IMPACT ECHO TESTING OF IN-SITU PRECAST CONCRETE CYLINDER PIPE

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Abstract

This paper presents recent research and field work performed in the area of Nondestructive Testing (NDT) of Precast Concrete Cylinder Pipe (PCCP). The NDT was performed using the Impact Echo (IE) and the Spectral Analysis of Surface Waves (SASW) methods from the inside of PCCP sections to determine the integrity of the outer grout layer and bonding of the concrete to the embedded steel cylinder. Delamination of the outer grout layer or debonding of the steel cylinder from the concrete has been associated with corrosion and failure of the prestressing wires in this type of pipe. Testing of PCCP has been performed with the IE method using both a 4-channel scanning system as well as a hand-held single point IE device. The SASW testing of PCCP has been performed using discrete transducers, and examined both the material velocity characteristics of the pipe for use in IE measurements, the integrity of the pipe concrete and grout, and the material characteristics outside of the pipe.

The paper includes a brief description of the NDT methods and equipment used to perform the testing, as well as sample data for each method. The data was collected on in-situ PCCP sections under real-world conditions. This paper also presents a brief review of previous research conducted on NDT of in-situ PCCP.

Introduction

The use of concrete pipe has been shown to be an effective solution to the problem of transporting large quantities of fresh water and sewage over long distances. Concrete pipelines are generally reliable and of relatively low maintenance in most applications. There have been reports, however, of failures of this type of pipe under certain conditions, leading to the need to evaluate the condition of the pipe in-situ. Various technologies have been proposed and tried for testing PCCP in-situ, including a version of Acoustic Emission (AE) to listen for wire breaks, visual inspection and sounding from the inside, and NDT methods such as these presented here. Each of the techniques has been shown to have benefits and drawbacks, including cost, reliability,

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ease of use, and the information obtainable. In this paper, the use of the acoustic based NDT techniques of IE and SASW for evaluating the current condition and integrity of the pipe wall is presented.

Analysis of PCCP failures and previous research conducted by the Bureau of Reclamation have shown that many of the failures are due to corrosion of the prestressing wires and subsequent breakage, leading to loss of pressure capacity. The research has also shown that where the wires have corroded, there is also usually a failure (delamination) of the protective grout layer which is over the prestressing wires. The IE method is a nondestructive way to measure the effective thickness of the concrete pipe wall without requiring access to the outside of the pipe. This is important because excavation around a pipe can be expensive and time consuming.

Background and Previous Research

A previous paper by the authors presented the results of initial research into the use of the IE method in testing PCCP, as well as the use of a prototype IE scanner system in high-speed testing of this type of pipe. This previous research by the authors for the Bureau of Reclamation showed that the IE method is effective in measuring the wall thickness of sound, undamaged PCCP, even with an embedded steel cylinder and prestressing wires (Sack and Olson, 1994). The earlier work showed that where corroding wires have caused delamination of the grout layer, this damage is detectable with the IE method as long as the grout layer thickness is at least 4%-5% or more of the total wall thickness. This limitation is due to the resolution of the IE method in detecting small changes in wall thickness in practical applications.

The IE scanner system prototype developed as part of the previous research project used the IE method with scanning technology to measure the wall thickness of the pipe along given test lines on a near-continuous basis. The IE measured wall thickness could then be compared to the design wall thickness. Losses in wall thickness of 1.9 to 2.5 cm (3/4 to 1 inch) would normally be associated with the delamination of the outer mortar layer due to wire corrosion. The initial research into the scanner system used a buried section of damaged pipe for testing, followed by a field test in an in-situ pipeline. The scanner system worked relatively well for this pipeline, resulting in plots of wall thickness versus location along a number of lines in the pipe. The scanner did have problems, however, due to mud on the walls and the prototypical nature of the hardware.

Current Usage of the IE Method

Recent testing in PCCP sections under field conditions has shown that a practical application of the IE method for many pipeline evaluation scenarios is with an easily applied and used hand-held IE device. The hand held IE testing system has the advantage of being easy to bring into the pipe, and easy to transport within the pipe to areas of concern. The basic limitation of the hand held device is that only one point at a time can be tested, but data can be collected at rates of 4-5 seconds per point or more, depending on access conditions and the desired grid. Recent use of the pipe scanner prototype system has shown that rapid testing is possible, but that changes to the transducers may be required if testing is to be done under the wide range of surface conditions which can be encountered in real-world situations. A brief description of the IE method and the hand-held IE device is included in the next section.

IE Test Method Description

The IE test method and its use in testing concrete pipe have been described in detail in previous publications (Sack and Olson, 1994; Olson et al, 1992; Sansalone and Carino, 1986). The IE method is performed on a point-by-point basis by hitting the test surface at a given location with a small (90 gm (0.2 lb)) instrumented impulse hammer or impactor and recording the reflected wave energy with a displacement or accelerometer receiver mounted to or pressed against the test surface adjacent to the impact location. A simplified diagram of the method as applied to PCCP is shown in Fig. 1.

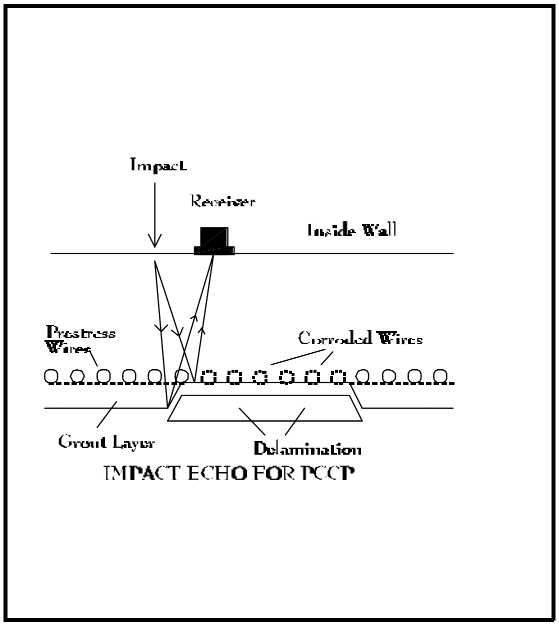

Figure 1 Impact Echo Test Method

Reflections from sound areas of the pipe cover a longer path and thus take a longer time to reflect to the receiver. Over an area with an outer grout delamination, the signals cover a shorter path and thus reflect quicker to the receiver. Since the reflections are more easily identified in the frequency domain, the time domain test data of the impulse hammer (if measured) and receiver are processed by the data acquisition PC for frequency domain analyses. For data collected with the impulse hammer and accelerometer, a transfer function (system output/input) is then computed between the hammer (input) and receiver (output) as a function of frequency. If an impactor is used instead of an instrumented hammer, then just the linear spectrum of the receiver signal is computed and displayed. Reflections, or "echoes", of the compression wave energy are typically indicated by pronounced "echo" peaks in the transfer function or frequency spectrum test records. These peaks correspond to the effective thickness of the pipe at the test location. If the velocity of the concrete is known or can be measured (as is generally the case for pipes), then the depth of a reflector can be calculated from the echo peak frequency. This will be the design thickness at sound locations, or about 1.9 to 2.5 cm (3/4 to 1 inch) less than the design thickness at locations with a grout delamination.

Single Point IE Test System

The single point IE testing system consists of a hand-held test head connected by a long (15-30m) cable to a battery powered data acquisition computer. The test head incorporates an electrically driven solenoid impactor and a piezoelectric displacement transducer which is used as a receiver for the received echoes. In operation, the test head is manually pressed against the wall of the pipe, and the solenoid is triggered. Triggering can be accomplished from either the data collection computer of from a switch on the test head. The received echoes are amplified and filtered at the data collection computer, and stored for analysis. Generally, two to three tests are done at each location the verify repeatability and assure high-quality data. The entire testing process takes about 3-5 seconds once the test head is pressed against the wall. Most of the testing time is taken up in moving between points and establishing the test grid.

Pipe Scanning System

The IE pipe scanning system has also been used in recent tests to evaluate its performance. The pipe scanning system was described in detail in the report on the previous research (Sack and Olson, 1994). Briefly, the pipe scanning system consists of 4 scanning heads which are spaced at 90 degrees around the interior of the pipe circumference, and are pressed against the walls pneumatically. The scanning heads use rolling transducer assemblies to receive the signals from solenoid impactors mounted adjacent to the receivers. As the scanner assembly is pulled down a pipe, data is collected sequentially from each scanner head, resulting in a linear test spacing of about 6 cm (2.5 inches) per test. The data is collected into a large data file and saved. Analysis of the data results in plots of distance versus effective pipe wall thickness for each of the scanner heads, which reveals any areas of delamination or other defects. Testing rates in clean pipe have been found to be about 6 m (20 feet)/ 5 minutes for the prototype system, not including initial set-up and take-down time.

Recent Pipe Test Results

The most recent field testing done on in-place PCCP were conducted by the author’s firm on a pipeline in Texas for an American Water Works Association Research Foundation (AWWARF) research project by Texas Research Institute (TRI). This pipe is about 2 m (6 feet) I.D. and has a wall cross-section of about 13 cm (5.25 inches). Of this cross section, the outer 2-3 cm (0.75-1.25 inches) is the grout layer. The core has an embedded steel cylinder about 6 cm (2.5 in) from the inside wall face. Visual inspection of the inside face of this pipeline showed a generally clean concrete surface, but with small visible pock marks and aggregate. Scratching the surface of the concrete showed the surface material to be unusually soft.

Initial testing of a section of this pipe was done with the 4 channel pipe scanner. The results of this testing showed that, while some usable data was obtained, the soft surface conditions damped out the higher frequencies from the impactor required to test the pipe. The high receiver gains used to compensate for the damped impact force resulted in unacceptable levels of rolling noise riding on the received signals. The excessive noise resulted in signals which could not be analyzed by the automatic scanning software, and instead required manual interpretation.

Additional testing of the pipe was done with the previously described single point IE system at selected locations. The results of this testing showed that the single point system worked well, even on the softer concrete, due to the high-sensitivity transducer used and the lack of rolling noise (which the scanner showed) during testing. A typical result from a sound location in the pipe is presented in Fig. 2. This figure presents the receiver time domain raw data in the upper trace, and the frequency domain spectrum in the lower trace. As seen in the figure, very little information can be directly determined from looking at the time domain trace. The frequency spectrum, however, shows a single clear echo peak at 12,800 Hz, which corresponds to a thickness of 14 cm (5.6 in) using a compression wave velocity of 3,660 meters per second (12,000 feet per second, fps) in the impact echo equation:

$$T = V/(2 * Fp) \qquad (1)$$

Where: T = Thickness in meters
V = Velocity in meters/second
Fp = Frequency peak in Hz

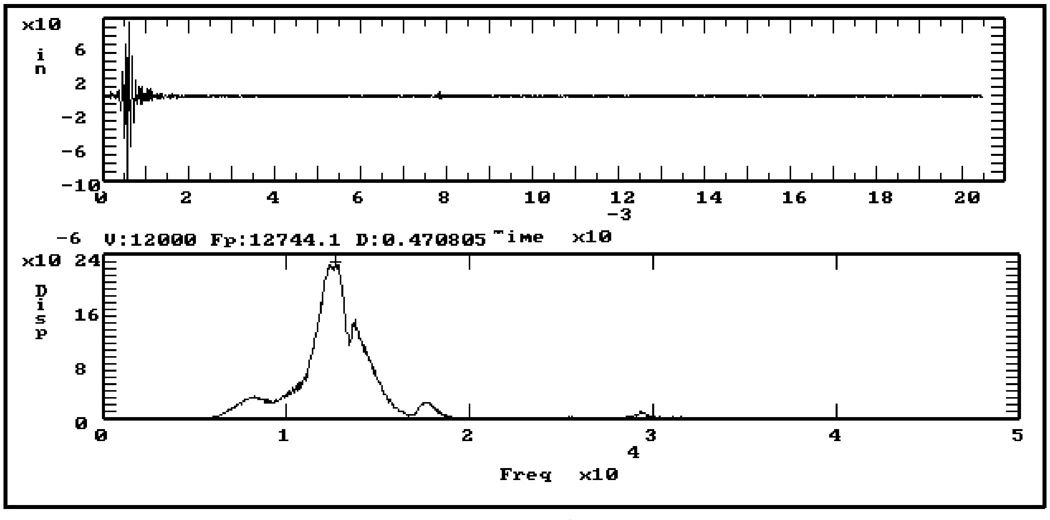

Figure 2 Sample Impact Echo Result for Sound Conditions

This thickness echo corresponds to the expected total cross section of the pipe wall. This indicates that the tested point is sound with no delaminations.

A typical test result from a location with a suspected delamination is shown in Fig. 3. Again, this figure presents the receiver time domain raw data in the upper trace, and the frequency domain spectrum in the lower trace. As seen in this figure, the frequency spectrum shows two distinct frequency peaks, one at about 18,000 Hz, and

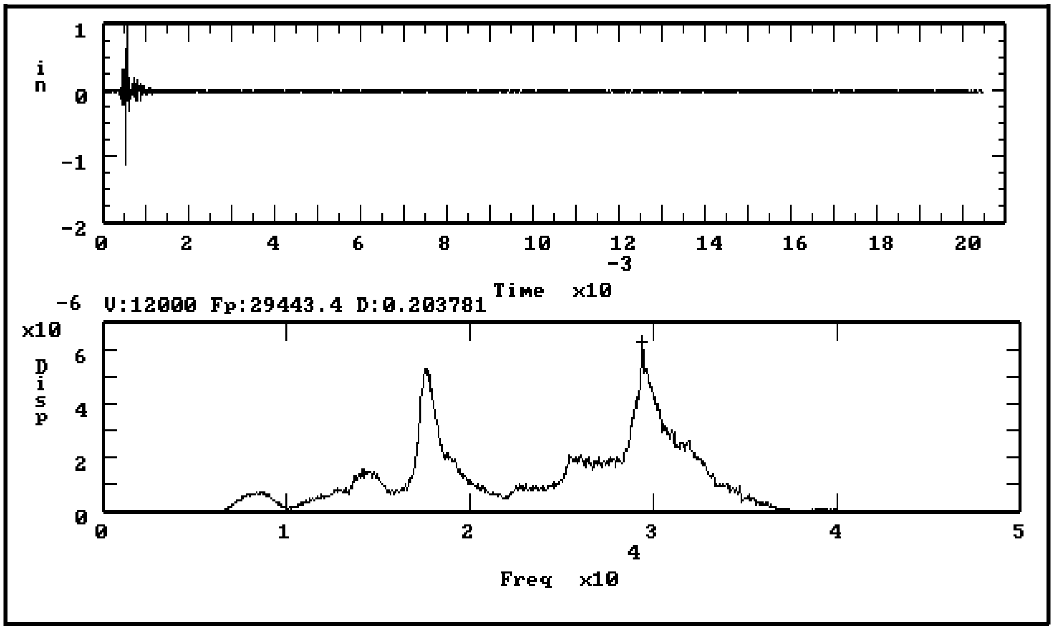

Figure 3 Sample Impact Echo Test Record from Delaminated Conditions

the other at 29,500 Hz. No frequency peak is seen in the 12,500 to 14,500 Hz range expected for sound locations. Using the impact echo equation, the lower frequency peak corresponds to a thickness of 10 cm (4.0 in), and the higher peak corresponds to a thickness of 6 cm (2.5 in). The thickness of the pipe wall without the grout is about 10 cm, and the distance from the inner face to the embedded cylinder is about 6 cm. Thus, this record indicates that the grout layer is delaminated, and the concrete is beginning to debond from the embedded cylinder. Debonding can occur when the steel wires have failed and there is no longer prestress on the concrete.

The overall results of the single point testing are best presented in the format of Fig. 4. This is a plot of pipe wall thickness (in inches) and signal strength versus position (in feet) within the pipe. This type of plot can be easily made by the automated data scanning and plotting software for the scanning system as long as the data was collected along a line of points at equal intervals. Note that the data shows three distinct thickness ranges throughout the plot. The thicker points all correspond to echoes from the outer grout layer, and indicate sound conditions. The intermediate thicknesses shown correspond to echoes from the prestress wire level and indicate full or partial delamination of the grout from the wires and core. The final set of thicknesses seen are from echoes at the cylinder depth, indicating debonding of the steel cylinder from the concrete (likely from loss of prestress wires). Other thickness echoes are generally not seen, indicating that failures of these pipes occur in relatively predictable locations within the wall.

All of the single point IE testing for the most recent PCCP testing project was performed in areas where previous Acoustic Emissions (AE) monitoring indicated likely wire breaks, and thus was intended to find defects. Based on these results, one

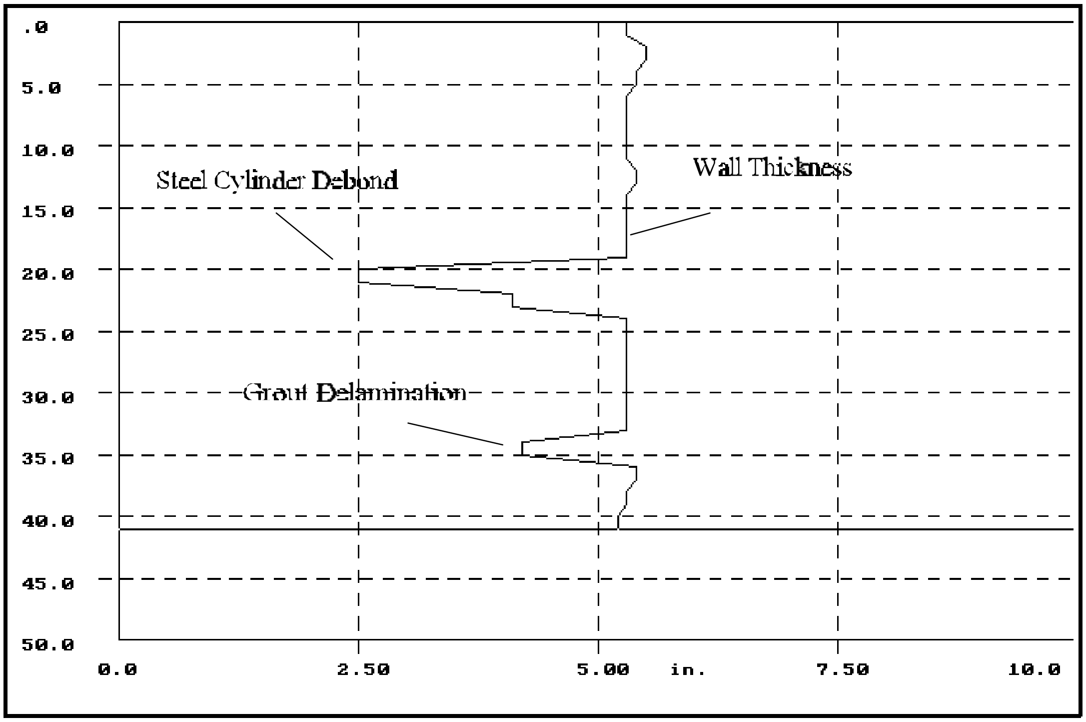

Figure 4 Sample Impact Echo Pipe Test Result - Wall Thickness vs. Location

likely effective application of the various NDT methods would be the use of AE for long-term monitoring of pipes in service to listen for wire breaks, followed by intensive IE testing of suspect locations after the pipeline is dewatered for maintenance. This would allow confirmation and localization of the suspect pipe section for repair. For this type of NDT program, the single point IE device would be the most applicable. If a baseline scan of unmonitored pipes is required, IE scanning could be used to locate areas which have already failed (and thus may not produce more wire breaks during AE testing).

Spectral Analysis of Surface Waves Test Method and Results

The Spectral Analysis of Surface Waves (SASW) test method was used at several locations on the pipe to measure concrete velocity for use in IE thickness calculations, as well as for investigating concrete conditions and soil conditions outside of the pipe.

The SASW method is based upon measuring surface waves propagating in layered elastic media and is pictured in Fig. 5. The ratio of surface wave velocity to shear wave velocity varies slightly with Poisson's ratio, but can be assumed to be equal to 0.90 with an error of less than five percent for most materials, including concrete. Measurement of the surface wave velocity with the SASW method similarly allows calculation of compression wave velocity for IE analysis. Surface wave velocity also equals 0.56 of the compression wave velocity for concrete (Poisson's ratio = 0.2).

Knowledge of the seismic wave velocities and mass density of the material layers allows calculation of shear and Young's moduli for low strain amplitudes.

Surface wave (Rayleigh; R-wave) velocity varies with frequency in a layered system with velocity contrasts, and this frequency dependence of velocity is termed dispersion. A plot of surface wave velocity versus wavelength is a dispersion curve.

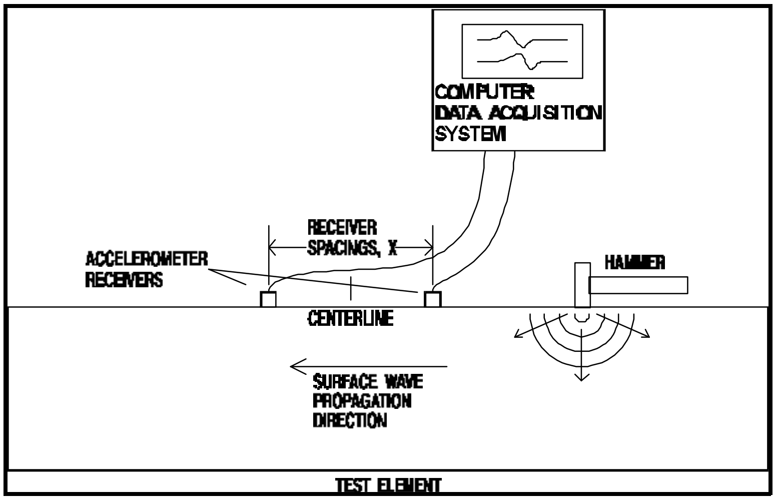

Figure 5 SASW Test Method Diagram

The SASW field tests consisted of impacting the test surface to generate surface wave energy at various frequencies that were transmitted through the material. Two accelerometer receivers were evenly spaced on the surface in line with the impact point to monitor the passage of the surface wave energy as illustrated in Fig. 5.

A PC data acquisition system digitizes the analog receiver outputs and records the signals for spectral (frequency) analyses to determine the phase information of the cross power spectrum between the two receivers for each frequency. The dispersion curve is developed by knowing the phase (N) at a given frequency (f) and then calculating the travel time (t) between receivers of that frequency/wavelength by:

$$t = N / 360*f \tag{2}$$

Surface wave velocity (Vr) is obtained by dividing the receiver spacing (X) by the travel time at a frequency:

$$Vr = X / t \tag{3}$$

The wavelength (Lr) is related to the phase velocity and frequency by:

$$Lr = Vr / f \quad (4)$$

By repeating the above procedure for any given frequency, the surface wave velocity corresponding to the given wavelength is evaluated, and the dispersion curve is determined.

A typical dispersion curve from an SASW test on a sound location of a PCCP section is shown in Fig. 6. This is a dispersion curve, or a plot of surface wave velocity versus wavelength. Note how the velocity is constant at a typical concrete surface wave velocity value (2,700 mps) until a wavelength corresponding to material outside of the pipe wall is reached. After this, there is a distinct drop to the apparent lower surface wave velocity (2,100 mps) of the material outside of the pipe wall. This result indicates that the pipe wall is sound with no apparent delaminations, and also that the material outside of the pipe wall is relatively dense and stiff compared to loose soils. Collection of data at longer wavelengths and forward modeling would be required to fully evaluate the characteristics of the material outside of the pipe.

Conclusions

The results of the ongoing research into the use of the IE method in testing PCCP lead to several conclusions. First, the IE method has been shown to be very effective in measuring pipe wall thickness and locating delaminations and cylinder debonding associated with wire breaks and strength loss. Scanning with the IE method does work, but requires more sensitive receiver transducers to work well in pipe where the inside surface has degraded. More sensitive transducers have been developed, and have been used in the single point IE test device, but have yet to be assembled into a rolling scanner head. The use of the single point IE device in recent tests has shown that this device is most effective when spot checking for quality, or when investigating areas where concern already exists. The use of AE monitoring during pipe operation can give an indication (by listening for wire breaks) of what areas to test intensively with IE once the pipe is dewatered. Finally, the SASW method, which has been used extensively in testing other types of concrete members, can be applied to the evaluation of PCCP conditions, although it is generally a slower method both during data collection and data analysis. The SASW method does, however, give information as to the condition of the material outside of the

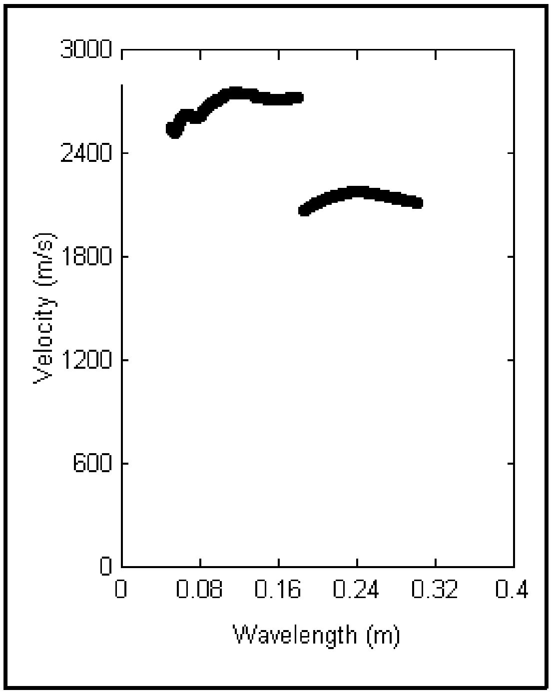

Figure 6 SASW Sample Result

pipe wall (void, soft, stiff, etc.), which can be very valuable in certain circumstances.

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