

Impact-Echo Scanning for Grout Void Detection in Post-tensioned Bridge Ducts - Findings from a Research Project and a Case History

(presented at ASCE Structures Congress, Long Beach, California, May 2007)

Authors:

Yajai Tinkey, Ph.D., Olson Engineering, Inc., 12401 W. 49th Ave. Wheat Ridge, CO 80033, USA, yajai@olsonengineering.com

Larry D. Olson, P.E., Olson Engineering, Inc., 12401 W. 49th Ave. Wheat Ridge, CO 80033, USA, ldolson@olsonengineering.com

ABSTRACT

This paper presents the findings from a research project funded by the National Cooperative Highway Research Program-Innovations Deserving Exploratory Analysis (NCHRP – IDEA) Program. Experimental results are presented herein from the research 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. Finally, a case study using an Impact Echo Scanner to locate grout voids inside the Orwell Bridge in UK is included in this paper.

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.

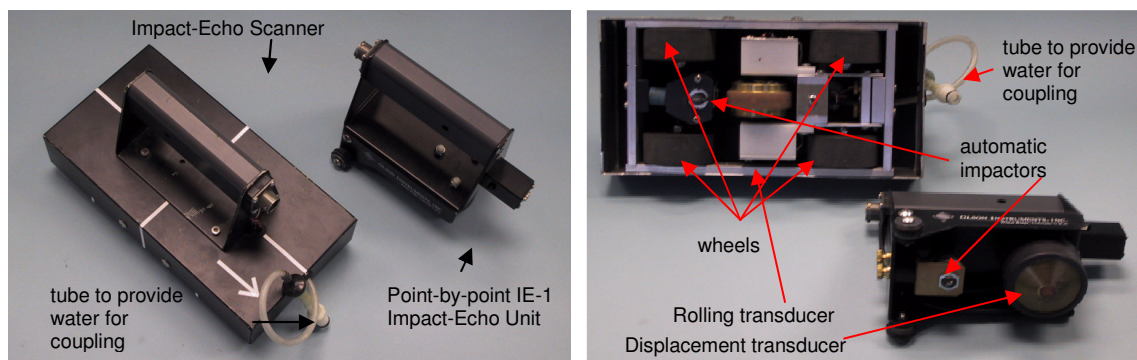


FIGURE 1 – IMPACT-ECHO SCANNER UNIT AND POINT-BY-POINT IMPACT-ECHO UNIT

GENERAL DESCRIPTION OF THE SPECIMENS AND DEFECTS

The specimen used in this study is a full scale pre-cast girder with eight steel ducts inside. 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.

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

TABLE 1 – STYROFOAM DEFECT SIZES



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)

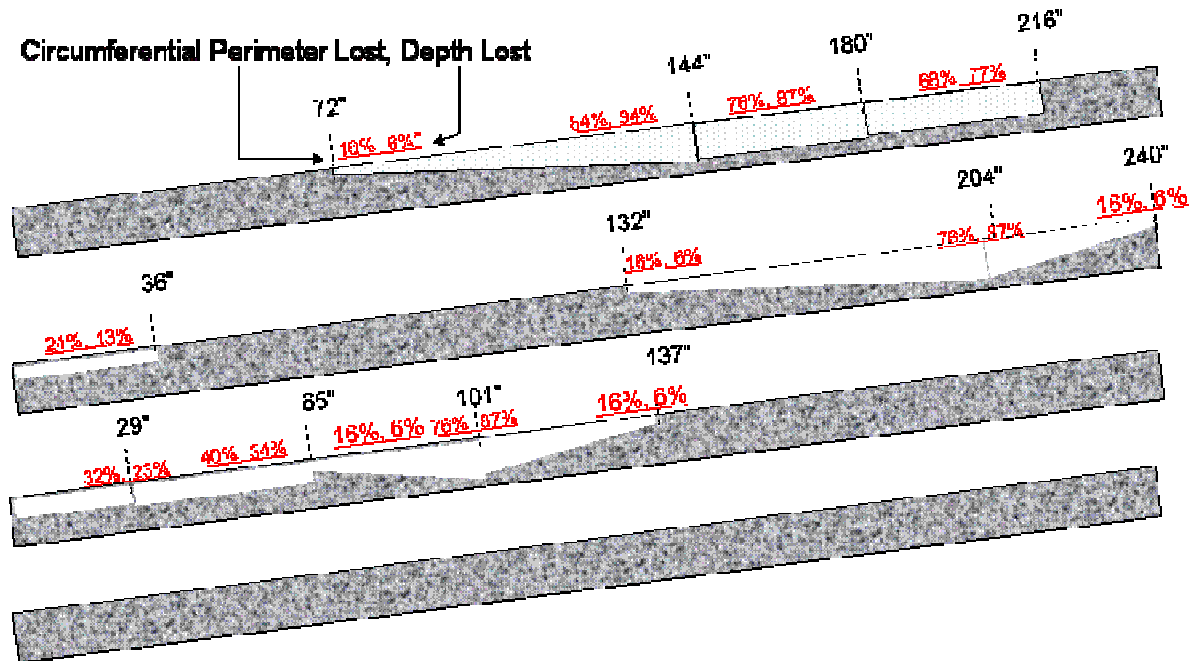


FIGURE 4a – DESIGN GROUT DEFECTS (STYROFOAM VOIDS) IN THE SOUTH WALL IN 101.6 MM (4 INCH) METAL DUCTS FROM TOP DOWN

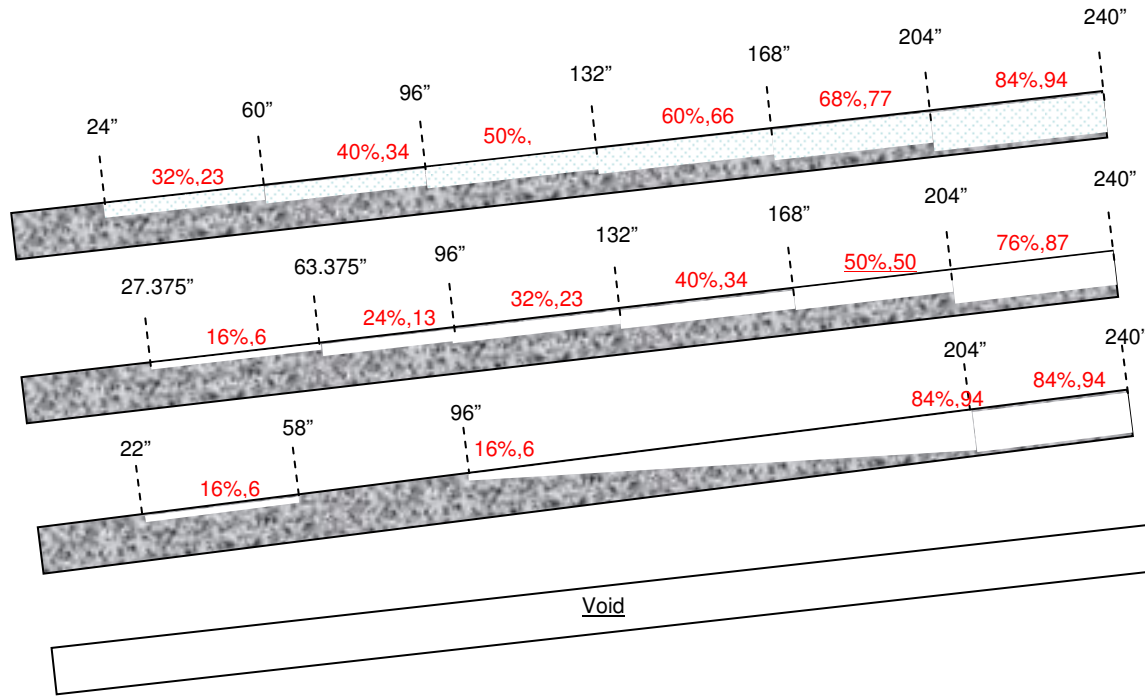


FIGURE 4b – DESIGN GROUT DEFECTS (STYROFOAM VOIDS) IN THE NORTH WALL IN 101.6 MM (4 INCH) METAL DUCTS FROM TOP DOWN.

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 6 – 8 from the South wall and in a normalized thickness tomogram as shown in Figures 9 - 11 from the North wall. Figures 6 – 11 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.

Experimental Results from the South Wall

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.

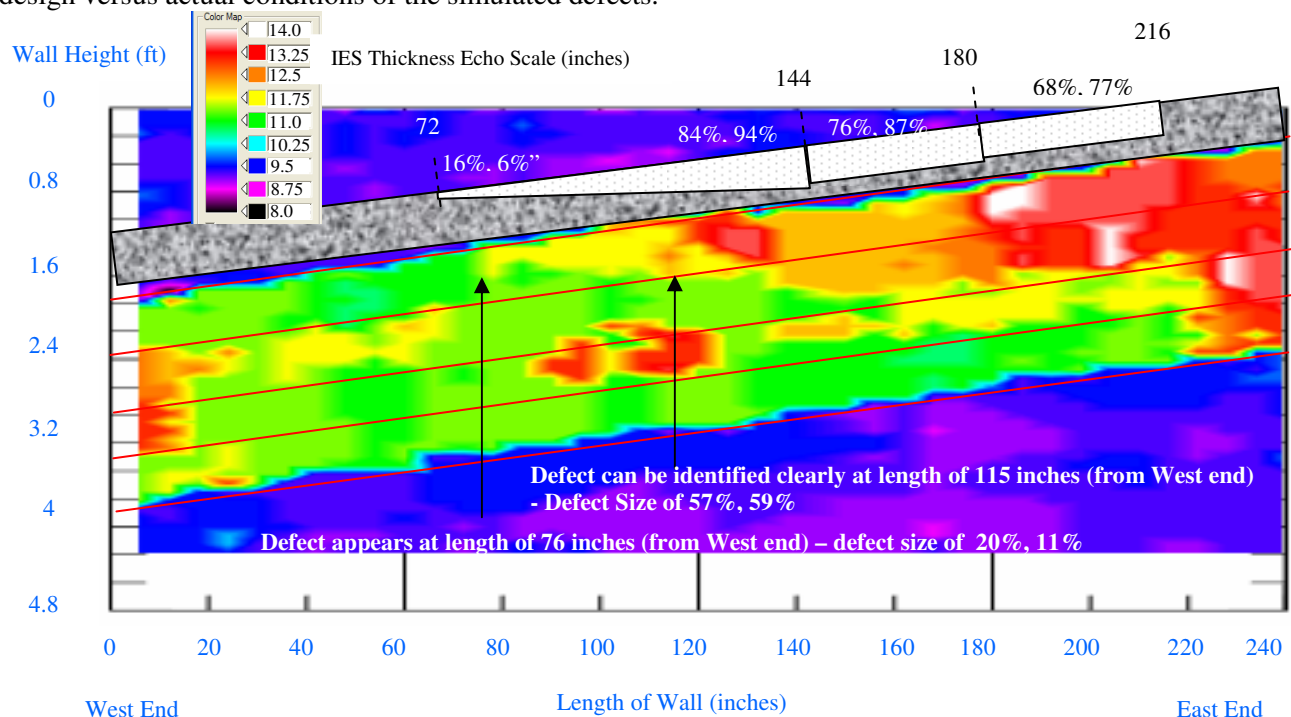


FIGURE 5 – IE RESULTS FROM THE SOUTH WALL WITH ACTUAL DESIGN DEFECTS OF TOP DUCT

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.

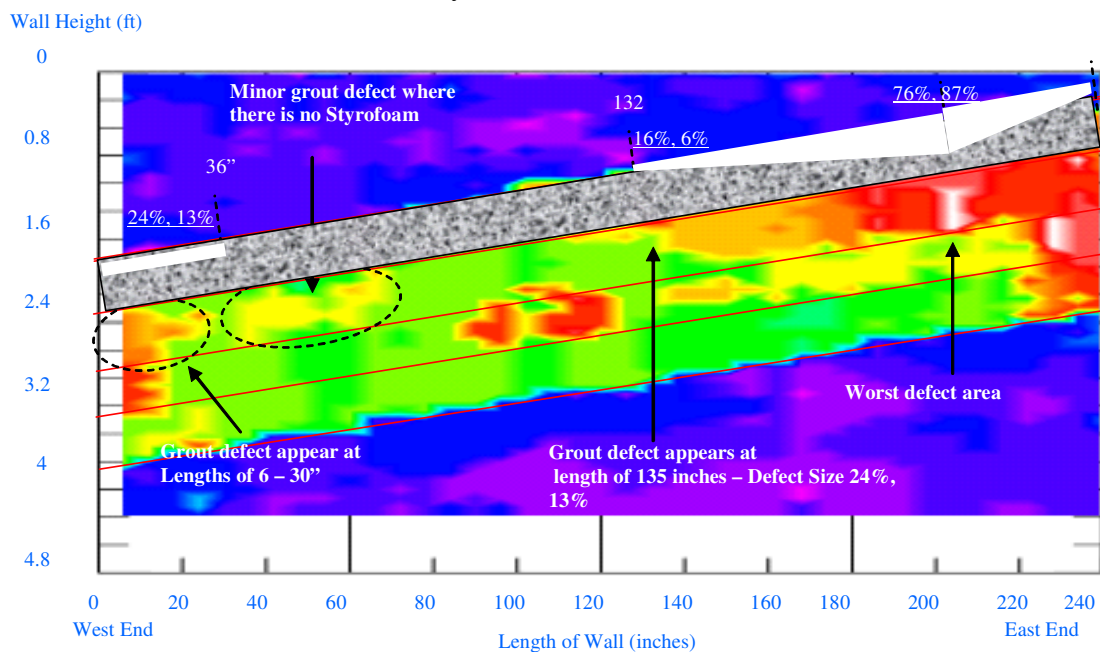


FIGURE 6 – IE RESULTS FROM THE SOUTH WALL WITH ACTUAL DESIGN DEFECTS OF SECOND DUCT

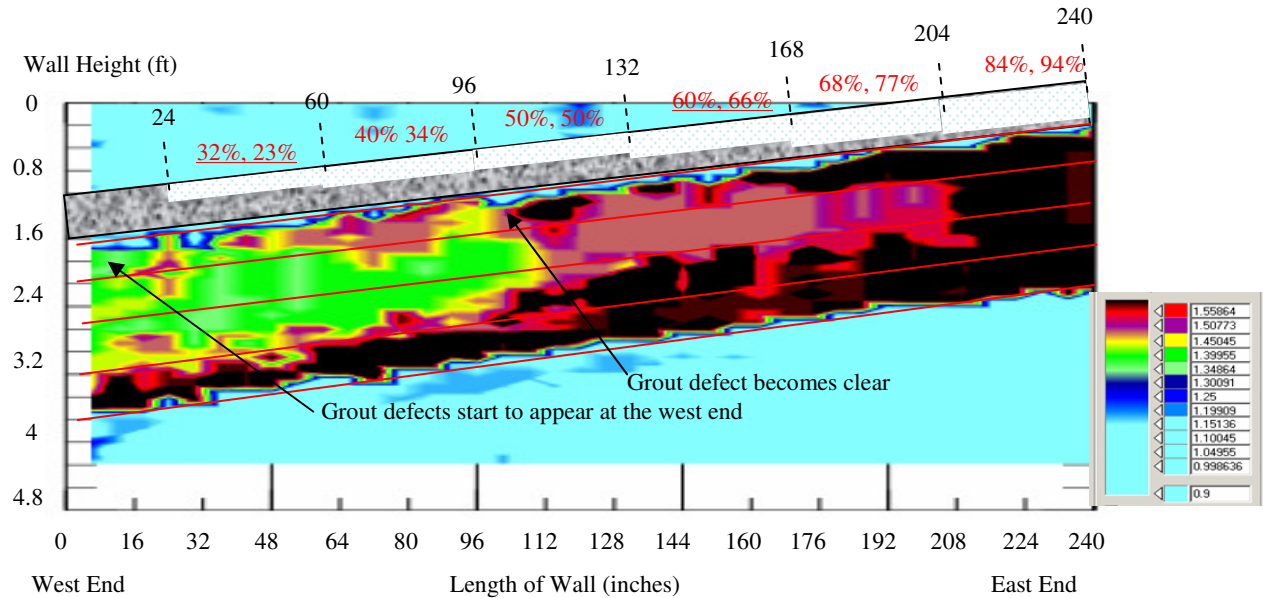


FIGURE 8 - IE RESULTS FROM THE NORTH WALL WITH ACTUAL DESIGN DEFECTS OF TOP DUCT AND THE NORMALIZED THICKNESS SCALE

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 - Third Duct from Top: 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.

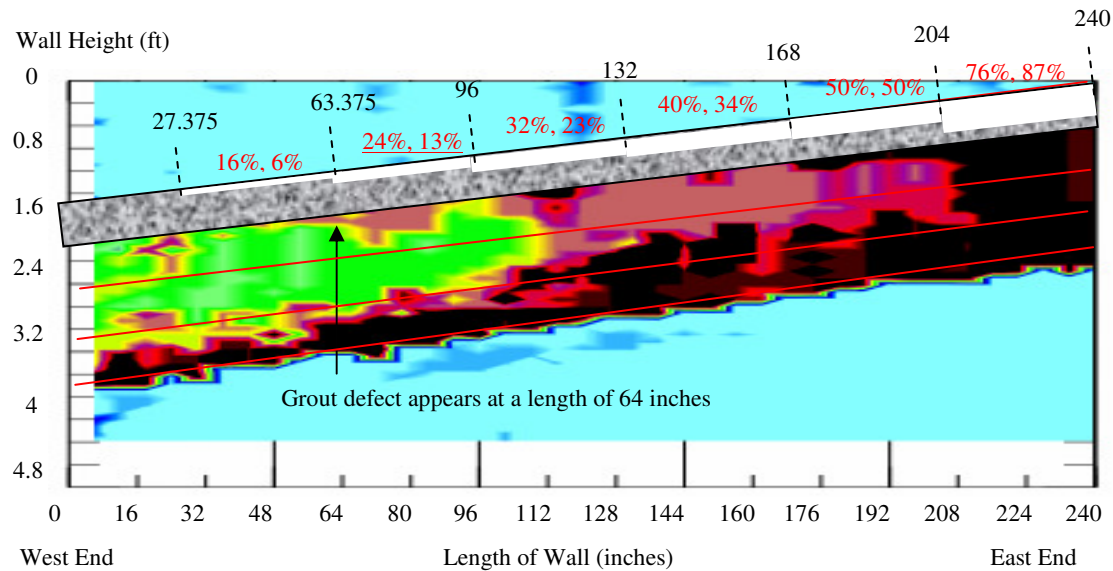


FIGURE 9 – IE RESULTS FROM THE NORTH WALL WITH THE ACTUAL DESIGN DEFECTS OF THE SECOND DUCT

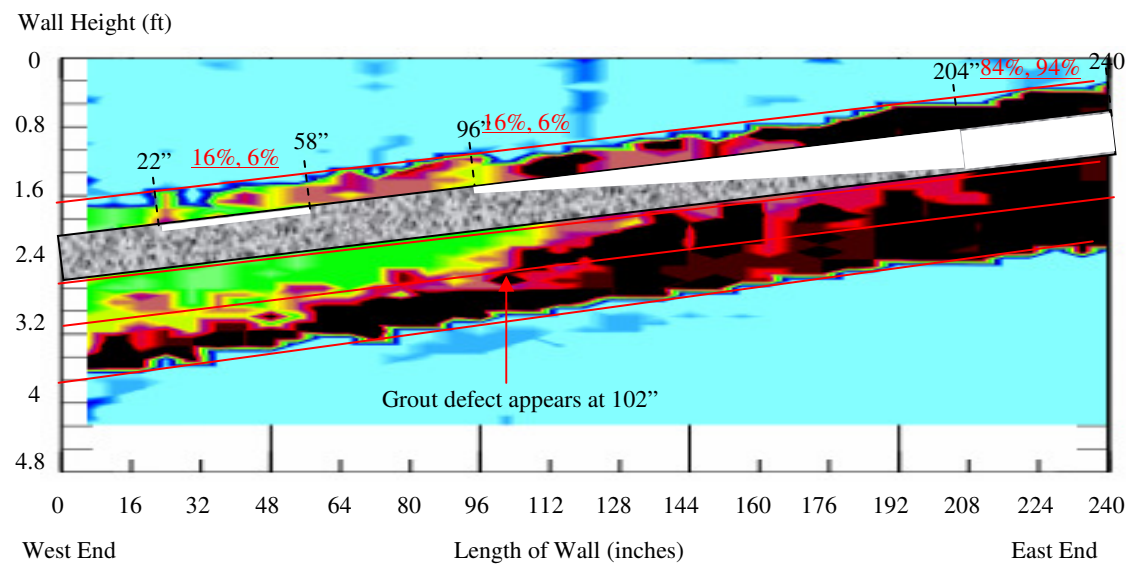


FIGURE 10 – IE RESULTS FROM THE NORTH WALL WITH THE ACTUAL DESIGN DEFECTS OF THE THIRD DUCT

CASE HISTORY

The results obtained from the research project were applied to a real world application. This section presents an example case history using the Impact Echo Scanner to locate anomalies inside post-tensioned bridge ducts inside the Orwell Bridge in UK (Figure 11). The testing was conducted typically from inside each bridge from one side of each of the web walls with the Impact Echo (IE) Scanning system. The tests were typically performed in vertical lines located approximately every 2 meters (m) along a web wall and each vertical scan generally started from

the bottom inside chamfer and ran to the top inside chamfer of the tested web walls for about 72 tests over 1.8 m of wall. A 2-D scan vertically up the wall from 0 to 2 m is shown in Figure 12. The 2-D results shows a single time domain result and the corresponding linear frequency displacement spectrum showing the resonant thickness echo peak along with the thickness vs. distance plot that is the 2-D IES result. Potentially voided ducts are indicated by the greater thicknesses in 2 locations (lower resonant frequency echo peaks due to voiding) in Figure 12. The results from the tests are presented in a thickness tomogram fashion for each web wall for each tested span with thicker areas indicative of potential void in the PT Ducts. An example test result from one of the spans is presented in Figure 13. Review of Figure 13 shows discontinuities or voids located at 20 m from Pier 2 and from the bottom of the wall (location where the scan started) to a height of 0.6 m. The IE records indicated cracks/voids at depths of 12 – 15 cm from the test surface. In addition, the plot in Figure 13 also indicated a thicker area (presented in black color) representing voids inside the duct(s) located at 42 m from Pier 2 and from heights of 0.9 – 1.15 m. The color map in Figure 13 shows normalized thicknesses (the IE thickness divided by the nominal thickness at the tested line) by color from 0.1 to 1.3.



FIGURE 11 – ORWELL BRIDGE

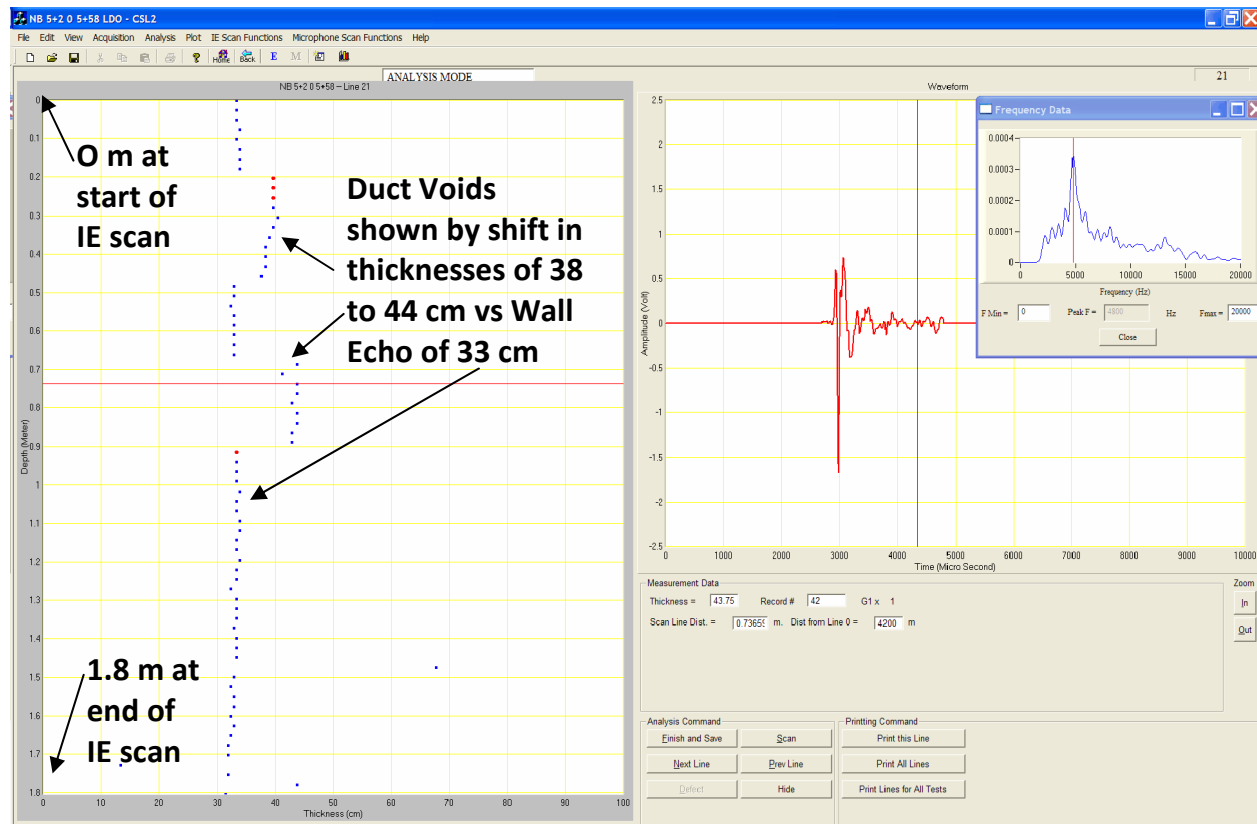


FIGURE 12 – VERTICAL IMPACT ECHO SCAN WITH 2 DUCT VOIDS OF 33 CM THICK WALL SECTION WITH 100 MM DUCTS

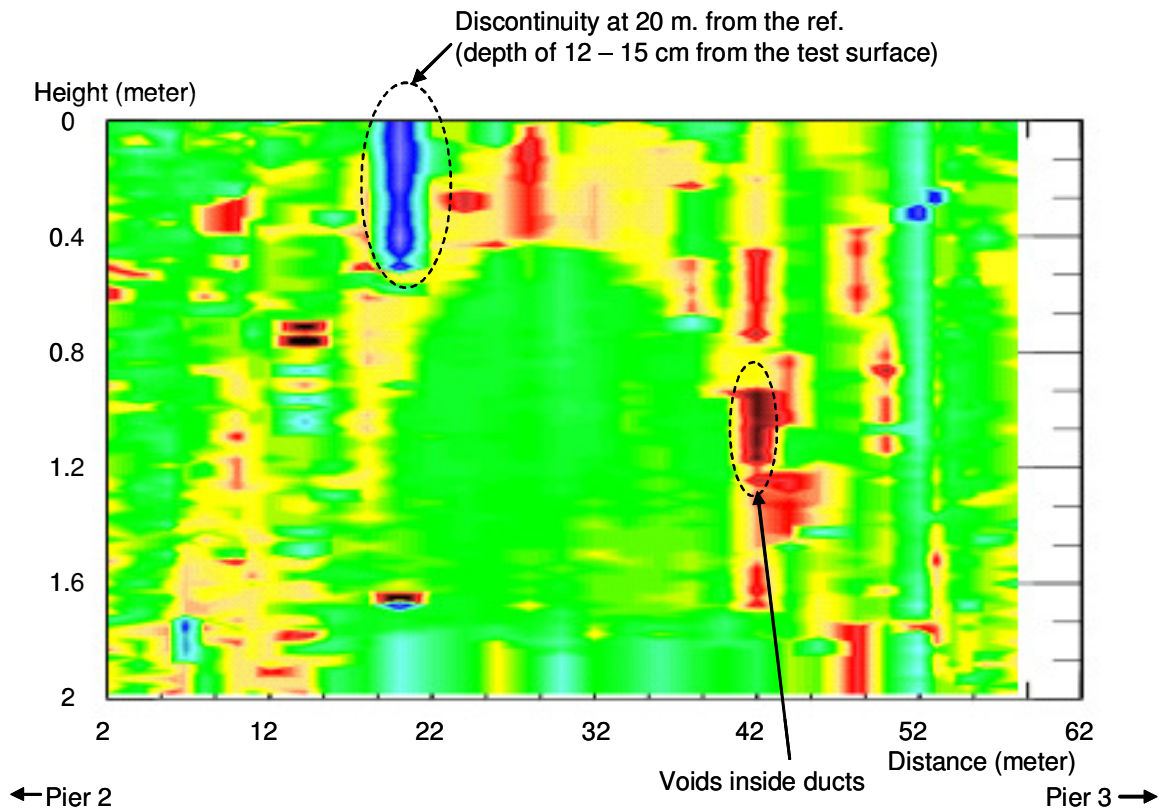


FIGURE 13 – 3D NORMALIZED THICKNESS TOMOGRAM OF SPAN 2 OF NORTH BOX (GENERAL CONDITION)

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.

ACKNOWLEDGEMENTS

The financial support from the NCHRP-IDEA program of the Transportation Research Board of the National Academy of Sciences which made this research project possible is greatly appreciated by the authors. The authors would also like to express their gratitude to Mr. Jim Fabinski of EnCon Bridge Company (Denver, Colorado) for donating a full scale bridge girder for use of this research and the assistance of Restruction Corporation in grouting the ducts.

REFERENCES

- [1] Concrete Society Technical Report No. 47, "Durable Bonded Post-Tensioned Concrete Bridges", Concrete Society, 1996
- [2] Woodward, R.J. and Williams, F.W., "Collapse of the Ynys-y-Gwas Bridge, West Glamorgan," *Proceeding of The Institution of Civil Engineers*, Part 1, Vol. 84, August 1988, pp. 635-669.
- [3] Florida Department of Transportation (FDOT) Central Structures Office, "Test and Assessment of NDT Methods for Post Tensioning Systems in Segmental Balanced Cantilever Concrete Bridges, Report, February 15, 2003.
- [4] J. S. West, C. J. Larosche, B. D. Koester, J. E. Breen, and M. E. Kreger, "State-of-the-Art Report about Durability of Post-tensioned Bridge Substructures", Research Report 1405-1, *Research Project 0-1405*, Texas Department of Transportation, October 1999.
- [5] Sansalone, M. J. and Streett, W. B., Impact-Echo Nondestructive Evaluation of Concrete and Masonry. ISBN: 0-9612610-6-4, Bullbrier Press, Ithaca, N. Y, 1997 339 pp.
- [6] D. Sack and L.D. Olson, "Impact Echo Scanning of Concrete Slabs and Pipes", International Conference on Advances on Concrete Technology, Las Vegas, NV, June 1995
- [7] ASTM C1383 "Test Method for Measurement P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method".