THREE DIMENSIONAL IMAGING OF CONCRETE STRUCTURES USING ULTRASONIC SHEAR WAVES

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KEYWORDS: 3D Imaging, Concrete, Nondestructive Testing, Shear Waves, Tomography, Ultrasonic Testing, *MIRA* Equipment, Internal Evaluation

ABSTRACT

Unlike the medical field, where significant advances in the area of three dimensional (3D) imaging of the human body has advanced considerably, reliable 3D imaging of concrete structures has not progressed much until recently. Among the nondestructive testing methods, Ground-penetrating radar (GPR) has been one of the most successful techniques in which 3D imagery can be produced. Although 3D GPR Images have been very successful in showing the orientation and location of the embedded targets, such as reinforcing steel, utility lines, etc., less successful results have been obtained when trying to produce a 3D image of internal voids and cracks. In addition, the use of GPR to locate voids in post-tensioned metal tendon ducts systems has yielded unsatisfactory results.

Scanning Impact-echo (SIE) systems have also been recently developed to provide 2D and 3D images of concrete structures. The SIE systems have developed a more automated approach, thus relying less on the interpretation of the operator. Although test results to located internal voiding in concrete have shown some success, further research and testing is necessary to fully understand the capabilities and shortcomings of these SIE systems. Some of these SIE systems produced images that are based on computer algorithms that only compare the spectral response to that of a theoretical back wall or the full thickness of the section. Scanning impact-echo systems have not been very successful in assessing the grout condition in plastic ducts or embedded elements that have much lower acoustic impedance than concrete. Similarly, because of limitations intrinsic to the equipment, assessment of voids in thick concrete elements (thicker than 1 m) has been very difficult, and in some cases impossible to do.

Conventional ultrasonic pulse velocity (UPV) testing has been used to painstakingly create 2D and 3D images of internal voiding. Such testing requires access to both sides of the structure and many readings at multiple angles or offset positions between the transmitter and receiver. The collected data is then analyzed in terms of propagation velocities and the arrival of the transmitted ultrasonic pulse. Finally, signal reconstruction computer algorithms are used to produce 2D or 3D images. 3D UPV testing of concrete is commonly used these days to assess deep foundations by means of the Cross-hole Sonic Logging (CSL) test method.

This paper discusses the use of a recently developed instrument known as ***MIRA***, which utilizes a patented phased array of dry point contact shear wave transducers to produce 2D and 3D tomography images of concrete structures. This new technology has allowed the operator to obtain in-situ, real time test results.

The *MIRA* system is capable of creating cross-sectional 2D scans and 3D images of the concrete elements in less than 4 seconds after data collection. Similarly, data at individual inspection points are collected at a rate of about 3 seconds per location.

The *MIRA* test method and recent equipment and analysis innovations are described; case studies from two real-life structures are presented and discussed. Similarly, the advantages and disadvantages of the system are discussed and conclusions regarding the overall feasibility of the system to accurately and efficiently detect internal voids, honeycombing, delaminations, and air voids in grouted post-tensioned cable duct systems will be presented.

INTRODUCTION

The ***MIRA*** equipment is not based on any new test concept, rather a merging of well-known stress wave propagation principles and the advent and application of advanced hardware and analysis software packages. The use of ultrasonic stress wave propagation dates back more than 60 years. In fact, the end of the Second World War propelled research into stress wave propagation in construction materials, particularly steel and concrete [1]. Laboratory equipment development, known as soniscope [2] and the ultrasonic tester [3], paved the way to the development of a widely used nondestructive test method for concrete known as the ultrasonic pulse velocity (UPV) method. The UPV test method traditionally employed the use of two transducers; a transmitting transducer and receiving transducer. To allow the transfer of the mechanically induced ultrasound waves, both transducers (transmitting and receiving) typically required a coupling agent to make the proper contact between the transducers and the surface of the concrete structure. Furthermore, a fairly smooth concrete surface is required. Similarly, development of other stress wave propagation techniques such as, the pulse-echo test method, which employs the use of only one transducer, has seen tremendous continuing improvement in recent years. However, despite recent hardware and software innovations, the use of a coupling agent to provide the proper transfer of the ultrasound signal continues to be a challenge for both methods (through-transmission (UPV) and pulse-echo).

LONGITUDINAL vs. TRANSVERSE WAVES

When a stress wave is induced into a concrete structure, three types of propagating mechanical waves are introduced; compression waves, also known as longitudinal or P-waves; Shear waves, also known as transverse or S-waves; and surface waves, also known as Rayleigh or R-waves. Each of these waves travel at a discretely different velocity. P-waves travel at a much faster speed than S-waves and R-waves. In concrete structures, Shear waves and Rayleigh waves travel at velocities with about 60 and 55 percent disparity from the longitudinal waves, respectively [1].

Commonly used UPV and pulse-echo equipment utilize transducers that generate longitudinal waves inducing particle motion, due to the stress, that propagates parallel to the direction of the wave front. Alternately, transverse waves have particle motion that propagates perpendicular to the direction of the wave front, that is, parallel to the concrete surface. The velocity of the propagating wave is directly proportional to the frequency f and wavelength λ of the wave motion by:

$$V = f\lambda \qquad (1)$$

where the frequency is measured in hertz (cycles per second), and the wavelength in units of linear distance. Consequently, an increase in the frequency of the wave causes a decrease in the wavelength, and vice versa. Similarly, in infinite elastic solids, the longitudinal wave speed C_p is a function of the Young's modulus of elasticity, E, the density, ρ, of the material, and the Poisson's ratio, ν, by:

$$C_p = \{ E\,(1 - \nu) \,/\, \rho\,(1 + \nu)\,(1 - 2\,\nu)\}^{\frac{1}{2}} \qquad (2)$$

The study of propagation of transient stress waves through a heterogeneous medium, such as concrete, is a very complex phenomenon. As the longitudinal wave propagates through a solid concrete medium, the energy is scattered away from the original wave path when the material properties of the medium changes. The same type of scattering occurs when a propagating longitudinal stress wave encounters voids, cracks, and other internal flaws, that is, scattering of the incident waves is produced. Furthermore, rapid attenuation of the signal occurs when the amount of signal scattering is intensified, that is, when the wavelength of the propagating wave coincides in size or smaller than the size of the internal discontinuity or internal flaw that is causing the wave scattering In addition, the inherent inhomogeneity of concrete causes a large amount of backscattering (deflection of incoming waves from their original direction) of the longitudinal waves, which leads to signal noise and a decrease in the ability to detect the particle motion travelling parallel to the propagating waves. Conversely, transverse, or Shear waves, travel normal to the propagating longitudinal waves. Research has shown that using Shear waves instead of compression (longitudinal) waves has offered advantages in reducing the amount of backscattering and signal attenuation in the direction parallel to the propagating wave [4].

LOW FREQUENCY DRY POINT CONTACT (DPC) ULTRASONIC TRANSDUCERS

Research work performed at the Research Institute of MSIA “Spectrum” in Moscow, Russia lead to the development of the low frequency dry point contact (DPC) ultrasonic transducers at the end of the 1980s. The DPC transducers primarily addressed the long-term problem of acoustic contact between the surface of the ultrasonic probe and the face of the concrete structure. Also there was improved sensitivity of the transducers by improving the directivity characteristics of the probes. In an essence, DPC transducers have been designed so that the size of the acoustic crystal in the piezoelectric element is several times smaller than the size of wavelength typically used to test concrete (40 mm or less). For example, if the wavelength of the propagating stress wave is nominally 40 mm, the contact zone between the transducer’s piezoelectric tip and the concrete surface is nominally between 1-2 mm for this transducer; thus the transducer tip becomes a point contact. In addition, a proprietary damper, made from a composite liquid which surrounds the entire free space of the piezoelectric element, has made it possible to provide higher oscillation attenuation with an increase in the ability to perceive the propagating wave. Finally, the directivity (longitudinal or transverse) of the propagating wave at the wearing tip of the transducer can be controlled by incorporating a dual piezoelectric element in the transducer casing. The longitudinal and transverse stimulation at the tip of the transducer is produced when both piezoelectric elements are either in-phase or out-of-phase, respectively [5]. Figure 1 below shows a view of several DPC transducers in either a single or an array configuration.

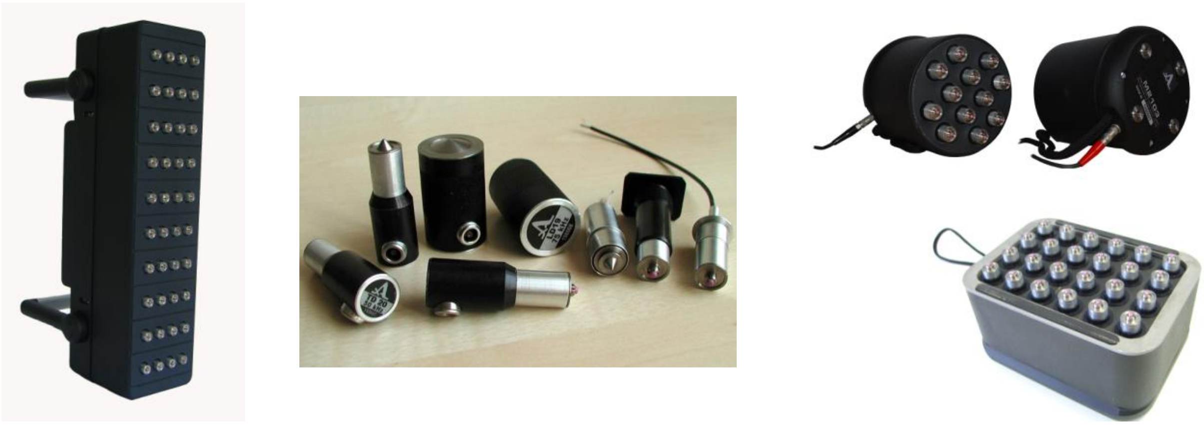


Figure 1- View of various DPC transducers in various configurations

SYNTHETIC APERTURE FOCUSED TECHNIQUE (SAFT)

Assessment of internal flaws in concrete structures has been traditionally performed using point by point stress wave propagation methods; for example, the previously mentioned test methods of UPV (using two transducers) or pulse-echo methods (using one transducer) are placed at a point to evaluate that point. In both cases, longitudinal waves are typically employed and analyzed to assess the condition of the test concrete at that point. With the constant improvement in computing power (faster computers), the ability to acquire data fast is most useful. More recently, however, data obtained from traditional ultrasonic stress wave propagation methods, combined with imaging reconstruction techniques have led to development of analysis software capable of imaging concrete in a manner similar to the medical radiology profession using magnetic resonance imaging (MRI) techniques. The MRI technique is, almost in real time.

Because of the inhomogeneity nature of concrete, many combinations of data points are required to map out and accurately reconstruct an image depicting the internal condition of a concrete structure. To overcome this obstacle, spatial averaging of a large number of single measurements per unit area under testing is typically performed using an array of low frequency, short pulse, dry point contact (DPC) transducers and a mathematical algorithm that uses a 3D synthetic aperture focusing technique (SAFT). SAFT is a signal processing tool use to improve the resolution of an ultrasonic image with focusing distortion [6, 7, 8].

DESCRIPTION OF THE *MIRA* TEST METHOD AND SYSTEM

The Ultrasonic Shear Wave Test Method, commercially known as *MIRA,* is a concrete flaw detection system capable of generating 3D tomographic images of concrete elements. The basic system consists of a console with 40 transducers configured in 10 rows of single modules containing 4 Shear wave transducers each. The transducers are spring-loaded, dry-point contact (DPC) piezoelectric sensors with a center frequency of 50 kHz. Each transducer is built with a wear-resistant ceramic tip, which allows testing even on very rough surfaces. Once the ultrasonic shear wave signal is emitted, the received signals are processed by the controlling console and then transferred to a laptop computer via Wi-Fi wireless technology for further analysis by a proprietary software. A synthetic aperture focusing technique (SAFT) data processing method is then performed to generate the 3D images of the concrete element. The reconstructed images are displayed almost instantaneously (3 sec) on the computer screen as a plan view, cross-section, or isometric view. Images are generated from the signals received from all the combinations of PDC transducers (transmitting and receiving) in the antenna array. The *MIRA* system is commonly used in concrete, stone, and masonry structures to detect internal flaws such as delaminations, cracks, poorly consolidated or honeycombed concrete, as well as voids in grouted tendon ducts systems. Figure 2 below shows a view of the *MIRA* system.

Shear wave DPC transducers in a 4 x 10 array

Laptop with SAFT analysis software

Figure 2- View of the Shear wave ultrasonic tomography *MIRA* System

CASE STUDIES

Case Study No.1 - The first case study is of a concrete underground pedestrian tunnel constructed in 2006. The two-level tunnel structure consists of a rectangular lower section (utility tunnel) and an arched upper section (pedestrian walkway). The pedestrian tunnel is nominally 5.5 m wide, 2.7 m high at the crown, and 40 m long. Nondestructive testing (NDT) methods were used to determine if large voids were present in the tunnel's concrete liner. Testing was limited to assessing the section of the concrete liner in the crown section from the right springline to the left springline. Several NDT techniques were investigated to assess the concrete liner including: impact-echo (IE), ground-penetrating radar (GPR), and the *MIRA* ultrasonic shear wave tomographic technique. Figures 3 and 4 show a cross section of the concrete tunnel and a longitudinal view of the cast-in-place pedestrian tunnel, respectively. *MIRA* testing was performed at selected test points. Two methods of collecting data were used. The first method consisted of collecting the data at each of the test grid points and producing a single cross-sectional image of the test location. This first data collection method is preferable when an overall global approach of the structure is desired; often times mandated by size of the structure being tested and time constrains. The second collection method entailed collecting the data using a very close test grid; typically in this case the grid spacing is on the order of 50 to 100 mm, which can then be used to produce a 3-D image of the structure.

The results of the single profile *MIRA* readings indicated variable thicknesses throughout the tunnel liner. At some locations, reflections from about 200 to 250 mm were obtained (see Figure 5). At other locations thicker thickness, on the order of 300 to 400 mm were estimated (see Figure 6). Figure 5 below shows a cross section image from a *MIRA* test point. The center point of the red spot represents approximately the depth of the Shear-wave reflection at close to 230 mm. Similarly, Figure 6 shows a cross section image from a *MIRA* test showing a Shear-wave reflection at nominally 330 mm.

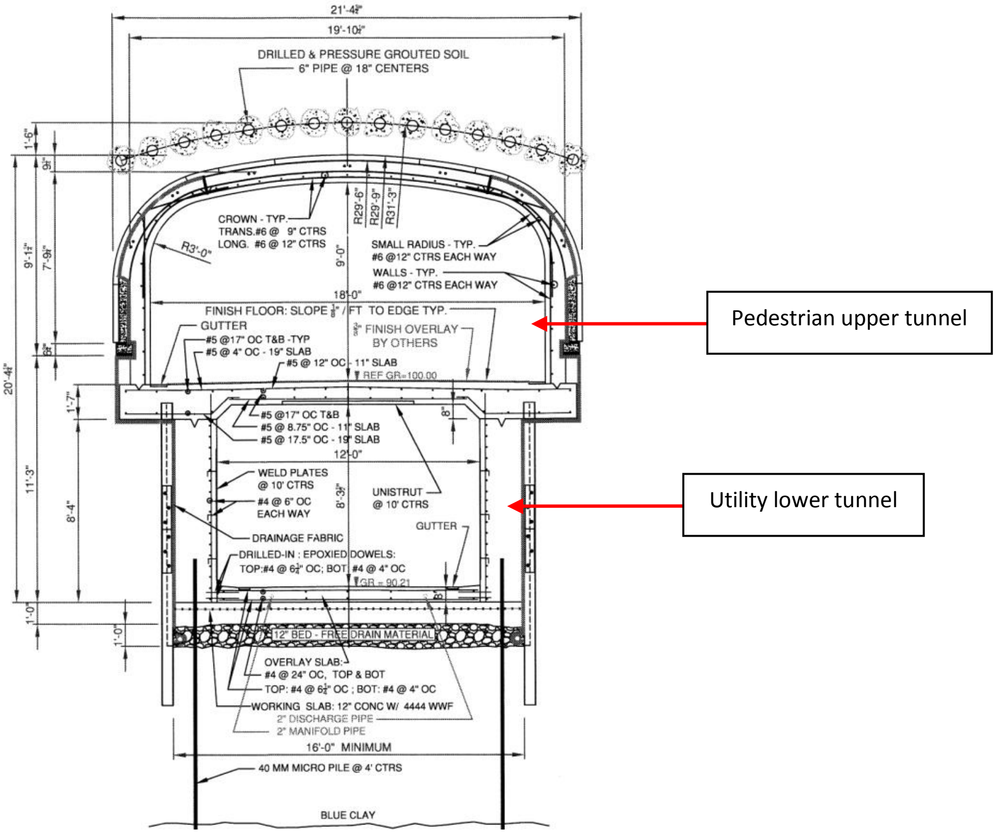


Figure 3- View of the tunnel's cross-section

Figure 4 - Longitudinal view of the cast-in-place pedestrian tunnel

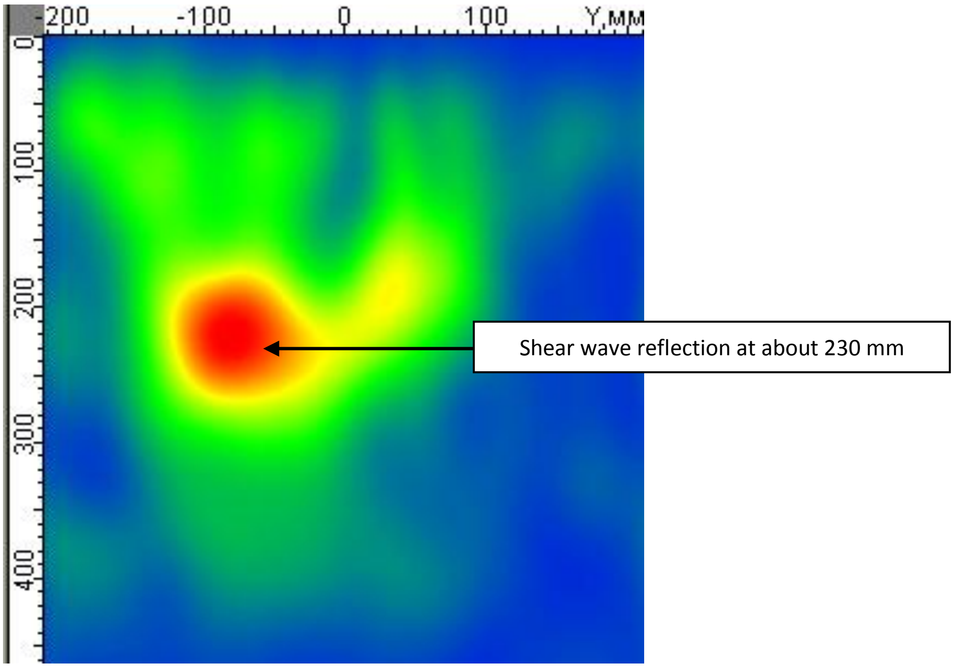
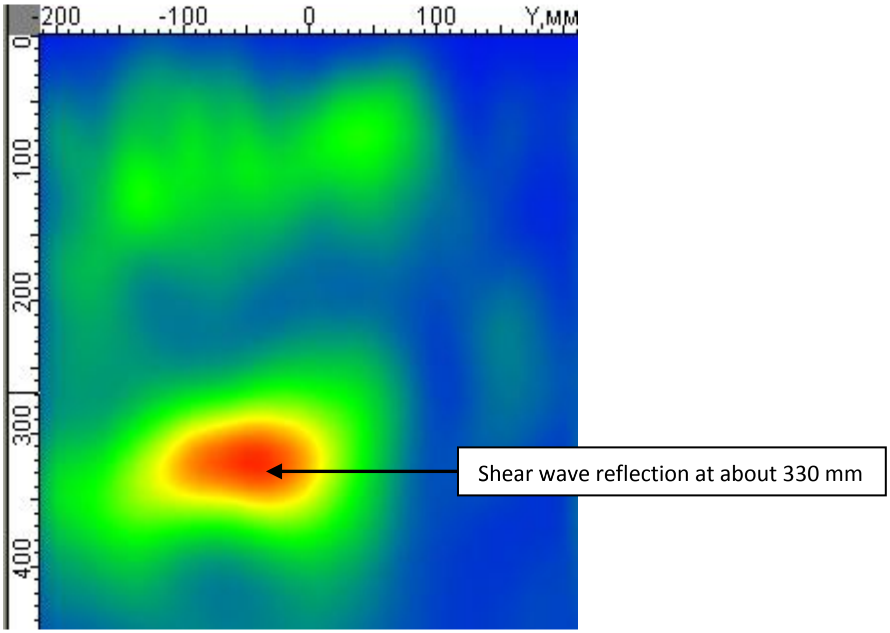


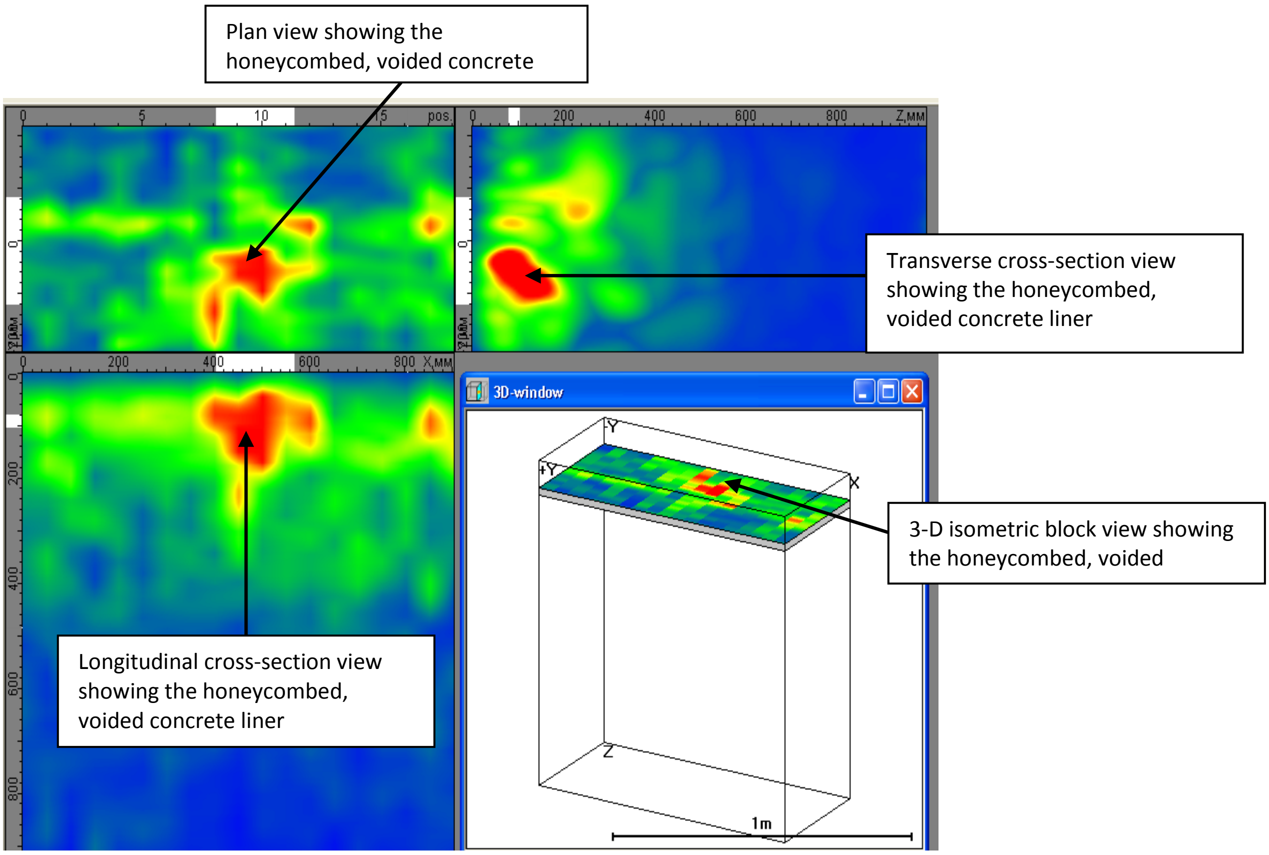
Figure 5- Transverse cross-section showing a *MIRA* shear wave reflection at about 230 mm



Shear wave reflection at about 330 mm

Figure 6- View of a transverse cross-section showing a *MIRA* shear wave reflection at about 330 mm

Finally Figure 7, shown below is a *MIRA* test result from test point above the right springline. At this test location several closely space readings, approximately 50 mm apart, were collected to generate the 3D block image. This test location corresponds to an area where a core was taken to verify noted conditions. At this location, honeycombed concrete was found nominally 190 mm deep followed by a void with lateral extent. The images shown in Figure7 represent a plan view (upper left), which in this case represents looking at the right springline. The upper right image and lower left images represent a transverse and longitudinal cross-section view of the upper left image, respectively. Finally, the lower right image represents a 3D isometric view. The red spot shown in each of the images in Figure 7 coincides with the location where the honeycomb voided concrete found using *MIRA* and verified by removing a core.



Plan view showing the honeycombed, voided concrete

Transverse cross-section view showing the honeycombed, voided concrete liner

3-D isometric block view showing the honeycombed, voided

Longitudinal cross-section view showing the honeycombed, voided concrete liner

Figure 7- View of a *MIRA* test result showing a plan view, cross-section views, and an isometric 3D block view

Case Study No. 2 -The second case study is of a precast parking garage in the eastern part of the United States erected about 2 years ago. Nondestructive test methods, GPR and the *MIRA* ultrasonic instrument, were used to performed field studies to document the continuity of the grout within splice sleeves making the connection between precast concrete wall panels. The field studies were performed at 65 representative locations throughout various levels of the north, south, west, and middle bearing walls. The perimeter spandrel precast wall panels were nominally 300 mm thick. Figure 8 shows a view of the exterior of the precast wall panels. Figure 9 shows a sketch of the typical splice sleeve grouted connection used between wall panels.

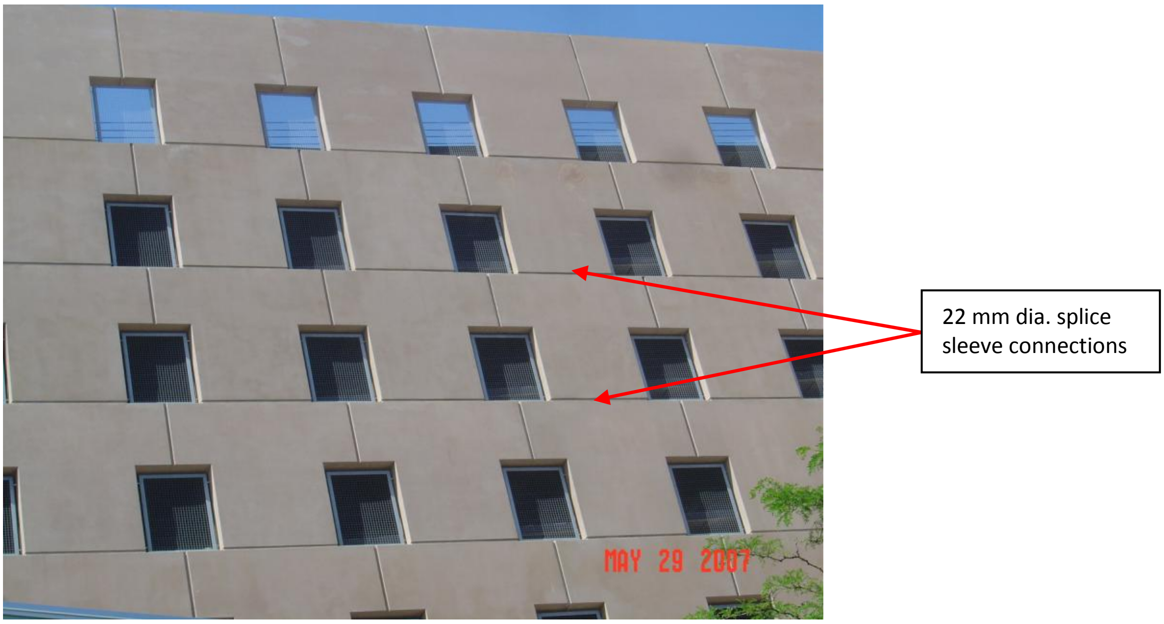


Figure 8- View of a typical exterior elevation showing the precast spandrel wall panels and the location of the splice sleeves connections

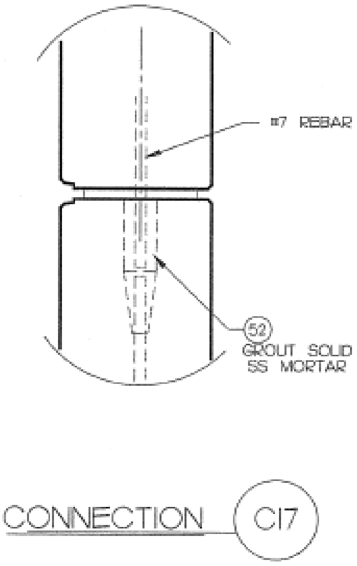


Figure 9- View of a typical splice sleeves wall panel connection

Figure 10 shows a view of a *MIRA* test in progress conducted across an embedded splice sleeve, that is, the splice was perpendicular to the instrument. At each splice sleeve location, several *MIRA* readings were taken at various cross sections along the length of the embedded sleeves. The interpretation of the splice sleeve-grout continuity tests were categorized into two groups according to the output of the *MIRA* as “grouted” or “void.” Figure 11 and 12 below show representative cross section images of the test results. Figure 11 shows a typical *MIRA* test result showing a cross-sectional image from a test point with a grouted splice sleeve. At this location, Shear-wave reflection from the backwall is shown at about 300 mm. Similarly Figure 12 shows a *MIRA* test result showing a cross-sectional image from a test point where the splice sleeve was found to be filled with water. At this location, a Shear-wave reflection from the empty splice sleeve and the backwall reflection at about 300 mm are shown. To verify the results of the *MIRA* test output, several inspection openings were made by drilling a small diameter hole through the concrete and embedded splice sleeve. Figure 13 below shows a view of a verification opening where a splice sleeve was found filled with water.

Ground penetrating radar (GPR) was also used to locate the centerline of each of the splice sleeves in order to define a test area for the use of the *MIRA*.

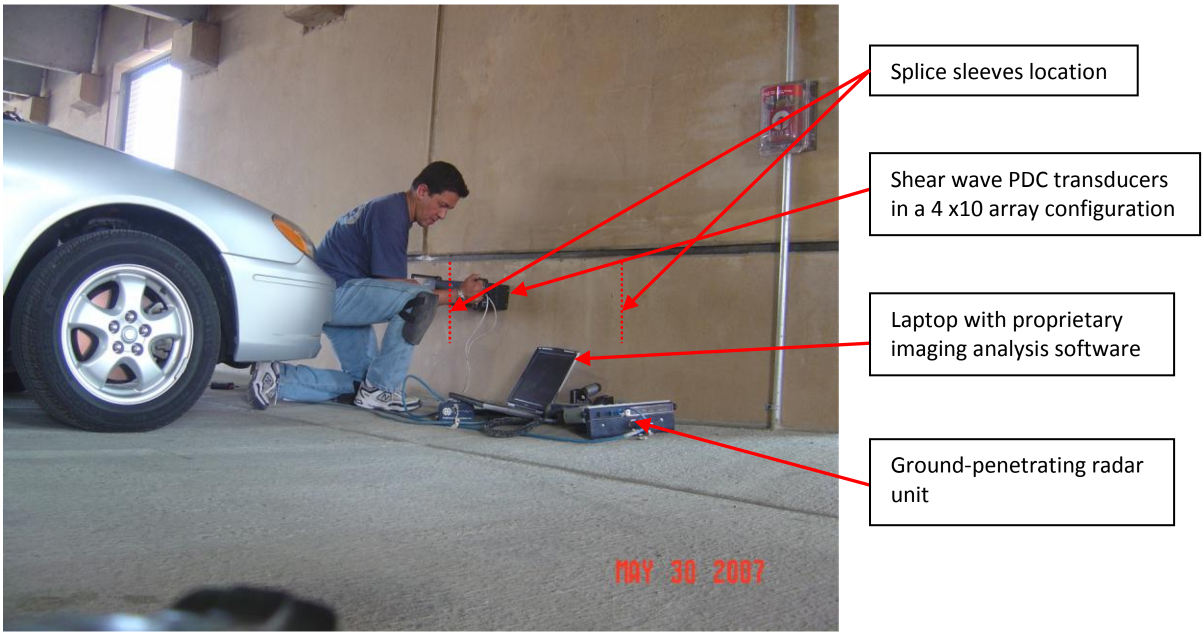
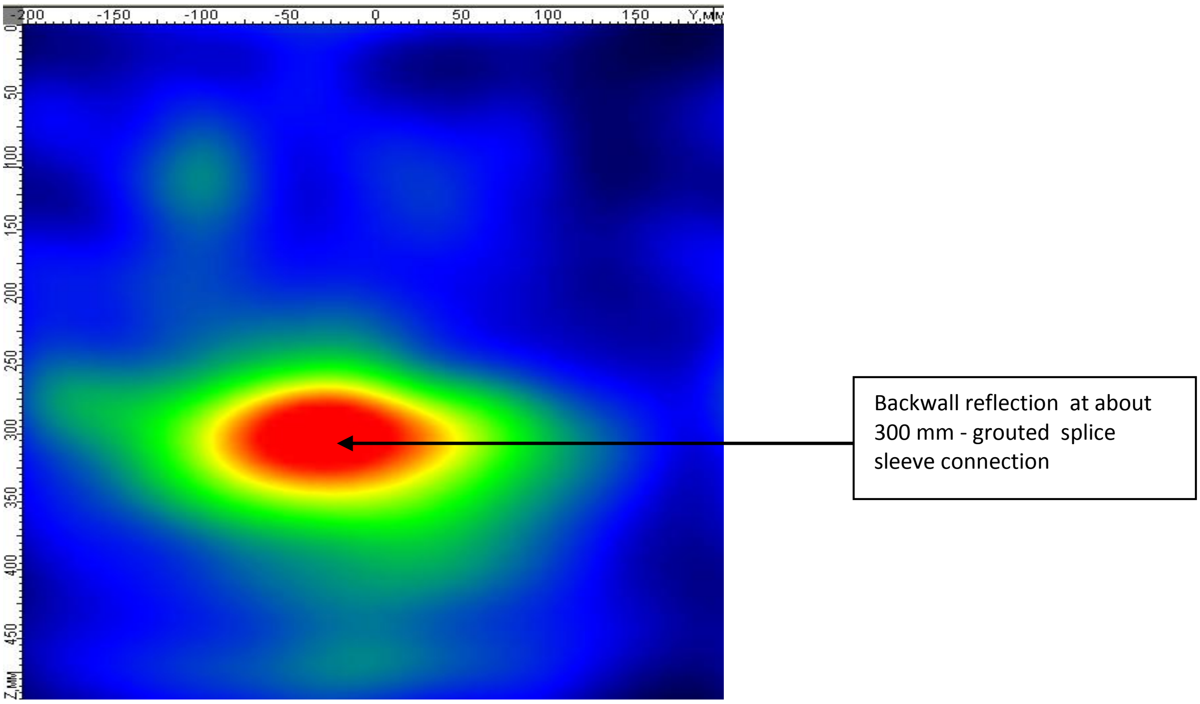
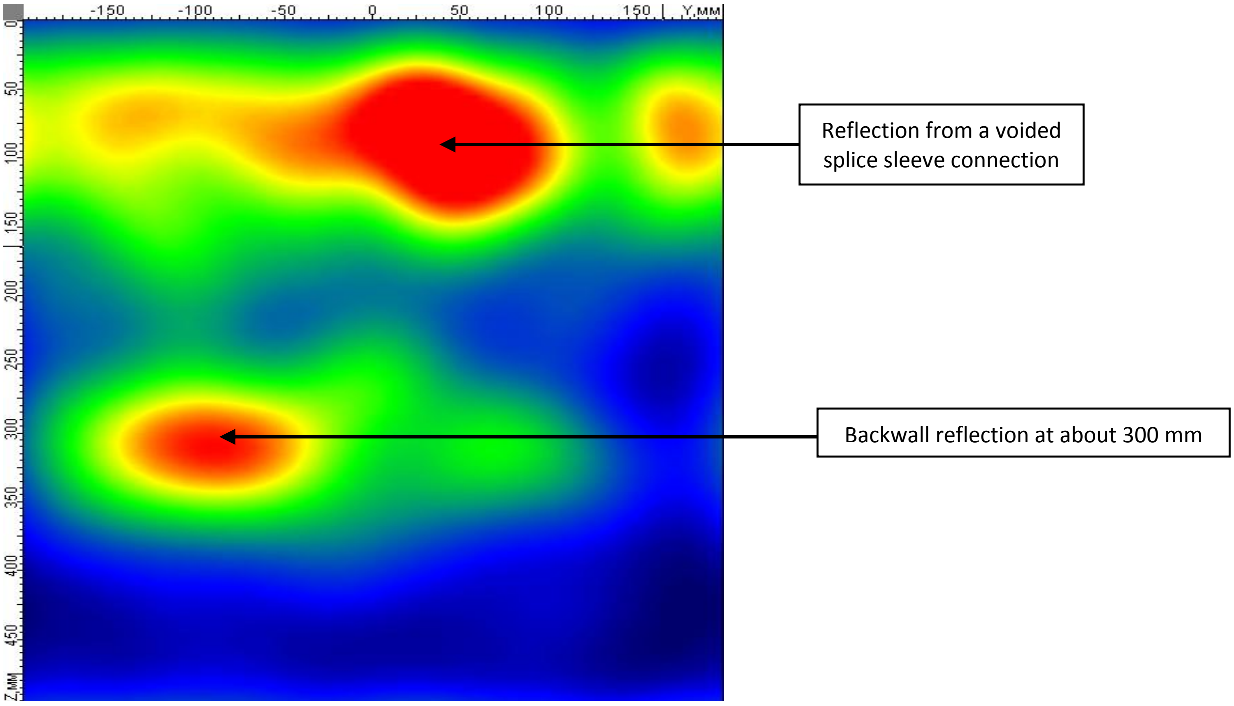


Figure 10- View of a *MIRA* test in progress at a splice sleeve location



Backwall reflection at about 300 mm - grouted splice sleeve connection

Figure 11- View of a *MIRA* cross section image showing the backwall reflection at about 300mm and a grouted splice sleeve connection



Reflection from a voided splice sleeve connection

Backwall reflection at about 300 mm

Figure 12- View of *MIRA* test result showing a voided wall panel splice sleeve connection and the backwall reflection at about 300 mm

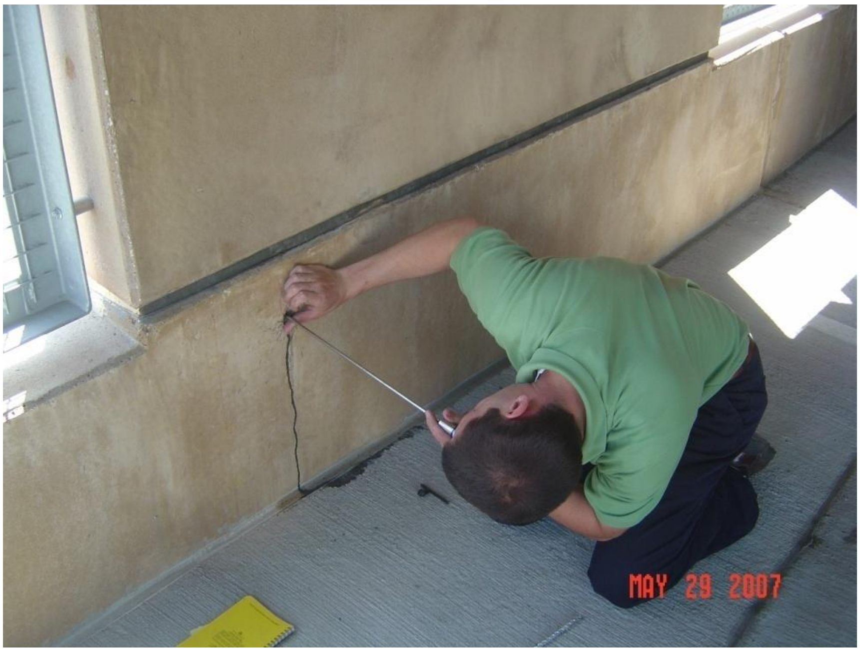


Figure 13- View of an exploratory opening at a voided splice sleeve

CONCLUSIONS

Advancements in the studies of stress waves propagation principles and improvements in the ever-changing world of computers have lead to the development of advanced hardware and analysis methods capable of generating 2D and 3D tomographic images of concrete structures in a manner similar to that is performed within the medical MRI field. The Ultrasonic Shear Wave Test Method, commercially known as *MIRA,* was used in two real-life structures to determine in one case the presence of large voids in a reinforced concrete tunnel liner and in the second case, the presence of grout in a splice sleeve connector between precast concrete wall panels. In both cases the interpretation of the *MIRA* images were confirmed with exploratory openings. To date, the *MIRA* system has been successfully used to locate voids, delaminations, poorly consolidated concrete, air voids in grouted post-tensioned cable duct systems, etc. Some of the main advantages of the *MIRA* test system is its portability, the ability to collect data in a fairly rapid manner, and more important the ability to generate 2D and 3D images in just a few second after completing the data collection. The disadvantage of the *MIRA* system is that it is still a new test system that is not widely used yet, and therefore, not enough information about test experiences in concrete applications is available. There are many questions regarding capabilities and limitations of the system that need to answered. For instant,

- What are the minimum dimensions of a void in concrete that can be detected?
- What is the maximum depth of penetration that can be expected?
- How much do changes in material properties affect the test result?

Fortunately, as researcher and practitioners continue to use the system the gap in lack of information is getting much narrower every day.

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