Ultrasonic Cross Hole Testing of Deep Foundations – 3D imaging

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Sonic Coring (or more properly ultra sonic cross hole logging) is a common test for concrete foundations and has been since the late 1960's . (Refs 1, 2 and 3) Three or more tubes are cast into the concrete during construction so that a series of tests can be carried out between pairs of tubes, eg tubes 1-2, tubes 2-3 etc.

Traditionally, these results have been presented and interpreted in a two dimensional plot, time of arrival versus depth. Anomalies in the concrete show up as a relative increase in first arrival time. From these profiles, the engineer has to try and determine the three dimensional magnitude of any anomalies. This is difficult, time consuming and unreliable.

A new approach to the problem has recently been introduced by applying the principles of cross hole tomography, such that a series of sonic profiles are combined to produce a three dimensional view of the concrete shaft. Anomalies are clearly shown as dark areas, the colour density representing the severity of the anomaly. The size and position of the anomaly is apparent from the visual presentation.

This paper describes the equipment and methodology as well as the new 3D imaging technique.

In homogenous concrete, free of defects, inclusions and variations in quality and density, the velocity of sound is constant, in the order of 4000m/sec. Concrete containing soil inclusions, bentonite, honeycombing etc has a lower sound propagation velocity. This means that measurements of wave speed or transit time can be used as a non destructive method of assessing the quality of buried concrete foundations.

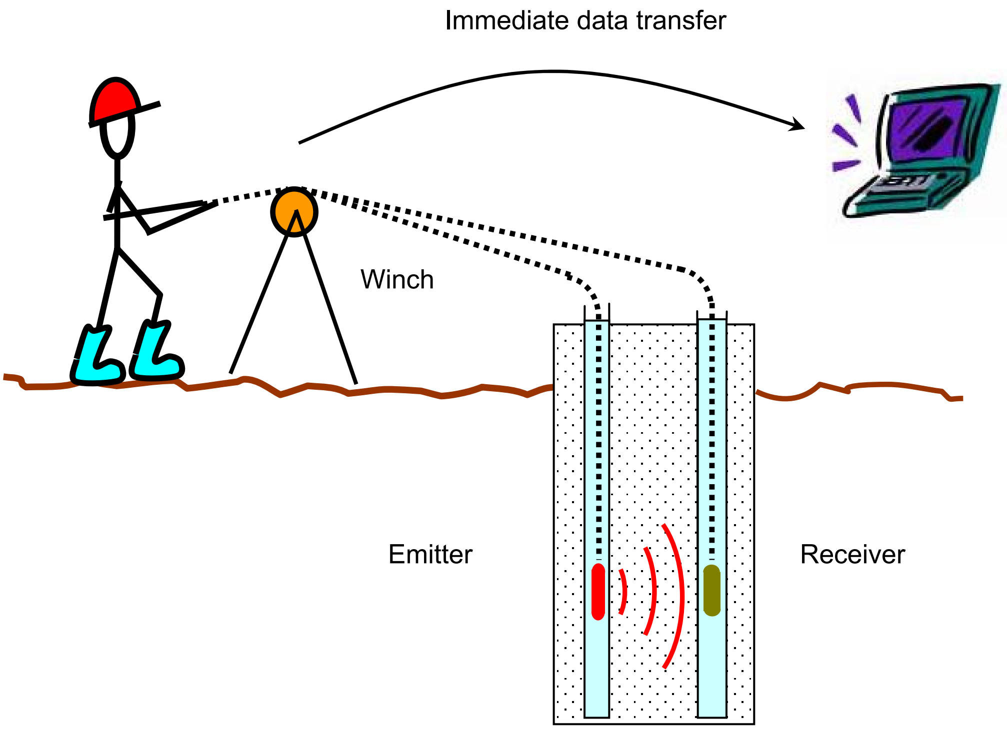


Fig 1. Schematic of Sonic Coring system in operation

Sonic coring is based on measuring the transit time of a signal between two vertical tubes, cast into the concrete during construction. The sound source is normally a piezo-electric probe which is lowered down to the base of the first tube. A receiver is lowered to the base of tube No 2, both tubes being filled with water to act as a coupling medium. Both of these probes are raised simultaneously, keeping the emitter and receiver on the same horizontal plane and, if the tubes are parallel, the same distance apart.

Fig 2. Sonic Coring winch

The probes are pulled by their connecting cables over a specially designed “winch” which serves three functions:

- allows smooth controlled raising of the probes in unison
- continually measures the depth of the probes
- triggers a pulse emission at depth increments

Three cables are connected to the computer data acquisition system, one from each of the probes, emitter and receiver, and one from the winch.

As they are raised, the emitter sends out a short pulse signal of about 50 – 60 KHz every 20mm length of pile and this travels through the water, the tube, the concrete and into the second tube and the receiver. The detected signal can be displayed and digitised and the first arrival time (FAT) measured. A typical single signal is shown below as well as typical built up sonic profile.

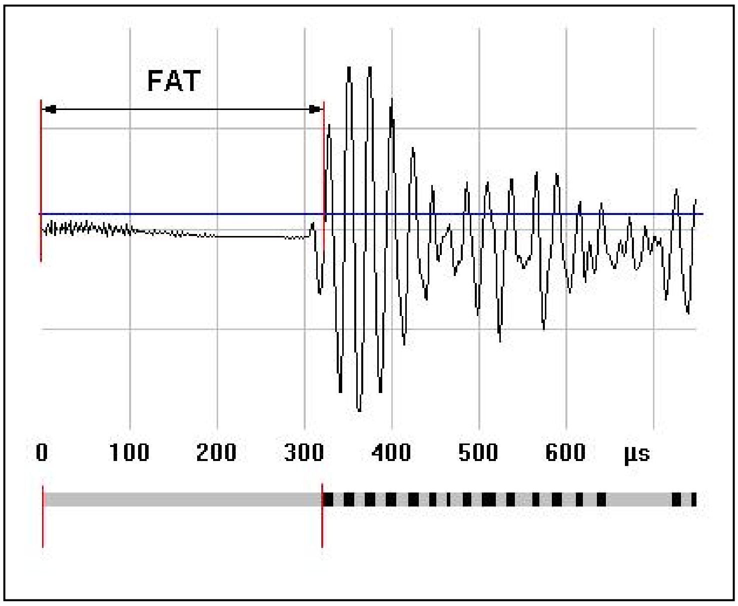


Fig 3. Single signal showing first arrival time (FAT) Below is a modulated signal.

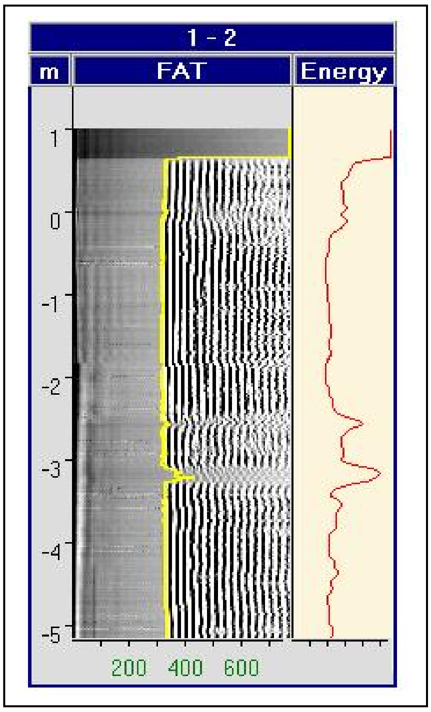


Fig 4. Sonic profile made from a series of modulated signals.

The wave speed of ultrasonic waves in concrete is given by :

$$V^2 = \frac{E\,(1-\mu)}{\rho(1+\mu)\,(1-2\,\mu)} \quad \text{, where}$$

V - wave speed, ρ - density, E - dynamic modulus and μ – Poisson’s ratio

However, the sonic coring test does not measure velocity, it measures transit time between the probes and the conversion to true velocity is rarely possible. If the tube spacing is known an *apparent* velocity can be calculated by dividing the probe spacing by the transit time. It must be remembered however, that this apparent velocity includes the water and the tubes. It should also be borne in mind that a signal travelling around a void could yield the same velocity as one travelling through a zone of low modulus material.

On a typical large diameter pile, four tubes would be installed so that 6 separate profiles are possible as shown below. Each profile represents a two dimensional slice through the pile and it is difficult to properly assess the size and three dimensional position of any anomaly from these profiles.

This difficulty has been solved to a large extent by developing 3D imaging software, and this in turn has only become possible with the advent of very fast analogue to digital conversion and high storage capacity computers. For example, each profile, for a 20m deep pile, consists of 1000 separate signals, each consisting of up to 1000 data points. (sampled at 1 MHz)

The new approach – 3D Imaging.

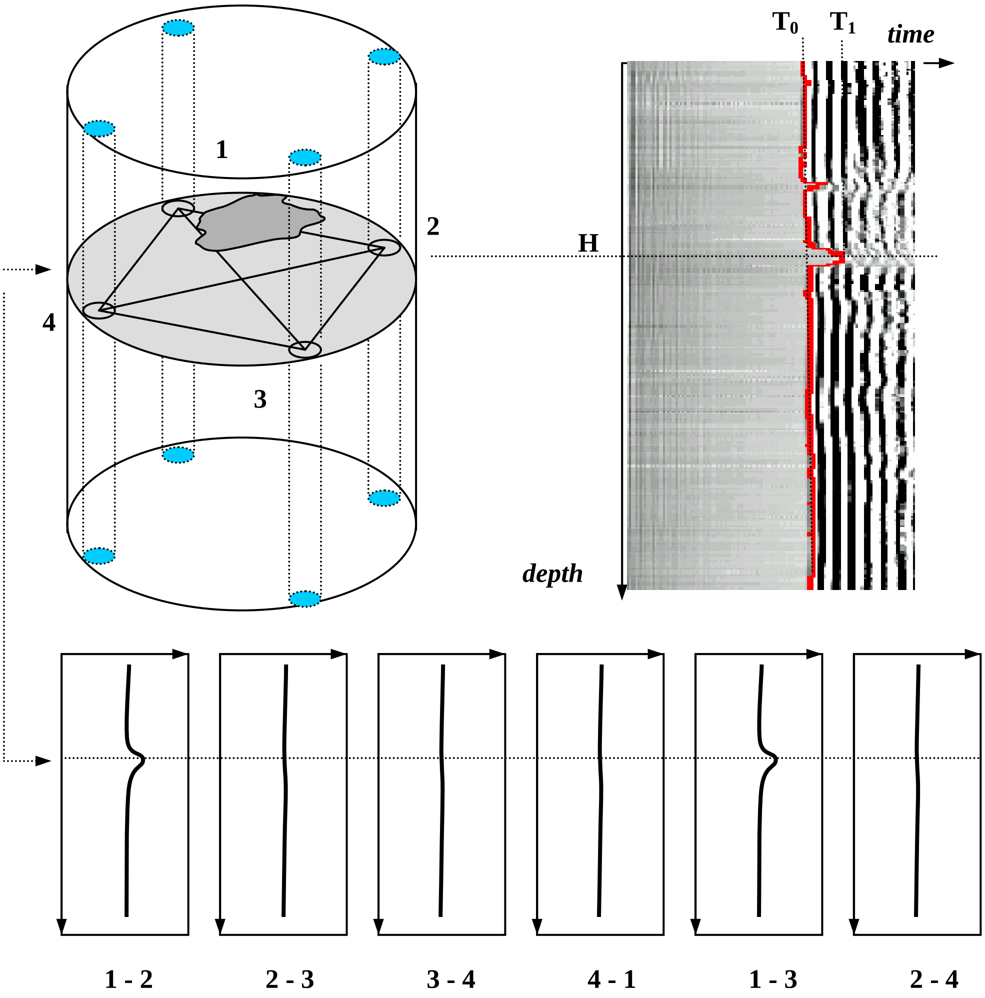
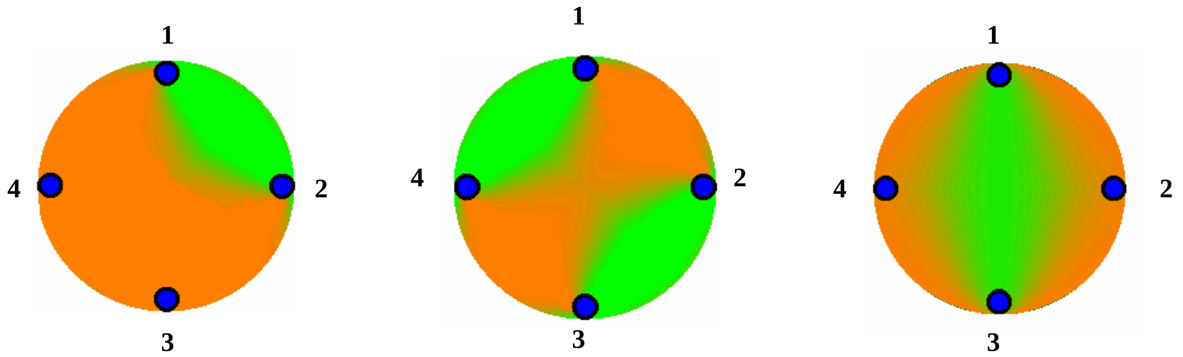


Fig 5. First Arrival Time

The aim of 3D imaging for ultrasonic cross hole testing data is to produce a geometrical visual presentation showing the location of any anomalies and defects in concrete detected in the pile. For a pile with 4 testing tubes there are 6 vertical profiles of first arrival time of ultrasonic impulse. It is due to the procedure that at every moment of testing the data is available only for one pair under test. So, if there is a defect, for example as shown in **Fig 5.** it will have an influence on output data for one or more profiles. In the example shown, profiles 1 – 2 and 1 – 3 have been affected. The anomaly does not lie in the path of the other profiles and they are not affected. When analysing data after test it is not obvious how many anomalies are present nor their position and magnitude. The 3D imaging method described below shows how the data from all 6 profiles can be combined to produce three-dimensional model of pile.



Trace **1- 2** has maximum brightness. All other traces brightness is 0.

Traces **2 - 3** and **4 - 1** have maximum brightness. All other traces brightness is 0.

Trace **1- 3** has maximum brightness.

Fig 6. Some examples of the trace areas.

For a three-dimensional visualisation of the real site data the cylindrical pile model is divided into a number of slices (layers). Each layer corresponds to some particular depth and six values of FAT (first arrival time) can be selected from arrays of profile data. In other words six vertical profile arrays of FAT data are crossed by each layer and the resulting six FAT values ($\mathbf{T_{1-2}}$, $\mathbf{T_{2-3}}$, $\mathbf{T_{3-4}}$, $\mathbf{T_{4-1}}$, $\mathbf{T_{1-3}}$, $\mathbf{T_{2-4}}$) are to be represented on the layer canvas. To convert these values into graphical presentation the colour palette method was chosen, i.e. any changes of the FAT values will create some specific changes in a colour distribution over the surface of that particular layer.

For this purpose the whole layer surface is divided into six smaller, slightly overlapped areas and the colour of such areas is chosen to be in good contrast with the layer background. For example in **Fig 6** the background colour is orange and the area colour is bright green. Each area is coupled with one pair of tubes (1 – 2, 2 – 3, 3 – 4 and so on). The shape of such green areas is designed to cover the most sensitive region for the pair. That is, any void or defect of concrete in the sensitive area will make a considerable influence to FAT value for the pair. So, the shape looks like a trace of two light rays falling from one tube to another. Some particular traces are shown in **Fig 6**.

The brightness of these 6 traces is a linear function of the FAT values respectively:

$$B_{1-2} = F(x,y)^* \max (0 ; 1 - (T_{1-2} - T_0) / \sigma),$$

where:

F(x,y) – two-dimentional function for green area shape geometry construction;
T_0 - average FAT value, $T_0 = 1/N * \Sigma T_{1-2}$;

σ - time variation specifier, σ = 75 ... 150 μsec ;
i.e. if the time difference $T_{1-2} - T_0$ equals σ , then the brightness $B_{1-2} = 0$.

The closer the FAT is to to its average value the brighter the trace and vice versa. Thus, a large defect in concrete in between pair 1 – 2, for example, will cause a great FAT increase and this, in turn, will result in a considerable brightness reduction of the trace 1 - 2. Finally, the background colour will be revealed in that area of trace 1 – 2, producing a geometric presentation of the anomaly. Combining all 6 traces of a particular layer gives us information about the defect position in this cross-section of pile.

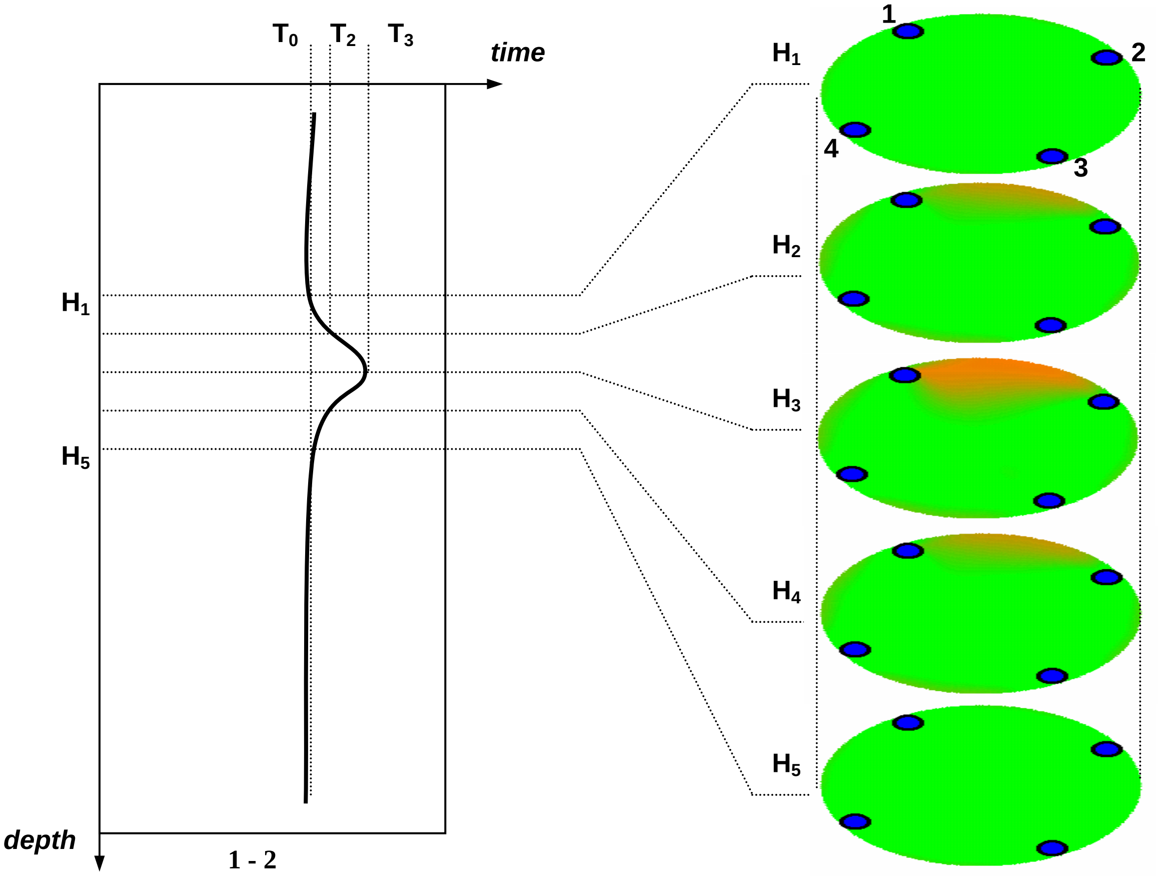


Fig 7. FAT to area colour convertion for trace 1 – 2.

As an example, **Fig.7** represents how changes of first arrival time can be converted into changes of a colour pattern of a particular layer. The FAT graph corresponds to the profile **1-2** and all colour variances should be expected in the area between tube 1 and tube 2.

As shown, the values $\mathbf{T_2 – T_4}$ of FAT are far away from the mean $\mathbf{T_0}$ from depth $\mathbf{H_1}$ to $\mathbf{H_5}$. Thus, going layer by layer:

- $\mathbf{H_1}$: the value $\mathbf{T_1}$ of FAT is quite close to average $\mathbf{T_0}$ and there are no changes in the layer colour filling.
- $\mathbf{H_2}$: the first arrival time $\mathbf{T_2}$ is slightly increased due to some defects in concrete structure and orange colour area appears along line **1 - 2**.
- $\mathbf{H_3}$: the difference of FAT value $\mathbf{T_3}$ and $\mathbf{T_0}$ reaches its maximum, and a considerable area of orange colour is presented.
- $\mathbf{H_4}$: the FAT value is going back to the average, thus causing decreasing colour change in layer $\mathbf{H_4}$
- $\mathbf{H_5}$: The colour is constant over all layer $\mathbf{H_5}$ area.

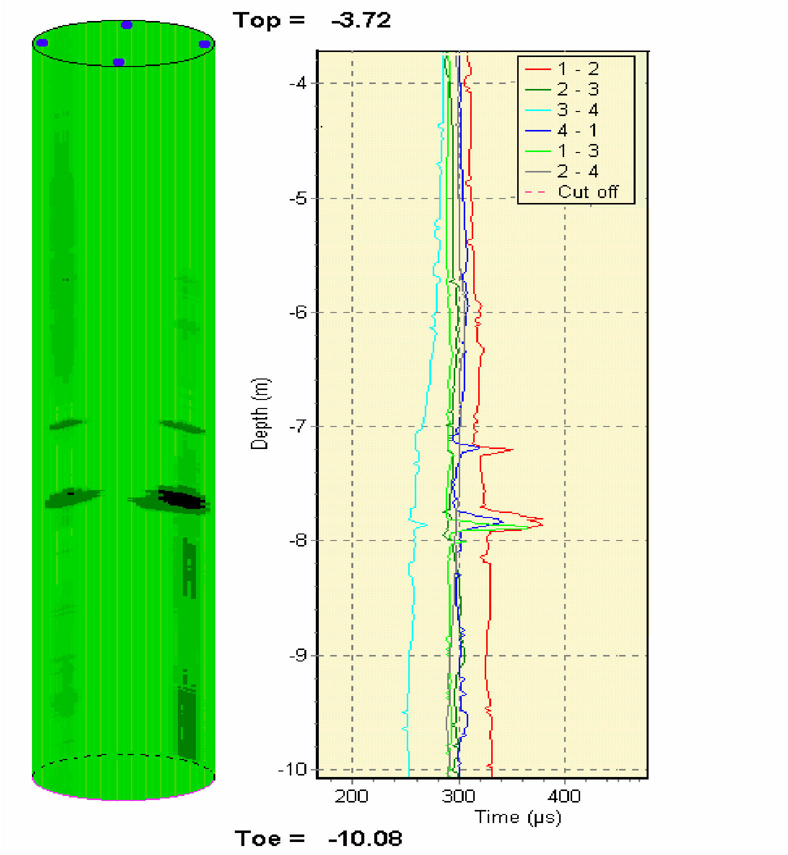


Fig 8. The complete 3D image of real data

All 6 traces of FAT data are used when creating the complete 3D image. Several hundred layers of that kind are superimposed with vertical shift according to each layer depth. The green colour chosen for undisturbed impulse transition (FAT is close to average value) is transparent and all fluctuations of the colour are clearly visible inside the image as shown in **Fig. 8**

Conclusion.

With the advent of rapid analogue to digital systems and high storage capacity computers it is now possible to store whole sets of signals that make up sonic coring profiles.

This paper describes a new processing method that allows a set of 6 two dimensional sonic profiles to be combined and presented visually as a 3D image.

This form of presentation has led to a significant improvement in the analysis and interpretation of sonic coring data.

References.

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