Relative Energy in Cross-Hole Ultrasonic (CSL)

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Background

Right after First Arrival Time (FAT), the relative energy (RE) is the second most important parameter of a cross-hole ultrasonic test. Intuitively, a flaw in the wave path will block some of the wave front and lower the received signal energy hence a reduction in signal energy is a possible predictor of flaws

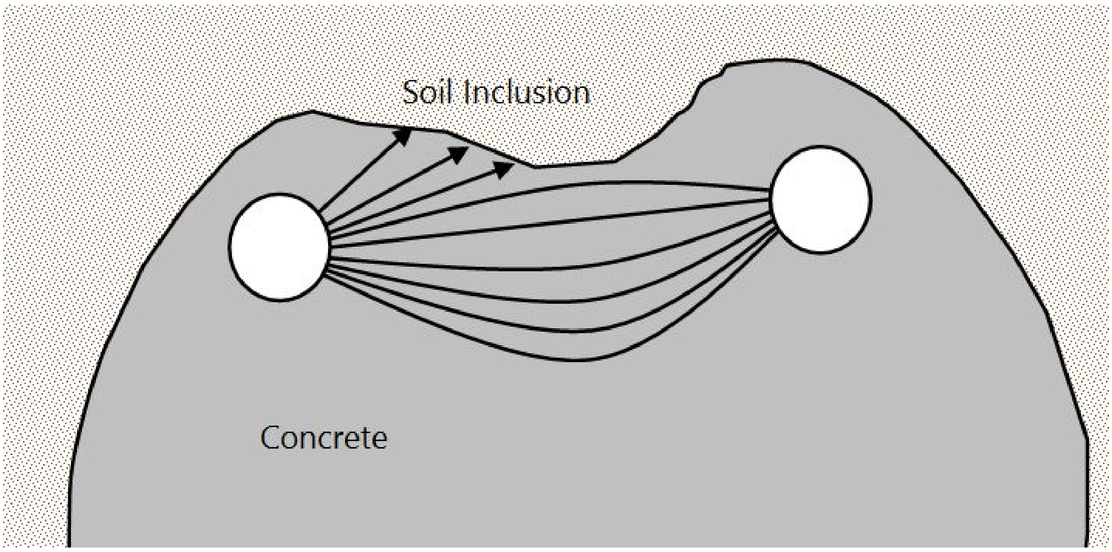

Figure 1: Some of the wavepath is blocked due to a soil inclusion, resulting in reduction of relative energy

Added information

Why should one bother with examining the relative energy?

1. While FAT only check the fastest wave path, RE is calculated by looking at all wave paths and therefore covers a larger area of the cross section
    a. RE can potentially indicate flaws which are outside the cage (Figure 1)
    b. A solid RE line gives a stronger assurance to the quality of the pile
2. While FAT picking (especially in the presence of noise) might be tricky and subjective, RE calculations are straightforward and objective. Hence, no user defined parameters and tweaks are needed.

3. Usually, FAT and RE are interconnected: at the presence of a flaw, FAT increases and RE decreases - Seeing such indication from two independent parameters gives the test results higher credibility and lower uncertainty.

Theoretical background

When a wave front moves away from the emitter, it becomes larger with distance. If we assume that no energy is lost during the process, the energy per unit area of the front (or per ray) declines with distance. The rate of decrease depends on the shape of the wave front. If the front is spherical, the wave energy per unit area will change as the inverse of the square of the distance from the source:

$$\frac{E_2}{E_1} = \left(\frac{r_1}{r_2}\right)^2$$

Equation 1

Where: E_1 and E_2 denote the wave energies at points 1 and 2, respectively, while r_1 and r_2 are the respective distances from the source of points 1 and 2. Since the energy E is proportional to the square of the amplitude A, Equation 1 can be re-written as:

$$\frac{A_2}{A_1} = \frac{r_1}{r_2}$$

Equation 2

Equation 2 describes what we define as geometric attenuation, which occurs in all types of media and is the only source of energy loss in perfectly elastic materials. In real materials, which also exhibit viscous and frictional behavior, part of the mechanical energy of the waves is constantly converted into heat. This phenomenon, defined as material loss or intrinsic attenuation, is represented by the following equation (Santamarina et al. 2002):

$$A_2 = A_1 \cdot e^{-k \cdot f(r_2 - r_1)}$$

Equation 3

in which k is a medium-dependent constant and f is the wave frequency. Equation 3 shows clearly that material attenuation causes the wave amplitude to decrease with increasing distance from the source, at a rate that is dependent on the frequency. Higher frequency waves attenuate much faster than those with lower frequencies and therefore have a smaller range.
Since wave amplitudes may vary over a few orders of magnitude, it is convenient to express amplitude ratios on the decibel scale, defined as

$$dB = 20 \cdot log(A_2/A_1)$$

Equation 4

Since $20 \cdot log(^1/_2) \approx 6$, every 6 dB represent an amplitude ratio of 2.

Figure 2 is an example obtained by passing ultrasonic waves in a concrete pile while varying the distance between the emitter and the receiver. The exponential character of the attenuation is immediately apparent.

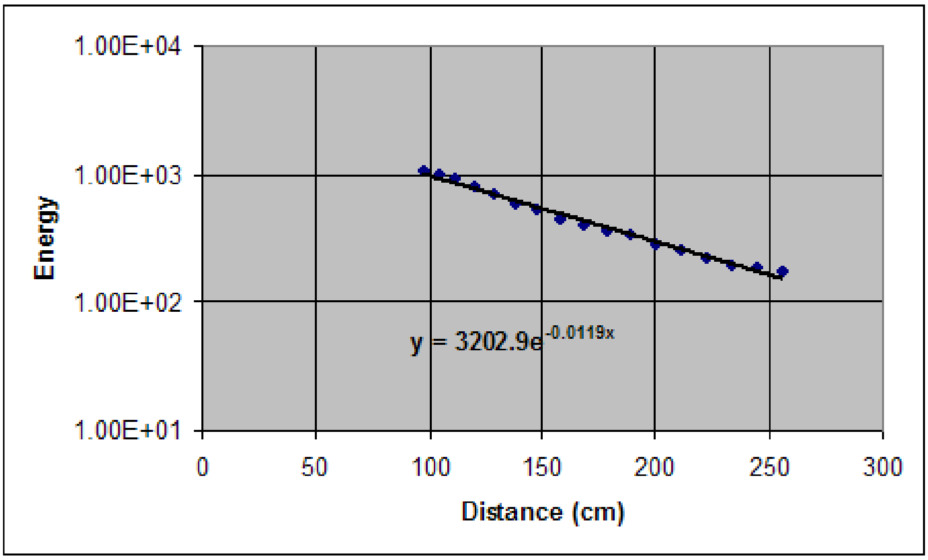

Figure 2: Attenuation of Ultrasonic Waves in Concrete

How is RE calculated

Unlike FAT, which is a tricky, sometimes subjective parameter, signal level and its reduction are a well-defined physical entities.

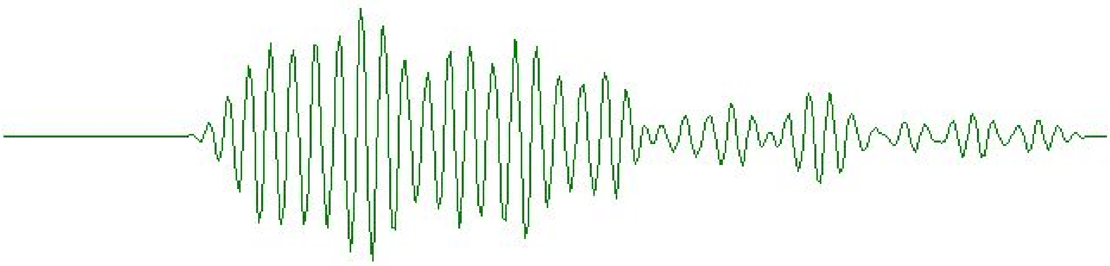

Fig. 2 - A typical Ultrasonic Pulse

Definitions
T_i - Time of sample i
V_i - the digitized voltage (Amplitude) of the signal at time T_i
FAT - First arrival time

The Strength (Average Amplitude) of the signal between samples i_1 and i_2 can be expressed as

$$A = \sum_{i=i_1}^{i_2} |V_i|$$

(Which is the area of the pulse envelope)

Since the noise before the FAT and the tail of the signal are relatively small, (Especially if the noise level is below 1mV as with the Piletest CHUM), it is convenient to set i_1 to 0 and i_2 to n (sum all samples)
Although summing the noise before the FAT might seem less accurate, it has negligible practical effect and the benefit is removing the dependency on FAT (which is less well-defined and subjective). Therefore, without FAT dependency, one only

needs to acquire two independent parameters, which makes the test results more consistent.

And the reduction in decibels

$$RelativeEnergy_{[dB]} = 20 \cdot log(A/A_{max})$$

Where

A_{max} - a fixed amplitude level, higher than A
A - Amplitude of a specific signal

Should A_{max} be set to a fixed high value, or to the maximal amplitude of the profile?
The difference is only a fixed shift
At Piletest we selected a fixed A_{max} value (for all profiles and piles) as this makes comparing piles/profiles AND attenuation-based tomography possible - more on those techniques to come in our following technical notes.

References:

Santamarina et al. 2002