EVALUATION OF CONCRETE USING ACOUSTIC TOMOGRAPHY

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INTRODUCTION

The evaluation of existing structures is becoming increasingly important as the nation's infrastructure ages. Structural evaluation of infrastructure facilities is a critical component of service life prediction and requires accurate condition assessment information to determine if these facilities can remain in operation or if strengthening or reconstruction is required.

A preliminary study has been conducted to determine the feasibility of using acoustic tomographic imaging for defect location and characterization of the interior of concrete sections. The imaging method uses a large number of ultrasonic pulse velocity readings obtained on the exterior of the concrete object as input to a tomographic reconstruction computer program to create a map of velocities on the interior of the object. From the velocity profile the location, shape and nature of internal features can be identified. This preliminary study applied the technique to a number of small and medium sized concrete specimens in which were embedded various objects simulating flaws or defects in concrete. The results of the study have shown that the tomographic imaging method can locate objects such as large steel bars, voids and zones of low density in the interior of concrete specimens.

BACKGROUND

Acoustic tomography is a method which utilizes information from acoustic wave transmission to construct a map of velocities on a slice through the interior of the object. As the wave travels through the object being studied its travel time and hence velocity is affected by the variations in the condition of the interior material. Regions of high or low density, inclusions, and defects such as voids or cracks will affect travel time. In contrast to X-rays, which travel in straight lines, acoustic waves will refract or reflect at boundaries between regions of different velocities. The actual ray path of an acoustic wave may bend around regions of low velocity and voids. The tomographic reconstruction method used for concrete is, therefore, considerably different from that used in medical applications of X-ray tomography.

Acoustic tomography software used here was developed in the mining industry to locate objects such as ore bodies or blast damaged areas using geophysical data obtained from measurements in parallel boreholes and on the surface between boreholes. The area to

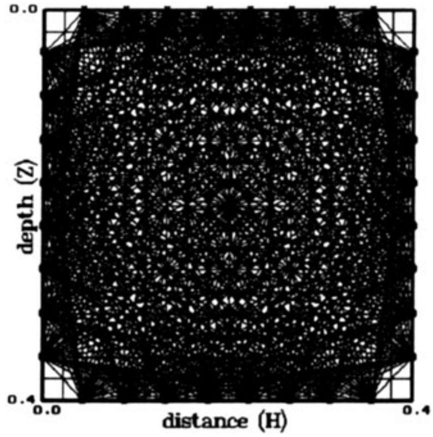

Figure 1. Complete set of 384 ray paths used for imaging of small concrete specimens.

be investigated is first divided into a number of pixels, each of which has its own velocity. The time of travel between two points on the perimeter of the area is the sum of the product of the pixel velocity times the wave travel lengths in the pixels. Starting from an assumed velocity distribution, the computer program calculates the travel times between all transmitter-receiver pairs and compares these to the measured values. The reconstruction algorithm is based upon the simultaneous iterative reconstruction technique (SIRT), where the velocities of individual pixels are successively modified to minimize the differences between measured and calculated travel times. The distribution and magnitude of velocities when a prescribed convergence criteria has been satisfied can be associated with zones of sound or deteriorated materials or with inclusions in the material.

The simplest analytical technique assumes each incident stress wave travels in a straight line between the transmitter and receiver (Figure 1). This approximation is adequate for uniform materials but, if velocities of adjacent regions vary by more than about 40 percent, refraction and bending of the waves become significant. Curved ray techniques were developed to consider this effect. The curved ray method traces rays between transmitter and receiver but, because the ray paths may be curved, large "shadow" zones associated with low velocity material may be created in which no rays travel. To overcome this problem, the current software models each pulse as a migrating wavefront based upon Huygen's Principle of wavefront propagation (Figure 2). This procedure insures that all pixels are involved in the reconstruction process while still permitting wave path refraction. The program uses a limited number of straight ray path iterations to obtain a rough pixel velocity map after which the migrating wave front model is used to refine the velocity distribution.

In addition to the developments by the mining industry discussed above, acoustic tomography has been employed by Italian engineers utilizing the crosshole method to investigate the condition of large concrete dams [1]. The equipment and methods are similar to those used in crosshole geophysical tomography. Atkinson-Noland & Associates conducted a limited effort to investigate repair techniques on unreinforced masonry walls and piers [2,3]. Tomograms prepared for masonry walls in a damaged state and after repair by injection grouting show damaged areas and indicate the degree of improvement as evidenced by increased velocity magnitude and velocity uniformity. A research program is presently underway by Ontario Hydro to develop the ultrasonic tomography technique for

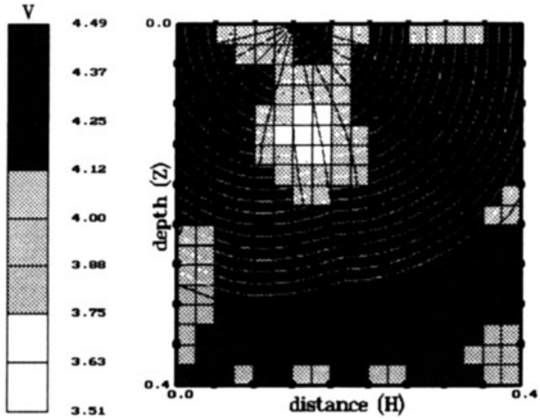

Figure 2. Migrating wavefronts technique used during velocity reconstructions.

evaluation of concrete structures [4]. The research program proposes obtaining successive tomographic slices of a structure and using three-dimensional volume rendering methods to define the shape of an inclusion.

RESEARCH PROGRAM

The objective of this research project was to demonstrate the feasibility and investigate the capability of using acoustic tomography for location of features concealed within reinforced concrete. The research consisted of several series of experimental tests and analytical investigations. The preliminary phase of the effort consisted of an investigation of equipment parameters to determine characteristics of different transducers, waveform generators, and processors including identification of beam spreading and attenuation parameters. The main effort was directed towards applying acoustic tomographic methods to specimens containing idealized anomalies and realistic concrete properties. A parametric study was conducted to determine data acquisition requirements and program input parameters such as data accuracy, ray path coverage, pixel resolution and boundary constraints.

TOMOGRAPHIC INVESTIGATIONS

Small-Scale Specimens

Six small-scale concrete specimens were constructed for tomographic analysis. These specimens were essentially flat plates with a length and width of 0.45 m and a thickness of 0.09 m. The first set of three specimens were cast with a cement and sand mixture to provide a suitable medium for pulse transmission. A second set of small-scale specimens were cast with concrete containing cement, sand and aggregate with 25 mm maximum aggregate size. This concrete mix was chosen to be more representative of actual concrete construction.

Either a 50 mm diameter steel rod or a 50 mm diameter void were cast in the center of two of the specimens from each series. Low density concrete using perlite aggregate was cast in a small region of the third specimen (Figure 3). The three types of anomalies were chosen to be an idealized representation of conditions that may be present in actual reinforced concrete construction. Cylinders (75 mm diameter by 150 mm height) were cast for

Table 1. Materials used for small-scale specimens.

Material	Max. Aggregate Size (mm)	Density (g/cc)	Measured Velocity (m/sec)
Sand Concrete	1	2.11	4270
Standard Concrete	25	2.36	4040
Low Density Concrete	3	1.09	2840
Steel	N/A	7.92	6130

each type of concrete to obtain density and benchmark velocity readings. Data for the low density concrete, sand concrete, and steel control specimens are listed in Table 1.

For each specimen an in-plane section was imaged with a total of 384 separate ray paths using ultrasonic transducers having a resonant frequency of 100 kHz operating at 500 volts peak power. Transmitter and receiver locations were spaced at 50 mm intervals around all four sides of each section. A complete set of ray paths is shown in Figure 1. Stress waves were generated and transit times measured using a James Instruments V-Meter. Data from the first specimen set was used to investigate appropriate program input parameters, including the required accuracy of time-based measurements, the number of ray paths and pixels, ray path coverage, boundary conditions, and constraint information.

Final velocity reconstructions for cement/sand concrete sections with steel, void, and low-density concrete inclusions, shown in Figure 3, all show the location of included anomalies. The image for the specimen containing a low-density inclusion shows a distinct region of low velocity located where the anomaly was cast. The remainder of the concrete has a uniform velocity. The steel bar and void are also present in the velocity reconstruction of the remaining two sections. The anomalies are represented in the correct locations but are shown to be somewhat larger than their actual 50 mm sizes.

Velocity reconstructions for the specimens containing large aggregate concrete are shown in Figure 4. Pulse velocity data for this Series showed more variation than data from the Series I cement/sand specimens. This effect is expected as minor variations in aggregate density and distribution will affect measured stress wave transmission. Velocity profiles are similar to those developed during Series I analyses and show the anomalies in the correct locations for the steel bar and void specimens. Analysis of the section containing low density concrete was not successful due to severe attenuation of the incident wave.

Large-Scale Specimen

A single, larger concrete specimen was cast to investigate use of the technique on mass concrete. Whereas Series I and II specimens were essentially flat plates, this large section introduced the possibility of stress waves traveling in the third dimension, i.e., waves traveling around low velocity inclusions out of the analysis plane.

The specimen was cast using normal concrete (25 mm maximum aggregate size) and had dimensions of 1.5 m (length) by 0.38 m (width) by 1.2 m (height). Several internal features were placed in the formwork prior to concrete placement, as shown in Figure 5. Two low velocity inclusions formed using foam pellets and 25 mm aggregate with no cement paste were included to be representative of clay balls (improperly mixed concrete) or unconsolidated concrete with honeycombing. The large "clay ball" had an approximate diameter of 190 mm; the small clay ball was fist sized and had a diameter of 100 mm. Travel time

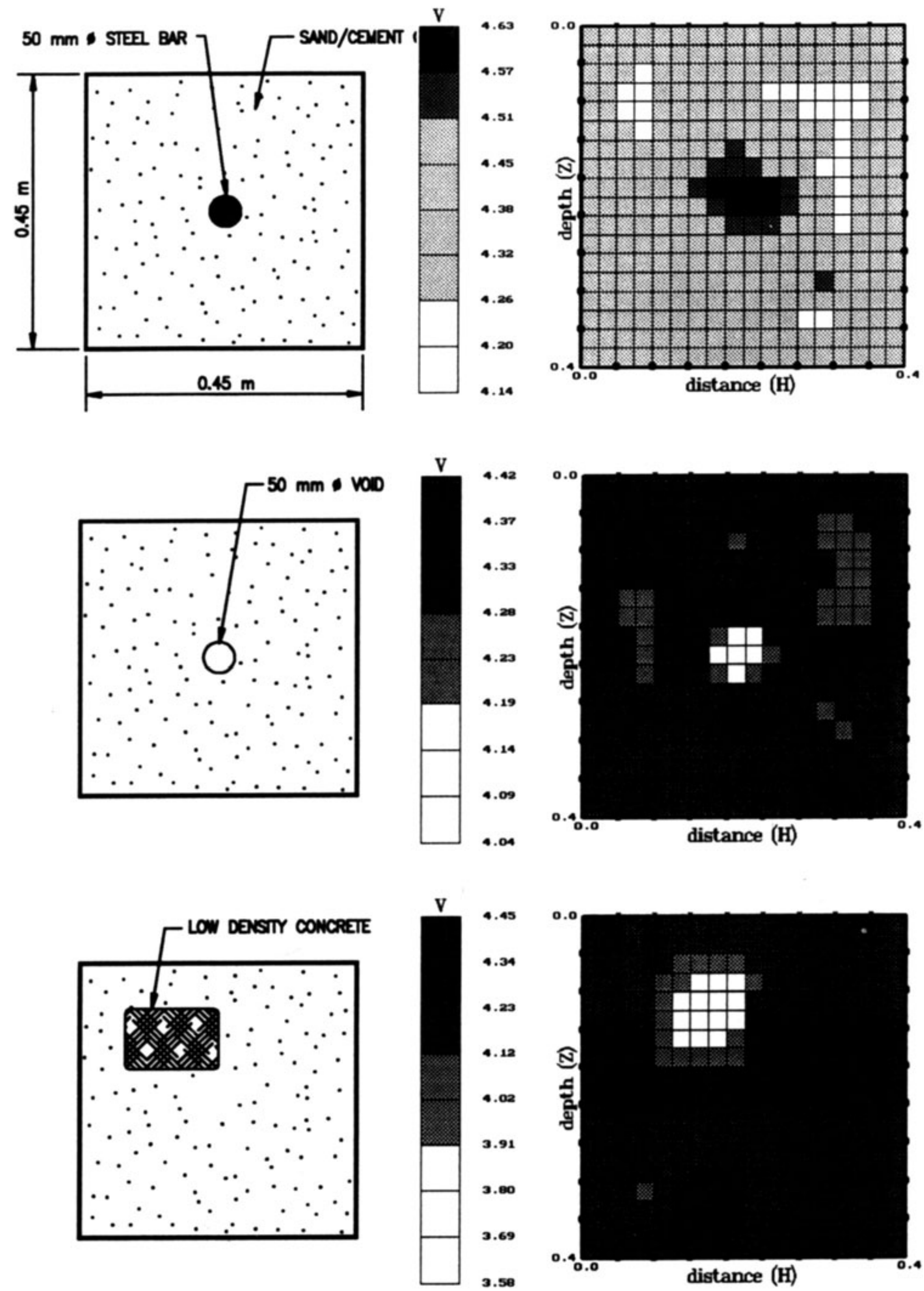

Figure 3. Tomographic velocity reconstructions for Series I specimens. (a) Top: steel bar at center; (b) middle: void at center; (c) bottom: area of low density concrete. Shading represents velocity in km/sec according to scale at left of each image.

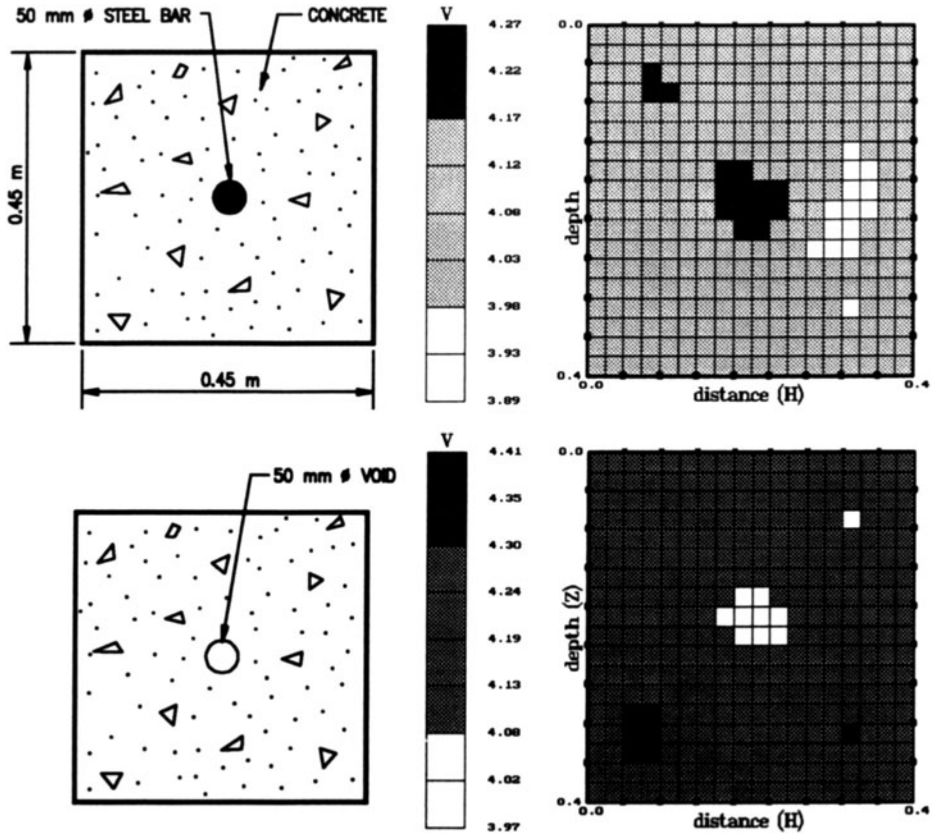

Figure 4. Tomographic velocity reconstructions for concrete specimens. (a) Top: steel bar at center; (b) middle: void at center. Shading represents velocity in km/sec according to scale at left of each image.

data was obtained using ultrasonic transducers with center frequency of 54 kHz operating at 500 volts peak power.

For this case a preliminary analysis using transducer spacings of 100 mm was not able to locate both features. Additional data was obtained by reducing transducer spacing from 100 to 50 mm. Results of the second analysis (Figure 5) show both low velocity anomalies. The small clay ball is accurately sized and located, whereas the size of the large clay ball is smeared over a larger area due to incomplete ray path coverage near the specimen base.

CONCLUSIONS AND RECOMMENDATIONS

The research effort demonstrated that acoustic tomography can locate internal anomalies in concrete. Anomalies located were high velocity (steel), zero velocity (void) and intermediate velocity (low density concrete) regions. The algorithm used was developed for identification of zonal velocity differences and is not well suited for identification of discrete velocity changes, tending to smear anomalies over an area larger than the actual feature.

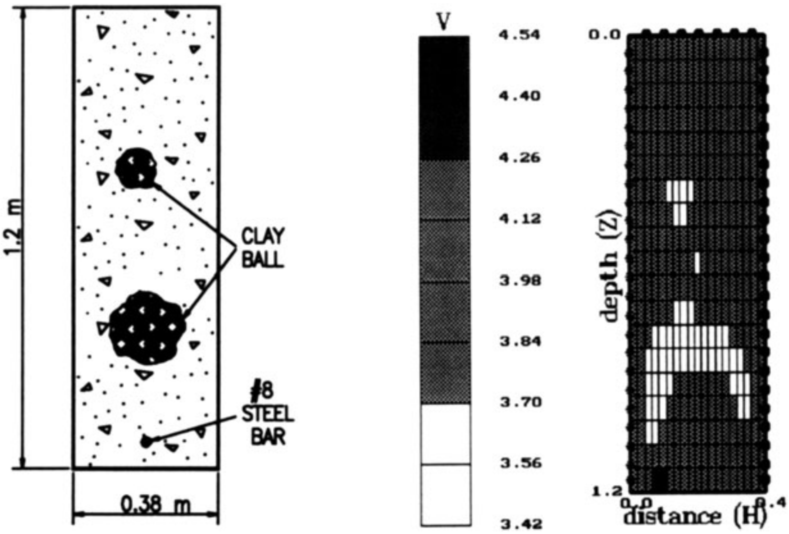

Figure 5. Velocity reconstruction for a vertical plane through mass concrete specimen.

The analysis also underestimates the effect of anomalies on measured velocities. For the three cases investigated, the computed velocity for each anomaly approaches but does not equal velocities measured through control specimens. The system needs to be optimized to allow accurate identification of velocities. The procedure places erroneous velocity variations at the area boundaries, where conditions are known to be uniform. This effect can be avoided by placing constraints on the velocities at the section boundaries.

This preliminary evaluation study, employing software developed for the mining industry and hardware used for ultrasonic testing of concrete, successfully demonstrated the feasibility of applying acoustic tomographic for evaluation of concrete structures. Modification to both the software and hardware employed should permit considerable improvements to the resolution and accuracy of the technique.

ACKNOWLEDGMENTS

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