake values. For normal soil conditions, SRD is usually a fraction of the static ultimate soil resistance. Some engineers determine the SRD by taking a percentage of the static soil resistance while others prefer to use some form of remoulded strength values. For the purpose of hammer selection, a conservative SRD is normally used, i.e. a save upper bound strength value. This will ensure that the hammer selected will be adequate to drive the piles. For cohesive soil, SRD based on 30% of static ultimate value is normally considered an upper bound for continuous driving. This is consistent with the findings reported by Wong [2]. Actual or expected values are usually much lower. Sam and Cheung [6] has reported that the actual SRD value may be as low as 16% of static ultimate value.

Typical offshore piles are open ended steel pipes. During continuous driving, the pipe pile will penetrate in an "unplugged" manner. The SRD will act on the external and internal surfaces of the pipe, and end bearing on the annulus area of the steel. The internal soil column exerts a lower SRD than the external surface. Sam and Cheung [6] has reported that the internal column exerts about half the external value and further it is effective only for the lower half of the pile. Wong [2] has also indicated that the internal SRD is about 50% of the external and effective only for the bottom 50-75% of the penetration. Therefore, the internal SRD may be assumed to be 50% of the external.

From the driveability analysis results based on the upper bound SRD values, the appropriate size of hammer can be selected, by limiting the blow count to 300 blow/ft for example [7]. Actual pile driving, however, is expected to show lower blow counts compared to the predicted blow counts based on upper bound SRD values. This is expected and should not be a cause for concern.

It is still a common practice for offshore piles to be provided with extra length for "overdrive". This is probably inherited from the onshore practice, where piles are often driven not to specified length but to reach pile set. The set criterion determines the capacity in this case. However, offshore pile capacity design is normally based on the "static" approach [7]. Therefore, the "overdrive" length serves no purpose in this design approach, especially when the "overdrive" length is typically less than 5% of the penetration depth. Without the above understanding, an engineer may feel concerned when the actual blow counts are less than predicted based on upper bound SRD values. This may lead the engineer to conclude erroneously that the pile did not have adequate capacity and required the "overdrive". The provision of "overdrive" length is no longer the right approach. Any requirement for "overdrive" should have been incorporated in the base design. If the "overdrive" length were not used, then it would be a cost adder to transport it back to shore. Leaving the decision offshore to decide whether to drive the "overdrive" length usually result in a decision to drive. If this is taken, then it might as well be incorporated in the base design and eliminate the need to decide on a probably known decision.

When the "static" approach is used for the pile design, the installation criterion should be to drive to the designed depth. It is not practical, or even possible, to apply the blow count criterion, as SRD does not appear at all in the pile penetration depth design equation.

CONCLUSION

The background to the dynamic pile testing and wave equation driveability analysis has been presented. The interpretation of the test data was also explained. Application of the wave equation for driveability analysis has also been described. Associated geotechnical issues with regards to the proper use of the method have also been illustrated. ■

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