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Pile integrity testing and analysis

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ABSTRACT: The methods of installation of drilled shafts give rise to concern among engineers regarding the structural integrity of the shafts. This has led to a reluctance to use these foundations by some engineers. Alternatively, many engineers are willing to accept these foundations provided that adequate inspection and integrity verification testing are performed.

Low strain integrity testing has seen substantial improvement in recent years. The testing cost has been substantially reduced and, as a result, the methods are now widely employed. However, the results of these tests must also be accurately evaluated. The evaluation may be a simple visual inspection of the data by an experienced engineer. Recent improvements in analysis capabilities now offer less intuitive interpretations at a reasonable cost. These new automated procedures are superior to the visual techniques of the past both from the standpoint of operator required know-how and user confidence in results.

1 INTRODUCTION

Pile Integrity Testing (P.I.T.), a low strain method for integrity testing of driven piles and drilled shafts, uses a variety of techniques for the interpretation of force and velocity records taken under the impact of a light hammer blow (Rausche, Shen, Likins 1991). In its most basic form, the input pulse signals are inspected directly in the time domain for reflections or echoes and hence are referred to as the "Sonic Pulse Echo Method". The interpretation of the pile top velocity traces is further enhanced by an amplification which increases exponentially in time (Paquet 1968). This concept became practical with the development of digital data processing.

The advent of fast spectral analyzers made possible the development of the frequency domain Non Destructive Testing (NDT) methods generally applied to structural concrete. NDT was then applied to low strain pile testing resulting in the "Transient Dynamic Response Method" which displays the records in the frequency domain in a so-called mobility plot.

Interpretations in frequency and/or time domain are selected either according to individual preference or locally developed practice. Generally, civil engineers feel more comfortable in the time domain, particularly if they have been working with high strain Case Method testing. However, the experienced P.I.T. engineer should take advantage of all interpretation tools. This paper discusses various analysis methods applicable to a low strain test. It also compares the results obtained with different hammers and sensors.

2 EQUIPMENT

Three devices are needed to perform a low strain integrity test: the hammer (with or without force sensor), the sensor and the processor (Figure 1). The primary difference between various interpretation methods lies in the programming of the processor. The hammers and sensors are, with slight exceptions, very similar for transient dynamic response and sonic pulse echo methods.

2.1 The hammer

Depending on the pile size to be tested, the hammer mass should be between .5 and 5 kg. Smaller hammers have shorter rise times and higher frequency content, while larger hammers apply greater energies to the pile top. To

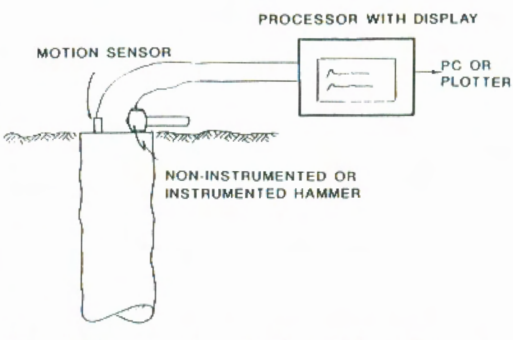

Fig. 1 Schematic of low strain pile integrity testing

be useful, the test must resolve pile deficiencies over short distances along the test shaft. Sharp, narrow input pulses are better suited for this task than wider ones and therefore smaller hammers are preferable. However, as the frequencies contained in a pulse increase, more energy is lost in the wave propagation and the ability of investigating a long pile decreases. Actually, it is often worthwhile to test with different hammer sizes on any site: the smaller hammer tends to reveal more detail about impedance variations (the product of shaft cross sectional size and concrete quality), while the larger hammer may be able to generate a pile toe reflection.

Figure 2 shows velocity records obtained under three hammer sizes on a 500 mm diameter drilled shaft of 6.1 m length and with a defect at 4 m depth. The soil consisted of hard and gravelly silt and clay. Obviously the smallest hammer did not have a significantly sharper signal than the medium sized hammer. On the other hand, the largest hammer did not improve the resolution of the pile toe signal, compared with the medium sized hammer, which would be the obvious choice for testing this shaft.

If the hammer blow causes damage to the pile top surface the signal is adversely affected by inelastic and non-repetitive waves. Therefore, the hammer's impact surface must be cushioned with a material which is soft compared to concrete but sufficiently hard to generate a short pulse duration. A good cushioning material takes the art out of hammering and aids interpretation of results.

The hammer may be instrumented to measure the applied force. Two systems are commonly employed: the pressure sensor and the accelerometer. The pressure sensor is located between the hammer's mass and the impacting surface, while the accelerometer is attached rigidly behind the mass. Typically, the measured force is one thousand times greater than the hammer weight (for the larger hammers the forces may therefore reach a momentary peak value of 50 kN).

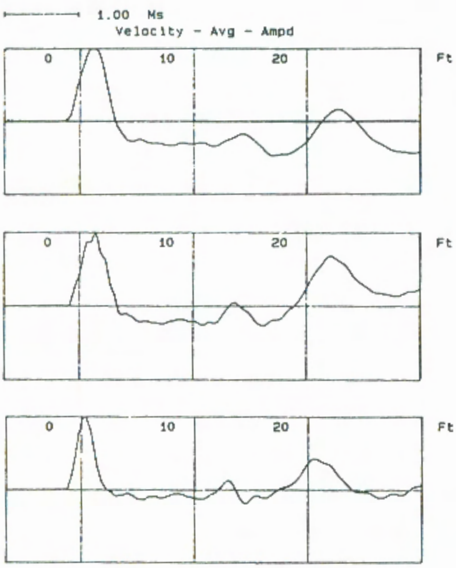

Fig. 2 Velocity traces from a 20 ft long pile taken with .9, .45, .22 kg hammer (top to bottom, respectively) - 1 ft = .305 mm.

Ideally, the frequency spectrum of the hammer force is a smooth, monotonically decreasing function. Small hammers tend to have non-monotonic spectra if their handles are relatively stiff and heavy (Figure 3). Such erratic force spectra adversely affects the mobility curves in an important frequency range. The hammer's response in Figure 3 was improved by "tuning" the hammer's handle.

2.2 The motion sensor

Motion sensors are either accelerometers or geophones. Although acceleration contains all the information, velocity traces are easier to interpret and therefore acceleration is digitally integrated. Geophones directly produce a velocity proportional signal.

Accelerometers and geophones have different properties in their high and low frequency ranges. Accelerometers, for example, yield more truthful results at high frequencies. Geophones have a lower frequency range but do not require the calculation of an integration constant. Geophones are generally heavier than accelerometers and therefore present more difficulty in the attachment process.

2.3 Processors

The development of the processors has evolved as the analysis techniques have matured. The sonic pulse was originally viewed only in the time domain on an analog oscilloscope, later results were obtained using a personal computer (Reiding, Middendorp, Van Brederode 1984), and today all data collection uses a small specialized unit. Figure 4 shows the "P.I.T. Collector" which signal conditions hammer and motion sensors, stores the data for later transfer to computer, performs calculations for data interpretation, and plots the processed data.

For sonic mobility analysis, initially a spectral analyzer was always necessary; however, modern PC's now perform fast Fourier transform (FFT) analyses and are therefore well suited to both time and frequency domain calculations.

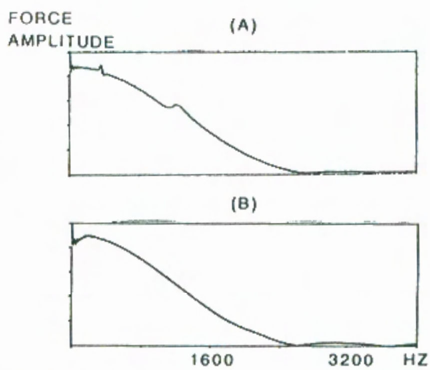

Fig. 3 Force spectra (A) from normal and (B) from a hammer with "tuned" handle.

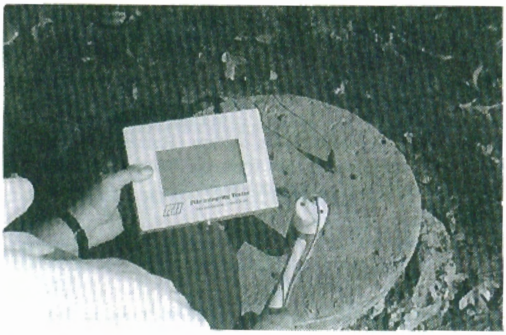

Fig. 4 P.I.T. Collector

3 DATA MANIPULATIONS AND ANALYSES

As discussed in the literature (Rausche, Shen, Likins 1991) the interpretation of the pile top velocity or mobility can be considerably enhanced with a few transformations. These manipulations will be demonstrated using an example test shaft recently prepared for the United States Federal Highway Administration at Texas A&M University.

3.1 Filtering

Probably all electronic measurements are filtered to remove unwanted signal components. In fact, most electronic amplifiers have an inherent built in frequency response limit. The most common filtering removes fully or partially those frequency components above some value, the nominal low-pass filter frequency. Conversion of continuous analog signals to discrete, digital representation requires a low-pass filter limit of at most one half of the sampling frequency. In P.I.T. the usual digitizing frequency is approximately 30 kHz and hardware low pass frequency response limits 10 kHz. Additional user controlled digital low pass filtering is sometimes necessary when unwanted high frequency components mask the important low frequency signal.

High-pass filtering removes low frequency components such as a constant shift or a slow drift. Velocity records derived from acceleration records have been unjustly blamed for an erratic low frequency behavior which then yield useless dynamic stiffness (see mobility calculations below). While accelerometers are dynamic instruments whose signals slowly drift towards zero, the average velocity (actually the zero frequency component) is always set to zero. This means that the displacement calculated from the velocity is also zero at the end of the record, surely a reasonable assumption considering the low impact energy. However, removing or reducing other low frequency components, as suggested by Paquet (1968) and demonstrated below, may distort records and would be tolerable only if exactly the same filtering is always applied. Clearly, the calculated stiffness values then only have relative value. However, such a relative effect can also be easily evaluated by merely comparing force and velocity at the time of impact.

3.2 Amplification

Before the signals are converted to digital form, they are usually amplified by the analog signal conditioning to take advantage of the full digitizing range (e.g., 5 volts). This assures that small signal changes are optimally resolved by the digital record. However, a high resolution analog-to-digital converter, such as the 16 bit A/D of the P.I.T. Collector, makes this less critical. The input wave returns at 2L/c after being reflected by the pile toe. Of course, since the wave then has traveled the longest distance, its magnitude is usually strongly reduced by either internal (concrete) or external (soil) damping. Reflections from defects are also reduced by these damping effects; defects which are at deeper depths are therefore more difficult to detect. A effect of uniform friction on detecting defects or the toe can be minimized by using an amplification which increases exponentially in time until time 2L/c. By applying this increasing amplification, extreme weak signals from deeper locations are more easily detected. However, in general, friction effects are not uniformly distributed and therefore the beginning of the amplification should be delayed until the time when the major friction effects begin. An example is given in Figure 5.a and 5.b. In this calculated example (pile length 20 m and high side damping of 5 times pile impedance) the pile toe response was practically invisible at time 2L/c but was clearly apparent after 25X amplification. The amplification started at 4 m with unit intensity and then increased exponentially as indicated below Figure 5.b.

3.3 Fourier transform and mobility

Fourier transformation of pile top velocity and force versus time signals leads to the corresponding velocity and force spectra. Dividing the velocity spectrum by the force spec-

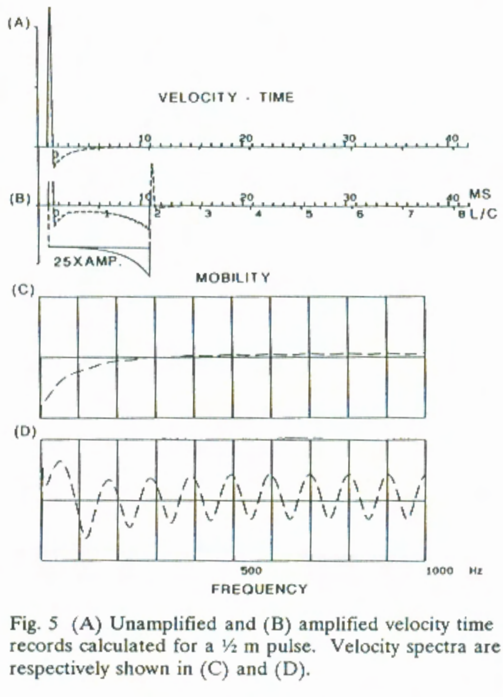

Fig. 5 (A) Unamplified and (B) amplified velocity time records calculated for a ½ m pulse. Velocity spectra are respectively shown in (C) and (D).

trum yields the mobility curve which normalizes the velocity spectrum (i.e., pile velocity response per unit force at each frequency). If the pile is infinitely long or critically dampened at its toe, then force and velocity both have exactly the same half sine wave appearance. Obviously, the mobility is then constant and exactly equal to 1/Z where Z is the pile impedance (elastic modulus times cross sectional area divided by wave speed). A pile with less than critical damping and no friction has greater mobility and a free pile has infinite mobility. In both cases, the mobility graph is not linearly increasing and does not begin at the origin. The frequency response in Figure 5.b shows a nearly constant behavior above 500 Hz because high soil damping reduces the toe response such that the pile behavior is similar to an infinitely long pile. Amplification (Figure 5.d) brings out the repetitive response peaks but strongly distorts the mobility graph near the origin. Thus, amplification is useful for pile length or defect detection but not for pile stiffness calculations.

The dynamic pile stiffness is only meaningful if the mobility is linear in the 0 to 100 Hz range. In order to check the pile stiffness concept, several cases were analyzed with an input pulse as in Figure 6, but with different resistance distributions, resulting in more or less concentrated negative velocities over the first 2L/c time period and with final pile displacements being zero. Clearly, the mobility behaves non-linearly near zero frequency, a fact that cannot be attributed to signal defects since all velocities were calculated. In summary, the stiffness analysis gives no absolute quantitative result.

3.4 Velocity reflectors

The so-called velocity reflectors are obtained when the velocity transform itself is subjected to an FFT. Of course, these "reflectors" have the dimension of velocity and are then again a function of length (or time) like the original signal. Choosing only the positive values of this FFT, the location of the pile toe signal often becomes quite clear. Also shaft defects can then frequently be located.

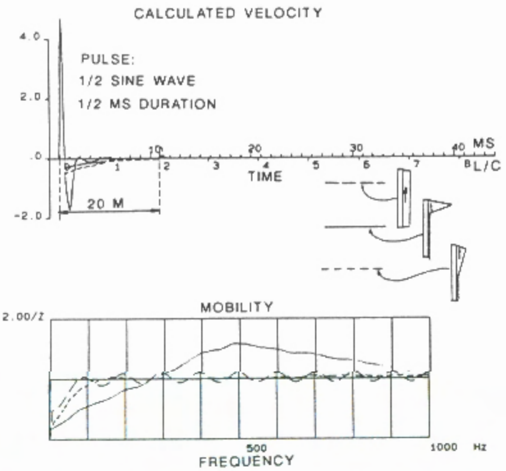

Fig. 6 Calculated responses for piles with different soil resistance distributions.

3.5 The Beta method

To assess the relative change of a cross section from an observed upward wave arrival in the pile top velocity record, the Beta value can be calculated based on simple wave mechanics. This number is the ratio of lower to upper pile impedance or cross section (Rausche, Goble 1979) and is easily calculated from the relative magnitude α of the reflection to the impact wave.

$$\beta = \frac{1-\alpha}{1+\alpha} \tag{1}$$

Soil resistance effects have not been included in this equation since it is assumed that they have been accounted for by exponential amplification. Since it also assumes that the length of cross sectional change is greater than the pulse length, the method may underpredict the severity of a short cross section change.

3.6 Impedance profile

This method is based on a simple algorithm which yields a pile shape as a function of depth (Davis, Hertlein 1991). Rather than relying on the relative peak value of a reflected wave as in the Beta method, the impedance profile is directly calculated as the integral of the enhanced reflected pulse relative to the impact pulse. Soil resistance effects must be properly considered before the impedance profile can be calculated. In complex cases, misinterpretation may occur if the necessary record adjustments and integration are performed completely automatically.

3.7 PITWAP

This wave equation analysis program uses either the measured force or an assumed force (proportional to the velocity during the early impact event) as an input at the pile head. The soil must be considered and a model is usually assumed based on results obtained on other "reference" piles. PITWAP™ then calculates the ensuing pile top velocity which is then compared with the measured one. If these two curves do not agree, the pile model is adjusted and the analysis repeated until a best match is achieved. This process is similar to CAPWAP™ where the pile geometry is assumed to be known and the soil parameters are calculated. Actually, the soil resistance effects are never definitively known and for that reason engineering judgements may seriously affect the results. On the other hand, PITWAP computes a pile shape relatively quickly (and automatically) for any chosen soil model. Therefore the effect of soil model variations on calculated pile shape can be very easily investigated thus allowing the engineer to assess the structural condition of a shaft.

4 EXAMPLE

The methods described above have been used to evaluate the records obtained on a special test shaft of known shape containing a major defect. Figure 7 shows the velocity and force record over time/length, the PITWAP and the impedance profile which closely matches the design shape (these results are in terms of cross sectional area).

Figure 8 shows the results also in the frequency domain. The pile length and the defect location are clearly contained in the mobility graph. Also, after high-pass filtering and smoothing of the curve, the low frequency dynamic stiffness was calculated to be 480 kN/mm (the stiffness of the pile itself, considering a fixed toe, was 980 kN/mm).

5 SUMMARY AND CONCLUSIONS

This paper presents a summary of required equipment and available interpretation methods for low strain testing. The following conclusions are applicable.

1. Sonic pulse echo and transient dynamic methods are closely related. The sonic pulse method does not require an instrumented hammer; however, it is easy to make this additional measurement. The signals are then used to calculate results in either the time or frequency domain.

2. Powerful data enhancement techniques are available for time domain analysis to aid locate and estimate the size of defects or confirm the pile length.

3. For mobility calculations, a "tuned" hammer must be used.

4. The value of the dynamic stiffness calculated from the relationship between velocity and force spectra at low frequency is at best questionable and highly dependent on the filtering technique used.

5. Various methods are available for the calculation of the pile impedance profile. For simple cases, impressive and reasonably accurate results can be obtained. For complex cases with more than one major impedance variation (decrease or increase), these methods become less reliable.

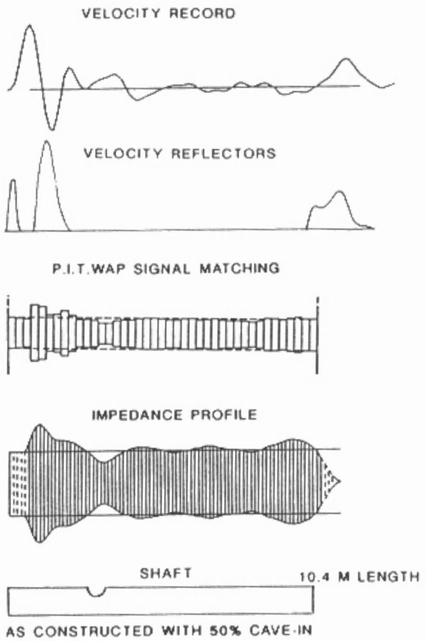

Fig. 7 Low strain testing results in the time domain

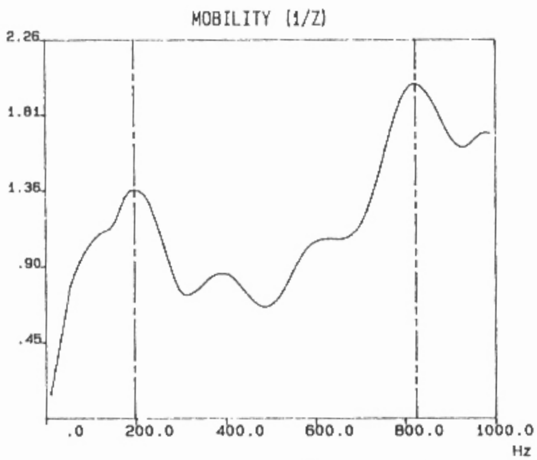

Fig. 8 Low strain mobility versus frequency result

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