

Measurement of Concrete Thickness and Detection of Defects Using Ultrasound Methods

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Abstract

The use of Non-destructive Evaluation (NDE) techniques has proven to be effective in determining the thickness of plate like concrete elements and locating defects such as cracks, delaminations, voids, honeycombing, and debonding. Some of the problems that have plagued the concrete paving industry are testing for quality assurance and verification of thickness of existing concrete slabs without compromising their structural integrity by traditional coring methods. There are several Non-Destructive Evaluation (NDE) techniques that have been proven to be an effective way to combat these problems. This paper outlines one of these techniques, Ultrasound-Echo (UE). UE utilizes two ultrasonic probes, one transmits a stress wave field into the concrete specimen, and the other receives the natural response of the concrete specimen in the time domain. A Fast Fourier Transform (FFT) is then applied to the received response so it can be examined in the Frequency Domain. Using the wave speed of the concrete, the peak or resonant frequency can be used to calculate the thickness of the concrete element where the concrete element is free of defects. In areas of detectable defects, there will be pronounced shift in the resonant frequency. Requirements for self calibration of the wave speed and testing procedures for the ultrasound test equipment are discussed. To verify the accuracy of UE to identify defects, a test slab with purpose-built delaminations and air voids at known locations was constructed. A comprehensive measurement of this special test slab was performed using an UE device, and analyzed results are presented. Defective sections of the test slab are clearly identified by the UE method with recommendation given for detection of the defects.

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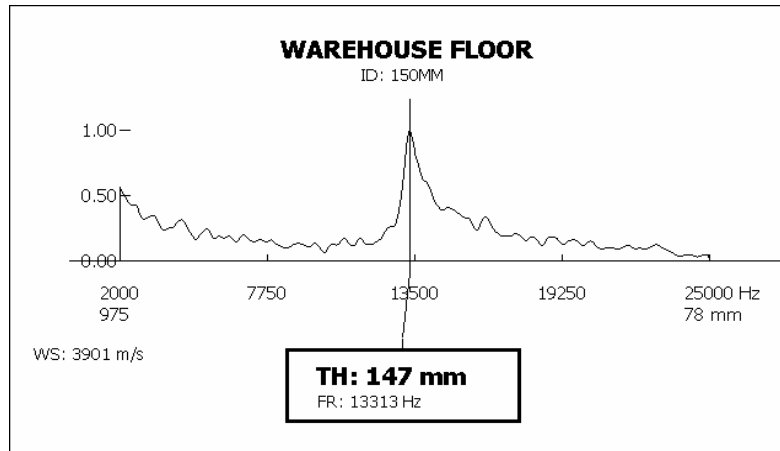


Figure 1 Thickness Measurement (normalized)

Wave Speed Measurement

As noted in equation 1, the wave speed (measured or assumed) is used to convert the measured resonant frequency to a concrete thickness. According to ASTM C 1383, the concrete P-wave speed of an unknown thickness can be determined by measuring the direct surface P-wave in the concrete. P-wave speed is then calculated by dividing the distance between two probes (Δd) by the arriving time delay (Δt). The measured P-wave speed gives a more accurate thickness than an assumed wave speed.

If a specimen with a known thickness is available, the wave speed can be “calibrated”. If the thickness is unknown, a destructive core could be obtained to determine thickness but usually an assumed wave speed is used (with resulting uncertainty). However, the standard UE test equipment is equipped to measure the P-wave speed of an unknown thickness. The transmitter and receiver probes are spaced from 450 mm (18 in) to 610 mm (24 in) apart on a clean concrete surface. The Δt is measured as the P-wave initiation time (T_0) subtracted from the direct surface P-wave initial arrival time at the receiver sensor (T_1). Figure 2 shows the resultant P-wave speed measurement. Improved wave speed accuracy may be achieved by averaging several measurements at varied probe spacing.

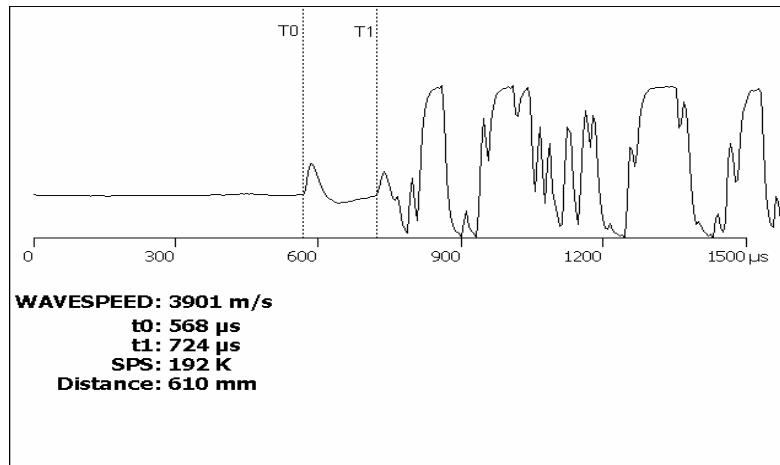


Figure 2 Wave speed Measurement

Thickness Testing

To verify the accuracy of the UE method, surface P-wave speed and thickness measurements were performed on several vertical cast in place walls. The walls were of known thickness. Specimens tested had thicknesses of 197 mm, 305 mm, 315 mm, 405 mm, 415 mm, and 510 mm. For the specimens tested, there was a variance in the thickness over the length of the wall. The tolerance for the actual thicknesses was conservatively determined to be ± 2 mm.

For each structure a thickness and percent error was determined from the dominant peak frequency using the measured wave speed and assumed wave speed. The measured wave speed was determined by measurement of the surface P-wave (method used for unknown thicknesses). For the assumed wave speed, 4000 m/s was used. (Nominal values of good concrete wave speed are 3505 m/s to 4520 m/s).

Test Procedure: For each structure, a 300 mm X 300 mm grid area was tested. The measurement grid spacing was $\Delta X = \Delta Y = 50$ mm. Thus, a total of 49 measurements were obtained for each structure. The measurements consisted of the peak resonant frequency. The peak resonant frequency was automatically converted to a thickness using a calibrated wave speed and assumed wave speed. The calibrated wave speed was the average of 9 measurements using probe spacing of 450 mm, 500 mm, and 550 mm along the coordinate line of $Y = 0$ mm, 150 mm, and 300 mm. A thickness measurement percent error was determined for each structure using the measured wave speed and assumed wave speed. The percent error using the measured wave speed was identified as ϵ_m and the percent error using the assumed wave speed was identified as ϵ_a . Results of the measurements are detailed in Table 1.

Table 1 Thickness Measurements and percent error

Actual TH	Measured THm	Measured THa*	Measured Ws	Error ϵ_m	Error ϵ_a^*
mm (in)	mm (in)	mm (in)	m/s (ft/sec)	%	%
197 (7.8)	196 (7.7)	214 (8.4)	3672 (12,047)	-0.5	8.6
305 (12.0)	305 (12.0)	290 (11.4)	4200 (13,779)	0	-4.9
315 (12.4)	314 (12.4)	324 (12.8)	3879 (12,726)	-0.3	3.1
405 (15.9)	402 (15.8)	424 (16.7)	3791 (12,437)	-0.7	4.7
415 (16.3)	418 (16.4)	439 (17.3)	3806 (12,487)	0.7	4.6
510 (20.1)	516 (20.3)	531 (20.9)	3890 (12,762)	1.2	4.0

* thickness and % error using assumed wave speed of 4000 m/sec (13123 ft/sec)

Results: Measured thicknesses using the measured resonant frequency and measured wave speed were within 2% of the actual thickness. Measured thicknesses using the measured resonant frequency and the assumed wave speed were within 8.6% of the actual thickness. The results clearly show that thickness measurements using a measured wave speed versus an assumed wave speed were significantly better. Using the same test method, it is reasonable to achieve similar thickness measurement accuracy on slabs with unknown thicknesses.

Delamination Testing

To demonstrate the defect detection capability of the UE method, a concrete slab was constructed where delaminations and air voids were incorporated (Figure 3). The slab has a length of 1520 mm (60 in) and width of 3040 mm (120 in) with depths of 200 mm and 100 mm (8 in and 4 in). The slab was constructed upon excavated compacted clay with a level crushed limestone base using steel reinforcement. A 305 mm X 610 mm (12 in X 24 in) section had a 20 mm (3/4 in) thick foam sheet over the limestone and a 610 mm X 610 mm (24 in X 24 in) section had a 25 mm (1 in) thick layer of river rock over the limestone.



Figure 3 Test slab with purpose built defects

Defects were incorporated in the 200 mm (8 in) depth only. Delaminations were artificially created with .8mm (1/32 in) thick adhesive backed ethylene propylene diene monomer (EPDM) rubber Sheets. Three (3) delaminations were 305 mm X 305 mm (12 in X 12 in) and located at depths of 50 mm, 25 mm, and 38 mm (2 in, 1/2 in and 1-1/2 in). Two (2) delaminations were 150 mm X 150 mm (6 in X 6 in) and located at depths of 25 mm and 100 mm (1 in and 4 in). An air void was artificially created with a 80 mm X 80 mm X 580 mm (3-1/8 in X 3-1/8 in X 23 in) sealed plastic conduit with the top surface at a depth of 110 mm (4-1/2 in). A steel plate, 305 mm X 305 mm X 6mm (12 in X 12 in X 1/4 in), was located over the river rock sub grade at a depth of 130 mm (5 in). The test specimen also included a 610 mm X 610 mm (24 in X 24 in) honeycomb defect (grout and hermiculite mix). Figure 4 details the design of the test slab.

Test Procedure: An UE scan of the slab was performed. The scan comprised of 1121 data points using a 50 mm (2 in) grid pattern on an X-Y coordinate system ($\Delta X = \Delta Y = 50$ mm). No data points were collected along the edges. Use of a telescoping pole allowed efficient and accurate probe placement during data collection. For each data point a peak resonant frequency within a range of 2K – 30K Hz was obtained. Importing the collected peak frequency data into a spread sheet allowed enhanced display of results for analysis. A contour plot of the results is depicted in Figure 5. A 2-D gray scale was used with white being the lowest frequency and dark gray the highest.

Results: In areas where defects were not present, the peak resonant frequency (thickness resonance) corresponded to the slab thickness of 200 mm and 100 mm (8 in and 4 in). In areas of delaminations or air void, the peak resonant frequency shifted from the thickness resonance to a low frequency flexural resonance. The lower frequency gave thickness measurements that were greater than the actual thicknesses. The low frequency resonance (flexural response) was very dominant compared to the thickness resonance. Figure 6 and Figure 7 show the normalized resonant frequency response for the 200 mm thickness and delamination respectively.

For the 305 mm square delaminations the low frequency shift increased as the depth to delamination decreased. For the 150 mm square delaminations the low frequency shift also increased as the depth to delamination decreased. The 305 mm square 50 mm deep delamination had a greater frequency shift than the 150 mm square 25 mm deep delamination. Results indicate that for a given depth, a larger delamination (surface area) had a greater resonant frequency shift from the thickness resonance. And for a given delamination size a shallower delamination had a greater resonant frequency shift from the thickness resonance.

For the sealed plastic conduit, the low frequency shift was similar to that of the 100 mm deep delamination. However, a shift in the peak frequency did not occur over the entire conduit. It is likely that grout filled the conduit at the standoff locations resulting in only a partial void.

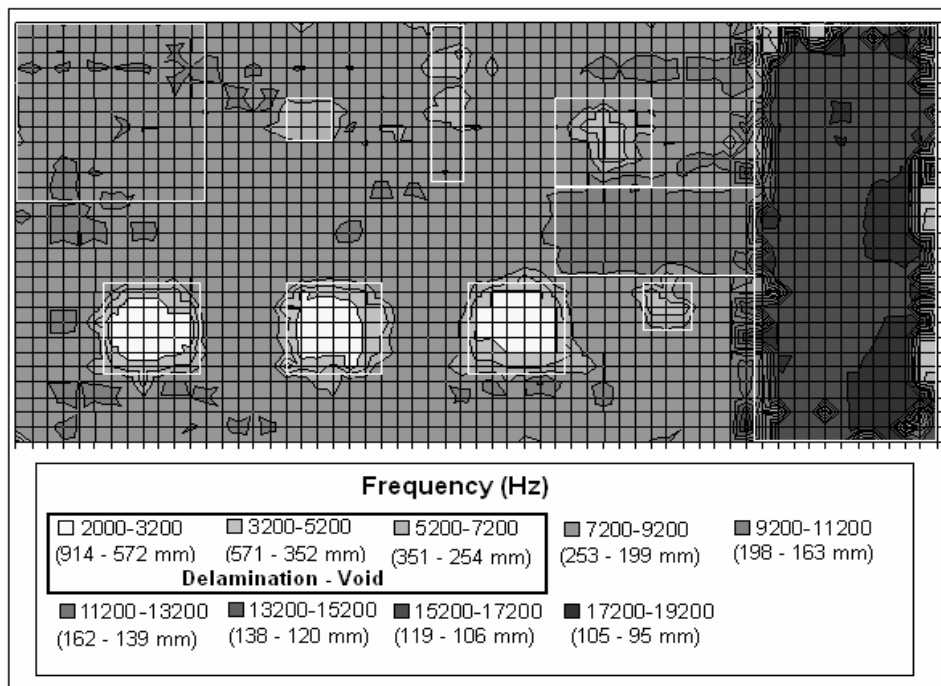
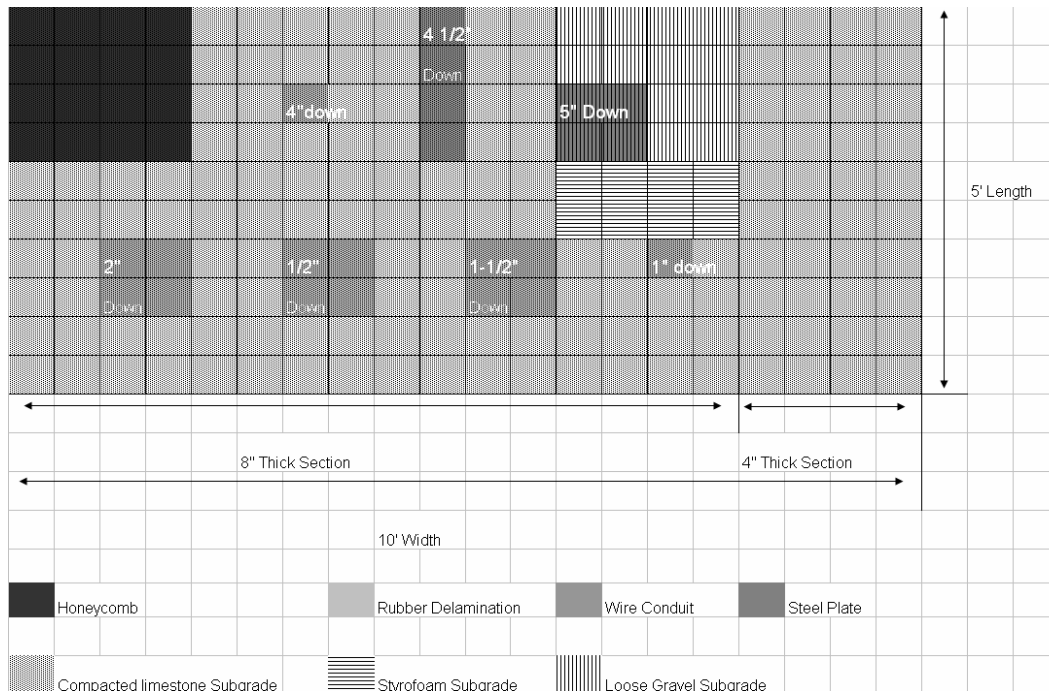


Figure 5 Frequency scan of purpose built test slab

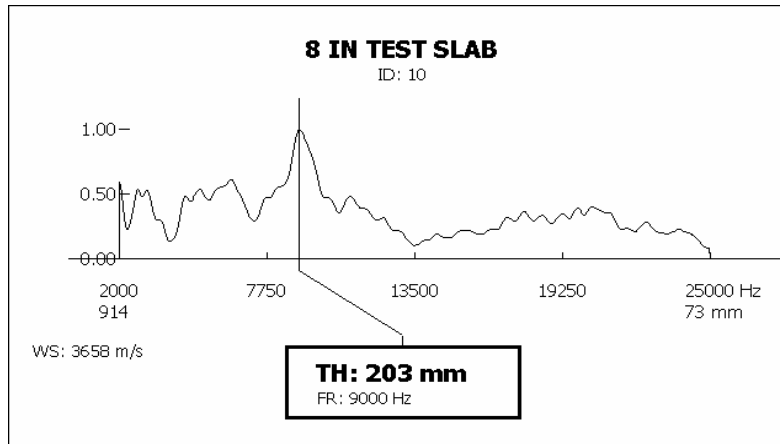


Figure 6 Resonant frequency response of 200 mm thick slab

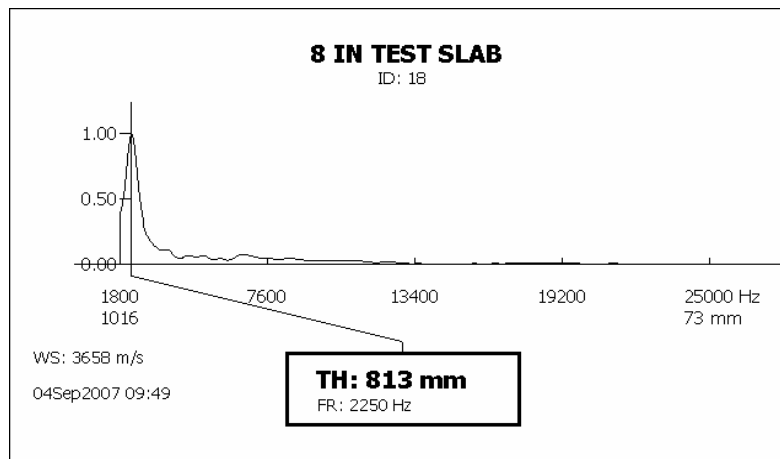


Figure 7 Resonant frequency response of a delamination

In the area of the foam base, a higher peak resonant frequency resulted corresponding to the decrease in concrete thickness. In the areas of the river rock base and honeycombing, the peak resonant frequency closely matched the thickness resonant frequency. Due to a wet concrete mix and honeycomb simulation material, the honeycomb simulation was not effective and the concrete easily seeped around the river rock incorporating the rock into the slab thickness. Defect location and scan results were superimposed clearly showing the accuracy in identifying the delaminations and voids (Figure 5).

Void Application Testing

In addition to the purpose build test slab, the capability of the UE method to verify an incomplete concrete fill (air void) within a concrete test shell (structure) was performed. The test shell was fabricated as verification testing of an ongoing project.

Test Shell Details: The test shell was constructed as verification testing supporting design and installation process for a dam located along the Ohio River. The test shell was approximately 7.9 m (26 ft) wide, 13.7 m (45 ft) long, and about 3 m (10 ft) in height. The sides and top had a design thickness of 610 mm (24 inches).

To enable nondestructive visual inspection after filling, one side and one end of the shell remained open. A sheet pile was placed over the opening during the filling process. The test shell was then filled using gravity fed tremie through two, approximately 305 mm (12 in), openings in the top of the shell. Upon completion of the filling process the sheet piles were removed from the side and end exposing significant portions of test shell that did not fill completely with concrete. See Figures 8 and 9 for details. Based on the significant voiding, NDE has been considered for post installation Quality Assurance. Prior to destructive testing of the test shell the UE method was requested for validation of a viable NDE method.

Test Methodology: In areas of incomplete concrete fill, a void will exist between the concrete fill and the bottom of the test shell. Resonance testing above a void will result in a peak resonant frequency corresponding to the test shell thickness (610mm). Although a void or incomplete fill will be detected, the depth size of the void can not be determined. In areas of complete fill, the concrete thickness will be near 3 m or a resonant frequency near 640 Hz. However, the UE test equipment has a frequency band pass filter near 2000 Hz thus attenuating or completely filtering frequencies less than 2000 Hz. As such, in areas of complete concrete fill, the normalized frequency response will not consist of a thickness resonance but rather an increase in the noise floor (normalized response of frequencies present on the receiver circuitry) with a peak resonant frequency near 2000 Hz.



Figure 8 Concrete filled test shell



Figure 9 Known void area of concrete filled test shell

Test Procedure: For the main test area, a point by point scan was performed using a 305 mm (12 in) grid pattern on an X – Y coordinate system. The entire surface of the test shell was not scanned due to the regions that were significantly under filled. Instead a portion of a known under filled area was included in the surface scan area to give a known void area baseline that the remainder of the scanned area could be compared to. The scan was over a 5 m X 10 m (17 ft X 33 ft) area (612 points). The areas that were tested with respect to the overall surface area are shown in Figure 10.

The wave-speed of the Test Shell was determined using the Calibrate Wave speed feature. The average of several calibrations was taken resulting in an average wave-speed of about 3840 m/sec (12,600 ft/sec). Using Equation 1, the resonant frequency for the 610 mm thickness was 3150 Hz. The measured frequency range for the known under filled area was 3094 Hz – 3234 Hz (or approximately $\pm 3\%$ of the expected thickness frequency using measured wave speed). Conservatively, a measured frequency of $3150 \text{ Hz} \pm 5\%$ (3000 Hz – 3300 Hz) was considered a potential for an under filled area.

Importing the collected peak frequency data into a spread sheet allowed enhanced display of results for analysis. A contour plot of the measured frequencies is shown in Figure 11. A 2-D gray scale was used with light gray identifying an area suspected to be under filled and dark gray identifying an area suspected to be completely filled.

Results: The resonant frequency response of an area known to be under filled was measured to establish a base line for an under filled or void area. As expected, a clear resonant frequency corresponding to the shell thickness was measured as depicted in Figure 12. The frequency response for an area suspected to be completely filled is shown in Figure 13. As expected, the frequency response consists of the normalized noise with the largest amplitude peak frequency near 2000 Hz (not near 3150 Hz).

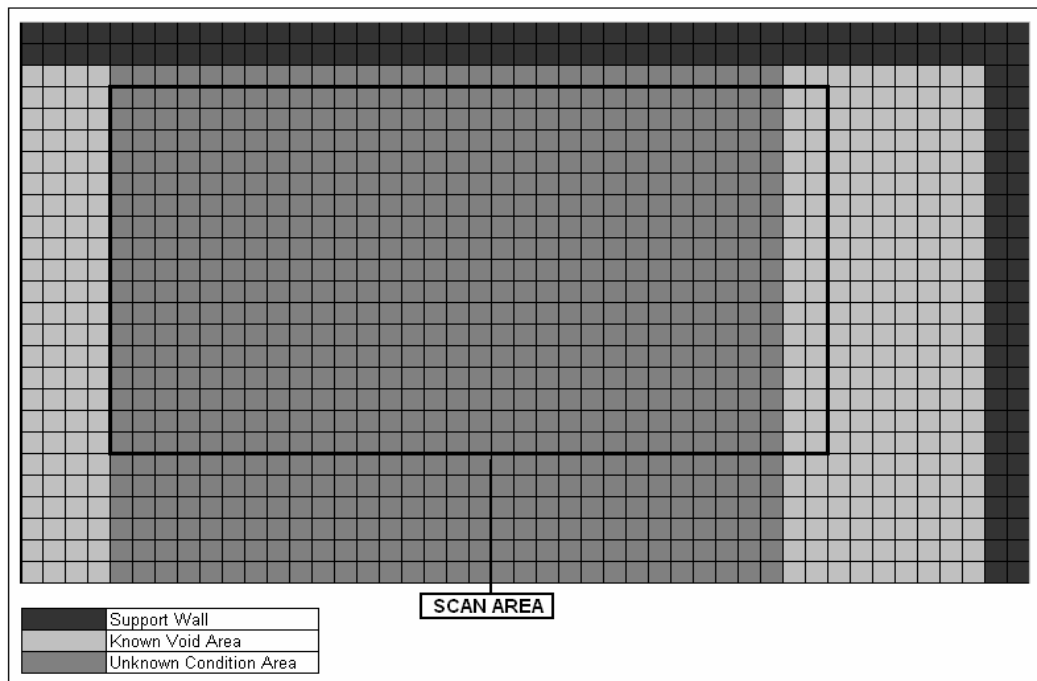


Figure 10 Scan area layout

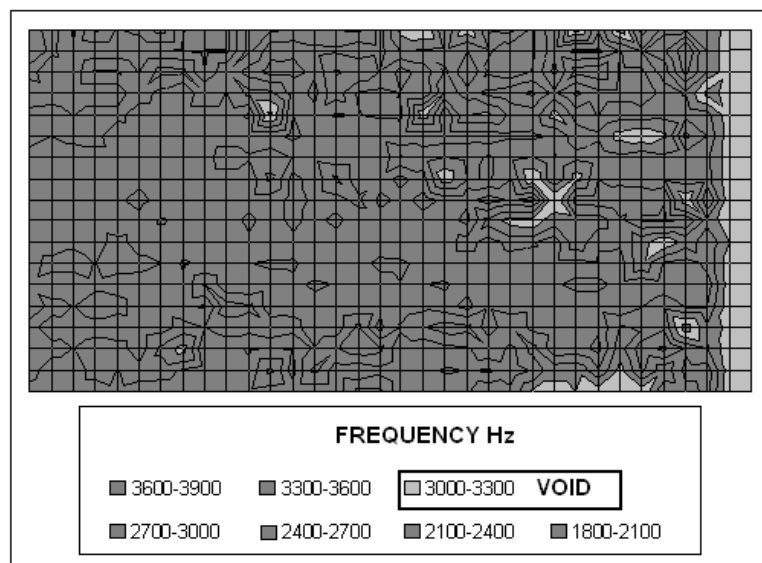


Figure 11 Frequency scan results of unknown condition area

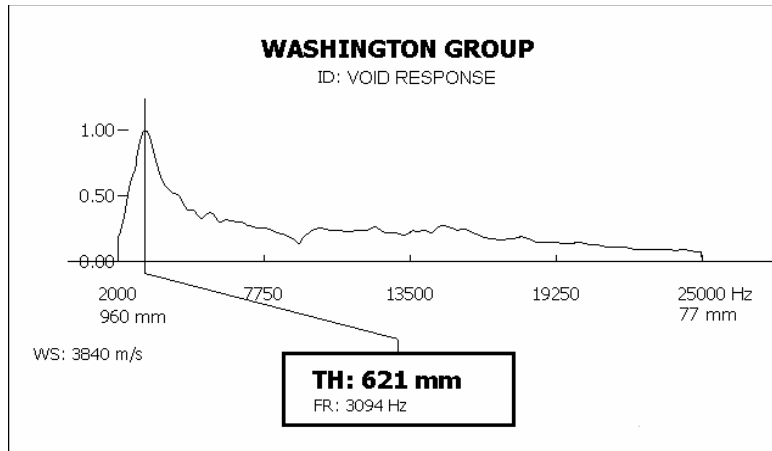


Figure 12 Frequency response of an under filled (void) area

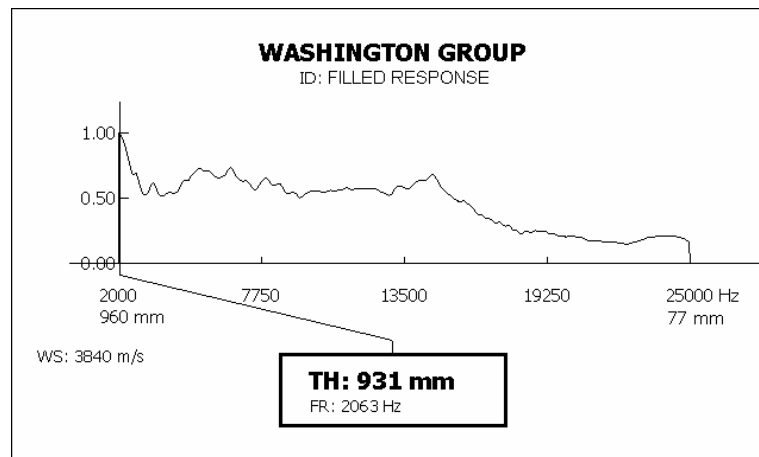


Figure 13 Frequency response of satisfactory fill

By examining the plot of the peak resonant frequencies obtained during the surface scan (Figure 11), it was concluded that the potential for significant under filled regions within the unknown fill condition area is greatly reduced. Nineteen (19) data points from the unknown fill condition area resulted in measured frequencies indicating a void. These 19 data points were generally localized in 5 areas. Because there was not a significant grouping of response that indicated 610 mm thickness, the few that did occur can be reasonably assumed to be a small void or possible cold joint between the fill concrete and the bottom of the test shell, or a small entrapped air pocket.

As part of the fill verification of the test shell, planned areas of destructive testing were built into the structure. The planned testing consisted of cutting the structure into 7 pieces at pre-determined locations (designed into the shell prior to the fill) and coring at 22 locations. The cutting was completed and photographs were taken of the individual pieces. At the cut lines the test shell was completely filled with indication of small voiding only at 1 location. The areas of complete concrete fill measured with the UE equipment matched the completed fill depicted in the photographs. The void was at a location outside of the UE scan area. The areas of

void measured with the UE equipment were located outside of the cut lines and must be verified by coring or additional cutting. At the time of this report, investigative coring at the suspect void areas was not completed.

Conclusion

The Ultrasound-Echo method proved to be effective in the measurement of concrete slab thicknesses and in the detection of delamination and void areas. Using the measured P-wave speed gave accurate thicknesses in cases of known actual thicknesses. Testing on the purpose built defect test slab clearly identified areas of delamination and air void. At the location of a delamination or air void the peak resonant frequency shifted from the thickness resonance to a low frequency resonance. In general, the low frequency shift increased as the delamination size increased and as the depth decreased. A contour plot of the collected data clearly showed the accuracy in identifying the delaminated and air void locations. The functionality of the UE method was clearly demonstrated when testing a large test shell for insufficient concrete filling. Destructive investigation (to date) confirmed that the measured resonance using the UE method accurately detected areas of complete filling. Planned coring will determine the accuracy of detecting voids within the test shell of unknown fill condition.

References

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