

Impact Echo (IE)

System Reference Manual





Olson Instruments, Inc.

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1.0 INTRODUCTION

The Olson Instruments Impact Echo (IE) system is commonly used for rapid flaw detection and thickness evaluation of concrete and masonry structural materials. The method is normally applied to plate-like objects such as slabs and walls, but is also used on columns, mat foundations, and beams. The method requires access to only one side for testing, and can measure not only flaw location, but also depth. This method is used extensively for slab thickness profiling without the need to drill, core or excavate.

A variation of the impact echo principle for use on large areas and for high resolution imaging is the **Impact Echo Scanning (IES)** method. The IES method is based on the Olson Engineering patented technology of a rolling transducer and automated impactor for near-continuous Impact Echo based thickness and flaw scanning of structural concrete and pavements. Literally thousands of tests can be performed per hour when "imaging" of internal concrete conditions is required. Examples of applications include slab thickness profiling and flaw detection, pavement testing, and for the location of ungrouted sections of post-tensioning ducts in bridge structures.

The NDE-360 is a light, handheld data collection platform with a touch screen feature that allows a single operator to collect data easily and fast. When used for quality assurance, forensic testing, and condition evaluation of structures, the NDE-360 with IE-1 system is a powerful, easy to handle and operate tool for verifying structure integrity, locating defects and determining the thickness of a structure.

The NDE-360 system with the IE test consists of several basic components, with additional available optional components. The basic components include the 4 channel NDE-360 platform for data acquisition, analysis and display, an IE head with automated solenoid and a displacement transducer, and cables. Optional components include an accelerometer / instrumented hammer combination for use on very thick structures (IE-2 Option), a test head with a removable second transducer to allow velocity calibration via Spectral Analysis of Surface Waves (SW Option), and a modified test head with a moveable anvil assembly to allow Super-Thin IE testing (ST Option). Details of the hardware and its usage are included in Section 2.0.

While the bulk of the normal data analysis can be done right on the NDE-360 platform, some users may want to post-process the data to perform more detailed analysis. The Windows WinIE software is a post data analysis program with a number of specialized IE analysis tools built-in. This manual covers step-by-step hardware assembly, software setup, data acquisition, data analysis, and output generation.



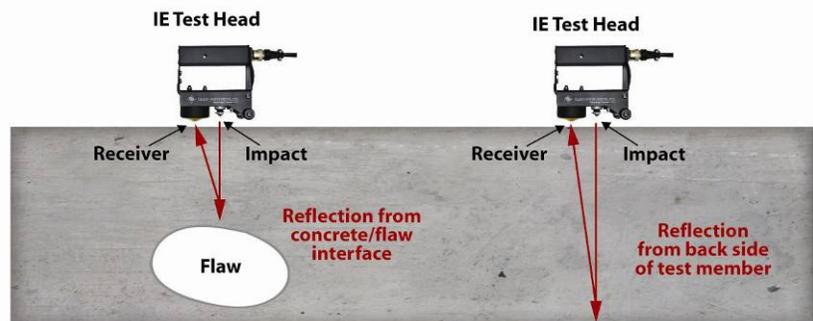
1.1 Organization and Scope of Manual

This operation manual for the IE test with the NDE-360 system manufactured by Olson Instruments includes all required instruction for the use of the hardware and software included with the system. If any problems with the system appear that are not covered in this manual, please call Olson Instruments at the number included in the front of this manual. Note that training in the use of the system by Olson Instruments personnel is recommended for the most effective operation of this system.

1.2 Test Methodology

Impact Echo (IE) – IE investigations are performed to assess the condition of slabs, beams, columns, walls, pavements, runways, tunnels, dams, and other structures. Voids, honeycomb, cracks, delaminations and other damage in concrete, wood, stone, and masonry materials can be found utilizing the IE method. IE investigations are also performed to predict the strength of early age concrete if the member thickness is known, and to measure the thickness of structural members. An advantage of the IE method over the Ultrasonic Pulse Velocity (UPV) method is that only one side of the structure needs to be accessible for testing. The IE method will also provide information on the depth of a flaw or defect, in addition to mapping its lateral location and extent. For large area investigations such as slabs, bridge decks, beams, pipes, etc. where shallow voids or delaminations are of primary concern, Olson Instruments manufactures an IE Scanner, which can record data at 1 to 2 inch increments for an entire scan path. IE Scanning is used in locating ungrouted post-tensioning (PT) cable ducts used in reinforcing various structures. The scanning technology allows tracing of ungrouted areas through slabs and beams. The scanning device application of the IE method was developed by Olson Instruments and is a patented technology. For simple investigations on slabs, pipes, or walls where the overall thickness is the primary concern, a hand-held NDE360 with an Impact Echo option will quickly and easily provide the thickness of an unknown concrete member or locate cracks, flaws, voids, and other anomalies.

The IE tests with the normal test head involve impacting the concrete/masonry member with an impactor solenoid and identifying the reflected wave energy with a displacement transducer as shown in the figure below. Note that the solenoid impactor and displacement transducer are built into the IE head. The test head is pressed against the top of the tested member and held



Reflection from back side occurs at a lower frequency than that from shallower concrete/flaw interface.



while tests are performed at each test point. The resonant echoes of the displacement responses are usually not apparent in the time domain, but are more easily identified in the frequency domain. Therefore, amplitude spectra of the displacement responses are calculated by performing a Fast Fourier transform (FFT) analysis to determine the resonant echo peak(s). The relationship among the resonant echo depth frequency peak (f), the compression wave velocity (V_p) and the echo depth (D) is expressed in the following equation:

$$D = \beta V_p / (2 * f) \quad (1)$$

where β is a geometric shape factor ranging in value from 0.8 for a pier/column shape to 0.96 for a slab/wall shape. A slab/wall shape has a single thickness resonance while beam and column shapes have multiple resonances due to their cross-sectional shape.

For thicker members, such as mat foundations or large pedestals, an instrumented or larger non-instrumented hammer and an accelerometer can be used in place of the test head to excite the member and collect the data. Measurement of the concrete velocity can be done with any of the NDE-360 IE systems using the “thickness calibration” option at a location with a known thickness of concrete. For systems with the SW option, the velocity calibration can be done on any concrete member with a thickness of greater than 5 inches (13 cm).



2.0 HARDWARE

The IE system with the NDE-360 platform consists of several basic components packaged into a padded carrying case. The padded case stores the NDE-360 data acquisition platform, battery charger, IE test head, grease, and cables. A description of each of these components as well as their connection and operation is included in the following sections.



2.1 Hardware Component Listing

COMPONENT NAME		QTY	DESCRIPTION
	1.) Olson Instruments NDE-360 Platform	1	Platform for data acquisition, analysis and display of IE time domain data.
	2.) IE Test Head	1	The test head includes an automated solenoid impactor and a displacement transducer. Optional ST model includes ST anvil mechanism.
	3.) IE Cable	1	To connect the IE head and the NDE-360.
	4.) Battery Charger	1	Battery charger for the NDE-360 platform.
	5.) Battery	1	Nickel metal hydride battery
	6.) Card Reader and Compact Flash Card	1	Compact Flash Card to hold the firmware file and store IE data files. Card Reader to transfer the IE data files to the analysis computer.
	Optional SW Test Head	1 (optional)	Used for surface waves (SW) velocity calibration



2.2 Basic Components and Maintenance of NDE-360 Platform

Battery Charging: The external battery charger (Item 4) automatically switches between 100/240 Volts AC. In order to charge the battery, the battery charger must be plugged into the line voltage supply (110/220 VAC) using the correct plug adapter. The other end plugs into the NDE-360 next to the CF card slot. **The NDE-360 must be turned off during charging.** The battery is charged when the light on the charger unit blinks at a slow, steady rate.



If the NDE-360 is turned on and the charger is plugged in, it is possible to use the NDE-360 for data acquisition, but the charger will not automatically turn off when the battery is fully charged. Therefore, be aware that the battery can be overcharged and possibly damaged if the NDE-360 is turned on with the charger connected over an extended period of time. **To properly charge the NDE-360, be sure it is turned off when the charger is plugged in and charging.** If a 12 VDC source (like an automobile power outlet) is plugged directly into the NDE 360, it will run the NDE 360 but it will not charge the battery. **(If a car battery is used, do not run the car engine.)** If plugged into a 12 VDC source (like an automobile power outlet) while the battery is removed, it will also run the NDE 360.

Turn the unit off promptly when the yellow "low battery" indicator on the NDE 360 lights up, otherwise the battery may discharge to the point where it requires a 12VDC boost so that the charger can recognize the battery and start charging.



Time required to fully charge the battery is 8 hours. The fully charged battery will power the NDE-360 system for 8 – 10 hours.



Location of Battery: The compartment housing the battery is located on the back of the NDE-360 system. Move the slider latch to remove the battery cover if the battery needs to be replaced.



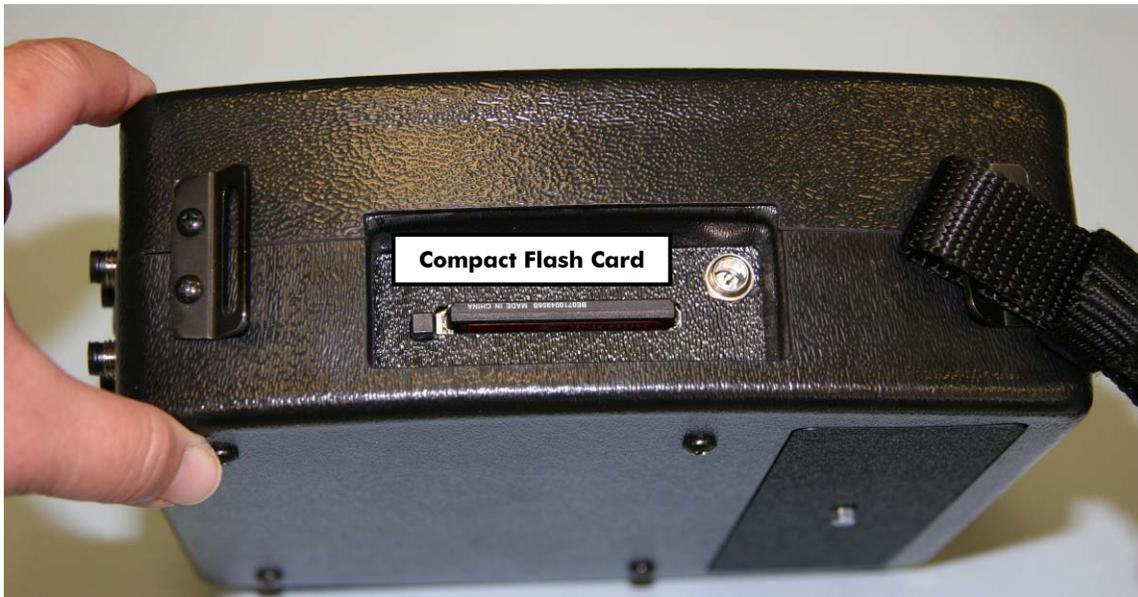
Do not expose the NDE-360 system or the battery to water.

Channel Arrangement: The NDE-360 system is equipped with 4 channels. There is one 4 pin connector for each channel. Channel 1 is located on the right hand side if facing the front screen of the NDE-360 system. The IE-1 unit uses the special Impact Echo Channel connector to run the test head. The IE channel is connected internally to channel 1 and thus the four 4 pin channel connectors are not normally used for the IE-1 test.





Data Storage: A compact flash card is used to store the IE data files. In addition, the master firmware program controlling the IE test is stored on the compact flash card. The system must start up with the compact flash secured in place. The card is located on the left side of the NDE-360 system if looking at the front screen.



If the compact flash card is missing from the system, the system will not function. Do not insert or remove the compact flash card while the system is turned on.

NDE-360 Operation Notes: The NDE-360 system is a self-contained data conditioning, collection, basic processing and data display platform usable for a number of types of NDT tests. The system is designed to make it user friendly and easy to handle and operate by a single operator. The main screen can be navigated using the touch screen feature.



Never impact the screen with any sharp object!



2.3 Hardware Setup

1. Connect the IE cable (Item 3) to the IE head (Item 2) by aligning the pins on the cable with the corresponding holes in the IE head, pushing in the connector part-way, and then rotating the connector sleeve until it locks.



2. Connect the other end of the cable to the IE Channel on the NDE-360.



3. The picture below shows the complete hardware setup for the IE test.





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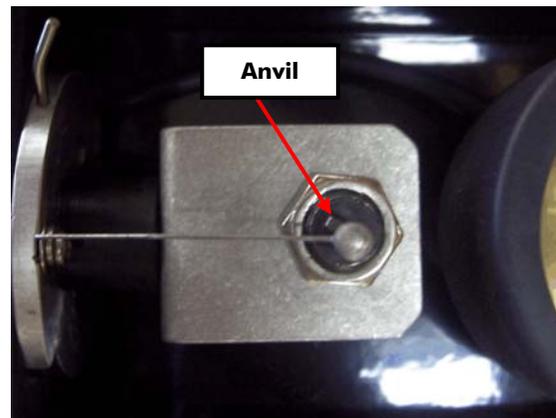
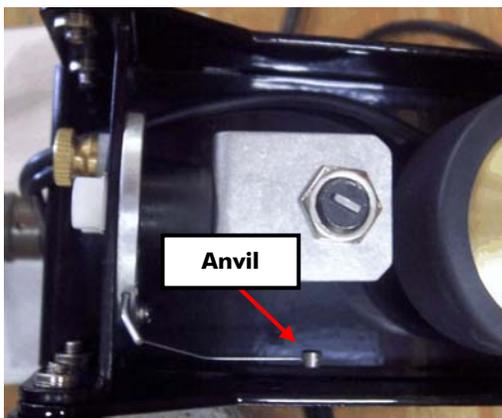
4. The picture below shows the complete IE system with the IE head on top of a concrete cylinder (ready to acquire data). Note that the concrete cylinder is not included in the system.





2.4 Superthin Option

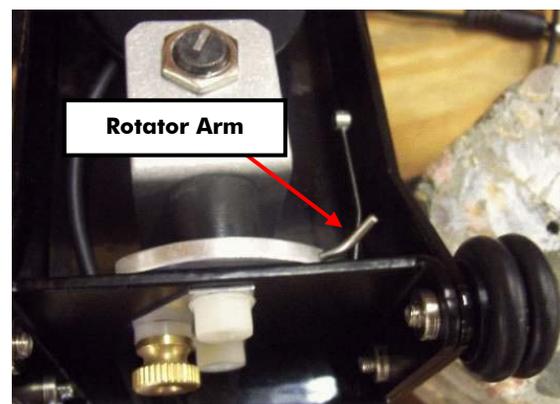
Testing in the superthin mode on an NDE-360 system is done with a modified test head which is supplied when the superthin option is purchased for the IE system. The modified test head has a small steel anvil on a spring wire which is attached to a rotating mechanism that the user can use to move the anvil in and out. The basic mechanism with the anvil rotated out of the way is shown in the left figure below. The anvil rotated into place for superthin testing is shown in the right figure.



Note that the anvil must be fully rotated in place for superthin mode testing, and rotated out of the way for normal operation. In addition, for superthin mode testing to work correctly, the anvil must be directly under the impactor and spaced about $\frac{1}{2}$ inch away. If the anvil is not directly under the impact, the wire can be gently bent until it lines up as shown in the photo.

Rotating the anvil in and out from below the impactor is done by finger, moving the rotating mechanism from fully right to fully left. The arm for this mechanism is shown the in the photo below.

Operation of the IE test head in the superthin mode (with the anvil rotated in place) should only be performed on concrete that is about 4 inches thick or less. The superthin test head has been used to measure actual concrete thicknesses down to 1.5-2.0 inches. On the NDE-360 platform, the minimum thickness that can be measured is about 1.1 inches based on sample rates. The normal sample rate used for superthin testing is 7 microseconds per point for the NDE-360.





3.0 IE DATA AQUISITION

This section includes instructions for IE data collection with the NDE-360. If you have an area of known thickness that can be used for velocity calibration or if your system includes the Surface Waves (SW) option, please refer to Sections 3.2 and 3.3 before testing.

3.1 IE Data Acquisition without Velocity Calibration

1. Turn on the NDE-360 system (with the hardware in Section 2.0 connected). Make sure that the compact flash card is secured in place. The master software to run the system is located on the compact flash card. Press on the “Continue” button on the upper right corner of the screen. If the compact flash card is not in place, the “Continue” button will not appear on the screen.



If the continue button is not seen on the screen, turn off the system and insert the compact flash card in place and turn the system on again.

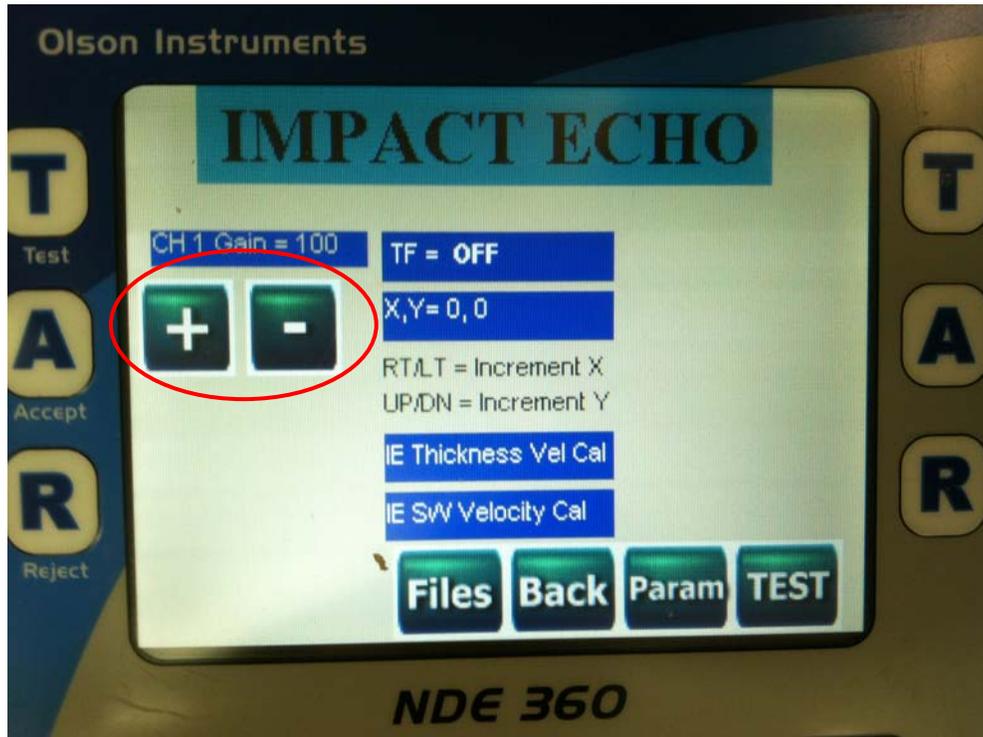


2. Press on the "IE" option. The picture below shows a screen with IE and UPV (Ultra Sonic Pulse Velocity) options enabled. The options on the unit may be different depending on the system ordered.





- The system is ready to acquire data. In the IE test, the initial gain will be automatically set to 100. This is a good value for most IE tests. However, if higher gain is required, simply press on the + button to change the gain for Ch 1.



- The system is loaded with a default parameter that is applicable for most IE tests. However, if the parameters need to be adjusted, press the “Param” button. In the parameter setup screen, the user can change the following parameters by touching the button to toggle the value. Touch the “Back” button after the parameter setup is complete.

Change Date/Time. This option allows the user to enter the correct date and time of testing.

Time/Point or Sampling Rate means how often (in the time domain) the system will acquire data points within a given data trace. In the case shown in the picture below, the Time/Point was set at 12 microseconds. This means the system will acquire data at 12 microsecond intervals. **This parameter can not be changed after the data is taken.**

Points Per Record is number of sampling points for each waveform. The higher this value, the more data is acquired in each waveform. The total time of a record is affected by both the Sample Rate and the Record Size. **This parameter can not be changed after the data is taken.**

Velocity. The software uses this velocity to calculate the thickness echo. If velocity calibration is not possible, a typical concrete velocity of 12,000 ft/sec may be used as a default. This parameter can be changed later in the post data analysis.



Sol. This value can be “on” or “off”. If the solenoid is on, the system will use the solenoid in the IE head as a source. If this value is off, the system will wait for the external hammer as a source.

Sol Time. This is the time to drive the solenoid. The default value is 14 us. However, this value may need to be adjusted depending on the actual test head used, or may be set higher for inverted testing or underwater testing (in shallow puddles only).

Recs. Number of Records is the total number of IE data records you want to save. **This parameter can not be changed after the data is taken.**

Pre-Trigger is number of points before the triggering point that data collection starts. This parameter must be 0 for the IE test with the solenoid on (enabled) or non-zero for external hammer use (solenoid off or disabled). **This parameter can not be changed after the data is taken.**

Trigger Level % is the minimum signal amplitude (in terms of percentage full scale) to trigger data acquisition when an external hammer source is used. In this case, the trigger level is set at 4%. Therefore, the system will start acquiring data once the absolute amplitude of the signal exceeds 0.4 volt. **This parameter can not be changed after the data is taken.**

Channel Setup. For the IE test, only one channel (connected to the IE head) is used. Ch 1 must be turned on for the IE test and this should not be changed. More details are provided below.

REF: Press a button in the REF column to assign the reference channel. Generally, this is the hammer or Force channel. This sets the numerator term in Transfer Function (IR) analysis.

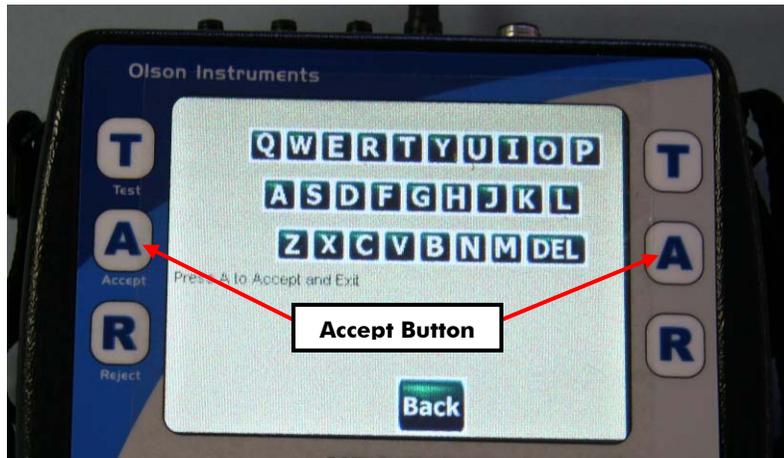
TRIG: Press a button in this column to assign the trigger channel. This is the channel that determines when data collection occurs, along with the “Trig Lev %” setting.

CAL: These entries are used to enter the transducer calibrations, in terms of unit/volt where “unit” is the engineering unit (Metric or English) desired for the final result on a given channel. Note that default calibrations are filled in for some “typical” English units.

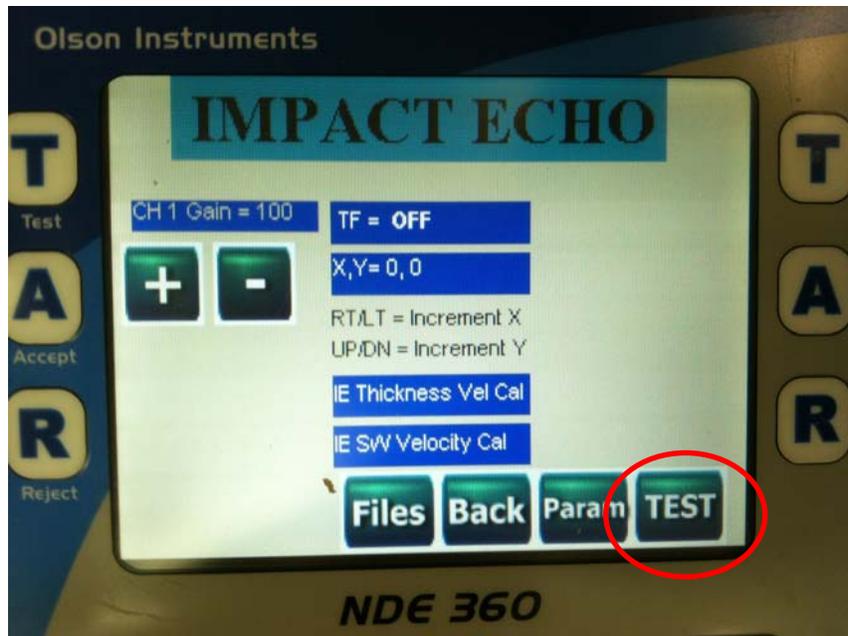




- The filename arrangement of the NDE-360 uses a fixed alphabetical prefix and a numerical suffix. The prefix can be set at the beginning of any test. If the prefix is not changed, a higher suffix number will be added to the current prefix for the new filename. To change the prefix, press on the “Files” button and press number 5 and then number 1. Then a virtual keyboard will appear on the screen and the user can change the prefix part of the filename. Press the “A” button on either side to accept the new prefix of the filename.

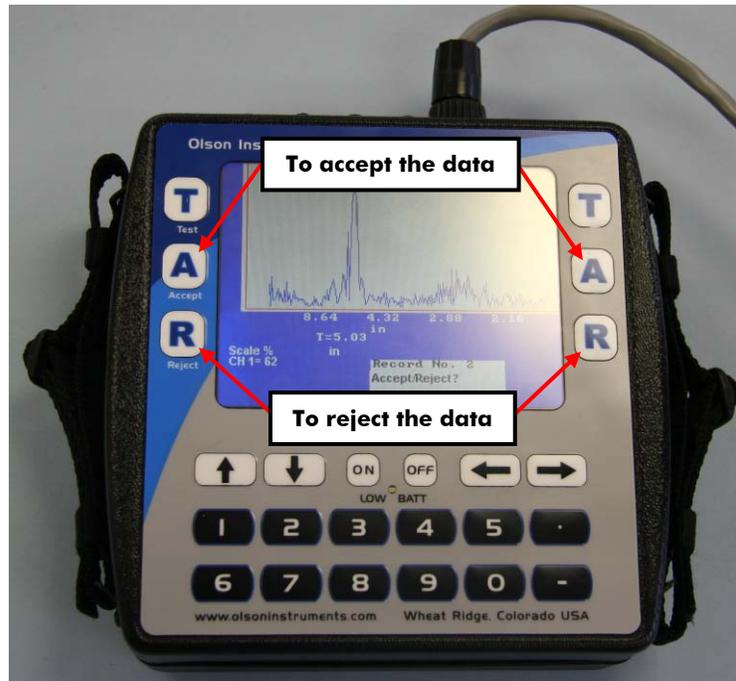


- After the parameter setup is complete press the “Back” button to return. Now the system is ready to take the IE data. Push the IE test head on the tested member and press the “Test” button to acquire the IE data.

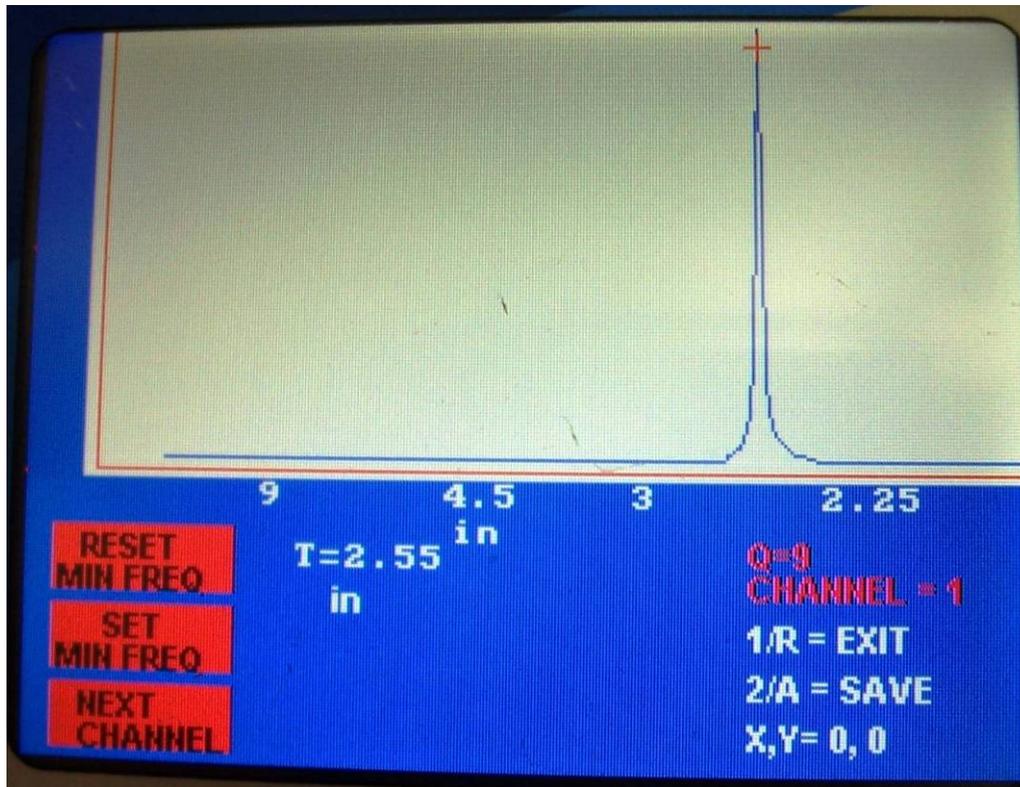




7. If the solenoid mode is on, the NDE-360 system will immediately fire the solenoid inside the IE head and the displacement transducer in the IE head will record the data. If the solenoid mode is off, hit the external hammer on the structure next to the IE head. The screen below shows the spectrum of the time domain data acquired from a 5 inch concrete cylinder. Press the “A” (Accept) button if the data is good or push the “R” (Reject) button if it is poor quality data.



8. Repeat Step 7 until all the records are collected.
9. After all the records are collected. Press “2” to save the data or “1” to exit without saving.
10. To perform more IE tests, repeat Steps 6 – 9.

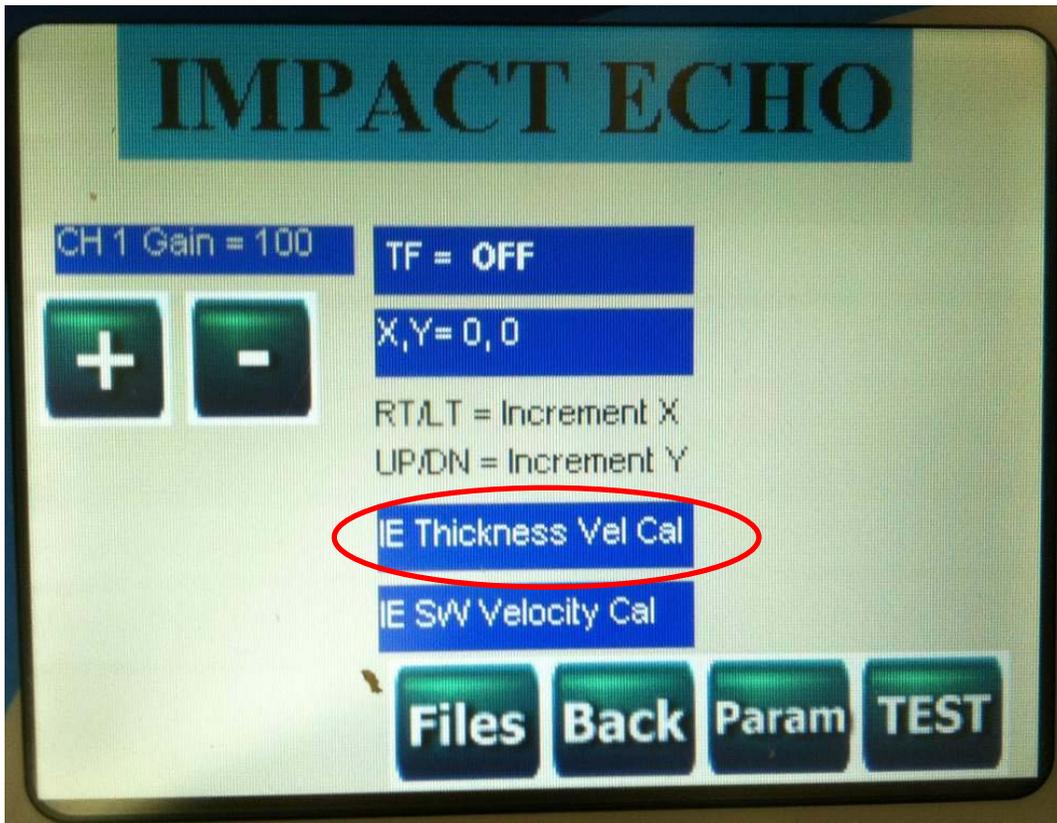


11. During the display of the final data, several user options are available to allow additional data processing and display. First, a cursor function is available to allow the user to see the thickness values of peaks other than the largest one. Simply touch the screen at the desired location, and/or use the left/right arrows to activate the cursor and move it around on the screen.
12. Also on screen are three red buttons on the left. The bottom button allows selection of a second (or third/fourth) channel of data if other transducers are used in addition to the IE test head. The middle button, "Set Min Freq", acts as a hard high pass filter to eliminate all data on screen for thicknesses greater (frequencies lower) than the current cursor location. The remaining data is then auto-scaled and replotted. This allows small, thin peaks to be easily analyzed. The top button turns off the "Set Min Freq" function and plots all of the spectral data across the screen.
13. The data can be recalled in the NDE-360 system by pressing the "File" button on the main screen and then selecting Option 2.
14. The data files on the compact flash card can be moved to the analysis computer for post-data analysis.



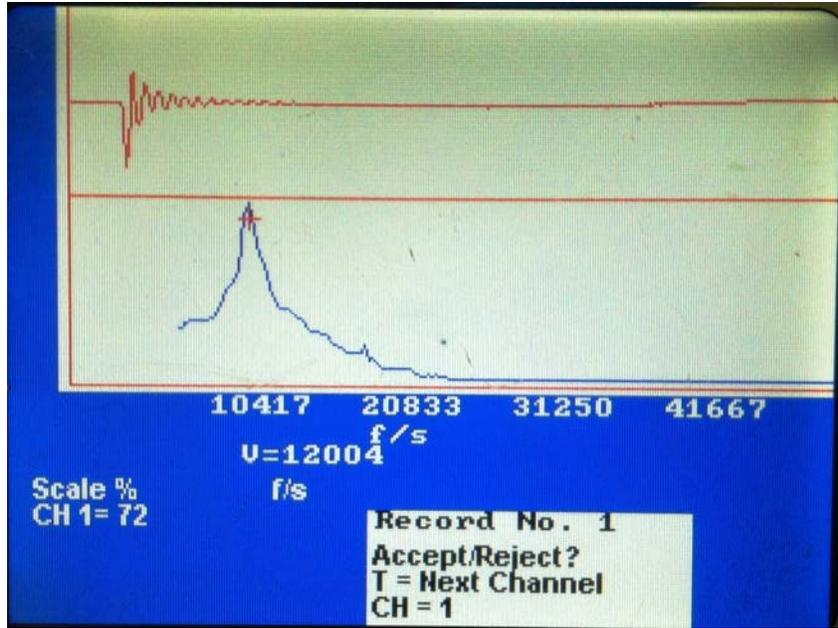
3.2 Known-Thickness IE Velocity Calibration

The IE firmware for the NDE-360 includes a feature that allows accurate calibration of the concrete velocity at any location where the user knows the actual concrete thickness and can collect good-quality IE data. Typical locations for this include next to coreholes, cutouts, slab edges, etc. It can also be done on walls near holes or edges, on curbs, or other known-thickness features. To use, select the “IE Thickness Vel Cal” option button shown circled below on the main menu.

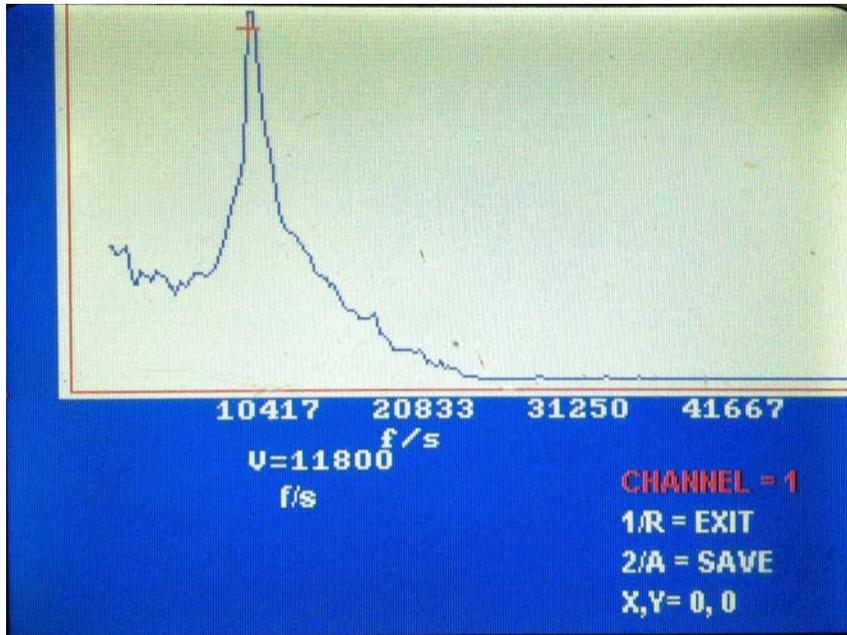


Once this button is pressed, a screen will appear asking the user to enter the known concrete thickness in either inches (English units) or mm (Metric units). Enter the value, then make sure the test head is pressed firmly against the test surface and press “A”. The solenoid in the test head will immediately fire and a waveform will be collected. The data should show a clear, single IE echo peak and corresponding velocity. Typical good-quality data is shown in the two images below, with the first during data collection and the second after data collection is complete. Note that the final resulting number shown for the peak is in velocity rather than thickness.

The velocity calibration mode can also be used to measure relative velocities of concrete in a member with known thicknesses (such as a wall) to find degraded or low-strength zones.



Thickness Calibration Plot During Data Collection



Final Thickness Calibration Plot – Note Velocity of 11,800 fps measured for this location



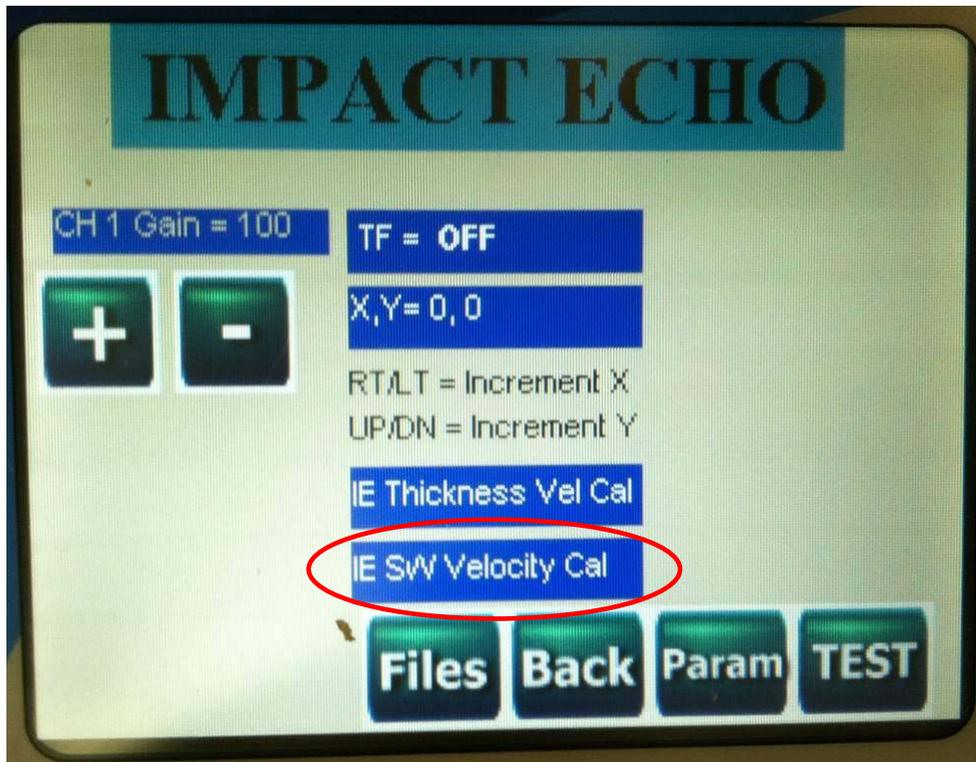
3.3 SW Arm Use for Velocity Calibration

For systems purchased with the SW (Surface Waves) velocity calibration option, there is an extension arm (shown at top below) provided which adds a second receiver to the IE test head to allow surface waves testing. This extension arm and transducer are mounted to the IE test head by simply pushing it onto the end of the square arm connector on the test head. Push the extension arm onto the test head connector while pressing in the spring-loaded lock to allow the arm to fully seat onto the connector assembly. The end of the arm should butt against the test head frame when properly attached (shown at bottom below). All electrical connections are made automatically when the arm is attached.



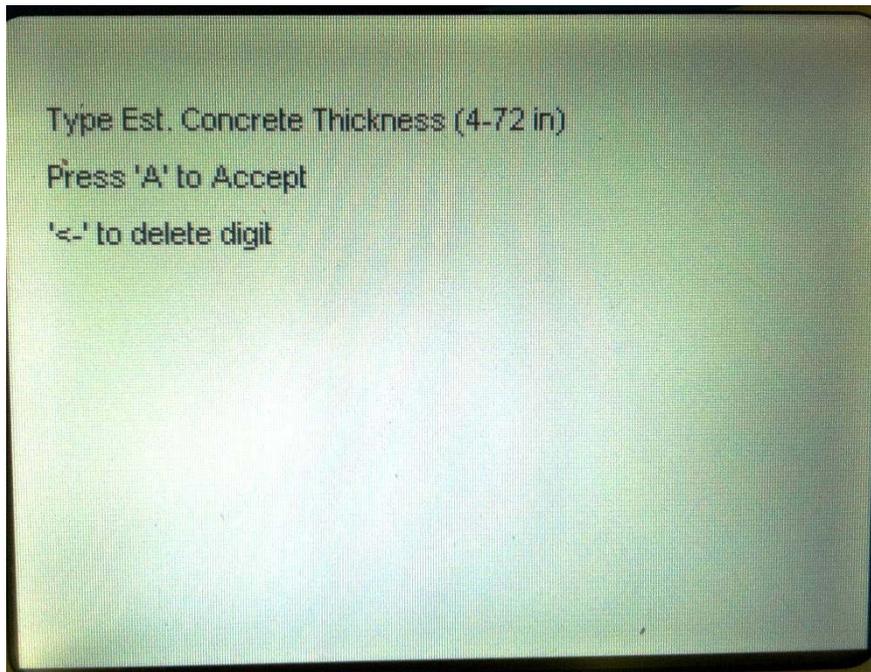


To use the arm, first make sure that both the receiver on the end of the arm and the receiver in the test head are touching the test surface when the assembly is resting on the test surface under its own weight. If not, the receiver at the arm end can be adjusted up or down by loosening the thumb screw, adjusting the height, and re-tightening the thumb screw. When the head is adjusted properly, perform the SW calibration test by selecting the “SW Velocity Cal” option button from the main menu on the NDE-360, as circled below.

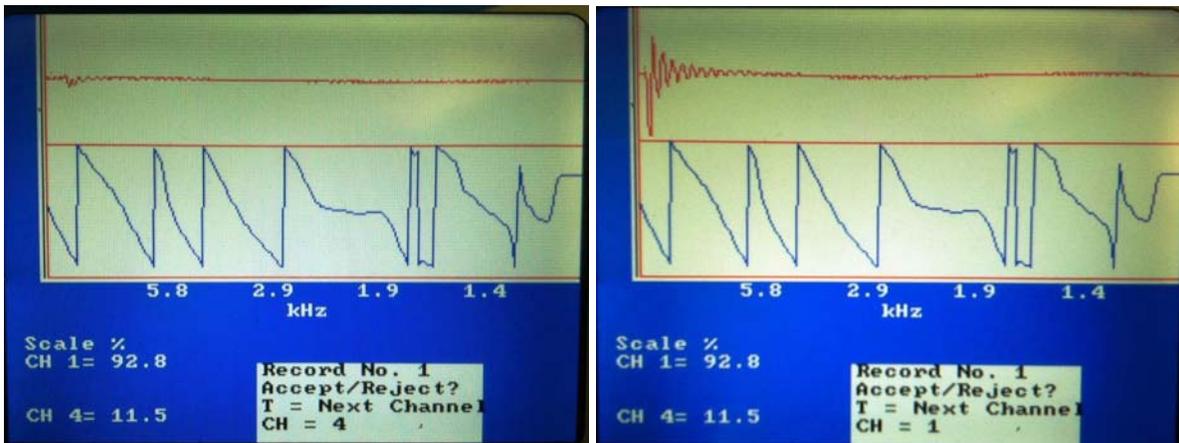


The program will first ask for an estimated concrete thickness. Enter the estimated thickness of the member to be tested in either inches (English units) or mm (Metric units). Press the test head against the concrete and then press “A” to continue. Make sure that no cracks or flaws are present below the test head or between the two transducers or the impactor.

Note: if the member thickness is unknown, enter a thickness equal to or less than the minimum possible thickness for the member. The thickness entered is used to set the depth range over which the velocity is computed. If set too high, the NDE-360 will attempt to compute a velocity using data beyond the back side depth of the concrete. This will result in incorrect velocities.



Once the “A” button is pressed, the program will automatically fire the solenoid and collect the first waveform from both channels. Typical “good quality” data from the first and second channels are shown below. Press the “T” button to switch between the channels for display of the collected time domain data.



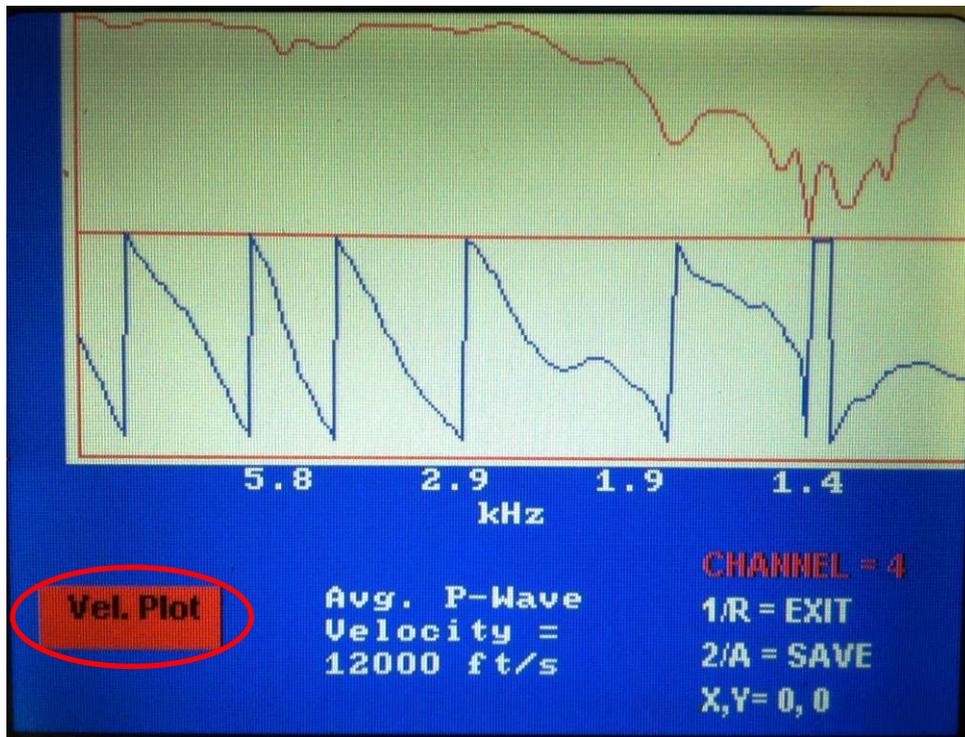
Note that the “percent full scale” readings will generally be higher for channel 2 than channel 4. This is normal. The phase data seen in the lower plot should appear as a “sawtooth” plot in at least the left half of the screen, with the ramps going down to the right.



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If the data looks good, press the “A” button to accept and perform the next test (make sure to keep the test head pressed against the test surface throughout the course of the testing). If the data is poor or noisy, press the “R” button to reject and retest.

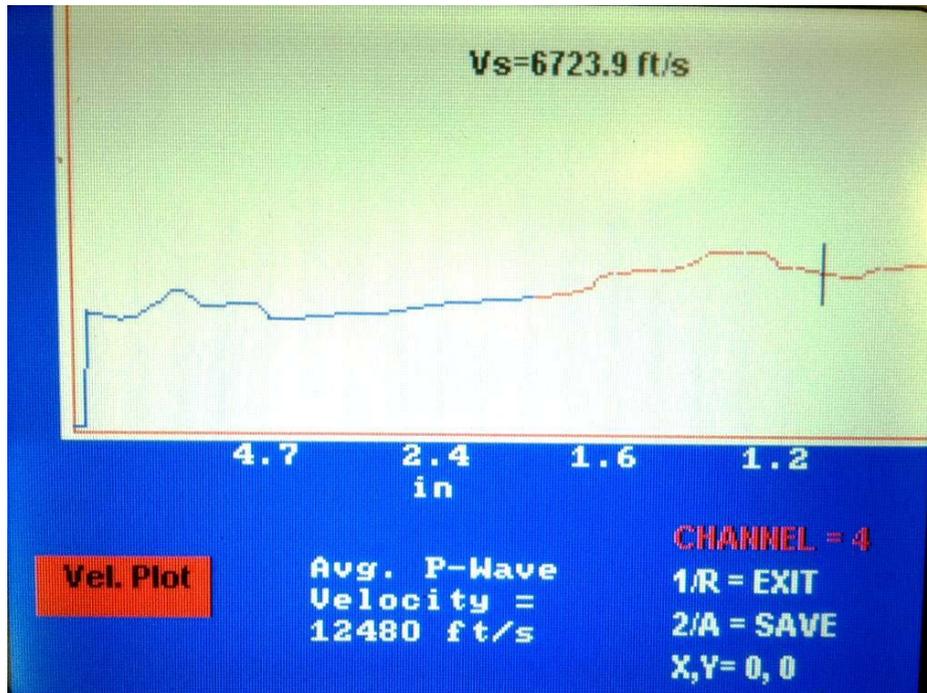
Once all of the waveforms have been collected and accepted, the final phase and coherence plots will appear. A typical phase and coherence plot from good-quality data is shown below.



The phase plot is at the bottom of the touch screen, and the coherence is at the top. The coherence plot is a measure of data repeatability (quality) versus frequency. It should be near the top of the plot in the left half of the plot (or more). If the coherence is very rough or low, the test should be repeated by pressing “R” to go back to the main menu.



If the coherence is good and the phase looks reasonable, press the “Vel. Plot” button (circled above) to display the velocity versus wavelength/depth plot (dispersion curve). A typical velocity plot is shown below.



As seen, the velocity plot shows wavelength (corresponding to depth in sound concrete) on the horizontal scale and velocity on the vertical scale. The red portion of the plot is the portion used by the software to compute an average velocity for IE tests. The red portion of the plot should be relatively flat, and the measured velocity shown in the lower portion of the screen should be in the reasonable range for concrete. If not, repeat the test.

A cursor is available by touching the plot line. The displayed value will be the surface wave velocity at the depth/wavelength indicated. Note that the surface wave value and the compression wave values are different by a factor of 0.54.

If a reasonable Average P-wave velocity is shown, press either the “R” or the “A” key. The “R” will save the velocity and exit to the main menu, while the “A” will save the velocity and the data and then exit to the main menu. The displayed velocity will be used as the new default velocity value for subsequent tests, unless changed by the user.



4.0 WinIE SOFTWARE SETUP

This section covers the steps required to install the WinIE software on a laptop or desktop computer from the supplied installation jump drive.

4.1 Prerequisite Software

Windows .Net Framework 4 is required for the WinIE software. The software is fully compatible with Windows XP, Vista and Windows 7 (32 or 64 bit).

4.2 Software Installation

1. Uninstall any previous version of WinIE.
2. Run WinIE Setup (located in WinSEIR Setup/Release). The default location for the software installation is either ProgramFiles(x86)/OlsonInstruments/WinIE or ProgramFiles/OlsonInstruments/WinIE unless the user changes the location during the installation process. Note that the parameter.prm file will also be installed in the selected directory and “write protect” will be added to the parameter file. Therefore, the user needs to manually change the security setting of the parameter.prm file (see Step 3 below). Also note that the installation process may take several minutes.

If .Net Framework 4 is not found during the installation process, the user will be prompted to install this prerequisite and the following web address will be prompted on the web browser:

<http://www.microsoft.com/en-us/download/details.aspx?id=17851>



Note that .Net Framework 4 Full Version is required. The .Net Framework 4 Client Profile is not compatible with this software. Internet web access is REQUIRED to complete the installation of this software if the .Net Framework 4 is not present on the target computer already.

3. For Vista and Windows 7 operating systems, go into the application folder and locate parameter.prm. Right click on parameter.prm and click on “Properties”. Go to the General tab and make sure that the “Read-only” box is unclicked. Then go to the Security tab and make sure that “Full control” is checked to allow write access to the file. See Figure 1 for the setup.



Step 3 is not required for the Windows XP operating system.

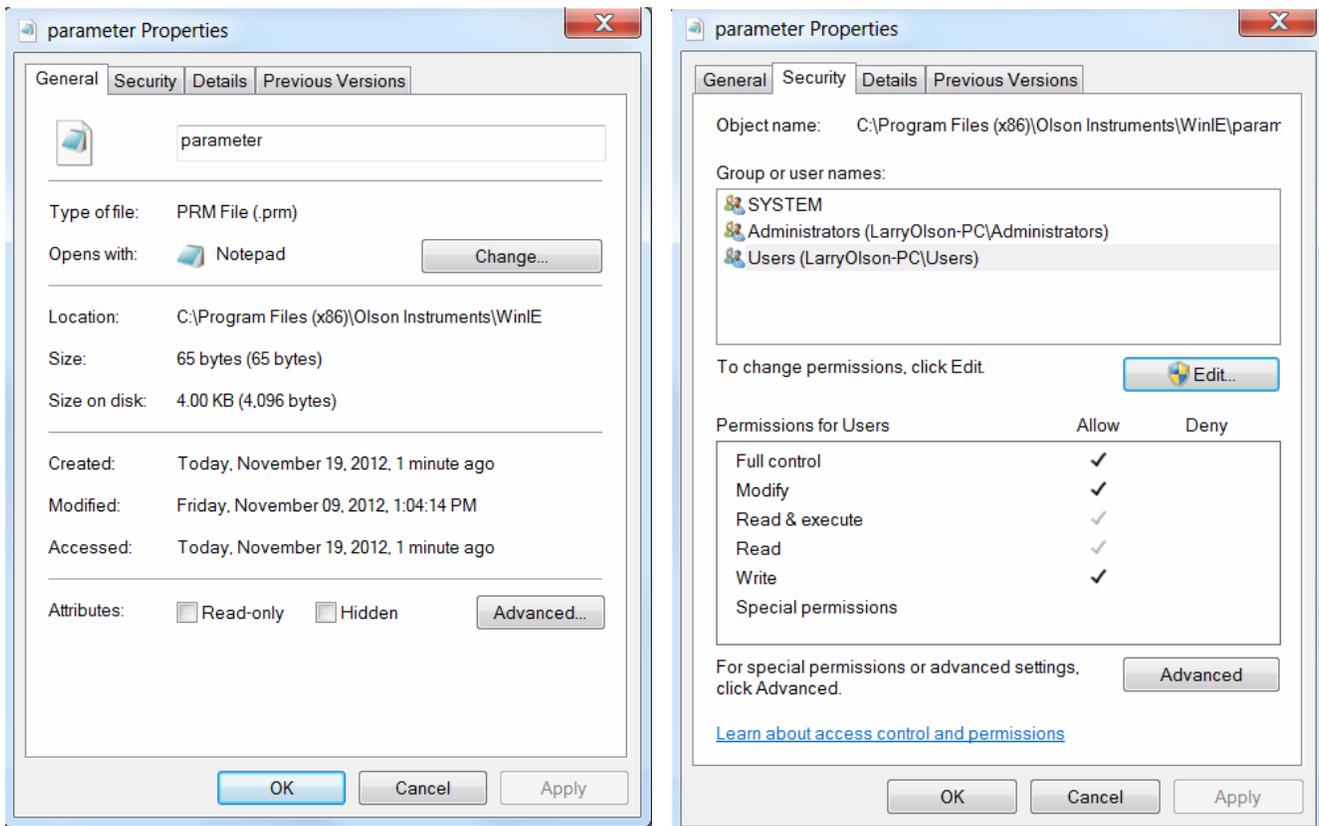


Figure 1 – General and Security Properties for parameter.prm

4.3 Software Updates

To update the software, completely uninstall the WinIE Setup software per Section 4.4 and re-install the new version of WinIE Setup.

4.4 Software Uninstallation

The following steps are required to uninstall the WinIE Software

1. Click on “Start/Settings/Control Panel”
2. Select “Add/Remove Programs”
3. Highlight WinIE Setup, select “Remove”
4. The uninstall process will begin automatically, removing all installed components including the shortcut.



5.0 WinIE SOFTWARE ANALYSIS

5.1 Start Program

Click on WinIE.exe in the application folder or on the desktop. The screen, as shown in Figure 2, will appear.

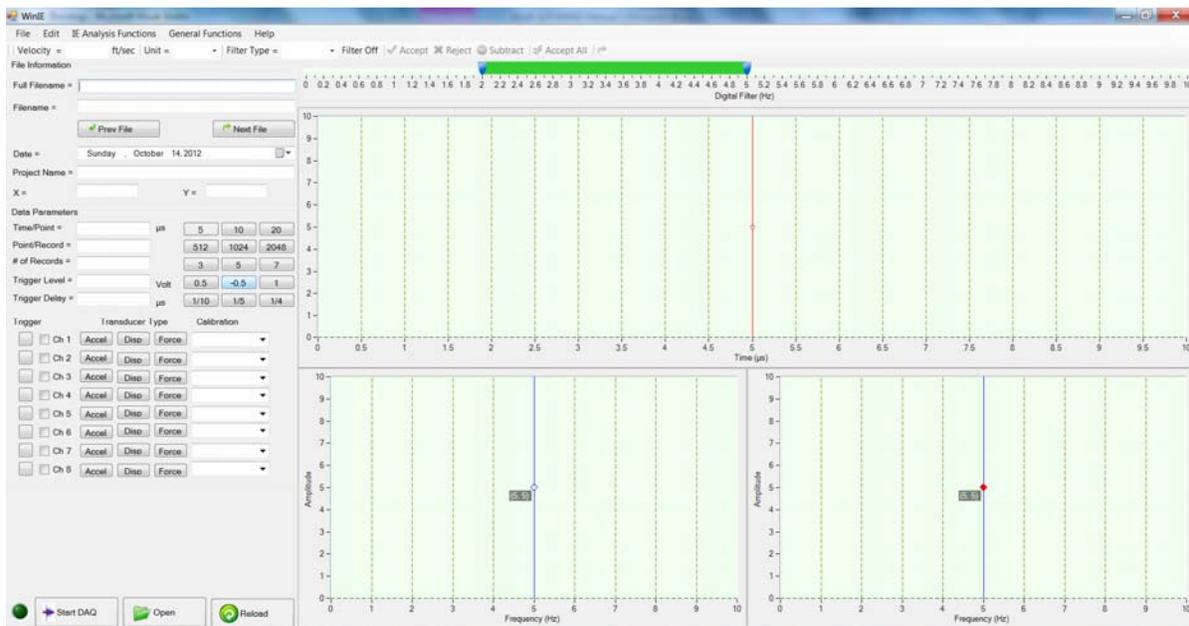


Figure 2 - Main Screen for WinIE Software

5.2 Open and Accept/Reject NDE-360 Data

1. Click on the “Open” button on the main screen (or go to “File/Open”) and select the data file (.nde) downloaded from the NDE-360. The first record from all the channels will appear in the top plot box on the screen, as shown in Figure 3. The data parameters used to acquire the data will be highlighted in green and disabled. Note that these data parameters cannot be changed during the analysis process. However, transducer type and calibration values (as well as velocity and filter settings) can be changed during the data analysis. The top screen shows the current time domain IE data. The bottom left screen shows the spectrum of the current time domain IE data from the test head.
2. Click on the “Accept” or “Reject” buttons to either include or exclude the current records in the analysis. Once the first records (from all channels) are accepted, the current average spectrum is calculated and displayed in the bottom right plot box on the screen, and the next set of records of the time domain IE data are shown on the top screens, as shown in Figure 4.



Click Accept, Reject or Accept All

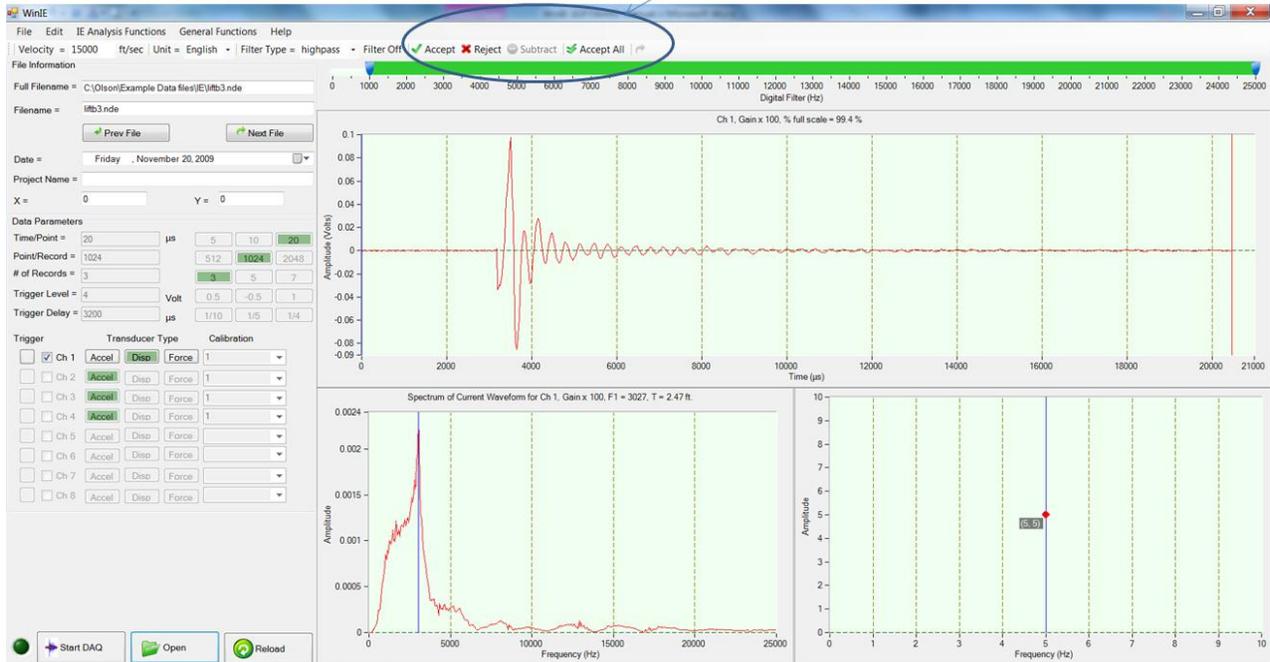


Figure 3 – Screen with the First IE Data Records (1 channel shown)



Figure 4 – Screen with the First Record Accepted



3. Repeat Step 2 until all the data are accepted or rejected. Note that the user can reject the records that were previously accepted by clicking on the “Subtract” button. The “Subtract” button automatically removes the previously accepted data from the average. The “Accept All” button can be used to accept all the acquired records.

Note: The time domain waveform displayed in the top graph has been processed by removing the DC offset, de-gaining, calibrating and filtering the raw time domain data.

5.3 Calibration Values

The calibration values are loaded from the NDE 360 data files into the WinIE application. If these values need to be corrected, simply type the correct calibration values into the calibration boxes on the left side of the screen. Note that a calibration database is built into the software and can be edited as needed (see Section 5.9). Once the correct calibration values are entered, these values are used in the analysis and the waveform plot(s) are updated. Note that if the WinIE application is installed within the Program Files or Program Files (x86) directories, edits or updates will only be allowed on the calibration database file if the properties of the parameter.prm file is not Read-only and Full control is set for the user for the file.

Note that the calibration number for the displacement transducer is irrelevant because the output is affected by the contact pressure. The displacement transducer measures relative displacement and not absolute displacement. The software will disable the calibration box if the displacement transducer is used to collect the data, which is normally the case for an IE-1 system.

5.4 Filtering

Interactive filtering is implemented in this software. A Butterworth filter with the 4th order is used. The type of pass-band can be selected with the top tool bar. The default pass-band filter for IE data is “Highpass” which is the recommended filter for most situations. The frequencies are set using the marks on the slider bar just above the top plot box windows, as shown in Figure 5. There are three options for pass-band filtering:

- Lowpass – Passes the frequencies below the right mark. This type of pass-band is NOT recommended for general IE data analysis. This type of pass is recommended for Sonic Echo data analysis.
- Highpass – Passes the frequencies above the left mark. This type of pass-band is recommended for Impact Echo data analysis.
- Bandpass – Passes the frequencies between the left and right mark. This type of pass-band can be used for IE data analysis if there is interference from low frequency noise.



Figure 5 – Filtering

The following guidelines can be used for selecting appropriate filters:

1. When the expected thickness is less than 3 inches, a bandpass filter of 10,000 to 50,000 Hz is appropriate
2. When the expected thickness is between 3 inches and 6 inches, a highpass filter of 6000 Hz is appropriate.
3. When the expected thickness is between 6 inches and 12 inches, a highpass filter of 3000 Hz is appropriate.
4. When the expected thickness is greater than 12 inches, a highpass filter of 1000 Hz is appropriate.

5.5 Windowing

Interactive time-domain windowing is implemented in this software. Two cursors (left blue and right red) present on the top graph can be dragged into the data to window the front and back of the time domain waveform. This feature is very important in getting rid of any front interference from the solenoid (front end) and/or the interference from double hitting or other noise (back end). Figures 6A and 6B show the effect on the spectrum before and after windowing (front and back) is applied to a typical time domain data waveform with noise present. Notice that the spectrum from the windowed time domain data (in Figure 6B) is smoother than the un-windowed data in Figure 6A.



Figure 6A – Time domain and Spectrum before Windowing is Applied

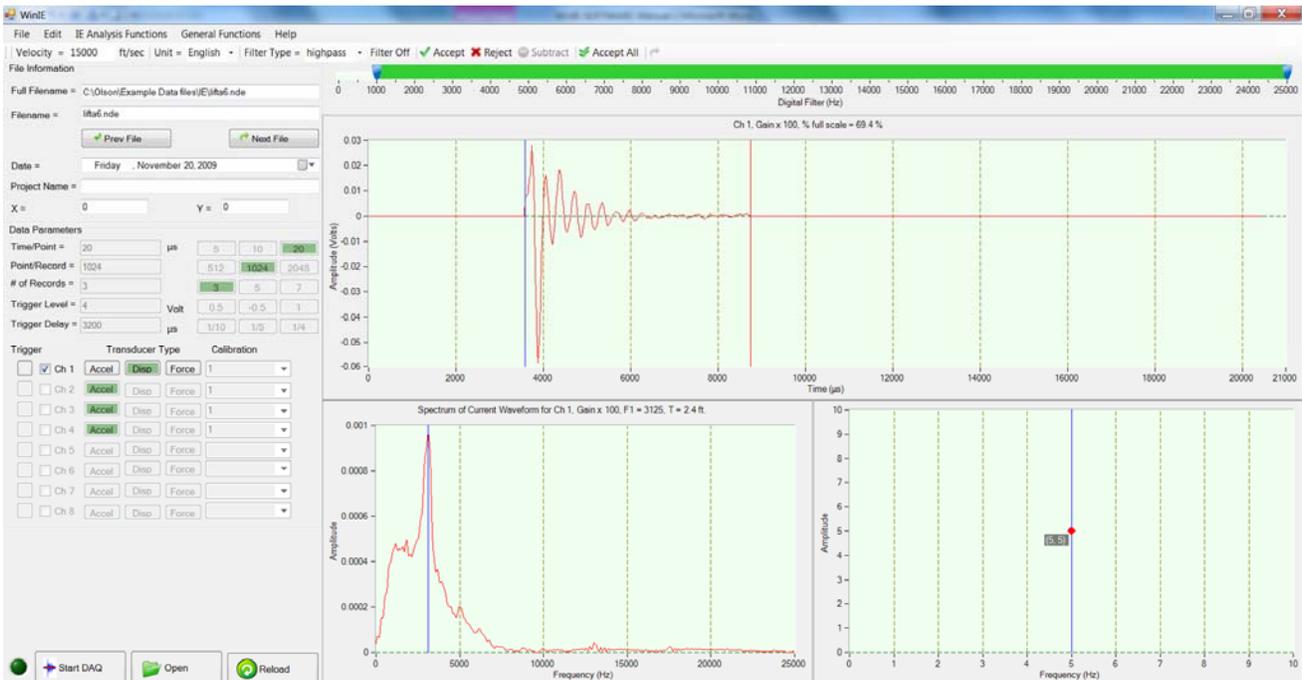


Figure 6B – Time domain and Spectrum after Windowing is Applied



5.6 Concrete Velocity

The concrete velocity used for thickness calculation (or depth of the echo) is read from the value saved in the NDE-360 data file. If this velocity needs to be modified, simply enter the new velocity value in the “Velocity” box on the tool bar, as shown in Figure 7. Note that the user can select to keep the velocity for future IE files.



Figure 7 – Concrete Velocity



Typical concrete velocity is 12,000 – 13,000 ft/sec or 3,600 – 4,000 m/s. Higher strength concrete may have a higher velocity. Young concrete (less than 7 days old) may have a slower velocity.

5.7 Units

The units used in the program are the units saved in the NDE-360 data file. The units can be changed from Metric to English or vice versa during the analysis process. Click on the “Unit” box, as shown in Figure 8, to change the units.

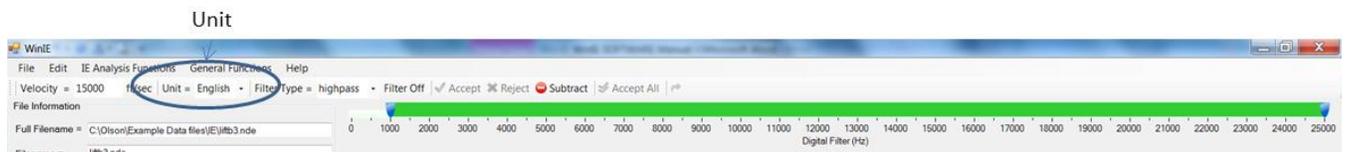


Figure 8 – Units



5.8 Next Channel

If there is more than one transducer channel, click on the “Next Channel” arrow on the toolbar to view the average spectrum for the next active channel, as shown in Figure 9. The average spectrum will be updated. The “Next Channel” button remains disabled if there is only one transducer used in the data acquisition (such as for IE-1 systems)

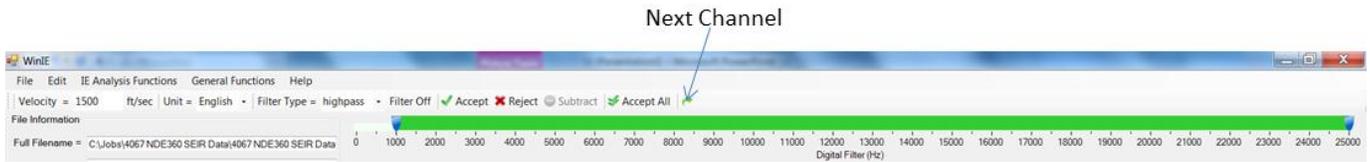


Figure 9 – Next Channel

5.9 Calibration Database

The software has a built-in database for the calibration values of the transducers. To edit the database, go to the Main Menu and select “General Functions/Enter Calibrations” and the applet, as shown in Figure 10, will appear on the screen. This applet will allow users to input new transducer calibration values into the database.



Calibrations are not applicable for displacement transducers (for IE-1). This function is only applicable for accelerometers and instrumented hammers

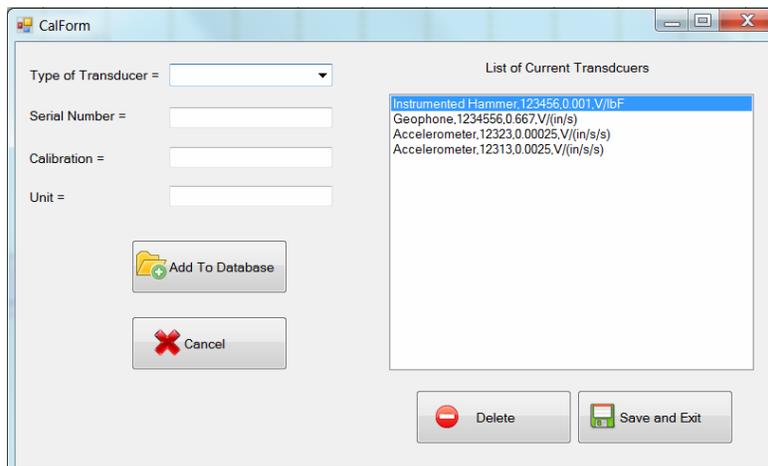


Figure 10 – Calibration Applet



5.10 Open Next Data File

If the data filenames have a fixed alphabetical prefix and are numbered sequentially in the suffix, it is possible to scroll quickly through the data. Note that this is the normal way files are saved on the NDE-360. Use the buttons “Next File” and “Prev File” to quickly open the files, as shown in Figure 11.

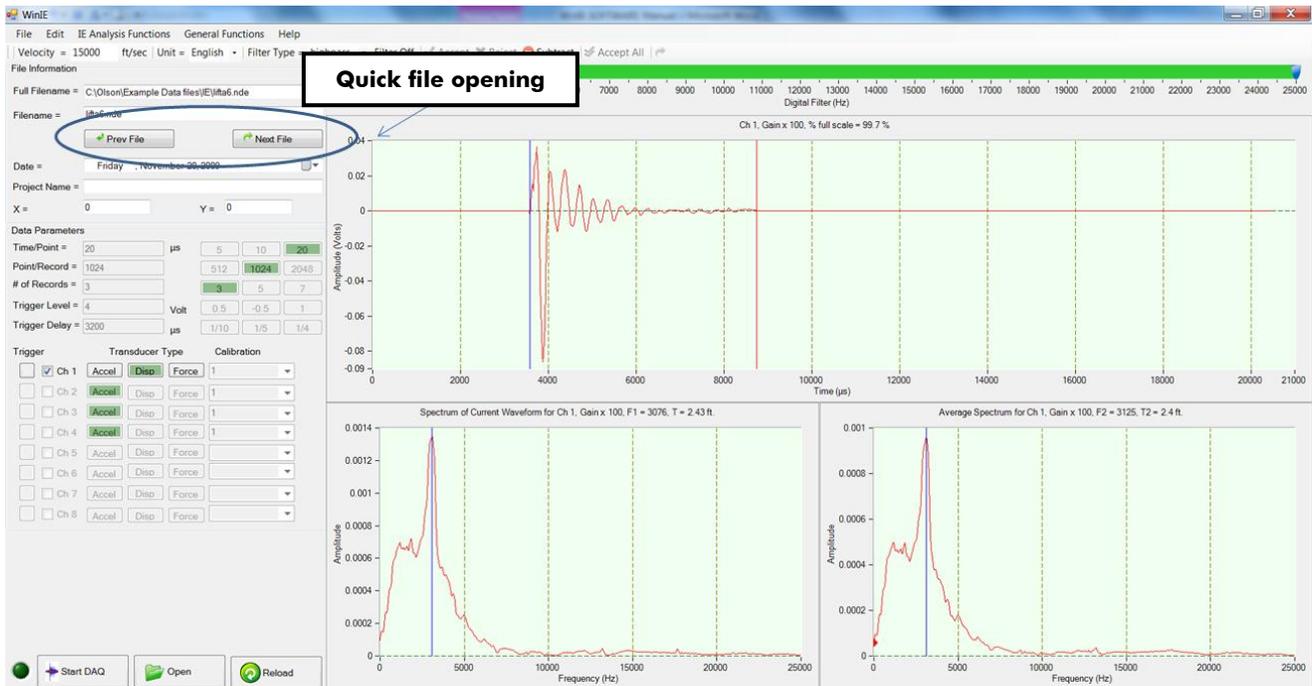


Figure 11 – Quick File Opening



6.0 WinIE SOFTWARE EXPORTING OPTIONS

6.1 Copy Image to the Clipboard

After the IE file is opened, the top and bottom two plots can be copied to the clipboard for easy pasting into reports or other documents. Go to “Edit/Copy Time Domain Plot” or “Edit/Copy Current Spectrum Plot” or “Edit/Copy Average Spectrum Plot” to copy the desired plot to the clipboard.

6.2 Save Image to .jpg

After the IE file is opened, the top and two bottom plots can be saved to .jpg format. Go to “File/Save Top Time Domain Image” or “File/Save Current Spectrum Image” or “File/Save Avg Spectrum Image” to save the desired plot in .jpg format.

6.3 Export Waveform to a Comma Separated Format

The raw waveform data can be exported to a text file readable by Excel, MatLab, or similar programs by going to the Main Menu and selecting “File/Export Raw Data to Comma Separated Format”.

6.4 Export Test Results to an Excel Spreadsheet

The WinIE software application includes an embedded Microsoft Excel spreadsheet (currently only compatible with MS Excel version 2007 or higher). To open the embedded MS Excel spreadsheet, go to “General Functions/Start Excel Spreadsheet”. The spreadsheet will be launched with a test result template. Once the software detects that the Excel spreadsheet is embedded, it will export the IE test results onto the Excel spreadsheet directly. Values that are written to the spreadsheet include F1 (the main frequency from the left bottom plot), F2 (the main frequency from the right bottom plot), F3 (an additional selected frequency from the right bottom plot), and the velocity used for analysis for every file that is processed (accepted/rejected). Using these values, the spreadsheet automatically calculates the thickness.

If MS Excel version 2007 or higher is available and the Excel worksheet is not embedded in the right panel of the WinIE software, follow these steps (for Windows 7 Operating System): Run the Microsoft Fix it # 52298 program found on the installation jump drive provided by Olson Instruments.

RELATED PEER REVIEWED PAPERS

**Sensitivity Studies of Grout Defects in Post-Tensioned Bridge Ducts using
Impact-Echo Scanning Method
(published in the Journal of Transportation Research Board, 2007)**

Word Count:

Abstract:	240
Text:	3859
Tables 2@250:	500
Figures 11@250 :	2750
Total Words:	7349

Date Submitted: August 1, 2006

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ABSTRACT

This paper presents the findings from a research project titled “Non-destructive Evaluation Method for Determination of Internal Grout Conditions inside Bridge Post-tensioning Ducts using Rolling Stress Waves for Continuous Scanning”. This project was funded by the NCHRP – IDEA Program. This paper discusses the experimental results from the studies which involved a defect sensitivity study of an Impact-Echo (IE) Scanner to detect and image discontinuities in post-tensioned ducts of a mockup U-shaped bridge girder and a mockup slab. Different sizes of ducts were included in this study as well as varying sizes of void defects. Detailed sensitivity study of non-destructive grout defect detection with Impact-Echo Scanning of 8-four inch diameter ducts with constructed defects was the main focus in this study. Comparisons of the IE defect interpretation and the actual design conditions of the ducts inside the bridge girder/slab are presented. The IE results are presented in a three-dimensional fashion using thickness surface plots to provide improved visualization and interpretation of the internal grout to void defect conditions inside the ducts of the girder. The Impact-Echo tests were performed with a Scanner which greatly facilitates the Impact-Echo test process by allowing for rapid, near continuous testing and true “scanning” capabilities to test concrete structures. The paper summarizes the general background of the Impact-Echo technique and the Impact-Echo Scanner. Descriptions of two mock-up specimens used in the experiment and the discussion of the results from the Impact-Echo Scanner are presented herein.

INTRODUCTION

Post-tensioned systems have been widely used for infrastructure bridge transportation systems since late 1950s. However if a good quality control plan is not implemented during construction, there is the potential problem during construction that the duct may not be fully grouted. This results in voids in some areas or inefficient protection for prestressing steel. Over the long term, water can enter the tendon ducts in the void areas resulting in corrosion of the tendon. The collapse of the Brickton Meadows Footbridge in Hampshire (UK) in 1967 is the first serious case of corrosion of tendons leading to major catastrophe (1). In 1985, the collapse of a precast segmental, post-tensioned bridge in Wales (Ynys-y-Gwas Bridge) was attributed to corrosion of the internal prestressing tendons at mortar joints between segments (1 and 2). Corrosion-related failures of post-tensioning tendons have been found in several major segmental bridges such as the Niles Channel Bridge near Key West, FL in 1999 and Midway Bridge near Destin, FL in 2000 (3). In addition to actual failures, corrosion damage was found in many post-tensioned bridge ducts in bridges still in use in Florida and East Coast areas (4).

In post-tensioned structures, quantifying the incidence of corrosion is further complicated by limitations in techniques for detecting corrosion. Condition surveys of post-tensioned structures are often limited to visual inspections for signs of cracking, spalling and rust stain. This limited technique may overlook corrosion activity. Corrosion damage in post-tensioned elements has been found in situation where no exterior indications of distress were apparent (4). As a matter of fact, the Ynys-y-Gwas Bridge in Wales had been inspected 6 months prior to the collapse, and no apparent signs of distress were observed (2). Examples such as this one lead some to fear that inspection based on limited exploratory or visual inspections may be unconservative and may produce a false sense of security. The X-ray method is the oldest technique applied successfully to detect unfilled ducts. However, the method suffers from many disadvantages. The first disadvantage is that the X-Ray test needs accesses to both sides of the structure, which is not usually practical in testing bridge ducts. Second, the inspection areas are relatively small and the test time relatively large resulting a slow testing process. Finally, the need for sufficient radiation protection and personnel evacuation is usually a problem. Therefore, it is important to develop a reliable method to practically inspect the quality of grout fill inside the ducts non-destructively after the grouting process is complete and for inspection of older bridges.

BACKGROUND OF THE IMPACT-ECHO TECHNIQUE

The Impact-Echo test involves dynamically exciting a concrete structure with a small mechanical impactor and measuring the reflected wave energy with a displacement transducer. The resonant echoes in the displacement responses are usually not apparent in the time domain, but are more easily identified in the frequency domain. Consequently, linear amplitude spectra of the displacement responses are calculated by performing a Fast Fourier Transform (FFT) analysis to determine the resonant echo peak frequencies in the frequency domain from the displacement transducer signals in the time domain. The relationship among the echo frequency peak f , the compression wave velocity V_p , and the echo depth D is expressed in the following equation:

$$(1) \quad D = \beta V_p / (2 * f)$$

where β is a shape factor which varies based on geometry. The value of β was found by theoretical modeling to be equal to 0.96 for a slab/wall shape (5).

Impact-Echo Scanner

The Impact-Echo rolling Scanner was first conceived by the second author of this paper and subsequently researched and developed as a part of a US Bureau of Reclamation prestressed concrete cylinder pipe integrity research project (6). This technique is based on the Impact-Echo method (5 and 7). In general, the purpose of the Impact-Echo test is usually to either locate delaminations, honeycombing or cracks parallel to the surface or to measure the thickness of concrete structures with typically one-sided access for testing (pavements, floors, retaining walls, tunnel linings, buried pipes, etc.). To expedite the Impact-Echo testing process, an Impact-Echo scanning device has been developed with a rolling transducer assembly incorporating multiple sensors, attached underneath the test unit. When the test unit is rolled across the testing surface, an opto-coupler on the central wheel keeps track of the distance. This unit is calibrated to impact and record data at intervals of nominally 25 mm (1 inch). If the concrete surface is smooth, a coupling agent between the rolling transducer and test specimen is not required. However, if the concrete surface is somewhat rough, water can be used as a couplant to attempt to improve displacement transducer contact conditions. The maximum frequency of excitation of the impactor in the scanner used in research is 25 kHz. The impactor in scanner can be replaced for an impactor that generates higher frequency. A comparison of the Impact-Echo Scanner and the point by point Impact-Echo Scanner unit is shown in Figure 1. Typical scanning time for a line of 4 m (13 ft), approximately 160 test points, is 60 seconds. In an Impact-Echo scanning line, the resolution of the scanning is about 25 mm (1 inch) between IE test points. Data analysis and visualization was achieved using Impact-Echo scanning software developed by the first author for this research project. Raw data in the frequency domain were first digitally filtered using a Butterworth filter with a band-pass range of 2 kHz to 20 kHz. Due to some rolling noise generated by the Impact-Echo Scanner, a band-stop filter was also used to remove undesired rolling noise frequency energy. Automatic and manual picks of dominant frequency were performed on each spectrum and an Impact-Echo thickness was calculated based on the selected dominant frequency. A three-dimensional plot of the condition of the tested specimens was generated by combining the calculated Impact-Echo thicknesses from each scanning line. The three-dimensional results can be presented in either color or grayscale.

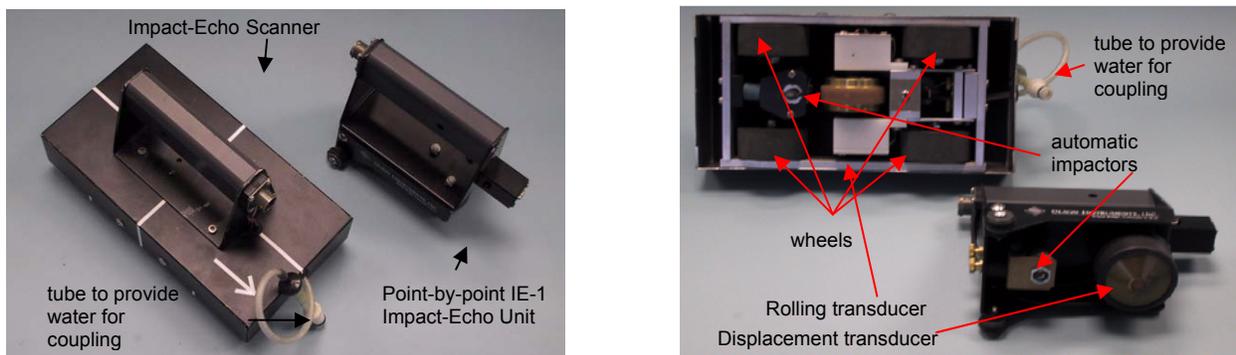


Figure 1 – Impact-Echo Scanner Unit and Point-by-Point Impact-Echo Unit

GENERAL DESCRIPTION OF THE SPECIMENS AND DEFECTS

Two mockup specimens were used in the study. The first specimen is a full scale pre-cast girder with eight steel ducts inside. The second specimen is a mockup slab located at the BAM facility in Berlin, Germany (8). Construction of the modified Styrofoam defects for the mockup girder is described in this section as well.

Description of the Mockup Girder and Constructions of Grout Defects

A full scale pre-cast bridge girder (U-shaped) was donated to the research team by EnCon Bridge Company (Denver, Colorado) for use in grout defect sensitivity studies. The length of the girder is 30.48 m (100 ft) with a typical wall thickness of 254 mm (10 in). There were four empty metal ducts (101.6 mm or 4 inches in diameter) inside each wall (Figure 2). The west end of the girder (6.1 m or 20 ft long) was selected for this study.



Figure 2 – U-Shaped Bridge Girder with Eight Empty Ducts - West End View

Stepped and tapered Styrofoam rods (101.6 mm or 4 inches in diameter) were inserted into the ducts before grouting to form internal voids with sizes ranging from small to almost full diameter voids. Figure 3 shows a Styrofoam rod being inserted into the top duct of the north wall. A wire (3 mm or 1/8 inch in diameter) was bent to form a leg for the Styrofoam rod so that the foam would be positioned on the roof of the duct, which simulates the real world grout defects formed by air and water voids. Smaller defects were glued directly to the roof of the duct since they were too thin for the wire leg. Figure 3 also shows the front view of a Styrofoam defect inside a duct. The defect sizes are presented in Table 1 in terms of their circumferential perimeter and duct depth lost. The defect designs are shown in Figure 4a for all four ducts in the South web wall and Figure 4b for all four ducts in the North web wall. The actual percentage of circumferential perimeter and diameter depth lost due to the defect are shown in the underlined numbers placed directly above the defects in Figures 4a and 4b.

Table 1 – Styrofoam Defect Sizes

Defect ID	Circumferential Lost (mm, in)	Depth Lost (mm, in)	Percentage Lost in Circumferential Perimeter (%)	Percentage Lost in Depth (%)
1	50.8, 2	6.35, 0.25	16	6
2	77.2, 3	13.6, 0.535	24	13
3	101.6, 4	23.4, 0.92	32	23
4	127, 5	34.8, 1.37	40	34
5	159.5, 6.28	50.8, 2	50	50
6	192.3, 7.57	66.8, 2.63	60	66
7	217.7, 8.57	78.2, 3.08	68	77
8	243.1, 9.57	87.9, 3.46	76	87
9	268.5, 10.57	95.2, 3.75	84	94



Figure 3 – Styrofoam supported by wire rod (left), the foam rod being inserted into the duct to form voids (center) and view of Styrofoam defect inside a duct (right)

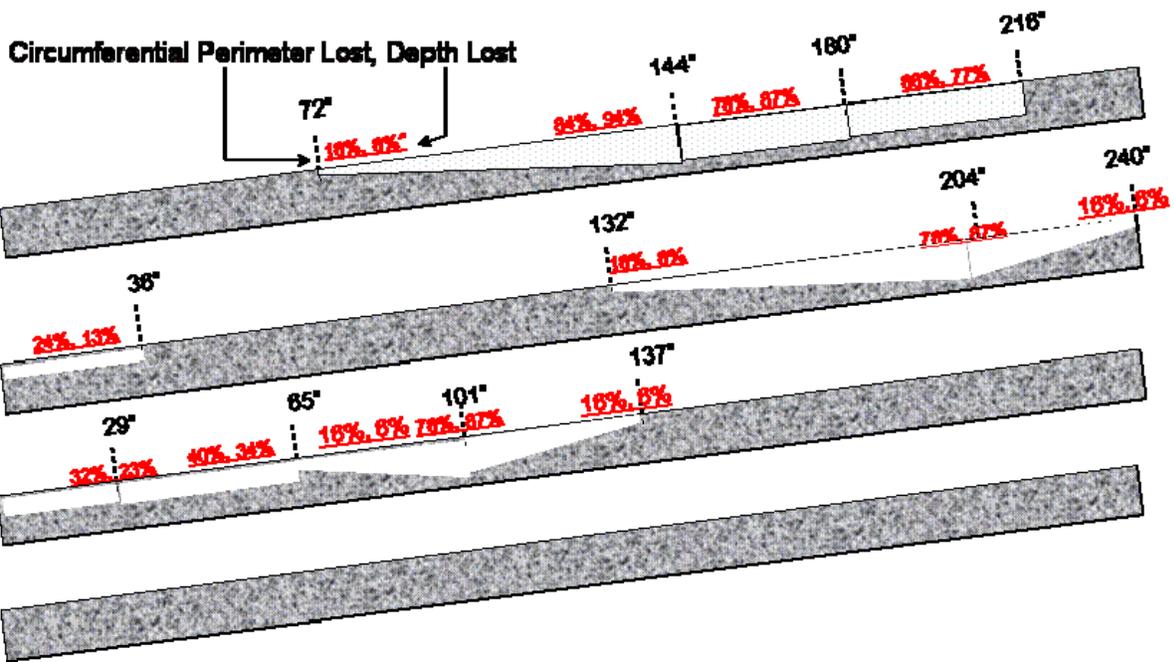


Figure 4a – Design Grout Defects (Styrofoam Voids) in the South Wall in 101.6 mm (4 inch) Metal Ducts from top down

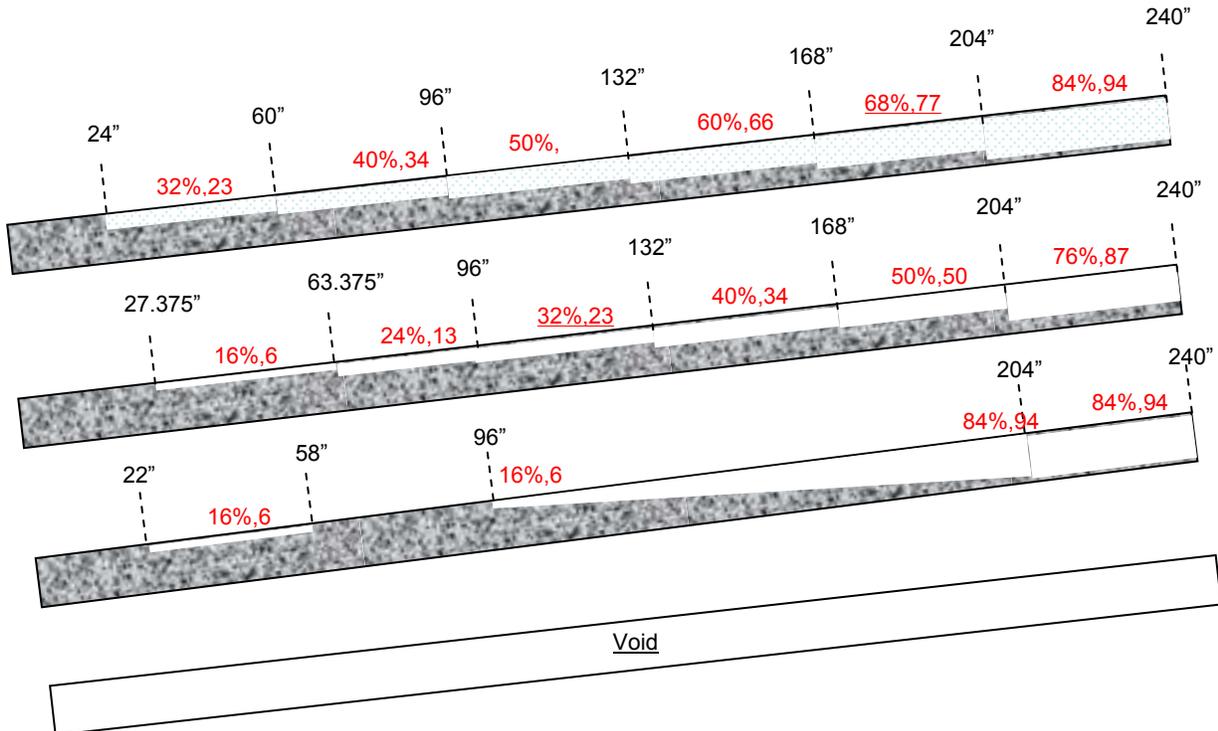


Figure 4b – Design Grout Defects (Styrofoam Voids) in the North Wall in 101.6 mm (4 inch) Metal Ducts from top down.

Figure 4 – Design Grout Defects

Description of the Mockup Slab and Grout Defects

A mockup concrete slab was designed and constructed at the BAM main campus in Berlin, Germany in 2002 (8). The concrete slab covers an area of 32.8 x 13.1 ft² (10 x 4 m²) with a nominal thickness of 11.8 inches (300 mm). The large dimensions of the specimen are necessary to minimize boundary effects on the measured signals and to establish well-defined defects without interference between them.

The concrete slab contains tendon ducts with varying diameters and grouting defects and different amounts of post-tension wire strand cables. The slab contains eleven tendon ducts with well defined grouting defects. The metal ducts were chosen and positioned to represent typical testing situations as they are encountered in structures. Because of the difficult testing problem, test situations were created without introducing crossing ducts.

Tendons with the following properties were built in:

- Diameter: 40, 80, 100, and 120 mm (1.57, 3.15, 3.94, and 4.72 inches)
- Concrete Cover: 70, 80, 100, 110, 115, 140, 170, 190 mm (2.75, 3.15, 3.94, 4.33, 4.52, 5.5, 6.7, 7.5 inches) and one sloped duct 50 – 160 mm (1.96 – 6.3 inches) deep
- Size and location of grouting defects: the size of each of the grouting defects is at least 200 mm (7.9 inches) in length and represents either a fully ungrouted section (void) or a half-filled duct. (The exact position of the defects is not revealed to the public herein in order for others to be able to perform future blind tests.)
- Varying numbers and position of wire strand cables (individual diameters of 0.6 inch) in the tendon ducts.

EXPERIMENTAL IE SCANNER RESULTS FROM THE MOCKUP GIRDER

Interpretation of Impact-Echo Data

Localization of grouting discontinuities through Impact-Echo in the mockup girder was based on an analysis of variations in the Impact-Echo thickness echo depth/frequency. A direct echo from the void or duct wall, measured as an Impact-Echo frequency corresponding to the depth of the discontinuity (given by the formula in equation (1) above) has not yet been observed with the IE Scanner. However, as previously found by others, the IE results indicate the presence of well-grouted, filled tendon ducts by a nil to minor increase in apparent wall thickness over a grouted duct (typically on the order of 12.7 mm or 0.5 inches or less but larger in the research due to the 3 day age of the comparatively weak grout versus the hardened, mature concrete). Grouting defects (Styrofoam voids) inside the ducts cause a more significant increase of the apparent wall thickness in IE results as presented herein vs. well-grouted ducts). This is in accordance with the interpretation of the Impact-Echo signal as a resonance effect, rather than a reflection of a localized acoustical wave, i.e., the void may be simply thought of as a hole in the web wall that due to decreased section stiffness causes a reduction in the resonant IE echo frequency and a corresponding increase in thickness.

Discussion of Impact-Echo Results

The Impact-Echo tests were performed using a rolling IE Scanner at 1, 3 and 8 days of grout age after the duct grouting process was completed by Restruction Corporation of Sedalia, Colorado. This paper presents results from the South and North walls for testing conducted 3 days after the grouting of the ducts was completed. Ultrasonic Pulse Velocity tests were performed on a sample of the grout placed on-site in a 406.4 mm (16 in) long duct section. The grout velocity at 3 days old was 11,400 ft/sec, indicative of solid grout but about 25 % slower than the velocity of the mature, hardened web wall concrete. The results from the IE scanning of the South wall are presented in a thickness tomogram fashion as shown in Figures 5– 7 from the South wall and in a normalized thickness tomogram as shown in Figures 8 - 10 from the North wall. Figures 5 – 10 all show the experimental results compared with the actual defect designs of the ducts. The drawing of the actual defect design is placed above the experimental results of the duct for comparison purposes.

South Wall – Top Duct: The IE Scanner results from the South Wall with the actual defect design of the top duct placed above the IE results of the top duct are shown in Figure 5. The results are interpreted to indicate that the grout defect started to appear at a length of 1.93 m (76 in) and becomes clearly evident at length of 2.92 m (115 in) from the west end of the duct. The location that the defect starts to appear corresponds to void with 11% depth lost or 20% circumferential perimeter lost. The location that the grout defect become more evident corresponds to void with 59% depth lost or 57% circumferential contact diameter lost. The dominant frequency of the fully grouted duct is approximately 6.4 kHz, resulting in an apparent Impact-Echo thickness of 28.37 mm (11.17 in.). The dominant frequency shifted downward to approximately 5.37 kHz for an empty duct, which corresponds to an apparent Impact-Echo thickness of 340 mm (13.4 in). This is a relatively large thickness shift of over 30% compared to the nominal thickness of the wall. The interpretation of the Impact-Echo Scanner results, however, shows a downshift in frequencies from lengths of 5.49 to 6.1 m (216 to 240 in), indicating voids at duct locations where no discontinuities were intentionally placed. It is likely that grout did not flow into the higher east duct end due to the big voids in front of it. Radiographic tests will be performed in the future to verify the design versus actual conditions of the simulated defects.

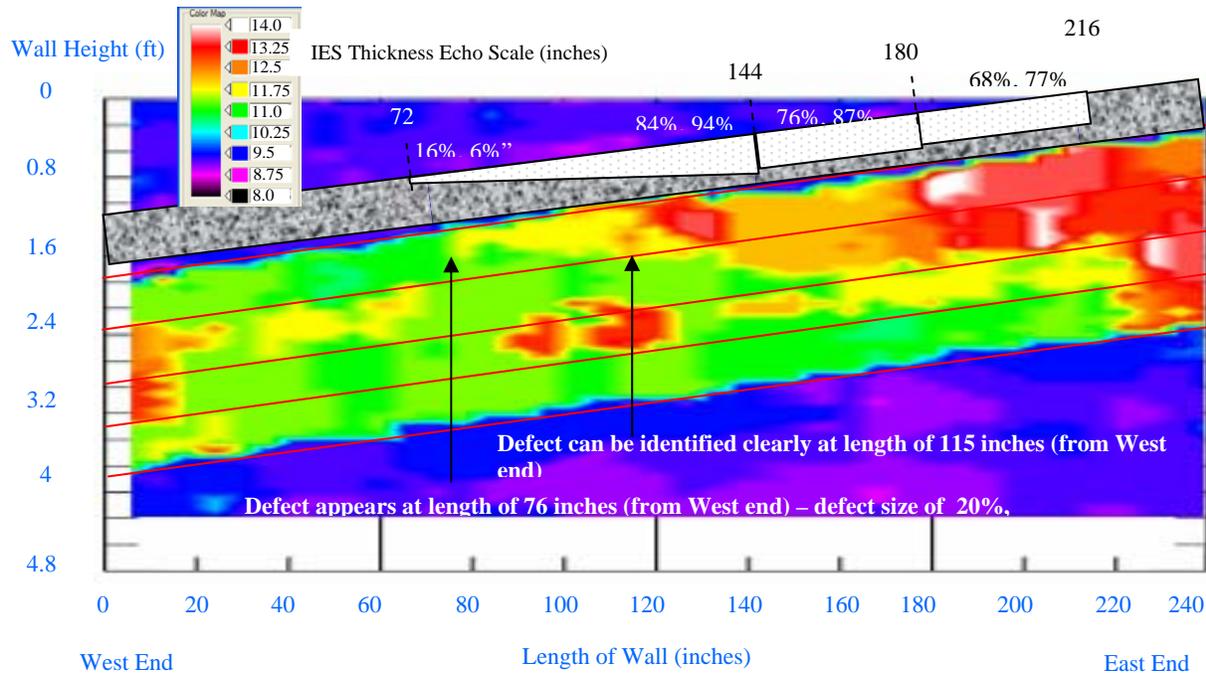


Figure 5 – IE Results from the South Wall with Actual Design Defects of Top Duct

South Wall – Second Duct from Top: Review of Figure 6 shows that there are three grout defect zones. The first grout defect zone correlates with the end defect (13% depth lost or 24% circumferential lost). The second defect zone shows minor grout problem from lengths of 0.91 – 1.67 m (36 – 66 in) from the west end of the duct. However, there is no actual defect placed in this area. Radiography is required to confirm the realization of defect designs. The third defect zone appears at a length of 3.35 m (132 in) which corresponds to defect of 9% in depth lost or 18.5% in circumferential lost. The most apparent grout defect appears at a length of 5.18 m (204 in) corresponding to the location of the largest Styrofoam in the duct (87% depth lost or 76% circumferential perimeter lost). Similar to the results from the top duct, the interpretation of the Impact-Echo Scanner results, however, shows a downshift in frequencies from lengths of 5.18 to 6.1 m (204 to 240 in), indicating major voids at duct locations where actual defect shape tapers down toward the east end. It is likely that grout did not flow into the east end due to the large voids in front of it.

South Wall – Third Duct from Top: Figure 7 shows three zones of grout defects. The first area is located at the west end where Styrofoam Defect ID# 3 (see Table 1) is in place. However, the IE results show that the duct is fully grouted between lengths of 0.45 – 2.13 m (18 – 84 in) from the west end where there are actual Styrofoam defects placed in these locations. The grout defect appears again between lengths of 2.13 – 3.2 m (84 – 126 in). The starting location of the second defect zone corresponds to actual defect of 49% depth lost or 48% circumferential lost. The end location of the defect zone corresponds to actual defect of 30% depth lost or 34% circumferential lost. The interpretation of the Impact-Echo Scanner results, however, shows a downshift in frequencies from lengths of 3.48 – 6.1 m (137 to 240 in), indicating minor to major voids at duct locations where no actual Styrofoam defect in place. Radiography is required to confirm the actual location of Styrofoam voids.

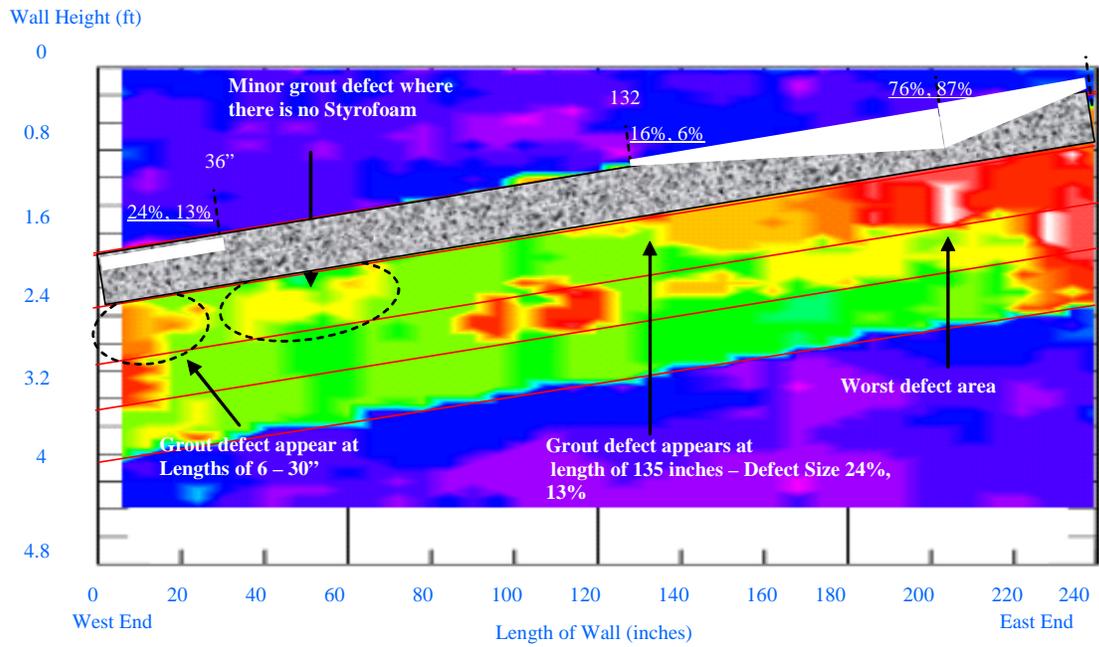


Figure 6 – IE Results from the South Wall with Actual Design Defects of Second Duct

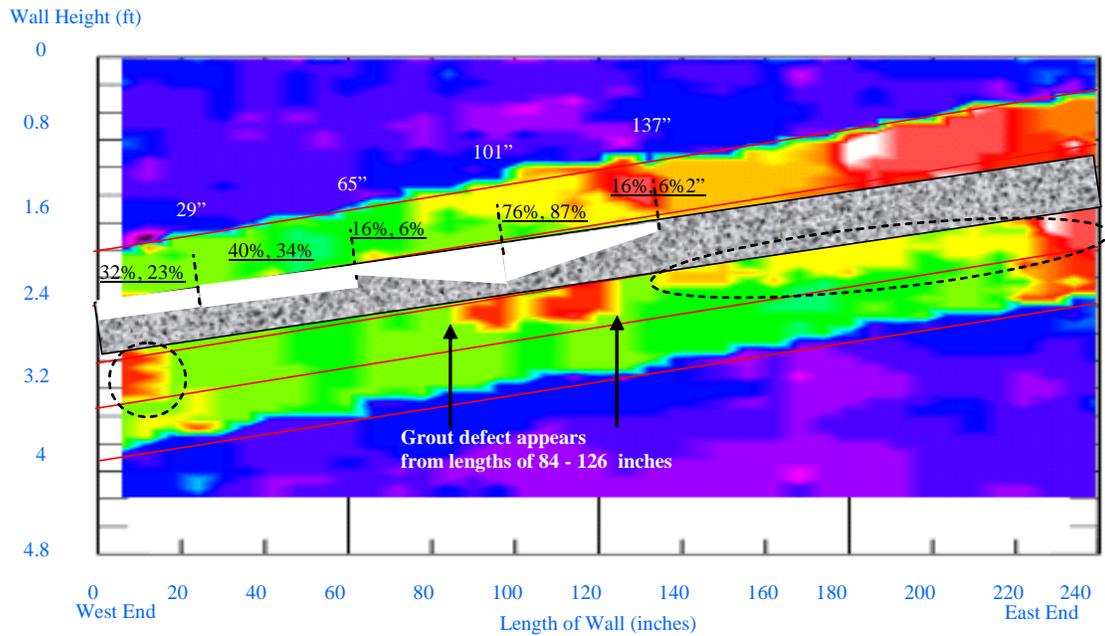


Figure 7 – IE Results from the South Wall with Actual Design Defects of Third Duct

Experimental Results from the North Wall

North Wall – Top Duct: The IE results from the North Wall with the actual defect design of the top duct placed above the IE results of the top duct are shown in Figure 8. Several pieces of stepped Styrofoam were inserted inside this duct ranging from depth lost of 23% to 94% or circumferential lost of 32% to 84%. All the results from four ducts from the North wall are presented with normalized thickness tomogram. The results are interpreted to indicate that the grout defect started to appear at the west end of the girder although there was not Styrofoam inside the duct for the first 6.10 m (24 inches) from the west end. However, visual inspection indicated there was honeycomb around the top duct of the north wall. Figure 8 showed that the IE test was able to detect the grout defect of 23% depth lost or 32% circumferential lost. The location that the grout defect is more evident corresponds to void with 50% depth and 50% circumferential contact diameter lost.

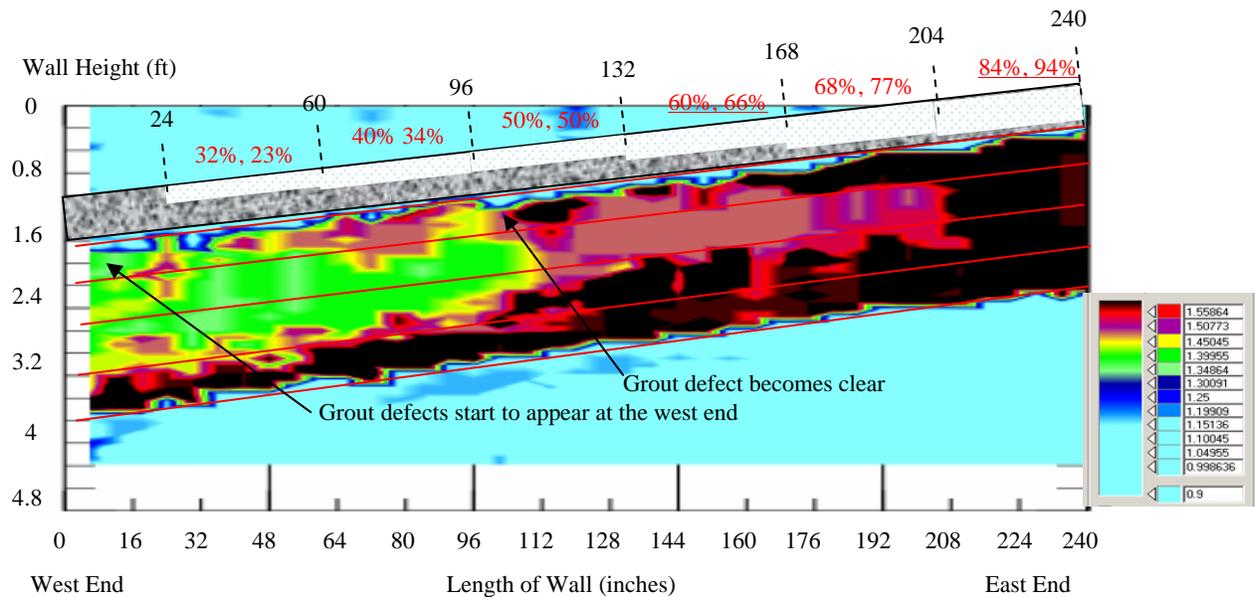


Figure 8 - IE Results from the North Wall with Actual Design Defects of Top Duct and the Normalized Thickness Scale

North Wall – Second Duct from Top: Several pieces of stepped Styrofoam were inserted inside this duct ranging from depth lost of 6% to 87% or circumferential lost of 16% to 76%. Review of Figure 9 shows that the grout defect started to appear at a length of 1.62 m (64 in) from the west end of the girder. This length corresponds with location with voids of 13% lost in depth or 24% circumferential lost.

North Wall - Review of Figure 10 shows that the grout defect started to appear at a length of 2.59 m (102") from the west end of the girder. This location corresponds to void of 11% depth lost or 19% circumferential lost. In this case, the grout defect appear to be apparent (full depth void) right at a length of 3.35 m (132 in) from the west end. This location corresponds to void of 35% depth lost or 39% circumferential lost.

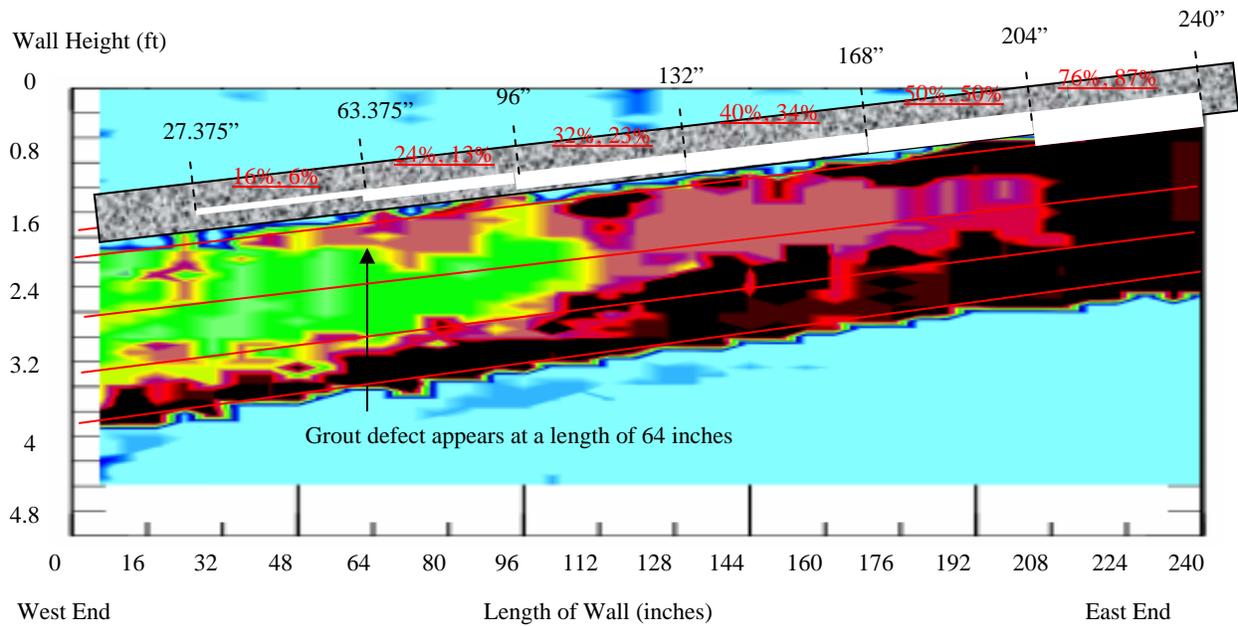


Figure 9 – IE Results from the North Wall with the Actual Design Defects of the Second Duct

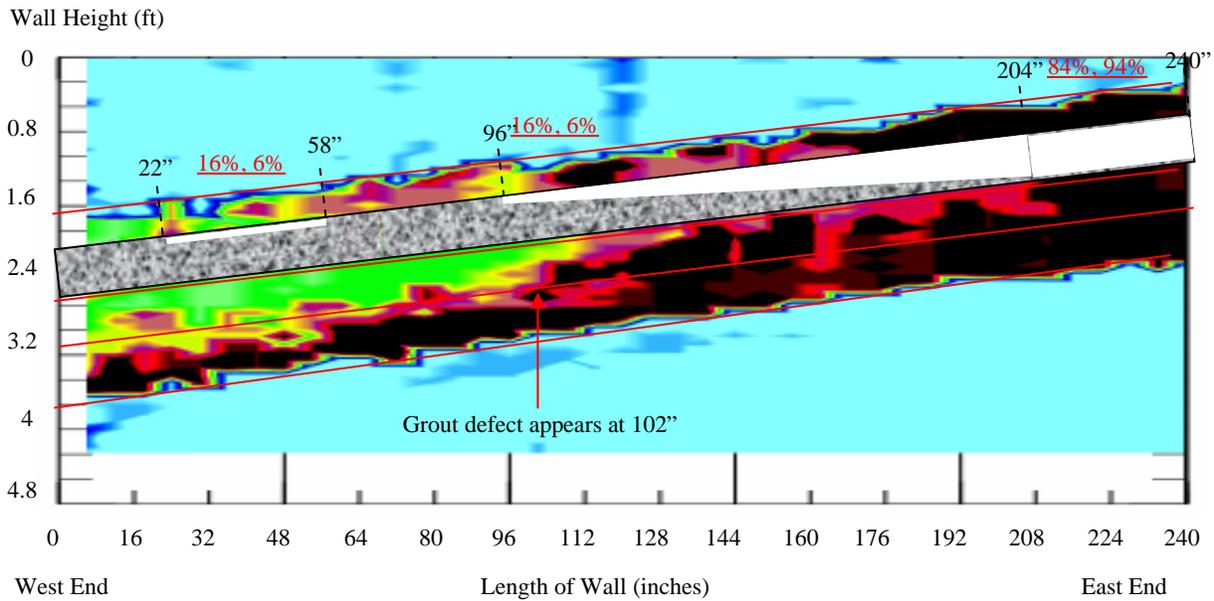


Figure 10 – IE Results from the North Wall with the Actual Design Defects of the Third Duct

EXPERIMENTAL IE SCANNER RESULTS FROM THE MOCKUP SLAB

An IE scanner was used on the mockup slab to perform the Impact-Echo Scanning. The tests were performed every 50 mm in a line fashion parallel to the direction of the ducts across the 13 ft (4 m) wide slab. A total of 200 scan lines was performed on this specimen. This paper includes data interpretation from only one duct from the slab. A zoomed-in 3D surface plot of the IES thickness result

from a duct and its actual defect design are presented in Figure 11. The diameter of Duct A is 120 mm or 4.72 inches with concrete cover of 70 mm or 2.76 inches. Figure 11 shows a 3D surface plot of the IE thickness from Duct A in the top picture. The middle picture in Figure 11 shows an interpretation of the IE results in the top picture and the bottom picture in Figure 11 is the actual defect design. Reviews of Figure 11 show half diameter grout void (Defect A) was detected and complete grout voids (Defects B and C) were also detected. However, the IE test result shows more defects than the actual defect design. The IE result shows grout defects toward the right end of the duct where grout defects were not intended to be at the location. This may be due to local debonding between the grout and metal duct at that location. In addition, the IE results cannot identify the difference between the silicone contamination (simulates debonding) and actual grout defects.

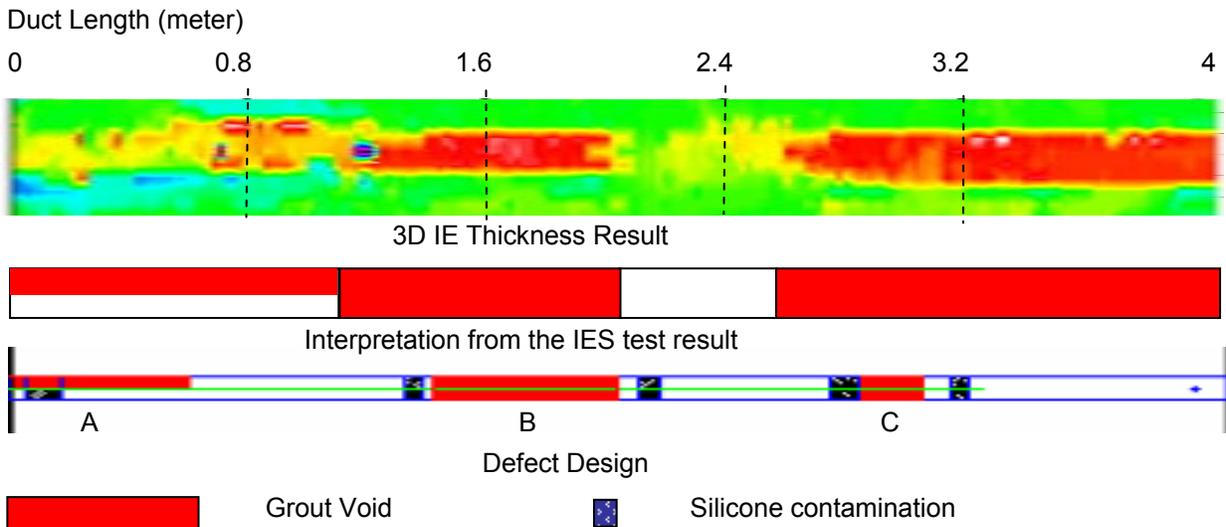


Figure 11 – Comparison of IES Test Results (and its interpretation) and the Actual Defect Design – Duct A

Results from the Sensitivity Studies in the Mockup Slab

Table II summarizes the grout defect size that can be detected in ducts of different diameters and concrete covers.

Table II – Impact-Echo Scanning Duct Void Sensitivity Study Results from the BAM Mockup Slab (Maximum Frequency Generated by the Excitation = 25 kHz)

Duct Diameter (inches)	Cover (inches)	Half Size Void Detected	Full Size Void Detected
4.72	2.76	Yes	Yes
3.94	3.15	Yes	Yes
3.15	3.94	No	Yes
3.15	5.5	No	No
3.15	6.7	No	Yes/No
2.36	3.94	No	Yes
1.57	4.33	No	Yes
1.57	6.7	Yes	Yes
1.57	7.48	No	No
1.57	1.97 - 6.3	No	Yes

SUMMARY

The results from the IE tests using portable rolling IE Scanner system show good agreement with the actual defect design. In the IE testing by the authors to date, the clearest indication of the presence of grouting defects is the apparent increase in the thickness due to a reduction in the IE resonant frequency as a result of the decrease in stiffness associated with a defect. No direct “reflection” from the ducts with grouting defects was observed in these experiments. This is because of larger wavelength generated by the impactor inside the Impact-Echo Scanner. In this study, with the help of 3D visualization, the IE scanning was able to identify voids as small as 9% depth lost or 20% circumferential diameter lost of a 101.6 mm or 4 inch diameter steel duct. Areas of disagreement between planned voids and IE results need to be investigated to determine the cause with X-ray radiography in the future. Studies from the mockup slab shows that half size and full size voids can be detected with the IE tests in 4.72 and 3.94 inches in diameter. Only full size voids can be detected inside ducts with a diameter of 3.15 inches. However, once the concrete cover is 5.5 inches and higher, the IE results become intermittent and unreliable. In summary, it is easier to detect grout defect in ducts with bigger diameters. In addition, the deeper the duct is inside the concrete, the harder it is to detect grout defects with the IE tests.

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