Determining First Arrival Time and Wave Speed in Cross-Hole Ultrasonic (CSL)

Erez I Amir. Piletest
Piletest Technical Notes
Apr-2016

Background

If we'll reduce any Cross-Hole Ultrasonic system to its very essence, ignoring all the "bells and whistles" that are there to make our work faster and easier The very heart of the system is simply a timer: Transmitting a pulse from one end and measuring the time it takes it to arrive at the other end.
The waves in the tested element are reflected from the sides, attenuated, and create constructive and destructive interferences. We are only interested in the arrival time of the first wave, which travels in the fastest route, and yields the most deterministic measurement. This is called First Arrival Time (**FAT**)

Noise and FAT

With no noise, FAT can be determined as the time the signal is non-zero. However, noise is a part of any physical measurement, and determination of the arrival time turns out to be a non-trivial task.
Figures 1 and 2 demonstrate pulses with no apparent noise and with typical noise, respectively.

At the presence of noise FAT is no longer objective and the human eye is still considered the best in picking the FAT point.

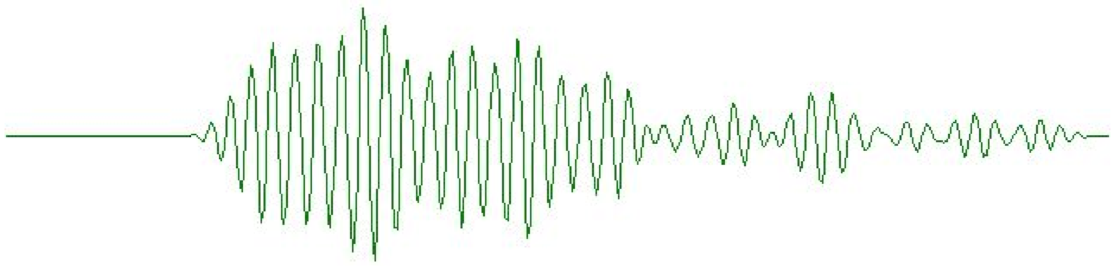

Fig. 1 - Clean pulse with no apparent noise

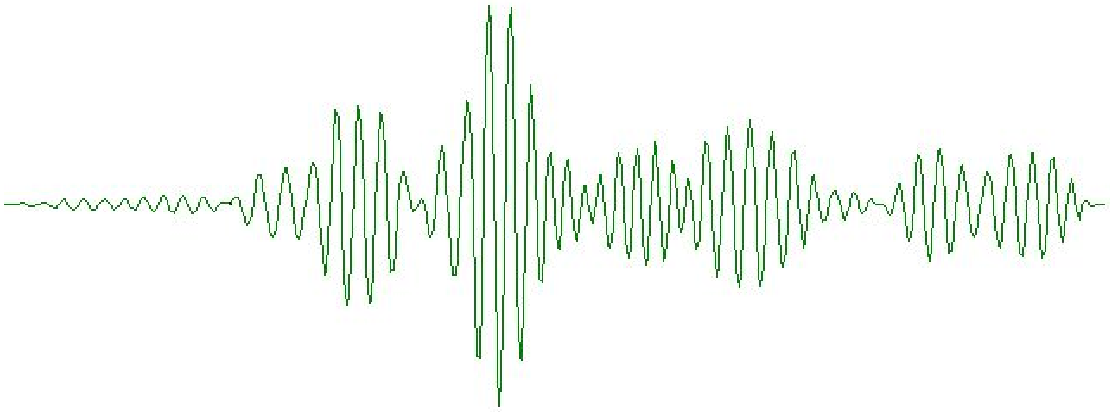

Fig. 2 - A pulse with typical noise

Sources of noise

Noise comes from external and internal sources
External: Environmental noise, probes brushing against the access tube walls all create sound waves which are mixed with the real signal in non-predictable ways.
Internal: Any electronic system has self noise. This is a voltage ripple that always exists and eventually enters the measurement by the A/D (Analog to Digital) circuit. In ultrasonic systems, the transmitter voltage is typically raised to more than 1 kV while the receiver voltage is often measured in mV - 5-6 orders of magnitude smaller. Leakage of transmitter voltage into the receiver circuitry is called “Crosstalk”. Modern systems, such as the CHUM, use special means to prevent such crosstalk.

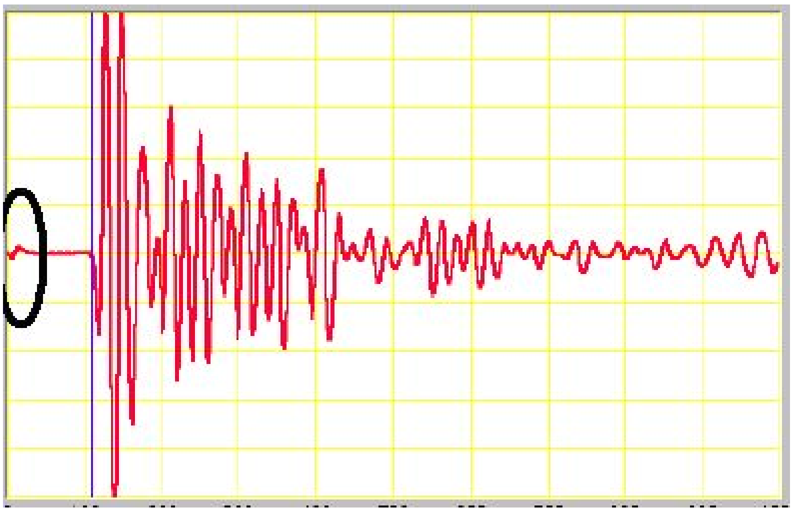

Fig. 3 - A signal with cross-talk noise

FAT Picking Algorithms

A typical test of pile may easily be made of several thousands of signals. Manual FAT picking by eye for this amount of data is both tedious and exhausting, which is why it tends to be error-prone. The need for a computerized algorithm to do most (or all) of the hard work for us is therefore clear.

The CHUM software offers four different algorithms. Out of which the "Automatic" is most advanced and recommended while the other three are kept in the software mainly for backwards compatibility and for very rare cases.

Jump to [Fixed Threshold] [Dynamic Threshold] [STA/LTA] [Automatic]

Fixed Threshold FAT picking Algorithm

In this naive, traditional algorithm, a fixed threshold level is set by the operator for the whole profile. The voltage level of the digitized signal is scanned from the first sample which reaches the threshold level, which determines the FAT point

Advantages:

1. Simplicity

Disadvantages:

1. Since the receiver amplitude spans several orders of magnitude, the operator is required to adjust the threshold level for each profile
2. An ultrasonic wave amplitude at the receiver is often starting low, and gaining amplitude gradually. Since we are interested to pick the FIRST arrival time (FAT), we want to lower the threshold level as much as possible, however at lower levels, early noise is picked instead of the signal.
   See Fig.5 where different threshold levels will pick different FAT

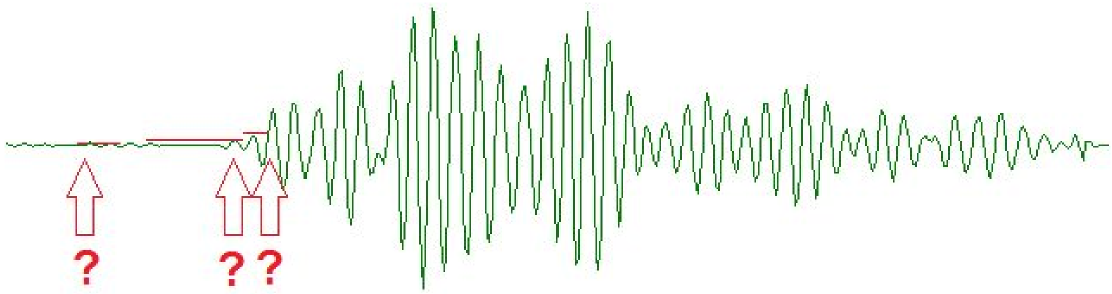

Fig. 5 - A typical ultrasonic wave with a gradually increasing amplitude

3. Signals at the edge of a flaw, or when taking diagonal readings (Tomography) are much weaker than "good"/horizontal ones. Hence fixed threshold, being set "too" high to avoid noise, might pick late signals, or miss good ones altogether

Dynamic Threshold FAT picking Algorithm

This evolution of the Fixed-Threshold algorithm, requires the operator to set a ratio. The signal is first scanned to find out the maximal amplitude A, and for each signal trace, the threshold level is set as A/ratio.

Advantages

1. More adaptive to amplitude span of different signals. Therefore, less frequent adjusting is required.

Disadvantages

1. If there is NO signal, just noise (as expected inside a severe defect, or when the sensors are in the tube-stickup in air) - the algorithm fails and picks up random noise.
2. Due to the above, additional tweaks & adaptations are required, which makes accurate adjusting very sensitive.

STA/LTA

Adapted from seismic measurements, where the earthquake event needs to be timed very accurately in order to calculate the epicenter

Description:
A window of defined size is moved along the time axis and measures the average of samples in this window.
Another window of larger size follows the first one
FAT is defined as the earliest point where the ratio between the two averages exceeds a user-defined ratio
Typical values are:
Window size: 6
Ratio: 1.6
Advantages:

1. insensitive to short peaks of noise

Disadvantages

1. Requires frequent adjustment of the parameters by trial-and-error. It is impossible to tell from the parameters how the algorithm will behave.

“Automatic”

Since this algorithm requires NO parameters, it is called “Automatic”
Note: A few technical details have been eliminated for brevity.

Principle:
An iterative, graphical solution, based on the signal shape

Symbols:

- T(n) - Arrival time determined at iteration #n
- V(t) - Signal amplitude at time=t
- [t,V] - a point on time=t and amplitude=V

The Algorithm:

1. Set T(0) = time where the signal amplitude is maximal
2. Draw a diagonal line between [0, V(T(n))] to [T(n), 0]
3. Set T(n+1) to the first crossing point of the diagonal line and the pulse envelope
4. If T(n+1) is not equal to T(n) - go to step 2

Example:

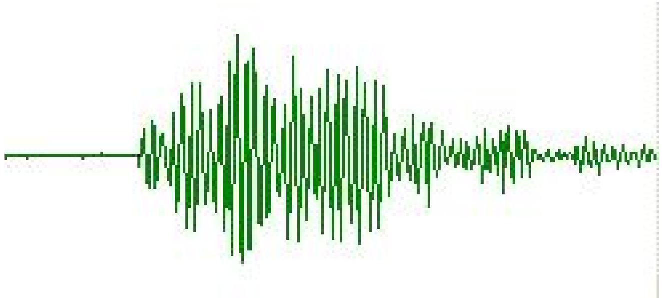

Figure 4a - Original Pulse

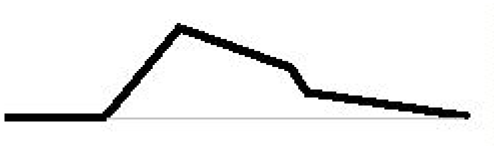

Figure 4b - Pulse Envelope

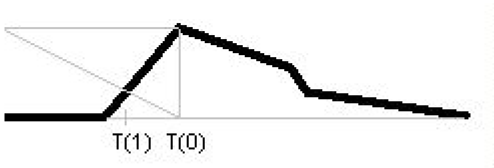

Figure 4c - Initial $T_{(0)}$ and first $T_{(1)}$ iteration

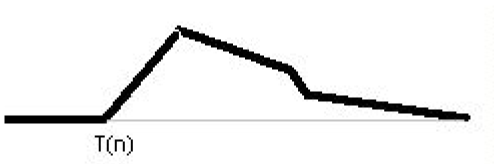

Figure 4d - Final iteration

Advantages

1. Requires no parameters
2. Better than all the above, with typically fewer wrong pickings compared to any other algorithm when best parameters are applied.

Wave Speed Calculations

Note: *Wave Speed* is a more accurate term than *Velocity* as speed is a scalar (non-directional) term while velocity is a vector and must always be called with the direction of the wave.

Apparent wave speed is always calculated as

$$C = \frac{Distance}{FAT}$$

Since the wave trajectory is not alway straight, the distance they travel may be longer than the tube spacing. In addition, the concrete through which the waves travel is non-homogeneous so that the wave speed calculated is apparent rather than a measured physical property.

Wave speed is a property of the compressive strength of the concrete.
In CHUM software, two modes of Wave Speed calculations exist:

1. Naive calculation - Using the entered tube spacing and picked FAT
2. Advanced calculations - knowing the tube diameter, the sensor diameter and the wave speed in water, we can compensate the time and distance traveled in water
    a. The distance is reduced to the concrete-only travel distance, taking off the distance the wave travels in the water inside the access duct
    b. FAT is reduced to compensate the time the signal traveled in water (Assuming a fixed wave speed in water of 1500m/s)

The difference between the two method might become considerable when the tube spacing is small.
The above method is a by product of regular cross hole testing. In addition, CHUM software includes a utility to measure the wave speed with better accuracy (see CHUM Manual http://piletest.com/CHUM_USER_MANUAL/#WaveSpeedCalculator)

Conclusions

The cross hole ultrasonic integrity test is the fastest way to accurately determine the wave speed in concrete piles. With accurate wave speed values we can:

- Perform QC/QA on large diameter concrete piles
- Calculate the compressive strength of the concrete
- Perform advanced analysis as to the location and shape of any flaw in the pile.

References

1. Caltech Earthquake Detection and Recording (CEDAR) system [Johnson, 1979].

2. Amir, J.M., Amir, E.I. & Felice, C.W. (2004): "Acceptance Criteria For Bored Piles By Ultrasonic Testing", Proc. 7th Intl. Conf. on Application of Stress Wave Theory to Piling, Kuala Lumpur