Applications and Limitations of Impact-Echo Scanning for Void Detection in Post-Tensioned Bridge Ducts

Word Count:

Abstract:	213
Text:	2,779
Tables 1@250:	250
Figures 5@250:	1,250
Total Words:	4,492

Date Submitted: August 1, 2007

Yajai Tinkey
Senior Engineer
Olson Engineering Inc.
12401 W. 49th Ave. Wheat Ridge, Colorado 80033
Telephone No.: (303) 423-1212
Fax: (303) 423-6071
E-mail: yajaipromboon@yahoo.com

Larry D. Olson
Principal Engineer
Olson Engineering Inc.
12401 W. 49th Ave. Wheat Ridge, Colorado 80033
Telephone No.: (303) 423-1212
Fax: (303) 423-6071
E-mail: ldolson@olsonengineering.com

ABSTRACT

This paper summarizes findings from an internal research study to determine applications and limitations of the Impact-Echo Scanning (IES) system for void detection in post-tensioned bridge ducts. The nominal thickness of the test panels ranged from 0.2 – 0.7 m with plastic and steel ducts inside. The diameter of the ducts ranged from 50 to 120 mm. One tapered section (with wall thicknesses between 0.2 – 0.7 meter), had draped ducts, with the rest being straight ducts. The Impact-Echo (IE) testing was performed using the IE scanner system. This system, as rolled, automatically performs an IE test at 25 mm (1 inch) intervals. All of the IE scans in this investigation were performed on lines perpendicular to the general PT duct direction. The maximum frequency of excitation of the impactor in the scanner used in research is 25 kHz. This internal research is an expanded study from a previous research project funded by the NCHRP-IDEA program titled "Non-destructive Evaluation Method for Determination of Internal Grout Conditions inside Bridge Post-tensioning Ducts using Rolling Stress Waves for Continuous Scanning". The purpose of the study was to better understand the nominal thickness limitation of the structures for the IE tests using a scanner with a maximum excitation of 25 kHz to correctly identified voids in post-tensioned bridge ducts.

INTRODUCTION

This paper summarizes findings from an expanded internal study from a previous research project funded by the NCHRP-IDEA program titled "Non-destructive Evaluation Method for Determination of Internal Grout Conditions inside Bridge Post-tensioning Ducts using Rolling Stress Waves for Continuous Scanning". 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 ducts which carry the post-tensioning cables may not be fully grouted. This results in voids in some areas therefore insufficient protection for post-tensioning steel tendons. Over the long term, water can enter the tendon ducts in the void areas resulting in corrosion of the tendon. The collapse of a two bridges in UK *(1 and 2)* and a corrosion related failure in a bridge in Florida *(3)* have shown that it is important to have a reliable method to practically inspect the quality of grout fill inside the ducts after the grouting process is complete. It is equally important to be able to evaluate the condition of older bridges which were never inspected for voids. The previous research from the NCHRP-IDEA program was conducted by the authors to address this ongoing problem using nondestructive testing methods.

The findings from the previous NCHRP research project showed that Impact-Echo Scanning can be used to located voids as small as 9% depth lost or 20% circumferential diameter lost in a 101.6 mm (4 inch) diameter steel duct inside a wall with a nominal thickness of 0.254 m (10 in) *(4)*. The previous research also showed that it is easier to detect grout defects in ducts with larger diameters. Conversely, the greater the cover depth between the duct and the test surface, the harder it is to detect grout defects with the IE tests. The purpose of this study is to better understand the applications and limitations of the IES method in terms of wall thickness, duct diameters and concrete cover for the reliable location of grout voids. The findings in this paper came from the results of both the previous NCHRP research project and the recent expanded internal study.

IMPACT ECHO SCANNING (IES) TECHNIQUE

The background of the IE method and the relationship between the dominant frequency and the apparent thickness of the structure can be found in several references *(4, 5 and 6)*. This section describes the basic concept of the scanner used for the IE test. The IE 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 *(7)*. This technique is based on the IE method *(4, 5 and 6)*. In general, the purpose of the IE 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 IE testing process, an IE 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 generate an 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 with impactors that generate higher or lower maximum frequencies. A comparison of the IES and the point by point IE 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 IES scan line, the resolution of the scanning is about 25 mm (1 inch) between IE test points. Data analysis and visualization was achieved using IE 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 1 kHz to 20 kHz. Due to some rolling noise generated by the IES, 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 IE 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 IE thicknesses from each scanning line. The three-dimensional results can be presented in either color or grayscale.

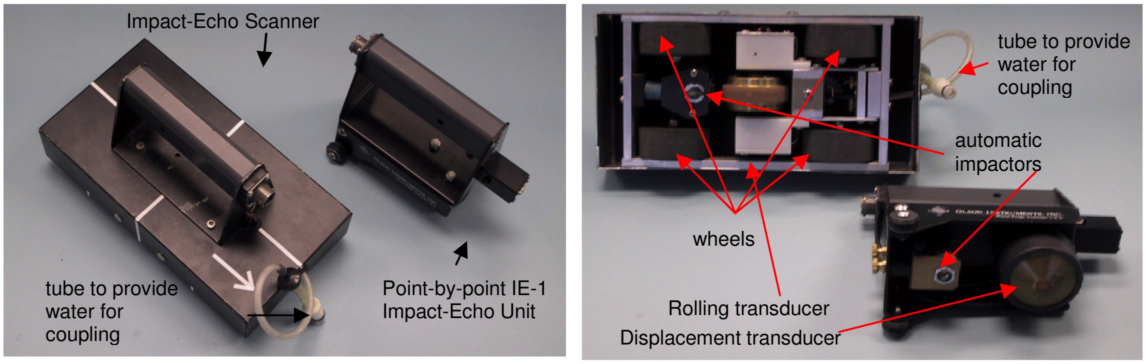

Figure 1 – Impact-Echo Scanner Unit and Point-by-Point Impact-Echo Unit

GENERAL DESCRIPTION OF THE SPECIMENS AND DEFECTS

The results from five mock-up panels are included in this paper. The actual design of each panel and grout defect construction of each duct cannot be disclosed in the paper since the panels will continue to be used in blind research studies. However, a summary of the findings will be presented herein without referring to the name of the panel or the duct. In general, the thickness of the panels ranged from 0.2 -0.7 meter, with one panel having a tapered thickness. Both plastic and steel ducts were included in this study with duct internal diameters ranged from 50 – 120 mm. The ducts are generally located in the middle of the section with the same concrete cover on both sides of the panel except for the tapered panel, where the ducts were located 0.1 m from one side of the panel and there was thus a variable thickness cover from the other side of the panel. The ducts were completely grouted, empty or half grouted (one side of the duct was grouted and the other side was empty).

IMPACT-ECHO SCANNING ON THE MOCK-UP PANELS

The Impact-Echo (IE) testing was performed using the IE scanner; which, as rolled, automatically performs an IE test at 25 mm (1 in) intervals. All of the IE scans in this investigation were performed in lines which were perpendicular to the general PT duct direction. The interval distance between each scan line was typically 0.15 meter. The maximum frequency of excitation of the impactor in the scanner used in research is 25 kHz. Picture 2 shows the IE test performed on a mock-up panel with the IE scanner.


Figure 2 – Impact-Echo Test Using an Impact-Echo Scanner on a Mock-up Panel

FINDINGS FROM THE INTERNAL STUDY

Previously from the NCHRP-IDEA research project *(8)*, the interpretation from the IES tests to locate grout voids in bridge ducts showed that a direct echo from the void or duct wall, measured as an Impact-Echo frequency corresponding to the depth of the discontinuity is not normally observed with the IE Scanner. However, 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 Grouting defects inside the ducts cause a significant step-like increase of the apparent wall thickness in IE results as presented herein vs. well-grouted ducts.

In this study, five more mock-up panels were tested with a focus on the effects of different nominal wall thicknesses, different duct diameters and different concrete covers to the identification of the grout voids. A summary of findings from this internal research study are listed below:

- The IES test results from a panel with a nominal wall thickness of 0.2 m and with steel and plastic ducts (with an internal diameter of 70 mm) located in the middle of the section (concrete cover of 50 mm) and are presented below:
    - The presence of a well-grouted steel duct was indicated by an approximately 20% increase in apparent wall thickness.
    - The presence of voids inside the steel duct was indicated by up to a 40% increase in apparent wall thickness.
    - The presence of a partially grouted steel duct was indicated by an approximately 30% increase in apparent wall thickness.
    - The presence of a partially grouted plastic duct was indicated by an approximately 35 - 40% increase in apparent wall thickness.
    - Partial debonding around the fully grouted plastic duct was detected in this panel. The presence of the higher frequency peak (of the dual peaks) in the frequency spectrum (shown in Figure 3) indicated that the plastic duct was fully grouted and the lower frequency indicated partially debonding around the plastic duct. Note that there was no shift in the higher frequency (compared to the frequency of the wall thickness) over the grouted plastic duct with no debonding present.

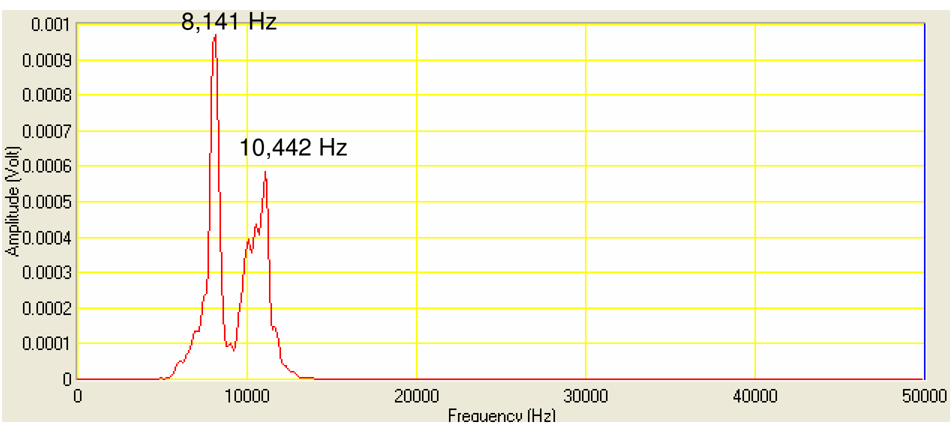

Figure 3 – The Presence of Dual Peaks from a Partially Debonded Plastic Duct

- A typical result from an IE scan line across five ducts and the actual defect design of the ducts are presented in Figure 4. Reviews of Figure 4 show a smaller increase of apparent thickness over a well grouted steel duct and a more significant increase of apparent thickness over empty and partially grouted ducts. Note that partial debonding around the well grouted plastic duct was identified and some manual picks (shown in red dots) for the higher frequency peak (of the dual peaks) were implemented.

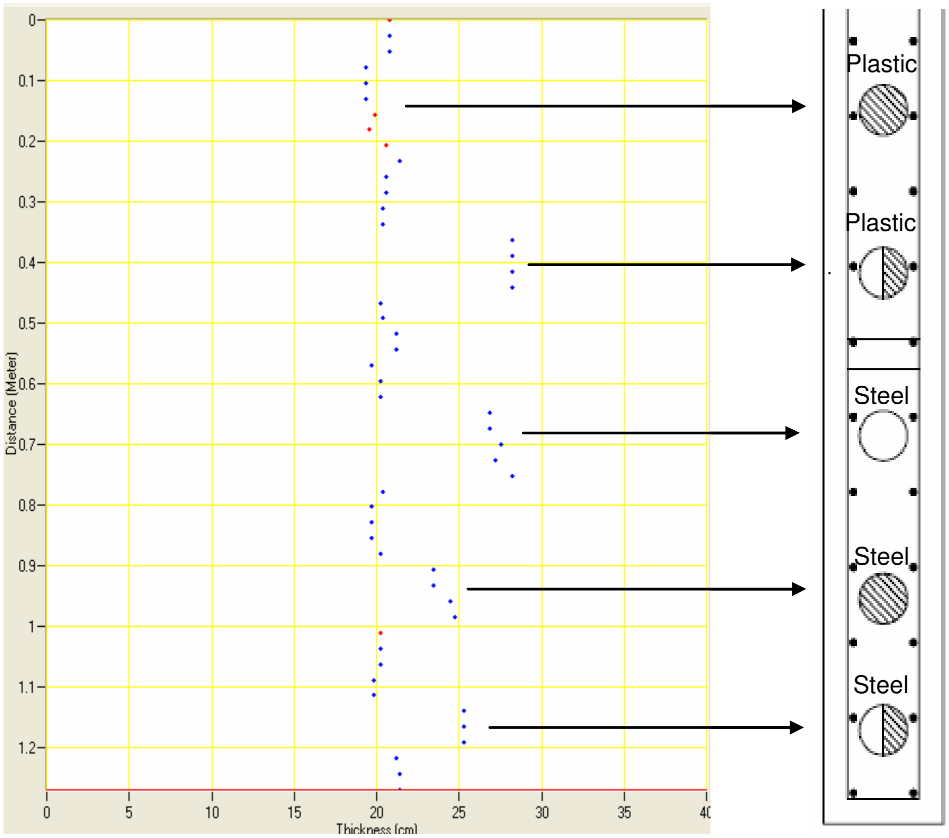

Figure 4 – Apparent Thickness Results from an IE Scan Line

- The IE results are presented in a three-dimensional fashion using normalized thickness surface plots (from all the IE scan lines in the panel) to provide improved visualization and interpretation of the internal grout to void defect conditions inside the ducts of the panel. The normalized wall thickness tomogram from this panel is presented in Figure 5 (black denotes an echo of 1.6 times the actual wall thickness, which indicates the most severely voided duct area).

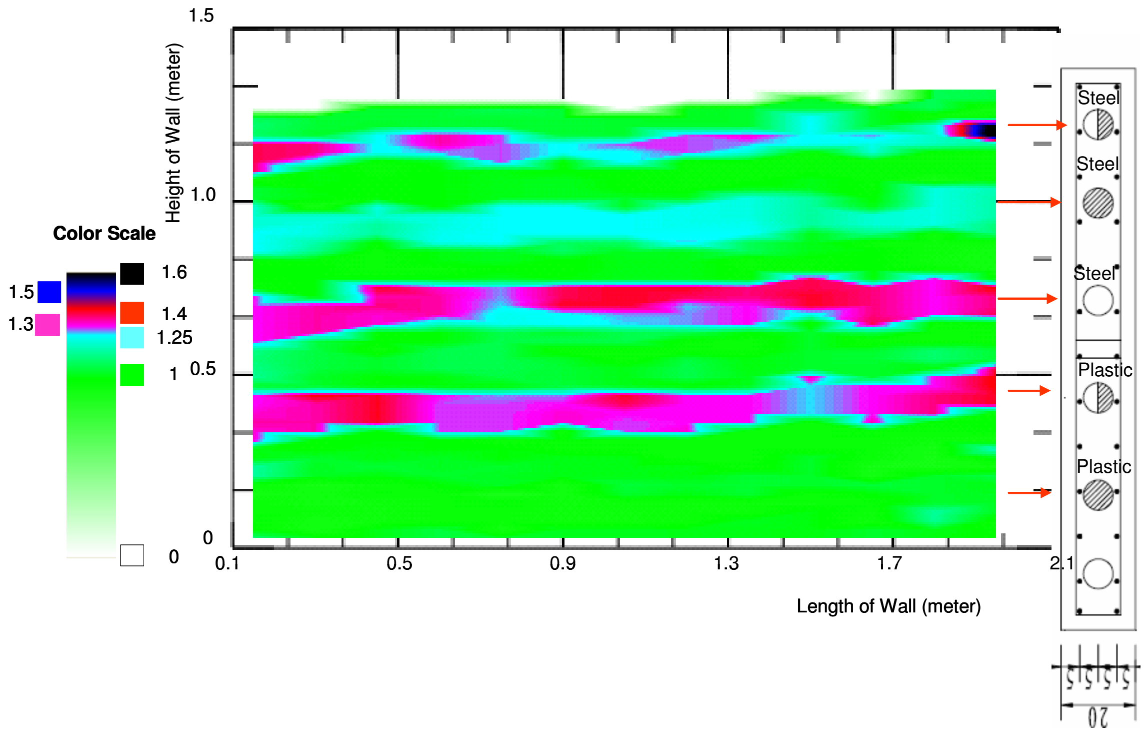

Figure 5 – IE Normalized Thickness Tomogram from a Panel with a Nominal Wall Thickness of 0.2 m.

- The following results were obtained from three mock-up panels with a nominal thickness of 0.3 m and with steel ducts (with internal diameters that ranged from 50 - 120 mm) located in the middle of the section:
  - The presence of well-grouted steel ducts with an internal diameter ranging from 50 – 120 mm was indicated by no increase in apparent wall thickness compared to areas away from the ducts.
  - The presence of an empty steel duct with an internal diameter of 120 mm (concrete cover of 90 mm) was indicated by an approximately 40% increase in apparent wall thickness.
  - The presence of an empty steel duct with the internal diameter of 70 mm (concrete cover of 115 mm) was indicated by an approximately 25% increase in apparent wall thickness.

- This final section summarizes findings from the tapered mock-up panel. This mock-up panel has a tapered thickness from 0.2-0.7 m and steel ducts (with an internal diameter of 70 mm) located with a concrete cover of 50 mm from one side of the wall and therefore a variable thickness cover from the other side of the wall. The IES tests were performed from both sides of the wall. Table I summarizes the detectability of grout voids (completely empty duct) for different wall thicknesses when testing from the non-tapered side of the wall. Note that this means that the concrete cover from the test side is a constant value of 50 mm in this case. Reviews of Table I show that the presence of empty steel ducts can be detected by an increase in the apparent thickness of the wall for nominal wall thicknesses of 0.2-0.35 meter. The presence of the empty steel ducts could not be identified in the panel in the area where wall thicknesses were between 0.350–0.388 m. For the areas of the panel with nominal thicknesses ranging from 0.425 – 0.630 m, however, a shallow echo or high frequency peak was detected at locations where the ducts were empty. Note that this high frequency peak was not associated with the depth of the grout void inside the ducts. Although destructive tests have not yet been performed on the panel to identify the actual integrity of the concrete panel, IES test from the other side of the wall showed that the concrete wall was sound with no internal cracks identified.

Table I – Impact-Echo Scanning Duct Void Sensitivity Study Results from the Tapered Panel (Maximum Frequency Generated by the Excitation = 25 kHz)

			Voided Ducts				Grouted Ducts		
Nominal Wall Thckness (meter)	Cover (mm)	Dia of Duct (mm)	Thickness Increase over Voided Ducts	% Upward shift Up to	Echos over Voided Ducts	% downward Shift	Thickess Shift over Grouted Ducts	% Upward Shift	Shallow Echos over Grouted Ducts
0.2	50	70	Yes	40%	No	No	Yes	0 - 25%	No
0.2375	50	70	Yes	30%	No	No	Yes	0 - 15%	No
0.275	50	70	Yes	15%	No	No	Yes	0 - 7.5%	No
0.282	50	70	Yes	7 - 17 %	No	No	No	0	No
0.35	50	70	No	No	No	No	No	0	No
0.3875	50	70	No	No	No	No	No	0	No
0.425	50	70	No	No	Yes	19% (at 0.35 m)	No	0	No
0.4625	50	70	No	No	Yes	38% (at 0.33 m)	No	0	No
0.5	50	70	No	No	Yes	56% (at 0.32 m)	No	0	No
0.5357	50	70	No	No	Yes	82% (at 0.29 m)	No	0	No
0.6121	50	70	No	No	Yes	115% (at 0.28 m)	No	1	No

FINDINGS FROM THE PREVIOUS NCHRP-IDEA RESEACH *(8)*

This section summarizes the findings from the recently finished research funded by the NCHRP-IDEA program. For a specimen with a nominal wall thickness of 0.254 m, the presence of an empty steel duct with the internal diameter of 101.6 mm (concrete cover of 76 mm) was indicated by approximately 35% increase in apparent wall thickness compared to areas with no ducts. The presence of well-grouted steel ducts was indicated by only small increase (up to 10%) in apparent wall thickness. In addition, the findings from the research also indicated that the presence of empty steel ducts with a diameter of 40 – 120 mm can be detected in a panel with a nominal thickness of 0.3 meter. However, when the concrete cover of the duct was as deep as 190 mm for a duct with a diameter of 40 mm, the IES was unable to detect the presence of empty steel duct.

SUMMARY OF CURRENT RESEARCH

The results from the previous NCHRP-IDEA research project and the expanded internal research study show that ideal applications for the use of the IES to locate grout voids in bridge ducts include:

- Structures with a nominal wall thickness of 0.30 m or less. If a structure with a nominal thickness of 30 cm is tested, the depth of the concrete cover will normally have to be less than 190 mm for the IES to still correctly locate internal grout voids.
- With a constant concrete cover of 50 mm for steel ducts with internal diameter of 70 mm and the thickness of the panel between 0.20 – 0.30 m, the presence of grout voids (empty or partially filled) can be detected with a downward shift of the dominant frequency, in another words, an increase in the apparent thickness of the wall. The thinner the wall, the higher percentage of downward shift in the dominant frequency (upward shift in the apparent thickness). The results from this research showed that the use of the IES test was limited when the thickness of the panel is between 0.350 – 0.388 m. However, the presence of grout voids can be then again identified by shallower echoes (or higher frequency peak) when the thickness of the wall is between 0.425 – 0.612 m for ducts with the 50 mm cover noted. More research and/or theoretical modeling would be needed to verify the exact causes of this phenomenon.

- Fully grouted plastic ducts can be detected and verified as being grouted even if the ducts are partially debonded. It was discovered in the research that the spectrum of the partially debonded fully grouted ducts showed dual frequency peaks. The lower frequency represented the partially debonded condition around the ducts and the higher frequency represented the actual condition inside the duct, which was fully grouted in this case.

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] Tinkey, Y. and Olson, L.D., “Sensitivity Studies of Grout Defects in Post-Tensioned Bridge Ducts using Impact-Echo Scanning Method”, Journal of Transportation Research Board, 2007.

[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] ASTM C1383 "Test Method for Measurement P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method".

[7] 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

[8] Tinkey, Y., and Olson, L.D., “Non-destructive Evaluation Method for Determination of Internal Grout Conditions inside Bridge Post-tensioning Ducts using Rolling Stress Waves for Continuous Scanning”, submitted to IDEA Program Transportation Research Board National Research Council, Contract Number 102, July 2006