IDEA

Innovations Deserving
Exploratory Analysis Programs

Highway IDEA Program

Void Detection in Post-Tensioning Ducts Using Time-Domain Reflectometry

Final Report for Highway IDEA Project 98

Prepared by:
Robert G. Hunsperger and Michael J. Chajes; University of Delaware, Newark, DE

October 2006

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, http://www.nationalacademies.org/trb/idea)

Acknowledgements

The principal investigators gratefully acknowledge the many significant contributions of the following participating investigators:

Dr. Wei Liu
Department of Civil & Environmental Engineering

Jian Li
Laura Akl
Department of Electrical & Computer Engineering

University of Delaware
Newark, DE 19716

Eric G. Kunz, President & CEO
Vetek Systems Corporation
1660 Linda Drive
West Chester, PA 19380

Table of Contents

1. EXECUTIVE SUMMARY

Both the US and UK have developed significant concerns regarding the condition of post-tensioned segmental concrete bridges. The problem revolves around the fact that it is difficult to ensure proper grouting of post-tensioning ducts. When post-tensioned ducts are not completely grouted, and voids are present, the steel tendons are left vulnerable to premature corrosion.

The goal of this project was to develop an effective and economic nondestructive evaluation (NDE) procedure that will enable bridge owners to determine whether or not post-tensioned ducts are properly grouted (i.e., have no voids). The proposed NDE procedure utilizes Time Domain Reflectometry (TDR), a technique developed years ago by electrical engineers. TDR was originally developed for use in detecting discontinuities in transmission lines. The technique involves sending a signal through a transmission line using a pulse generator, seeing whether or not the signal is reflected back using an oscilloscope, and, if it is reflected back, using the time elapsed to determine the location of the discontinuity (in this case, a void in the grout).

To detect and evaluate voids the transmission line is placed either in, or adjacent to, the region in which a void is suspected. The presence of a void affects the electric field surrounding the transmission line and causes a reflection. We have previously used TDR to locate and evaluate corrosion sites on concrete-encased steel strands by observing reflections of the pulse from damage sites. In that case, a strand was used as one wire of the transmission line and a parallel sensor wire was added as the other. The corrosion represented a partial discontinuity in the line. In the case of a void, the discontinuity is in the material surrounding the transmission line. Such a change will also cause a reflection of the signal. In fact, studies indicate that the reflection due to a void is far stronger than that due to corrosion damage.

The research program has been set up to address the following questions: (1) Can TDR be used to effectively identify voids in grouted post-tensioning ducts, (2) How do various parameters affect the performance of the method, and (3) How can the methodology be implemented successfully and economically in the field.

Through the research, detection of voids using TDR with an internal sensor has been studied and evaluated. The basic possible geometries of the internal sensing transmission line have been investigated, and the most applicable and flexible geometries have been identified. It has been confirmed that voids can be detected by using a single sensor wire in conjunction with an existing tensioning cable to form the two-wire transmission line[3]. However, voids can also be detected by using commercially available transmission lines, such as lamp cord or 300 ohm TV cable as the sensor. These commercially available lines provide uniform geometry over their length and are relatively inexpensive. Detection of voids by using TDR with an external sensor has also been studied and evaluated. For external detection, the problem becomes more complex, because the reflected signal strength may be weaker and background noise reflections from other structural elements may make the signal difficult to measure. The methods used in internal detection must be modified for external detection. Possible variations include the change of the shape of the sensor wire, as well as the selective usage of single steel strands existing in the structure. The effects of different dimensions and geometry on signals measured externally were studied and evaluated. Results have shown that 1 inch diameter voids can be detected with an external sensor spaced up to 3 inches away, using an output pulse voltage of 200-250 mV and a rise time of 40-100 ps. The effect of increasing the peak pulse voltage was also studied. Data indicate that transmitting a larger pulse voltage can be expected to improve the signal to noise ratio. Some commercially available TDR meters that we have tested, with peak pulse amplitudes of several volts, may be applicable to void detection in the field.

Based on several experiments, factors that can influence the void detection signal have been identified and their effects on the signal have been quantified. The presence of sand, water or moisture in the void tends to decrease the positive amplitude of the reflected TDR signal. However, in all cases tested, the void was still detectable. In fact, in the case of a water-filled void in concrete, the negative amplitude of the reflected pulse was larger than the positive pulse from an empty void, making the water-filled void easier to detect. Compared with water, which could be dissipated after a short term, moisture is a long-term factor that influences the void signal. The moisture could come from water residue in the void or moisture penetration from outside the void. The moisture level appears to play a consistently significant role among the factors, while water, if it exists, plays a dominant role.

In Stage 1 of this project the work was concentrated on detecting voids by TDR using an internal sensor. In Stage 2 of this research we have concentrated on developing methods of void detection using an external sensor wire, such as would be necessary in the case of retrofitting existing structures. Data has been collected that indicates that voids can be detected with an external sensor, but the void signal is much weaker than that observed in internal detection. This weaker signal may be strengthened by use of a pulser with higher output voltage. Results have shown that, in the laboratory, 1 inch diameter voids can be detected with an external sensor spaced up to 3 inches away, using an output pulse voltage of 200-250 mV and a rise time of 40-100 ps. An ideal pulse generator for lab research also should have low-reflection connections and high data output resolution. In field practice, the situation is not always more complicated. When dimensions of the structure under test are much larger than the 1 meter size of our laboratory

samples, the situation actually becomes simpler, in that pulses of greater width can be used. Some commercially available TDR meters that we have tested, with peak pulse amplitudes of several volts, may be applicable to void detection in the field, whereas they are not effective with laboratory sized specimens.

The potential payoff of this research is significant as it is currently very difficult to ensure proper grouting of post-tensioning tendons. When post-tensioned ducts are not completely grouted, and voids are present, the steel tendons are left vulnerable to premature corrosion. This very issue led to the declaration of a moratorium on the construction of post-tensioned bridges by the UK's Department of Transport in 1992. More recently, distress and failure of post-tensioning tendons due to improper grouting were found in Florida on the Mid-Bay Bridge, and on others in Texas as reported by Moshen Shahawy of SDR Engineering Consultants at the 2005 TRB Bridge Engineering Conference in Boston, MA. While it is well known that incomplete grouting of ducts (i.e., voids) can leave tendons vulnerable to corrosion, effective and economic methods for detecting voids in post-tensioning ducts do not exist. In order to ensure that new post-tensioned, segmental concrete bridges will not prematurely deteriorate, which could result in major economic losses as well as potentially threaten the safety of the traveling public, new NDE methods are needed to ensure proper grouting in new post-tensioned applications. The research conducted on this project has demonstrated that TDR can be used effectively in this application.

In terms of technology transfer, the results of this project have been presented at TRB meetings and conferences as well as at ASCE conferences. The research team also maintains an ongoing cooperative effort with VETEK Systems Corporation, a commercial supplier of corrosion detection technology, and with the Delaware Department of Transportation (DelDOT). These interactions will help to facilitate implementation of TDR as a void detection tool for field application. On November 5, 2004 the research team met with a panel of regional experts to review the work done on this project. The members of the panel are: Dan Faust, Chief Engineer, Delaware River Port Authority; Dennis O'Shea, Asst. Director, DelDOT; Jiten Soneji, Bridge Design Engineer, DelDOT and Doug Finney, Bridge Management Engineer, DelDOT. A presentation describing our research and the results to date was made, and a demonstration of the process of locating a void using TDR was given. Following the presentation and demonstration, we had a very useful discussion with the panel members. The panel of experts said that they believed that our approach to void detection was a viable method for use in the field, and also that they did not think that the cost of the equipment required would be prohibitive. Current plans include use of TDR for monitoring post-tensioning cables in the soon to be constructed Indian River Inlet Bridge in Delaware. Other applications are being considered.

2. BODY

2.1 IDEA PRODUCT

The product of this idea project is a measurement system and technique for using Time Domain Reflectometry to locate and evaluate voids in grouted post-tensioning ducts. This is a nondestructive evaluation method that can be applied to both new and existing structures. Since voids tend to collect moisture and leave post-tensioning strands susceptible to corrosion damage, detecting and repairing them is very important to the maintenance of bridges and other structures.

2.2 CONCEPT AND INNOVATION

2.2.1 Introduction

Void detection in civil engineering has become an increasingly important issue in various applications such as bridge and infrastructure monitoring. The detection methods such as Ground Penetrating Radar and Tapping and Listening, however, are not as ideal as people would like them to be. Thus, a detection method that has improved feasibility, field-applicability and low cost, as well as accuracy, is needed.

Void detection using Time Domain Reflectometry (TDR) is a method currently under investigation in our laboratory. It has proven to be a useful method for detecting voids and also for detecting corrosion sites that are present. Corrosion detection using TDR has been established previously, both theoretically and practically[1-6]. A two-wire transmission line model of a sensor has been developed that can be used for either void or corrosion detection. In many cases, the steel tensioning cable can be used as one of the two wires and only a single sensor wire must be added in parallel to it. In other cases, a two-wire transmission line sensor is used. The relationship between model geometry and impedance has been thoroughly studied, and corresponding experimental results have been obtained. It has been found that the existence of voids is a major reason why corrosion occurs on steel strands. This is due to the accumulation of moisture in these voids. It has also been found that voids tend to occur prior to corrosion. Void and corrosion detection share a similar theory of TDR, though there are distinct differences experimentally.

This project, titled "Void Detection in Post-Tensioning Ducts Using Time Domain Reflectometry", has sought to solve the void detection problem. In the first stage of this project, possible geometries with a transmission-line sensor located internal to the sample under test were applied to detect voids, and the causes of signal returns from voids were thoroughly studied. Detection of voids with an external transmission-line sensor, or "external" detection, was investigated in the second stage of the project. External void detection using TDR is very important because it can be used to evaluate existing structures.

2.2.2 Basic TDR Theory in Void Detection

TDR is a well-established method in electrical engineering. It is widely used for detecting discontinuities in transmission lines. In TDR a microwave pulse is launched on a transmission line sensor as shown in Figure 1.

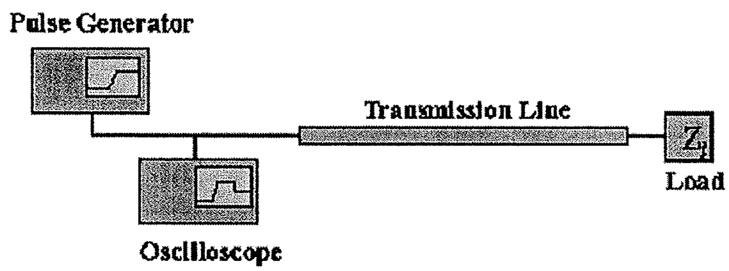

FIGURE 1 TDR measurement system.

Any discontinuity on the line, such as that created by a void or by a corrosion site, causes a reflection of the pulse that can be used to detect and locate the defect. The transmission line system is a two-conductor pathway for electromagnetic signal waves that are generated by the test-signal source. This transmission line is typically characterized using a distributed element model. Distributed elements have either a much larger or at least comparable size compared to the wavelength of the test signal. The elapsed time that the wave takes when passing these distributed elements is not negligible. The behavior of distributed elements can be described by a network of basic elements, which are resistance (R), capacitance (C), inductance (L) and conductance (G). Thus the characteristics of the transmission line system can be described using these basic elements.

With all four parameters, the characteristics of the transmission lines can then be described using the characteristic impedance (Z_0), which is given by:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \approx \sqrt{\frac{L}{C}},$$

where ω is the frequency of the signal waves on the transmission line and j indicates an imaginary number component.

Because both of the parameters L and C are directly related to the material properties, the impedance Z_0 is affected by the environment. When voids appear around the transmission line, the transmission line is no longer in contact with concrete, and thus the impedance changes. In transmission line theory, electromagnetic waves are reflected either partly or completely when the impedance changes. The magnitude of the reflection depends on the amount of change that occurs in impedance at the interface. The equation describing the fraction of the signal that is reflected, or "reflection coefficient" (Γ), is as follows:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z - Z_0}{Z + Z_0},$$

where V_r is the peak voltage of the reflected wave, V_i is the peak voltage of the incident wave, and Z is the line impedance at the point of reflection.

An example of a typical reflected voltage wave signal produced by a void is shown in Figure 2.

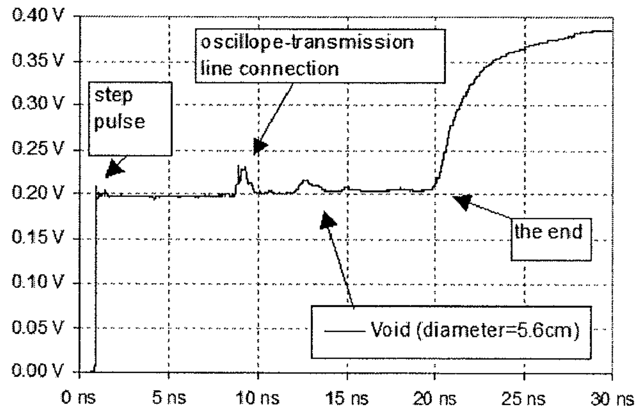

FIGURE 2 Reflected voltage wave signal.

This TDR return is a void detection result that is recorded by an oscilloscope located at the front end of the transmission line. The horizontal scale is the time at which the voltage change at the front end is recorded. The vertical scale is the voltage. A positive step pulse of 200 mV is generated by a pulse generator and sent down the transmission line. When the pulse first encounters the connection between the coaxial cable, which is at the outlet of the oscilloscope, and the transmission line, part of the pulse is reflected back to oscilloscope due to the impedance mismatch between the 50-ohm coaxial cable and the transmission line. The result is the bump indicated as the oscilloscope-transmission line connection. It is the reflection recorded by the oscilloscope at about 9 ns. The rest of the pulse continues traveling along the transmission line until it comes to a void that is present in the concrete. The void is located near the transmission line. The rest of transmission line, which is buried in the concrete, has a different impedance than that at the void. Because of the reflection of this void, a signal bump is formed and recorded by the oscilloscope. It is indicated as a 5.6 cm void in the signal chart. Because the velocity of the signal wave on the transmission line is known, the time scale on the horizontal axis can be converted to distance, so that the location of the void can be determined.

In this example, it can be seen that TDR utilizes the impedance change to detect the void. This impedance change involves many factors, such as geometry, material, weather, etc.

2.3 INVESTIGATION

The particular transmission line geometries used for void detection depend on whether the transmission line sensor can be placed internally within the concrete element under test or must be placed external to the structure. Both of these situations will be introduced in this section.

2.3.1 Analysis of Geometry Used for Void Detection with an Internal Sensor

Void detection shares a similar theory with corrosion detection in that the environment surrounding the transmission line determines its characteristic impedance, and discontinuities in the impedance indicate the occurrence of faults, such as voids or corrosion sites. The change in impedance results from the change of geometry of the steel cable in corrosion detection and the dielectric constant change in void detection. If a suitable sensor wire geometry is chosen for a particular steel cable for corrosion detection, often this geometry can also be used to detect voids that occur in the vicinity of the cable. However, in some other situations no steel cables are present, but sensors still have to be installed to monitor for the presence of voids. In that case a suitable two-wire transmission line sensor must be added. The transmission line model is composed of two conductors that can be varied to suit different situations. It is important that the characteristics of the transmission line be as uniform as possible over its length to avoid the generation of spurious reflections. As a result, some traditional transmission lines intended for other applications rather than void detection, such as lamp power cords and TV cables, have been considered for implementation. These transmission lines share some common features that make them attractive for void detection applications. Lamp cords and TV cables have a nearly perfect homogeneous geometry that can avoid background signals that are generated in the strand-sensor wire geometry due to inhomogeneous spacing between the wires. They are more flexible for application without the support of a strand and can be applied anywhere voids are suspected to occur without the required presence of a strand or rebar. In addition,

lamp cord and standard TV cables are relatively low cost products that are readily available. Experimental results show that TV cables and lamp cords are good candidates for void detection. These results are discussed in the Results and Analysis section.

2.3.2 Analysis of Geometry Used for Void Detection with an External Sensor

The previous analysis is primarily based on internal void detection using internal sensor wires. For detection of internal voids using external sensor wires, the problem becomes more complex, because the reflected signal strength may be weaker and background noise reflections from other structural elements may make the signal difficult to measure. Some preliminary data show that the methods used in internal detection must be modified for external detection. The geometries of a strand-sensor wire or TV cables and lamp cords cannot always be used effectively for external detection. New geometries, based on the theory of the transmission line model, will help avoid the difficulty encountered in external detection of voids. Possible variations include the change of the shape of the sensor wire, as well as the selective usage of single steel strands existing in the structure. In Stage 2 of this project, the effects of different dimensions and geometry on signals measured externally were studied and evaluated. The effect of increasing the peak pulse voltage was also studied. Data indicate that transmitting a larger pulse voltage can be expected to improve the signal to noise ratio.

2.3.3 Major Factors Affecting the Void Detection Signal

The research on void detection began with internal void detection, and many experiments were carried out to find the relationship between void signals and the surrounding environmental situations. Factors that affect the signal returns from the voids and thus jointly contribute to the visibility of the defect sites are as follows:

1. Corrosion
2. Sand or corrosion products
3. Water from rain or snow
4. Moisture which may fluctuate with weather

Corrosion will have various degrees of influence on the signal from a void depending on the particular situation. In the experiments, a 20% reduction of cross section was used as the standard degree of corrosion. Sand in the void was used to represent the corrosion products, sand/soil, or other natural materials that are used as an insulator and a dielectric media. Water and moisture play a very important role in determining the magnitude of the signal returned from a void. Experiments show that the void signal is very sensitive to both water and the level of moisture, and therefore the signal may fluctuate with the change of weather throughout the year. Water comes in the form of rain or melted snow, and it tends to gather in the void. Moisture, on the other hand, may be the result of water dissipation or can come by itself. All of these different factors are quantified in the Result and Analysis section, and their influences are analyzed in detail. However, it is convenient at this point to consider the general form of the relations that describe their effect on the signal returned by a void.

Both positive and negative effects occur due to these factors. Signal returns from defect sites where voids reside can be enlarged or reduced due to the presence of one or more factors. The reflection coefficient is just the sum of the reflection coefficients (positive and negative) of all of the factors.

Thus

$$\Gamma_{total} \approx \Gamma_{corrosion} + \Gamma_{void} + \Gamma_{sand} + \Gamma_{water/moisture}$$

From the equation, it can be seen that the reflections due to different factors can be separated and added. This provides a simple way in which factors can be easily subtracted from complicated experimental conditions and also can be investigated individually. When a real application environment is under consideration, on the other hand, the influence from several possible factors can be added and used to explain the final results. Experimental data will be presented and explained in the following sections.

2.3.4 Development of Experimental Techniques and Apparatus

2.3.4.1 The Sandbox Simulator

During the first stage of the project, it was found that a sand box is a good simulation tool that can substitute for the role of concrete in experiments because of the similar dielectric constants that the two share. Use of the sandbox simulator permits the collection of many more data points in a given experiment because the controlled variables can be much more quickly changed than would be the case if a multiplicity of concrete samples had to be fabricated. A comparison between results from a concrete sample and a sandbox sample is shown in Figure 3.

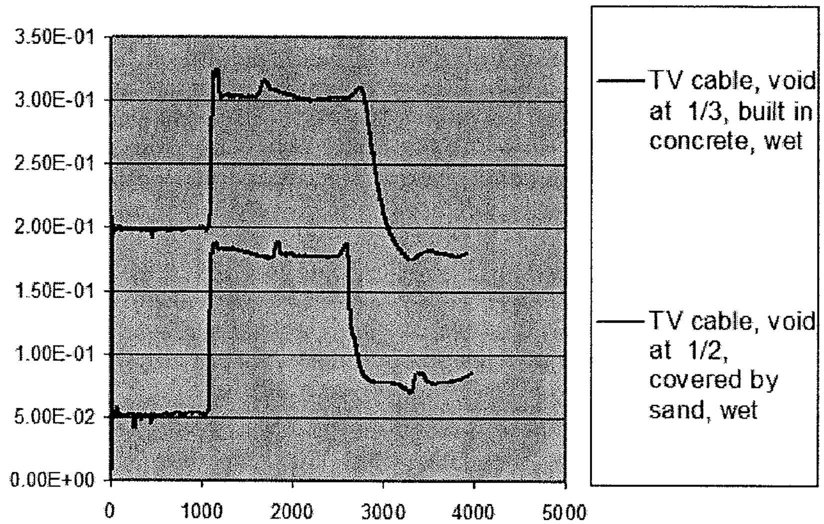

FIGURE 3 TDR returns from TV cables in concrete and sandbox simulation.

In the plot above, the reflection peaks returned from the concrete and the sandbox share the same shape and height, and the base lines of the curves also appear very similar. This, and other similar comparison data, verifies that a sandbox represents a good simulation of concrete. Because concrete samples take time to cure and the water content is constantly changing as the specimens dry out over the first month or so, the experimental process is prolonged and less controlled. With sandbox simulation, however, the experimental process is significantly shortened and more controlled.

2.3.4.2 Oscilloscope-TDR Sensor Connection Improvement

In TDR measurement, a signal is generated by the oscilloscope pulser and sent down the transmission line. This process unavoidably includes the two-way path that runs though the connection between the oscilloscope, coaxial cable and the sensor transmission line that is present in the form of a strand-wire or wire-wire geometry. At this connection a change in characteristic impedance occurs. The characteristic impedance of the cable is 50 Ohms. The transmission line, however, usually has larger impedance and thus a partial reflection of the input pulse occurs and the available electromagnetic energy used to detect voids is reduced. The solution to this problem varies according to different geometries. Strand/sensor wire geometry, for internal void detection, is particularly useful because of its easy installation and similar characteristic impedance compared to the oscilloscope coaxial cable. The solution for this situation is to try to decrease the physical size of the connection, making a smooth transition, and thus decrease the reflections from it. Figure 4 shows an example of connection improvement results.

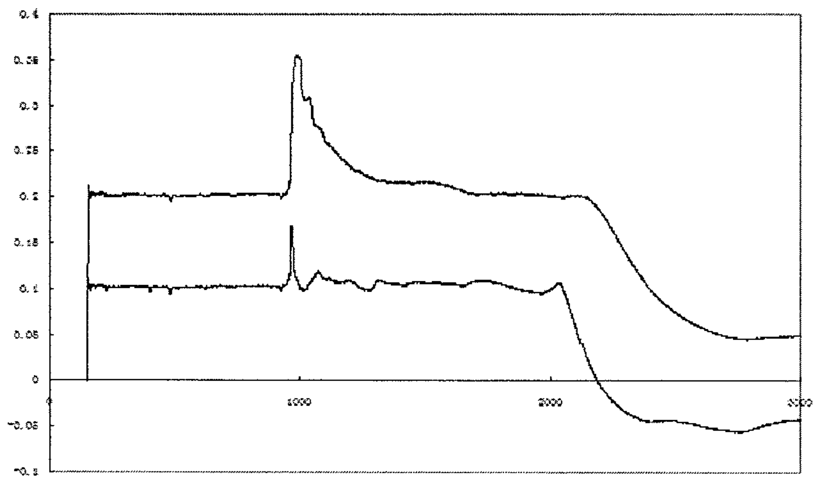

FIGURE 4 TDR return before (upper) and after (lower) connection improvement.

The plot shows that when the adverse reflection from the connection is reduced, the TDR system appears to be more sensitive, and thus the details of the environment surrounding the transmission line will be more visible. This definitely helps to enhance the detection ability of the TDR system. The method used to make this improvement in the case of strand-wire geometry is shown in Figure 5.

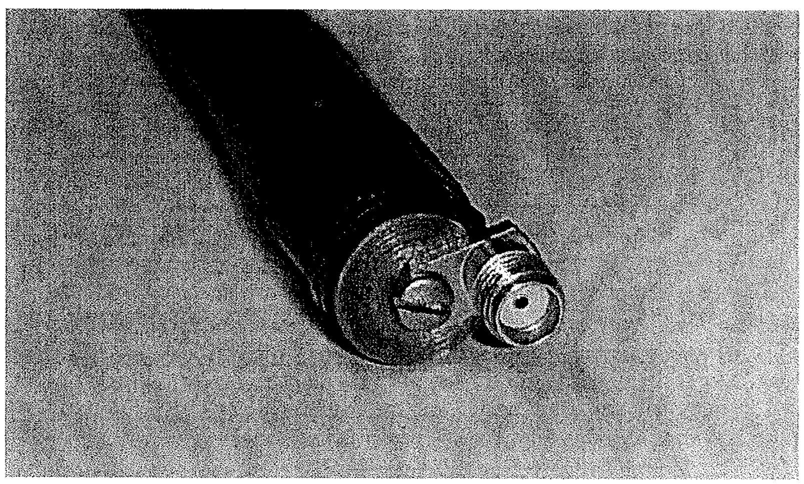

FIGURE 5 Improved connection to strand-wire sensor.

The geometry of the strand-sensor wire is very close to that of the connector, thus the connection geometry can be manipulated to diminish the reflection. The geometries of strand-strand or wire-wire sensors have proven to be more difficult ones in which to implement connection improvement. Experiments using a matching network of capacitors and resistors have shown some promise.

2.3.4.3 *Differential measurements*

Spurious reflections from the connection point to the sample can also be eliminated by making differential measurements. An initial reference baseline is measured either from a control sample known to be free of voids or from the test sample after the sensor is installed but before concrete or grout is poured. This baseline signal is electronically stored and later subtracted from the signal from the test sample. The resulting differential signal has low noise and is very sensitive to the presence of any voids, as shown in Figure 6.

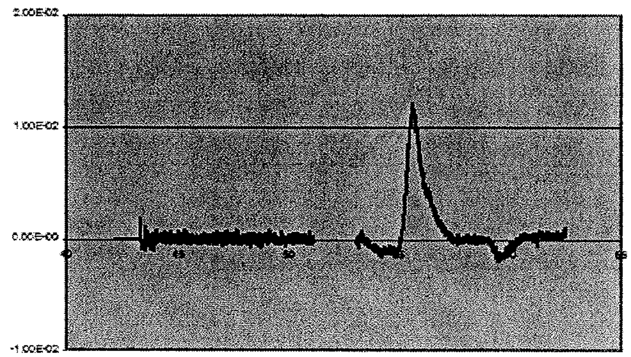

FIGURE 6 TDR differential signal from TV-cable sensor passing through a void

The plot shows the differential result from a TV cable that runs through a void simulated by a racquet ball. The sharp peak shows the sensitivity of differential measurements as compared to standard measurements.

2.3.5 Geometry Analysis, Comparison and Selection

2.3.5.1 Sensor Wire Geometry

Experiments have shown that inexpensive standard transmission lines, such as a 300 ohm "twin-lead" TV cable and two-wire lamp "zip" cords can be effectively used in internal and external void detection.

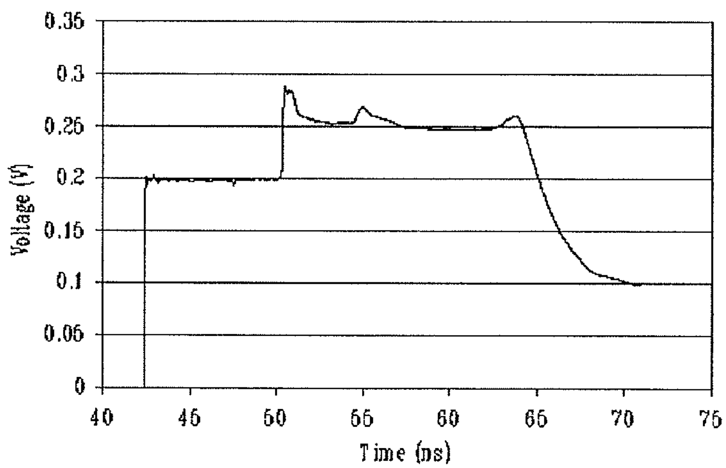

FIGURE 7 TDR return from void using lamp cord as sensor wire

Figure 7 shows the data obtained from a lamp cord that runs through a 2 inch diameter racquetball used to simulate a void in concrete. The curve exhibits less background noise than similar data obtained using the strand-sensor wire geometry, and the signal bump caused by the ball (at 55 ns) is also sharper.

Compared to two-wire lamp cords, the TV cable has a larger characteristic impedance than the lamp cord. The signal measured using a TV cable as the sensor is shown in Figure 8. It appears that there is not much of a difference from that obtained with the lamp cord except that the baseline of the curve is raised by 50mV due to the higher impedance.

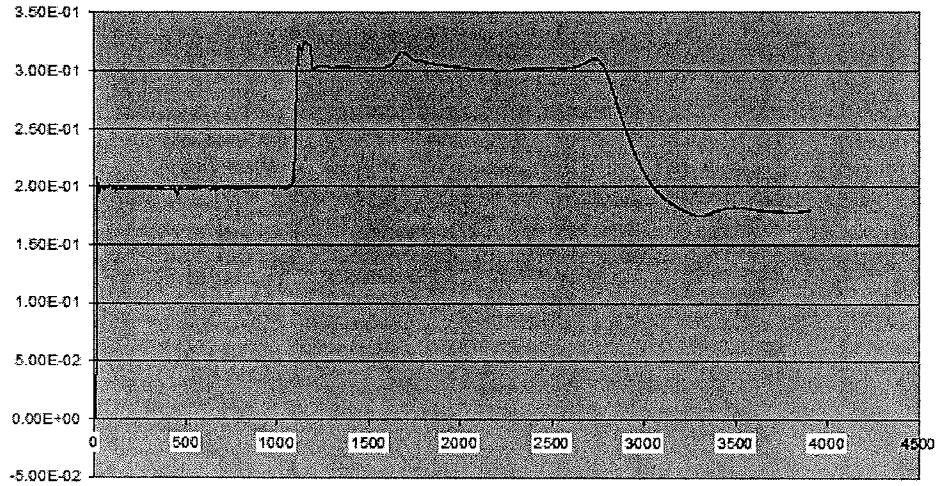

FIGURE 8 TDR return from void using TV cable as sensor wire

There are a few minor differences between the TV cable and lamp cord. The spacing of the two sensor wires is different. The TV cable has a spacing of about 1 cm while the lamp cord has about a 2 mm spacing. For internal void detection, if the cables run through the void, this may not make a difference. For situations in which voids may not be located directly on the path of the sensor but in the vicinity instead, the TV cable may show some advantage because of its wider spacing. The data obtained shows that both the twin pair and TV cable would be good candidates of sensors for internal and external void detection because of their consistent geometry, low noise, easy installation, good flexibility and low cost.

2.3.5.2 Standard Transmission Line Geometry Comparison and Selection

Standard, commercially available, transmission line geometries have proven to be very effective in suppressing the background noise signal due to the uniform geometry they have as compared to the variations in wire spacing that are inevitably incurred in the process of manually producing transmission lines. Therefore standard transmission line geometries are preferred in internal void detection, where another conductor, such as a steel strand, may or may not exist. Standard transmission line geometries are usually composed of two conductors running parallel to each other. The spacing between the two conductors is a more important parameter than others possessed by this geometry, such as conductor dimensions, insulation materials, etc. Among the standard transmission lines that are commercially available, inexpensive and with appropriate dimensions are the 300 ohm TV cable and conventional lamp cord, which represent the two ends of the range of wire spacing.

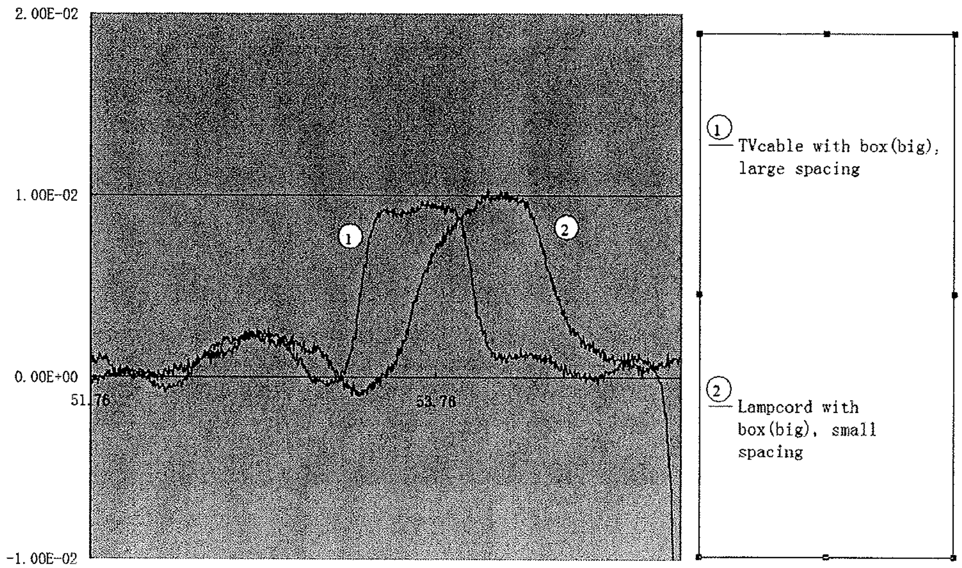

FIGURE 9 TDR returns from void using TV cable and lamp cord as the sensor

Figure 9 shows these two types of transmission lines running through a box-shaped void (3"x2"x5/4") with the line passing through the 3" dimension. The magnitudes of the void signals for the two transmission lines with different conductor spacing are very similar except for a small difference in timing that results from different propagation velocities of the waves on the different lines.

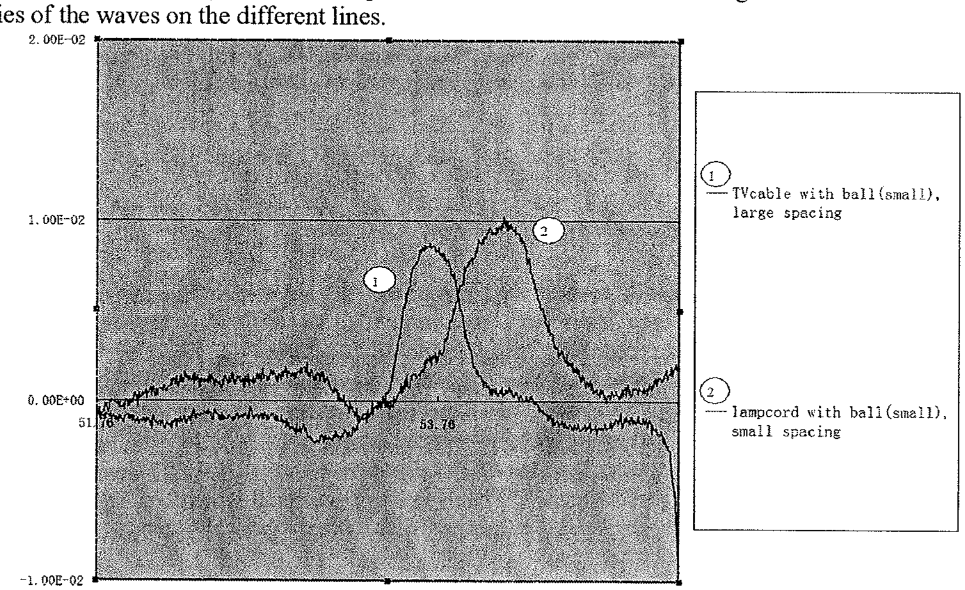

FIGURE 10 TDR returns from smaller void using TV cable and lamp cord as the sensor

Figure 10 shows TV cable and lamp cord running through a smaller ball-shaped void, which is 2" in diameter. Compared with the signals from the larger void of Figure 9, signals from the smaller void do not show a significant reduction in magnitude. However, there is a difference in the width of the signals due to shorter time elapsing for the electromagnetic wave to travel through the smaller void.

Multi-conductor computer ribbon cables are another source of standard transmission lines. They have the advantage of alterable spacing, since two conductors with the desired spacing can be selected and any conductors between them can be stripped out. Ribbon cables can be easily customized to transmission lines with conductor spacing ranging from being similar to that of lamp cord to even larger than that of TV cable. Although they cannot be applied

directly to field use due to variations that inevitably occur in the conductor stripping process, they are still an excellent simulation tool for choosing the proper spacing for standard transmission lines.

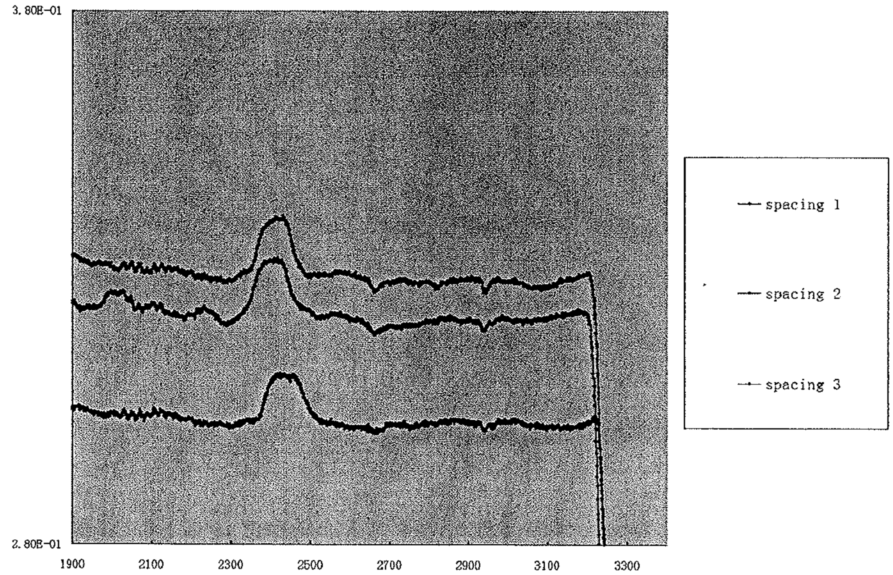

FIGURE 11 TDR return from void using computer ribbon cable as the sensor.

Figure 11 shows the results obtained from ribbon cables with various spacing. The top curve shows the spacing similar to a TV cable while the bottom one shows the spacing slightly smaller than a lamp cord. The middle curve shows spacing that is the average of the previous two. The void signals range from about 9 mV to 11 mV, which is in a range consistent with signals from the TV cable and lamp cord. Some minor differences in magnitudes and shapes are negligible considering differences of materials, metal dimensions, experimental conditions and other errors that may arise from equipment, etc.

From these experiments and observations, some conclusions can be drawn regarding the choice of the standard transmission lines for internal void detection. The spacing of conductors is not a critical factor that can influence the signal magnitude and thus the "visibility" of the voids. Smaller spacing might contribute to slightly sharper pulses and higher magnitudes of void signals. However, this slight advantage may be offset by its vulnerability to the smaller vicinity that the sensing field extends over. As for the commercially available standard transmission geometries of the TV cable and lamp cord, we prefer the TV cable for most of the cases in general use. This is because the TV cable is commercially used for transmission lines for high frequency signals; thus it has a perfectly uniform geometry. Its composing dielectric material is also more suitable for carrying electromagnetic waves than that of Lamp Cord, which is originally designed only for carrying electrical power at a very low frequency. We may not, on the other hand, exclude the lamp cord from field use in case small dimensions are preferred in a particular application.

2.3.5.3 Sensitivity research in a special geometry for external void detection

In the case of internal void detection discussed in the previous section, two conductors were both located in the structure with a fixed geometry and spacing. However, the sensing transmission line may also come in another form in which only one conductor is present in the structure, and this conductor can be used to detect voids that lie on it by using another conductor externally. This is demonstrated by experimental results obtained from our sand box layout described below. Experimental test results have shown that measurements made in the sandbox are equivalent to those made in concrete.

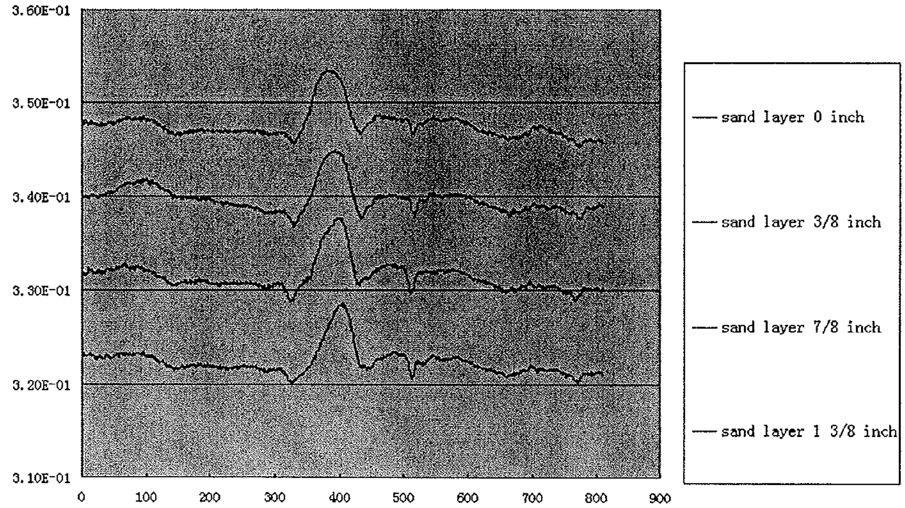

FIGURE 12 TDR return from void using an external sensor wire with different sand layer thickness

Figure 12 shows the data we obtained from our experimental layout. One conductor bearing a void was built in the sandbox, and the second conductor was laid on the top of the sand layer, composing the TDR transmission geometry together with the first one. From the top to the bottom in Figure 12, the four curves represent the TDR returns from different layer thicknesses of 0, 3/8, 7/8 and 1 3/8 inches. With the increase of thickness, there is a trend that the signal bump gets narrower in width and sharper in shape, but the magnitude does not show any significant decrease with the increasing distance between the two conductors. This data proves that an externally deployed sensor wire can work effectively with an existing conductor in a structure to detect voids and the signals will still have very favorable shape. This conclusion could be widely applied to detect voids in the situation where a conductor, such as a steel strand, exists in the structure.

2.3.6 Effects of Major Factors on Void Detection

2.3.6.1 Effects of Corrosion By-Product Accumulation in the Void

Corrosion by-product accumulation in the void is an important issue because it is suspected to suppress the void signal, making detection more difficult. During Stage 1 investigations, experiments were carried out on this topic, and significant data was obtained.

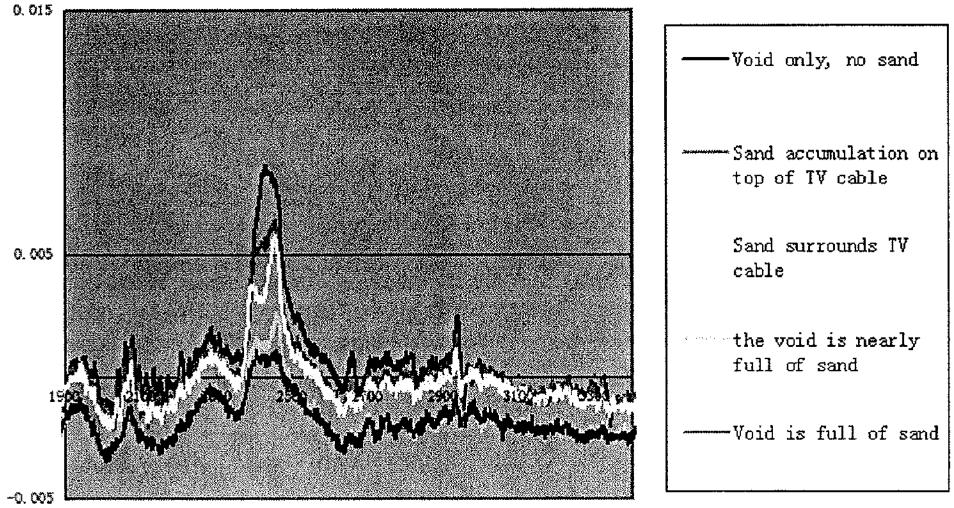

FIGURE 13 Sand accumulation in void in sandbox

Figure 13 shows the process of sand accumulation in the void. From the top to bottom, the curves represent different amounts of sand in the void, with the top the least and the bottom the most. It can be seen that sand does play an important role in suppressing the void signal. When the sand accumulation reaches roughly the half of the inner volume of the void, especially the space which the transmission line spans, the void signal could be reduced to half.

The previous experimental results are based on measurements made in the sandbox, which has proven to be a very efficient tool compared with real concrete that usually takes weeks to dry completely and is very hard to probe into in case a question arises. However, corresponding measurements in concrete are necessary to prove the validity of the data and conclusions, even though concrete and sand share very similar electrical properties.

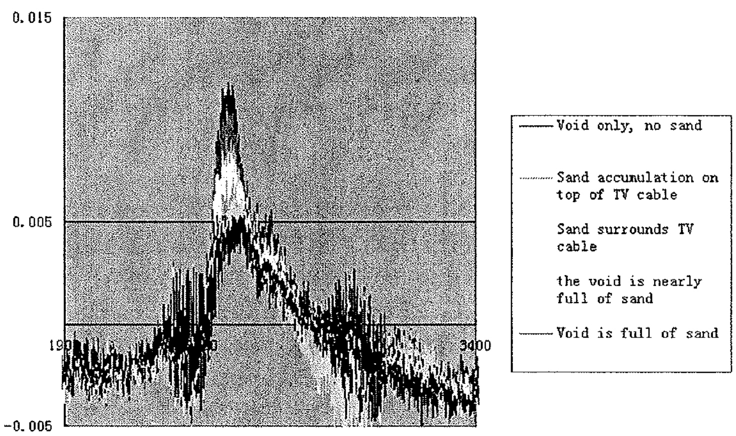

FIGURE 14 Sand accumulation in void in concrete

Figure 14 shows the same experiment as Figure 13, but carried out in concrete. The curves are in the same sequence from the top to the bottom of the figure. It can be seen that the internal void signal in concrete has a higher magnitude than that in the sandbox. The sand accumulation, on the other hand, does not appear to have a similarly strong suppressing effect on the void signal. These bring us two conclusions. First, the sandbox is a relatively "conservative" tool for internal void detection; if a simulated void can be detected in the sandbox, it can be expected to be visible in concrete as well, with even a larger signal. Thus the sandbox can be of great use considering its flexibility for

reassembling and control of experimental conditions. Secondly, we can conclude that sand accumulation is not such a bad factor in concrete as in sandbox simulation. This fact is favorable for real practice where concrete is the normal situation.

2.3.6.2 Effects of Water or Moisture Accumulation in the Void

The existence of water and moisture is believed to be the major condition in which corrosion initiates. When water or moisture gathers in the void, both of them have a strong influence on the void signal, and different levels of moisture correspond to different degrees of influence. On the other hand, water or moisture level basically indicates the potential problem of corrosion, and thus they have to be monitored carefully. Thorough work has been done on the effects of water and moisture both in the sandbox and in concrete, and positive results were obtained.

Water has the strongest negative effect on the void signal because of its dielectric constant of 81. It will completely devour the positive signal bump from the void and form a negative signal bump.

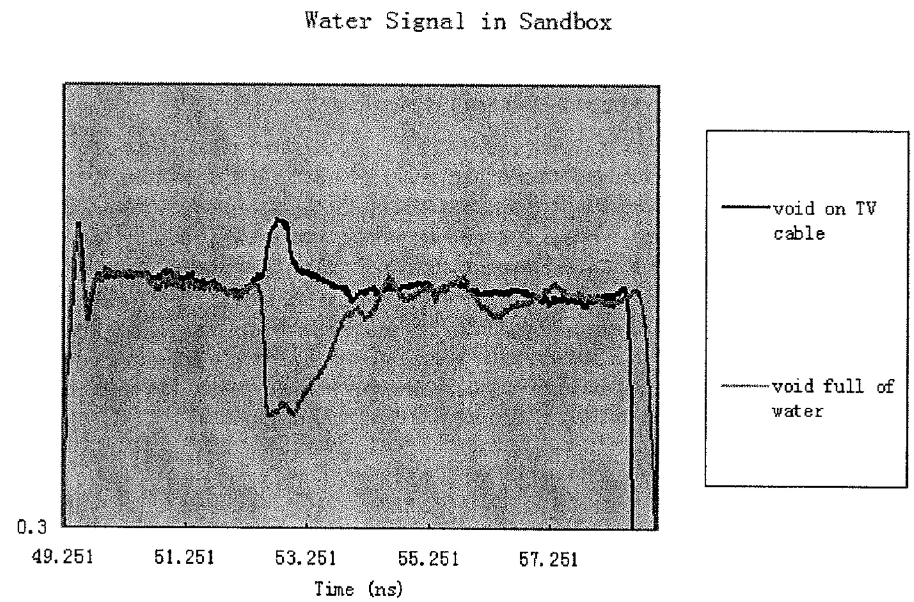

FIGURE 15 TDR return from void filled with water in sandbox.

Figure 15 is the signal curve recorded from the void filled with water in the sandbox. The original void signal bump is roughly half the size of the water bump. The water-filled void is even more apparent than the empty void and will be easily detected. Thus water, in some cases such as after a rainy season, would be beneficial for indicating the possible existence of voids. This also suggests a way of detecting voids in which the degree of the signal fluctuation due to the environment can be used as an indication of the existence of voids.

Compared with water, which could be dissipated after a short term, moisture is a long-term factor that influences the void signal. The moisture could come from water residue in the void or moisture penetration from outside the void. The influence from moisture usually fluctuates with weather and season, and other factors such as rain, moisture in air, temperature, etc. will change the moisture level. The influence from detailed moisture levels has been studied, and data was obtained and analyzed.

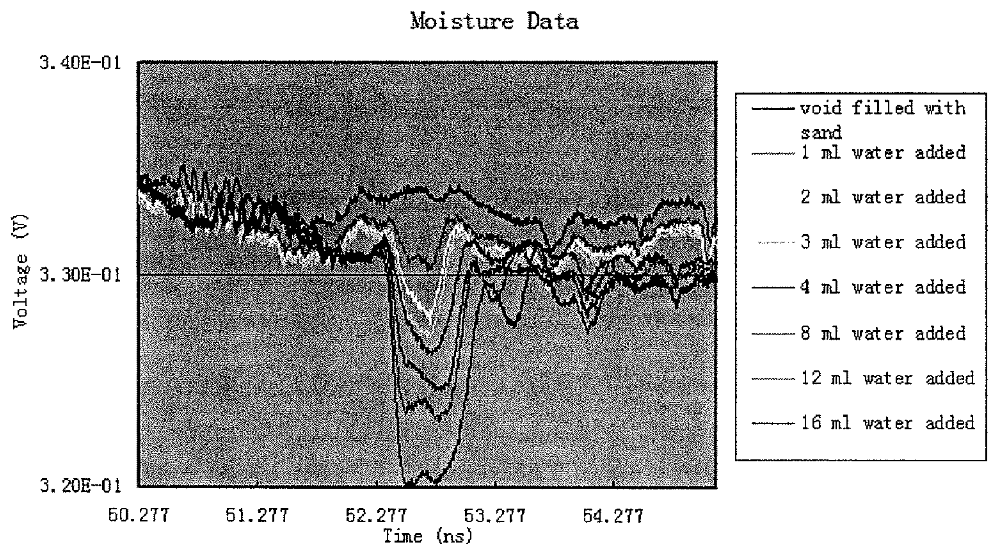

FIGURE 16 TDR return from void influenced by different moisture levels.

Figure 16 shows the results of signal bumps from different moisture levels.

The sandbox has proven to be an excellent experimental tool for research in void detection. It has, on the other hand, some minor deviations from real structures composed of concrete. The same moisture experiments also were carried out in concrete, and similar results were obtained, as shown in Figure 17.

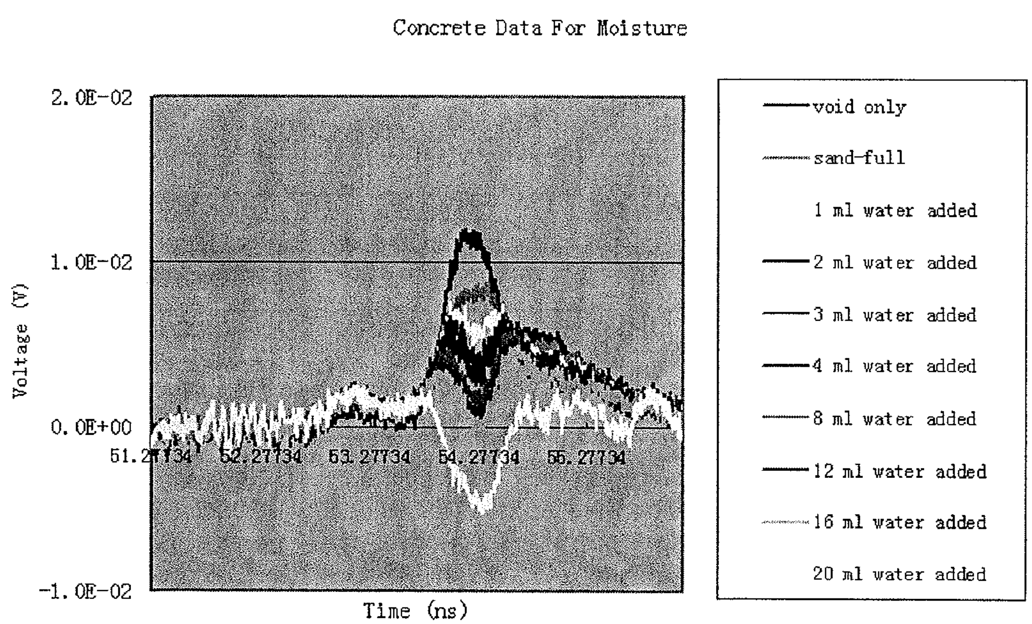

FIGURE 17 Different moisture levels in concrete.

Compared with the results from sandbox, it can be seen from this plot that voids have higher magnitudes when they are surrounded by concrete rather than sand. Moisture, on the other hand, has a weaker influence on the void signal

bump than it does in concrete. This result brings the benefit that voids in the real environment could be slightly easier to detect.

2.3.7 Test of Commercial TDR Meters and Pulsers

There are a number of portable TDR meters that are produced commercially for use in testing electrical cables and transmission lines, such as telephone lines, high-voltage power lines and cable television lines. These are all battery powered, lightweight, suitable for field use and relatively inexpensive. A table listing the advertised characteristics of these meters is provided below. Fortunately, we have been able to borrow some of these meters in order to experimentally test them and to evaluate their suitability for use in detecting voids. The results of these tests are reported in the paragraphs following the table.

Meter name and model	**TDR900 Hand-held TDR meter/ Cable Length Meter**	**E2550 Handheld Battery Powered TDR meter**	**Biddle CFL510E TDR meter**	**Metallic Cable Tester 1502C**	**Biddle CFL535E TDR meter**
Manufacturer	Megger	Instronics, Inc.	Megger	Tektronix	Megger
Detection method	Open or Short end only	Locate faults on cables	Identify a wide range of cable faults		Identify a wide range of cable faults
Peak to peak output voltage		5V	5V	300mV	14V PtoP into open circuit, 7V PtoP into 120 Ω
Impedance	Auto output impedance adjustment to match 25 Ω, 50 Ω, 75 Ω, 100 Ω, 125 Ω, 150 Ω	25 Ω, 50 Ω, 75 Ω, 100 Ω	25 Ω, 50 Ω, 75 Ω, 100 Ω	50 Ω	25 Ω, 50 Ω, 75 Ω, 100 Ω
Range	5m-3km	10m-3km	30-9000feet, approx.10-3km	2,000 feet, approx. 600meters	150-48,000 feet, approx. 50-16 km
Accuracy, Resolution	±2%, 50cm throughout entire range	±1%,	4 in on shortest range	±3% voltage accuracy, 0.05in(0.12cm) resolution	±0.1% for all ranges, 4in up to 600ft, 8in up to 1200ft
Applications	Any cable consisting of 2 metals and up	Most types of cables from telecom, power cables, etc.	Telephony, CATV/Cellular, power cables with various faults	Telephony, CATV/Cellular, power cables, etc. with various faults	Telephony, power cables with various faults

Meter name and model	TDR900 Hand-held TDR meter/ Cable Length Meter	E2550 Handheld Battery Powered TDR meter	Biddle CFL510E TDR meter	Metallic Cable Tester 1502C	Biddle CFL535E TDR meter
Other features		128x64 pixel LCD	128x64 pixel LCD	Rise time 200ps	Adjustable pulse width for different range. Dual input/output ports, 15 internal memory positions, RS232 interface
Dimension and Weight	9.25Hx3.94Wx1.73D in., 450g	199Hx90Wx54D mm., 0.6kg	9.05Hx4.5Wx1.88D in., 0.6kg	6.5Hx12Wx19D in., 23lb (10kg)	9.8Hx7.9Wx4.3D in., 3.3lb (1.5kg)
Price	$350	$1,305	$1,475	$1,545	$2,795

Table 1. Specifications of commercially available handheld TDR meters

2.3.7.1 Test of Tektronix 1502 TDR Meter

The Tektronix 1502 TDR meter has a rise time of 200ps and a magnitude of 300 mV. The results show that this instrument has a similar performance in internal-sensor detection as our Agilent 54754A TDR module, which has a rise time of 40ps and a magnitude of 200mV. They can both detect a defect with the size of 2 inches and give out a good magnitude of signal. Using a 200 ps step pulse, however, the 1502C meter cannot capture details of this defect, such as the influence of different moisture levels. While the 300 mV magnitude pulser can work similar to the 54754A in internal detection, neither of them will yield good data in external void detection.

The advantages of 1502 meter are its portability and simplicity compared to the Agilent counterpart. As a commercial unit, it has a smaller dimensions and simplified real-time differential operations. This makes it an attractive field application unit in cases in which the length of the element under test is several tens of feet or more, and an internal sensor wire is used. In laboratory research, it cannot replace the Agilent 54754A.

2.3.7.2 Test of Megger CFL 535E TDR Meter

The Megger CFL 535E TDR meter has a rise time of 20 ns and a pulse magnitude of 14V. The results from this unit show that the rise time is too long for laboratory research. However, it can still detect a moisturized area with the size of 4 feet. This capability makes the unit suitable for long range and large defect detection.

2.3.7.3 Test of Riser Bond 1270A TDR Meter

This unit has a rise time of "sub-ns" to 2 ns and a magnitude of 4 volts. Preliminary data show that this unit has a large range of 10-20km. It therefore can be a good candidate for field applications where the target is long. Although it has a rise time of several hundreds of ps to 2 ns, it does not perform very well in internal void detection. The results show that it can only detect a moisturized area with the size of 3-4 feet. It cannot internally detect a defect with the size of inches, neither can it detect externally. One reason that it cannot perform as well as expected from a meter with a sub-ns rise time is that it has a high noise connection and very "bumpy" signal baseline. Because of the background noise and bumps, and its low resolution because of long range, this unit insufficiently utilizes its inherent detection ability with its sub-ns rise time.

This unit thus can be used for long cables, in which the noise generated at the initial connection point is not so significant. It also may be used for short range measurements after its connection noise is reduced by a suitable microwave connector.

2.3.7.4 Test of Higher Voltage Pulsers

Since preliminary results have suggested that a larger pulse voltage would produce greater detection sensitivity when using an external sensor, we ran a series of experiments using separate pulsers, with larger output voltages than the 200 mV output of our Agilent TDR Meter.

Figure 18 shows a setup used to detect voids externally with a higher power pulser and a separate oscilloscope... A pulse generator was connected to a 300-ohm TV twin-lead cable. A void was simulated by a racquetball buried in the sandbox. The 300-ohm TV twin-lead cable was laid next to the surface of the sandbox and used as the sensor wire. The oscilloscope was connected to the sensor wire to detect the void.

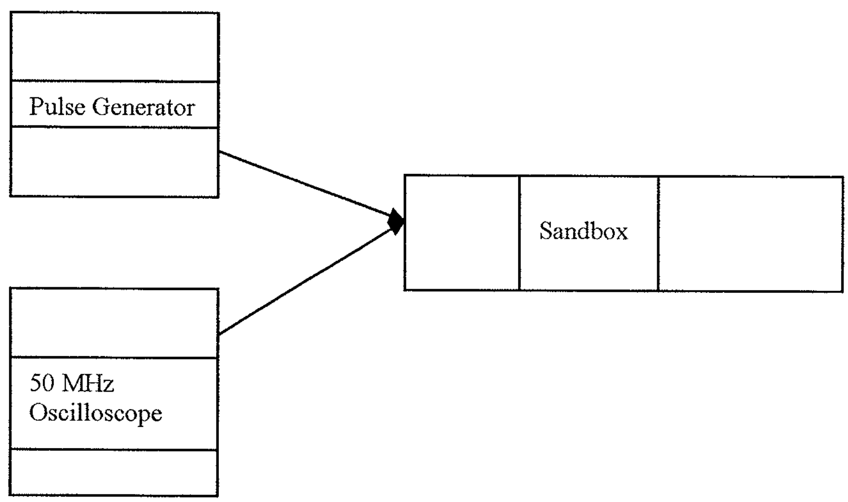

Figure 18. Setup of External-Sensor Void Experiments.

Two types of pulse generators were used, one with a 500 ns rise time and the other with a 40 ns rise time. Figure 19 shows the plot using a pulse generator with a 500 ns rise time and an output voltage of 1 volt. The uppermost plot is the measurement with no void. The lower plot is the measurement with the void; and the middle plot is the differential measurement between the other two plots. Results show that this pulse generator and oscilloscope combination was not sensitive enough to produce a strong signal at the location of the void, even with an output voltage of 1 volt rather than the 200mV output that we have used in previous void detection experiments with our Agilent TDR apparatus.

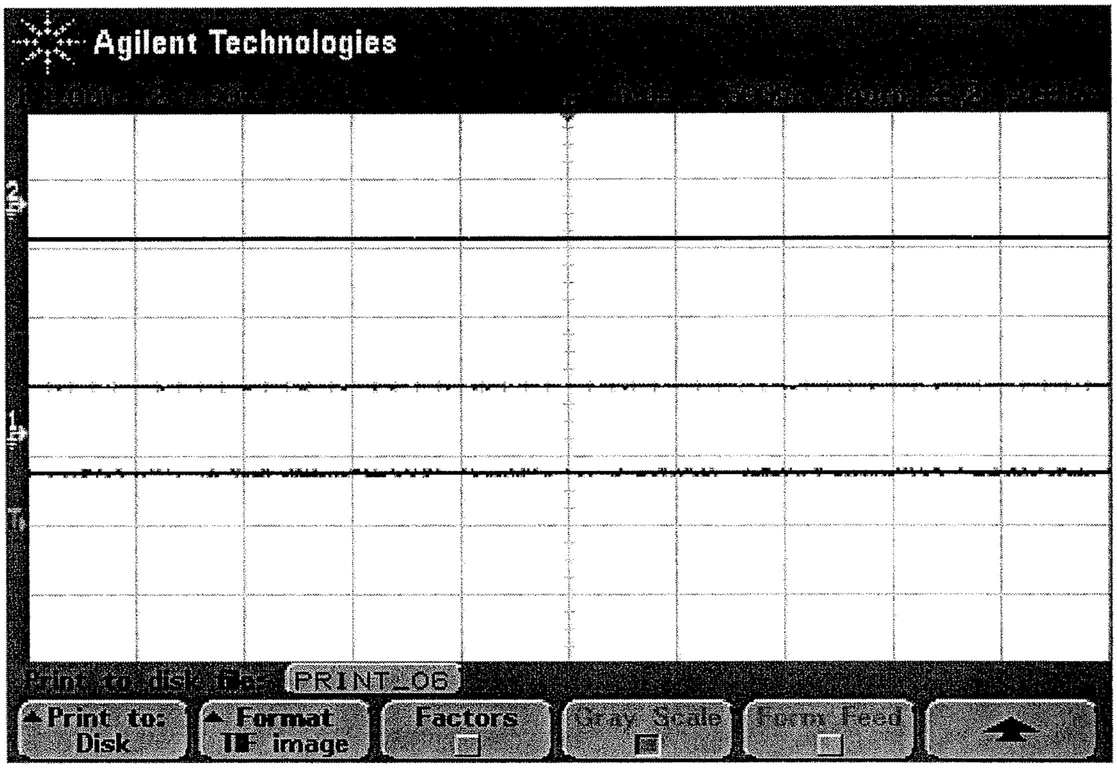

Figure 19. Plot for External Void Detection

Because past experiments have proven that a void filled with water is easier to detect an empty void, an experiment was conducted to determine if a stronger signal would result at the location of the void if it were filled with water. The peak (negative) voltage should increase in magnitude with increasing water. However, the results were the same as in the figure above. The system did not sense the void filled with water. As a result, the experiments were repeated with an output voltage of 5 volts and a 500 ns rise time. The experiment was repeated with an out put voltage of 5 volts, and then 10 volts, on both empty void samples and samples filled with water. Still the change in the signal at the location of the void was too small to easily differentiate it from the background noise. It was concluded that the void was not detected because of the 500 ns rise time of the previous pulse generator, so a pulse generator with an improved rise time of 40 ns was used. The output voltage in this setup was 2 volts, the maximum obtainable with this pulse generator. However, this setup also did not sense the void.

These results demonstrate the difficulty of using a separate pulse generator and oscilloscope rather than a congruently designed TDR meter that embodies both functions. Mismatches in impedance between the separate components cause reflections that raise the background noise level and mask the desired signal.

2.3.7.5 TDR Measurements Using Tektronix TDS 8200 TDR Meter

The Tektronix Model 8200 TDR Meter is a laboratory instrument akin to the Agilent combined pulser and oscilloscope that we used for the internal-sensor measurements. It is not battery operated, and it has a peak output voltage of only 250 mV. However it has a very fast rise-time of less than 35 ps, and it features real-time differential measurements. In real-time differential measurements, data is collected simultaneously from the sample under test and from a control sample. This is in contrast to comparison of the signal from the sample under test to that of a digitally stored control sample. The real-time differential approach did increase the sensitivity of TDR measurements with an external sensor. TDR response signals were measured in the sandbox, comparing the signal from a control sample with no void present to another line spaced at various distances from a 1-inch diameter void. The sensor in each case was a length of 300 ohm TV cable. The reflection from the void was detectable with the sensor placed externally as far as 3 inches away from the void. The results are shown in Figure 20.

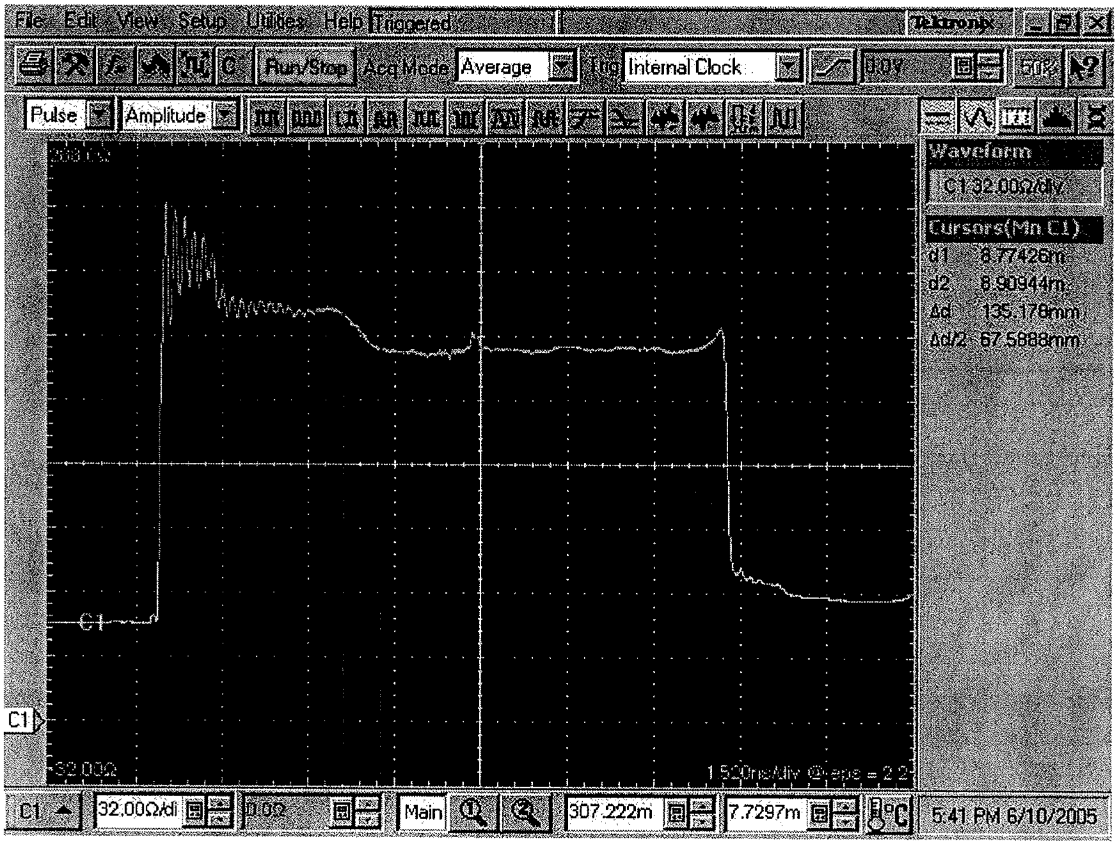

Figure 20 Real-Time Differential TDR Signal from Void Spaced 3 in from External sensor.

The reflected pulse from the void can be clearly seen at the center of the waveform. In similar external-sensor measurements made with our Agilent TDR meter, using a digitally-stored reference signal for differential comparison, a sensor spacing of only 1.5 inch was possible before the reflection from the void was undetectable. Most of this improvement is attributed to the real-time differential method, since the peak pulse voltage was only slightly larger than that of the Agilent TDR meter.

2.4 PLANS FOR IMPLEMENTATION

To implement these techniques on post tensioning cables, we must first define the scenario of the field application. The following are planned uses: New construction, and existing construction with external cables and with internal cables. Lets us discuss the new construction case first.

For new construction, the opportunity exists to install, at the time of construction, a simple, inexpensive run of insulated braided copper wire, about 14 gauge, along the length of the PT cable strand bundle before grouting. This can be a single wire strand, or lamp cord, or a run of 300-ohm TV cable. Either way it should be run the full length and be left hanging out of the grout bleed-ports in the tie off plates at each end. Then, after grouting, a signal can be sent and the completeness of the grouting from one end to the other can be evaluated, even before the grout has cured when repairs and back fills are the easiest. The next step would be for DOT's to begin using this technique as a QA/QC tool on new construction projects. Planning is currently underway to use this technique on post tensioning cables on the Indian River Inlet Bridge, a structure that is soon to begin construction in the State of Delaware. The technique will first be evaluated on ducts that are used to test the grouting procedure.

For existing construction, fewer opportunities exist. In cases of internal post tensioning, typically no internal insulated second wire exists to act as the return signal wire (the strands are the first wire). Thus, only in cases of external post tensioning can cables be inspected where an insulated wire, lamp cord, or 300-ohm TV wire can be applied to the outside surface of the PT cable duct. In this configuration, using a strong, minimum 5 volt, pulser with a rise time in the 100 picosecond range is appropriate. A sensitive digital oscilloscope for the readings is also called for. Thus, trained professionals should carry out these inspections.

Further, to inspect the PT cable ends near the anchorage plates, an inspection wire of the 300-ohm variety would have to be inserted into the bleed ports at each end where a void is assumed to be present. Once the bleed ports on the ends of any or all existing PT cables are opened it would probably be more prudent to employ a bore scope type inspection technique and gain a visual record of the interior condition should a void at the end plate actually be present. That way the extent of the existing voids and the attendant corrosion damage can be learned before the void is refilled with fresh grout. There are no present plans to conduct post construction inspections although it certainly wouldn't be cost prohibitive to do so.

2.4.1 Regional Experts Meeting

On November 5, 2004 the research team met with a panel of regional experts to review the work done on this project. The members of the panel are: Dan Faust, Chief Engineer, Delaware River Port Authority; Dennis O'Shea, Asst. Director, Delaware Department of Transportation (DelDOT); Jiten Soneji, Bridge Design Engineer, DelDOT and Doug Finney, Bridge Management Engineer, DelDOT. We gave a presentation describing our research and the results to date, and also demonstrated the process of locating a void using TDR, with the help of the sandbox simulator. Following the presentation and demonstration, we had a very useful discussion with the panel members. They said that they believed that our approach to void detection was a viable method for use in the field, and also that they did not think that the cost of the equipment required would be prohibitive.

3. CONCLUSIONS

An inexpensive NDE technique has been developed in an effort to locate and identify voids in newly grouted post tensioning ducts. These voids, if undetected, can leave post tensioning strands vulnerable to corrosion. Corrosion caused by such grout voids have led to the failure of several post tensioning strands in recent years. This same NDE technique is also useful in some cases to inspect existing PT cables whose ducts are external (i.e. not encased within the cross-section).

Detecting voids using TDR with either an internal sensor or an external sensor has been studied and evaluated. The basic possible geometries of the internal transmission line have been studied, and the most applicable and flexible geometries have been identified. It has been confirmed that voids can be detected by using a single sensor wire in conjunction with an existing tensioning cable to form the two-wire transmission line. However, voids can also be detected by using commercially available transmission lines, such as lamp cord or 300 ohm TV cable as the sensor. These commercially available lines provide uniform geometry over their length and are relatively inexpensive.

Factors that could influence the void detection signal have been identified and their effects on the signal have been quantified. The presence of either sand, water or moisture in the void tends to decrease the positive amplitude of the reflected TDR signal. However, in all cases tested, the void was still detectable. In fact, in the case of a water-filled void in concrete, the negative amplitude of the reflected pulse was larger than the positive pulse from an empty void, making the water-filled void easier to detect.

Results have shown that, in the laboratory, 1 inch diameter voids can be detected with an external sensor spaced up to 3 inches away, using an output pulse voltage of 200-250 mV and a rise time of 40-100 ps. An ideal pulse generator for lab research also should have low-reflection connections and high data output resolution. These characteristics are achievable with an Agilent 54754A TDR module in an Agilent 54750A digitalizing oscilloscope or with a Tektronix Model TDS 8200 digital oscilloscope fitted with an 80E04 TDR sampling module. However, the output voltages of 200 mV and 250 mV (respectively) are believed to be too small for field applications, where distances are greater and background noise may be higher. The commercially available, higher-output TDR meters that we borrowed and tested were not as effective in external-sensor void detection as we had hoped they would be. Even though they had higher output voltage, the rise times were in the nanosecond or millisecond range rather than the desired picosecond range. Similarly, the higher-voltage pulse generator/ separate oscilloscope setup that we used in our lab proved to be ineffective in detecting small voids with an external sensor because of the relatively slow 20 ns rise time.

However, in field applications, conditions are different. The dimensions of target cables usually range from several meters to hundreds of meters in length; thus, the range must be greatly expanded from our current lab range of several meters. The size of defects, on the other hand, may also be larger than the 1-2 inches we used for experiments. A voided area may run from several inches to a foot or more. The smaller the defects, the less detrimental they are to the infrastructure. With these two features in mind, the TDR meters used for field applications can have a rise time of several hundreds of picoseconds. Based on the previous analysis and on our experience, this rise time should have a good resolution for a defect with a size of several inches or more.

The magnitude of the step pulse can be increased because there is no need for severe compromising with rise

time, as the requirement on rise time is no longer as critical. Thus some commercially available meters, with pulse magnitudes of several volts, possibly can be applied directly in field applications. Considering the cost of acquiring a pulse generator with both high voltage and short rise time, and the difficulty we faced in external void detection with a 200-250 mV step pulse, we suggest a compromise of voltage and rise time at a voltage of about 2-10 volts with a rise time range from 100 ps to several hundreds of ps.

4. INVESTIGATOR PROFILES

MICHAEL J. CHAJES, PhD, PE, is a Professor and Chair of Civil and Environmental Engineering at the University of Delaware. Dr. Chajes is also a registered Professional Engineer in Delaware, and served on the state's Professional Engineering Registration Board from 1995 to 2000.

Dr. Chajes is a member of the ASCE and currently serves on the Department Heads Council Executive Committee (DHCEC). Dr. Chajes is also a member of the American Concrete Institute, and the American Society of Engineering Education. He serves on several committees, including TRB's Committee A2C05, Dynamics and Field Testing of Bridges.

Dr. Chajes was an undergraduate civil engineering student at the University of Massachusetts at Amherst and graduated with honors in 1984. After receiving his bachelor's degree, he attended the University of California at Davis (UCD) and received his M.S. in 1987 and his Ph.D. in 1990.

In September of 1990, Dr. Chajes joined the faculty at the University of Delaware as an Assistant Professor of Civil and Environmental Engineering. He was promoted to Associate Professor in 1996, and to Professor in 2002. He served as Acting Associate Chair in 1996, and as Associate Chair from 1998-2001. In July of 2001, Chajes was appointed Chair of the Department of Civil and Environmental Engineering. Dr. Chajes is currently a member UD's Chairs Caucus Steering committee and also serves on the University's Task Force on Oral and Written Communication.

In terms of research, Dr. Chajes' areas of specialization is bridge evaluation and rehabilitation, including the use of nondestructive evaluation techniques and the application of advanced materials, primarily fiber-reinforced polymers (FRP). Dr. Chajes has an active research program in these areas. He has served as PI or co-PI for research grants funded by the National Science Foundation, the National Academy of Sciences, the Federal Highway Administration, the National Cooperative Highway Research Program, the Delaware Department of Transportation, and several industrial groups and foundations. Based on this research, Dr. Chajes has published more than 90 papers and presented his work through more than 70 talks.

ROBERT G. HUNSPERGER, PhD received the Bachelor of Science in Electrical Engineering from Drexel University in 1963, the Master of Engineering from Princeton University in 1963, and the Ph.D. in Applied Physics from Cornell University in 1967.

He became a Professor of Electrical Engineering at the University of Delaware in 1976. Prior to this he spent ten years in semiconductor microwave and optical device research as a member of the technical staff of Hughes Research Laboratories in Malibu, California. He has taught at the University of Southern California and at UCLA, and has served as a Consultant in the fields of semiconductor and optical devices and systems. Organizations that have called upon Dr. Hunsperger's expertise in this area include Hughes Aircraft Company, Martin Marietta Laboratories, E.I. DuPont Company, ISC Defense Systems, National Institute of Standards and Technology (NIST) and the U.S. Army.

Dr. Hunsperger has over 100 publications and holds 18 patents. He is the author of the book *Integrated Optics: Theory and Technology,* 5th Edition, (Springer-Verlag, 2002) which is widely used as a basic text in the field of integrated optics, being available in Russian , Chinese and Ukrainian translations, as well as English. He is also the editor of the multi-author volume Photonic *Devices and Systems* (Marcel Dekker, 1994).

Dr. Hunsperger is a Fellow of the Institute of Electrical and Electronic Engineers, and is a member of the Optical Society of America, the American Association for the Advancement of Science and the Society of Photo-Optical Instrumentation Engineers.

ERIC G. KUNZ, MS in ME, is President and CEO of VETEK Systems Corporation. He received his Bachelor of Mechanical Engineering from Cornell University in 1963 and his Master of Science in Mechanical Engineering from Georgia Institute of Technology in 1965. He also completed all course work for a Masters in Business Administration in 1973 at the University of Delaware.

After serving 3 years in the Air Force as an Aerospace Engineer Project Officer, he joined Thiokol Corporation as a Project Manager doing research, development, production and delivery of solid propellant rocket motors for military and civilian needs. After 20 years he left Thiokol and became a Vice President of Operations for a major custom bindery operation with several plants. He also started working as a consulting engineer in various fields including site selections for manufacturing operations.

In 1994 he formed and started an internationally based company to provide high technology equipment for corrosion monitoring systems called VETEK Systems Corporation. He is presently President and CEO of that continuing company. In addition, he has initiated and promoted continuing research into NDT methods for corrosion monitoring in various elements of our infrastructure.

Mr. Kunz has published several papers in this field and is a member of the IABSE and Sigma Xi, research honorary.

5. GLOSSARY AND REFERENCES

5.1 GLOSSARY

5.1.1 Characteristic Impedance

The characteristic impedance, Z_0, of a transmission line is a parameter that gives a measure of its opposition to the flow of high frequency electromagnetic waves.

5.1.2 Impedance Matching

All devices attached to a transmission line ideally should have the same impedance as the characteristic impedance of the line. Otherwise, some of the waves (electromagnetic energy) traveling on the line will be reflected at the point of connection.

5.1.3 Rise Time

An electrical pulse is a relatively short duration increase in voltage and/or current of an electrical signal traveling on a transmission line. The rise time is the time that it takes for the signal pulse to increase from its minimum to its maximum value.

5.2 REFERENCES

1. W. Liu, R. Hunsperger, M. Chajes, K. Folliard, and E. Kunz. Corrosion Detection of Steel Cables Using Time Domain Reflectometry, ASCE Journal of Materials in Civil Engineering, Vol.14, No.3, 2002, pp.217-223.

2. W. Liu, R. Hunsperger, M. Chajes, D. Li, and E. Kunz. Nondestructive Corrosion Monitoring of Prestressed HPC Bridge Beams Using Time Domain Reflectometry, Proc. of Transportation Research Board 80th Annual Meeting, Washington, DC, 2001.

3. Robert Hunsperger and Michael Chajes. *Detecting Corrosion of Steel Strands Using Time Domain Reflectometry*, Research Report DTI 119, Delaware Transportation Institute, Newark, DE 19716, 2002.

4. Robert Hunsperger, Jian Li, Wei Liu, Michael Chajes. *Detecting Corrosion in Existing Structures Using Time Domain Reflectometry*, Research Report DCT 154, Delaware Center for Transportation, Newark, DE 19716 ,2003.

5. Jian Li. *Void Detection in Post-Tensioning Ducts Using Time Domain Reflectometry*, Thesis submitted for the degree of Master of Electrical Engineering, University of Delaware, Newark, DE 19716, August, 2004

6. Jian Li, Laura Akl, Robert Hunsperger, Wei Liu, Michael Chajes, Eric Kunz, Void Detection in Post-Tensioning Ducts Using Time-Domain Reflectometry, Proceedings of National Academy of Sciences, Transportation Research Board, 6th International Bridge Engineering Conference, Boston, MA, July, 2005