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APPLICATIONS OF STRESS WAVES NONDESTRUCTIVE METHODS TO BUILDINGS AND BRIDGES

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ABSTRACT

Nondestructive methods based on propagation of stress waves are increasingly being used in the United States for forensic investigations of existing structures and for quality assurance of new construction. This paper deals primarily with field investigations performed by the authors to demonstrate the applications of each of the NDT methods. Brief descriptions of the methods, field setups and case histories are presented herein. Ultrasonic Pulse Velocity (UPV), Impact Echo (IE), Spectral Analysis of Surface Waves (SASW), and Slab Impulse Response (SIR) methods are used for forensic investigation of existing structures to identify defects such as internal cracks, poor quality concrete, honeycombing in beams, columns and slabs, and poor subgrade support conditions of slabs-on-grade. The relative merit of each of the above methods for defect identification is discussed in this paper. For quality assurance of drilled shaft foundations of bridges, the Crosshole Sonic Logging (CSL) and Sonic Echo/Impulse Response (SE/IR) methods are routinely used. The CSL method requires access tubes to be installed in the shaft prior to concrete placement. SE/IR measurements require that the top of the shaft be accessible after concrete placement. Based on our experience, the CSL method is more effective in locating defects than the SE/IR method. Case studies are presented herein to illustrate the advantages and disadvantages of each of these methods. CSL measurements are effective in determining anomalies and defects between two access tubes. However an accurate image of the defect cannot be determined. The Crosshole Tomography (CT) method uses multiple CSL logs with varying receiver locations to produce a 2-D image of the defect, thus a better characterization of the defect. The CT method is briefly discussed in this paper. The CT method requires more time for data collection and analysis than the CSL method, and presently its use is justified only for critical drilled shaft foundations.

INTRODUCTION

In recent years, nondestructive testing (NDT) has been applied for forensic investigation and for quality assurance of concrete structures. Two major advantages are offered by NDT methods: 1) extensive coverage of the testing area and 2) structure elements remain intact after testing is completed. To better use NDT methods in the evaluation of structures, research has continued into the new methods and improved procedures. In addition to the widely used Ultrasonic Pulse Velocity (UPV) method (ASTM C 597-83), one method which has been used in recent times is the Impact Echo (IE) method (Sansalone and Carino, 1986). A more recent addition to the available NDT tests is the application of the Spectral Analysis of Surface Waves (SASW) method (Nazarian and Stokoe, 1985; Aouad, 1993). The three methods are used to determine the condition of concrete elements through propagation of stress waves (compression or surface waves). To evaluate support conditions underneath concrete slabs, the Slab Impulse Response (SIR) method is widely used. The first part of this paper deals primarily with these four NDT methods as applied in forensic investigation to evaluate structure members such as walls, slabs, beams, etc.

The second part of the paper deals with the application of NDT methods used in quality assurance of drilled shaft foundations and diaphragm walls. Discussions are presented for the Crosshole Sonic Logging (Olson et al, 1994), Sonic Echo/Impulse Response (Davis and Dunn, 1974) and Crosshole Tomography (Olson et al, 1993).

NDT METHODS USED IN FORENSIC INVESTIGATIONS OF BUILDINGS

Ultrasonic Pulse Velocity (UPV) Method

The UPV method is a direct compression wave velocity measurement method used in structural applications to evaluate the condition of materials such as concrete. The method requires access to two sides of the test element. This method allows relative comparisons of concrete strength based on the measured compression wave velocity as well as allowing the location of defects. The UPV method has been traditionally applied at fixed locations. Recent innovations with the method include scanning UPV measurements (Sack and Olson, 1995). Due to the simplicity of the method, results from actual tests are not presented herein and can be found in previous publications (Sack and Olson, 1995). However, one can easily picture strong signal arrivals in sound concrete and delayed signals to total loss of signals in defect areas depending on the severity of defects.

Impact Echo (IE) Method

The IE method was researched and developed at the National Institute of Standards and Technology (Sansalone and Carino, 1986). The method involves hitting the concrete surface with a small impactor or impulse hammer (0.09 kg (0.2 lb)) and identifying the reflected wave energy with a displacement or accelerometer receiver mounted on the surface about 50 mm (2 in) from the impact point. The output force of the hammer (if used) and the resulting displacement or acceleration response of the receiver are recorded. The resonant echoes are usually not apparent in the time domain. The resonant echo peak frequencies in concrete slabs are more easily identified in the frequency domain. Consequently, the time domain test data are processed with a Fast Fourier Transform (FFT) which allows easier identification of frequency peaks (echoes). The auto power spectrum of the receiver or the transfer function (receiver output/hammer input vs. frequency) can be used to determine the resonant peaks. If the thickness of the test member is known, the compression wave velocity (C_P) can be determined by the following equation:

$$C_P = 2*d*f/\beta \qquad (1)$$

where d = member thickness, f = resonant frequency peak, β= shape factor (equal to 0.96 for slabs, Sansalone, 1997).

The IE method can be used for measuring concrete thickness, evaluating concrete quality, and detecting hidden flaws such as cracks, honeycombs, etc. Concrete quality is related to compression wave velocity and elastic modulus and increases in compression wave velocity generally correlate with increased concrete strength and better concrete quality. Example results from IE tests performed on a concrete wall are presented in Figs. 1 and 2 to illustrate this point. In the example shown, the wall thickness in Fig. 1 was equal to 50 cm (20 in). A resonant peak of 2,370 Hz was identified in Fig. 1 which translates into a compression wave velocity of 2,500 m/sec (8,200 ft/sec) using Equation 1. The wall thickness in Fig. 2 was equal to 69 cm (27 in). A resonant peak of 2,750 Hz was identified in Fig. 2 which translates into a compression wave velocity of 4,000 m/sec (13,000 ft/sec). Assuming that the concrete strength is proportional to the fourth power of velocity (per ACI Manual of Concrete Practice, ACI 228.1R-89), the concrete strength at Location 1 is equal to only 15% of the concrete strength at Location 2, a tremendous loss of strength at Location 1.

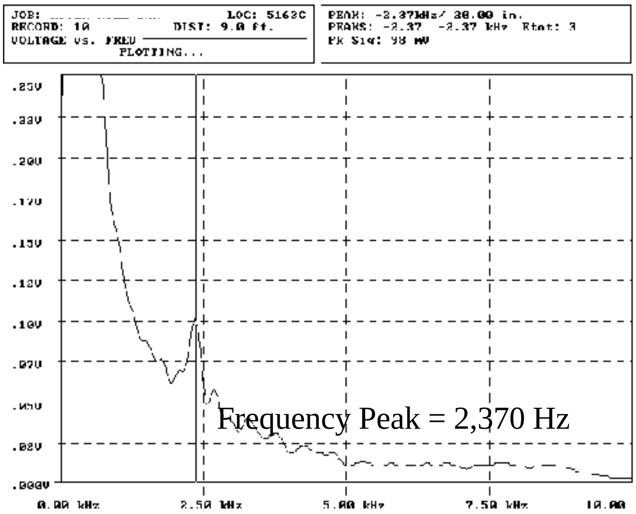


Figure 1- Impact Echo Test Results Performed at Location 1

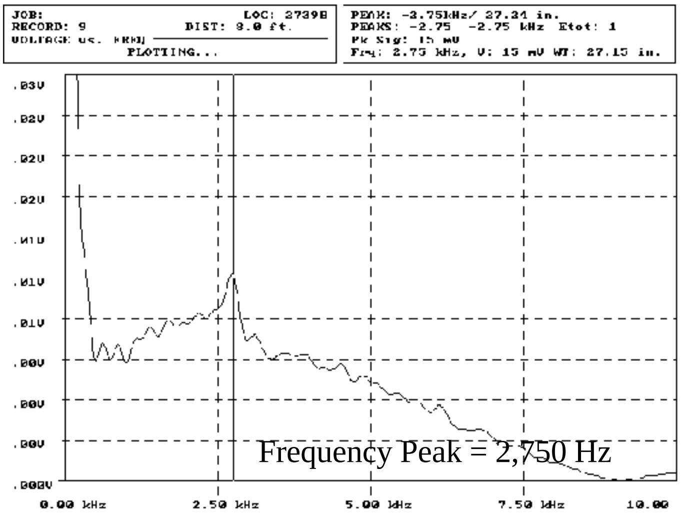


Figure 2- Impact Echo Test Results Performed at Location 2

Spectral Analysis of Surface Waves (SASW) Method

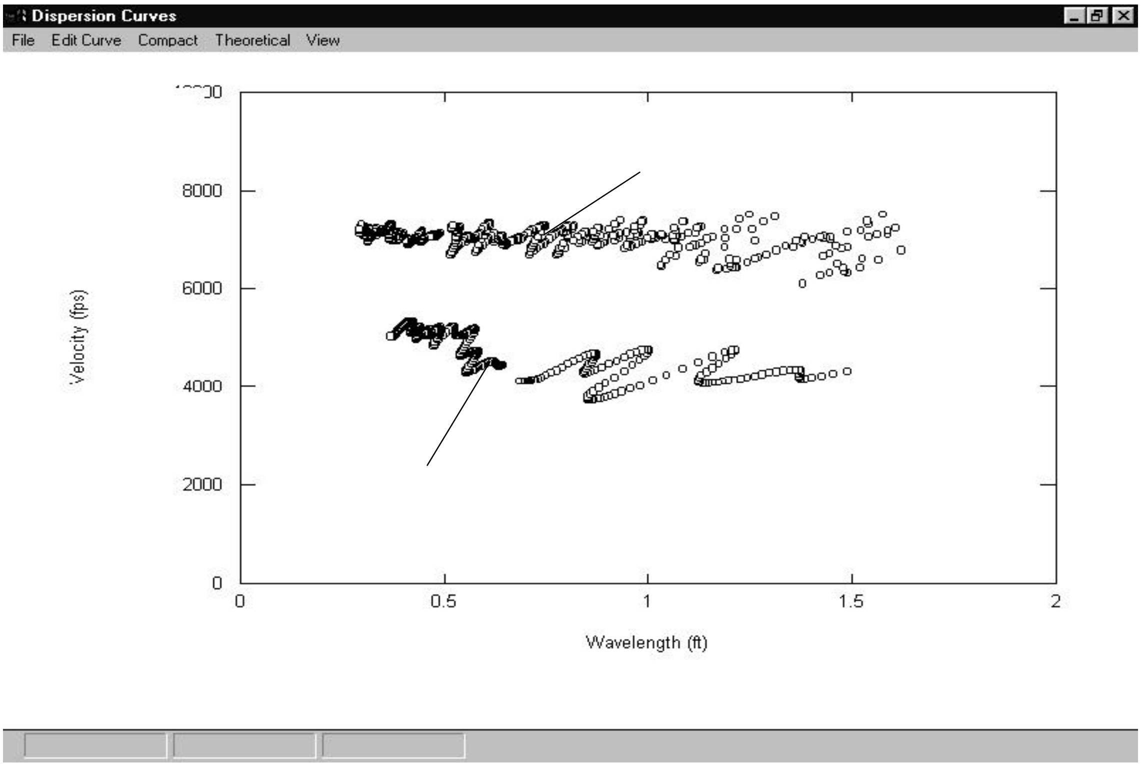
One stress-wave based NDT method which has recently been applied to structural and geotechnical testing is the SASW method (Bay and Stokoe, 1990). This is based on a similar procedure which has been used for the determination of shear moduli profiles at soil sites (Stokoe et al, 1988) and Young's moduli profiles at pavement sites (Nazarian and Stokoe, 1985). The method relies on the dispersion characteristics of surface waves.

In SASW tests, two receivers are placed on the ground/structural member surface to monitor the passage of surface waves due to an impact from a source placed at distance from Receiver 1 equal to the distance between the two receivers. A digital analyzer is used to record the receiver outputs for spectral (frequency) analyses. The result of the analysis is a plot of the phase difference between the two receivers versus frequency. A dispersion curve (surface wave velocity versus wavelength) is calculated from the phase plot using the following equations:

$$t = \phi/360 \qquad (2)$$
$$V_R = X/t \qquad (3)$$
$$\lambda_R = V_R/f \qquad (4)$$

where t = Time, V_R = Surface Wave Velocity, X = distance between receivers, λ_R = Wavelength, f = Frequency. The final process in SASW testing is the Forward Modeling process to determine the shear wave velocity profile. The forward modeling process is an iterative process, and involves comparing the actual dispersion curve with a theoretical dispersion curve calculated from an assumed shear wave velocity profile.

To illustrate the use of the SASW test method, concrete SASW results from Locations 1 and 2 (where IE tests were also performed above) are presented in Fig. 3. Note that the surface wave velocity at Location 1 is equal to 1,370 m/sec (4,500 ft/sec) and the surface wave velocity at Location 2 is equal to 2,130 m/sec (7,000 ft/sec). For a Poisson's ratio of 0.2, the surface wave velocity is equal to 0.56 * compression wave velocity. Therefore, the compression wave velocity at Location 1 is equal to 2,450 m/sec (8,000 ft/sec) and the compression wave velocity at Location 2 is equal to 3,800 m/sec (12,500 ft/sec), which agree extremely well with values back-calculated from IE tests. Therefore, a combination of IE and SASW tests performed at the same locations can be very useful if the thickness of concrete elements is not known. In this case, the compression wave velocity determined from SASW tests can be used as an input for thickness evaluation from IE tests.



SASW Results at Location 2

SASW Results at Location 1

Figure 3- Comparison of Experimental Dispersion Curves from SASW Tests Performed at Locations 1 and 2 where Impact Echo Tests Were Performed

Slab Impulse Response (SIR) Method

Subgrade support conditions for slab-on-grades can be nondestructively evaluated with the Impulse Response (IR) method. The SIR tests detect and define the extent of good versus void/poor support conditions, but do not provide information on the depth of void. The method was developed from a force-response modal vibration test for investigating the integrity of deep foundations and was originally adapted for slabs by a European group.

The SIR tests are usually conducted from the surface of the slab. Test equipment includes an impulse hammer, geophone receiver, and a signal analyzer. The tests involved hitting the slab to generate vibration energy in the slab. The 3-lb impulse hammer has a built-in load cell with a plastic head to measure the force of the impact. The vibration response of the slab to the impact are measured with the geophone held in contact with the concrete close to the point of impact. The analyzer performs Fast Fourier Transform (FFT) operations on the time domain data to produce the mobility plots.

Support condition evaluation includes two measurement parameters in particular. The slope of the initial straight line portion of the mobility plot indicates the quasi-static flexibility of the system. The low frequency flexibility provides a general indication of the slab stiffness since the inverse of flexibility is dynamic stiffness. The steeper the slope of the line, the more flexible and less stiff the system. Dynamic stiffness can be correlated to static stiffness. In a simple sense then, the dynamic SIR test is analogous to placing a weight on the slab and measuring the deflection of the slab to calculate the low strain static stiffness (pounds force per inch displacement). The shape and/or magnitude of the mobility at frequencies above the initial straight line portion of the curve is the second indicator of support conditions. The response curve is more irregular and has a greater mobility for void versus good support conditions due to the decreased damping of the slab vibration response for a void.

To illustrate the use of the SIR method, results from tests performed on a slab after a water pipe rupture and washout of the support material occurred are presented in Fig. 4. Note the high mobility and the irregular shape of the mobility plot as shown by the dashed line in Fig. 4. SIR tests were performed after slabjacking at the same location. Note the lower mobility and the smoother mobility curve after slabjacking as shown by the solid line in Fig. 4.

Figure 4- Slab Impulse Response Mobility Plots before and after Slabjacking

NDT METHODS USED IN QUALITY ASSURANCE FOR DRILLED SHAFT FOUNDATIONS

Crosshole Sonic Logging (CSL) Method

The CSL method was adopted in the U.S. in the mid 1980's for quality assurance of drilled shaft foundations, slurry walls and seal footings. The CSL method relies on direct transmission of sonic/ultrasonic waves between 2 or more access tubes placed in a drilled shaft prior to concrete placement. The number of access tubes per drilled shaft is dependent on the diameter of the shaft, typically 1 tube per 0.3 m (1 ft) of diameter, and the tubes are installed around the perimeter of the shaft and tied to the inside (or outside) of the cage of the shaft. The tubes are usually 38 to 50 mm (1.5 to 2.0 in.) inside diameter schedule 40 steel or PVC pipe. Tube debonding from the surrounding concrete can occur at an earlier time in PVC tubes as compared to steel tubes. Most State DOT’s specify that CSL tests be performed in 10 days or less after concrete placement for PVC tubes and in 45 days or less for steel tubes to avoid problems associated with tube debonding.

To perform a CSL test, two probes (hydrophones) are lowered to the bottom of two access tubes, and are retrieved to the top of the shaft while CSL measurements are taken approximately every 50 mm (2 in.). The ultrasonic wave pulser is controlled by a distance wheel to trigger the transmission of waves at preselected vertical intervals. Automatic scanning of the collected records produces two plots, time (or velocity) and energy, versus depth. Anomalies and defects between tested tubes are manifested by time delays (or velocity decreases) and energy drops in the scanned CSL plot. Concrete velocities are calculated by simply dividing the distance between the two tubes by the time required for the wave to travel from the source hydrophone to the receiver hydrophone. CSL tests are typically performed between all perimeter tubes to evaluate the concrete conditions of the outer part of the shaft and between major diagonal tubes to evaluate the concrete conditions of the inner part of the shaft. Figure 2 shows an illustration for the interpretation of a CSL log. NDT methods which could be used in conjunction with the CSL method to better identify anomalous zones include Crosshole Tomography (CT), Singlehole Sonic Logging (SSL), Gamma-Gamma Nuclear Density Logging, Downhole Sonic and/or Sonic Echo/Impulse Response (SE/IR) tests. The CT and SE/IR methods are briefly discussed below.

Crosshole Tomography Method

The Crosshole Tomography method uses the same equipment as the CSL method with more tests being collected (many source and receiver locations). Once a defect is identified in CSL tests, CT tests can be performed to produce an image of the defect between the test tubes. Tomography is an inversion procedure that can provide for ultrasonic images of a concrete zone from the observation of transmitted compression or shear first arrival energy. The CT data is used to obtain an image of the defect. The test region is first discretized into many cells with assumed slowness values (inverse of velocity) and then the time arrivals along the test paths are calculated. The calculated times are compared to the measured travel times and the errors are redistributed along the individual cells using mathematical models. This process is continued until the measured travel times match the assumed travel times within an assumed tolerance. Tomographic analysis can be performed using series expansion algorithms with a curved ray analysis from geotomography. Tomography is time consuming and its use is justified for critical shaft. For more details on how tomography is applied for imaging defects, the reader is referred to Olson et al (1993).

Sonic Echo / Impulse Response Methods

Sonic Echo Test Method

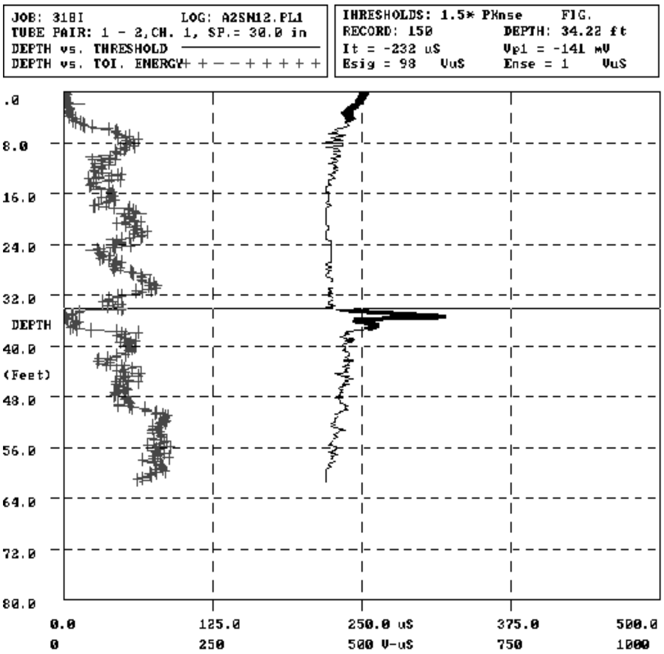
The SE method is a low strain integrity test conducted from the surface. Test equipment includes an impulse hammer (optional, an ordinary plastic tipped hammer) and an accelerometer (or geophone) on the shaft. The impulse hammer has a built-in load cell that can measure the force and duration of the impact (needed for IR tests). The test involves hitting the foundation top with the hammer to generate wave energy that travels down the foundation. The wave reflects off irregularities and/or the bottom of the foundation and travels up the foundation to the foundation top. The receiver measures the vibration response of the foundation to each impact. The signal analyzer or PC processes and displays the hammer and receiver outputs. Foundation integrity is evaluated by identifying and analyzing the arrival times, direction, and amplitude of reflections measured by the receiver in time. The receiver output is usually integrated (if an accelerometer is used) and exponentially amplified with time (Koten and Middendorp, 1981) to enhance weak reflections. Digital filtering with a low-pass filter of about 2,000 Hz is usually applied to eliminate high frequency noise. In some cases, where reflections are difficult to identify, an impedance imaging procedure is used to obtain a 2-D image of the shaft (Paquet, 1991).

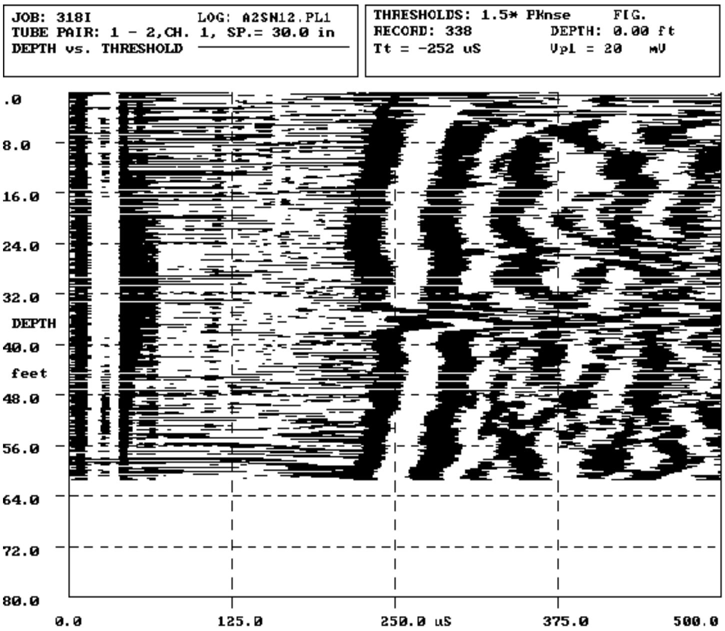
Impulse Response (IR) Test Method

The IR method is also an echo test and uses the same test equipment as the SE method. The test procedures are similar to the SE test procedures, but the data processing is different. The IR method involves frequency domain data processing, i.e., the vibrations of the foundation measured by the receiver are processed with Fast Fourier Transform (FFT) algorithms to generate transfer functions for analyses. The coherence of the impulse hammer impact and accelerometer receiver response data versus frequency is calculated to indicate the data quality. A coherence near 1.0 indicates good quality data. In the IR records the linear transfer function amplitude is in velocity/force on the vertical axis (mobility) and frequency in Hz on the horizontal axis.

Case Studies

Discussed below are results from CSL and SE/IR tests performed by the authors on a drilled shaft foundation in New Mexico. The CSL results between tube pair 1-2 of a shaft tested in New Mexico are presented in Fig. 5. A significant delay in arrival times of compression waves and a significant drop in energy were observed in this CSL log at depths ranging from 10.4 to 11.6 m (34 to 38 ft) below the top of the shaft. The CSL results between other tubes showed similar anomalies at the same depths. Another commonly used display for CSL data is the banded time versus depth (also known as Z-axis modified). In this display, a line is plotted for each point of each record for which the positive or negative signal peaks are greater than the threshold value. This results in a series of bands vertically down the plot for a shaft with no defects. A defect will be seen as a disappearance of the bands at the defect depth. Figure 6 shows this type of display for the shaft tested in New Mexico with the negative peaks as the black bands. Sonic Echo/Impulse Response tests were performed on the same shaft. Echoes from a depth of 11 m (36 ft) were identified in the SE records as shown in Fig. 7. The upper trace in Fig. 7 represents the accelerometer output and the lower trace represents the upper trace after integration (to velocity) and exponential amplification. The IR results showed an echo from a depth of 10.8 m (35.3 ft) as shown in Fig. 8. The upper trace in Fig. 8 represents the coherence function to reflect data quality and the lower trace is the mobility function which is equal to velocity divided by pound force. No echoes from the bottom of the shaft at a depth of 18.9 m (62 ft) were identified in the SE/IR records. It was then concluded that the encountered defect is a major defect since bottom echoes could not be identified. Note also the good agreement between the CSL and SE/IR results.

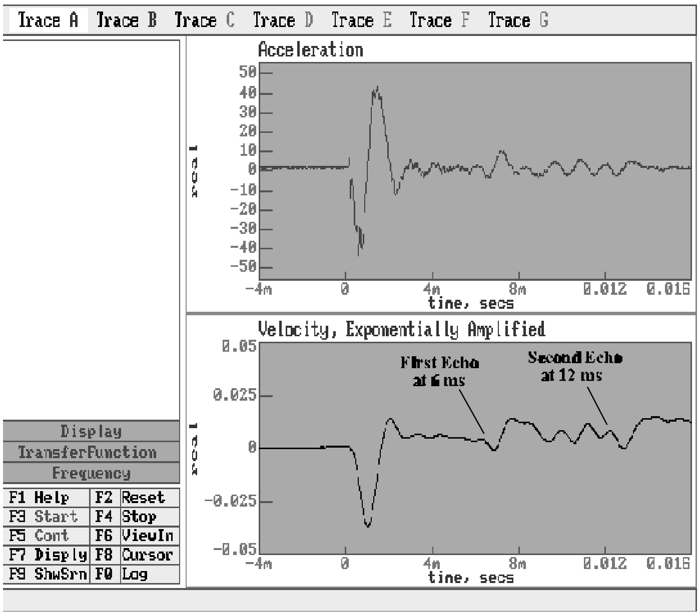


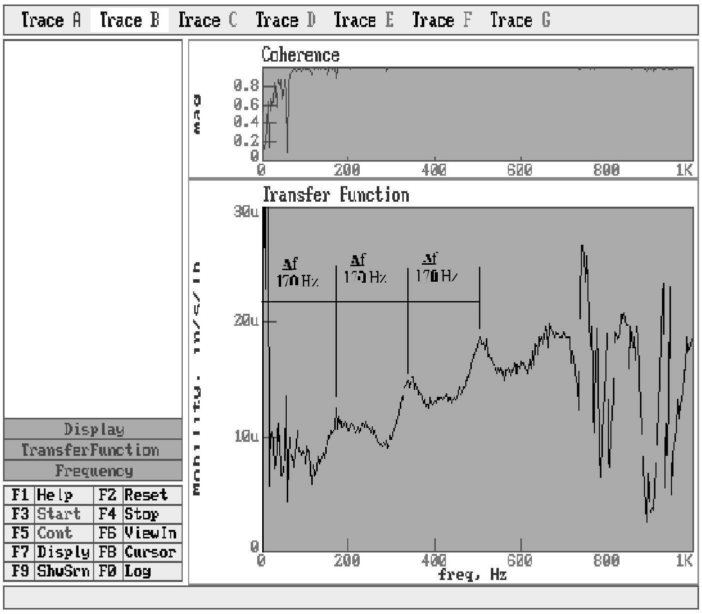


If there were additional defects below the major encountered defect at a depth of 11 m (36 ft), they most likely would not have been identified by the SE/IR method, but could easily have been identified with the CSL method

Figure 5- CSL Results Between Tubes 1-2 in a Drilled Shaft in New Mexico

Figure 6- Alternative Banded Time Display of CSL Results





Depth of Reflector = Velocity * Δt/2

Depth of Reflector = Velocity/(2 * Δf)

Figure 7- Sonic Echo Test Results, Drilled Shaft in New Mexico

Figure 8- Impulse Response Test Results, Drilled Drilled Shaft in New Mexico

CONCLUSIONS

Presented in this paper are some stress waves based NDT methods used in evaluating structural members of buildings and drilled shaft foundations. It was the intent of the authors to give a brief description of each of the NDT methods and a case study to alert the reader to the specific application of the method and its limitations.

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