SYSTEM REFERENCE MANUAL 2008

IMPACT ECHO TEST
NDE-360

NDE-360 Platform with WinTFS Software Version 2.3

NOTICES

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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.

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

The NDE-360 system with the IE test consists of several basic components. These 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. Details of the hardware and its usage are included in Section 2.0.

The Windows WinTFS 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. Also included at the end of the manual is a troubleshooting guide for the system to help overcome any problems experienced or answer any questions. 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, and dams. 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. In addition, the IE method will 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 manufacturers an IE Scanner, which can record data at 1 to 2 inch increments for an entire scan path. IE Scanning is used in locating post-tensioning (PT) cables used in reinforcing various structures and determining duct grout condition. The scanning technology allows tracing of the PT cables 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 provides the thickness of an unknown concrete member.

The IE tests involved 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 a displacement transducer are built in the IE head.   The test head was pressed against the top of the tested member and held while tests were 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. Consequently, 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:

$$D = \beta V_p/(2*f) \hspace{3cm} (1)$$

where β is a geometric shape factor equal to 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.

Olson Instruments Echo Test Head incorporating source and receiver

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, power supply, battery charger, accelerometer, hammer, 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
 3) IE Cable	1	To connect the IE head and the NDE-360

| Component Name	QTY	Description
 4) Power Supply	1	Power supply for the NDE-360 platform.
 5) Charger	1	Battery charger must be connected to the power supply on one end and the NDE-360 on the other end
 6) Card Reader and Compact Flash Card	1	To transfer the IE data files to the analysis computer

2.2   Basic Components and Maintenance of NDE-360 Platform

Battery Charging: The power supply (Item 4) must be plugged into the charger (Item 5) only. Then the charger (Item 5) must be connected to the NDE-360 system.

> **Time required for a fully charge of battery is 8 hours.   Fully charged battery will power the NDE-360 system for 8 – 10 hours.**

Location of Battery: The panel housing the battery is located on the back of the NDE-360 system. Move the switch to remove the battery cover if battery needs to be replaced.
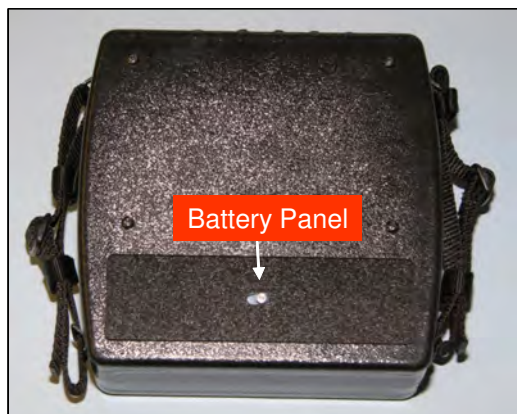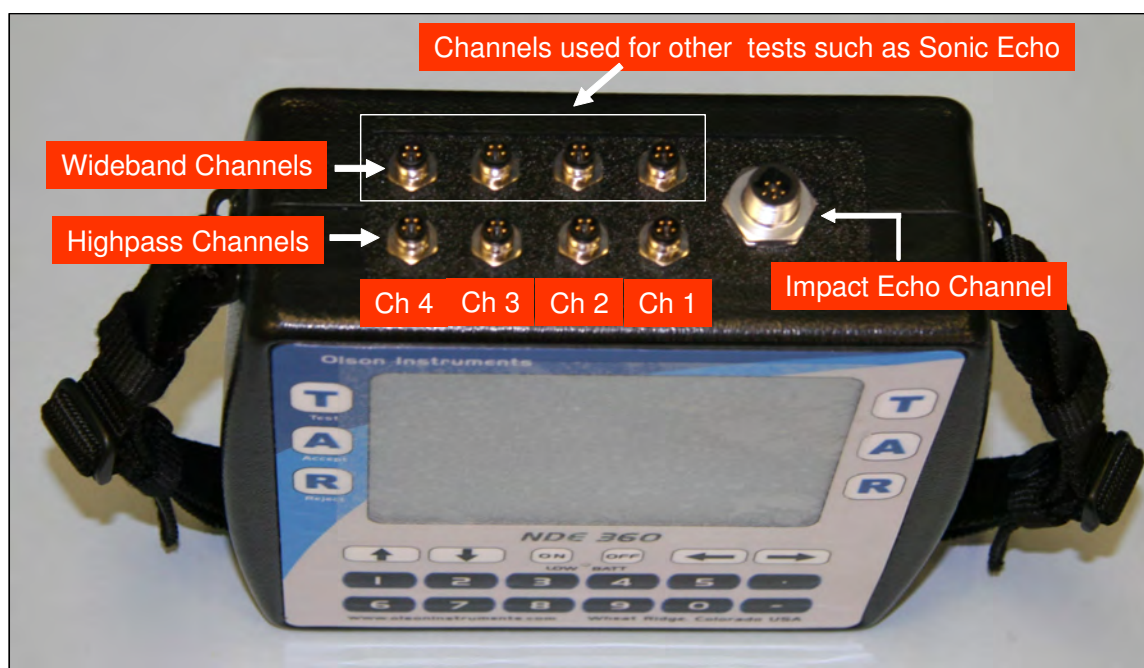
Do not expose the NDE-360 system or the battery to water.

Channel Arrangement: The NDE-360 system is equipped with 4 channels. There are two 4 pin connectors per each channel. Channel 1 is located on the right hand side if facing the front screen of the NDE-360 system. In this case, the IE test uses the Impact Echo Channel. Thus four 4 pins channel will not be used for the IE test.


Channels used for other tests such as Sonic Echo

Wideband Channels

Highpass Channels

Ch 4 Ch 3 Ch 2 Ch 1

Impact Echo Channel

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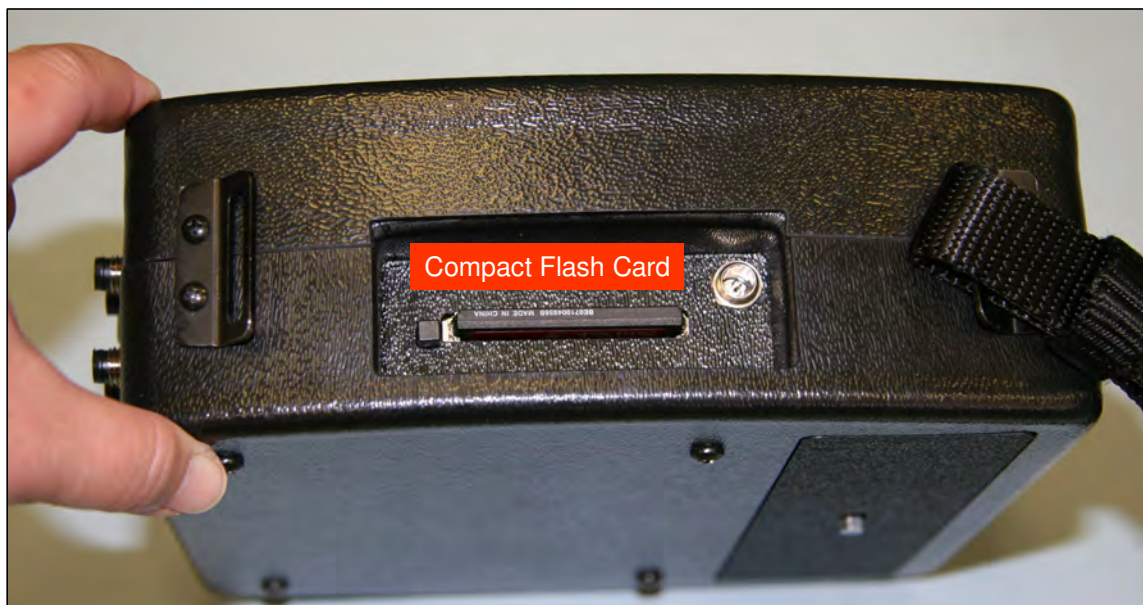
Compact Flash Card

If the compact flash card is missing from the system, the system will not allow the test to continue. Do not 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 was designed to make it user friendly and easy to handle and operate by a single operator. The main screen can be navigated using a touch screen feature.

Never impact the screen with any sharp object!

2.3 Hardware Setup

1. Connect the cable (Item 3) to the IE head (Item 2) by aligning the pin on the cable with the corresponding hole in the IE head

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

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

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.

3.0 IE DATA ACQUISITION

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 in 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.

Press on this button to continue

Press on this button to turn on the system
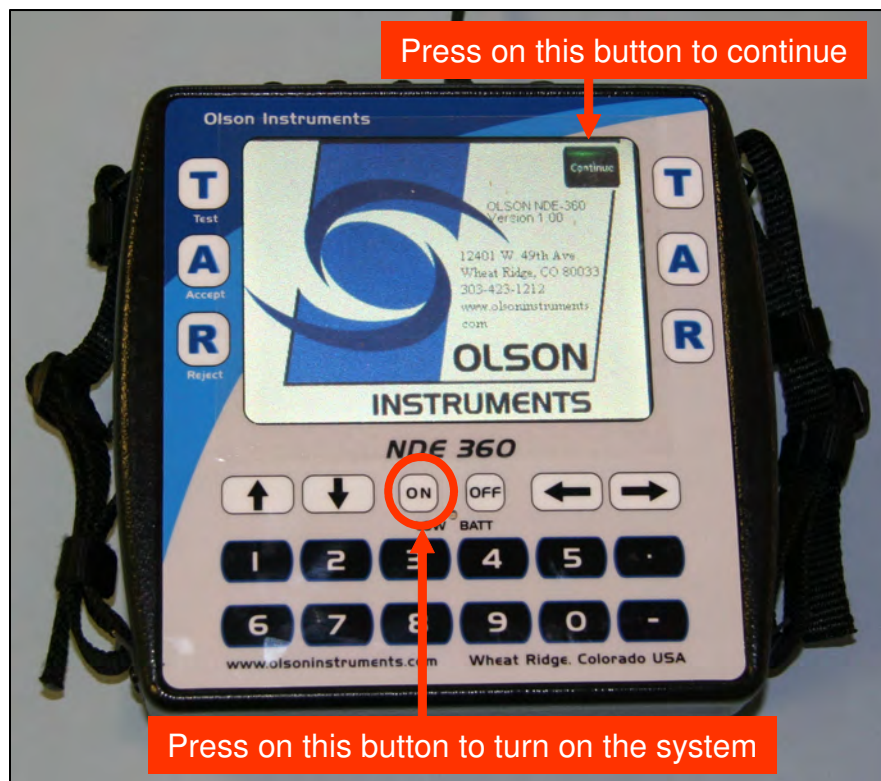
> If the continue button disappears from the screen, turn off the system and insert the compact flash card in place and turn the system on again.

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

3.   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 of the IE test. However, if higher gain is required, simply press on the + button of the gain for Ch 1.

4.   The system is loaded with a default parameter that is applicable for most of the IE tests. However, if the parameters need to be adjusted, press the Param buttom. 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 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 20 microseconds. This means the system will acquire data at 20 microsecond intervals. This parameter can not be changed after the data was 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 was 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.

- **# Recs.** Number of Record is a total number of IE data records you want to save. This parameter can not be changed after the data was taken.
- **Pre-Trigger** is number of points before the triggering point that data collection starts. This parameter must be 0 for the IE test. This parameter can not be changed after the data was taken.
- **Trigger Level %** is the minimum signal amplitude (in terms of percentage full scale) to trigger data acquisition. In this case, the trigger level was set at 6%. Therefore, the system will start acquiring data once the absolute amplitude of the signal exceeds 0.6 volt. This parameter can not be changed after the data was taken.
- **Channel Setup.** For the IE test, only one channel (connected to the IE head) will be used. Ch 1 must be turned on for the IE test and this cannot be changed.
- **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 12 us. However, this value may need to be higher for the underside or underwater testing.

5. The filename arrangement of the NDE-360 uses a fixed prefix of letters and a suffix of number. 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.
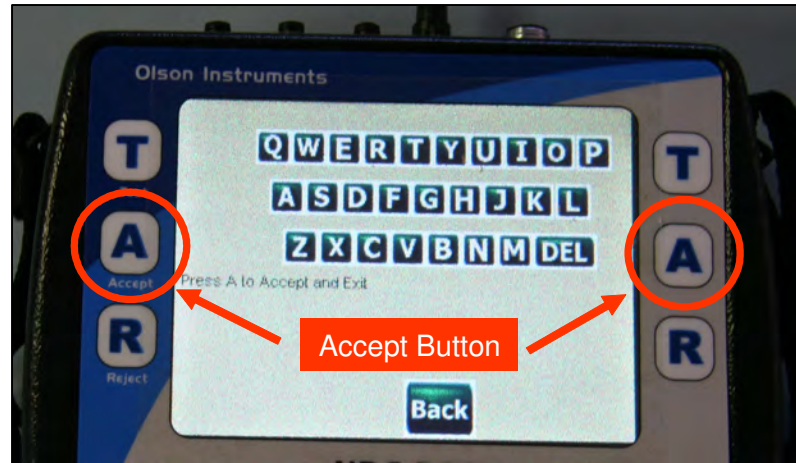
6. After the parameter setup is complete press the "Back" button to return. Now the system is ready to take the IE data. Push the IE test head on the tested member and press "Test" button to acquire the IE data.

7. If the solenoid mode is on, the NDE-360 system will 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 (or accelerometer). The screen below shows the spectrum of the time domain data acquired from a 5 in concrete cylinder. Press "A" button

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 7 – 9.
11. The data can be recalled in the NDE-360 system by pressing the "File" button on the main screen and then select Option 2.
12. The data files on the compact flash card can be moved to the analysis computer for post-data analysis.

4.0   WinTFS Software

This section covers step-by-step instructions for post data analysis and output generation for the Windows WinTFS software.

4.1   WinTFS Software Installation

1. Prerequisite software (NIDAQ version 7.4 or higher) prior to installing the WinTFS software is required. The NIDAQ drivers can be located in the enclosed CD or downloaded at:

   http://joule.ni.com/nidu/cds/view/p/id/319/lang/en

   If retrieving files from the web, download the file named NIDAQmx8.1.ZIP.   Unzip the file and install the NIDAQ program. Note that an account (free of charge) may be required to proceed to the download page.

> **Failing to install the prerequisites will result in an error when running the WinTFS software**

2. Uninstall the previous version or delete "c:\program files\olsoninstruments\WinTFS\WinTFS.exe" if the older file exists
3. Run "Setup.exe" from the Olson Instruments install CD
4. Follow the default setup
5. After finishing the installation, the "WinTFS.exe" file will be found on: drive C:\Program Files\Olson Instruments\WinTFS\ . The shortcut to the WinTFS.exe can be located on the desktop/

> **Failing to uninstall the previous version of the WinTFS software will prevent the installation of the new version**

4.2   Software Updates

For updates to software, the only file that is necessary is the WinTFS.exe file. This file must be copied into the C:\Program Files\Olson Instruments\WinTFS directory. If not, the shortcut on the desktop references the old version of WinTFS. Simply replace the existing WinTFS.exe by copying and pasting the new version into the directory.

4.3   Software Uninstallation

The followings are steps to uninstall the WinTFS Software
1.   Click on Start/Settings/Control Panel

2.   Select "Add/Remove Programs"
3.   Highlight WinTFS, select "Remove"
4.   The uninstall process will begin automatically, removing all installed components including the shortcut.

4.4   First Time Executing the WinTFS Software

If the WinTFS software is executed for the first time, the program detects missing software key (OlsonWinTFSKey.dat). The program will display a warning that the software key file is missing and will only enable two options on the main menu. Select the "Software Key" button and then enter the software key attached to the case of the installation disk. Exit the software and restart the software.

Now the software will detect missing parameter file and then will automatically generate a default file. The user will notice an applet shown below for the type of acquisition card. Select "No data Acquisition Card" option to continue.
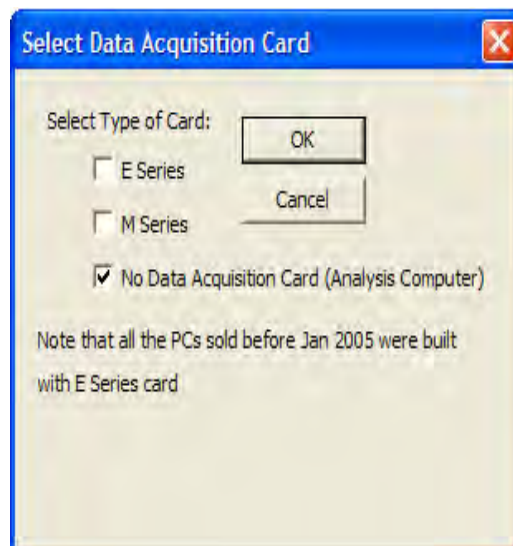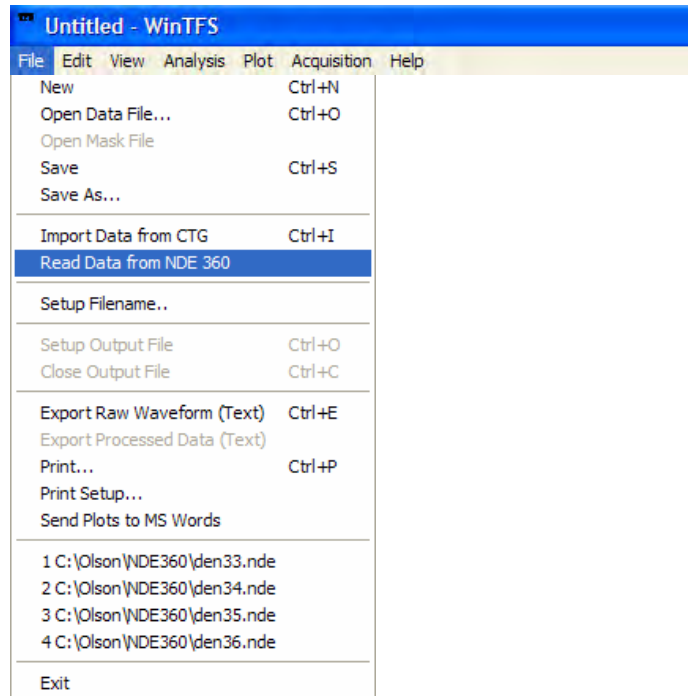
4.5   Data Analysis

1.   Read the Data file: To read the data file, go to File/Read Data from NDE-360 and select the filename to analyze.

2.   Accept or Reject Data: The IE time domain raw data will appear on the top trace of the plot. The second trace shows a spectrum of the data from the top trace. The third trace shows a spectrum from an average of data. Click on "Accept" or "Reject" button to either include or exclude the current record on the screen.
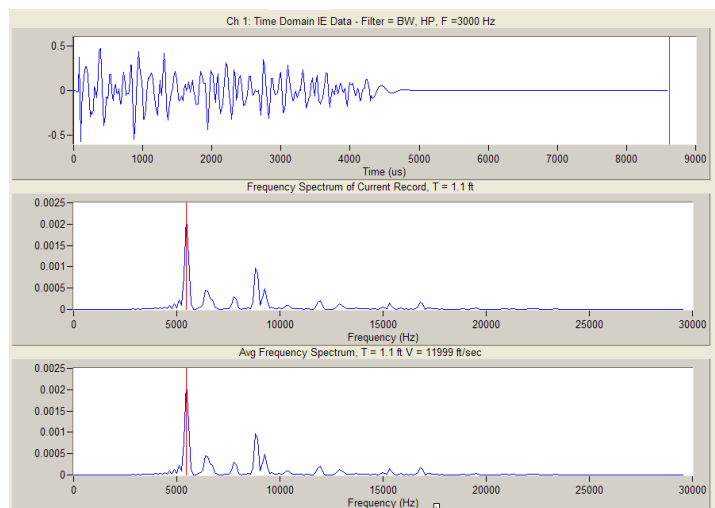
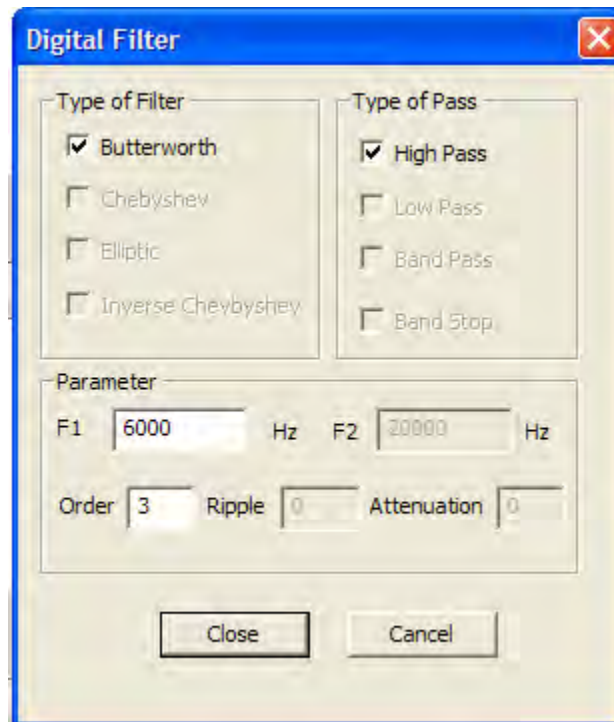3. Filter Function: In most of the cases, filtering is required for the IE data. Go to Analysis/Digital Filter Function or press F4 to set the desired filter. The dialog box below will appear on your screen. There are four options for digital filtering; Butterworth, Chevbyshev, Elliptic and Inverse Chevbyshev. Digital filter will be applied to all the data. To disable filtering, simply leave all the filter options unclicked.

Digital Filter

Type of Filter
- ☑ Butterworth
- ☐ Chebyshev
- ☐ Elliptic
- ☐ Inverse Chevbyshev

Type of Pass
- ☑ High Pass
- ☐ Low Pass
- ☐ Band Pass
- ☐ Band Stop

Parameter

F1 [6000] Hz   F2 [20000] Hz

Order [3]   Ripple [0]   Attenuation [0]

[Close]   [Cancel]

Common filter used for the IE data is Butterworth (Highpass)

4. Concrete Velocity: The next important aspect in the IE analysis is the velocity setting. To access the velocity being used to calculate the thickness, simply click on Analysis/Change Velocity. The IE velocity of the tested structure should be set correctly in order for the program to calculate the echo depth of the foundation accurately.

**Enter Correct Velocity**

Velocity = [12500] [ft/sec ▼]

[OK]
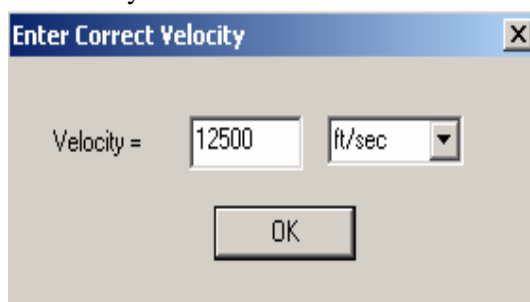
Typical concrete velocity is 12,000 – 13,000 ft/sec or 3,658 – 3,962 m/s. Higher strength concrete may have higher velocity. Young concrete (less than 7 days old) may have slower velocity.

5. Pick the frequency echo: At this point, the data can be analyzed. The software automatically detects the dominant peak, place a cursor on the dominant peak and calculate the corresponding thickness. However, the user can manually pick the frequency peak by placing the cursor on the frequency and the software will automatically calculate the corresponding thickness.

6. Open the next IE data File: For speedy data recall, simply click on the +/- button to open the next data file.

7. Data Export: The plots can be sent to MS Word for print out. Go to File/Send Plots to MS Word. Then setup the orientation and figure number and click the OK button.
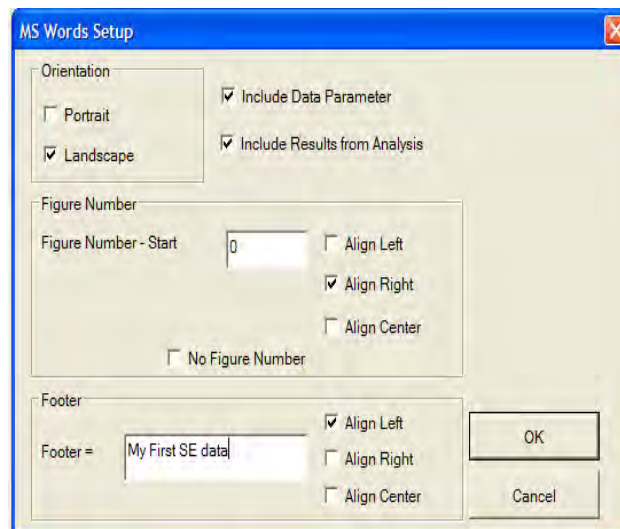
4.6   Example IE Data

This section shows several example time domain and frequency domain records of sound concrete, concrete with internal cracks and concrete with bad consolidation (internal honeycomb). As mentioned previously in Section 1.2, data analysis of the IE test is performed in the frequency domain. Sound concrete is determined by a sharp single dominant peak in the frequency data and the calculated depth (from the peak) should match the expected thickness of the tested structure. The pictures below show the IE test data from a 15" thick transfer wall. The first spectrum shows sound concrete. The second spectrum shows concrete with internal honeycombing and the third picture shows concrete with internal cracks
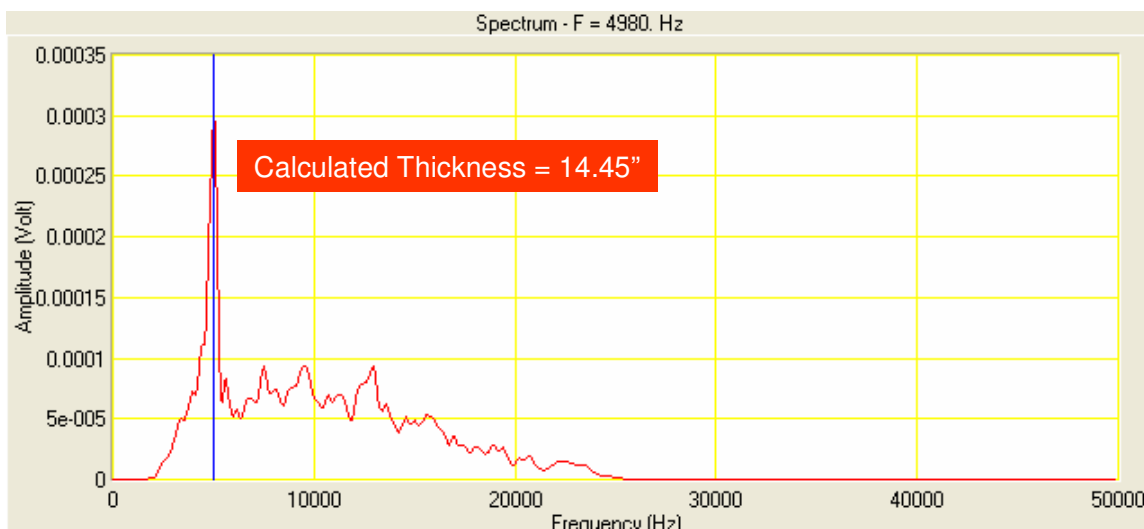
Typical internal honeycomb or voids can be indicated by a downshift in the frequency peak resulting in an increase in the apparent thickness. In addition, possible multiple peaks can also present in the spectrum of concrete with internal honeycombing. The picture below shows an example of concrete with poor consolidation (with internal honeycomb).
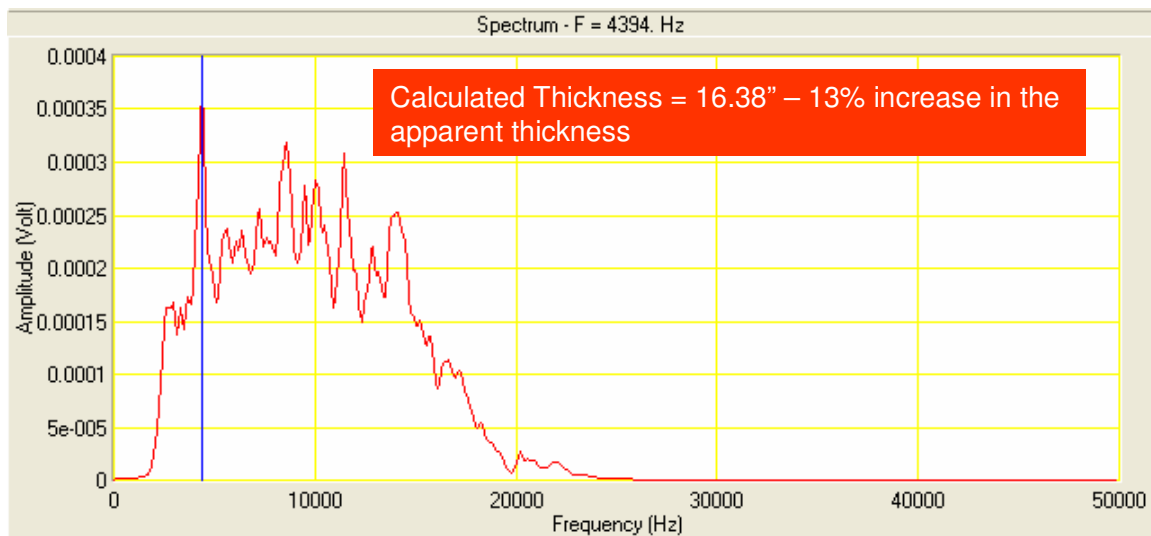
An indication of internal cracks is the multiple peak character in the frequency domain with the dominant peak representing shallower than the expected thickness. The picture below shows the data with internal cracks detected at approximately 6.5" measured from the test surface.

Spectrum - F = 11035. Hz

Calculated Echo Depth = 6.5"
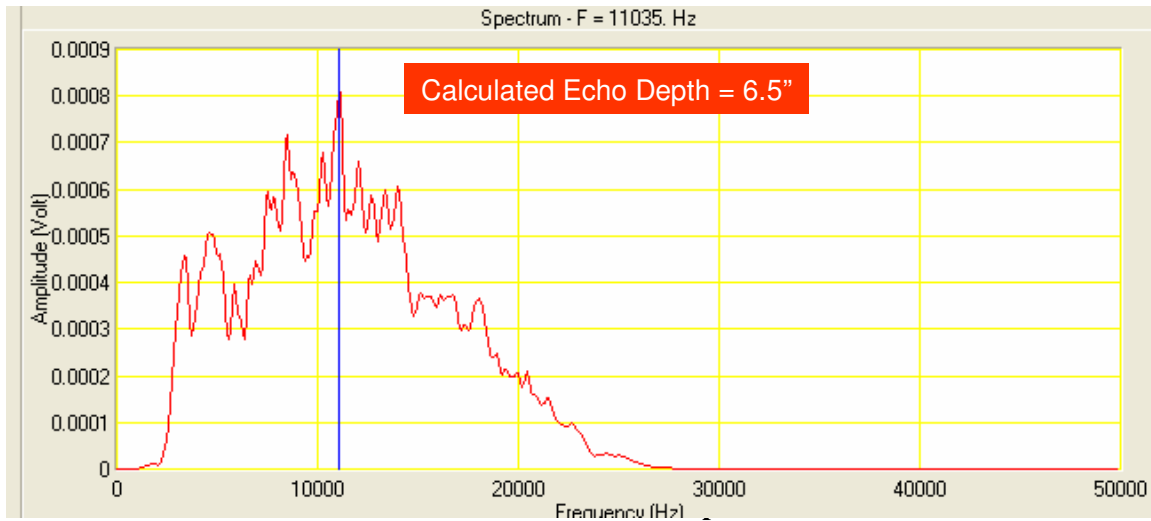
Related Peer Reviewed Papers

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

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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.
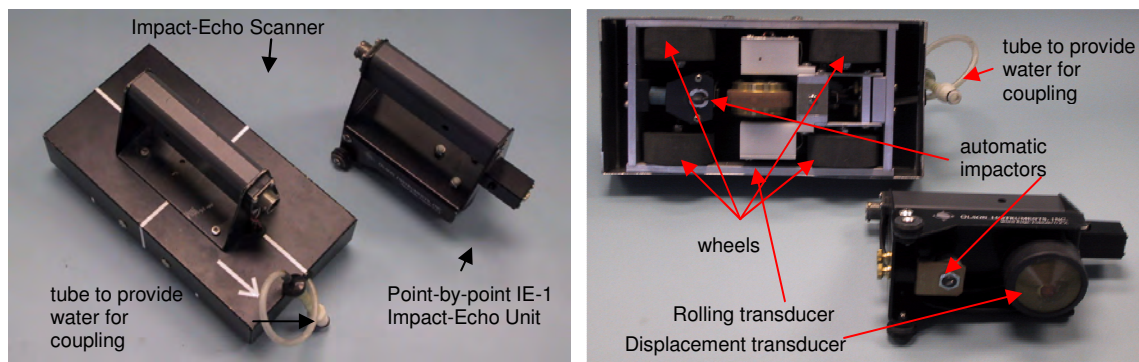

Figure 1 – Impact-Echo Scanner Unit and Point-by-Point Impact-Echo Unit

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 Permineter (%)	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)
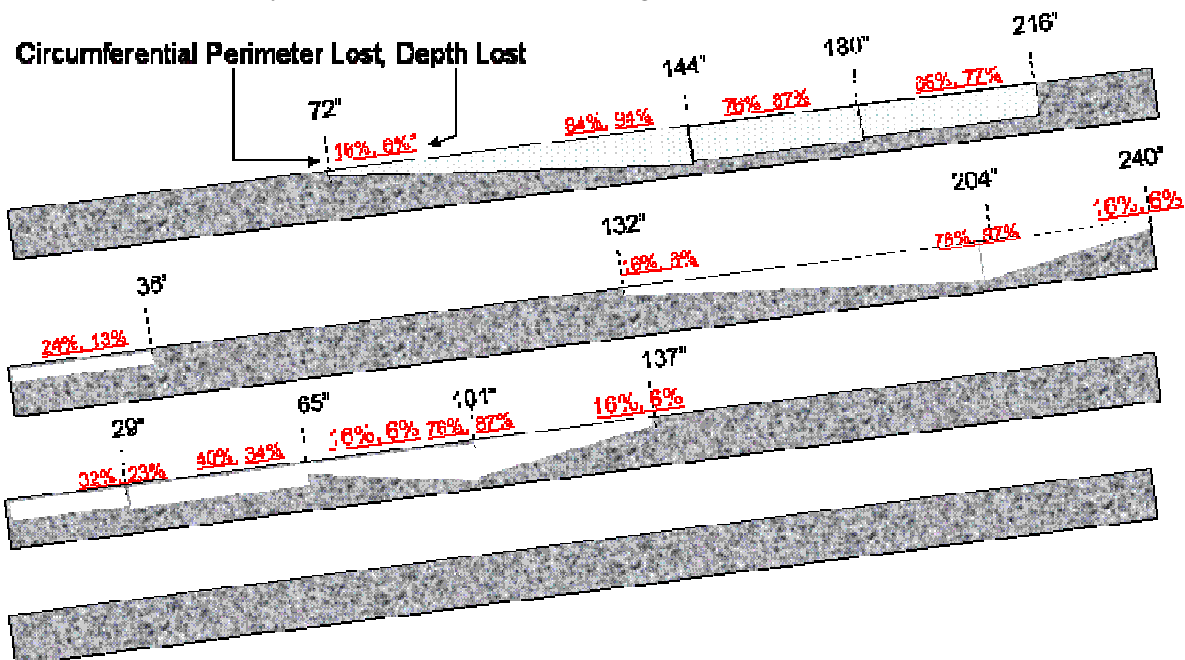

Figure 4a – Design Grout Defects (Styrofoam Voids) in the South Wall in 101.6 mm (4 inch) Metal Ducts from top down
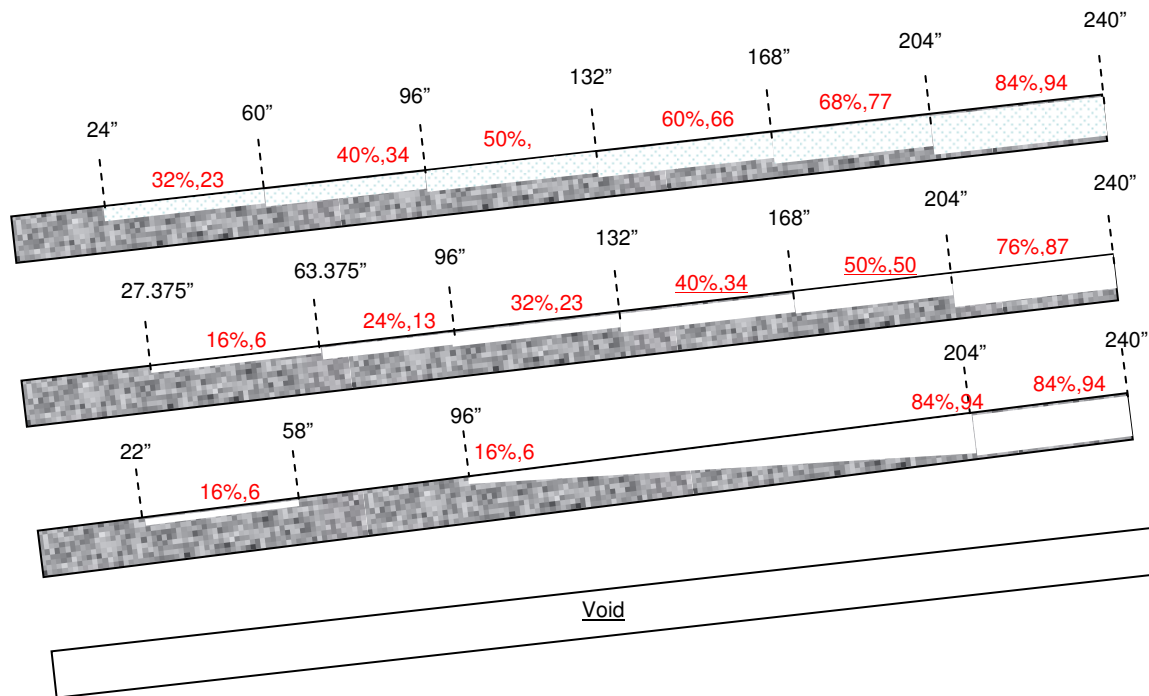
Figure 4b – Design Grout Defects (Styrofoam Voids) in the North Wall in 101.6 mm (4 inch) Metal Ducts from top down.

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 ft^2 (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.
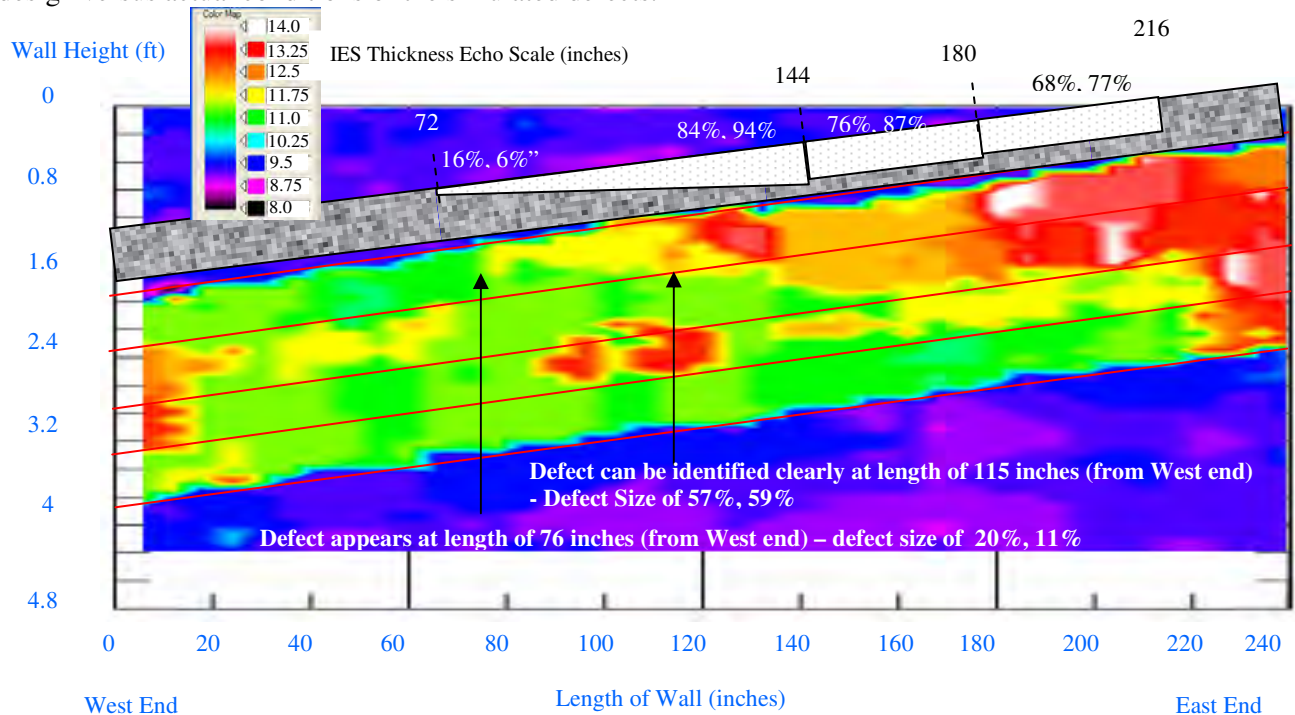

Figure 5 – IE Results from the South Wall with Actual Design Defects of Top Duct

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.
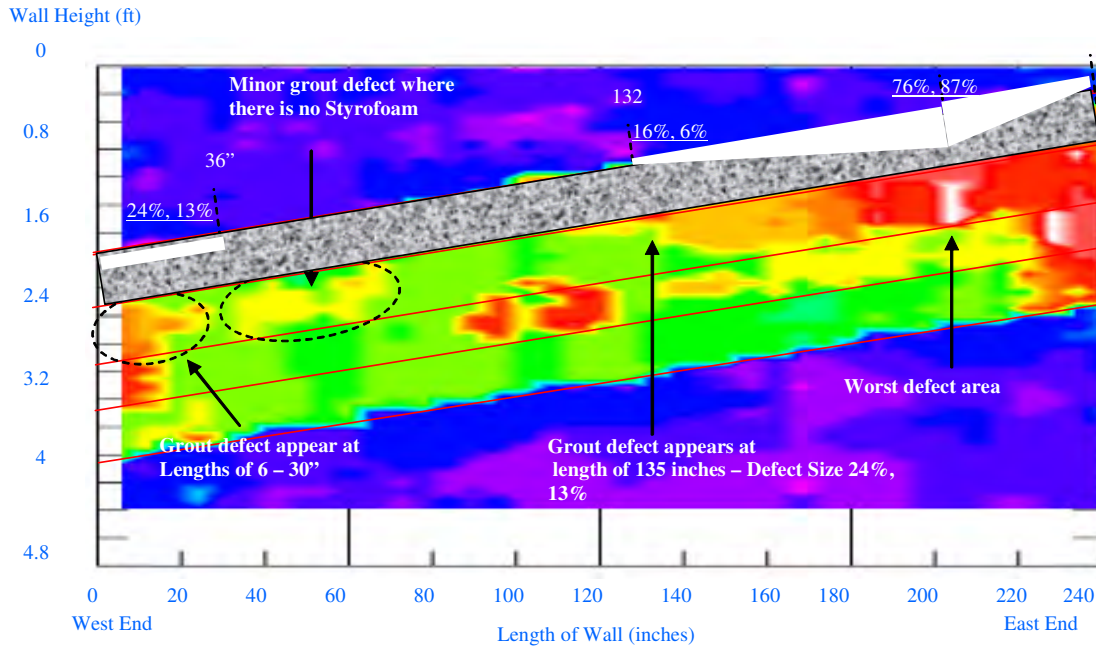

Figure 6 – IE Results from the South Wall with Actual Design Defects of Second Duct
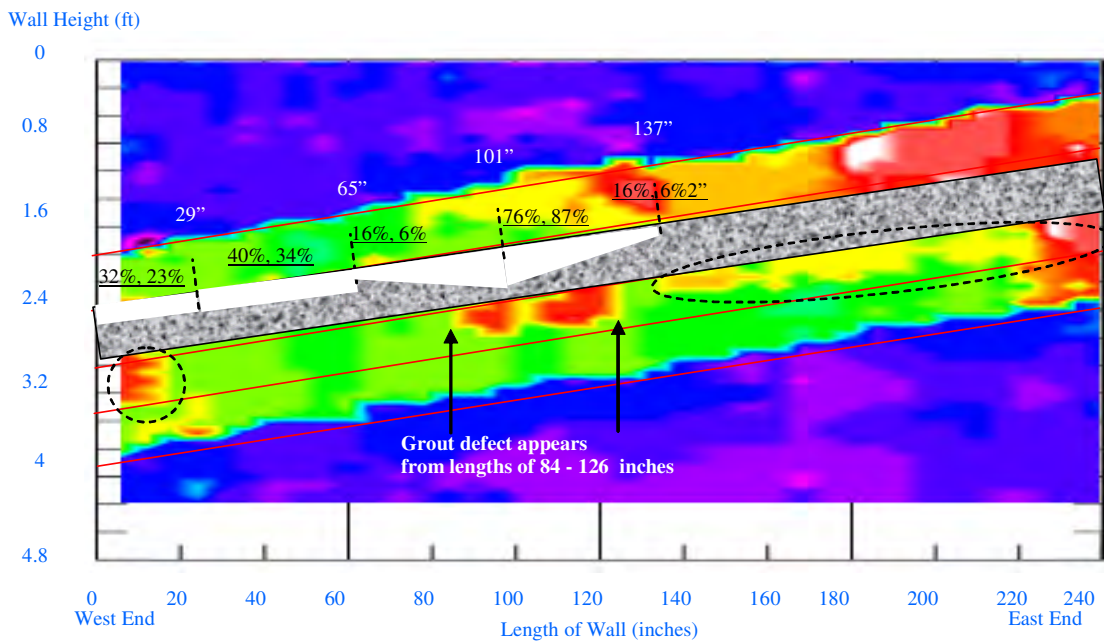

Figure 7 – IE Results from the South Wall with Actual Design Defects of Third Duct

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.
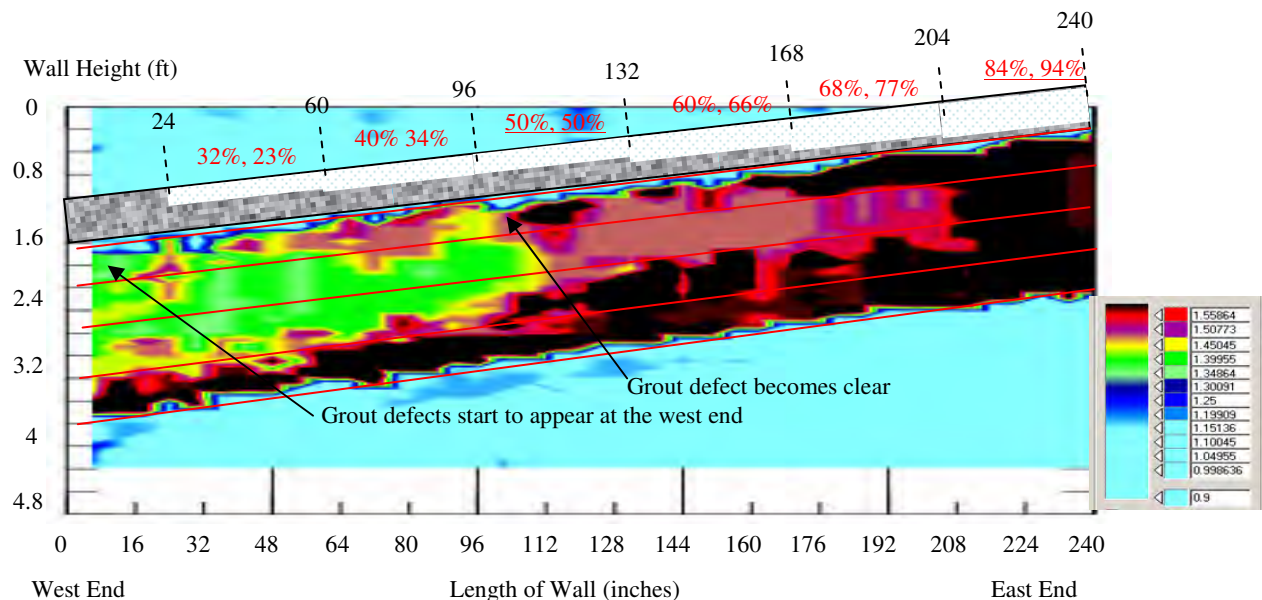

Figure 8 - IE Results from the North Wall with Actual Design Defects of Top Duct and the Normalized Thickness Scale

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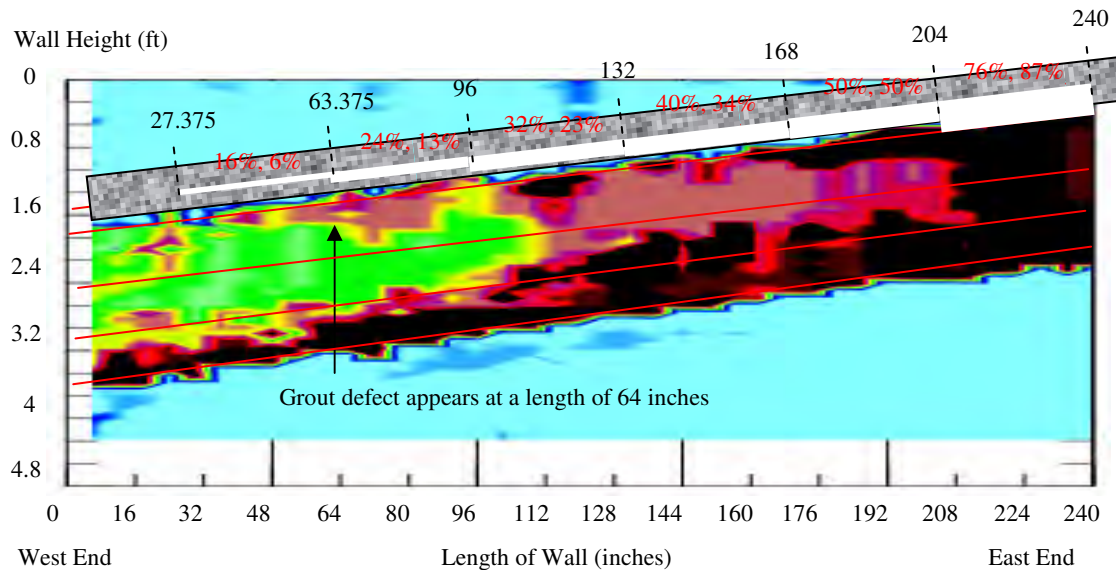
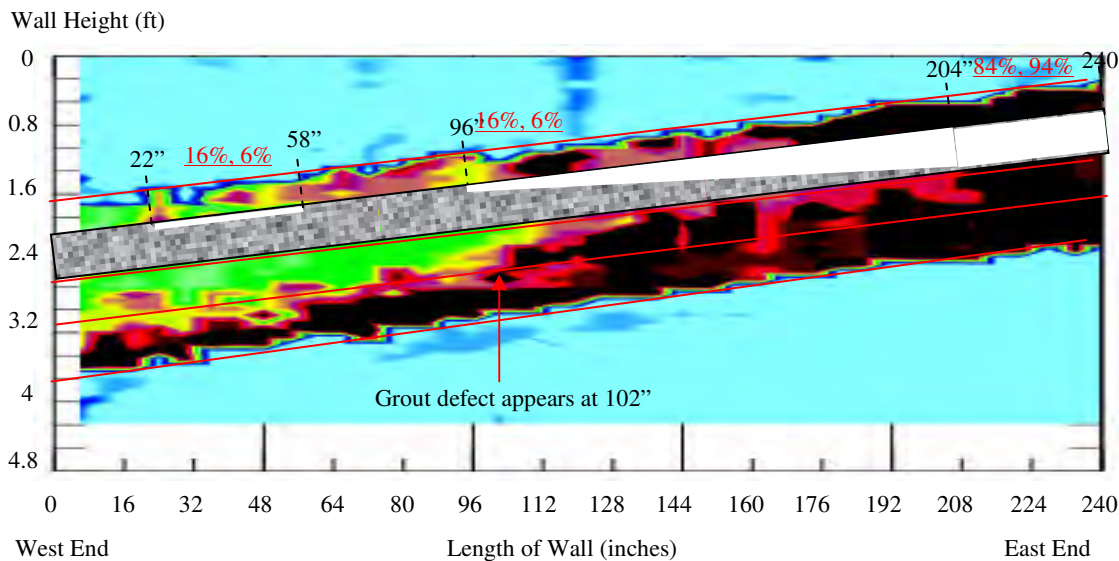Figure 9 – IE Results from the North Wall with the Actual Design Defects of the Second Duct

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.
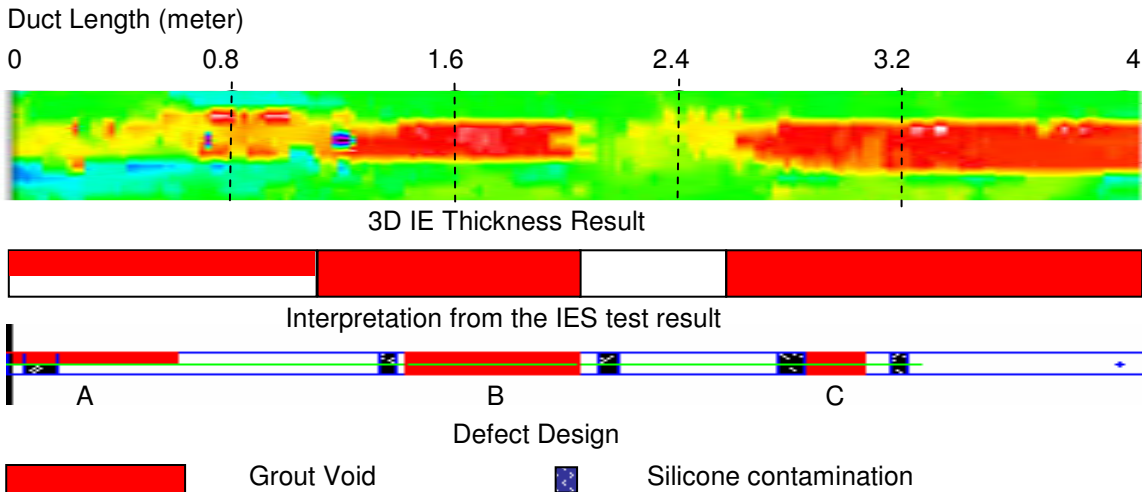

Figure 11 – Comparison of IES Test Results (and its interpretation) and the Actual Defect Design – Duct A

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.

ACKNOWLEDGEMENTS

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