

Stress-Wave Nondestructive Testing of Tunnels and Shafts

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Case histories of the application of stress-wave methods, such as impact echo, impulse response, and spectral analysis of surface waves, to evaluate conditions of concrete-lined tunnels and shafts are presented. These nondestructive evaluation methods provide data on the concrete integrity, the contact condition at the interface between concrete and rock or soil, and the stiffness (velocity, elastic modulus, or both) profile. Conditions such as fractures, void, and comparatively weak materials can all be identified from the test surface without drilling coreholes into the materials. A brief technical description of each nondestructive evaluation method is included along with the respective case history data. In addition, the potential for rapid, near-continuous testing using innovative stress-wave measurement instrumentation with PC-based data acquisition and analysis is discussed.

The evaluation of the condition of tunnel and shaft liners is an area of great concern to both the owners and the users of these structures. Traditional methods of evaluation have been based primarily on visual inspection coupled with destructive coring at selected locations to attempt to relate the visual condition of the liner with the actual conditions. Recent evaluations of tunnel and shaft liners have used nondestructive testing (NDT) techniques based on stress waves to better define the actual in situ conditions of the liner as well as those of the rock or soil behind. The basic advantages of NDT techniques are that they are faster than coring and do not damage the liner material. Thus, a more extensive evaluation of the tunnel and shaft integrity conditions can be undertaken than would be practical with destructive methods. The NDT techniques discussed herein include the spectral analysis of surface waves (SASW), impact echo (IE), and impulse response (IR) methods. Each method was used in a mine shaft liner evaluation case history.

CASE HISTORY BACKGROUND

The mine shaft tested provided vertical access at a potash mine owned by the Potash Corporation of Saskatchewan, Incorporated (PCS Inc.). The shaft was constructed about 25 years ago as the production shaft for one of the PCS Inc. mines in Saskatoon, Saskatchewan, Canada. This NDT investigation was undertaken to evaluate various NDT methods

and their overall effectiveness for determining the physical condition of the liners, liner and wallrock interfaces, and, to a lesser degree, the wallrock itself. All testing was conducted under normal field conditions and was subject to the unique constraints associated with a high-production mine shaft. Logistics and effectiveness were assessed to determine the basis for future programs.

The shaft, which was lined with concrete from the ground surface to a depth of 1020 m (3,344 ft), was 4.9 m (16 ft) in diameter. The liner varied in thickness from 0.61 to 1.22 m (2 to 4 ft). The concrete liner thickness in the interval over which the SASW, IE, and IR tests were conducted varied from 0.56 to 0.81 m (22 to 32 in.). Design specification on liner concrete was 34.5 MPa (5,000 psi) minimum, and actual 28-day strengths varied from 37.2 to 48.3 MPa (5,400 to 7,000 psi). Observed concrete conditions were generally good in the shaft, although some mineral deposits had formed on the liner concrete in the lower portions of the shaft, which hindered the testing.

The Prairie Formation, from which sylvinitic is mined and that the shaft services, was overlain by 1037 m (3,400 ft) of sediments. Immediately overlying the Prairie Formation was 427 m (1,400 ft) of Devonian carbonates, shales, and evaporites. These layers included the Watrous, Nisku, Duperow, Beaverhill Lake, Upper and Lower Souris River, Davidson, First Red Beds, Dawson Bay, and Second Red Beds. NDT testing was conducted over sections adjacent to the Nisku, Duperow, and Upper and Lower Souris River. The majority of the SASW tests were conducted in the Duperow Formation. The test locations were selected based on a priority list supplied by PCS, which identified those regions that were considered to be most critical and that would give the maximum variety of test conditions to evaluate the various methods. Actual tests were typically performed in a 3.05-m (10-ft) vertical grid within each region for IR and IE tests, with SASW lines interspersed throughout the regions.

NDT TEST METHODS

The NDT methods used included the SASW, IE, and IR methods. Because the majority of the testing was conducted using the first two of these methods, detailed descriptions of these follow. The IR method was used less extensively and proved to be less useful because of the great thickness of the liner concrete [over 0.6 m (2 ft)]. An overview of the IR method is also included because it can be very useful for evaluating thinner concrete liners.

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Impact Echo Test Method

The IE tests typically involved hitting the surface of the test area at a given location with a small [0.09-kg (0.2-lb)] instrumented impulse hammer to measure the pounds-force of the impact and recording reflected wave energy with an accelerometer receiver mounted with grease on the liner. The IE method was developed at the National Institute of Standards and Technology, Gaithersburg, Maryland, in the 1980s (1). A simplified diagram of the method is presented in Figure 1. Because the reflections are more easily identified in the frequency domain, the time domain test data of the hammer and receiver are processed with Fast Fourier Transform (FFT) operations by the dynamic signal analyzer for frequency domain analyses. A transfer function is then computed between the hammer (input) and receiver (output). Reflections or "echoes" of the compression wave energy are typically indicated by pronounced "echo" peaks in the test records that correspond to thickness or flaw depth resonant frequencies. With an echo peak and knowledge of the thickness of the test member, the compression wave velocity can be calculated. Conversely, if the velocity of the concrete is known, the depth of a reflector is calculated from the echo peak frequency. Concrete quality is related to compression wave velocity, and increases in compression wave velocity generally correlate with increased concrete strength and better concrete quality. Correspondingly, poor-quality concrete, damaged concrete, or both result in slower wave velocities that are reflected by lower-frequency echo peaks for a given concrete thickness.

At a concrete-to-air interface, virtually all of the compression wave energy is reflected back into the concrete. This near total energy reflection is due to the large difference in acoustic impedance (Z), which equals velocity (v) times mass density (ρ), between the concrete (high Z) and air (low Z). The geophysical equation governing the amount of energy reflected (R) back into material from an incident wave coplanar with the interface between materials 1 and 2 is as follows:

$$R = (Z_2 - Z_1)/(Z_2 + Z_1)$$

= ratio of amount of reflected energy to total energy (1)

In a shaft, if the concrete and rock have similar velocities and densities, very little energy is reflected back into the concrete from the rock interface provided there is good contact (bonding) between the concrete and the rock. In areas where the concrete and rock do not have similar acoustic properties, more energy is reflected from the interface. In the case of cracks, tight cracks produce weaker echoes with deeper echoes still identifiable (if present). An open, air-filled crack completely reflects the energy. A shallow, open crack [typically less than 0.1 to 0.15 m (4 to 6 in.) deep] parallel to the

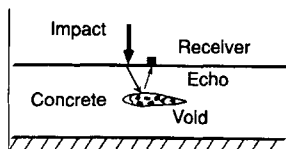


FIGURE 1 Impact Echo test method.

test surface will flexurally resonate and sound hollow and is referred to as a delamination.

Spectral Analysis of Surface Waves Method

The SASW method is based on the theory of stress waves propagating in layered elastic media. The ratio of surface-wave velocity to shear-wave velocity varies slightly with Poisson's ratio, but it can be assumed to be equal to 0.90 with an error of less than 5 percent for most materials, including concrete and the rock tested in the potash mine shaft. Measurement of the surface-wave velocity with the SASW method similarly allows calculation of compression wave velocity. 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 called a *dispersion curve*. The SASW tests and analyses are performed in three phases: (a) collection of data in situ, (b) construction of an experimental dispersion curve from the field data, and (c) forward modeling of the theoretical dispersion curve to match the experimental curve and provide the shear-wave velocity versus depth profile.

The SASW field tests consisted of blows to the concrete surface to generate surface-wave energy at various frequencies that was transmitted through the concrete. 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 Figure 2. To obtain increasingly deeper data, several tests with different receiver spacings can be performed by doubling the distance between the receivers about the imaginary centerline between the receivers. The tests on the liner were typically conducted with receiver spacings ranging from 11.43 cm to 3.65 m (4.5 in. to 12 ft). For this project, five impacts and the associated receiver responses were typically obtained at each receiver spacing. Also, the impacts were applied typically at each end of a given receiver spacing with the distance from the impact point to the closest receiver about that of the receiver-to-receiver spacing. The

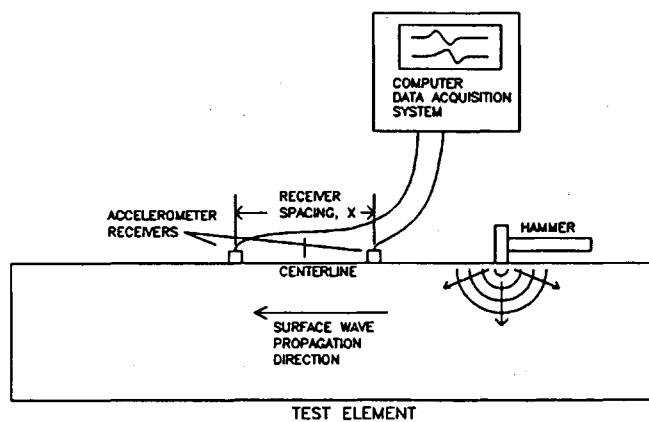


FIGURE 2 SASW test method diagram.

majority of the tests were conducted in the vertical axis of the tunnel to minimize the effects of wall curvature.

A signal analyzer 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 (ϕ) at a given frequency (f) and then calculating the travel time (t) between receivers of that frequency or wavelength by

$$t = \phi/360 * f \quad (2)$$

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

$$V_r = X/t \quad (3)$$

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

$$L_r = V_r/f \quad (4)$$

By repeating the above procedure for every frequency, the surface-wave velocity corresponding to each wavelength was evaluated, and the dispersion curve was determined (2,3).

Forward modeling is the process of determining the "true" shear-wave velocity profile from the "apparent" velocity of the dispersion curve. The forward modeling process is iterative and involves assuming a shear-wave velocity profile and constructing a theoretical dispersion curve. The experimental and theoretical curves are compared, and the assumed theoretical shear-wave velocity profile is adjusted until the two curves match. The SASW method and an interactive computer algorithm for both two-dimensional and three-dimensional analyses have been developed by Jose Roesset of the University of Texas at Austin to compute a theoretical dispersion curve based on an assumed shear-wave velocity and layer thickness profile.

Impulse Response Test Method

The IR tests were conducted from the surface of the liner. The test equipment included an impulse hammer, a geophone receiver, and a signal analyzer. The tests involved hitting the concrete to generate vibration energy in the liner. The 3-lb impulse hammer had a built-in load cell to measure the force of the impact. The vibration response of the liner to the impact was measured with the horizontal geophone held in contact with the concrete close to the point of impact. The output from the hammer and the receiver was viewed and processed on the signal analyzer. The digital data were stored on magnetic disks for later recall.

The IR test record produced by this test was a plot of mobility (vibration velocity amplitude per pound force) as a function of frequency measured in cycles per second or hertz. The mobility indicates support conditions and stiffness. The greater the mobility, the less stiff is the liner-subgrade system. Support condition evaluation includes two measurement parameters in particular. First, the dynamic stiffness is measured. 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 liner wall stiffness because the inverse of flexibility is dynamic stiffness. The steeper the slope of the line, the more flexible and less stiff is the system. The shape, magnitude, or both, of the mobility at frequencies above the initial straight-line portion of the curve are the second indicators of support conditions. The response curve is more irregular and has a greater mobility for void versus good support conditions because of the decreased damping of the wall vibration response for a void. This factor is not as usable in the case of the mine shaft liner because of the relatively thick cross section of the liner wall. This thick cross section tends to damp vibration responses and thus decreases the difference between the response from void versus sound conditions.

NDT TEST RESULTS

The NDT test results presented include typical results of both the SASW and the IE methods. As stated above, the IR test results were not as meaningful for this application because of the liner thickness and are thus not presented.

Impact Echo Records and Results

The integrity of the concrete liner was nondestructively investigated with the IE method in 86 tests at 77 stations. The IE method is a sonic echo test that measures concrete thickness, evaluates concrete quality, and detects flaws from one surface as detailed previously in this paper.

Representative IE Test Record

A typical IE test record is presented in Figure 3 for the case of a sound concrete liner backed by rock of a slower velocity. The IE test is most sensitive to cracking and interfaces parallel to the test surface because of the test configuration. The top trace in the figure is the coherence of the transfer function data, indicating data quality. A coherence near 1.0 indicates good quality, repeatable data. The bottom trace in the figure is the doubly integrated transfer function between the hammer and the accelerometer, giving vertical axis units of millimeters displacement of the surface per newton input by the hammer. The horizontal axis is linear frequency measured in thousands of hertz. The depth indicated in the sample record was calculated based on a compression-wave velocity of 3813 m/sec (12,500 fps). This value was obtained from the average compression-wave velocity as measured on the cores and corrected for use with the IE method. Note that compression-wave velocities measured with the ultrasonic pulse velocity (UPV) scanning system are typically 10 percent higher than those found using the IE method (1). In the record, the clear, single echo peak that corresponds to multiple reflections of the wave energy from the backside of the liner is apparent at 2.35 kHz. Using a velocity of 3813 m/sec, a thickness of about 0.81 m (33 in.) was calculated, which is reasonable considering the potential overbreak. Because no other higher-frequency echo peaks indicative of potential flaws were identified, this IE location is indicated to have sound concrete.

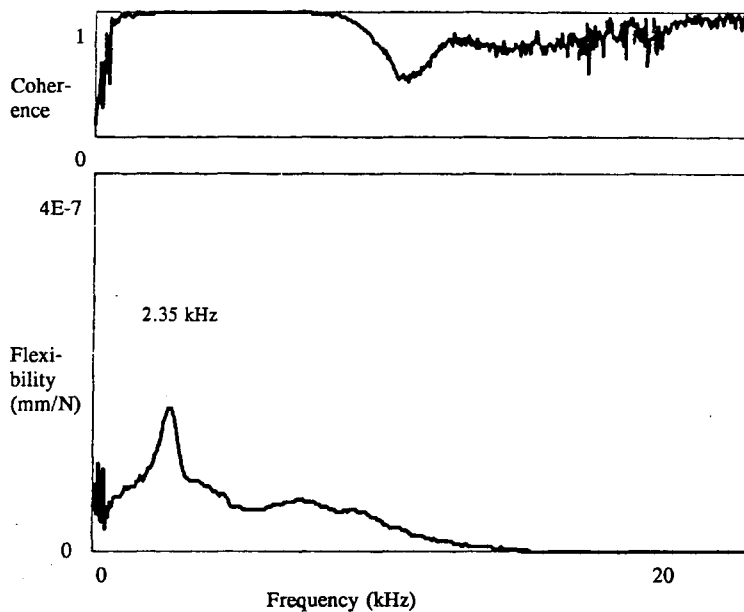


FIGURE 3 Impact Echo test record (sound concrete conditions).

IE Test Results

The IE results were analyzed to identify significant echo peak frequencies and condition ratings assigned according to criteria developed for typical IE data. These IE results showed the ability of the IE method to evaluate concrete liner thickness and integrity conditions, even under the difficult field conditions in the vertical shaft. The results also showed that this method is also useful in giving some indication of the relative velocity and bonding conditions at the rock-concrete interface, although it is not as useful as the SASW method in this type of evaluation.

SASW TEST RECORDS AND RESULTS

The SASW method is comparatively new; it was developed to determine shear modulus profiles with depth in layered systems such as pavements and earth (4,5). The method is based on the field measurement of surface-wave velocity as a function of wavelength and subsequent theoretical modeling to determine the shear-wave velocity profile versus depth. The SASW method is capable of determining the "stiffness" and thickness profiles for layered concrete, pavement, soil, and rock systems without drilling borings. (The SASW method was detailed earlier in this paper.)

SASW Phase Record

A sample phase record from the SASW testing is shown in Figure 4, which is an example of a good-quality phase data record. The record plots phase versus frequency. The trace in the plot has the phase difference between the two received signals on the vertical axis in degrees, with phases of less than -180 degrees or greater than 180 degrees being "wrapped" with a vertical line. The horizontal axis is the frequency in

hertz. Not shown is the coherence plot for these data, which indicated almost perfect coherence (near 1.0) for the entire frequency range. Note that it is possible that a phase can be accurate, even with poor coherence, if the test results are consistent and enough averages can be obtained. A total of 360 degrees of phase (-180 to 180 degrees) represents one wavelength, which equals the receiver-to-receiver spacing for a given test, and one cycle of surface-wave energy at a given frequency. The calculation of surface-wave velocity for 360 degrees of phase (one wavelength) is determined from the wave frequency at the one wavelength point in Figure 4.

SASW Results of Dispersion Curve and Inversion Analyses

Dispersion curves were calculated from the phase data for each survey line where sufficient quality measurements could be obtained. These curves were then used to determine the layer depths and the condition at each point. The dispersion curves were calculated from the raw data after the data were "masked" to eliminate data in frequency ranges with poor coherence or other obvious "glitches" in the phase data. The SASW phase data measurements were complicated by the existing variety of surface conditions, including the surface deposits present in some parts of the shaft. Nonetheless, SASW measurements were able to provide data on most tested locations.

SASW Inversion Analyses for Shear-Wave Velocity versus Depth Profiles

A typical dispersion curve and the shear-wave velocity profile computed from it are presented in Figures 5 and 6. The dispersion curve plots surface-wave velocity versus wavelength, and the velocity profile plots shear-wave velocity in feet per

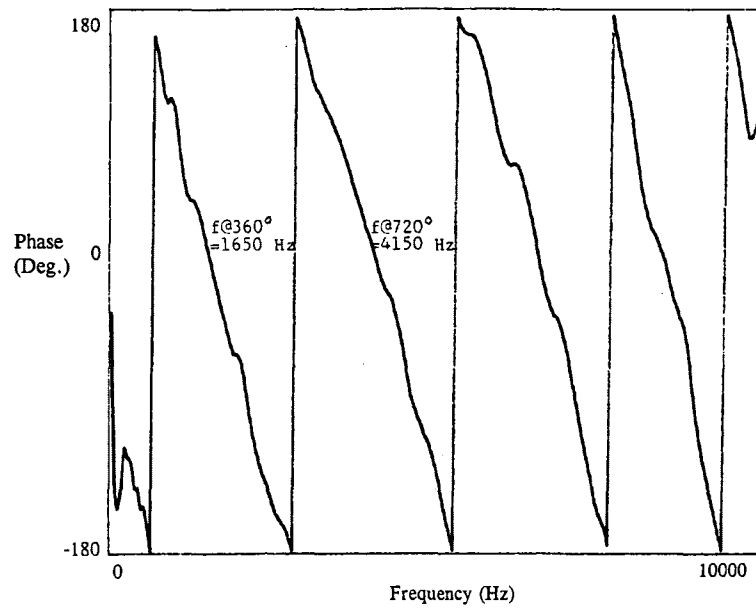


FIGURE 4 Sample phase/frequency plot from an SASW test.

second versus depth into the shaft wall concrete and rock in feet. A total of 11 SASW measurement locations were inverted at the University of Texas at Austin. The theoretical inversion analyses were reviewed by one of the authors (Stokoe). Only one SASW location had insufficient data quality that prevented inversion.

Inversions were performed of representative test locations to compute the theoretical shear-wave velocity versus depth model (inversion) that best matches the field experimental dispersion curve data. The field dispersion curve data and two-dimensional and three-dimensional (more accurate) theoretical inversion analysis produced dispersion curves that present the data in terms of velocity versus wavelength, whereas the final inversion process produced a plot of velocity versus

depth. The dispersion curves are typically plotted with velocity on the vertical linear axis scale and wavelength in feet on a horizontal logarithmic (base 10) scale. The shear-wave velocity profiles are plotted on linear scales with velocity on the horizontal axis and depth of each analysis layer on the vertical axis in feet.

The inversion curve presented (velocity versus depth profile) is from station 2110 and shows the constant good velocity [about 3000 m/sec (9,840 fps)] of the liner concrete out to about 0.91 m (3.0 ft), followed by an abrupt transition to the rock velocity of about 2500 m/sec (8,200 fps). Thus, the data for this location showed competent concrete followed by competent but less stiff rock with no appearance of a debonding or void zone between them. In the associated dispersion curve,

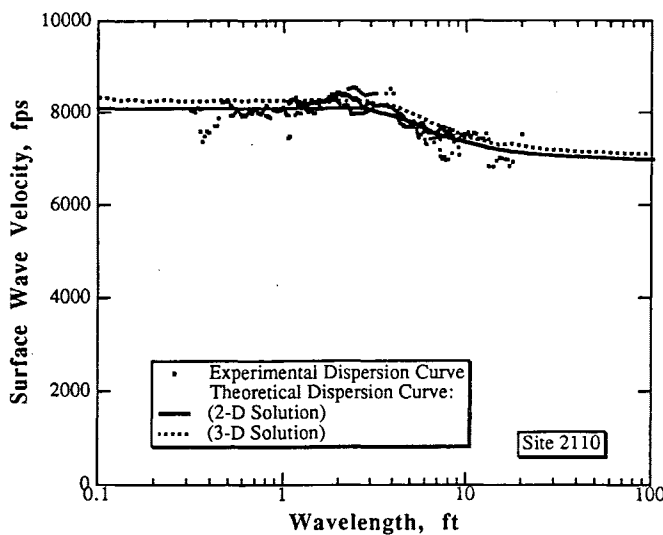


FIGURE 5 SASW dispersion curve (sound concrete over slower rock).

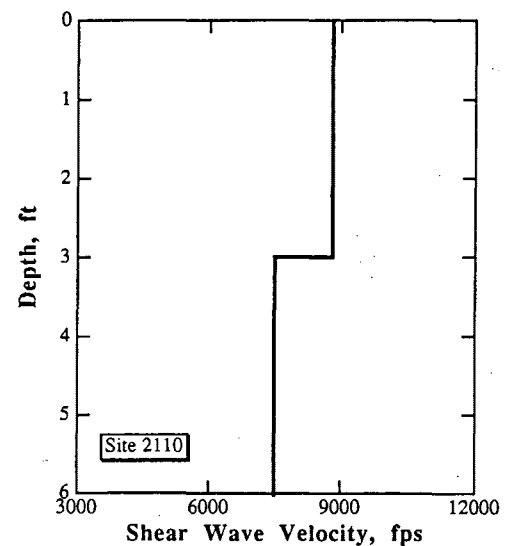


FIGURE 6 SASW velocity profile (sound concrete over slower rock).

the transition is evident as a smooth change from the velocity of the concrete only to that of the rock only as the wavelength increases.

The overall inversion results indicated shear-wave velocities of up to 3048 m/sec (10,000 fps) in the near-surface concrete with underlying rock velocities ranging from 1890 to 3354 m/sec (6,200 to 11,000 fps). The SASW results indicate that 9 of the 12 locations tested had relatively high-velocity (indicating higher quality) concrete with relatively high-velocity, sound rock behind. The remaining points had either poor-quality test data or other anomalies in the results. One important finding from the SASW data was that at every point tested where wavelengths into the rock layer were generated and measured, the rock layer shear-wave velocity was ≥ 1830 m/sec (6,000 fps). In addition, at locations where the surface-material velocity was slower (degraded surface conditions), the shear-wave velocity continued to improve with depth. These results indicate that, in general, only the surface of the liner has been significantly affected by surface deposits or other conditions at the points tested.

IMPULSE RESPONSE TEST AND RESULTS

Concrete liner support conditions and stiffnesses were non-destructively evaluated with the IR method. The IR tests detect and define the extent of good versus poor support conditions, but do not provide information on the depth of void and may not easily differentiate between back-side voids and near-surface delamination cracking. The method was developed from a forced-response modal vibration test for investigating the integrity of deep foundations and was originally adapted for slabs and tunnels by a European group.

The IR method is useful to determine the support conditions of the material behind a tunnel liner, provided the stiffness of the tunnel liner is not too high. For this investigation, the stiffness of the 0.6- to 0.9-m (2- to 3-ft) thick liner did not allow differentiation between good versus poor substrate support conditions. The method has been used successfully on other tunnel liners and slabs with thinner cross sections.

NDT METHOD EVALUATION

Of the three methods used on this shaft, the IE and SASW methods appear to provide the most useful information as to the condition of the concrete liner, interface, and rock conditions. When performed together, these two methods are able to effectively and fairly quickly evaluate the overall condition of a mine shaft liner, especially if used in conjunction with limited coring to establish overall velocities and other baselines. The results also agreed well with the destructive (coring) results, with the SASW-determined shear-wave velocity agreeing to within 5 percent of the shear-wave velocity in a core at the same point (2885 m/sec from SASW versus 2911 and 2776 m/sec from the cores). The IR method does not appear to be as useful for the thick shaft liner tested, although it should perform much better in thinner-walled linings. The NDT methods used for this investigation are all fairly quick relative to other methods (especially coring), but actual testing time will vary significantly depending on the actual shaft liner conditions. This investigation was carried out in three night shifts. The investigation extended over nearly

305 m (1,000 ft) of the south side of the shaft liner with much of the liner requiring chipping of surface deposits to test.

RECENT NDT TECHNIQUE DEVELOPMENTS

Recent developments in the equipment used for several of the more common NDT methods promise to greatly increase the speed and utility of these methods. One development that will aid in testing tunnel liners is the IE scanning system, which will allow the performance of rapid, close-spaced IE tests on any relatively smooth, continuous concrete or rock surface.

The IE scanning system (patent pending) is diagrammed in Figure 7. It is similar to the UPV scanning system, which was developed in conjunction with this system and uses much of the same hardware. The IE scanner is used from only one surface and requires only one scanner unit, which encompasses both signal source and receiver. The IE scanner is composed of an electrically driven solenoid with an impulse hammer mounted to it and a coated piezoelectric ceramic receiver that is used to pick up the echo signals. The electrical impulses to drive the hammer can be generated automatically based on time or distance, or manually from an operator switch. This allows the maximum flexibility for IE testing at various speeds, locations, and data densities.

The IE test involves impacting the concrete at a point. A surface receiver measures the vibration of the concrete. With the scanning system, the surface receiver rolls while measuring vibration responses to the hammer impacts. An analysis of the return echo resonant frequency peaks of the test results provides information on the condition of the concrete.

An IE scan of a concrete slab on grade is presented in Figure 8. The scan covers about 0.7 m (2.25 ft) of the 127-mm (5-in.) thick slab. The scan is presented as a three-dimensional waterfall plot that is composed of the data records from each of about 10 individual test points. In the plot, the series of peaks at about 1.30 kHz corresponds to echoes from the back side of the slab with a concrete compression-wave velocity of about 3300 m/s (10,800 fps). If a defect were present, it would show as a series of adjacent, matched frequency peaks at a frequency higher than the backside frequency. Due to the close spacing of adjacent test points, intermittent peaks at lower and higher frequencies are indicated because of random noise and frame vibrations. Because the intermittent peaks

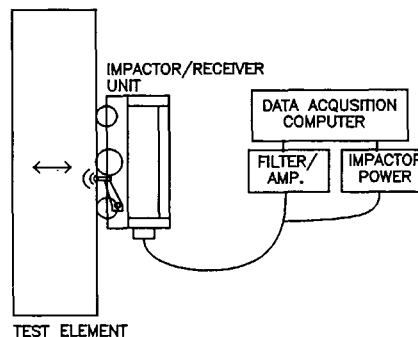


FIGURE 7 Impact Echo scanner system.

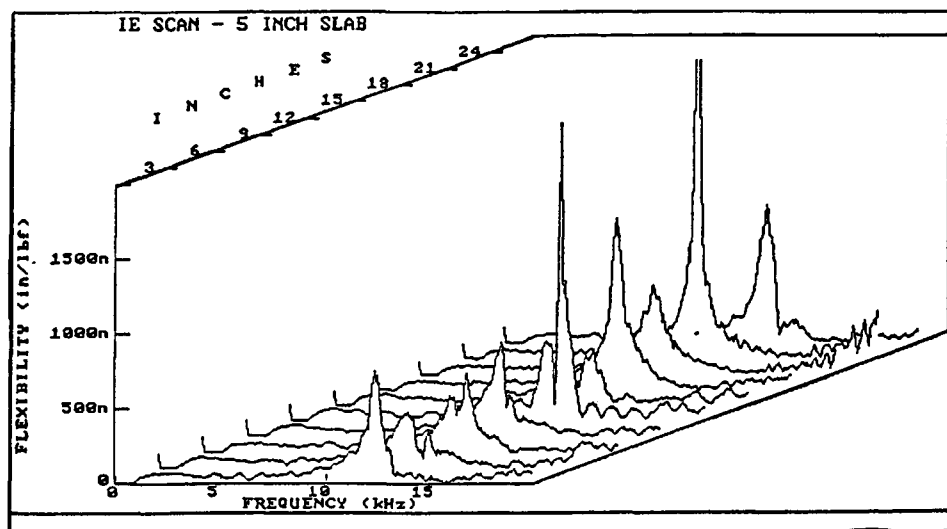


FIGURE 8 Impact Echo scan of a sound concrete slab.

did not repeat in adjacent tests, this indicates that they do not represent structural defects or other elements.

The individual data records that make up the scan are plots of vibration displacement (integrated from the accelerometer output) as a function of frequency. The dominant frequency peaks at 13.0 kHz correspond to the periodic compression wave reflections between the front and back sides of the slab.

As can be seen, the IE scanning system promises to greatly improve the speed and utility of the IE method for field applications, especially for large structures such as tunnel and shaft liners. Currently, efforts are under way to develop such a scanning system for SASW tests as well. These scanning technologies in turn are expected to eventually result in a completely automated pipe-tunnel-shaft liner testing system that would be capable of conducting a complete NDT evaluation of a structure with minimal down time and interaction.

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