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Recent advances in ultrasonic pile testing

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ABSTRACT: The cross hole ultrasonic test has proved to be the most powerful means for the quality control of bored piles. After a short overview of the relevant theory, the paper presents the shortcomings of existing testing systems. It then goes on to describe a new generation of ultrasonic instrumentation, made possible by recent advances in portable computing power. The main advantages of these instruments are: Improved signal processing, reliable determination of first arrival time and real-time tomographic capability. The test results may be further processed in the office and then presented in various forms, thus enhancing the interpretation process.

INTRODUCTION

In spite of the rapid progress in piling techniques (and maybe because of it), defective piles are still encountered. Among all the methods designed to test the integrity of bored piles, only two have proved to be of real practical value: The sonic (echo) and the ultrasonic (cross-hole) methods.

The sonic method is widely applied, mainly due to its rapidity and low cost, but has important drawbacks that severely limit its capabilities. First of all, it is applied on the top of the pile, far away from any possible defects. Another limitation stems from the fact that the sonic test uses a wavelength of at least two meters, resulting in rather limited resolution. Such limitations made certain workers (Samman & O'Neill 1997) claim that the sonic method "may not be reliable enough to be regarded as a stand-alone measure of the assurance of drilled shafts"

Ultrasonic logging overcomes both these shortcomings: It is performed in access tubes cast inside the pile, so the equipment is brought close to potential defects. Moreover, this method utilizes ultrasonic frequencies, with typical wavelengths of 50 to 100 mm. This enables the discovery of even minute defects and also allows the wave to travel in any direction.

In their original version, introduced almost three decades ago (Levy 1970), the ultrasonic testing systems were based on analog oscilloscopes. The results obtained were necessarily qualitative, with zero or minimal processing capabilities. The latter replacement of the analog oscilloscope by a digital one brought little change to the format of the test report: A matrix of black and white pixels from which the first arrival and the energy were visually deduced.

The recent progress in portable computers, and especially ruggedized units fit for site work, enabled the revolution in ultrasonic logging instrumentation. The main advantages of the new instruments are increased range, sophisticated real-time analysis and a wide choice of presentation forms.

This paper describes the CHUM (Cross Hole Ultrasonic Monitor), a typical ultrasonic system of the new generation. The system was used to test a pile with a prefabricated defect made of a 30cm wooden cube, placed at a depth of 3.5m. The results are then presented in different forms, demonstrating the capabilities of the system.

THEORETICAL BACKGROUND

Since the wavelengths produced by ultrasonic instrumentation are by an order of magnitude smaller than the typical pile diameter, they do not obey the classic one-dimensional wave theory familiar to the piling community. The main differences are:

1. There are two main types of ultrasonic body waves moving at different velocities, namely dilatational (P-waves) and shear(S-waves).
2. P-Waves are the fastest, traveling with a velocity c_p equal to:

$$C_p = \sqrt{\frac{E}{\rho}\cdot\frac{(1-\nu)}{(1+\nu)(1-2\nu)}}$$

This velocity is typically 10 percent higher than that of a one-dimensional wave in the same material.

3. Because of geometrical and material damping, P-waves are attenuated according to:

$$A = A_0 e^{-kx}$$

In this equation A is the amplitude, k is proportional to the square of the wave frequency and x denotes the distance traveled. This means that wave energy decreases quickly with distance, at a rate which increases with frequency.

4. Voids in the concrete cause incident P-waves to reflect as a combination of both P- and S-waves.

5. Inclusions of foreign material in the concrete cause incident P-waves to partly reflect back from the inclusion and partly refract into it. Both reflections and refractions include P- and S-wave components.

6. Under certain circumstances, waves will diffract around voids or inclusions with sharp corners.

From the above principles, one can draw the following practical consequences:

1. Whenever a defect is located on the straight line between them, it is unlikely that a pulse from the transmitter will reach the receiver
2. Even if a pulse will manage to diffract around a defect, it will reach the receiver with a much decreased energy.
3. Due to the exponential attenuation of waves, a large increase in the transmitted energy will extend the range only marginally. At the same time, it will increase the noise and lower both battery and sensor life.

DRAWBACKS OF EXISTING SYSTEMS

Existing ultrasonic systems, based on either analog or early computerized equipment, have very limited signal-processing capabilities. Their resulting drawbacks may be summarized as follows:

1. Most systems do little more than graphically represent the waves intercepted by the receiver in a matrix form. This kind of presentation is over-dependent on both instrument and copier settings (Figure 1) and can thus be manipulated to satisfy either the contractor or the supervisor.
2. Other systems present a graph of the first arrival time (FAT) versus depth, totally disregarding energy.
3. Traditionally, the signal is amplified by a user-defined value (gain) which is fixed throughout the whole profile. in some cases, the whole pile section is logged before this value is proven wrong. The user then adjusts this "knob" and re-tests the section. Sometimes, even this does not help since samples within the same profile may extend over a range too large for a fixed gain. This may cause inaccurate, and even lost, measurements.
4. FAT "picking" is done by setting an arbitrary threshold level and comparing this value to the pulse amplitude. This intuitive method, that works well for strong signals, gets wrong results for medium-strength signals and is useless for weak signals (Figure 2). Under this situation, the user tends to lower the threshold level. Soon enough some noise, which is an unavoidable part of any physical measurement, is incorrectly picked as the FAT, making the results worthless.
5. all these system are essentially one dimensional, that is they show only the depth limits of a given defect. There is no indication as to the lateral locations and extent of the defects.
6. FAT is arbitrarily determined where the signal amplitude first exceeds a given threshold value. In a noisy environment, this may lead to serious errors and to reduced range.The other important parameter, the energy, is represented only qualitatively.

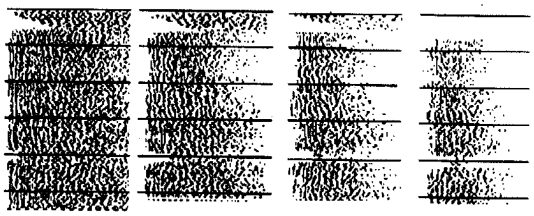


Figure 1: Conventional presentation. Gains decrease from high (left) to low (right).

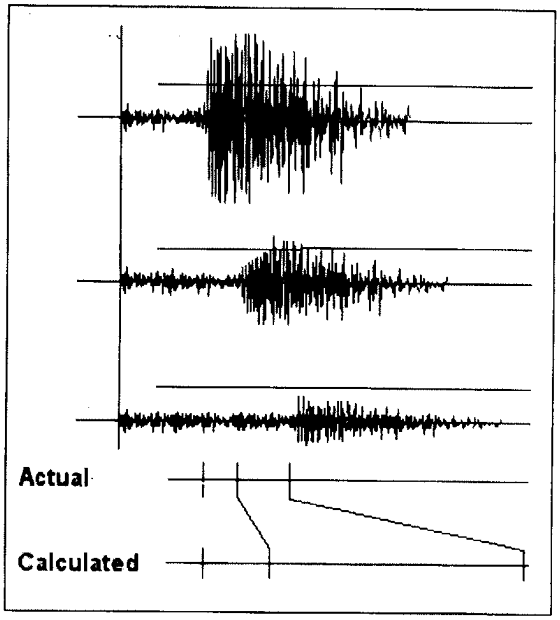


Figure 2: FAT picking using threshold values

MODERN ULTRASONIC SYSTEMS

General description

The CHUM (Cross Hole Ultrasonic Monitor) is a compact new ultrasonic testing system, making use of up-to-date computing resources (Figure 3). It is based on a commercially-available, ruggedized Pentium computer with Windows operating system and an analog-to-digital PC card. This system is capable of sophisticated real-time signal processing, and supports advanced post-processing and presentation techniques. A software "wizard" guides the user through the various logging stages, automatically saves the data and keeps track of the work progress on a site map.

Additional hardware components of the system are:

1. Signal generating and conditioning electronics.
2. A pair of ultrasonic probes (transmitter and receiver) with a frequency of either 50 or 100 kHz, (Approximate wavelength of 100mm and 50mm, respectively)
3. Twin pulleys with separate depth encoders (patent application).

Testing procedure

Each CHUM profile is commenced by lowering both probes to the bottom of the access tubes, then simultaneously pulling them upwards. Ultrasonic pulses, produced by the transmitter at a predetermined vertical spacing, cross the concrete and eventually reach the receiver. The intercepted signals are then sent, via the A/D card, to the computer. Whenever a sharp increase in arrival time and/or a sharp decrease in energy are encountered during the test, it probably signifies a defect. The operator then continues to raise the probes until normal readings are resumed. The suspect zone is then re-tested several times, each time with a different relative probe position. Very soon, both the location and shape of the defect are formed on the monitor (Figure 4)

Since operators see the results in real-time, they can concentrate in detail on suspect zones. At the same time, a single pass only is performed on "good" zones of the pile. Since the largest part of a normal pile is usually sound, this method optimizes the test process.

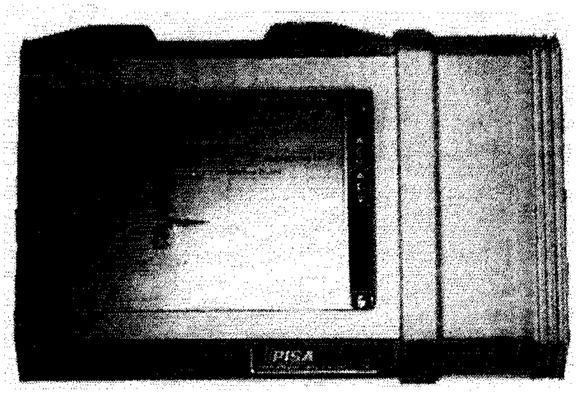
Real-time signal processing

The computing power of the system enables the following real time analyses to be performed on each pulse:

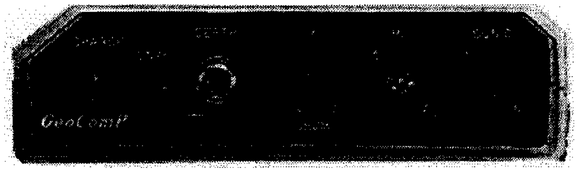
a. Automatic gain control (AGC)

The ad-hoc electronic limit for digital ultrasonic sampling in a noisy environment is 12 to 14 bits, at least 6 of which are significant. In comparison, common ultrasonic samples extend over four orders of magnitude and cannot be covered even with a 16-bit sample. The situation becomes even worse when tomography is performed, since the varying distance caused by diagonal measurements changes the amplitude exponentially.

CHUM solves this problem by dynamically adjusting the gain, allotting the maximum number of significant bits for each individual signal. As a result, each sample contains 8-10 significant bits.



a. General view



b. Connector panel

Figure 3: CHUM (Cross Hole Ultrasonic Monitor)

b. Automatic FAT picking and energy determination

CHUM performs this task automatically, using a special FAT detection algorithm which is amplitude-insensitive, fully automatic and free of user defined arbitrary constants. The exact details of this algorithm are behind the scope of this paper. Basically, it first applies a band-pass software filtering that eliminates background noise and accentuates the signal. Then, by examining the shape of the signal rather then its amplitude, it calculates both the FAT and the total energy of the arriving signal.

c. Real-time Fuzzy-Logic tomography

The available computing power also enables the operator to obtain a two-dimensional picture of any defect while doing the test. This process, called tomography, necessitates multiple sampling of the defects from different angles. The advanced signal analysis procedures of the CHUM produce stable, low-noise readings even at probe spacings reaching four metres. This means that useful tomographic procedures are still possible in barrettes with access tubes more than two metres apart. There are several tomographic techniques available, the simplest one being fuzzy logic tomography. This is performed as follows:

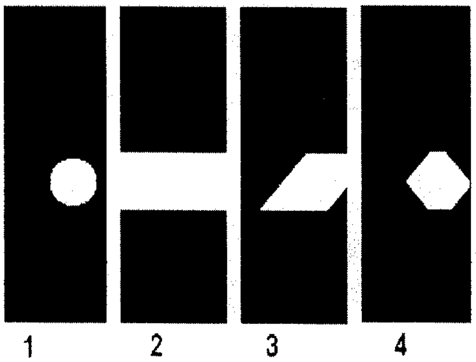


Figure 4 - Stages in real-time fuzzy-logic tomography

1. The real defect
2. horizontal measurements can only indicate the vertical defect location
3. adding diagonal (/) measurements reveals the location of the defect
4. backward diagonal (\) measurements refine the defect shape (note unavoidable "shadow" areas)

Each measurement (pulse) is assigned a "soundness" value from 0 to 1, with 0 representing a void and 1 standing for solid concrete. Each pile element ("pixel") is considered as good as the highest measurement made through it. The matrix of pixels can then be painted by assigning each value a color from a desired palette. The resulting image can be further enhanced by image processing methods (these can improve the presentation but cannot add any information)

When a defect is first spotted (usually using horizontal measurements), the "bad" pulses are crossing many pixels, and the defect looks as if it extents the whole pile section width. If no more measurements are done at this stage, only traditional 1-D results are obtained. If, on the other hand, diagonal measurements are added, the "good" pixels within the pile section width are detected, constraining the defect shape (Figure 4).

CHUM is designed to support a number of presentation methods and inversion algorithms, each with it's own advantages. and can be extended to support more:

1. One-Dimensional methods: Relatively simple and fast algorithms with good axial resolution. No information about the horizontal position and shape of anomalies is provided.
2. Two-Dimensional methods: Sometimes extensively consume computing resources. During the calculation process, some information is inevitably lost and some values, bases on ad-hoc assumptions, are added. The result must therefore always be considered as an *interpretation* of the measurements, meant to reveal information otherwise hidden within abundance of data.

Post processing and presentation

After the in-situ testing, a set of raw measurements of the pile section is saved and can later be post-processed. At this stage interesting information, otherwise hidden, can be revealed.

Comparative testing was performed on a special test pile with pre-fabricated defects. The results obtained with the CHUM (Figure 5) are clearly superior to those obtained for the same pile with a conventional testing instrument (Figure 1).

1. Conventional matrix

this popular 1-D presentation is much enhanced (compare to Figure 1) when the improved FAT and AGC algorithms are applied. Although fully supported by CHUM, this presentation is somewhat misleading and is 'photocopier sensitive' (using different contrasts changes the result) Anomalies are recognized by a right-shift of the left side of the matrix, together with fading in matrix density

2. Dual presentation

Here signal attenuation is superposed on FAT. This compact presentation reveals all relevant 1-D information: The left-hand side of the band is relative to the FAT and the width of the band to the inverse of the energy (wide band means low energy). By visual display criteria such as Data-Ink maximization, chartjunk and multifunctioning elements (Tufte 1983), this presentation method is superior to the conventional matrix. Anomalies are recognized by a right-shift of the of the time band and increase of it's width.

3. Time & energy versus depth curves

Anomalies are recognized by increase in FAT and decrease in energy.

4. Fuzzy-logic tomography

By painting dark any pixel crossed by a "good" pulse, this 2-D presentation shows the shape and horizontal position of major anomalies. No quantification should be asserted by this relative image besides an estimation of the defect position. Real world defects are sometimes cloud of gradually decaying mixed material with no definite borders shape and size, a situation well described by this presentation

5. Parametric tomography

A symbolic model of a pile with defects is repeatedly matched against the raw measurements using a forward model until a minimal disagreements between the two is found. The resulting model can be expressed with an extremely low number of values (each defect taken 4

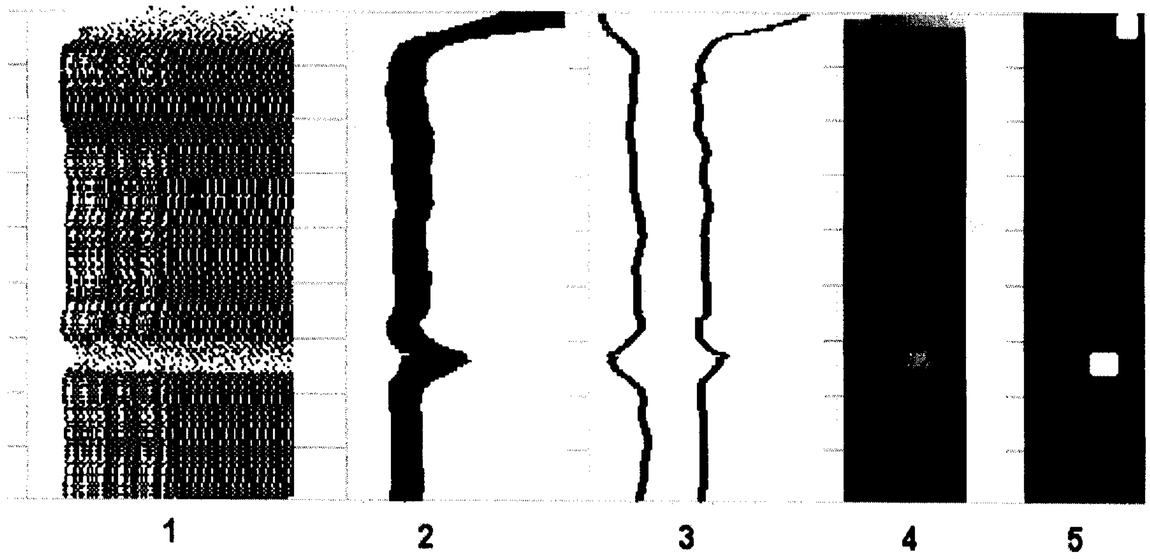


Figure 5 - Different presentation methods of the same profile

numbers). The assessment is of the form "The measurements taken from the real pile are approximately equivalent to those taken from a simplified pile with such and such void anomalies". The results are measurable, easy to work with and surprisingly accurate (the actual defect was only 5cm larger then what was found in this example)

SUMMARY

New ultrasonic instruments for pile integrity testing make optimum use of portable computing power, with the following benefits:

1. Higher resolution
2. Improved FAT, AGC and energy determination
3. Real-time tomographic capability
4. Multiple options for both inversion algorithms and presentation forms

All these lead to improved analysis and bring the integrity testing industry closer to its goal: Reporting all significant defects, with zero false alarms.

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