NON-DESTRUCTIVE EVALUATION OF STAY CABLE BRIDGE SYSTEMS

A Thesis

by

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ABSTRACT

Stay cable bridge systems have been used for centuries and as engineering knowledge and new materials has developed, these bridges have become larger, more elegant, and overall greater engineering feats. As these bridges become more popular, it is not only important to carefully design these bridges, but also to routinely inspect the health of the in-service bridges. Detrimental conditions such as corrosion, section loss, strand breakage, segregated grout, voided grout, water infiltration, and general tendon deterioration in the anchorage system are documented issues that can occur within stay cable bridges and can have extremely harmful effects. In order to monitor the health of these bridges, non-destructive evaluation (NDE) can be a very useful tool in order to inspect these bridges without having to repair the system after inspection.

In this research, ground penetrating radar, magnetic flux leakage, infrared thermography, ultrasonic tomography, sounding, and borescope inspections are all performed on a series of mock-up stay cable specimens fabricated with certain detrimental conditions located within. The applicability, capabilities, and limitations of each NDE method are evaluated based on empirical data from physical testing. Furthermore, each method is ranked in categories of precision, accuracy, ease of use, inspection requirements, and cost.

This research concludes that only magnetic flux leakage has the ability to determine any sort of steel strand defects, including corrosion, section loss, and strand breakage; and it was very effective in doing so, as testing data closely matched fabricated

defects. Ground penetrating radar, infrared thermography, ultrasonic tomography, and sounding were all able to accurately identify grout voids within the tendon but could not differentiate between a voided region and a region infiltrated with water or poor grout conditions. In future research, additional testing to differentiate testing results between these three conditions should be explored, as each one can require completely different solutions to remedy the problem. In addition, none of the methods explored in this research were able to detect any defects within the concrete masses representative of the anchorage regions, although infrared thermography and sounding were effective at determining voided areas within the grout caps. Lastly, borescope inspection was a very useful tool to qualitatively evaluate conditions that have already been identified by one of the other methods.

DEDICATION

This thesis is dedicated to my family, whose support throughout both undergraduate and graduate school has been incredible.

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1. INTRODUCTION

Stay cable bridges were first built in the 1950s and are growing in popularity because they are typically very economical for bridges with longer, multi-span bridges and are also publicly endorsed for their structural beauty (Irwin et al., 2007). As shown in Figure 1.1, a stay cable bridge can be defined as a bridge that contains at least one tower, or pylon, from which cables extend to support the deck of the bridge below. Stay cable bridges have proven to be the most cost efficient type of bridge for bridges with spans ranging from 500 to 1,500 feet, although not all stay cable bridges are designed within this span range (Irwin et al., 2007). In fact, the longest span of any stay cable bridge today is the Vladivostok-Russky Isle Bridge in Russia with a central span of 3622 feet (Syrkov & Krutikov, 2014).

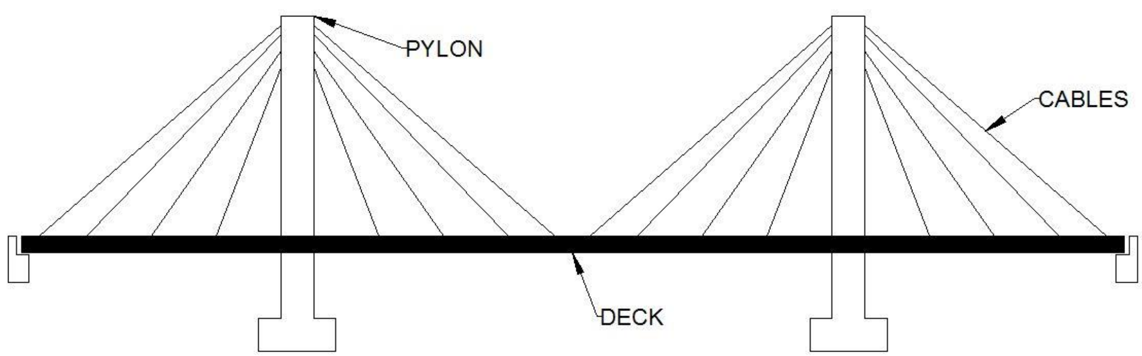


Figure 1-1: Typical Stay Cable Bridge Configuration

Along with careful design of these important bridges, it is equally critical for the structural health of all in-service stay cable bridges that continuous maintenance and inspection be performed. This can help ensure that detrimental conditions do not develop within any element of the structure, in particular the structural cables. Unanticipated deterioration of stay cable bridge systems can cause several undesirable results: a reduction in bridge capacity, costly rehabilitation projects, and traffic disruptions to name a few.

Currently, the most common method of inspection for the cables used in stay cable bridges is visual inspection. This entails a trained inspector monitoring the cables for indicators of physical changes that may be detrimental to the structure. These cables, also known as the main tension elements (MTEs), can be extremely long and absorb very large tensile forces and are essential to the overall performance of stay cable bridges. The primary problem with visual inspection of stay cable MTEs is that the steel prestressing strands are enclosed in opaque ducts, meaning that the true condition of the grout and prestressing steel cannot be determined without opening the duct at a location for inspection, which can allow for intrusion of water vapor, chlorides, or other unwanted contaminants. This means that detrimental conditions within a duct can often go undetected when limiting inspection techniques to visual inspection. One of the most harmful conditions that can occur within any MTE is corrosion of the prestressing steel, which when left unattended, can cause major safety problems for the bridge and be very expensive to repair. There are several corrosion protection systems that have been used in the past and continue to be used today, none of which is perfectly effective to prevent corrosion (Tabatabai, 2005). Similarly, there are several other detrimental conditions that can exist within stay cable MTEs, such as steel wire breakage, tendon section loss, grouting voids, water infiltration, other undesired grout conditions such as segregation, and general tendon deterioration due to a combination of conditions. It is also very possible that several of these conditions can be found along the length of a single MTE. For instance, voids or water infiltration of the grout can potentially create an environment for the steel strand to corrode within the duct.

Although there are numerous different MTE materials and configurations being used around the world, this research focuses on the system consisting of seven-wire parallel strands encased in a sheathing. As stay cable bridge expertise has grown over past decades within the engineering field, so has the recognition of the importance for proven corrosion protection systems within the MTEs. Four commonly used corrosion protection systems that were evaluated in this research include grouted strands in a steel pipe, grouted strands in a high-density polyethylene (HDPE) duct, ungrouted greased and sheathed strands in an HDPE duct, and ungrouted epoxy coated strands in an HDPE duct.

Because visual inspection of stay cable bridges is typically ineffective to detect grouting or strand problems within a given MTE, many different non-destructive evaluation (NDE) techniques have been developed over past decades in order to provide more accurate assessments of the true condition of these structures. Timely NDE testing of stay cable systems is essential to help identify undesired conditions so they can be addressed prior to reaching serious levels that can impact bridge strength and serviceability. Numerous different technologies exist today and can be employed depending on the type of surface being tested and the defect that is being investigated.

For example, Mehrabi (2006) used ultrasonic tomography to effectively determine the presence of grouting voids and wire breaks in the Talmadge Bridge and the Cochrane Bridge in Georgia and Alabama, respectively. Similarly, ground penetrating radar can be effective in finding grouting defects within HDPE duct but not within steel pipe (Mehrabi, 2006). The applicability of using NDE technologies on stay cable bridges is a complicated issue, as each method has its advantages along with its disadvantages, meaning that often times, the most effective NDE testing of a bridge can involves implementing a number of different technologies in tandem. A result of this proposed research was to identify the capabilities and limitations of infrared thermography, sounding, borescoping, ground penetrating radar, ultrasonic tomography, and magnetic flux leakage for finding detrimental conditions that can exist within a stay cable MTE.

1.1. Research Significance

The significance of this research lies in the applicability of NDE testing on the different stay cable MTE systems. By using the results of the NDE methods different mock-up specimens, the testing results were evaluated for different cable arrangements. Four mock-up specimens were designed to simulate conditions that exist in current stay cable bridges around the world, all using parallel wire systems with different sheathing and corrosion protection systems. The development of NDE technologies and usage on different stay cable bridge MTE systems has the potential to identify many detrimental conditions that can exist within a duct prior to reaching a critical level, which can save money on emergency repairs or in worse cases, potentially prevent the failure of a tendon or collapse of a bridge.

Another significance of this proposed research lies in the development of metrics for NDE method selection based on investigative criteria. This development will allow stay cable bridge owners to easily choose NDE methods based on the condition they are investigating and other parameters of individual bridges, such as duct type and corrosion protection system.

Additionally, this research was done as part of NCHRP Project 14-28 "Condition Assessment of Bridge Post-Tensioning and Stay Cable Systems Using NDE Methods."

1.2. Research Objectives

The primary objective of this research was to determine the applicability of certain NDE technologies to detecting detrimental conditions that can exist within a stay cable MTE. This objective was separated into four primary goals: (1) design a series of mock-up stay cable specimens using common MTE systems, (2) construct all of the mock-up specimens and induce detrimental conditions at known locations along the tendon according to the fabrication procedures, (3) use the aforementioned NDE methods to test the known defect locations and compare the results of all four mock-up specimens, and (4) develop metrics to provide end-users with a systematic approach for choosing the optimal NDE technology starting with a known condition.

The first goal of this research was to design a series of mock-up stay cable specimens using common MTE systems. The systems that were explored are intended to replicate the most commonly used systems in stay cable bridges around the world, with respect to cable material, sheathing, and corrosion protection systems. The four systems evaluated in this research were grouted strands in a steel pipe, grouted strands in HDPE sheathing, ungrouted greased and sheathed strands in HDPE sheathing, and ungrouted epoxy coated strands in HDPE sheathing.

The second goal of this research was to construct the series of mock-up specimens using the previously defined stay cable MTE systems. Each mock-up specimen was constructed to contain a number of defects at known locations along the tendons: corrosion, breakage, tendon section loss, grouting voids, water infiltration, other undesired grout conditions such as segregation, and general tendon deterioration due to a combination of conditions. All detrimental conditions were constructed according to the fabrication procedures.

The third objective of this research was to test all four of the mock-up specimens using all of the NDE methods proposed for this research: infrared thermography, sounding, borescoping, ground penetrating radar, ultrasonic tomography, and magnetic flux leakage. All of the known detrimental conditions were blind tested using all of the NDE methods. Acquired data was then accumulated and analyzed, and the applicability of using each method to detect each condition is outlined.

The final goal of this research was to develop metrics to provide end-users with a systematic approach for choosing the optimal NDE technology starting with a known condition. After all of the data was obtained and analyzed in the third objective, the ability of each NDE method to detect each condition for stay cable system was ranked and used to create a metrics chart. Five categories that each NDE method was ranked on are precision, accuracy, ease of use, inspection requirements, and cost.

1.3. Research Outline

This research was separated into six distinct tasks. These tasks include a literature review, NDE procedures, experimental program, experimental results, metrics development, and presentation of results and conclusions.

The first task of this research was to perform a thorough literature review of several topics with respect to non-destructive evaluation of stay cable bridges. Firstly, bridge stay cable systems was researched, including the basics of stay cable bridge construction, different types of corrosion protection systems used both currently and in the past, as well as the different materials used in these systems. Secondly, all detrimental conditions that can exist within a stay cable MTE were investigated: the causes of each condition, typical methods for their occurrence, and the problems caused by each phenomena. Thirdly, case studies of bridges of which any of these conditions were discovered was studied in order to understand the harmful effects that they can cause on real structures. Lastly, the applicability of all NDE methods was investigated in detail: their capabilities, limitations, and expected use in the future. Prior testing using NDE technologies to detect detrimental conditions was explored and the conclusions were outlined and compared to the results of this research. The primary resource that was used for this task was Evans Library at Texas A&M University along with online databases.

The second task was to develop procedures to outline the use of infrared thermography, sounding, borescoping, ground penetrating radar, ultrasonic tomography, and magnetic flux leakage for the testing of the mock up specimens. These procedures describe the setup of all required equipment, develop instructions for testing, and if applicable, outline the steps for data processing.

The third task of this research was to outline the experimental program. Firstly, a series of mock-up specimens using common stay cable MTE systems was designed. The four systems represented by the mock-up specimens are intended to replicate the most commonly used systems in stay cable bridges around the world, with respect to cable material, sheathing, and corrosion protection systems. The systems that were evaluated in this research are grouted strands in a steel pipe, grouted strands in an HDPE duct, ungrouted greased and sheathed strands in HDPE duct, and ungrouted epoxy coated strands in HDPE duct. Secondly, the four mock-up specimens were constructed. The geometry of the mock-up specimen represents the anchorage regions of the pylon and bridge deck, respectively, as shown in Figure 1.2. Additionally, each specimen was identically reinforced as to replicate common field construction practices. These specimens were constructed with defects introduced at known locations along the cables, according to defect fabrication procedures.

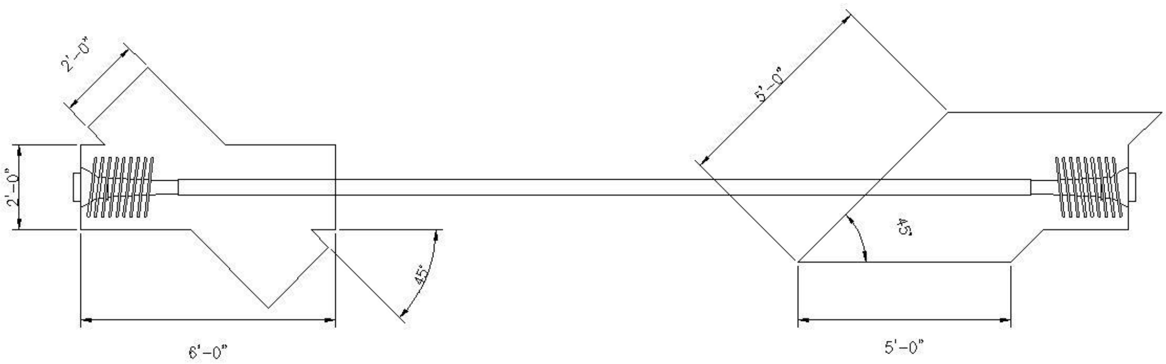


Figure 1-2: Plan View of Typical Stay-Cable Mock-Up Specimen Showing Anchorages in Representative Bridge Deck and Pylon

The fourth task of this research was to test all four of the mock up specimens using infrared thermography, sounding, borescoping, ground penetrating radar, ultrasonic tomography, and magnetic flux leakage according to the procedures provided in Task 2. Data was then analyzed in order to compare experimental testing results to each known condition at its respective known location. The results were outlined to show the applicability of detecting each detrimental condition by using each of the NDE methods. Similarly, testing data was differentiated for each specimen being tested, according to materials used and corrosion protection system.

After completion of the testing of the mock-up specimens, a set of metrics was developed to evaluate any general NDE method for specific condition types. The primary goal of developing the metrics was to provide stay cable bridge owners with an organized approach for selecting the best NDE method for the investigation of their bridge based on which condition for which they are probing. This was done by ranking each method for detecting a certain condition based on five categories: precision, accuracy, ease of use, inspection requirements, and cost. The final deliverable is a series of decision matrices, which investigators can use to select the best NDE method based on bridge characteristics and the condition being investigated.

This task compiles and organizes all of the final results from this research into a thesis format and makes conclusions drawn from all of the research tasks outlined above. Additionally, recommendations for future research with respect to using NDE methods to evaluate corrosion, section loss, breakage, voids, water infiltration, poor grout conditions, and general tendon deterioration of the anchorage systems within stay cable bridge MTEs are shared.

1.4. Thesis Organization

This thesis is organized to contain seven sections. Section II outlines the thorough review of literature that was conducted. This review includes an investigation into the basics of stay cable bridge construction and the different types of steel cables, sheathings, and corrosion protection systems being used around the world to construct the MTEs. Next, problematic conditions that can exist within stay cable MTEs are outlined, including their causes, methods for occurrence, and the problems that can be caused by each. A number of bridges around the world that were subjected to one or more of these detrimental conditions are also shared. Lastly, prior research involving the applicability of NDE technologies on detecting these conditions is examined.

Section III outlines the procedure of which the NDE testing was to be performed, including the setup of the equipment, instructions for testing, and if applicable, data analysis steps. Any major challenges of stay cable MTE testing is explained in this section.

Section IV encapsulates the experimental program of this research. This includes the design of the four mock-up specimens, construction of the specimens, and defect placement for each specimen.

Section V summarizes the results of the testing of the mock-up specimens for each NDE method. All experimental results are presented and explained.

Section VI outlines the development of the metrics rankings from the results outlined in Section V. This includes the explanations for the rankings of each method to detect each detrimental condition based on the experimental results.

Section VII summarizes this entire thesis, and the overall conclusions of the research are drawn and shared. Also, recommendations for future research and NDE testing of stay cable systems are presented.

2. LITERATURE REVIEW

This literature review investigates several topics with respect to non-destructive evaluation of bridge stay cable systems. First, bridge stay cable systems are explained, including the basics of stay cable bridges, different types of systems used both currently and formerly, as well as the different materials used in these systems. Secondly, detrimental conditions are investigated, including their causes and the problems caused by each of them. Thirdly, case studies of bridges that have experienced one or more of these conditions are explored and summarized. Lastly, the applicability of the non-destructive evaluation methods being used in this research are outlined, including their capabilities, limitations, and expected use in the future.

2.1. Stay Cable Systems

There are several systems for stay cable bridge cables that have been used in the past and continue to be used today. The three most important features of the cable system are the main tension elements, sheathing, and corrosion protection system. The steel main tension elements span from the pylon to the deck of the bridge and must absorb all of the tensile force required per the design. Sheathing is essentially a duct made of various materials that encases the MTE to form the first barrier from the environment, as well as to allow grout to be injected within it. Lastly, the corrosion protection system includes any additional precautionary measures taken to protect the strand.

2.1.1. Main Tension Elements

Main tension elements can be composed of numerous arrangements in order to absorb the large tensile forces and span the free length of the cable. Early European and Japanese stay cable bridges commonly used locked coil cables while early U.K. bridges used helical wires (Hamilton et al., 1995). Over the decades, structural advancements have evolved the choices of steel used in main tension elements. Today, structural cables are typically composed of parallel solid bars (ASTM A722), parallel wires (ASTM A421), parallel strands (ASTM A416), and arrangements of structural strands (ASTM A586) (Weseman, 1994). Low-relaxation parallel strands are most commonly used prestressing steel in the United States for use in stay cable MTEs, in which 75% of U.S. bridges use parallel seven-wire strands (Hamilton et al., 1995). Parallel strands are manufactured by laying consecutive layers of wires around a center wire, of which the seven wire system wraps six running wires around a central wire. Depending on the design forces for a cable, the number of seven-wire strands used within a cable can range from 7 to 127 (Ohaski, 1991).

2.1.2. Sheathings

Sheathings were first used in 1961 in the Schillerstrasse pedestrian bridge in Stuttgart, Germany. They encase the steel from anchorage region to anchorage/saddle region and serve two main purposes. First, they provide an initial barrier to protect the strand from the outside environment. Secondly, sheathings allow corrosion-resistant grout to be injected into the cable. Grouted cables will always be encased within a sheathing but cables with a sheathing are not all necessarily grouted, as other corrosion protection systems may be used with sheathings (Weseman, 1994).

Two commonly used types of sheathing materials are steel pipe and high-density polyethylene (HDPE). Steel pipe sheathing is only used in three bridges in the United States: Dame Point Bridge in Florida, Sunshine Skyway Bridge in Florida, and the C & D Canal Bridge in Delaware (Tabatabai, 2005). Black steel pipe (ASTM A53) is generally lifted into place and fixed by butt-welding in the field (Weseman, 1994). The strands are passed through the pipe and stressed to design loads. The tensile strength of the steel pipe is not to be accounted for in the strength of the MTEs. Typically, grouting is used as the corrosion protection system when steel pipe sheathing is used (Weseman, 1994). The grout bonds the strand to the steel sheathing, which causes the sheathing to oscillate as the MTEs oscillate and in turn, experience the same fatigue loadings as the strands. This is the primary reason that steel pipe is the least commonly used sheathing (Hamilton et al., 1995).

High-density polyethylene sheathing is more commonly used than steel pipe as a sheathing material. HDPE is advantageous in that it is both nonreactive and almost impermeable, assuming that it is undamaged. The HDPE sheathing is lifted into place segmentally and either fusion welded or coupled together in order to form a continuous stay. Corrosion resistance systems used with HDPE ducts include but are not limited to: grouting, greasing-and-sheathing the individual strands, or epoxy-coating the strand. The latter two corrosion protection systems are applied during the manufacturing process and not in the field. When HDPE sheathing is grouted, the hardened grout is susceptible to thermal expansion within the sheathing, causing expanding hoop stresses on the sheathing. These expanding hoop stresses, acting simultaneously with bending stresses due to cable oscillations, can lead to cracking of the HDPE sheathing, allowing possible intrusion of water, chlorides, or other contaminants (Hamilton et al., 1995).

2.1.3. Corrosion Protection Systems

Just as important as the structural properties of the strand is the corrosion protection system. Corrosion can both reduce strength and decrease fatigue life of the strands and is currently a major issue in many stay cable bridges across the world. The importance of corrosion protection is more known today than in the past and new methods of protecting the MTEs from the environment have been developed over past decades. A worldwide survey of bridge owners concluded that the average expected life of bridge stay cables is 75 years, which requires a very effective corrosion protection system (Hamilton et al., 1995). The three corrosion protection systems that will be outlined in this thesis are grouting of the tendons, greasing and sheathing the strands, and epoxy-coating the strands.

Grouting of the tendons is the most widely used corrosion protection system, particularly in older bridges. The basis for this system lies not only that grout fills the duct, not allowing the bare strand to be exposed to the environment, but also that portland cement used in grout has alkalinity that is able to prevent corrosive activity. Prior to 1999, grouts were composed of cement, water, and an expanding admixture but a study by Schokker (1999) recommended the addition of fly ash and the removal of the expanding admixture. In 2003, the first generation of pre-bagged thixotropic grouts became available, which is a Type C and most recommended type of grout today per PTI. There are several different specifications for grout provided by different entities, including PTI, ASTM, AASHTO, DOTs, and possibly bridge owners (Merrill, 2014).

Typically, the strands are placed in a duct and the duct is then injected with a cement grout to prevent corrosion. Grouting is an ideal corrosion protection system in a laboratory but proper grouting procedures may not be followed in the field and quality of the grouting depends on many factors: grout quality, weather, grouting team experience, etc. (Merrill, 2014). Improper grouting procedures may lead to conditions such as grouting voids, water infiltration, or other detrimental grouting conditions. These unfavorable conditions allow water and oxygen to enter into the duct over time, nullifying the alkaline environment of the grout and creating a potentially corrosive environment.

Greasing and sheathing of prestressing strands is a corrosion protection system applied to the steel in the manufacturing plant. The process is done by lubricating the strand with a corrosion-inhibiting grease, wax, or epoxy and extruding a high-density polyethylene over the strand. The sheathing is placed as tightly around the strand as possible in order to ensure that no differential movement between the strand and the sheathing occurs during stressing and that no air voids exist in the space between the strand and sheathing (Weseman, 1994). This sheathing also protects the strand from fatigue problems due to rubbing against other strands or the duct within the saddle regions.

There are several advantages to this system, the first being that because the corrosion protection is applied in the manufacturing plant, the strand is not only protected during its service life, but also during storage, shipping, and installation. Secondly, because no grouting is used within the sheathing, it is possible to individually detension, remove, and replace each strand if maintenance is required (Weseman, 1994). Greasing and sheathing of strands does require special corrosion protection in the anchorage regions because the teeth of the wedges have to penetrate through the sheathing and grease, exposing the strand to potentially a corrosive environment (Shinichi, 2006).

Epoxy-coating of prestressing steel is one of the most commonly used factory-applied corrosion protection systems and must conform to ASTM A882. It entails applying a thick layer of corrosion-resistant epoxy to the exterior of the strand (0.63 – 1.14 mm per PTI recommendations) as well as within the interstices (Weseman, 1994). This epoxy must adhere to the strand in order to prevent the epoxy from peeling off as it rubs with mechanical equipment, adjacent strands, etc. As with the greasing and sheathing system, epoxy coating also protects the strand during storage, shipping, and installation.

Overall, epoxy-coating is extremely efficient at protecting the strand from corrosion. In a corrosion test performed by Sumiden Wire Products Corporation, corrosion resistance of epoxy-coated strand was compared to that of bare strands and galvanized strands when subjected to water, several chemical solutions, and a salt spray. The bare strand showed rust in three of the five test conditions, the galvanized strand showed rust in all five of the test conditions, and the epoxy-coated strand showed no visible corrosion in any of the tests (Shinichi, 2006). Epoxy-coating has several advantages to grouting: there is typically higher quality control of corrosion protection in a manufacturing plant than in the field, it saves costs of labor due to grouting, and can be inspected more easily. A primary disadvantage to coating the strand is that nicking of the coating can lead to peeling of the coating, exposing the bare strand. Similar to the greased and sheathed strands, the teeth of the wedges can penetrate the coating when gripping the strand leading to potential corrosion problems in the anchorage regions if not properly accounted for (Shinichi, 2006).

2.2. Detrimental Conditions

There are numerous different unwanted conditions that can exist within a stay cable MTE. Seven conditions that will be explored in this research: corrosion, breakage, tendon section loss, grouting voids, water infiltration, other undesired grout conditions such as segregation, and general tendon deterioration.

2.2.1. Corrosion

Corrosion is an electrochemical process that can negatively affect the strength capacity or service life of any metal element. It is the most common and harmful condition that exists within stay cable MTEs, but also is a condition that exists across many other fields of society, including buildings, automobiles, and storage tanks, to name a few. The estimated annual cost of atmospheric corrosion has been estimated as

3.1% of the GNP of the United States, costing about $276 billion in 1998 (Griffin, 2006).

It is well documented that moisture and oxygen are required for the corrosion process to occur, but corrosion is a more complex process requiring the transfer of an electric charge in an aqueous solution. The complete electrochemical reaction of corrosion can be described in four individual steps. First, the iron is oxidized, which is an anodic process that transfers electrons, creating positively charged iron ions which are hydrolyzed and produce acidity. Next, oxygen is reduced by the transferred electrons, which produces alkalinity. Thirdly, as the negatively charged electrons are transferred from the anodic region produced by iron oxidation to the cathodic region produced by oxygen reduction, a nominal positively charged electrical current is created and flows in the opposite direction of the electrons. Lastly, the circuit is completed as ions have the ability to be transferred in a pore solution, typically water (Bertolini et al., 2013). Although moisture and oxygen are the only necessary entities for the corrosive process to begin, there are several other factors that can significantly affect the rate or method of corrosive activity of metal, including temperature, wind, airborne contaminants, alloy content, biological organisms, and others (Griffin, 2006). Depending on these factors and many more, there are numerous different methods of corrosion, including: uniform corrosion, atmospheric corrosion, chloride induced corrosion, carbon dioxide concentration, pitting corrosion, corrosion cracking, fretting fatigue, galvanic corrosion, and hydrogen-induced stress corrosion (Hurlebaus et al., 2013).

Corrosion is a critical problem in stay cable MTEs because the prestressing steel within the cables are long, slender, and absorb such large tensile loads. Corrosion can cause many types of premature failure of these crucial stay cable bridge elements, endangering the structure as a whole. The first type of failure that can occur is a brittle failure due to corrosion pitting, in which localized corrosion essentially notches the strand, reducing its ability to hold the required load. Secondly, a common phenomenon called hydrogen-induced stress corrosion cracking is occurs when a crack forms and propagates under the influence of a corrosive environment and tensile stresses. This method of failure can occur without visible corrosion product, making it particularly difficult to detect (Numberger et al., 2003). Lastly, the fatigue life of the prestressing strands is significantly affected. Li et al. (2012) performed fatigue testing on parallel wire cables and determined that the yield and ultimate strengths of the strands were somewhat unaffected by uniform corrosion but the ductility was greatly decreased and the variability in mechanical properties increased significantly. Similarly, the fatigue life of corroded strands was significantly less than non-corroded wires, as corrosion sped up fatigue crack propagation and ultimate fatigue fracture of the strands (Li et al., 2012).

Although the negative effects of corrosion on the strength and serviceability of prestressing steel are known and numerous corrosion protection systems have been developed, corrosion continues to be a major problem in stay cable MTE design and construction. In 1988, a paper titled “Cables in Trouble” claimed that no cable protection methods is foolproof and that many stay cable bridges are in danger of collapse unless corrosion problems can be stopped. The authors travelled the world and surveyed over half of the stay cable bridges built at the time, concluding that premature corrosive degradation was found in cables everywhere (Watson & Stafford, 1988). Because of the prevalence and extremely harmful nature of corrosion on stay cable MTEs worldwide, it is essential for bridge inspections to include corrosion detection protocols.

2.2.2. Breakage

Breakage of steel strands or wires can occur as a result of numerous activities and can also significantly reduce the capacity of the tensile element. Firstly, broken wires or nicking have been known to develop in multi-strand ropes because of the torque-balancing assembly of the wires. This is because the different layers of wires touch at an angle, meaning when these ropes are stressed and bend at an anchorage or saddle region, they are subjected to a combination of radial loading, bending stresses, and relative motion between the wires, which can wear the rope (Weischedel, 2003). This method of breakage can be difficult or impossible to see by the naked eye because this breakage typically happens between the inner steel wire layers of the strand. Secondly, wires can break as a result of fatigue or shear loading on the strand (Hamilton et al., 1995). Thirdly, a strand or wire can be mechanically damaged in the field prior to placement by dragging on the ground, dropping equipment on it, driving machinery over it, etc. Breakage of prestressing steel is important to detect because such a localized breakage can reduce capacity and possibly lead to a brittle failure of the strand (Numberger et al., 2003).

2.2.3. Section Loss

Section loss can also occur to steel prestressing strands, resulting in a loss of strength or fatigue resistance. The primary cause of section loss is corrosion, in which corrosive activity reduces the cross-sectional area of the strand. Other possible causes of section loss are fatigue, inter-strand wear, or intra-strand wear (Weischedel, 2003). Section loss of prestressing steel is important for bridge inspectors to find as tensile strength of stay cable MTEs is closely related to the cross-sectional area of the prestressing steel within them, meaning that any section loss can reduce the total capacity.

2.2.4. Voids

Injection of grout is a commonly used stay cable MTE corrosion protection system but there are several issues that can cause problems with this system. Grout is not only intended to form a barrier from intruding moisture and chlorides due to its low permeability, but the alkalinity of the cementitious grout provides excellent corrosion protection (Salas et al., 2004). This protection system becomes ineffective if a voided region occurs tendon grout, which can leave the steel prestressing strand bare and unprotected from the environment.

There are several possible causes for voids within a tendon, including improper grouting procedures or poor materials. Voids can be caused by human error, including incomplete grouting, inadequate grouting pressure, leaks within the tendon, and insufficient grout discharge at vents (Pielstick, 2014). Similarly, grouting materials are just as important, as bad grouting mixtures can cause bleed water pockets, which can evaporate, leaving voided regions within the duct (Salas et al., 2004).

Voids can be a major problem in all stay cable bridges with grouted tendons but can be especially problematic near oceanic areas where moisture and chlorides can enter the MTE and create a corrosive environment within the duct very quickly. Although grouting is also used to bond to and transfer load from internal prestressing steel, this is not the case in stay cables, where the only purpose of the grout is corrosion protection (Pielstick, 2014). Since grout in stay cables serves no load-carrying purpose, the existence of a void does not necessarily mean there is a structural problem with the cable. Voided regions serve more as indicators that corrosive activity is likely to occur in that region, as engineering knowledge and experience has proven that corrosion occurs significantly more often in voided regions than in non-voided regions (Salas et al., 2004).

The threat of corrosion due to voided regions is one that needs to be taken into account during bridge inspections, as voids can be excellent indicators of corrosive activity. The Specification for Grouting of Post-Tensioned Structures, released by the Post-Tensioning Institute (PTI) (2012), requires that in no less than 24 hours after a grouting operation, all outlets and grout caps shall be inspected and filled with fresh grout if they are not full. Similarly, PTI recommends to inspect exit ports of vertical vent tubes at the trumpet end, vertical stand pipe, and any other inspection ports. If grouting uncertainties arise after the grout has set, the construction engineer shall arrange for nondestructive testing of the system (Post-Tensioning Institute , 2012).

2.2.5. Water Infiltration

Water infiltration of a grouted tendon has similar consequences to grouting voids in that it can allow a corrosive environment to be created around the steel strand. One possible cause for water infiltration within a tendon includes the existence of a void allowing water to accumulate in the voided area through either an opening in the duct or an accrual of humidity. Another cause, which is more commonly an issue in vertically angled tendons, such as stay cable MTEs, is bleed water. Bleed water is typically caused by poor mixing, poor materials, or excessive water in the grout but is essentially the formation of a water pocket that forms at the highest point of the grout as the particles settle downwards and force the water upwards. Because of the vertical orientation of the tendons, the required pumping head cannot be obtained to pump the entire tendon full of grout in one operation but rather it is done segmentally from bottom to top. This means that not only could bleed water accumulate at the top of the tendon but also at the interfaces between grouting operations, which are referred to as intermediate lenses, both of which are shown in Figure 2-1 (Pielstick, 2014).

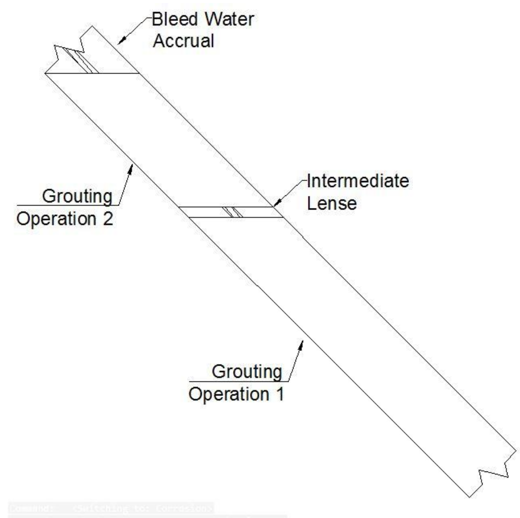


Figure 2-1: Bleed Water and Intermediate Lense Illustration

Another possible cause of water infiltration is using water to flush the duct. After the ducts are placed, it is common practice to flush the ducts in order to clean them prior to inserting the steel strands. Prior practices flushed the tendons with water, but this led to many problems, including water infiltration and over-hydrated grout. Currently, PTI requires ducts to be flushed with air as opposed to water to help avoid these problems (Pielstick, 2014).

A region within the duct where water has infiltrated has the potential to be more harmful than a voided region, as moisture is one of the constituents of the corrosion process. The presence of water can accelerate the corrosion process in comparison to a dry void leading to a reduction in strength or fatigue life of the stay cable MTE. Proper grouting procedures and use of bleed-resistant grouts can be used to minimize the chance of water infiltration, but inspection is still necessary to detect the condition.

2.2.6. Grout Conditions

There are several other undesired grout conditions that can occur within grouted tendons other than voids and water infiltration, including grout segregation and un-hydrated grout. Both of these conditions have the ability to compromise the corrosion protection of grout making them important to detect. Segregation can exist in many states, such as a wet plastic, a white powdery residue, or a dry low density grout (Merrill, 2014). There are numerous causes of segregation, including insufficient mixing of grout, poor or expired materials, and improper admixtures being added. Un-hydrated grout can be caused by either not adding enough water or water at too high of a temperature so that evaporation can reduce the water content of the grout. This is why PTI recommends not to use black water containers in regions with warmer climates, including Texas (Merrill, 2014).

2.2.7. General Tendon Deterioration

General deterioration of the tendon can occur in many forms, often times as a function of the existence of any of the aforementioned conditions or a combination of them. Coupled with overall wear and the large tensile forces of the MTE, deterioration can occur over time, particularly in the anchorage regions, and reduce the structural capacity or service life of the tendon.

2.3. Case Studies

Over past decades, detrimental conditions have caused significant problems in stay cable bridges around the world. Some of these harmful conditions can be extremely dangerous and require immediate action to fix the problems. Four case studies investigating stay cable bridges that experienced detrimental conditions include the Luling Bridge in Louisiana, the General Rafael Urdaneta Bridge in Venezuela, the Burlington Bridge in Iowa, and the Koehlbrand Bridge in Germany.

2.3.1. Luling Bridge, Louisiana

The Luling Bridge, also known as the Hale Boggs Bridge, was originally constructed in 1983 to span the Mississippi River with span distances 495, 1,222, and 508 feet, respectively. The bridge consists of two steel pylons and steel box girders, connected by seventy-two cables comprised of ASTM A421 prestressing wire (Elliott & Heymsfield, 2003). The bridge outline can be seen in Figure 2-2.

Figure 2-2: View of Luling Bridge (Mehrabi, 2009)

In 1985, the Louisiana Department of Transportation and Development (LADOTD) observed some of the HDPE sheathing encasing the cables had cracked, compromising the first layer of corrosion protection of the strand. Initially, this problem was solved by wrapping all seventy-two tendons with a PVF tape to protect the cracked ducts. But over a decade later, further investigation noticed more problems. In 1998, the LADOTD developed an inspection method using two trolleys to be used on the two different cable configurations. A four-cable trolley setup was used to inspect the cables on the side spans while a two-cable trolley setup was used to inspect the cables on the main span (Elliott & Heymsfield, 2003). Inspection of the free lengths of the cables found several detrimental conditions: corrosion of steel wires (Figure 2-3), damages to the PVF tape, and grouting voids to name a few. After the inspection, thirty-nine of the seventy-two cables were rated as critical and the rest were rated as poor, all a result of protective coating failure.

Figure 2-3: Corrosion of steel wires in Luling Bridge stay cable (Mehrabi, 2009)

The cumulative problems in the cables were evaluated using a deterioration model in order to determine the remaining strength and service life, but uncertainties regarding wire conditions brought up doubt in the model (Mehrabi, 2009). A life cycle cost analysis was performed in order to determine the plan of action to be taken. Ultimately, a complete replacement of all of the bridge stay cables was decided as the plan of action by the LADOTD and a new cable design was devised according to the Post-Tensioning Institute's Recommendations for Stay Cable Design, Testing, and Installation. This complete cable replacement design was the first of its kind in North America. Cable replacement a very expensive repair but the cost of "doing nothing" and risking the integrity of the bridge was significantly higher (Mehrabi, 2009).

2.3.2. General Rafael Urdaneta Bridge, Venezuela

The General Rafael Urdaneta Bridge, also called the Maracaibo Bridge, spans Lake Maracaibo in Maracaibo, Venezuela. The bridge was completed in 1962 and can be seen in Figure 2-4. The stay cable bridge is comprised of five main spans and two end spans with a total span distance of approximately 5.4 miles (Sarcos-Portillo et al., 2003).

Figure 2-4: View of the Maracaibo Bridge (Pipinato, 2012)

Because of navigational span and height requirements, possible damage from differential foundation settlement, or ground motion from earthquakes, the central spans had to be statically determinant. This was done by cantilevering girders from each pylon, supported by the structural cables. Each main span is comprised of A-frame towers resting on X-frame supports, of which the deck extends from, as shown in Figure 2-5 (Pipinato, 2012).

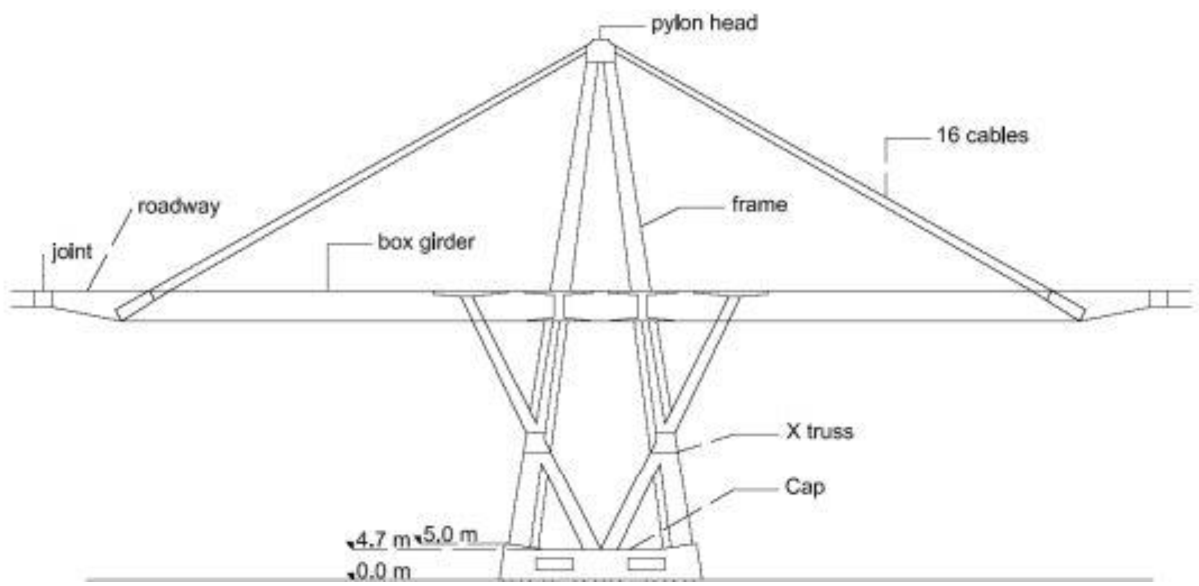


Figure 2-5: Design scheme of Maracaibo Bridge (Pipinato, 2012)

In 1980, four out of the 384 total cables failed. Because of the construction method involving all cables spanning the pylon head by passing anchorages, all cables stacked above a specific cable needing replacement must be detensioned and removed out of the way prior to replacement. This requirement, coupled with the identification of significant deterioration in other cables, led to the final decision to replace all stay cables. More updated construction and corrosion protection techniques were used in the cable replacement. Because of the cantilevered box girders construction, the girders had to be individually removed while the cable systems were being replaced and then reassembled (Pipinato, 2012). Figure 2-6 shows construction operations during the replacement.

Figure 2-6: Construction operations during cable replacement (Pipinato, 2012)

The replacement was completed and the last maintenance was performed in 1992, when the cables were painted. Inspection of the cables in 1997 and 1999 led to discoveries of new detrimental conditions of the cables. Corrosion in both the cables and the anchorage sockets were found, along with a large variation in tensile forces of the cable groups, leading to vertical deviations of the bridge deck. To remedy these problems, the bridge was then horizontally leveled, retensioned after further structural analysis to ensure uniformity of tensile forces within the cables, and the cables were cleaned, waterproofed, and lubricated (Sarcos-Portillo et al., 2003).

2.3.3. Burlington Bridge, Iowa

The Burlington Bridge, which spans the Mississippi River for US 34, was completed in 1993 and can be seen in Figure 2-7. The bridge consists of a 660-foot main span between a 405-foot side span and a 180-foot approach span. The bridge consists of a single H-shaped concrete pylon, from which cables extend to support the main and side spans. The stay cables consist of parallel epoxy-coated strands within polyethylene pipes and was injected with cementitious grout (Svensson, 2008).

Figure 2-7: View of Burlington Bridge (Svensson, 1981)

In June 1991, during construction of the bridge, testing was performed on bridge specimens. The stays did not pass PTI requirements for wire breaks during a fatigue test and did not reach the required stress during a static load test. The tested stay consisted of 31 epoxy-coated strands, anchored at the deck and pylon after stripping the epoxy from the anchorage regions to ensure no slippage during load testing. A small section of the duct was filled with an epoxy compound followed by a coal-tar epoxy transition for the grout to be injected above (Hamilton et al., 1995).

After the duct was vertically grouted, corrosion was found on the inside face of the steel transition pipe at the deck anchorage, where the epoxy compound was poured, and at the top anchorage to a lesser degree. This corrosion led to the failure of the testing, of which 24 wire breaks were found in the 31 strands. Different failure mechanisms were also determined upon investigation, as 10 of the 24 breaks were ductile and the others were determined to be fatigue or shear failures (Hamilton et al., 1995).

In order to determine the cause of corrosion, an examination of the corroded locations was conducted, of which three primary causes were found. The majority of the failures were brittle fractures due to fretting fatigue, of which many were located near the socket where the epoxy compound was added. Secondly, chlorides were also detected in the grout but concentrations were not released in the report of this study. Lastly, grout additives and bleed water may have caused corrosion by reacting with the epoxy compound (Hamilton et al., 1995). These corrosive activators had to be addressed prior to permanently grouting the stay cables and the cables must be monitored in order to determine that none of these corrosive activities arise during bridge operation.

2.3.4. Koehlbrand Bridge, Germany

The Koehlbrand Bridge, located in Hamburg, Germany spans the Süderelbe anabranch of the Elbe River and was completed in 1974. The bridge consists of a 1066-foot main span with two 320-foot side spans connected to two 322-foot tall pylons by use of 88 locked-coil strands. The original corrosion protection system used for the stay cables was filling the inside of the bare wires with a redlead and linseed oil and coating the exterior with two base coats of redlead and resin, followed by two finishing coats of ironglimmer and linseed oil (Hamilton et al., 1995). A current visual of bridge is provided in Figure 2-8.

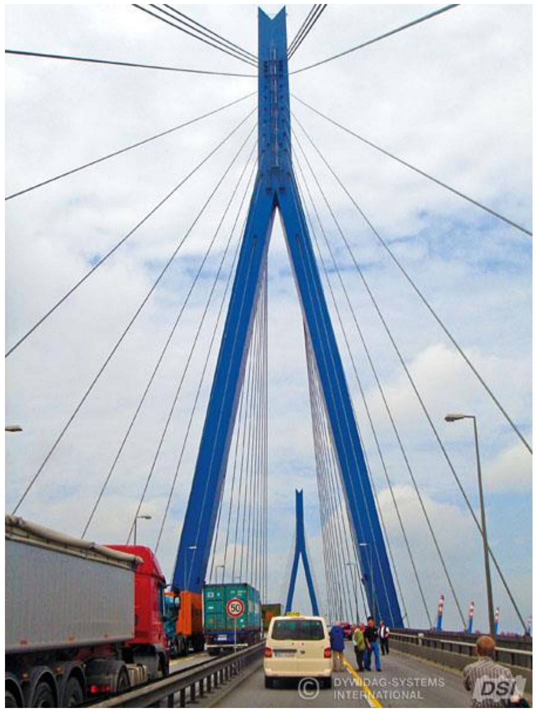


Figure 2-8: View of Koehlbrand Bridge (DWIDAG-Systems International, 2014)

In 1976, a routine inspection had found twenty-five broken wires, some of which can be seen in Figure 2-9. Factors that may have contributed to this rapid deterioration are poor protection of socket areas, excessive cable vibration under live loads, and salt use for ice protection on the deck, to name a few. The primary activator of these breaks was determined to be the salts because all of the wire breaks were found near the bottom anchorages in the bridge deck. All of the cables had to be replaced (Hamilton et al., 1995)

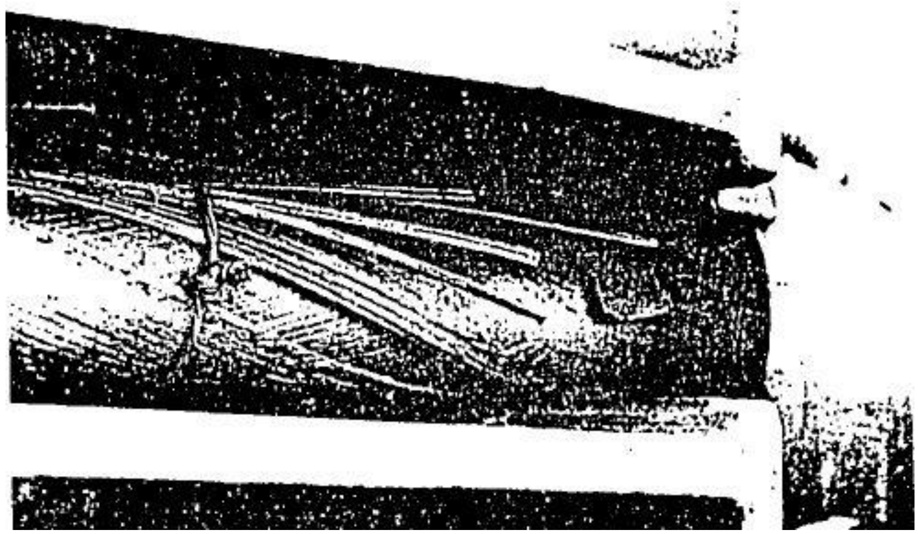


Figure 2-9: Broken wires in Koehlbrand Bridge (Saul & Svensson, 1990)

The initial deterioration of the Koehlbrand Bridge cables was extremely rapid and the rate of deterioration has since been significantly slowed, but not stopped. The Hamburg Port Authority has performed routine inspections, of which stay cable coating problems were recurrently found, requiring minor repair work to be done. Recently, extensive coating and corrosion damage was found on eight of the stay cables and the Hamburg Port Authority decided to rehabilitate the entire bridge. Because this bridge is very important for the Hamburg Port and Harbor, the bridge could not be closed to traffic (DWIDAG-Systems International, 2014).

In 2009, a contract was awarded to DYWIDAG Systems International to replace the eight damaged stays and update the corrosion protection systems of the other 80 stay cables. The cables requiring replacement had diameters between approximately 2.5 and 4.8 inches and a maximum length of 538 feet (DWIDAG-Systems International, 2014).

The corrosion protection system was updated from the corrosion coatings to use of a butyl rubber tape wrapping, which can be seen in Figure 2-10.

Figure 2-10: Repaired Corrosion Protection Coatings (DWIDAG-Systems International, 2014)

2.4. Non-Destructive Evaluation Methods

Methods to evaluate the condition of stay cable MTEs are crucial to the life-span of the structure and can be used to find detrimental conditions prior to them becoming very problematic. The NDE methods that will be analyzed in this research are sounding, borescoping, infrared thermography, ground penetrating radar, ultrasonic tomography, and magnetic flux leakage.

2.4.1. Sounding

Sounding is a very simple acoustic NDE method that can be applied to many different bridge components, including external post-tensioning ducts and stay cable MTEs. Sounding is performed by tapping an impactor or other tapping utensil along the tendon and listening for a change in the acoustic response produced by the tapping. The locations resulting in a changed acoustic response of the tapping typically can imply a void, requiring further examination of the location (Corven, 2001). Sounding is not the most accurate NDE method but is extremely easy and can be quickly performed in the field by a trained inspector (Hurlebaus et al., 2013). This method does not have the capability of detecting soft grout voids, smaller voids, or metallic defects (Azizinamini & Gull, 2012). Similarly, this method can be extremely difficult to perform on bridges without closing the bridge to traffic due to traffic noise interfering with testing.

2.4.2. Borescoping

Borescope inspection uses an optical device to visually inspect an area inaccessible to the naked eye. This NDE method can be extremely useful, as the imaging device typically is attached to a flexible tube and can be inserted into an MTE to visually inspect the interior of the duct. A primary problem with this method is there must be an entry location for the tube to enter the MTE, which may or may not be present depending on the stay cable system used. Because of the entrance problem, borescoping is sometimes referred to as a semi-destructive method because drilling small observation holes might be necessary (Limaye & Kakade, 2008). Depending on the system of the stay cable MTEs, grout ports or grout caps may be temporarily opened for tube entry but some systems will not contain entry areas and holes may have to be drilled in the sheathing for entry and plugged afterwards.

If entry of the imaging device into a tendon is available, borescoping can be an extremely useful NDE method for determining the actual conditions that exist within a stay cable MTE. Borescoping not only allows the inspector the ability to view strand or grouting conditions, but also to qualitatively evaluate the severity and shape of the defects in order to recommend remediation techniques. Corven (2001) inspected the Mid-Bay Bridge in Okaloosa County, Florida and used a borescope to inspect different anchorages, of which four still photos are shown in Figure 2-11, showing broken wires, corrosion, and grouting deficiencies.

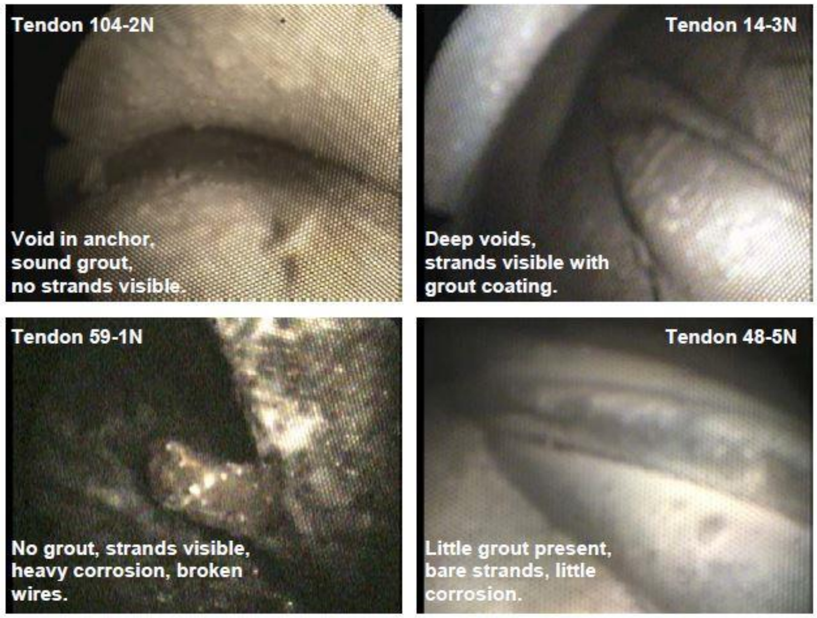


Figure 2-11: Images from Borescope Inspection of Post-tensioned Bridge (Corven, 2001)

2.4.3. Infrared Thermography

Infrared thermography (IRT) is a non-destructive evaluation technique that measures thermal energy in order to create an image. There are two different types of IRT today, active and passive, the difference of which is that active IRT will externally apply a thermal excitation such as infrared radiation and passive IRT will give information about the object's surface temperature while it is thermal equilibrium (Hain et al., 2009). In recent years, the sensitivity of IRT technologies has significantly increased, as infrared focal lenses can now have a sensitivity on the order of less than 0.01°C (Poulain et al., 1999). The increased capability of IRT has allowed for the detection of previously undetectable conditions to be visible, including subsurface flaws.

The thermal nature of IRT gives it the capability to locate detrimental conditions based on differences in the thermal properties of steel, concrete, air, water, or any other material present in a structure because abnormalities theoretically will affect the heat flow of the structure and be seen in the thermal image (Mehrabi, 2006). For instance, air has a much larger thermal conductivity than concrete, meaning that concrete containing an air void will produce observable surface temperature variation compared to that of a solid concrete region (Poulain et al., 1999). Pollock et al. (2008) attempted to study the feasibility of detecting voids within internal ducts. Their research team constructed a series of small, concrete specimens of different thicknesses with internal post-tensioning incorporating different sized and angled voids, with a typical specimen cross-section shown in Figure 2-12.

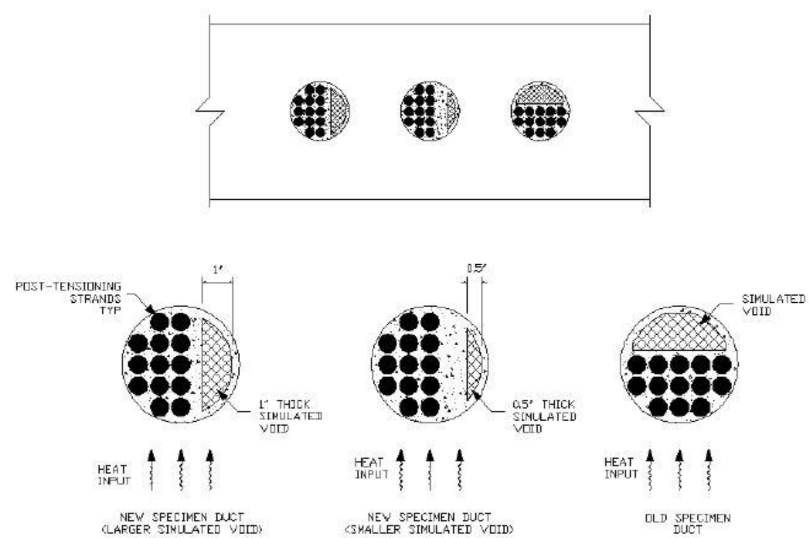


Figure 2-12: Typical Concrete Specimen Showing Various Voided Regions (Pollock et al., 2008)

After all of the specimens were completed, the test setup was designed. Active IRT was used for this testing, meaning that the specimens were subjected to external thermal heating, along with a reflective insulation. The insulation used in this setup was reflectix with an R-value of 14.3 and 97% reflectivity. The heater used was a heater manufactured by Fostoria (Model #CH-1324-3A). The entire setup is shown in Figure 2-13.

Figure 2-13: IRT Testing Setup with Suspended Heater (Pollock et al., 2008)

Lastly, testing was performed using different methods, which incorporated taking images of different faces of the specimens with respect to the side being heated. It was concluded that the simulated voids were much more detectable in the thinner (8 in. thick) specimens than the thicker (12 in. thick) specimens. Similarly, it was concluded that the method involving heating one face of the specimen and taking thermal images from the opposite side was the most productive method at detecting voids, as heat propagation through the specimen either increased or decreased as materials other than concrete were encountered. Another important conclusion, outlining a limitation of IRT, is that none of the voids within steel ducts were able to be detected, likely because as the heat reaches the steel duct, the thermal properties transfer the heat around the circumference of the duct, passing the air voids altogether (Pollock et al., 2008).

Similarly, IRT has been used for investigation of an external or stay cable ducts, including tape condition because it is a rapid, convenient, and contactless NDE technique. Figure 2-14 shows an example of an infrared thermographic image of a polyethylene external duct containing a split in the sheathing.

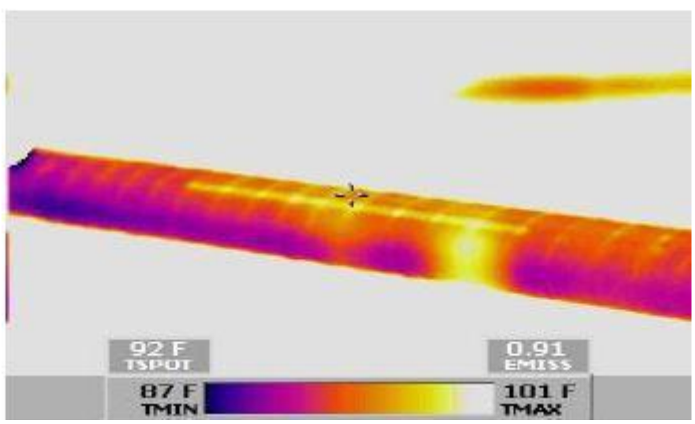


Figure 2-14: IRT Image Showing Splitting of Polyethelyne Sheathing (Azizinamini & Gull, 2012)

IRT has the proven ability to locate voided regions within internal ducts, identify honeycombed regions within concrete masses, as well as characterize external tendon surface conditions. These capabilities provide positive signs that IRT can be a valuable NDE technique to investigate stay cable MTEs. The potential for locating grouting defects using IRT has been outlined but currently, there is a lack of research in the method's ability to detect conditions within stay cables (Hurlebaus et al., 2013)

2.4.4. Ground Penetrating Radar

Ground penetrating radar (GPR) is an NDE technique that uses an electromagnetic radiation pulse to sense irregularities in a structure. A radar pulse is emitted from the GPR device into the structure, of which a portion of the pulse reflects back at each anomaly, including a material or geometric change. GPR is used for detection of numerous conditions and is expected to become more commonly used as a future inspection technique due to its ease of use, speed of testing, and low cost (Hurlebaus et al., 2013).

Currently, GPR is more common for the inspection of internal post-tensioning and less common for external post tensioning or stay cable MTEs, even though he testing of stay cable MTEs can be particularly easy (Azizinamini & Gull, 2012). GPR equipment typically just includes a handheld device, which can be moved along the length of a tendon to inspect the entire free span. Studies have shown GPR to be relatively accurate for detecting grouting defects in both internal and external post-tensioning as well as stay cable MTEs (Tabatabai, 2005). Telang et al. (2004) performed GPR testing on two mockup stay cable specimens with HDPE sheathing and concluded that GPR is a highly effective method for detecting grouting deficiencies. Similarly, Azizinamini and Gull (2012) explored the potential to detect grout conditions, such as voids, soft grout, or water intrusion within a plastic duct due to the higher levels of moisture and electrolytes of the grout. The higher reflection levels of these conditions were able to be seen using GPR, as the presence of a void is shown by the white pattern in Figure 2-15.

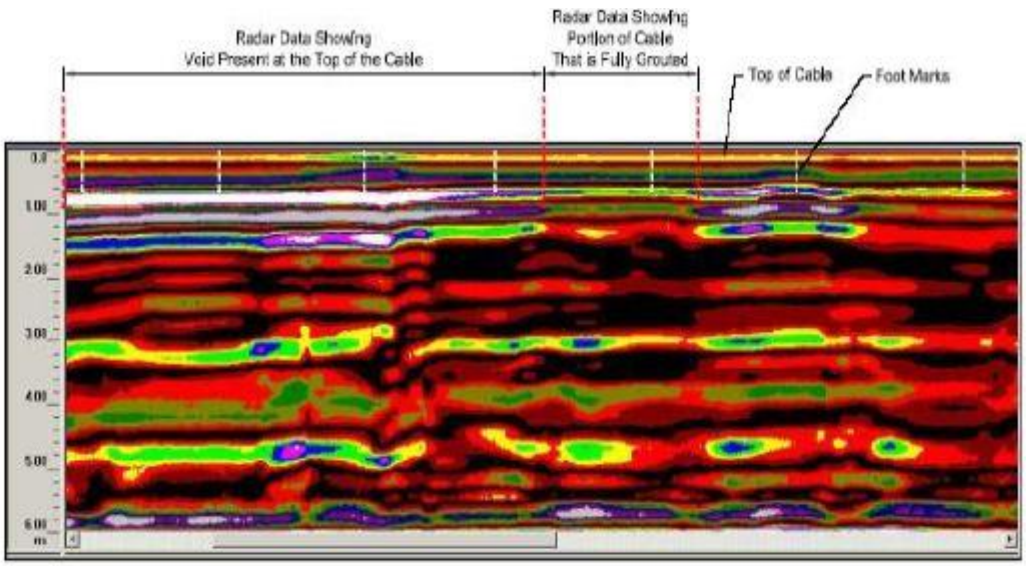


Figure 2-15: Sample Radar Scan showing Voided Region in Grout (Azizinamini & Gull, 2012)

A disadvantage to GPR is that it is highly sensitive to metallic matter, meaning not only that it is ineffective to assess corrosion or any defects of the steel strands within the tendons, but also incapable to detect grouting deficiencies within stay cable MTEs that use metal sheathing (Azizinamini & Gull, 2012). This limitation of GPR means that it can only be useful as an inspection technique provided that HDPE ducts are used.

There are several other limitations to this method, as it is also typically ineffective in detection of UV tape damage or splits in stay cable sheathing.

GPR has evolved since the early 1990s, when it was primarily used for inspection of internal post-tensioning (Bligh et al., 1994). Today, not only has it developed to be applicable for inspection of external post-tensioning or stay cable MTEs, but it is also commercially available and has can be used to create three-dimensional models of inspected structures (Giannopoulos et al., 2002).

2.4.5. Ultrasonic Tomography

Ultrasonic tomography (UST) is a widely used NDE method that uses acoustic waves to propagate through a structure, of which the waves reflect off of any irregularities and return to a series of sensors which can provide valuable data. Several different types of ultrasonic tomography exist today: some use piezoelectric transducers, others use magnetostrictive transducers, and the application of an ultrasonic guided waves has been studied (Hurlebaus et al., 2013).

Guided waves have shown the ability to detect strand defects in mock-up specimens but has not yet proven effective in field investigations because acoustic dissipation occurs between the strands and the grout, inhibiting investigation of significant lengths of strands (Chaki & Bourse, 2009). The UST technology to be used in this research is an array of ultrasonic transducers. This method is a dry-contact method, meaning a coupling material between the tested surface and transducer is not required, but all transducer must touch the testing surface. Testing is performed by each transducer emitting a linearly time-spaced shear wave into the structure, of which the wave reflects back to each of the adjacent transducers within the array (Azizinamini & Gull, 2012). Figure 2-16 shows typical shear wave transducer array equipment and a typical shear wave propagation arrangement.

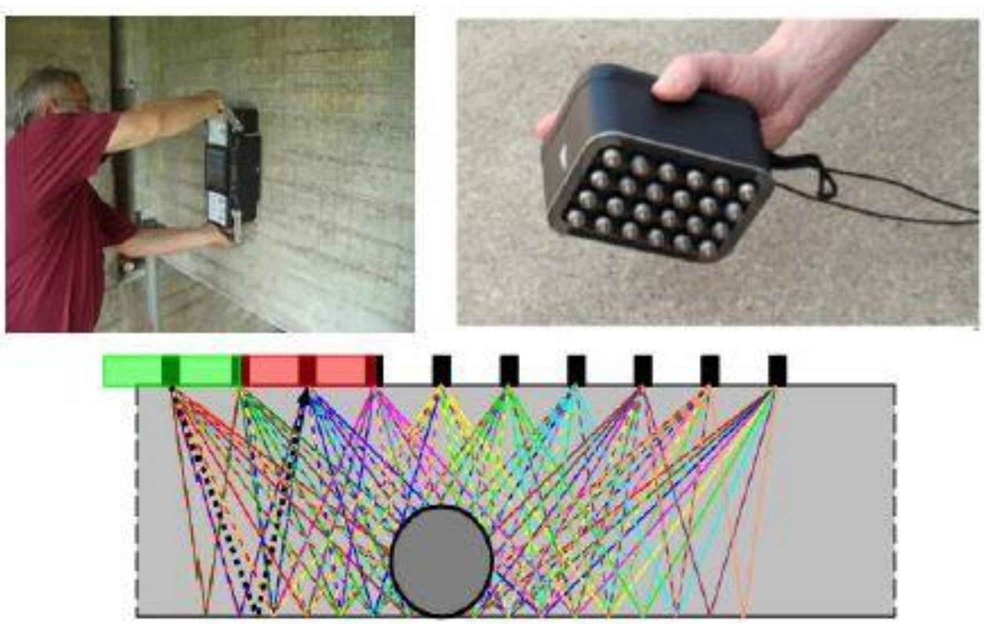


Figure 2-16: Typical Ultrasonic Tomography Equipment (Top) and Wave Propagation Scheme (Bottom) (Azizinamini & Gull, 2012)

These intersecting shear wave paths and recorded phases of each reflected wave can be used to generate data. Recent developments have allowed this data to be transformed into a map of the structure using post-testing data processing softwares. An example of a scan image of an internal tendon can be seen in Figure 2-17, in which the colors indicate the phase of the reflected waves.

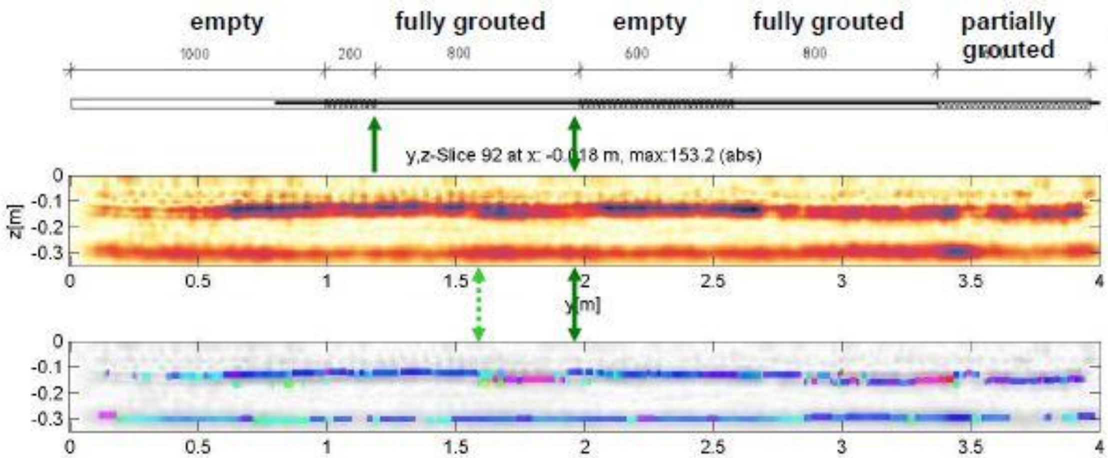


Figure 2-17: Ultrasonic Tomography Conventional (Top) and Modified (Bottom) Scans (Azizinamini & Gull, 2012)

Ultrasonic tomography has successfully detected defects within laboratory cable specimen testing (Baltazar et al., 2010) and successfully identified grouting voids and wire breaks in field testing (Mehrabi, 2006), making it very promising for the testing of stay cable MTEs. Similarly, the development of UST has potential to be applicable in the anchorage regions of the MTEs (Azizinamini & Gull, 2012). There are also several limitations for this method, the first of which is that signal processing and imaging softwares are not yet available in commercial equipment. Secondly, technology of air-coupled UST is still being developed and is not ready for field application (Azizinamini & Gull, 2012). The use of dry-coupled UST requires that an inspector needs to touch the device to the sheathing for every scan along the length of each stay cable, which can be very time consuming and labor intensive for the inspector.

2.4.6. Magnetic Flux Leakage

There are numerous magnetic and electronic NDE methods premised on using the interaction between magnetic/electrical fields and their interaction with matter. The magnetism-based NDE method to be examined in this research is magnetic flux leakage (MFL), which has the capability to inspect ferrous materials, e.g. steel bars or strands. MFL was first developed in the late 1970's and has been upgraded over the years for inspection use on prestressed concrete and stay cable bridges (DaSilva et al., 2009). The basis for the MMFM is to induce a magnetic field onto a ferromagnetic material, of which a flux will excite the steel as a function of cross-sectional area and the magnetic permeability of the material. Ghorbanpoor (1998) outlined the basic magnetic field strength relationship:

$$B = \mu * H$$

where

B = total magnetic flux density, (tesla or Wb/m2)

μ = material magnetic permeability, (Wb/Am or H/m)

H = magnetic field intensity, (A/m)

When the strength of the magnet inducing the flux onto the stay cable MTE is large enough, the atomic dipoles of the magnetized steel will completely align with the magnetic field, which is referred to as magnetic saturation (Ghorbanpoor, 1998). The MFL uses devices that align the induced magnetic field along the longitudinal axis of the tendons, meaning that the flux will align with the steel strands and data can be measured as the device is moved along the length of the tendon. Because the flux density of iron is roughly 100 times that of air, the flux follows the low-resistance path of the metallic matter (Xi et al., 2012). This flux can become disrupted by a loss in cross-sectional area of the steel, causing some of the flux to escape, or “leak”, into the air (Weischedel, 2003). This leaking flux can be measured by a variety of different sensors and MFL technologies to determine cross-sectional area loss and is illustrated in Figure 2-18. As the machine is pushed along the cable, point measurements can be taken along the entire length, giving the inspector the ability to identify a loss metallic material that cannot be viewed by the naked eye from outside the tendon.

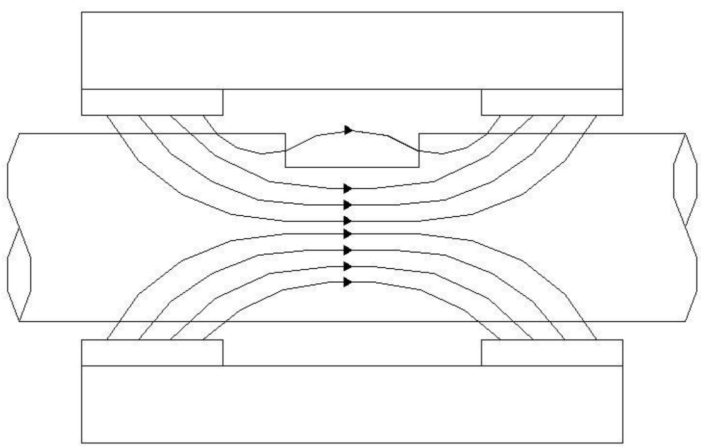


Figure 2-18: Representation of Flux Leakage due to Loss of Cross-Sectional Area

MFL technologies have proven to be both very precise and accurate in their determination of cross sectional area loss of external steel tendons, making them a very useful NDE technique. MFL testing has been performed by numerous researchers, of which the accuracy and capabilities slightly vary due to using different equipment or data interpretation software.

Park et al. (2014) fabricated a sensor head prototype using two high strength permanent magnets and 8 Hall sensors placed in equal intervals around the circumference of the sensor head, which is shown in Figure 2-19.

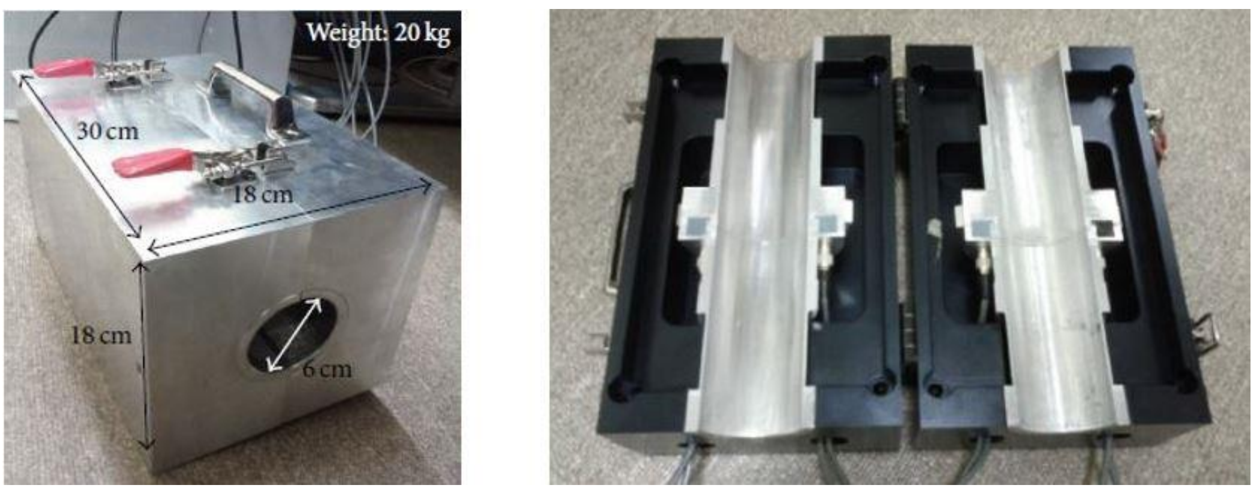


Figure 2-19: Proposed MFL Sensor Head (Park et al., 2014)

A testing specimen was fabricated by inserting twenty-five 10 mm steel strands into a 60 mm diameter pipe, as shown in Figure 2-20. Four levels of localized damage, corresponding to cross-sectional area loss, were applied to the strands in one meter intervals along the length of the specimen. The localized damage was not only placed at intervals along the length of the specimen but defected strands were also located in different cross-sectional locations within the tendon.

Figure 2-20: Testing Specimen Illustrations (Park et al., 2014)

This study used a 99.99% confidence level threshold of the intact sections and a calculated damage threshold value was determined to be 0.1358 V (equaling 0.1358 Wb/s), meaning that all flux leakages measured over this value signals a flaw in the tendon. Results of this study found that not only were all LF damages detected, but the circumferential location of each defect was found based on which Hall sensor(s) measured the leaking flux and the data was three-dimensionally graphed. An example of one of the 3-D tendon damage models is shown in Figure 2-21.

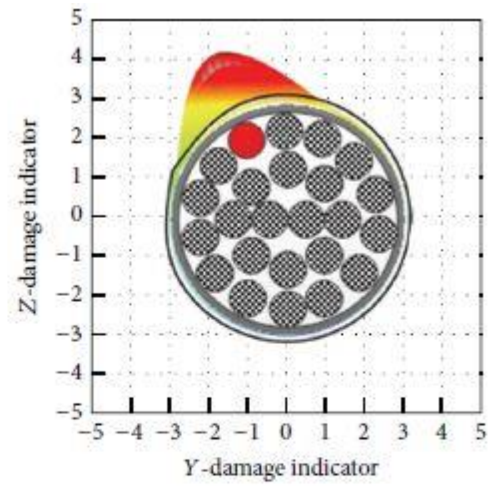


Figure 2-21: Localized Damage Representation (Park et al., 2014)

In Figure 2-21, the damaged strand within the tendon is colored red and the damage indication is based on data interpretation provided by the Hall sensors. Conclusions illustrated that the damage detection sensitivity was dependent on the distance between the localized damage and the hall sensors and the 3-dimensional graph can illustrate to the interpreter the location and size of the defect (Park et al., 2014). This use of Hall sensors in an MFL device can be extremely useful for locating a strand defect within a tendon but is not the only type of sensor. This type of data acquisition also assumes that the MFL device can be accurately installed to restrict rotation as it moves along a tendon, which is easily feasible in a lab but can be extremely difficult to do on a MTE in the field.

Several other researchers have performed research on NDE methods with different results. For instance, Virmani (2007) concluded that an MFL technique used by a FHWA could only detect flaws equivalent to a 5-10% loss of cross-sectional area while Bergamini (2001) concluded that an MFL technique used by EMPA (Swiss Federal Laboratories for Material Science and Technology) was able to detect a wire fracture with a gap width of approximately 20 mm at a depth of 80 mm from the duct, an equivalent of less than a 0.2% loss of cross-sectional area.

MFL provides many advantages compared to other NDE methods for detection of cross-sectional area loss of stay cable MTEs. Firstly, magnetic sensors are widely used to monitor steel structures such as aircrafts and ship hulls because of their excellent reliability and reproducibility (Park et al., 2014). Secondly, it is a contactless test that does not require a physical linking to the steel within the tendons. This means that MFL has the ability to initiate a flux onto the prestressing steel through the surrounding sheathing and can provide useful data on the cross-sectional area of the steel through both metal and plastic ducts. Thirdly, automated MFL systems have been developed using either towing wires or cable-climbing robots to scale the MTEs and record data along the length without requiring personnel to accompany the equipment (Park et al., 2014).

Although this NDE method can be very useful in some cases, there are also several limitations to these MFL technologies, both in the interpretation of the data and in the field applicability of the method. With respect to data interpretation, experienced personnel are required because data can be distorted due to several factors, including the diameter of the prestressed steel wires, number of prestressing steel wires in the tendon, bonding between prestressing steel and grout (affecting crack width), magnetic and magnetoelastic material properties of the type of prestressing steel (Scheel & Hillemeier, 1998), and limited accessibility to certain areas, including anchorage and saddle regions (Azizinamini & Gull, 2012).

Several challenges to the field applicability of MFL technologies also exist, including excessive equipment weight, difficulty in installation and removal of systems (Virmani, 2007), low speed of testing, increasing cable diameters requiring larger magnets (Xi et al., 2012), towing wires possibly wrapping around cables causing damage to cable surface or MFL equipment, and varying cable diameters for a bridge requiring an adjustable magnetic excitation device (Xi et al., 2012). Another challenge is that the accuracy and precision of this method is very much dependent on the type of equipment being used, capabilities of the data analysis software, experience of the tester, and many other factors.

According to Azizinamini and Gull (2012), the best application case for MFL technologies is identifying wire breaks in external plastic ducts and the biggest improvement that can be made is improved performance for congested steel sections and within the anchorage regions.

3. NDE PROCEDURES

3.1. Overview of NDE Procedures

In order to perform accurate NDE testing of the four mock-up stay cable specimens, testing procedures were developed to outline the use of sounding, boroscoping, ground penetrating radar, infrared thermography, ultrasonic tomography, and magnetic flux leakage to evaluate the specimens for detrimental conditions. These procedures describe setup of all required equipment, develop instructions for testing, and if applicable, outline the steps for data processing. The procedure for each NDE method follows a generic testing procedure shown below (Hurlebaus et al., 2014).

1. Identify the starting and ending spans/sections to be inspected.
2. Collect bridge structure files and all relevant information regarding spans/sections to be inspected (tendon profiles, anchorage location, reinforcement presence, etc.)
3. Gather all necessary tools, equipment, and inspection report forms prior to entering the span/section, including inspection procedures/manuals.
4. Enter the span/section to be inspected and ensure a dependable marking system is in place appropriate to the technique (this may be a grid, increments of length, etc.)
5. Record ambient temperature, humidity, and time of inspection. If any of these factors vary considerably (within a given tolerance) from one testing location to

another within the span/section to be inspected, update these factors for every testing location.

6. Perform preliminary walk-through inspection, noting damage indicators (including location) specific to the assessed condition on the appropriate inspection report form.
7. Power on the necessary tools and equipment.
8. Collect data along marking system.
9. Ensure data is properly stored/backed up prior to departing the span/section inspected.
10. Submit completed inspection forms and test samples (if any) to the inspection program manager.

Each NDE method has its own specific testing procedure that can be seen in full in Appendix A. Each of these procedures was adapted from Appendix B of Revised Interim Report No. 2 for the NCHRP on Project 14-28 and adjusted for testing on stay cable systems (Hurlebaus et al., 2014). Each testing protocol was given a numerical designation in accordance with NCHRP 14-28 and is shown in Table 3-1, along with the Appendix location.

Table 3-1: NDE Testing Protocols

NDE Method	Appendix	Protocol
Ground Penetrating Radar	A.1	TP001A
Magnetic Flux Leakage	A.2	TP004A
Infrared Thermography	A.3	TP005A
Ultrasonic Tomography	A.4	TP006A
Sounding	A.5	TP008A
Borescoping	A.6	TP009A

The protocols from NCHRP 14-28 were generalized procedures for testing and required adaptation for this research to specifically apply the procedures to external or stay cable tendons and their accompanying anchorage systems. Additionally, there are multiple variations and models for each NDE technology and only one technology was used per method in this research. Explanations of the changes in the testing procedures from the version used in Revised Interim Report No. 2 for NCHRP Project 14-28 are addressed in the following sections.

3.2. Ground Penetrating Radar

A StructureScan Mini HR was the GPR unit used in this research. This unit has wheels that turn as the device moves along the length of the structure being investigated. For anchorage region inspection, three-dimensional models were generated. Literature review of GPR technologies has asserted that GPR does not have the capability to detect any abnormalities through steel so only one model of each anchorage region was created. For inspection of the free spans, line scan data was acquired as the device moved along the free span of the specimens. Because of the circular shape of the tendons, temporary wooden support structures had to be constructed on each side of the duct to ensure that the wheels turned as the device was moving and data was being collected. An illustration of these temporary wooden supports can be seen in Figure 3-1.

(a) (b)

Figure 3-1: Temporary Wooden Supports for GPR Inspection of Tendon Free Span (a) Top View of Testing Method (b) Overview

3.3. Magnetic Flux Leakage

MFL testing was performed using an LMA-450 Sensor Head and a CC-04 USB Signal Console manufactured by NDT Technologies, Inc. This method requires several physical components that were all assembled in order to perform testing. The sensor head required a connection to the signal console using a specified cable and in order for data to be acquired electronically, a USB connection to a laptop was necessary. The connection from the signal console to the computer during lab testing is shown in Figure 3-2.

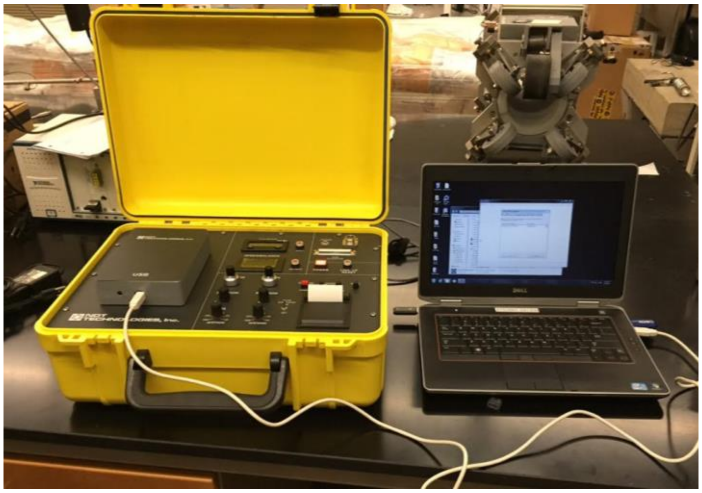


Figure 3-2: CC-04 USB Signal Console Connected to Laptop

Although the sensor head has a distance counter, these devices have many applications for metallic rope inspection, of which rope speeds can be constant so the default data acquisition is a function of time. This research, however, requires MFL inspection data as a function of distance because the machine is advanced along the cables and constant testing speed is very unlikely. In order to display the data as a function of distance, the data must be acquired within the data acquisition software and translated, requiring the laptop containing necessary software to be present and connected during all testing.

For MFL testing, the first thing to do was install the plastic guards onto the ducts, which serve to protect the inner surfaces of the sensor head. Secondly, the device was assembled on the plastic guard and locked. Once the wheels were adjusted so that the device moved smoothly and the distance counter rested well on the duct, the sensor head, signal console, and laptop could all be connected. Figure 3-3 shows the LMA-450 installed on a cable.

Figure 3-3: Installed LMA-450 Anchor Head

Once all components were properly installed and necessary software was running, a minimum of four inspections were performed on each specimen at different gain levels, since finding optimal gain levels for inspection is a trial and error process. Additionally, although this device has the capability to perform inspection in both directions, all inspections were performed in the forward direction. Lastly, once all data was acquired, NDT_CARE 2.00 was used for data processing, including post-calibration and signal enhancement.

3.4. Infrared Thermography

The primary basis for IRT inspection lies in the emissivity of the individual materials within the object being examined, meaning that it is extremely important to perform IRT testing at a time when environmental temperatures are changing, forcing the object to heat or cool in order to reach equilibrium with the environment. Depending on the emissivity of the different materials, each material within the object will release or collect heat at a different rate and the differential temperatures during this transition period can provide valuable information about the object.

In order to capture this transitional time period, photographs were taken around the times of both sunrise and sunset. Furthermore, in order to attempt to verify when the best time to test stay cable specimens using IRT, still photographs were taken from a tripod-installed camera in 15-minute increments starting prior to sunrise or sunset and ending when the specimens appeared to reach equilibrium. Additionally, photographs of the anchorage end caps were taken during warm up and during cool down in order to examine the anchorage regions. A FLIR T640 was used for IRT testing in this research and can be seen in Figure 3-4.

Figure 3-4: FLIR T640 Infrared Camera

3.5. Ultrasonic Tomography

UST testing was performed using an A1040 MIRA unit, as shown in Figure 3-5. This is a dry acoustic contact device, meaning that the device can be placed directly against the concrete surface for testing and the surface didn't need prepared. All UST testing was performed at 50 kHz, which is the nominal operating frequency of the array (Acoustic Control Systems, n.d.).

Figure 3-5: A1040 MIRA

UST testing was performed on both the concrete masses representing the anchorage regions as well as the free spans. Three-dimensional maps were created for each testing location. For each anchorage region, testing was performed on the top of each concrete mass as well as sides of the blocks that would be theoretically accessible in real-life stay cable structures. For repeatability and reproducibility data, four tests were performed on each testing grid. Two tests were performed with the device oriented both parallel and perpendicular to the post-tensioning duct in order to establish the best testing orientation in relation to the duct. For the free spans, testing was performed along the length of the duct in between the duct couplers. Figure 3-6 shows the testing grids on top of the concrete blocks and the free span for the deck and pylon anchorages. Figure 3-7 and Figure 3-8 display the testing grids on the sides of the deck and pylon anchorage systems, respectively.

(a) (b)

Figure 3-6: Testing Grids on Top of Anchorages and Duct (a) Deck (b) Pylon

(a) (b)

Figure 3-7: Testing Grids on Sides of Deck Anchorage (a) Face 1 and 2 (b) Face 3 and 4

(a) (b)

Figure 3-8: Testing Grids on Sides of Pylon Anchorage (a) Face 1 (b) Face 2

3.6. Sounding

Sounding inspection was performed using a ball pein hammer and acoustic responses were logged on a void mapping sheet, which was adapted from Im (2009). Figure 3-9 shows a void mapping sheet for an external tendon. For the specimens being examined in this research, sounding was also performed on the anchorage systems by tapping the grout caps and concrete masses, which are included in the void mapping sheets. Additionally, the spacing of sounding testing is decided at the discretion of the inspector and can range from inches to multiple feet for faster inspections. In this research, sounding inspection was performed in 1-foot intervals.

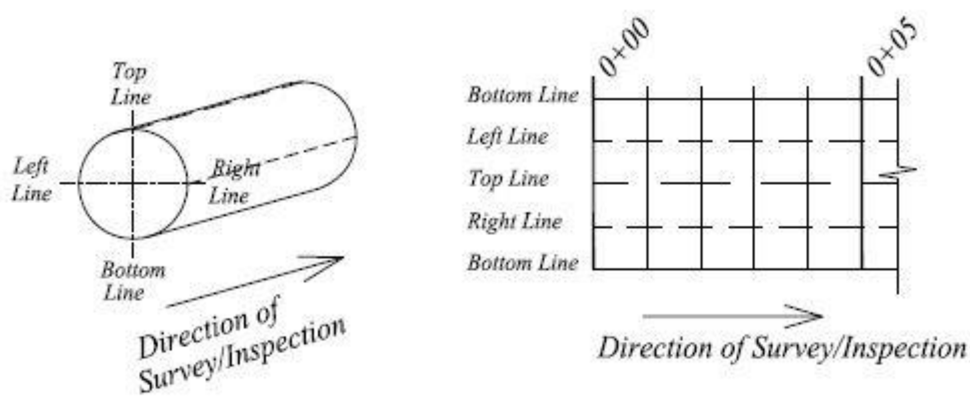


Figure 3-9: Void Mapping Sheet for Sounding Data Recording (Im, 2009)

3.7. Borescoping

Borescope inspections were performed using an Olympus IPLEX SX II, shown in Figure 3-10.

Figure 3-10: Olympus IPLEX SX II

As referenced in the literature review, borescope inspection requires an entry point for the camera to extend into the duct. In this research, threaded entry holes were drilled into the duct and sealed with a screw-in plug when not in use in order to protect the integrity of the defects. Figure 3-11 shows an example of a borescope access hole with the borescope sticking in the hole for inspection. In addition to drilled holes, grout ports were used as entry points. Although holes were drilled at each defect location, entry access was not necessarily available in each section, as fully grouted sections did not allow access of the camera even after the plug was removed.

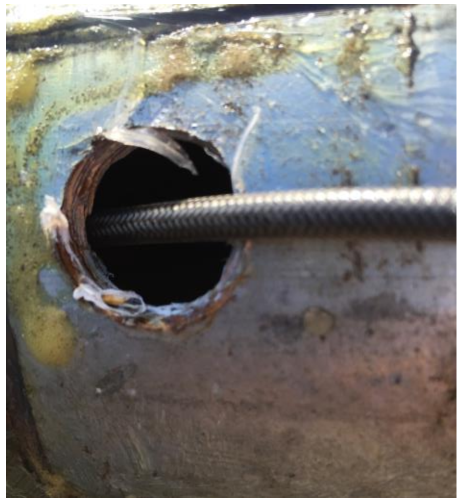


Figure 3-11: Drilled Borescope Inspection Hole

4. EXPERIMENTAL PROGRAM

The experimental program of this research includes the design and construction of the four mock-up specimens using common stay cable MTE systems. Each of the mock-up specimens is constructed with its own unique combination of sheathing material and corrosion protection system. Additionally, detrimental conditions were implemented along the length of the specimens, both in the free spans of the MTEs and sections encased in concrete, representative of anchorage regions. Firstly, the mock-up specimen design is discussed, which outlines the specimen geometry along with the construction materials and reinforcing details of the specimens. Secondly, the defect placement of each specimen is defined. Lastly, the construction of the specimens is summarized, including both construction steps and defect fabrication details.

4.1. Mock-Up Specimen Design

The primary goal of the stay cable mock-up specimens was to accurately mimic both the free span and end conditions of actual stay cable bridge systems, as shown in Figure 4-1. The end conditions that are intended to be represented by the specimens are the typical concrete deck superstructure and the typical concrete pylon, characterized geometrically by the mass concrete blocks shown in Figure 4-2. All four stay cable mock-up specimens consist of a 17-foot long free span restrained at both ends by the concrete blocks, which are 2 feet thick. The anchorage blocks for each specimen were dimensionally identical and contain typical steel reinforcement, as shown in Supplemental File A.

Figure 4-1: Stay Cable End Conditions Mimicked in Mock-Up Specimen (DYWIDAG-Systems International)

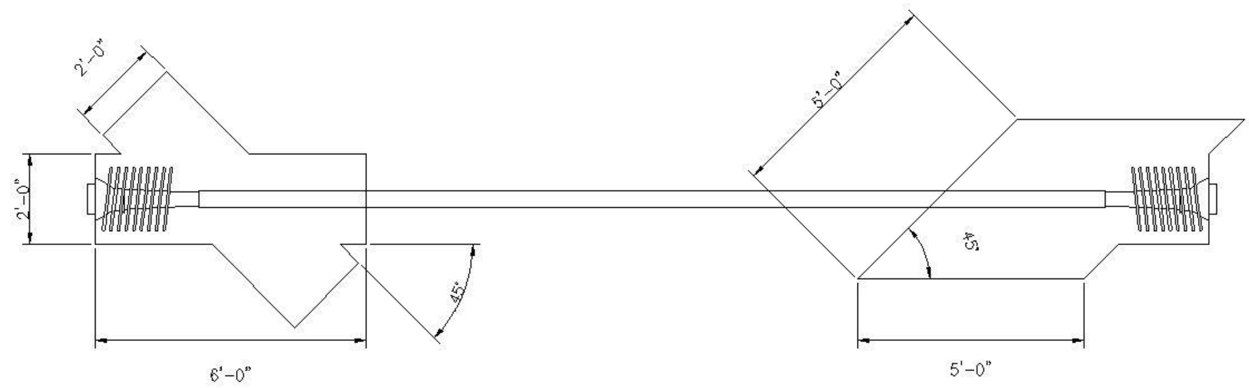


Figure 4-2: Stay Cable Mock-Up Specimen Plan View

In order to simplify construction, the mock-up specimens were designed and constructed horizontally. A slab was designed and poured with anchors protruding from the slab where the concrete anchorage blocks were to be poured, in order to provide shear capacity for partial stressing of the specimens. After construction of the specimens, the strand defects were placed and documented prior to grouting (for grouted systems). Supplemental File A provides all of the engineering drawings for the stay cable mock up specimens, including tendon configuration, placement of defects, and reinforcing details.

The differences in the mock-up specimens lie in the different sheathings and corrosion-protection systems that were implemented. The four systems that will be constructed are: (1) grouted strands in steel pipe, (2) grouted strands in HDPE duct, (3) un-grouted mono strands greased and sheathed in HDPE duct, and (4) un-grouted epoxy-coated strands in HDPE duct. Both the steel and HDPE sheathings have a nominal 4.0 in. diameter and each system will contain 19 seven-wire strands with a 0.6 in. diameter.

For the ungrouted specimens, the top three strands in each duct were each stressed to approximately 12 kips in order to ensure that the tendons are taut and deflection of the tendons is minimized.

4.1.1. Specimen 1: Grouted Strands in Steel Pipe

Specimen 1 was designed to investigate grouted parallel strands sheathed with steel pipe. This sheathing and corrosion protection system is the least common of the four mock-up specimen, as steel pipe sheathing was only used in three bridges in the United States as of 1995: Dame Point Bridge in Florida, Sunshine Skyway Bridge in Florida, and the C & D Canal Bridge in Delaware (Hamilton et al., 1995). Since then, the Maumee River Canal Bridge, also called the Veteran's City Glass Skyway was constructed using stainless steel sheathing (Tabatabai, 2005).

4.1.2. Specimen 2: Grouted Strands in HDPE Duct

Specimen 2 was designed to investigate grouted parallel strands sheathed with HDPE duct. Specimen 2 uses bare low relaxation parallel strands and grout also serves as the corrosion protection system. Specimen 2 uses high-density polyethylene sheathing instead of steel pipe that was used in Specimen 1. The Veterans Memorial Bridge and Fred Hartman Bridge, located in Port Arthur, TX and La Porte, TX, respectively, are two examples of bridges that incorporate parallel strands within grouted HDPE sheathing (Wood et al., 2008)

4.1.3. Specimen 3: Ungrouted Monostrands Greased and Sheathed in HDPE Duct

Specimen 3 uses the same HDPE duct as used in Specimen 2 but a different corrosion protection system is implemented. Instead of grouting the system as a corrosion barrier, greasing and sheathing of the individual parallel strands serves as the corrosion protection system. This method is popular internationally but is not commonly used in the United States (Hamilton et al., 1995). The Batam-Tonton Bridge in Indonesia is an example of a bridge that uses greased and sheathed strands (VStructural, LLC., 1998)

4.1.4. Specimen 4: Ungrouted Epoxy-Coated Strands in HDPE Duct

Specimen 4 also uses the same HDPE duct as used in Specimen 2 and 3 but uses epoxy-coating of the strands as the corrosion protection system, as produced by ASTM A882. This system does not include grouting, as the epoxy coating provides protection of the bare parallel strands from corrosion. There are several cable-stayed bridges in the United States that implement epoxy-coated strands, including the Bayview Bridge in Illinois, the Burlington Bridge in Iowa, and Clark Bridge in Illinois (Hamilton et al., 1995).

4.2. Condition Types and Locations

Coupled with the specimen design is the planning of both the steel and grouting conditions to be implemented into each mock-up specimen. In order to facilitate defect placement, a grid of each mock-up specimen was created in order to place the maximum amount of defects in each specimen while still providing ample space for accurate testing of each defect location. The final defect grid, shown in Figure 4-3, allows three feet per defect with the exception of one grid section being two feet due to the length of the stay cable specimens. Each specimen contains two defect locations in each anchorage regions and six defect locations along the free spans.

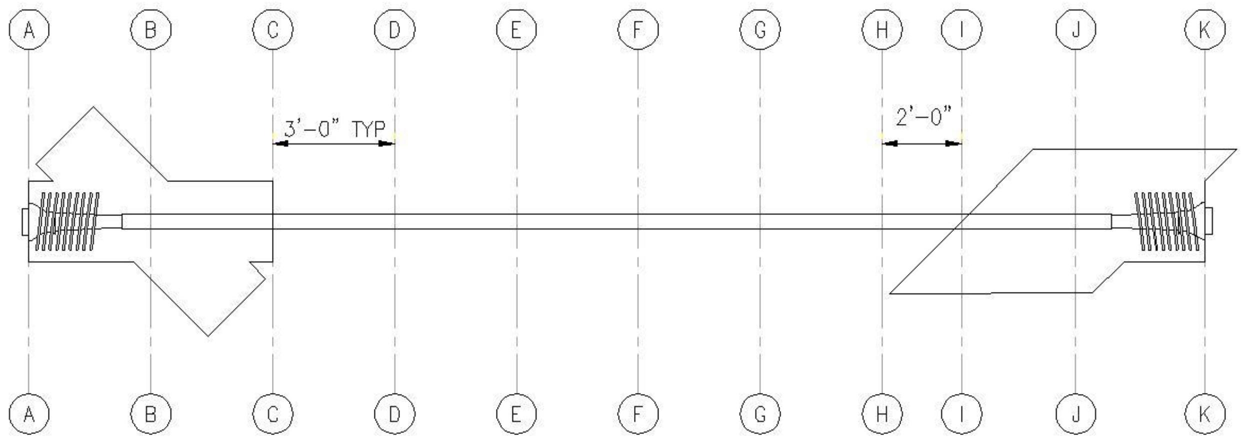


Figure 4-3: Typical Mock-Up Specimen Defect Grid

Each specimen was designed to include at least one of each type of condition applicable to that system. The grouted systems include a minimum of one condition of corrosion, section loss, breakage, grouting voids, water infiltration, other grout conditions, and general tendon deterioration while the ungrouted systems include at least one condition of corrosion, section loss, and breakage.

Each type of defect can have different levels of severity but due to limited defect locations, only certain levels of each defect could be implemented within the four specimens. Table 4-1 shows a list of all defects associated with this research project, an accompanying description of each defect, and a summary showing which defects the each of the four specimens contain. Due to the limited length of the specimens, not all defects were fabricated. Tables 4-2, 4-3, 4-4, and 4-5 display the location of each defect that was fabricated in Mock-Up Specimens 1, 2, 3, and 4, respectively, along with an explanation of each defect. The complete list of all defects and their accompanying descriptions can also be found in the engineering drawings in Supplemental File A.

Table 4-1: Condition Codes, Descriptions and Locations

Condition Type	Condition	Condition Description	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Strand Corrosion	BS1	1 of 7 wires fractured			X	X
	BS2	3 of 7 wires fractured				
Tendon Corrosion	BT1	1 of 19 strands fractured	X	X	X	X
	BT2	3 of 19 strands fractured				
	BT3	10 of 19 strands fractured				
	BT4	19 of 19 strands fractured				
Wire Corrosion	CW1	Light-moderate wire pitting		X		X
	CW2	Severe wire pitting				
	CW3	Extreme wire pitting				

Table 4-1 Continued

Condition Type	Condition	Condition Description	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Strand Corrosion	CS1	1-2 of 7 wires fully corroded			X	X
	CS2	3-4 of 7 wires fully corroded			X	X
	CS3	7 of 7 wires fully corroded				
Tendon Corrosion	CT1	1-2 of 19 strands fully corroded	X	X		
	CT2	3-4 of 19 strands fully corroded	X		X	
	CT3	9-10 of 19 strands fully corroded	X	X	X	X
	CT4	19 of 19 strands fully corroded				
Grout Conditions	GS1	Approximately 50% full of segregated grout	X	X		
	GS2	100% full of segregated grout				
	GU1	Approximately 50% full of unhydrated grout				
	GU2	100% full of unhydrated grout				
	GG	100% full of gassed grout				
Void	V1	Approximately 25% voided		X		
	V2	Approximately 50% voided				
	V3	Approximately 75% voided				
	V4	100% voided	X	X		
Water Infiltration	W1	Approximately 25% full of water	X			
	W2	Approximately 75% full of water	X	X		

Table 4-1 Continued

Condition Type	Condition Code	Condition Description	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Water Infiltration	W3	100% full of water				
Sheathing Damage	S1	Epoxy-coating of strand removed				X
	S2	Sheathing of strand removed			X	

Table 4-2: Defect Placement of Mock-Up Specimen 1

Location	Defect	Description
A-B	CT2	3-4 of 19 strands fully corroded (16-25% tendon cross section)
B-C	INTACT	No defect
C-D	INTACT	No defect
D-E	W2	Approximately 75% full of water
E-F	CT3	9-10 of 19 strands fully corroded (47-59% tendon cross
F-G	V4	100% voided
G-H	BT1	1 of 19 strands fractured (5% tendon cross section)
H-I	GS1	Approximately 50% of segregated grout
I-J	W1/CT1	Approximately 25% full of water / 1-2 of 19 strands fully corroded (5-16% tendon cross section)
J-K	W1	Approximately 25% full of water

Table 4-3: Defect Placement of Mock-Up Specimen 2

Location	**Defect**	**Description**
A-B	INTACT	No defect
B-C	CW1	Light-Moderate Wire Pitting (<1% tendon cross section)
C-D	INTACT	No defect
D-E	W2	Approximately 75% full of water
E-F	CT3	9-10 of 19 strands fully corroded (47-59% tendon cross
F-G	V4	100% voided
G-H	BT1	1 of 19 strands fractured (5% tendon cross section)
H-I	GS1	Approximately 50% of segregated grout
I-J	V1/CT1	Approximately 25% voided / 1-2 of 19 strands fully corroded (5-16% tendon cross section)
J-K	V1	Approximately 25% voided

Table 4-4: Defect Placement of Mock-Up Specimen 3

Location	Defect Type	Description
A-B	CT2	3-4 of 19 strands fully corroded (16-25% tendon cross section)
B-C	INTACT	No defect
C-D	CS1	1-2 of 7 wires fully corroded (<3% tendon cross section)
D-E	BS1	1 of 7 wires fractured (<2% tendon cross section)
E-F	CT3	9-10 of 19 strands fully corroded (47-59% tendon cross
F-G	BT1	1 of 19 strands fractured (5% tendon cross section)
G-H	INTACT	No defect
H-I	S2	Sheathing of strand removed
I-J	BS2	3 of 7 wires fractured (2-4% tendon cross section)
J-K	CS2	3-4 of 7 wires fully corroded (2-3% tendon cross section)

Table 4-5: Defect Placement of Mock-Up Specimen 4

Location	Defect Type	Description
A-B	CT3	9-10 of 19 strands fully corroded (47-59% tendon cross
B-C	CS2	3-4 of 7 wires fully corroded (2-3% tendon cross section)
C-D	BS1	1 of 7 wires fractured (<2% tendon cross section)
D-E	CT3	9-10 of 19 strands fully corroded (47-59% tendon cross
E-F	BT1	1 of 19 strands fractured (5% tendon cross section)
F-G	CW1	Light-Moderate Wire Pitting (<1% tendon cross section)
G-H	INTACT	No defect
H-I	S1	Epoxy-coating of strands removed
I-J	INTACT	No defect
J-K	CS1	1-2 of 7 wires fully corroded (<3% tendon cross section)

4.3. Mock-Up Specimen Construction

All four of the mock-up specimens were constructed at Texas A&M University Riverside Campus. Construction of the specimens included several parts: construction of the formwork, tying and placing of the reinforcement, installation of the post-tensioning system, pouring of concrete, fabrication and documentation of defects, and lastly, grouting of the two grouted specimens.

4.3.1. Formwork, Reinforcing, and Anchorage System

Formwork was built as a series of individual 2 foot stud walls. Once all of the walls were properly assembled and fastened to each other, plywood was placed on the face and the frames were anchored into the slab around the protruding shear connections. Installation of the mild reinforcement and the post-tensioning system were done concurrently, as closed stirrups had to be placed around the steel duct prior to the heatshrinking of the steel duct, trumpet, and anchor head. Figure 4-4 shows an example of each block's formwork, reinforcement, and PT system prior to pouring of the concrete.

(a) (b)

Figure 4-4: Stay Cable Ends Prior to Concrete Placement (a) Pylon (b) Deck

After all formwork, reinforcement, and anchorage systems were assembled and properly supported, the concrete was poured.

4.3.2. Material Properties

The concrete compressive strength test results in accordance with ASTM C39 are shown in Table 4-6 (ASTM, 2010c).

Table 4-6: 28-Day Concrete Compressive Strength Results

Specimen 1 (ksi)	Specimen 2 (ksi)	Specimen 3 (ksi)	Specimen 4 (ksi)	Specimen 5 (ksi)	Specimen 6 (ksi)	Average (ksi)
7.27	7.20	7.11	8.03	7.75	8.06	7.57

The free span ducts were then placed, connected to the protruding steel ducts, and supported by temporary wooden supports in order to help maintain linearity. After all ducts were assembled, the strands were cut, fabricated, and placed in their appropriate locations in accordance with the required condition locations. After all strands were placed, the grouting process could begin in order to both fully grout required sections and implement all grouting defects. For both intact and defective grouting, Class C thixotropic grout was used. For sections with proper grouting, the grout was mixed with the required amount of water and pumped into each section using a pneumatic pump. Numerous fresh property grout tests were performed in order to ensure proper grout quality, including Pumpability and Fluidity (ASTM, 2010a), Wet Density (API, 2003), and the Wick-Induced Bleed (ASTM, 2010b). The results of these tests are displayed in Table 4-7.

Table 4-7: Grout Fresh Property Results

Test	Limit	Results
Pumpability and Fluidity	Recommended 5-20 seconds (Merrill, 2014)	14.7 seconds
Wet Density	Min. 121.7 pcf (API, 2003)	124 pcf
Wick-Induced Bleed	0.0% bleeding at three hours (ASTM, 2010b)	No Bleed

Similarly, grout cube specimens molds were prepared. Compressive strength tests of the grout in accordance with ASTM C942 were performed at 7 and 28 days, the results of which are shown in Table 4-8 along with required compressive strengths of PTI and TxDOT.

Table 4-8: Grout Compressive Strength Results

Age (days)	PTI Required Strength (ksi)	TxDOT Required Strength (ksi)	Specimen 1 (ksi)	Specimen 2 (ksi)	Specimen 3 (ksi)	Average Strength (ksi)
7	3.0	4.0	5.01	5.49	4.10	4.87
28	5.0	4.6	5.97	6.84	6.64	6.48

After all grouting was performed, all grout tests met minimum requirements, and the grout cured for 28 days, construction of the four stay cable mock-up specimens was completed and ready for testing. Figure 4-5 shows the all four of the completed specimens.

Figure 4-5: Completed Stay Cable Mock-Up Specimens

5. EXPERIMENTAL RESULTS

Non-destructive testing of the mock-up stay cable specimens was performed at different time periods after the construction of the specimens was completed. Specimens 1 and 2 were tested a minimum of 28 days after grouting in order to ensure that the grout was fully cured. Specimens 3 and 4 were tested after all construction and defect placement was completed with no minimum waiting time. Table 5-1 provides an overview showing which NDE methods were able to detect defects located within the specimens, along with the physical parameters of the tested system. The remainder of this section summarizes and discusses all of the results from the NDE testing of all four mock-up specimens. All NDE testing results are shown in Appendix B.

Table 5-1: Overview of Defect Detection by NDE Methods

Specimen	Physical System	Location	Defect	GPR	MFL	IRT	UST	Sounding	Borescope
1	Anchorage	A-B	CT2						
	External Metal Duct	D-E	W2					X	X
	External Metal Duct	E-F	CT3		X				
	External Metal Duct	F-G	V4					X	X
	External Metal Duct	G-H	BT1		X				
	External Metal Duct	H-I	GS1					X	
	Anchorage	I-J	W1/CT1						
	Anchorage	J-K	W1			X		X	X
2	Anchorage	B-C	CW1						
	External Non-Metal Duct	D-E	W2	X		X	X	X	X
	External Non-Metal Duct	E-F	CT3		X				
	External Non-Metal Duct	F-G	V4	X		X	X	X	X
	External Non-Metal Duct	G-H	BT1		X				
	External Non-Metal Duct	H-I	GS1	X				X	X
	Anchorage	I-J	V1/CT1						
	Anchorage	J-K	V1			X		X	
3	Anchorage	A-B	CT2						
	External Non-Metal Duct	C-D	CS1		X				
	External Non-Metal Duct	D-E	BS1		X				
	External Non-Metal Duct	E-F	CT3		X				
	External Non-Metal Duct	F-G	BT1		X				
	External Non-Metal Duct	H-I	S2						
	Anchorage	I-J	BS2						
	Anchorage	J-K	CS2						
4	Anchorage	A-B	CT3						
	Anchorage	B-C	CS2						
	External Non-Metal Duct	C-D	BS1		X				
	External Non-Metal Duct	D-E	CT3		X				X
	External Non-Metal Duct	E-F	BT1		X				
	External Non-Metal Duct	F-G	CW1		X				
	External Non-Metal Duct	H-I	S1						
	Anchorage	J-K	CS1						

5.1. Ground Penetrating Radar

GPR results essentially reaffirmed all of the capabilities and limitations of the technology that was outlined in the literature review. Firstly, a major limitation of GPR is that it is extremely sensitive to steel, making it extremely difficult or impossible to detect anything beneath steel. This makes GPR inspection on steel ducts impractical, as the radar pulse just continually rebounds off of the steel duct. Results from the testing of Specimen 1 are shown in Figure B.1-1. Secondly, this limitation does not make GPR a useful NDE method for determination of defects within anchorage systems, which often incorporate steel ducts encased in concrete, as used in this research. One three-dimensional map was created for each anchorage system in order to illustrate this deficiency, of which the testing grid, origin, axes, and labeling method are shown in Figure 5-1.

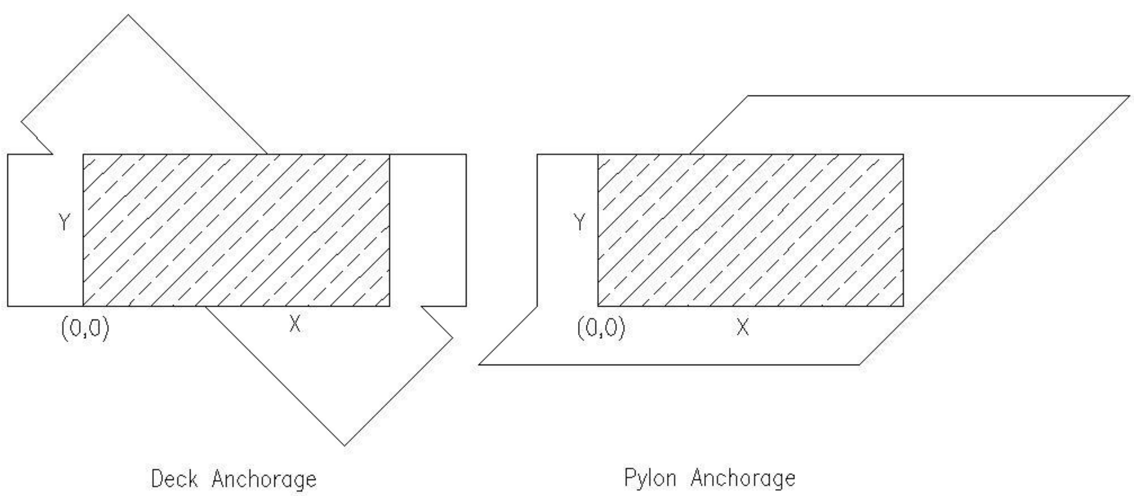
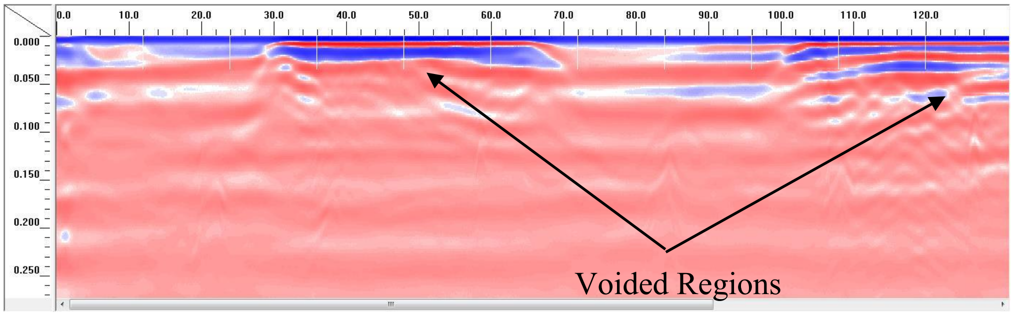


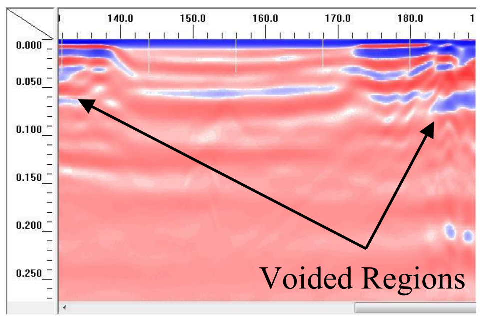
Figure 5-1: GPR 3-D Testing Coordinates and Labeling For Anchorage Zones

Each 3-D map was created and individual slices, or scans, of the map were taken in order to illustrate certain points. Scans parallel to testing grid are shown in Figure B.1-8 and Figure B.1-9 which clearly illustrate the top reinforcing grids for the deck and pylon anchorages, respectively. This inspection capability, however, is of no importance to this research and additional scans are provided in Figure B.1-10 and Figure B.1-11 showing the inability of GPR to detect any sort of post-tensioning defects within the anchorage region. In these images, 2-D scans parallel to the y-axis, called D-scans, were processed in data analysis software and noise interference lines were superimposed on the original D-scans. The noise interference lines show the inspection depth at which data becomes noisy and useless, which for both 3-D maps was at a depth of approximately 10 inches. It is possible that if there was less reinforcement or cover, GPR would be able to detect the post-tensioning duct but is not practical to determine anything occurring there within.

Although testing of Specimen 1 and the anchorage regions were ineffective, the ability of GPR to determine voided regions within non-metal ducts was confirmed. Figure 5-2 shows results from inspection of Specimen 2 which clearly illustrates the voided regions within.



(a)



(b)

Figure 5-2: Specimen 2 GPR Results (Test 1) (a) 1 – 130 in. (b) 130 – 190 in.

For the voided regions, alternating red-blue layers show the three voided regions on the top of the duct. An additional positive result of these tests is that Figure 5-2 matches almost exactly with the second test, shown in Figure B.1-3. Both figures are almost identical, making GPR inspection a very repeatable and reproducible inspection method. This method proved very effective in locating and determining the length of voided regions but void sizes are difficult to determine because once the radar signal hits the prestressing steel within the duct, the signal continually rebounds off the steel, making determination of void depth indeterminable. Additionally, GPR testing did not appear to detect a difference between the voided region, water infiltrated region, and region containing poor grout. Testing of Specimens 3 and 4, shown in Figure B.1-4 through Figure B.1-7, respectively, provided no useful data about the ungrouted systems, as GPR does not have the capability to determine any metallic defects.

Overall, GPR was able to accurately and precisely locate voided regions but was unable to provide any other quantitative or qualitative information regarding the depth of the void or grout quality within the duct. The only applicable system for GPR inspection is a grouted, non-metal specimen, as GPR does not have the capability to provide information on the conditions within metal ducts, ungrouted systems, or anchorage systems.

5.2. Magnetic Flux Leakage

Magnetic flux leakage results proved that this method is extremely effective at determining defects of the steel within a stay cable tendon. In this research, loss of metallic area (LMA) was examined, which means the sensor head records the differential area of steel as the device moves along the tendon. Table 5-2 shows quantitative MFL data to go along with Figure B.2-1 through Figure B.2-4, including the expected cross-sectional area losses and the measured cross-sectional area losses.

Table 5-2: Quantitative MFL Result Summary

Specimen	Defect	Expected LMA (%)	Expected LMA (%) incl. Area	Test 1 LMA (%)	Test 2 LMA (%)	Test 3 LMA (%)	Test 4 LMA (%)
1	CT3	47-59	27-34	29.9	35.1	30.3	29.4
1	BT1	5	3	2.3	2.4	2.6	2.4
2	CT3	47-59	N/A	46.3	45.0	46.6	44.8
2	BT1	5	N/A	7.3	7.0	4.1	4.9
3	CS1	<3	N/A	5.3	5.0	4.6	5.0
3	BS1	<2	N/A	5.0	1.5	4.0	3.9
3	CT3	47-59	N/A	42.6	46.6	43.4	44.7
3	BT1	5	N/A	8.2	6.7	6.2	5.6
4	BS1	<2	N/A	1.6	14.0	2.3	12.9
4	CT3	47-59	N/A	52.0	49.4	49.4	48.8
4	BT1	5	N/A	1.5	2.9	19.0	0.2
4	CW1	<1	N/A	11.4	10.6	12.7	12.0

Both the figures in Appendix B.2 and the data in Table 5-1 are very accurate in determining steel defects within the tendons, although there is variance within both the magnitudes of the defects and their locations. All four mock-up specimens produced easily interpreted shapes in the LMA data, with corrosion causing a slow gradual dip and rise in LMA and a breakage causing a sharp dip and rise. Specimen 1, shown in Figure

B.2-1, not only clearly shows both the corrosion and the breakage defects but also illustrates the locations in which five access holes were cut in the duct and caused flux leakage. Specimen 1 also has a variance in the baseline, or intact, sections. Steel duct is made with a longitudinal weld on the inside of the duct, causing the baseline LMA to slightly vary along the length of the duct, causing ripples in the MFL results. Overall, Specimen 1 testing produced the most accurate data of the four specimens, with the measured data being extremely close to the expected data with little variance.

Figure B.2-2 shows the MFL results of Specimen 2, which also produced accurate data. As with Specimens 3 and 4, the LMA of the CT3 locations is slightly less than the expected percentage, but is very likely accurate data. The expected LMA range is based on all corroded strands being severed at the exact same location, which is likely not the case. Strands are severed within an approximate 4-inch distance range, inferring that some strands are continuous at locations where others are broken.

Testing results of Specimens 3 and 4 are shown in Figure B.2-3 and Figure B.2-4, respectively, and also produced promising results. As with Specimens 1 and 2, each defect was located, although there was variance in the location and magnitude. Smaller defects, such as BS1, BT1, and CW1 were both highly exaggerated in their magnitudes within their respective specimen, although the exaggeration made the defect much easier to determine. Additionally, the magnitude variance within BS1 in Specimen 3 and BT1 in Specimen 4 were very high.

Overall, MFL proved very capable in detecting, locating, and quantifying steel defects within a stay cable tendon, making the accuracy of this method very high.

Although each defect was detected in each test of all four specimens, there were a few minor differences in location and magnitude of recorded data. This slightly lowered the precision of this method, although there are likely reasons for these minor issues and can be addressed.

Firstly, the distance counter signal from the sensor head is a function of testing time, meaning that speed of the device must be constant. Although testing attempted to advance the device at a constant speed, it is impossible to do manually so distance signals varied slightly in the data. Secondly, once the data is acquired and opened in the data analysis software, LMA enhancement and post-calibration of the data must be performed. The device is made of two heads that clamp together around the duct, the device allows a small amount of flux to leak between the joints, meaning that some flux leakage is not recorded. LMA enhancement is a post-acquisition data analysis tool that adjusts the data to best account for the flux that leaked from the device. This adjustment is based on the sensor head type and data values for adjustment are recommended in the device manual. After acquisition, all of the MFL data is stored as relative LMA percentages and the data must be post-calibrated in order to acquire net LMA percentages. This is done by adjusting one point on the output graph to a known LMA percentage and the rest of the graph adjusts linearly. It is likely that this calibration is not meant to comparatively adjust large defect data, such as CT3, with small defect data, such as CW1. This calibration could potentially cause an over adjustment of small defects in when being calibrated in the same test as large LMA defects.

It should be noted that the LMA-450 sensor head was made to be installed on external tendons and slide along the duct so only data for the free spans of the specimens were recorded in this research. This device has no ability to determine defects within the anchorage region, although there are MFL devices that are manufactured that claim to be able to detect tendon defects within internal tendons or anchorage regions. Since the LMA-450 does not have this capability, all metrics scores for MFL testing within anchorage regions did not receive a score since the technology was not investigated in this research.

5.3. Infrared Thermography

As mentioned in Section III, the primary applicability of this research lies in acquiring infrared data on the specimens during a time when they are either heating up or cooling off. Figure 5-3 shows an infrared photograph during the cool off period, which clearly shows the voided regions in Specimen 2.

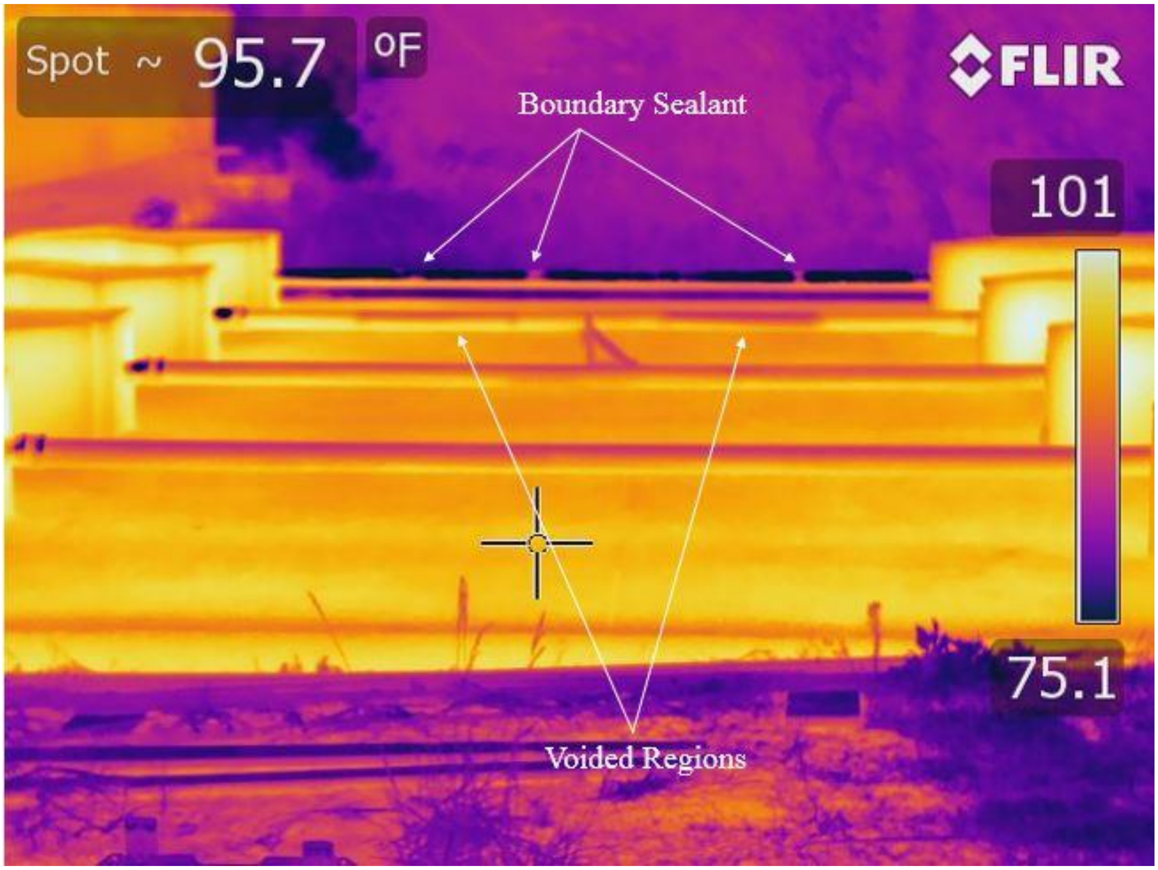


Figure 5-3: Enlarged Infrared Image of Mock-Up Specimens During Cooling Off Period

Figures C.3-1 through C.3-3 show all four specimens ordered 1-2-3-4 from back to front of each image. Figure B.3-1 and Figure B.3-2 show the progression of the specimens reaching thermal equilibrium with the environment during the cooling off and heating up periods, respectively. The heating up period showed more thermal change during the 3-hour time frame of which images were taken. The voided regions of Specimen 2 in Figure B.3-2 do not appear in infrared photos (a) or (b) but appear vividly in (c) and (d), which were taken roughly 45 and 75 minutes after sunrise, respectively.

On the contrary, all of the infrared photos during the cooling off period show both voided regions in Specimen 2.

The enlarged photo during the heating up period, shown in Figure B.3-3, also shows the two voided regions in Specimen 2 but not in Specimen 1. This result was expected from previous research outlined in Section II, as the emissivity of steel is very low, meaning that the steel reflects significantly more heat than the HDPE ducts. For infrared thermography, this characteristic results in steel ducts absorbing significantly less heat and being continually closer to thermal equilibrium with the environment and not allowing the thermal properties of the materials within to be shown. The sealant between grouting defects appears in both images because it is a polyurethane compound that absorbs practically no heat and remains at a very constant temperature despite environmental temperatures.

Figure 5-3 and Figure B.3-4 also not only show the voided regions of Specimen 2 but also outline their shapes and provide can rough estimates of their sizes. Although the smaller void in Grid D-E of Specimen 2 contains water, the water does not appear to create a different thermal response than a typical air void in Grid F-E, which could simply be due to the low amount of water in the duct. This result contradicts literature review, as the thermal properties of air and water are very different but the water did not distinctly appear in the thermal images. Additionally, no significant results were shown in Specimens 3 and 4, as thermal variation within ungrouted ducts is likely to be nonexistent even if prestressing steel is damaged or missing.

Figures C.3-5 through C.3-8 show all 8 of the grout caps during both heating up and cooling down periods. Grid K for both Specimens 1 and 2 contain voided regions, of which Specimen 1 is filled with water to represent water infiltration. Figure B.3-5 (a) and (c) are both the fully grouted Gridline A of Specimen 1 but (b) shows Gridline K, where a grout fill line is lightly visible but the presence of water is not determinable. Figure B.3-5 (d) does not show this grout line during the heating up period. Figure B.3-6 presents similar results of Specimen 2, but (b) and (d) display the grout fill line in Gridline K during the cooling down and heating up time periods, respectively.

The results from this research strongly aligned with the capabilities and limitations outlined for IRT in the literature review. Infrared thermography has a very good ability to detect and estimate void sizes in HDPE duct and grout caps but was unable to detect water or grout segregation. A major limitation of IRT is its inability to provide useful condition assessment information within steel ducts, as no data of use was found within Specimen 1 after inspection. Lastly, this method does not have the capability to determine any sort of steel defects in steel, grouted HDPE ducts, or ungrouted HDPE ducts.

5.4. Ultrasonic Tomography

In order to properly understand ultrasonic tomography results, it is especially important to understand the different scans that are taken with each model, which essentially show images that align with planes of each 3-D map. A C-scan is parallel to the testing surface, a D-scan is parallel to the device, and a B-scan is perpendicular to the device. Figure 5-4 provides an illustration of the planes of which each of these scans represent and was used for data presentation. Data analysis of UST testing results was performed using all three scans in combination with the 3-D model but the only the scan that best illustrates pertinent information to this research is presented in Appendix B.4.

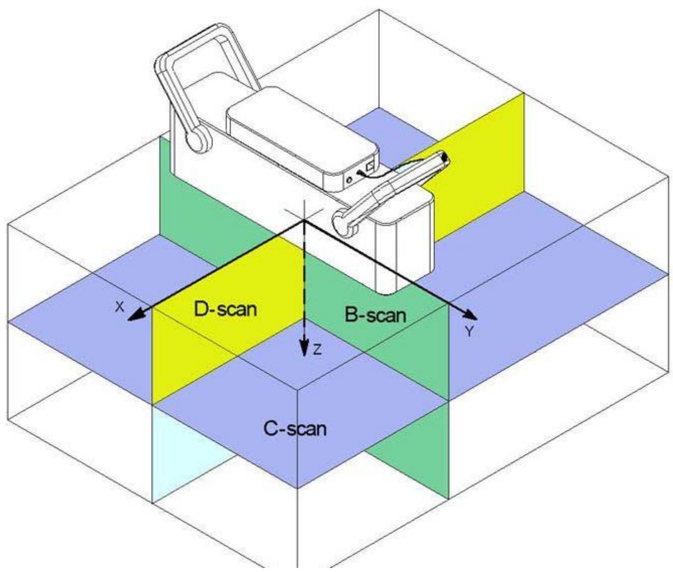


Figure 5-4: Illustration of Scan Planes for 3-D Maps (Acoustic Control Systems, n.d.)

Firstly, duct inspection results will be analyzed. The results of this research aligned somewhat with previous research from Section II but UST results can be very dependent on the specific inspection device being used. For instance, because of the circular shape of the duct, only three of the four rows of sensors were able to contact the duct for each test, but a smaller device could be able to acquire data from all sensors.

Figures C.4-1 through C.4-4 show B-scans along the length of a free span and because the device does not rest properly on the duct, the depth of each map is shifted downwards approximately 1-1.5 inches. This is why the bottom of the duct appears at a depth of approximately 6 inches instead of the nominal 4.5 inch outer diameter of the ducts.

Inspection of Specimen 1 did not show any useable data. The results of Specimen 1 are shown in Figure B.4-1 and Figure B.4-2 and the only glitches are access holes that act as air barriers. Ultrasonic tomography testing through steel pipe or duct is possible but the A1040 MIRA device does not reach testing frequencies required to accurately penetrate steel. The A1040 MIRA has a frequency range of 25 to 80 kHz but ultrasonic testing of steel is usually performed in the range from 500 kHz to 20 MHz (Werner Solken, 2015).

The results of Specimen 2 appear to provide better information on grouting quality within the duct, as shown in Figure 5-5. Figure B.4-4 shows a second scan which is similar to Figure 5-5, as both tests were extremely similar and presented identifiable characteristics. The first identifiable characteristic were the defective voided regions in D-E and F-G. Ultrasonic waves travel at a significantly different speed through air than concrete so the blue regions directly underneath the duct are strong identifiers of voided regions. The locations of the voids appear fairly accurate, as the void in F-G appears to extend slightly into G-H, which is likely due data interpolation from the device. Additionally, UST data was unable to determine the depth or size of the voided region. Although the water infiltration defect in D-E is a small void filled partly with water and the F-G void is a fully voided section, the UST images do not decipher the difference in the two defects. The second identifiable defect is what looks like an apparent void in C-D. During visual inspection prior to UST testing, the coupler connecting the steel anchorage duct to the HDPE duct was noted and the UST results in this section are likely due to testing over this coupler, not the presence of a void. The third identifiable characteristic is the bottom of the duct, which looks similar to a void but can be identified due to the depth and the second reflection of the prestressing steel below.

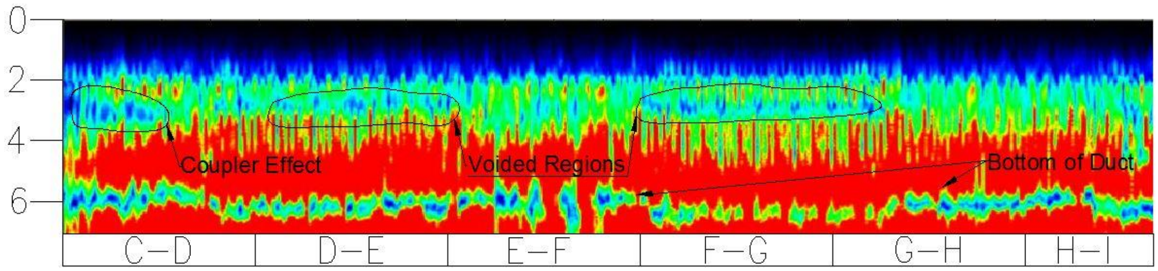


Figure 5-5: B-scan Results of Specimen 2 (Test 1)

As mentioned before, the A1040 MIRA does not have the capability of determining steel defects so testing of Specimens 3 and 4 was not performed. The strength of UST testing in this research was determined to be detection of voided regions within non-metal ducts. Additionally, repeatability and reproducibility of UST testing of the free spans is extremely high, due to the almost identical results from this research and the straightforwardness of testing in a straight line.

The second set of inspections using ultrasonic tomography were performed on the anchorage regions. A total of five testing grids were made and tested on the deck anchorage and three were made on the pylon anchorage. The top of both specimens were tested, along with each side that would be theoretically accessible in a real stay cable bridge with the given geometry. Figure 5-6 shows the labelling of each side of the deck (D) and pylon (P) anchorages.

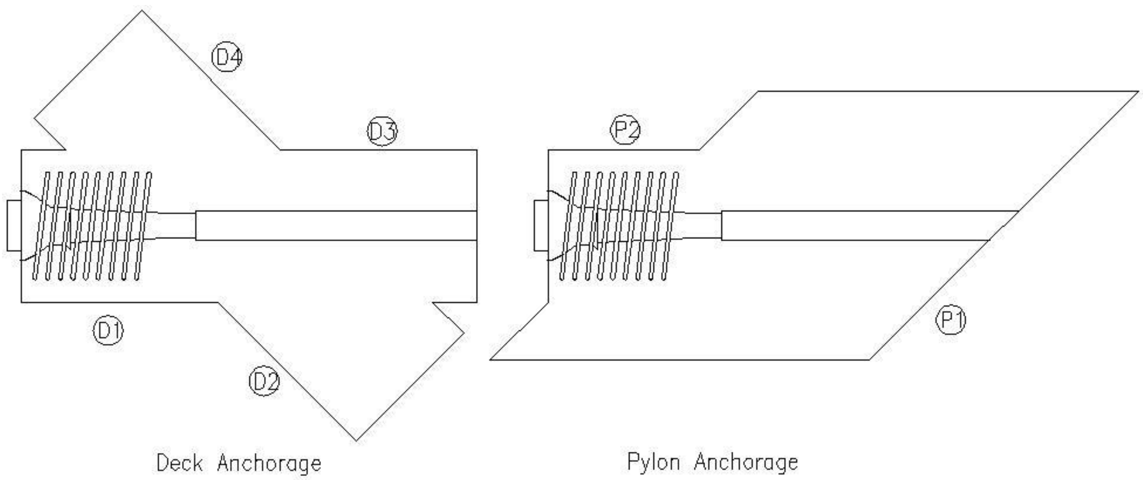


Figure 5-6: Testing Grid Labels for UST Testing of Anchorages

As mentioned in Section III, four inspections were performed on each grid, two with the device oriented parallel to the duct and two with the device oriented perpendicular to the duct. For simplicity of data labelling in Appendix B.4, a (I) label is used for parallel tests and a (II) label is used to designate perpendicular tests. Additionally, device orientation affects the origin and axes of the 3-D map. Figure 5-7 illustrates the orientation of each test, the labelling of each orientation, and the origin of each test on an actual testing grid.

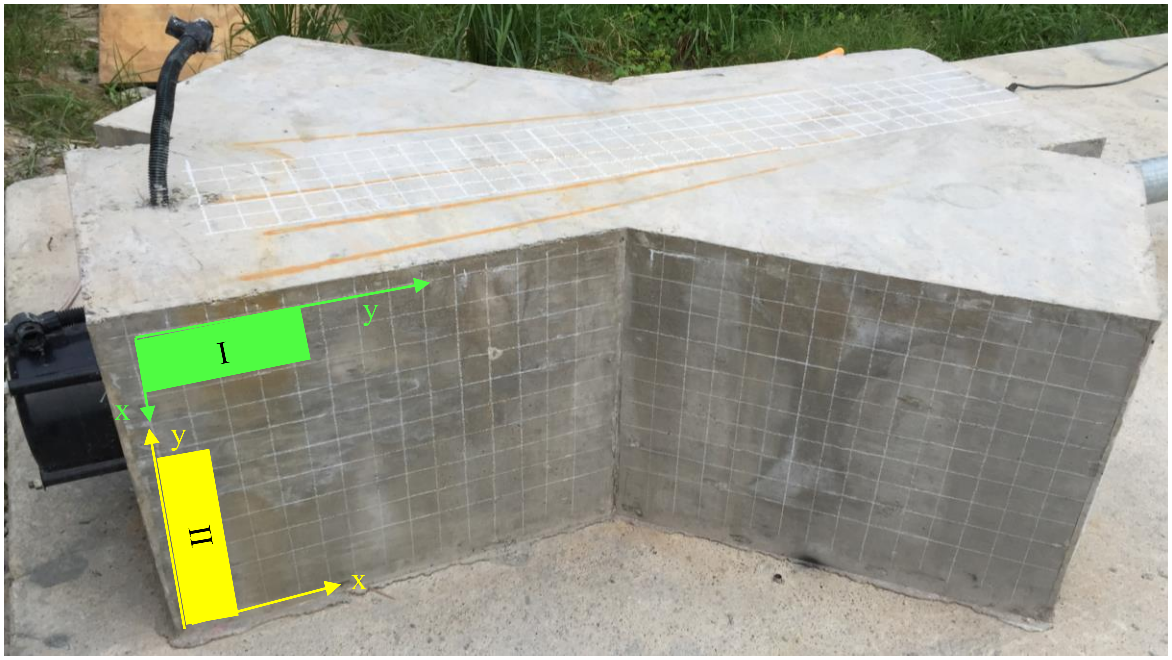


Figure 5-7: Device Orientation and Axes for UST Anchorage Testing

The results of the maps created from anchorage testing are all shown in Figures C.4-4 through C.4-57. Although literature review outlined that UST has the capability to determine detrimental conditions within anchorage regions, the results of UST testing in this research was unable to conclusively decipher any sort of defects in the mock-up specimen anchorage regions. Ultrasonic tomography testing was able to create very interactive three-dimensional maps that can provide useful information about the system, however, this UST device does not have the capability to acquire any data from within the steel ducts.

The first results presented are from scanning the top surfaces of the concrete masses, of which the testing areas are shown in Figure B.4-4. These models were the largest models with a 12 and 10 square-foot testing area for the deck and pylon anchorage systems, respectively, and each model can show the duct vividly underneath the top reinforcement. Figures C.4-5 through C.4-12 show the eight groups of 3-D models while Figures C.4-13 through C.4-20 show D-scans through the post-tensioning ducts for each anchorage. The images through the duct do not appear to decipher between a grouted, ungrouted, or water infiltrated system but are able to provide great information on the duct, including size and location.

The second results are from scanning the side surfaces of the anchorage regions that would be theoretically accessible in stay cable bridges. The labels for each of these scans can be seen in Figure B.4-21 and each testing area was approximately 2'x2'. A total of four sides were tested on the deck anchorage system and only two test locations, D1 and D3, were able to even detect the duct. On the pylon anchorage side, only two locations were tested but only the P2 location was able to detect the duct. All of the three-dimensional models and applicable scans from within the D1, D3, and P2 models are presented in Figures C.4-22 through C.4-57. As with the top surface testing, the testing of these locations were unable to determine any significant information from within the steel duct.

Although UST testing of the anchorage regions was unable to definitively detect any defective conditions from within the post-tensioning duct, several conclusions can be drawn from the testing of the specimens. Firstly, the most vivid images of the duct come from the testing orientation with the device perpendicular to the duct. When tested with the device parallel to the duct, most scans better detected mild reinforcing that was perpendicular to the device orientation. Secondly, out of the NDE methods in this research, UST was able to provide the best quality information about what is within the concrete. Although the device had an inability to see within the ducts, each model presented the true conditions of reinforcement and duct locations inside the concrete masses.

5.5. Sounding

Multiple sounding inspections of each specimen were performed and two sounding maps for Specimens 1 and 2 along with one sounding map for Specimens 3 and 4 are shown in Appendix B.5. Note that the distance counters in the sounding maps correlate to the defect grids as shown in Figure 4-3. Additionally, sounding inspection at the grid interfaces was offset to avoid the sealant between grouting defects, meaning that tapping that was to be done at 9’-0” from grid line A was likely done at 8’-8” and 9’4” on each side of the bounding region, where sounding data wouldn’t be distorted. The sounding maps for Specimens 1 and 2, however, were able to provide accurate information on voided regions existing within the ducts. Figure 5-8 shows the first sounding testing data from Specimen 1.

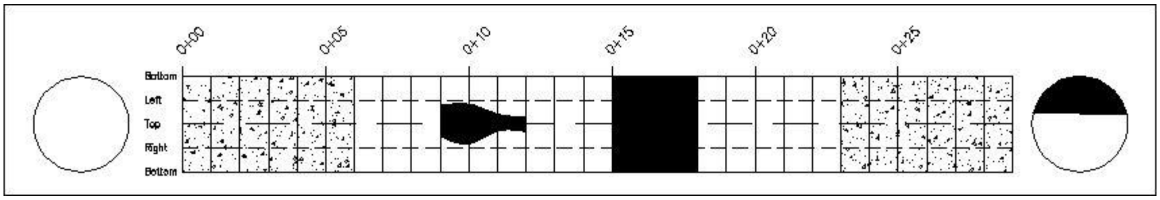


Figure 5-8: Sounding Map 1 of Specimen 1

Sounding did not differentiate between voided regions, water infiltrated regions, and regions with poor grout. The sounding maps for Specimens 3 and 4, Figure B.5-4 and C.5-5, respectively, do not show any important information, as these systems are ungrouted.

Due to the interpretation of acoustic responses by the inspector, sounding is a very subjective method and data can vary from each trial and inspector, as proven in this data. Both sounding maps for Specimen 1, Figure 5-8 and C.5-1, show the voided regions along the free span of the duct, however the shapes of the voids were not necessarily similar. Additionally, the second sounding map, Figure B.5-1, shows more voids, one region along the top of the duct in the C-D section and one small void at the right side of the H-I section.

The inspection of Specimen 2 was much more consistent and was able to determine the approximate sizes of each void. The sounding maps of Specimen 2 can be seen in Figure B.5-2 and C.5-3. The only difference in data lies in a small void at the right side of E-F. This void is likely true, as there was slight leaking of the fully grouted section during the grouting process which likely led to a small voided region at the top of the duct.

The inspection of the anchorage systems proved to be much more difficult and the only usable data was from sounding the grout caps, which worked very well. Figure 5-9 shows the grout condition of Specimen 1 after the removal of the grout cap, which closely matches the sounding results. As expected, sounding through the mass concrete was not able to determine anything.

Figure 5-9: Partial Grouting of End Cap

Overall, the sounding method proved capable in determining where there was an air interface between the grout and the duct but was unable to accurately determine the size of a void in terms of volume and could not differentiate between a voided region and a region of bad grout or water infiltration. The sounding inspection method also appeared to detect conditions equally in both metal and non-metal ducts. Additionally, if grouting voids exist behind concrete masses in the anchorage region, sounding would not be a usable method unless access to the grout cap is available, as the condition of the grout cap can often indicate the condition of the grout in that localized region.

5.6. Borescope

Borescope inspection was performed on all four specimens and a summary of the results is shown in Appendix B.6. The grouted specimens were bounded by a sealant between each of their grid regions, which did not allow the camera to enter in one grid location and extend to the next. Therefore, borescope inspection of Specimens 1 and 2 was performed grid by grid. Additionally, access was not available in each grid, which is noted in the Appendix B.6.

The inspection of Specimens 1 and 2 showed that the camera was able to enter and photograph all but one of the voided regions, determine there was water in the correct grids, and view the segregating grout in Specimen 2. Figure 5-10 shows a borescope photograph of a voided region along the top of Specimen 1.

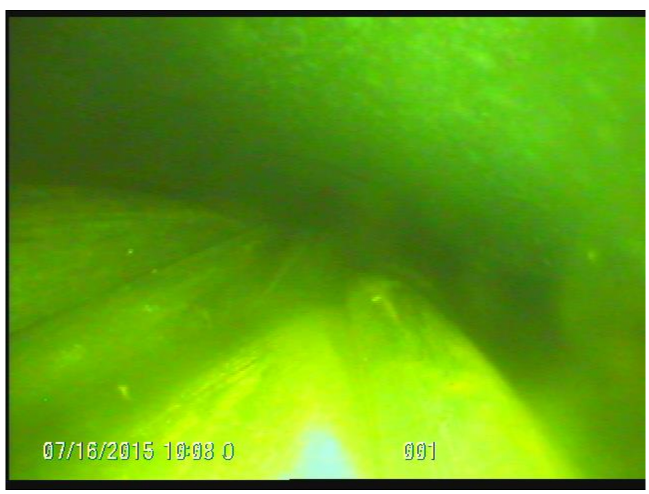


Figure 5-10: Borescope Photo of Voided Region in Specimen 1 Grid F-G

Figure B.6-2 and Figure B.6-5 clearly show voided regions along the top of the duct in grid F-G in Specimens 1 and 2, respectively. Figure B.6-1, Figure B.6-3, and Figure B.6-4 all show ducts where water has intruded. The still photos appear blurry due to distortion but video data and live operation of the device clearly show that the camera is moving through water. Although the grout segregation in grid H-I of Specimen 1 was not accessible, Figure B.6-6 shows the clear segregation of grout along the top of the Specimen 2 in grid H-I. In the inspection of Specimens 1 and 2, no detection of any corrosion, section loss, or strand breakage was made.

The inspection of Specimen 3 did not find any defects but access photographs can be seen in Figure B.6-7 and Figure B.6-8. This is due to the increased congestion of the duct making insertion and steering of the borescope very difficult. The sheathing on the strands increases the cross sectional area of the strand and significantly reduces the amount of area the borescope has to maneuver within the duct.

The inspection of Specimen 4 was more successful than Specimen 3 but maneuvering of the borescope was still very difficult. Figure B.6-10 and Figure B.6-11 show two instances of exposed strand in Grids C-D and E-F, respectively, but it was unable to determine that 10 strands were fully corroded within Grid E-F or even view the corroded regions within Grids A-B and J-K. No breakages were viewed during inspection.

Overall, borescope inspection proved much more effective in qualitative evaluation of predetermined defects as opposed to detection of them. Additionally, this method showed greater potential in evaluating void defects as opposed to strand defects.

Within grouted systems, a borescope camera can be pushed along the length of a void and map it, potentially viewing corrosive activity on exposed strands, if it exists. Borescope inspection of ungrouted systems was proved to be relatively ineffective. This method has potential to view and evaluate strand defects within ungrouted ducts but the intertwining of strands can make it very difficult to inspect more than a few feet of strand before the borescope cannot advance farther and another entry point is needed. Borescope inspection is independent of the physical system so each system received identical low scores in each of the precision and accuracy categories because by itself, it is an ineffective tool at detecting defects. However, it can still be a very useful evaluative tool when coupled with another NDE method that can locate defects.

6. METRICS DEVELOPMENT

The primary goal of developing metrics is to provide stay cable bridge owners with an organized approach for selecting the best NDE method for the investigation of their bridge based on which condition for which they are probing. Each NDE method will be ranked on its ability to both locate and evaluate seven defective conditions that can exist in stay cable MTEs:

- Corrosion
- Section Loss
- Breakage
- Grout Conditions
- Voids
- Water Infiltration
- Tendon Deterioration in the Anchorage System

Additionally, the metrics development differentiates the rankings between physical parameters that exist in stay cable MTEs and are represented in the stay cable mock-up specimens. The first metrics development parameter was for external metal ducts. These rankings were established using the testing from mock-up specimen 1, in which the sheathing is a smooth steel duct. The second metrics development parameter was for external non-metal ducts, which is represented by mock-up specimen 2, 3, and 4, all of which use a smooth HDPE sheathing. The last physical parameter that was taken into account for the development of the metrics rankings was the anchorage system. This condition was identically incorporated in each of the four mock-up specimens.

These physical parameters were important to take into account in order to develop more useful metrics rankings, as the NDE technologies each have their specific capabilities and limitations to detect and locate the detrimental conditions based on these factors. Although there are numerous other physical parameters that can affect the inspection ability of the NDE methods, metal ducts, non-metal ducts, and anchorage systems were decided to be the MTE characteristics addressed for these metrics rankings in order to produce a straight-forward decision-making tool. Additional parameters (e.g. effects of grouted strands, epoxy-coated strands, and greased and sheathed strands within non-metal ducts) are addressed in the data analysis of Section V.

6.1. Rankings System

For each of the detrimental conditions and physical parameters, each NDE technology will be ranked on a scale of 1-10 in five categories: precision, accuracy, ease of use, inspection requirements, and cost.

- **Precision** – This category is measured as a function of data correlation and analysis, of which repeatability and reproducibility are ranked. This category can be complicated, as some methods can be extremely repeatable and reproducible but without accuracy. In order to not mislead end users, methods with low accuracy rankings were given low precision rankings, as the precise ability of a given NDE method to measure inaccurate or useless data is of no importance to this research.

- *Repeatability* – This category refers to the ability of the same system or user to account the same measurement(s) under identical testing conditions and procedures.
- *Reproducibility* - This category refers to the ability of different systems or users to account the same measurement(s) under identical testing conditions and procedures

- **Accuracy –** Accuracy is ranked on the ability of the NDE method to both detect and quantitatively evaluate the detrimental condition in comparison to the true condition. This is a very important category, as determining the accurate condition within a stay cable MTE is crucial to structural engineers to determine what action needs to be taken, if any.
- **Ease of Use –** This category is separated into power demand and number of personnel, which can influence the end-user by affecting both cost and time of inspection.
    - *Power Demand* **–** Power demand is ranked on the power requirements of the equipment, as equipment can require anywhere from long-life battery power to high voltage direct power.
    - *No. of Personnel* – This category determines what the personnel requirement is for optimal testing and affects labor costs. Whether the NDE method is automated, requires one inspector, a

large inspection crew, or anywhere in between is addressed in this category.

- **Inspection Requirements –** Requirements of proper testing is addressed in this category, which is separated into operator qualifications, operator training, USD per hour, and complexity of data interpretation.
    - *Operator Qualifications* **-** Qualifications of the operator are ranked based on required operation experience for proper inspection.
    - *Operator Training* **–** Required trainings of the operator are ranked in this category based on time and money required.
    - *USD Per Hour* – This category estimates the relative cost of inspection, based only on the operator costs.
    - *Complexity of Data Interpretation* – Different methods can require extensive, modest, or little data analysis in order to obtain useful data after testing. Required data analysis experience and certifications are ranked for the operator.
- **Cost -** This category estimates the relative cost of inspection, separated into cost of the equipment and labor costs of the inspection.
    - *Cost of Equipment* – This category ranks each NDE method based on the cost of both the testing equipment and necessary data analysis tools.

- *Labor Costs for Inspection* – Labor costs are estimated based on testing personnel requirements, operator costs, and if applicable, data analysis personnel costs.

Definitions for each of the rankings are shown in Appendix C. Note that these ranking guidelines were adapted from Appendix A of Revised Interim Report No. 2 for the NCHRP on Project 14-28 (Hurlebaus et al., 2014).

6.2. Metrics Ranks and Explanations

Each NDE method evaluated in this research is ranked first based on the physical system implemented in the specimen (external metal ducts, external non-metal ducts, or anchorage system) and then more specifically for each of the seven defects. For each NDE method, physical system, and defective condition being examined, ease of use, inspection requirements, and cost were all given the same ranking for each defect. Accuracy and precision rankings may vary depending on the type of defect but the three other categories are all assumed to be equal for each defect. Metrics rankings for each NDE method are shown and explained in the following section. The full metrics tables can be seen in Appendix D.

6.2.1. Ground Penetrating Radar

External Metal Ducts

- Corrosion
  - Precision

        - Repeatability (Rank - 1): GPR has no ability to determine corrosion within a tendon.
        - Reproducibility (Rank - 1): GPR has no ability to determine corrosion within a tendon.
    - Accuracy (Rank - 1): GPR has no ability to determine corrosion within a tendon.
- Section Loss
    - Precision
        - Repeatability (Rank - 1): GPR has no ability to determine section loss within a tendon.
        - Reproducibility (Rank - 1): GPR has no ability to determine section loss within a tendon.
    - Accuracy (Rank - 1): GPR has no ability to determine section loss within a tendon.
- Breakage
    - Precision
        - Repeatability (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
        - Reproducibility (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
    - Accuracy (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
- Grout Conditions
    - Precision

            - Repeatability (Rank - 1): GPR has no ability to determine grout conditions within a metal duct.
            - Reproducibility (Rank - 1): GPR has no ability to determine grout conditions within a metal duct.
        - Accuracy (Rank - 1): GPR has no ability to determine grout conditions within a metal duct.
    - Voids
        - Precision
            - Repeatability (Rank - 1): GPR has no ability to determine voids within a metal duct.
            - Reproducibility (Rank - 1): GPR has no ability to determine voids within a metal duct.
        - Accuracy (Rank - 1): GPR has no ability to determine voids within a metal duct.
    - Water Infiltration
        - Precision
            - Repeatability (Rank - 1): GPR has no ability to determine water infiltration within a metal duct.
            - Reproducibility (Rank - 1): GPR has no ability to determine water infiltration within a metal duct.
        - Accuracy (Rank - 1): GPR has no ability to determine water infiltration within a metal duct.
    - General Tendon Deterioration in the Anchorage System
        - Precision

            - Repeatability (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.
            - Reproducibility (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.
        - Accuracy (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.

External Non-Metal Ducts

- Corrosion
    - Precision
        - Repeatability (Rank - 1): GPR has no ability to determine corrosion within a tendon.
        - Reproducibility (Rank - 1): GPR has no ability to determine corrosion within a tendon.
    - Accuracy (Rank - 1): GPR has no ability to determine corrosion within a tendon.
- Section Loss
    - Precision
        - Repeatability (Rank - 1): GPR has no ability to determine section loss within a tendon.
        - Reproducibility (Rank - 1): GPR has no ability to determine section loss within a tendon.
    - Accuracy (Rank - 1): GPR has no ability to determine section loss within a tendon.
- Breakage
    - Precision

        - Repeatability (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
        - Reproducibility (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
    - Accuracy (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
- Grout Conditions
    - Precision
        - Repeatability (Rank - 10): GPR testing of non-metal ducts is relatively intuitive for a trained inspector and the same conclusions are likely for multiple tests.
        - Reproducibility (Rank - 10): GPR testing of non-metal ducts is relatively intuitive for a trained inspector and the same conclusions are likely for multiple tests.
    - Accuracy (Rank - 5): GPR proved to be extremely accurate in locating voided regions in ducts and determining their length, which is a likely sign that grout conditions could be poor in that region. The testing results of this research could not determine a difference between good grout and poor grout, as the dielectrics are likely to be very similar. This category was given a score of 5 because voided regions are easily determined and can be a good indicator of poor grout conditions.
- Voids
    - Precision

            - Repeatability (Rank - 10): GPR testing of non-metal ducts is relatively intuitive for a trained inspector and the same conclusions are likely for multiple tests.
            - Reproducibility (Rank - 10): GPR testing of non-metal ducts is relatively intuitive for a trained inspector and the same conclusions are likely for multiple tests.
        - Accuracy (Rank - 9): GPR proved to be extremely accurate in locating voided regions in ducts and determining their length. This category was not given a score of 10 simply because GPR was not able to determine depth of the voids, meaning that it is very difficult to determine volumetric estimate of void sizes.
    - Water Infiltration
        - Precision
            - Repeatability (Rank - 10): GPR testing of non-metal ducts is relatively intuitive for a trained inspector and the same conclusions are likely for multiple tests.
            - Reproducibility (Rank - 10): GPR testing of non-metal ducts is relatively intuitive for a trained inspector and the same conclusions are likely for multiple tests.
        - Accuracy (Rank - 7): GPR proved to be extremely accurate in locating voided regions in ducts and determining their length, which is a likely sign that water could have infiltrated into the region. The testing results of this research could not determine a difference between voided regions and water infiltrated regions but literature review outlined this determination as a capability of GPR

- General Tendon Deterioration in the Anchorage System
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.
    - Reproducibility (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.
  - Accuracy (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.

Anchorage Regions

- Corrosion
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine corrosion within a tendon.
    - Reproducibility (Rank - 1): GPR has no ability to determine corrosion within a tendon.
  - Accuracy (Rank - 1): GPR has no ability to determine corrosion within a tendon.
- Section Loss
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine section loss within a tendon.
    - Reproducibility (Rank - 1): GPR has no ability to determine section loss within a tendon.
  - Accuracy (Rank - 1): GPR has no ability to determine section loss within a tendon.

- Breakage
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
    - Reproducibility (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
  - Accuracy (Rank - 1): GPR has no ability to determine strand breakage within a tendon.
- Grout Conditions
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine grout conditions within an anchorage region.
    - Reproducibility (Rank - 1): GPR has no ability to determine grout conditions within an anchorage region.
  - Accuracy (Rank - 1): GPR has no ability to determine grout conditions within an anchorage region.
- Voids
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine voids within an anchorage region.
    - Reproducibility (Rank - 1): GPR has no ability to determine voids within an anchorage region.
  - Accuracy (Rank - 1): GPR has no ability to determine voids within an anchorage region.
- Water Infiltration

- Precision
  - Repeatability (Rank - 1): GPR has no ability to determine water infiltration within an anchorage region.
  - Reproducibility (Rank - 1): GPR has no ability to determine water infiltration within an anchorage region.
- Accuracy (Rank - 1): GPR has no ability to determine water infiltration within an anchorage region.

- General Tendon Deterioration in the Anchorage System
  - Precision
    - Repeatability (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.
    - Reproducibility (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.
  - Accuracy (Rank - 1): GPR has no ability to determine tendon deterioration within an anchorage region.

All Physical Systems & Defect Conditions

- Ease of Use
  - Power Demand (Rank – 9): The GSSI ScructureScan Mini HR is a handheld device with multiple batteries, each of which has a lift of approximately 2-3 hours.
  - No. of Personnel (Rank - 6): One or two people can be used to set up for GPR testing, which includes defining the testing grid on the structure being tested. Once the test grid is identified, the operators manually acquire all data.
- Inspection Requirements

- Operator Qualifications (Rank - 6): Moderate knowledge of GPR is required, particularly equipment capabilities and limitations that are outlined by a manufacturer's training course.
- Operator Training (Rank - 6): GSSI offers a StructureScan Optical Training Course for $800 (Geophysical Survey Systems, Inc., 2015).
- USD per Hour (Rank - 5): Since moderate knowledge of GPR is required, it is likely that a Senior Field Inspector will perform or oversee all GPR operations. The U.S. General Services Administration (GSA) provides information on billable rates, for which an estimate of hourly rates for Senior Field Inspectors by bridge inspection firms is approximately $95/hour (U.S. General Services Administration, 2015).
- Complexity of Data Interpretation (Rank - 5): Moderate prior knowledge of GPR is necessary to interpret data. Two and three dimensional models can be built using software and data can be interpreted.

- Cost
    - Cost of Equipment (Rank - 6): The approximate cost of the GSSI StructureScan Mini HR is $25k (Hurlebaus, 2015). Note that this ranking is for the equipment used in this research and equipment costs can vary based on manufacturer, model, and other factors.
    - Labor Costs for Equipment (Rank - 5): If an additional Field Inspector is used to assist with GPR testing, an additional estimated $70/hour will be added to inspection costs (U.S. General Services Administration, 2015). A reasonable estimate of inspection speed is

that 35 feet of stay cable tendons can be tested per hour, meaning additional labor will cost approximately $2 per foot inspected. Inspection speed can vary based on how the device is advancing along the tendon, if a crane is necessary, inspector experience, and many other factors.

6.2.2. Magnetic Flux Leakage

External Metal Ducts

- Corrosion
  - Precision
    - Repeatability (Rank - 9): MFL testing was very repeatable for detection of corrosion within an external metal duct, as each test did detect the defects within the tendon. There was, however, slight variance in defect location and magnitude.
    - Reproducibility (Rank - 7): Although it is likely all trained inspectors would find each defect, location and magnitude would likely vary. Reproducibility received a slightly lower score than repeatability because each inspector has to have a very strong knowledge of the calibration technique and data processing strategies for the device being used.
  - Accuracy (Rank - 9): MFL provided excellent data in determining corrosion, although the data showed slight variance in location and magnitude.
- Section Loss

- Precision
  - Repeatability (Rank - 9): MFL testing was very repeatable for detection of section loss within an external metal duct, as each test did detect the defects within the tendon. There was, however, slight variance in defect location and magnitude.
  - Reproducibility (Rank - 7): Although it is likely all trained inspectors would find each defect, location and magnitude would likely vary. Reproducibility received a slightly lower score than repeatability because each inspector has to have a very strong knowledge of the calibration technique and data processing strategies for the device being used.
- Accuracy (Rank - 9): MFL provided excellent data in determining corrosion, although the data showed slight variance in location and magnitude.

- Breakage
  - Precision
    - Repeatability (Rank - 9): MFL testing was very repeatable for detection of corrosion within an external metal duct, as each test did detect the defects within the tendon. There was, however, slight variance in defect location and magnitude.
    - Reproducibility (Rank - 7): Although it is likely all trained inspectors would find each defect, location and magnitude would likely vary. Reproducibility received a slightly lower score than repeatability because each inspector has to have a

very strong knowledge of the calibration technique and data processing strategies for the device being used.

    - Accuracy (Rank - 9): MFL provided excellent data in determining corrosion, although the data showed slight variance in location and magnitude.

- Grout Conditions
    - Precision
        - Repeatability (Rank - 1): MFL does not have the capability of detecting grout conditions.
        - Reproducibility (Rank - 1): MFL does not have the capability of detecting grout conditions.
    - Accuracy (Rank - 1): MFL does not have the capability of detecting grout conditions.
- Voids
    - Precision
        - Repeatability (Rank - 1): MFL does not have the capability of detecting voided regions.
        - Reproducibility (Rank - 1): MFL does not have the capability of detecting voided regions.
    - Accuracy (Rank - 1): MFL does not have the capability of detecting voided regions.
- Water Infiltration
    - Precision
        - Repeatability (Rank - 1): MFL does not have the capability of detecting water infiltration.

            - Reproducibility (Rank - 1): MFL does not have the capability of detecting water infiltration.
        - Accuracy (Rank - 1): MFL does not have the capability of detecting water infiltration.
    - General Tendon Deterioration in the Anchorage System
        - Precision
            - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
            - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.

External Non-Metal Ducts

- Corrosion
    - Precision
        - Repeatability (Rank - 9): MFL testing was very repeatable for detection of corrosion within an external non-metal duct, as each test did detect the defects within the tendon. There was, however, slight variance in defect location and magnitude.
        - Reproducibility (Rank - 7): Although it is likely all trained inspectors would find each defect, location and magnitude would likely vary. Reproducibility received a slightly lower score than repeatability because each inspector has to have a very strong knowledge of the calibration technique and data processing strategies for the device being used.

- Accuracy (Rank - 9): MFL provided excellent data in determining corrosion, although the data showed slight variance in location and magnitude.

- Section Loss
  - Precision
    - Repeatability (Rank - 9): MFL testing was very repeatable for detection of section loss within an external non-metal duct, as each test did detect the defects within the tendon. There was, however, slight variance in defect location and magnitude.
    - Reproducibility (Rank - 7): Although it is likely all trained inspectors would find each defect, location and magnitude would likely vary. Reproducibility received a slightly lower score than repeatability because each inspector has to have a very strong knowledge of the calibration technique and data processing strategies for the device being used.
  - Accuracy (Rank - 9): MFL provided excellent data in determining corrosion, although the data showed slight variance in location and magnitude.
- Breakage
  - Precision
    - Repeatability (Rank - 9): MFL testing was very repeatable for detection of corrosion within an external non-metal duct, as each test did detect the defects within the tendon. There was, however, slight variance in defect location and magnitude.

        - Reproducibility (Rank - 7): Although it is likely all trained inspectors would find each defect, location and magnitude would likely vary. Reproducibility received a slightly lower score than repeatability because each inspector has to have a very strong knowledge of the calibration technique and data processing strategies for the device being used.
    - Accuracy (Rank - 9): MFL provided excellent data in determining corrosion, although the data showed slight variance in location and magnitude.
- Grout Conditions
    - Precision
        - Repeatability (Rank - 1): MFL does not have the capability of detecting grout conditions.
        - Reproducibility (Rank - 1): MFL does not have the capability of detecting grout conditions.
    - Accuracy (Rank - 1): MFL does not have the capability of detecting grout conditions.
- Voids
    - Precision
        - Repeatability (Rank - 1): MFL does not have the capability of detecting voided regions.
        - Reproducibility (Rank - 1): MFL does not have the capability of detecting voided regions.
    - Accuracy (Rank - 1): MFL does not have the capability of detecting voided regions.

- Water Infiltration
    - Precision
        - Repeatability (Rank - 1): MFL does not have the capability of detecting water infiltration.
        - Reproducibility (Rank - 1): MFL does not have the capability of detecting water infiltration.
    - Accuracy (Rank - 1): MFL does not have the capability of detecting water infiltration.
- General Tendon Deterioration in the Anchorage System
    - Precision
        - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.

Anchorage Regions

- Corrosion
    - Precision
        - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.

- Section Loss
    - Precision
        - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.
- Breakage
    - Precision
        - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.
- Grout Conditions
    - Precision
        - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.
- Voids

        - Precision
            - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
            - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - Water Infiltration
        - Precision
            - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
            - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.
    - General Tendon Deterioration in the Anchorage System
        - Precision
            - Repeatability (Rank - N/A): The MFL device used in this research was only for external tendon testing.
            - Reproducibility (Rank - N/A): The MFL device used in this research was only for external tendon testing.
        - Accuracy (Rank - N/A): The MFL device used in this research was only for external tendon testing.

All Physical Systems & Defect Conditions

- Ease of Use

        - Power Demand (Rank – 8): The MFL equipment used in this research does not require direct power but instead runs off of the rechargeable battery powered signal console and has an approximate battery life of 8 hours.
        - No. of Personnel (Rank – 8): Installation of the MFL device used in this research requires 3-5 people, as it weighs approximately 165 pounds. Once the equipment is properly installed, all data acquisition is automatic as the machine moves alone the duct.
    - Inspection Requirements
        - Operator Qualifications (Rank - 2): Extensive knowledge of MFL is required, including both theoretical and practical applications of the method and the specific device being used.
        - Operator Training (Rank - 1): The American Society of Non-Destructive Testing (ASNT) offers their Level III Course for MFL inspection for $2000, plus an additional $335 for the certification exam (The American Society for Nondestructive Testing, 2015).
        - USD per Hour (Rank - 1): Due to the extensive knowledge, training, and experience required by MFL operators, it is likely that a Senior Civil Engineer will operate or oversee all MFL investigations. GSA data shows that a Senior Civil Engineer charge rate is between $150-200/hour (U.S. General Services Administration, 2015).
        - Complexity of Data Interpretation (Rank - 1): Extensive prior knowledge of MFL is necessary to interpret data. In order to obtain accurate data, the equipment must be properly calibrated prior to use and an understanding of possible metallic defects and how the device

detects these defects is essential, as MFL data interpretation can vary depending on the type of sensors each device uses (annular coils, hall sensors, etc.).

- Cost
    - Cost of Equipment (Rank - 3): The approximate cost of the NDT Technologies, Inc. MFL equipment is $101k (Hurlebaus, 2015). This cost includes both the LMA-450 Sensor Head and the CC-04 USB Signal Console. Note that this ranking is for the equipment used in this research and equipment costs can vary based on manufacturer, model, and other factors.
    - Labor Costs for Equipment (Rank - 1): Since 3-5 additional personnel are required to install the MFL device on each tendon, an additional estimated $280/hour is required in order for installation and uninstallation of the device (U.S. General Services Administration, 2015). A reasonable inspection speed is 40 feet per hour, meaning that additional labor costs will be about $7 per foot of tendon inspected. Testing speed can be extremely variable for MFL testing due to the device being used, operator experience, device size and weight, and many other factors.

6.2.3. Infrared Thermography

External Metal Ducts

- Corrosion
    - Precision

- Repeatability (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
- Reproducibility (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.

▪ Accuracy (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.

o Section Loss

▪ Precision

- Repeatability (Rank - 1): IRT has no ability to determine section loss within a tendon.
- Reproducibility (Rank - 1): IRT has no ability to determine section loss within a tendon.

▪ Accuracy (Rank - 1): IRT has no ability to determine section loss within a tendon.

o Breakage

▪ Precision

- Repeatability (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
- Reproducibility (Rank - 1): IRT has no ability to determine strand breakage within a tendon.

▪ Accuracy (Rank - 1): IRT has no ability to determine strand breakage within a tendon.

o Grout Conditions

▪ Precision

        - Repeatability (Rank - 1): IRT has no ability to determine grout conditions within steel ducts.
        - Reproducibility (Rank - 1): IRT has no ability to determine grout conditions within steel ducts.
    - Accuracy (Rank - 1): IRT has no ability to determine grout conditions within steel ducts.
- Voids
    - Precision
        - Repeatability (Rank - 1): IRT has no ability to determine voided regions within steel ducts.
        - Reproducibility (Rank - 1): IRT has no ability to determine voided regions within steel ducts.
    - Accuracy (Rank - 1): IRT has no ability to determine voided regions within steel ducts.
- Water Infiltration
    - Precision
        - Repeatability (Rank - 1): IRT has no ability to determine water infiltration within steel ducts.
        - Reproducibility (Rank - 1): IRT has no ability to determine water infiltration within steel ducts.
    - Accuracy (Rank - 1): IRT has no ability to determine water infiltration within steel ducts.
- General Tendon Deterioration in the Anchorage System
    - Precision

            - Repeatability (Rank - 1): IRT has no ability to determine tendon deterioration within steel ducts.
            - Reproducibility (Rank - 1): IRT has no ability to determine tendon deterioration within steel ducts.
        - Accuracy (Rank - 1): IRT has no ability to determine tendon deterioration within steel ducts.

External Non-Metal Ducts

- Corrosion
    - Precision
        - Repeatability (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
        - Reproducibility (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
    - Accuracy (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
- Section Loss
    - Precision
        - Repeatability (Rank - 1): IRT has no ability to determine section loss within a tendon.
        - Reproducibility (Rank - 1): IRT has no ability to determine section loss within a tendon.
    - Accuracy (Rank - 1): IRT has no ability to determine section loss within a tendon.
- Breakage
    - Precision

            - Repeatability (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
            - Reproducibility (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
        - Accuracy (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
    - Grout Conditions
        - Precision
            - Repeatability (Rank - 6): The same inspector would likely be able to identify voided regions that could be accompanied with poor grout conditions. However, if the cable is not voided, poor grout conditions will likely go unnoticed.
            - Reproducibility (Rank - 6): Each IRT inspector would likely be able to identify voided regions that could be accompanied with poor grout conditions. However, if the cable is not voided, poor grout conditions will likely go unnoticed.
        - Accuracy (Rank - 4): IRT is only likely to identify grout conditions if there is an adjacent voided region, which will clearly be identified. If a tendon is injected with poor grout in its entirety, IRT will not be an effective inspection method.
    - Voids
        - Precision
            - Repeatability (Rank - 8): The timing of testing is very important for IRT inspection so a trained inspector would

likely be able to identify voided regions on each test unless he attempted to test at an ineffective time.

- Reproducibility (Rank - 8): Similar to the repeatability, each trained inspector would likely be able to identify voided regions on each test unless he attempted to test at an ineffective time.

- Accuracy (Rank - 10): IRT proved very effective in identifying and illustrating the sizes of voided regions within non-metal ducts.

- Water Infiltration
  - Precision
    - Repeatability (Rank - 6): Each IRT inspector would likely be able to identify voided regions that could be accompanied with water infiltration. However, if the cable is not voided, water infiltration will likely go unnoticed.
    - Reproducibility (Rank - 6): Each IRT inspector would likely be able to identify voided regions that could be accompanied with water infiltration. However, if the cable is not voided, water infiltration will likely go unnoticed.
  - Accuracy (Rank - 6): IRT is only likely to identify water infiltration if there is an adjacent voided region, which will clearly be identified. If a tendon is injected with watery grout in its entirety, IRT will not be an effective inspection method. This ranking is higher than the grout conditions accuracy ranking because literature review outlined that water infiltration detection is a capability of IRT.
- General Tendon Deterioration in the Anchorage System

  - Precision
    - Repeatability (Rank - 1): IRT has no ability to determine tendon deterioration.
    - Reproducibility (Rank - 1): IRT has no ability to determine tendon deterioration.
  - Accuracy (Rank - 1): IRT has no ability to determine tendon deterioration.

Anchorage Regions

- Corrosion
  - Precision
    - Repeatability (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
    - Reproducibility (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
  - Accuracy (Rank - 1): IRT has no ability to determine corrosive activity within a tendon.
- Section Loss
  - Precision
    - Repeatability (Rank - 1): IRT has no ability to determine section loss within a tendon.
    - Reproducibility (Rank - 1): IRT has no ability to determine section loss within a tendon.
  - Accuracy (Rank - 1): IRT has no ability to determine section loss within a tendon.
- Breakage

        - Precision
            - Repeatability (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
            - Reproducibility (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
        - Accuracy (Rank - 1): IRT has no ability to determine strand breakage within a tendon.
    - Grout Conditions
        - Precision
            - Repeatability (Rank - 6): The same inspector would likely be able to identify voided regions that could be accompanied with poor grout conditions. However, if the cable is not voided, poor grout conditions will likely go unnoticed. Additionally, access to the grout caps must be possible and active IRT may be required.
            - Reproducibility (Rank - 6): Each IRT inspector would likely be able to identify voided regions that could be accompanied with poor grout conditions. However, if the cable is not voided, poor grout conditions will likely go unnoticed. Additionally, access to the grout caps must be possible and active IRT may be required.
        - Accuracy (Rank - 4): IRT is only likely to identify grout conditions if there is an adjacent voided region, which will clearly be identified. If the anchorage region is injected with poor grout, IRT will not be an

effective inspection method. Additionally, access to the grout caps must be possible and active IRT may be required.

- Voids
  - Precision
    - Repeatability (Rank - 6): A trained inspector would likely be able to identify voided regions on each test unless he attempted to test at an ineffective time or the caps were shaded, in which case active IRT may be used. Access to the grout caps must be possible.
    - Reproducibility (Rank - 6): Every trained inspector would likely be able to identify voided regions unless he attempted to test at an ineffective time or the caps were shaded, in which case active IRT may be used. Access to the grout caps must be possible.
  - Accuracy (Rank - 8): IRT proved very effective in identifying and illustrating the sizes of voided regions within grout caps but not within concrete encased areas.
- Water Infiltration
  - Precision
    - Repeatability (Rank - 6): Each IRT inspector would likely be able to identify voided regions that could be accompanied with water infiltration. However, if the cable is not voided, water infiltration will likely go unnoticed. Additionally, access to the grout caps must be possible and active IRT may be required.

            - Reproducibility (Rank - 6): Each IRT inspector would likely be able to identify voided regions that could be accompanied with water infiltration. However, if the cable is not voided, water infiltration will likely go unnoticed. Additionally, access to the grout caps must be possible and active IRT may be required.
        - Accuracy (Rank - 6): IRT is only likely to identify water infiltration if there is an adjacent voided region, which will clearly be identified. If a tendon is injected with watery grout in its entirety, IRT will not be an effective inspection method. Additionally, access to the grout caps must be possible and active IRT may be required.
    - General Tendon Deterioration in the Anchorage System
        - Precision
            - Repeatability (Rank - 1): IRT has no ability to determine tendon deterioration.
            - Reproducibility (Rank - 1): IRT has no ability to determine tendon deterioration.
        - Accuracy (Rank - 1): IRT has no ability to determine tendon deterioration.

All Physical Systems & Defect Conditions

- Ease of Use
    - Power Demand (Rank – 9): The FLIR T640 has an approximate battery life of 2.5 hours (FLIR, 2012).
    - No. of Personnel (Rank - 7): IRT testing in this research requires one operator manually taking infrared photos of the structure over time.

- Inspection Requirements
    - Operator Qualifications (Rank - 6): Moderate knowledge of IRT is required, particularly equipment capabilities and limitations that are outlined by a manufacturer's training course.
    - Operator Training (Rank - 2): ITC offers its Level I, II, and III Thermography Training Courses for $1895 (Infrared Training Center, 2015).
    - USD per Hour (Rank - 5): Since moderate knowledge of IRT is required, it is likely that a Senior Field Inspector will perform or oversee all IRT operations. The GSA provides data that indicating that a reasonably hourly rate for Senior Field Inspectors by bridge inspection firms is approximately $95/hour (U.S. General Services Administration, 2015).
    - Complexity of Data Interpretation (Rank - 5): Moderate prior knowledge of IRT is necessary to interpret data. An understanding of heat transfer through structures is required, whether passive or active IRT is being used.
- Cost
    - Cost of Equipment (Rank - 6): The approximate cost of the FLIR T640 is $30k (Hurlebaus, 2015). Note that this ranking is for the equipment used in this research and equipment costs can vary based on manufacturer, model, and other factors.
    - Labor Costs for Equipment (Rank - 10): No additional labor is needed for IRT inspection in addition to the operator.

6.2.4. Ultrasonic Tomography

External Metal Ducts

- Corrosion
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
    - Reproducibility (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
  - Accuracy (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
- Section Loss
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine section loss within a tendon.
    - Reproducibility (Rank - 1): UST has no ability to determine section loss within a tendon.
  - Accuracy (Rank - 1): UST has no ability to determine section loss within a tendon.
- Breakage
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine strand breakage within a tendon.
    - Reproducibility (Rank - 1): UST has no ability to determine strand breakage within a tendon.

        - Accuracy (Rank - 1): UST has no ability to determine strand breakage within a tendon.
    - Grout Conditions
        - Precision
            - Repeatability (Rank - 1): UST has no ability to determine grout conditions within a metal tendon.
            - Reproducibility (Rank - 1): UST has no ability to determine grout conditions within a metal tendon.
        - Accuracy (Rank - 1): UST has no ability to determine grout conditions within a metal tendon.
    - Voids
        - Precision
            - Repeatability (Rank - 1): UST has no ability to determine voided regions within a metal tendon.
            - Reproducibility (Rank - 1): UST has no ability to determine voided regions within a metal tendon.
        - Accuracy (Rank - 1): UST has no ability to determine voided regions within a metal tendon.
    - Water Infiltration
        - Precision
            - Repeatability (Rank - 1): UST has no ability to determine water infiltration within a metal tendon.
            - Reproducibility (Rank - 1): UST has no ability to determine water infiltration within a metal tendon.

        - Accuracy (Rank - 1): UST has no ability to determine water infiltration within a metal tendon.
    - General Tendon Deterioration in the Anchorage System
        - Precision
            - Repeatability (Rank - 1): UST has no ability to determine tendon deterioration within a metal tendon.
            - Reproducibility (Rank - 1): UST has no ability to determine tendon deterioration within a metal tendon.
        - Accuracy (Rank - 1): UST has no ability to determine tendon deterioration within a metal tendon.

External Non-Metal Ducts

- Corrosion
    - Precision
        - Repeatability (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
        - Reproducibility (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
    - Accuracy (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
- Section Loss
    - Precision
        - Repeatability (Rank - 1): UST has no ability to determine section loss within a tendon.
        - Reproducibility (Rank - 1): UST has no ability to determine section loss within a tendon.

        - Accuracy (Rank - 1): UST has no ability to determine section loss within a tendon.
    - Breakage
        - Precision
            - Repeatability (Rank - 1): UST has no ability to determine strand breakage within a tendon.
            - Reproducibility (Rank - 1): UST has no ability to determine strand breakage within a tendon.
        - Accuracy (Rank - 1): UST has no ability to determine strand breakage within a tendon.
    - Grout Conditions
        - Precision
            - Repeatability (Rank - 10): UST results from this research proved that it is a very repeatable method for detecting grout defects in a non-metal external duct, as each model presented almost identical results.
            - Reproducibility (Rank - 7): Although UST is a very repeatable method, its reproducibility is slightly lower due to the necessary background in ultrasonics that is necessary for testing and data analysis. Properly trained UST inspectors should reach similar conclusions for a given test but undereducated inspectors may misinterpret data.
        - Accuracy (Rank - 5): The UST results from this research proved very accurate in locating voided regions within a non-metal external duct, but did not determine grout conditions underneath the voided region.

Because grout conditions are often associated with voided regions, this category gets a score of 5 but UST did not appear to have the capability to differentiate a properly grouted section from a fully grouted section of poor quality.

- Voids
  - Precision
    - Repeatability (Rank - 10): UST results from this research proved that it is a very repeatable method for detecting grout defects in a non-metal external duct, as each model presented almost identical results.
    - Reproducibility (Rank - 7): Although UST is a very repeatable method, its reproducibility is slightly lower due to the necessary background in ultrasonics that is necessary for testing and data analysis. Properly trained UST inspectors should reach similar conclusions for a given test but undereducated inspectors may misinterpret data.
  - Accuracy (Rank - 9): The UST results from this research proved very accurate in locating voided regions within a non-metal external duct. Additionally, this method was useful in determining the length of the duct but receives a score lower than 10 because it could not determine the difference between a partial and a full voided region, meaning it does not have a definite capability to quantify voided regions.
- Water Infiltration
  - Precision

        - Repeatability (Rank - 10): UST results from this research proved that it is a very repeatable method for detecting grout defects in a non-metal external duct, as each model presented almost identical results.
        - Reproducibility (Rank - 7): Although UST is a very repeatable method, its reproducibility is slightly lower due to the necessary background in ultrasonics that is necessary for testing and data analysis. Properly trained UST inspectors should reach similar conclusions for a given test but undereducated inspectors may misinterpret data.
    - Accuracy (Rank - 6): The UST results from this research proved very accurate in locating voided regions within a non-metal external duct, but did not determine water within the voided region. Because water infiltration is often associated with voided regions, this category gets a score of 6 but UST did not appear to have the capability to differentiate an air void and a void containing water.
- General Tendon Deterioration in the Anchorage System
    - Precision
        - Repeatability (Rank - 1): UST has no ability to determine tendon deterioration within a metal tendon.
        - Reproducibility (Rank - 1): UST has no ability to determine tendon deterioration within a metal tendon.
    - Accuracy (Rank - 1): UST has no ability to determine tendon deterioration within a metal tendon.

Anchorage Regions

- Corrosion
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
    - Reproducibility (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
  - Accuracy (Rank - 1): UST has no ability to determine corrosive activity within a tendon.
- Section Loss
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine section loss within a tendon.
    - Reproducibility (Rank - 1): UST has no ability to determine section loss within a tendon.
  - Accuracy (Rank - 1): UST has no ability to determine section loss within a tendon.
- Breakage
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine strand breakage within a tendon.
    - Reproducibility (Rank - 1): UST has no ability to determine strand breakage within a tendon.
  - Accuracy (Rank - 1): UST has no ability to determine strand breakage within a tendon.

- Grout Conditions
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine grout conditions within the anchorage system.
    - Reproducibility (Rank - 1): UST has no ability to determine grout conditions within the anchorage system.
  - Accuracy (Rank - 1): UST has no ability to determine grout conditions within the anchorage system.
- Voids
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine voided regions within the anchorage system.
    - Reproducibility (Rank - 1): UST has no ability to determine voided regions within the anchorage system.
  - Accuracy (Rank - 1): UST has no ability to determine voided regions within the anchorage system.
- Water Infiltration
  - Precision
    - Repeatability (Rank - 1): UST has no ability to determine water infiltration within the anchorage system.
    - Reproducibility (Rank - 1): UST has no ability to determine water infiltration within the anchorage system.
  - Accuracy (Rank - 1): UST has no ability to determine water infiltration within the anchorage system.
- General Tendon Deterioration in the Anchorage System

- Precision
    - Repeatability (Rank - 1): UST has no ability to determine tendon deterioration within the anchorage system.
    - Reproducibility (Rank - 1): UST has no ability to determine tendon deterioration within the anchorage system.
- Accuracy (Rank - 1): UST has no ability to determine tendon deterioration within the anchorage system.

All Physical Systems & Defect Conditions

- Ease of Use
    - Power Demand (Rank – 9): The A1040 MIRA has an approximate battery life of 5 hours (Acoustic Control Systems, n.d.).
    - No. of Personnel (Rank - 6): UST requires one or two inspectors to set up the testing grid and perform testing. Additionally, the device weighs approximately 10 pounds so more than one inspector may be required for continuous testing.
- Inspection Requirements
    - Operator Qualifications (Rank - 2): Extensive knowledge of UST is required, including both theoretical and practical applications of the method and the specific device being used.
    - Operator Training (Rank - 3): ASNT offers their Level III Course for UST inspection for $1200, plus an additional $335 for the certification exam (The American Society for Nondestructive Testing, 2015).
    - USD per Hour (Rank - 1): Due to the extensive knowledge, training, and experience required by UST operators, it is likely that a Senior

Civil Engineer will operate or oversee all UST investigations. GSA data shows that a Senior Civil Engineer charge rate is between $150-200/hour (U.S. General Services Administration, 2015).

    - Complexity of Data Interpretation (Rank - 1): Extensive prior knowledge of UST is necessary to interpret data. In order to obtain accurate data, the equipment must be properly calibrated prior to use and an understanding of ultrasonic wave propagation through a structure is necessary. The mirroring effect of ultrasonic waves can make data very difficult to deduce.

- Cost
    - Cost of Equipment (Rank - 5): The approximate cost of the German Instruments, Inc. A1040 MIRA Digitally Focused Array is $60k (Hurlebaus, 2015). Note that this ranking is for the equipment used in this research and equipment costs can vary based on manufacturer, model, and other factors.
    - Labor Costs for Equipment (Rank - 10): No additional labor is needed for UST inspection in addition to the operator.

6.2.5. Sounding

External Metal Ducts

- Corrosion
    - Precision
        - Repeatability (Rank - 1): Sounding has no ability to determine corrosive activity within a tendon.

            - Reproducibility (Rank - 1): Sounding has no ability to determine corrosive activity within a tendon.
    - Accuracy (Rank -1): Sounding has no ability to determine corrosive activity within a tendon.
- Section Loss
    - Precision
        - Repeatability (Rank - 1): Sounding has no ability to determine cross-sectional area loss within a tendon.
        - Reproducibility (Rank - 1): Sounding has no ability to determine cross-sectional area loss within a tendon.
    - Accuracy (Rank -1): Sounding has no ability to determine cross-sectional area loss within a tendon.
- Breakage
    - Precision
        - Repeatability (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
        - Reproducibility (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
    - Accuracy (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
- Grout Conditions
    - Precision
        - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids each time testing but

smaller voids along with the size and shape of large voids may differ.

- Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.

■ Accuracy (Rank - 3): Sounding will not determine grout conditions alone but will determine voided regions, which can often be a sign of grout conditions.

- Voids
  - Precision
    - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids each time testing but smaller voids along with the size and shape of large voids may differ.
    - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.
  - Accuracy (Rank - 7): All voided regions within the mock-up specimens were found but sounding also claimed grouted regions contained voids.
- Water Infiltration
  - Precision
    - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids each time testing but

smaller voids along with the size and shape of large voids may differ.

- Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.

- Accuracy (Rank - 3): Sounding will not determine water infiltration alone but will determine voided regions, which can often be a sign of water infiltration.

- General Tendon Deterioration in the Anchorage System
  - Precision
    - Repeatability (Rank - 1): Sounding will not determine deterioration of the anchorage system.
    - Reproducibility (Rank - 1): Sounding will not determine deterioration of the anchorage system.
  - Accuracy (Rank - 1): Sounding will not determine deterioration of the anchorage system.

External Non-Metal Ducts

- Corrosion
  - Precision
    - Repeatability (Rank - 1): Sounding has no ability to determine corrosive activity within a tendon.
    - Reproducibility (Rank - 1): Sounding has no ability to determine corrosive activity within a tendon.
  - Accuracy (Rank -1): Sounding has no ability to determine corrosive activity within a tendon.

- Section Loss
  - Precision
    - Repeatability (Rank - 1): Sounding has no ability to determine cross-sectional area loss within a tendon.
    - Reproducibility (Rank - 1): Sounding has no ability to determine cross-sectional area loss within a tendon.
  - Accuracy (Rank -1): Sounding has no ability to determine cross-sectional area loss within a tendon.
- Breakage
  - Precision
    - Repeatability (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
    - Reproducibility (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
  - Accuracy (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
- Grout Conditions
  - Precision
    - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids each time testing but smaller voids along with the size and shape of large voids may differ.
    - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.

        - Accuracy (Rank - 3): Sounding will not determine grout conditions alone but will determine voided regions, which can often be a sign of grout conditions.
    - Voids
        - Precision
            - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids each time testing but smaller voids along with the size and shape of large voids may differ.
            - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.
        - Accuracy (Rank - 7): All voided regions within the mock-up specimens were found but sounding also claimed grouted regions contained voids.
    - Water Infiltration
        - Precision
            - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids each time testing but smaller voids along with the size and shape of large voids may differ.
            - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.

- Accuracy (Rank - 3): Sounding will not determine water infiltration alone but will determine voided regions, which can often be a sign of water infiltration.

- General Tendon Deterioration in the Anchorage System
  - Precision
    - Repeatability (Rank - 1): Sounding will not determine deterioration of the anchorage system.
    - Reproducibility (Rank - 1): Sounding will not determine deterioration of the anchorage system.
  - Accuracy (Rank - 1): Sounding will not determine deterioration of the anchorage system.

Anchorage Regions

- Corrosion
  - Precision
    - Repeatability (Rank - 1): Sounding has no ability to determine corrosive activity within a tendon.
    - Reproducibility (Rank - 1): Sounding has no ability to determine corrosive activity within a tendon.
  - Accuracy (Rank -1): Sounding has no ability to determine corrosive activity within a tendon.
- Section Loss
  - Precision
    - Repeatability (Rank - 1): Sounding has no ability to determine cross-sectional area loss within a tendon.

            - Reproducibility (Rank - 1): Sounding has no ability to determine cross-sectional area loss within a tendon.
        - Accuracy (Rank -1): Sounding has no ability to determine cross-sectional area loss within a tendon.
    - Breakage
        - Precision
            - Repeatability (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
            - Reproducibility (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
        - Accuracy (Rank - 1): Sounding has no ability to determine strand breakage within a tendon.
    - Grout Conditions
        - Precision
            - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids in the grout cap each time testing but determining smaller voids may be more difficult.
            - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.
        - Accuracy (Rank -2): The ranking for determining grout conditions within the anchorage region is slightly lower than that of the external duct rankings because the inspector will only be able to determine grout conditions with access to the grout cap, which may or may not

be an accurate indicator of grout conditions within the rest of the anchorage region.

- Voids
  - Precision
    - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids in the grout cap each time testing but determining smaller voids may be more difficult.
    - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.
  - Accuracy (Rank - 5): The accuracy of sounding testing within the anchorage region is lower than that of the external ducts because the inspector can only perform testing on the grout cap, which may or may not be an accurate indicator of the grouting quality of the anchorage system as a while.
- Water Infiltration
  - Precision
    - Repeatability (Rank - 7): A trained sounding inspector is likely to be able to find larger voids in the grout cap each time testing but determining smaller voids may be more difficult.
    - Reproducibility (Rank -5): With sounding being such a subjective method, sounding results will vary depending on the inspector.
  - Accuracy (Rank -2): The ranking for determining water infiltration within the anchorage region is slightly lower than that of the external

duct rankings because the inspector will only be able to determine grout conditions with access to the grout cap, which may or may not be an accurate indicator of conditions within the rest of the anchorage region.

- General Tendon Deterioration in the Anchorage System
  - Precision
    - Repeatability (Rank - 1): Sounding cannot determine tendon deterioration.
    - Reproducibility (Rank -1): Sounding cannot determine tendon deterioration.
  - Accuracy (Rank - 1): Sounding cannot determine tendon deterioration. It can possibly determine voided regions in the anchorage system, which can indicate tendon deterioration but another method would have to be used to determine the extent of deterioration.

All Physical Systems & Defect Conditions

- Ease of Use
  - Power Demand (Rank – 10): No power is required for testing. The optional audio recording device is assumed to have an extended battery life of at least 8 hours.
  - No. of Personnel (Rank - 7): Sounding requires only one inspector manually tapping and recording data along the tendon.
- Inspection Requirements
  - Operator Qualifications (Rank -10): Minimal knowledge of sounding techniques is required. Although this method requires an experienced

inspector with an understanding of acoustic responses, it can be taught on the job to a future inspector.

    - Operator Training (Rank - 10): No required training courses were found for sounding inspectors.
    - USD per Hour (Rank - 10): Since sounding does not require extensive knowledge or experience, it can likely be performed by a Field Inspector. Data from the GSA shows that a reasonable estimated hourly rate of a Field Inspector is $70/hour (U.S. General Services Administration, 2015).
    - Complexity of Data Interpretation (Rank - 10): The data obtained by sounding is a series of acoustic responses at the each location being tested, of which the inspector deduces if a condition exists by his own judgment.

- Cost
    - Cost of Equipment (Rank - 10): The only required equipment for sounding is a sounding tapper or small hammer. For more extensive testing, a sound recording device may be used, but total cost would still be under $1k.
    - Labor Costs for Equipment (Rank - 10): No additional labor is needed for sounding inspection in addition to the operator.

6.2.6. Borescope

External Metal Ducts / External Non-Metal Ducts / Anchorage Regions

- Corrosion

        - Precision
            - Repeatability (Rank - 3): The entry location of the camera relative to the corrosion is the most important factor in whether the borescope will see it or not and if this remains constant, a borescope inspector is likely to provide very repeatable results. However, a score of 3 was given due to the low accuracy ranking.
            - Reproducibility (Rank - 3): If the entry location of the camera is the same, it is unlikely that different operators would determine different results, meaning borescope inspection has high reproducibility. However, a score of 3 was given due to the low accuracy ranking.
        - Accuracy (Rank - 2): If holes are drilled where corrosion has been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 2 is given here because accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do.
    - Section Loss
        - Precision
            - Repeatability (Rank - 3): The entry location of the camera relative to the section loss is the most important factor in whether the borescope will see it or not and if this remains constant, a borescope inspector is likely to provide very repeatable results. However, a score of 3 was given due to the low accuracy ranking.

        - Reproducibility (Rank - 3): If the entry location of the camera is the same, it is unlikely that different operators would determine different results, meaning borescope inspection has high reproducibility. However, a score of 3 was given due to the low accuracy ranking.
    - Accuracy (Rank - 2): If holes are drilled where section loss has been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 2 is given here because accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do.
- Breakage
        - Repeatability (Rank - 3): The entry location of the camera relative to the strand breakage is the most important factor in whether the borescope will see it or not and if this remains constant, a borescope inspector is likely to provide very repeatable results. However, a score of 3 was given due to the low accuracy ranking.
        - Reproducibility (Rank - 3): If the entry location of the camera is the same, it is unlikely that different operators would determine different results, meaning borescope inspection has high reproducibility. However, a score of 3 was given due to the low accuracy ranking.
    - Accuracy (Rank - 2): If holes are drilled where strand breakage has been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 2 is given here because

accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do.

- Grout Conditions
    - Precision
        - Repeatability (Rank - 3): The entry location of the camera relative to the grout conditions is the most important factor in whether the borescope will see it or not and if this remains constant, a borescope inspector is likely to provide very repeatable results. However, a score of 3 was given due to the low accuracy ranking.
        - Reproducibility (Rank -3): If the entry location of the camera is the same, it is unlikely that different operators would determine different results, meaning borescope inspection has high reproducibility. However, a score of 3 was given due to the low accuracy ranking.
    - Accuracy (Rank - 2): If holes are drilled where grout conditions have been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 2 is given here because accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do. Additionally, a borescope can only be used to examine grouting conditions if a void is already present.
- Voids
    - Precision

        - Repeatability (Rank - 5): The entry location of the camera relative to the void is the most important factor in whether the borescope will see it or not and if this remains constant, a borescope inspector is likely to provide very repeatable results. However, a score of 5 was given due to the average accuracy ranking.
        - Reproducibility (Rank -5): If the entry location of the camera is the same, it is unlikely that different operators would determine different results, meaning borescope inspection has high reproducibility. However, a score of 5 was given due to the average accuracy ranking.
    - Accuracy (Rank - 4): If holes are drilled where a void has been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 4 is given here because accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do. This accuracy score for a void defect is higher than all the other defects because the borescope can be used to map out a void along its length in order to provide a rough quantitative estimate of its size and shape.
- Water Infiltration
    - Precision
        - Repeatability (Rank - 3): The entry location of the camera relative to the water infiltration is the most important factor in whether the borescope will see it or not and if this remains

constant, a borescope inspector is likely to provide very repeatable results. However, a score of 3 was given due to the low accuracy ranking.

        - Reproducibility (Rank -3): If the entry location of the camera is the same, it is unlikely that different operators would determine different results, meaning borescope inspection has high reproducibility. However, a score of 3 was given due to the low accuracy ranking.
    - Accuracy (Rank - 2): If holes are drilled where water infiltration has been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 2 is given here because accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do. Additionally, a borescope can only be used to examine water infiltration if a void is already present.
- General Tendon Deterioration in the Anchorage System
    - Precision
        - Repeatability (Rank - 3): The entry location of the camera relative to the deterioration is the most important factor in whether the borescope will see it or not and if this remains constant, a borescope inspector is likely to provide very repeatable results. However, a score of 3 was given due to the low accuracy ranking.
        - Reproducibility (Rank -3): If the entry location of the camera is the same, it is unlikely that different operators would

determine different results, meaning borescope inspection has high reproducibility. However, a score of 3 was given due to the low accuracy ranking.

- Accuracy (Rank - 2): If holes are drilled where tendon deterioration has been previously located, a borescope can be an effective tool in qualitative evaluation. However, a score of 2 is given here because accuracy in this research refers to initial detection and quantitative evaluation of defects, which a borescope does not have a strong capability to do. Additionally, a borescope can only be used to examine water infiltration if a void is already present.

All Physical Systems & Defect Conditions

- Ease of Use
  - Power Demand (Rank – 5): The Olympus IPLEX SX II requires 110V direct power. There are other borescope models that are battery powered and this ranking can be adjusted if such equipment is to be used for borescope testing.
  - No. of Personnel (Rank - 6): Borescope inspection can require one or two inspectors, one can control the cord within the tendon while the other controls the camera and manually takes pictures or videos.
- Inspection Requirements
  - Operator Qualifications (Rank - 10): Minimal knowledge of borescope inspection is required. An engineer can examine the visual findings but the primary qualification of the operator is knowledge of device operation.

    - Operator Training (Rank - 10): No required training courses were found for borescope operation.
    - USD per Hour (Rank - 10): Since borescope operation does not require extensive knowledge or experience, it can likely be performed by a Field Inspector. Data from the GSA shows that a reasonably estimate for the hourly rate of a Field Inspector is $70/hour (U.S. General Services Administration, 2015).
    - Complexity of Data Interpretation (Rank - 10): Borescope inspectors can visually see the condition that exists within each duct and attempt to quantify defects using pictures and videos.
  - Cost
    - Cost of Equipment (Rank - 5): The approximate cost of the Olympus IPLEX SX II is $73k (Hurlebaus, 2015). Note that this ranking is for the equipment used in this research and equipment costs can vary based on manufacturer, model, and other factors.
    - Labor Costs for Equipment (Rank - 5): If an additional Field Inspector is used to assist with borescope testing, an additional estimated $70/hour will be added to inspection costs (U.S. General Services Administration, 2015). A reasonable estimate of inspection speed is that 25 feet of stay cable tendons can be tested per hour, meaning additional labor will cost approximately $3 per foot inspected. Inspection speed can vary based on how the device is advancing along the tendon, if a crane is necessary, if access holes are available, and many other factors.

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1. Summary

In this research, mock-up stay cable specimens were tested with selected non-destructive evaluation methods in order to determine their applicability, capabilities, and limitations in detecting corrosion, section loss, breakage, grout conditions, voids, water infiltration, and general tendon deterioration within the anchorage regions. Each specimen used a different corrosion protection system, of which only certain methods were applicable.

In order to perform this research, four mock-up specimens were built including the fabrication of all defects. Firstly, the anchorage regions were constructed be building formwork, tying reinforcement, installing the anchorage regions, and pouring the concrete. Secondly, steel defects were fabricated and placed at known locations along the ducts. Thirdly, Specimens 1 and 2 were grouted along with fabricating the grouting defects, as necessary. Each specimen contained a minimum of one type of defect applicable to that system. After grouting of the mock-up specimens had cured, NDE testing began. Ground penetrating radar, magnetic flux leakage, infrared thermography, ultrasonic tomography, sounding, and borescope inspections were all performed on each applicable mock-up specimen.

7.2. Conclusions

Each NDE method has its own capabilities and limitations that were determined by both the literature review and testing in this research. The following observations were made based on the results of the experimental program for the stay cable specimens.

Ground penetrating radar (GPR) was not applicable to external metal ducts, anchorage regions, or ungrouted specimens. However, GPR did produced usable data for testing Specimen 2, the grouted HDPE specimen, as it was able to determine voided and water infiltrated regions. In addition, GPR testing was found to be relatively quick and easy to implement.

Magnetic flux leakage (MFL) proved to be very effective for detecting corrosion, section loss, and strand breakage of each specimen. Within all of the acquired data, there was, however, a slight variation in both location and magnitude of the defects. MFL was the only method with the capability to detect any type of strand defect. Additionally, once the device was properly installed, inspection was relatively quick but would likely be much more difficult on inclined tendons as in actual stay cable tendons.

Infrared thermography (IRT) was able to detect voided regions within both Specimen 2 and the grout caps for Specimens 1 and 2. Testing using passive IRT requires proper timing, as the best data was acquired during either sunrise or sunset because the temperature change requires the system to heat or cool in order to reach equilibrium with its surroundings. The results of this research showed that the best time for IRT testing is after sunrise or sunset. IRT did not identify any defects in steel ducts or the anchorage regions.

Ultrasonic tomography (UST) was able to detect voided regions in Specimen 2. However, UST was not able to provide information about Specimen 1, 3, or 4 because it is not applicable to steel ducts or ungrouted systems. Although UST testing of the anchorage systems provided a vivid model of the interior the concrete masses, including reinforcement and tendon locations and orientations, this method could not detect any defects present within the anchorage region.

Sounding was the most intuitive of all the methods and was relatively accurate in both detecting and estimating void sizes found in Specimens 1 and 2. Additionally, this method is relatively quick so sound maps can be acquired efficiently in order to gather preliminary information on potential voided regions of ducts. This method was also the least expensive and requires the least amount of inspector training.

Although borescope in slightly invasive, it can be an excellent tool in stay cable inspection. If access is available, borescope inspections can be used to provide real time information on void sizes, water infiltration, or poor grout conditions, of which each of these were found in testing of Specimens 1 and 2. It also has the potential to provide information on corrosion, section loss, or breakage if such defects are present in a voided region. The primary drawback of this method is that the camera needs access, which could require drilling a hole for access inside a tendon.

Based on the limited results from this research, IRT and sounding are the most effective NDE methods for inspection of stay cable MTEs when investigating for grouting defects and MFL is the best NDE method for detection of corrosion, section loss, or breakage. However, this research is part of a larger project, of which additional testing will be performed on the mock-up specimens. The full project recommendations will be provided in the NCHRP Project 14-28 final report.

7.3. Recommendations for Fabrication of Future Testing Specimens

After performing all NDE testing of the mock-up specimens in this research, there are a few changes to the specimens that could be used to improve specimens for future NDE research. The alterations thought to be the most helpful are the following:

Increase the length of the specimens. If the length of the specimens is increased, more defects could be added. With only a seventeen-foot free span containing six defect grids, comparability of each defect was not available. A longer specimen would not only allow a greater number of defects to be implemented, but also the grid sizes could be increased.

Construct the specimens at an angle. Construct the specimens in a more realistic manner, at a vertical angle. The horizontal layout of the specimens simplified construction but also altered defects. Voided regions were created with gravity, as the grout fell to the bottom of the duct, leaving the top voided. This is not how voids, bleed lenses, or grout segregation would occur in a real cable, as it would more likely be longitudinally shorter and occupy more of the circumference of the duct.

Include grout cracking defects. As a result of the length of stay cable tendons and exposure to wind and rain, they can experience extreme vibrations. Literature review indicated that these oscillations can cause grout to crack, allowing for corrosion inducing materials to gain access to the strands. It is recommended that a procedure for development of this defect is developed and incorporated into future specimens.

Construct specimens with different tendon sizes. This research only constructed specimens with 4-in. inner diameter ducts with 19 strands placed. This is a common system but literature review indicated that stay cable ducts could contain anywhere from 7 to 127 strands (Ohaski, 1991). It is recommended that specimens are constructed with variance in duct size in order to determine the effect of NDE testing on different sized systems.

7.4. Recommendations for Future NDE Research

The ensuing thoughts are recommendations for future research of NDE inspection methods of stay cable systems:

Perform additional testing on poor grout conditions, voids, and water infiltration defects. Because Specimen 1 and 2 only contained one of each of these defects, there was very little comparability. NDE testing in this research was inconclusive in the difference in results between the three defects but increasing the number of each defect would allow for greater comparison.

Use of active infrared thermography on grout caps. Passive infrared thermography was used successfully on the free spans of the specimens, but it is likely that grout cap testing could provide better results using active infrared thermography. The grout caps in this research were exposed to the environment but in a real stay cable structure, it is likely that they would be within a deck or pylon and not receive direct sunlight.

Testing of ultrasonic tomography at higher frequencies. As discussed in Section V, the testing frequency of 50 kHz is not nearly high enough to detect any sort of steel defects. Research of higher frequency UST devices should be used on stay cable specimens to determine if there is an applicability of UST testing to detect steel strand defects within a tendon.

Develop an ultrasonic tomography device for curved surfaces. The A1040 MIRA has a flat testing surface and therefore was not designed for testing of curved surface. It is recommended that for future testing of stay cable tendons, a device be developed that incorporates the UST theory into a curved device that better fits onto stay cable sheathing.

Develop a ground penetrating radar device for curved surfaces. Similar to UST, the StructureScan Mini was not intended for testing of round surfaces. To account for this, temporary wooden supports were installed to ensure advancement of the data as the device advanced but installing some sort of support on an actual stay cable tendon is extremely impractical. To account for this, it is recommended that a GPR device that can advance on a curved surface should be developed.

Conduct MFL research on specimens with more uniform LMA. Quantified results of MFL testing showed that the magnitudes of many of the smaller defects were exaggerated when calibrated in the same data set as major defects. It is recommended that this phenomena be researched in specimens where only small defects exist to see if the calibration can better determine LMA values.

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APPENDIX A – NDE TESTING PROCEDURES

Appendix A outlines the testing procedures for each of the NDE technologies being investigated in this research. Note that these procedures were adapted from Appendix B of Revised Interim Report No. 2 for the NCHRP on Project 14-28 and adjusted for testing on stay cable systems (Hurlebaus et al., 2014).

Appendix A.1 – Ground Penetrating Radar Testing Protocol

TP001A

GROUND PENETRATING RADAR

Introduction

Scope:

Ground penetrating radar (GPR) is a widely used quantitative scanning tool that sends discrete electromagnetic (EM) pulses into a structure and captures the reflections from subsurface layer interfaces (Figure 1). GPR uses EM waves and therefore obeys the laws governing their reflection and transmission in layered media. At each interface within a structure, a part of the incident energy will be reflected and a part will be transmitted with a particular magnitude and phase. The reflection parameters depend on the dielectric constant of the material on either side of the interface. The depth of penetration is limited by the system's power, the medium's electrical conductivity, and the antenna's central frequency.

GPR antennas can emit EM pulses of different frequencies. The choice of frequency depends on the required depth of penetration and depth resolution. In general, lower frequency antennas (~10-500 MHz) have a better resolution at deeper depths (penetration greater than 50 ft in some materials). Higher frequency antennas (~500-3000 MHz) show better details of reflectors close to the surface, but do not penetrate as deep (approximately 24 in. in some materials). The choice of antenna is therefore task-dependent, and must be made from the user's experience and availability of other NDT methods.

Two types of GPR systems are typically used in structural investigations: air-coupled (AC) systems and ground-coupled (GC) systems. The air-coupled systems are high-speed (up to 55 mph in some applications) and operation involves moving an antenna along the surface at approximately 10-20 in. from the surface. Ground-coupled systems are typically fit on a rolling mechanism and moved at lower speeds (approximately 3 mph) with near contact to the ground.

GROUND PENETRATING RADAR

Terminology:

- *Dielectric constant*. The different constants for different materials enable the method to detect subsurface layers. The dielectric constant for water is 81, air is 1, and typical construction materials vary from around 4-9.
- *AC GPR*. Air-coupled ground penetrating radar.
- *GC GPR*. Ground-coupled ground penetrating radar.
- *Radargram.* This is a plot (line scan) of the series of amplitude vs. time signals along the line of testing.
- *Trace.* This is an amplitude vs. time plot at a specific location.
- *Reflector.* These are objects with different electrical conductivity than the surrounding medium causing EM reflections that are captured by the antenna. These show up as hyperbolic curves in the radargram, with the apex of the curve representing the location of the object.
- *DMI.* Distance measurement indicator.

Significance and Use:

The GPR method is best used to measure the depth of subsurface layer interfaces. Since EM signals are highly reflected by metallic objects, this method can typically easily locate such materials such as reinforcement, embedded beams, dowels, pipes, etc within the penetration limit. The changes in surface dielectric are highly influenced by the presence of water, therefore monitoring the surface dielectric has capabilities of detecting locations of moisture-related deterioration.

Interpretation of GPR radargrams may require a high level of experience and education about the method.

Capabilities and Limitations:

- *Duct location.* Acceptable for internal ducts only (testing on a concrete surface). AC GPR can technically be used for external ducts but there is no documentation of successful investigations for this approach.
- *Duct type.* Only applicable for non-metal tendons if it is desirable to detect conditions within the duct. Applicable for metal ducts if it is only desirable to locate the duct itself.

GROUND PENETRATING RADAR

- *Effect of concrete cover.* The effect of concrete cover is dependent on the scanning frequency. For high frequencies (~500-3000 MHz) penetration can typically exceed 24 inches.
- *Effect of layered ducts.* The effect of layered ducts is largely unstudied for GPR applications, but layered effects are expected to yield meaningless results due to the large reflection from the steel strands in the near duct.
- *Effect of reinforcement congestion.* Surrounding reinforcement will strongly affect any investigation since the presence of steel highly reflects the electromagnetic waves. In previous studies, spacing of reinforcement closer than 6 inches made internal investigation nearly impossible.
- *Accessibility requirements.* For AC GPR, the only accessibility requirements are a relatively undisturbed path of travel to ensure the antenna horn remains within 12-24 inches of the testing surface. Significant variation during scanning will yield undesirable variability of the radargram signals making interpretation very difficult. For GC GPR, the area required for scanning is device dependent. For the 2.8 GHz GSSI Mini HD, 3D imagine requires either a 2 ft x 2 ft or 2 ft x 4 ft manually accessible testing surface. Testing within the anchorage region is not possible using GPR due to the physical structure of the region and the highly reflective metal used in the anchorages.

Referenced Documents:

1. ASTM D6432 – 11, Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation

2. SHRP2 Report S2-R06(G)-RW, Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings

3. FHWA/TX-92/1233-1, Implementation of the Texas Ground Penetrating Radar System

4. GSSI Handbook for RADAR Inspection of Concrete (http://www.geophysical.com/)

TP001A

GROUND PENETRATING RADAR

Procedure

Data Collected:

- Amplitude of received EM signals vs time (traces)
- Radargrams (series of traces along a distance)

Apparatus:

- GPR antenna
- Data Acquisition System (DAQ)
- Computer with appropriate software
- Appropriate power source/charged batteries
- Appropriate connecting cables
- DMI attached to rolling systems
- Aluminum plate for ACGPR (4 ft x 4 ft. typical)
- Foam block for ACGPR (12-18 in. typical)
- Antenna deployment system for ACGPR (vehicle with appropriate attachments, cart, etc.)
- Appropriate marking system (landscaping paint, permanent markers, welder's soapstone, or pre-made grid systems)

Process Description/Data Collection Principle:

A marking system or other form of data collection management is used to perform testing and relate findings to the physical structure. GPR tests are used to detect concrete cover, as well as location and depth (within reflector and depth limitations) for reinforcement, structural components, conduits, cables, prestressing steel, post-tensioned ducts, voids, honeycombing, surface layers, member thickness, and other anomalies.

After performing the appropriate manufacturer's calibration, the antenna is moved along the inspected area. An attached DMI records distance traveled for post-analysis. The antenna receives and transmits data at a selected scan rate/density.

GROUND PENETRATING RADAR

Photo:

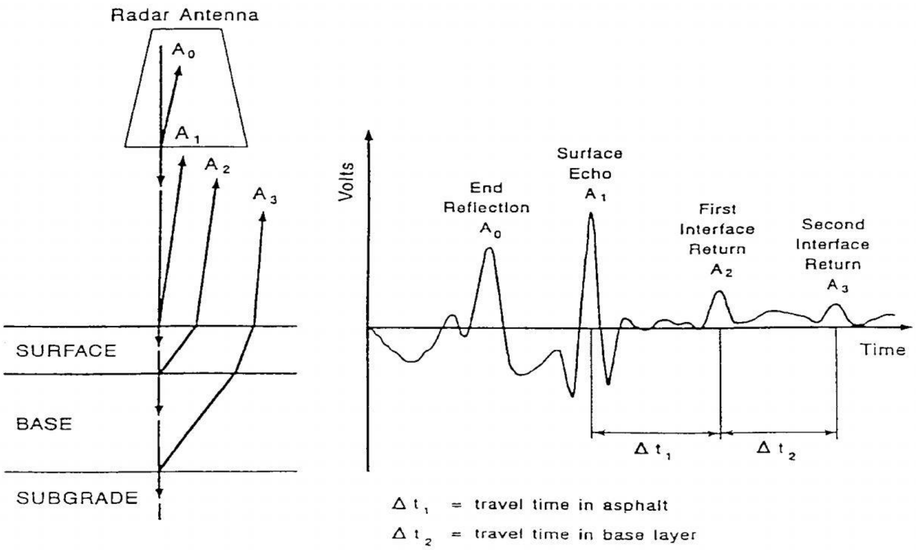

Figure A.1-1: GPR antenna sends and receives EM pulses after reflection from subsurface interfaces (left); GPR trace of signal amplitude vs time (right) (from FHWA

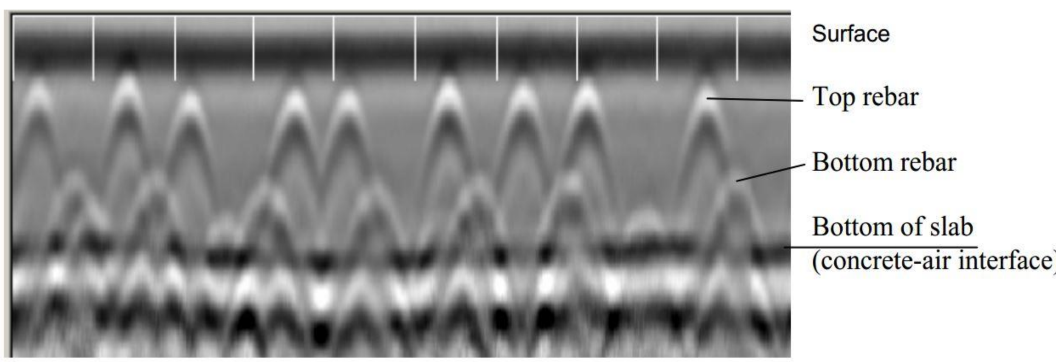

Figure A.1-2: Typical GPR radargram showing surface top, two layers of rebar, and member thickness (from GSSI).

Data Collection Procedure:

All manufacturer's manuals and procedures should be strictly adhered to in addition to the following data collection procedures.

GROUND PENETRATING RADAR

PREPARATION:

Step 1 – Collect bridge structure files.

Step 2 – Gather all required apparatuses named above.

Step 3 – Ensure proper working order of all system components.

Step 4 – Determine appropriate parameters for the type of inspection required (central frequency, desired coupling, scan density and rate, testing paths, etc).

Step 5 – Enter span under inspection and ensure appropriate marking system is in place

Step 6 – At a minimum, record all data specified in the section "Necessary Information for Data Collection". Keep this data updated for each span/section under inspection, noting any significant changes (particularly in temperature or humidity) during testing.

Step 7 – Perform preliminary walk-through of testing site, noting any damage indicators

Step 8 – Once a specific site is chosen for testing, ensure all surfaces are clean and free of debris.

Step 9 – Use appropriate marking system for reference.

Step 10 – Calibrate GPR unit (if required) as specified in the manufacturer's manual.

Step 11 – (RECOMMENDED) Create a sample file to ensure proper working order of all system components.

Step 12 – If necessary for free span inspection, construct or assemble an apparatus to ensure the device wheels will rotate as the device advances along the tendon. Temporary wooden supports were used in this research but would be impractical for inspection of real-world stay cables.

DATA COLLECTION:

Step 1 – Use the appropriate testing lines or paths and scan the selected area, making sure to note start and end time and location and other relevant data.

Step 2 – Continue to scan selected lines or paths until all areas are scanned, being diligent to name the saved data according to testing location. After each area is tested, repeat Steps 4-11 under "Preparation" as necessary before additional continuing data collection.

GROUND PENETRATING RADAR

DATA REPORTING:

Step 1 – Follow guidelines under “Reporting” section below in creating an inspection report.

Step 2 – Submit completed inspection report to inspection program manager.

Criteria for Data Validation:

Ground truth data is typically collected by using the DMI locations from the radagram at areas of interest and the marking system. All ground truth data should be properly recorded (precise location, photos, ambient temperature, humidity, etc.).

Note: For the NCHRP 14-28 mock-up specimens located at Texas A&M Transportation Institute, no ground truth data collection is allowed!

Calculation or Interpretation of Results:

All calculations or interpretation of results should be performed by experienced and educated personnel. System software often makes data interpretation easier, but care should be taken that interpretation is overseen by properly qualified personnel.

Reporting

Subdivision of the Structure for Inspection & Recordkeeping:

Investigators should always record the appropriate subdivisions of the structure for analysis, recordkeeping, and future tests. Every testing location should be clearly identified.

Next Process:

All final reports describing the test and visual representation of results are to be given to the owner of the structure or file manager. All key features noted from the investigation should be clearly identified and labeled with respect to the structures start and/or end locations.

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GROUND PENETRATING RADAR

Necessary Information for Data Collection

#	Description	Units/format	Values/Accuracy
	GENERAL		
1	State, City, Location		
2	Structure Name		
3	Personnel Performing		
4	Date of inspection		
5	Start Time		
6	End Time		
7	Transverse Origin Location		
8	Longitudinal Origin Location		
9	Transverse Sampling Spacing		
10	Longitudinal Sampling Spacing		
11	Temperature		
12	Device		
13	Manufacturer		
14	Data Acquisition System		
15	System Model		
16	System Serial Number		
17	Sensor Name		
18	Sensor Model		
19	Sensor Serial Number		
20	Pulse length		
21	Center Frequency		
22	Bandwidth		
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GROUND PENETRATING RADAR			
	RAW DATA		
36	Time Stamp		
37	Data Acquisition System		
38	Antenna Model		
39	Gain		
40	Range		
41	Word Size		
42	Pulse repetition rate		
43	Samples/scan		
44	Scans/second		
45	Spatial Mode		
46	Distance Units		
47	Scans/Unit		
48	Vertical Filters		
49	Vertical Filter Values		
50	Horizontal Filters		
51	Horizontal Filter Values		
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GROUND PENETRATING RADAR			
	CONDITIONED DATA		
74	Date File		
75	ASCII File		
76	Scan #		
77	Longitudinal Location		
78	Transverse Location		
79	Target		
80	Depth		
81	Amplitude		
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Appendix A.2 – Magnetic Flux Leakage Testing Protocol

TP004A

MAGNETIC FLUX LEAKAGE

Introduction

Scope:

Magnetic methods such as the magnetic flux leakage (MFL) methods are very promising techniques in the NDE field for locating steel section loss due to corrosion, strand/wire pitting, or breakage. There are two categories of the MFL method: active MFL and residual MFL. In the active MFL method, a ferrous material (steel) is subjected to a strong magnetic field by a portable magnet. This induces flux paths in the material between the two poles. Where section loss is present, the magnetic field in the material "leaks" from its typical path of least resistance. A magnetic field detector (comprised of Hall-effect sensors) between the poles of the magnet is sensitive to this change in magnetic field and indicates the leak. In the residual method, the steel is brought to full magnetic saturation in order to erase its unknown magnetic history, then the magnet is removed and the sensors are passed over the section for residual magnetic field measurements. Another recently developed magnetic method that has not yet been fully field-tested is the induced magnetic field (IMF) method. All of these methods are described below.

Terminology:

- *Hall-effect sensors*. These sensors produce output voltages in response to a change in the magnetic field.
- *Trace.* This is an amplitude vs. time plot at a specific location.
- *DMI.* Distance measurement indicator.

Significance and Use:

In a thorough review of NDE methods for PT tendons and stay cables for FDOT, Azizinamini et al. (2012) noted that active MFL was primarily useful for scanning specimens where large areas of corrosion are present while residual MFL was better at determining small areas of corrosion. Azizinamini et al. list the MFL technique as one of the most promising NDE methods for PT tendon and stay cable evaluation.

Interpretation of MFL charts may require a high level of experience and education about the method.

Capabilities and Limitations:

- *Duct location.* Acceptable for both internal and external ducts, but different equipment is typically used for either application.
- *Duct type.* Applicable for both metal and non-metal ducts.
- *Effect of concrete cover.* The effect of concrete cover is considered to be negligible by some researchers (DaSilva et al. 2009).

MAGNETIC FLUX LEAKAGE

- *Effect of layered ducts.* The effect of layered ducts is largely unstudied for MFL applications, but layered effects are expected to yield poor results due to the large amount of magnetization required.
- *Effect of reinforcement congestion.* Surrounding reinforcement will strongly affect any investigation since the presence of steel highly affects the magnetic field. Known acceptable amounts are largely unstudied.
- *Accessibility requirements.* For internal duct investigations, MFL demands the approximate accessibility of a small hand-pushed cart. Note that such testing is only commonly performed on a floor slab (not vertical walls such as girder webs). For external duct investigations, an approximate 12-in. radius is required from the center of the duct.

Referenced Documents:

1. ASTM E570 – 09, Standard Practice for Flux Leakage Examination of Ferromagnetic Steel Tubular Products

2. ASTM E1571 – 11, Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope

3. DaSilva, M., S. Javidi, A. Yakel and A. Azizinamini. 2009. "Nondestructive Method to Detect Corrosion of Steel Elements in Concrete".

4. Scheel, H. and B. Hillemeier. 2003. "Location of prestressing steel fractures in concrete." Journal of materials in civil engineering Vol. 15, No. 3, pp. 228-234.

Procedure

Data Collected:

- Amplitude of received voltage signals vs location (traces)
- Flux charts (series of traces along a specified distance)

Apparatus:

- Signal conditioning console
- Sensor head
- Data Acquisition System (DAQ)
- Chart recorder, paper
- Computer with appropriate software
- Appropriate power source/charged batteries
- Appropriate connecting cables
- DMI attached to rolling systems
- Duct guide system for external ducts

MAGNETIC FLUX LEAKAGE

- Deployment system for internal ducts (cart with appropriate attachments, etc.)
- Appropriate marking system (landscaping paint, permanent markers, welder's soapstone, or pre-made grid systems)

Process Description/Data Collection Principle:
A marking system or other form of data collection management is used to perform testing and relate findings to the physical structure. MFL is used primarily to detect loss of cross section in cables and prestressing steel.

After performing the appropriate manufacturer's calibration, the sensor array is moved along the inspected area. An attached DMI records distance traveled for post-analysis. The array receives and transmits data at a selected scan rate/density.

Photo:

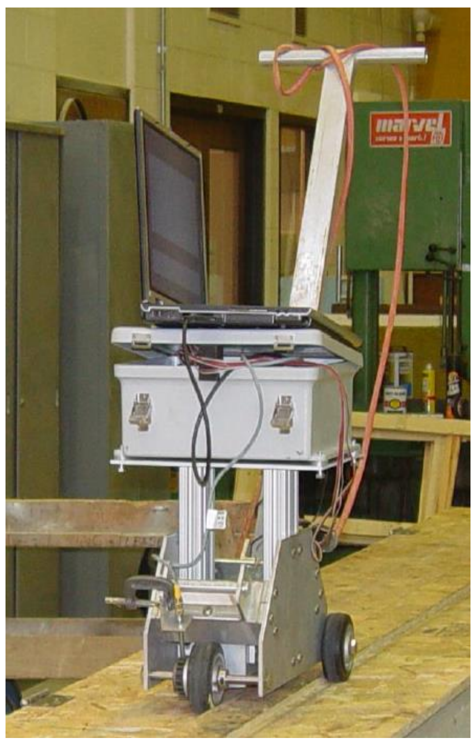

Figure A.2-1. MFL device for internal ducts (from DaSilva et al. 2009).

MAGNETIC FLUX LEAKAGE

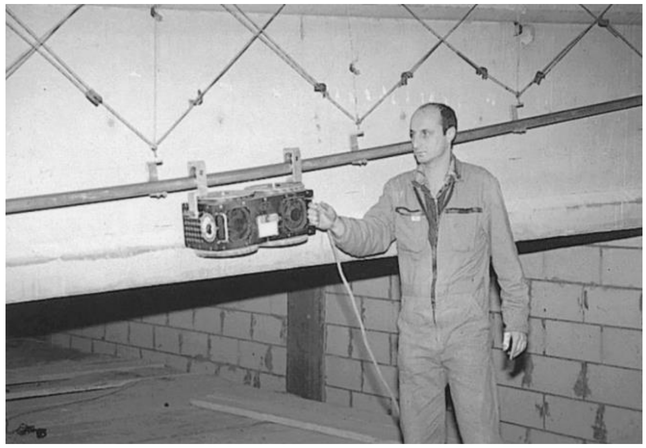

Figure A.2-2. Application of MFL on an external tendon specimen (from Sche
et al. 2003).

Data Collection Procedure:
All manufacturer's manuals and procedures should be strictly adhered to in addition to the following data collection procedures.

PREPARATION:

Step 1 – Collect bridge structure files.

Step 2 – Gather all required apparatuses named above.

Step 3 – Ensure proper working order of all system components.

Step 4 – Determine appropriate parameters for the type of inspection required (central frequency, desired coupling, scan density and rate, testing paths, etc).

Step 5 – Enter span under inspection and ensure appropriate marking system is in place

Step 6 – At a minimum, record all data specified in the section "Necessary Information for Data Collection". Keep this data updated for each span/section under inspection, noting any significant changes (particularly in temperature or humidity) during testing.

Step 7 – Perform preliminary walk-through of testing site, noting any damage indicators

Step 8 – Once a specific site is chosen for testing, ensure all surfaces are clean and free of debris.

MAGNETIC FLUX LEAKAGE

Step 9 – Use appropriate marking system for reference.

Step 10 – Calibrate unit (if required) as specified in the manufacturer's manual.

Step 11 – (RECOMMENDED) Create a sample file to ensure proper working order of all system components.

DATA COLLECTION:

Step 1 – Use the appropriate testing lines or paths and scan the selected area, making sure to note start and end time and location and other relevant data.

Step 2 – Continue to scan selected lines or paths until all areas are scanned, being diligent to name the saved data according to testing location. After each area is tested, repeat Steps 4-11 under "Preparation" as necessary before additional continuing data collection.

DATA REPORTING:

Step 1 – Follow guidelines under "Reporting" section below in creating an inspection report.

Step 2 – Submit completed inspection report to inspection program manager.

Criteria for Data Validation:
Ground truth data is typically collected by using the DMI locations from the MFL scanner at areas of interest in addition to the marking system. All ground truth data should be properly recorded (precise location, photos, ambient temperature, humidity, etc.).

Note: For the NCHRP 14-28 mock-up specimens located at Texas A&M Transportation Institute, no ground truth data collection is allowed!

Calculation or Interpretation of Results:
All calculations or interpretation of results should be performed by experienced and educated personnel. System software often makes data interpretation easier, but care should be taken that interpretation is overseen by properly qualified personnel.

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MAGNETIC FLUX LEAKAGE

Reporting

Subdivision of the Structure for Inspection & Recordkeeping:
Investigators should always record the appropriate subdivisions of the structure for analysis, recordkeeping, and future tests. Every testing location should be clearly identified.

Next Process:
All final reports describing the test and visual representation of results are to be given to the owner of the structure or file manager. All key features noted from the investigation should be clearly identified and labeled with respect to the structures start and/or end locations.

TP004A

MAGNETIC FLUX LEAKAGE			
Necessary Information for Data Collection			
#	**Description**	**Units/format**	**Values/Accuracy**
	GENERAL		
1	State, City, Location		
2	Structure Name		
3	Personnel Performing Inspection		
4	Date of inspection		
5	Start Time		
6	End Time		
7	Transverse Origin Location (x,y)		
8	Longitudinal Origin Location		
9	Transverse Sampling Spacing		
10	Longitudinal Sampling Spacing		
11	Temperature		
12	Device		
13	Manufacturer		
14	Data Acquisition System		
15	System Model		
16	System Serial Number		
17	Sensor Name		
18	Sensor Model		
19	Sensor Serial Number		
20	Pulse length		
21	Center Frequency		
22	Bandwidth		
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MAGNETIC FLUX LEAKAGE			
	RAW DATA		
37	Time Stamp		
38	Data Acquisition System		
39	Sensor Model		
40	Gain		
41	Range		
42	Word Size		
43	Pulse repetition rate		
44	Samples/scan		
45	Scans/second		
46	Spatial Mode		
47	Distance Units		
48	Scans/Unit		
49	Vertical Filters		
50	Vertical Filter Values		
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MAGNETIC FLUX LEAKAGE			
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75	Date File		
76	ASCII File		
77	Scan #		
78	Longitudinal Location		
79	Transverse Location		
80	Target		
81	Depth		
82	Amplitude		
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Appendix A.3 – Infrared Thermography Testing Protocol

TP005A

INFRARED THERMOGRAPHY

Introduction

Scope:

Infrared thermography is an imaging technique that translates thermal energy emissions that escape the surface under inspection to a temperature map. The images produced give information concerning the observed temperature gradients. This is extremely convenient for NDE as delaminations and voids act as thermal barriers for heat released from concrete. However, it can be difficult to perform this testing as IRT devices are highly dependent on ambient temperature conditions. Optimal results are obtained during the time of day when the temperature changes most rapidly.

IRT has continued to develop over the past few decades, becoming a highly useful device well known for its capability of detecting superficial flaws in concrete structures. Its use varies from being fixed on a vehicle for 360-degree tunnel inspections to handheld cameras (Wimsatt et al. 2013). IRT devices can be categorized as either active or passive systems. Passive infrared systems are contactless technologies that rely on the heat of the sun and different times of the day when the surroundings are either warming or cooling to provide temperature gradients for thermal inspection. Active infrared systems differ from passive systems only in the application of the heat source. In active IRT, a heater is introduced to warm the structure in a localized area and in a controlled environment (Figure 1). It is important to note that IRT technologies only provide images of surface energy emission; they do not provide any information regarding the depth of defects.

Terminology:

- *Detector*. Different IRT systems use different detectors. Typical handheld units use uncooled microbolometer types.
- *Optical lenses*. Common IRT lenses are 88.9 mm (7°), 41.3 mm (15°), 24.6 mm (25°), 13.1 mm (45°), and 6.5 mm (80°). These detail the full angle of detection available for a particular lense.

Significance and Use:

Pollock et al. (2008) used this technology in both field and laboratory investigations. As in passive IRT, they determined active IRT could very successfully and consistently locate air voids, but only in plastic ducts in thin specimens (no greater than 8-in. thick and 2-in. cover). The voided area had to be directly between the heat source and the steel strands to be effectively identified. Furthermore, they noted that it is more productive to place the heat source on the opposite side of the test specimen from where the thermal images will be collected to capture through-heating effects. Field evaluations, similar to passive IRT, were not successful at locating ducts in a 12-in. specimen (unknown cover), even after five hours of heating.

INFRARED THERMOGRAPHY

Interpretation of IRT images may require a low to moderate level of experience and education about the method.

Capabilities and Limitations:

- *Duct location.* Acceptable for both internal and external ducts; however, internal ducts will almost always require active IRT tools.
- *Duct type.* Successful investigations have only been performed on non-metal ducts.
- *Effect of concrete cover.* The effect of concrete cover can be significant for either IRT approach. Successful investigations have been reported under 2-in. of concrete cover.
- *Effect of layered ducts.* Layered duct inspection is not possible with IRT.
- *Effect of reinforcement congestion.* Surrounding reinforcement will strongly affect any investigation, but particular limits have been unstudied.
- *Accessibility requirements.* If using active IRT, the only accessibility required is for the heater used. The only requirement for passive IRT is the ability to be physically close to the area under inspection to avoid glare from light sources.

Referenced Documents:

1. ASTM E1934 – 99a, Standard Guide for Examining Electrical and Mechanical Equipment with Infrared Thermography

2. ASTM E2582 – 07, Standard Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications

3. SHRP2 Report S2-R06(G)-RW, Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings

4. Pollock, D. G., K. J. Dupuis, B. Lacour and K. R. Olsen. 2008. "Detection of voids in prestressed concrete bridges using thermal imaging and ground-penetrating radar".

5. FLIR User Manual (http://www.flir.com)

Procedure

Data Collected:

- Thermal images

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INFRARED THERMOGRAPHY

Apparatus:

- Camera
- Heat source (if using active approach)
- Computer with appropriate software
- Appropriate power source/charged batteries
- Appropriate connecting cables
- Deployment system for aerial scans (vehicle with appropriate attachments, cart, etc.)
- Appropriate marking system (landscaping paint, permanent markers, welder's soapstone, or pre-made grid systems)

Process Description/Data Collection Principle:

A marking system or other form of data collection management is used to perform testing and relate findings to the physical structure. IRT tests are used to detect presence of shallow voids, potential water infiltration, lining cracks, and other anomalies.

Photo:

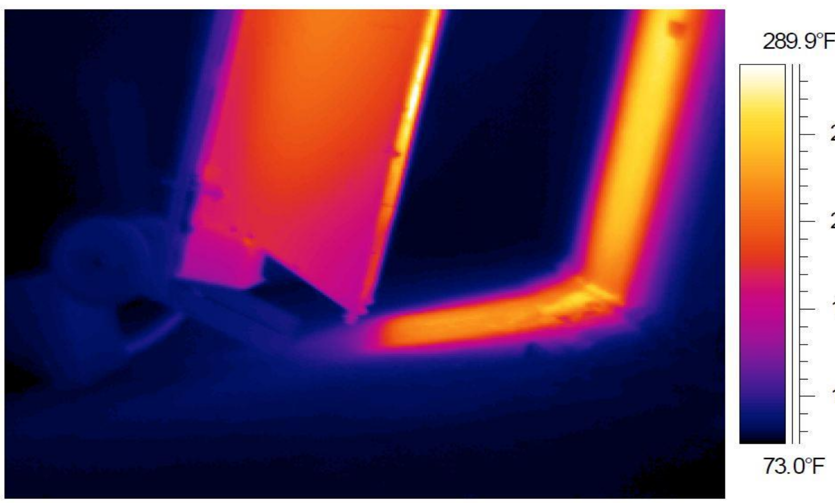

Figure A.3-1. Active IRT of a segmental box girder (from Pollock et al. 2008).

INFRARED THERMOGRAPHY

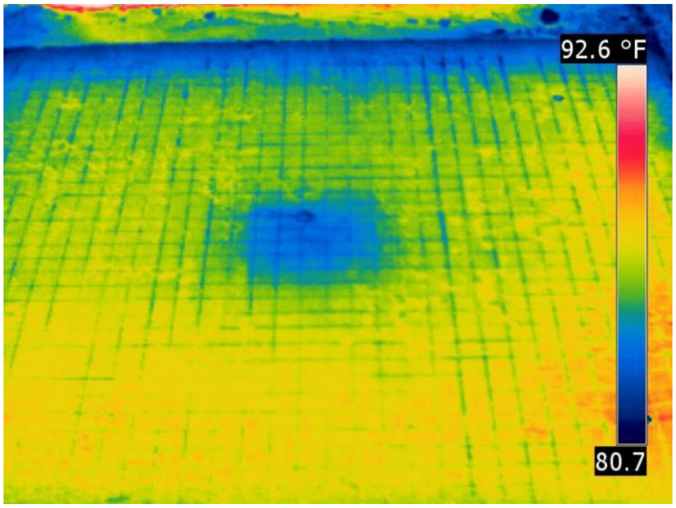

Figure A.3-2: Typical passive heat signature from internal voiding (from SHRP2).

Data Collection Procedure:
All manufacturer's manuals and procedures should be strictly adhered to in addition to the following data collection procedures.

PREPARATION:

Step 1 – Collect bridge structure files.

Step 2 – Gather all required apparatuses named above.

Step 3 – Ensure proper working order of all system components.

Step 4 – Determine appropriate parameters for the type of inspection required (testing paths, etc).

Step 5 – Enter span under inspection and ensure appropriate marking system is in place

Step 6 – At a minimum, record all data specified in the section "Necessary Information for Data Collection". Keep this data updated for each span/section under inspection, noting any significant changes (particularly in temperature or humidity) during testing.

Step 7 – Perform preliminary walk-through of testing site, noting any damage indicators

INFRARED THERMOGRAPHY

Step 8 – Once a specific site is chosen for testing, ensure all surfaces are clean and free of debris. Note that any activity from removing debris may leave heat signature due to material removal. Handprints especially can remain for extended periods of time.

Step 9 – Use appropriate marking system for reference.

Step 10 – Calibrate unit (if required) as specified in the manufacturer's manual.

Step 11 – (RECOMMENDED) Create a sample file to ensure proper working order of all system components.

DATA COLLECTION:

Step 1 – Use the appropriate testing lines or paths and image the selected area, making sure to note start and end time and location and other relevant data.

Step 2 – Continue to image selected locations or paths until all areas are imaged, being diligent to name the saved data according to testing location. After each area is tested, repeat Steps 4-11 under "Preparation" as necessary before additional continuing data collection.

DATA REPORTING:

Step 1 – Follow guidelines under "Reporting" section below in creating an inspection report.

Step 2 – Submit completed inspection report to inspection program manager.

Criteria for Data Validation:

Ground truth data is typically collected by using the notes from each image location and the existing marking system. All ground truth data should be properly recorded (precise location, photos, ambient temperature, humidity, etc.).

Note: For the NCHRP 14-28 mock-up specimens located at Texas A&M Transportation Institute, no ground truth data collection is allowed!

Calculation or Interpretation of Results:

All interpretation of results should be performed by experienced and educated personnel. System software often makes data interpretation easier, but care should be taken that interpretation is overseen by properly qualified personnel.

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INFRARED THERMOGRAPHY

Reporting

Subdivision of the Structure for Inspection & Recordkeeping:
Investigators should always record the appropriate subdivisions of the structure for analysis, recordkeeping, and future tests. Every testing location should be clearly identified.

Next Process:
All final reports describing the test and visual representation of results are to be given to the owner of the structure or file manager. All key features noted from the investigation should be clearly identified and labeled with respect to the structures start and/or end locations.

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INFRARED THERMOGRAPHY

Necessary Information for Data Collection

#	Description	Units/format	Values/Accuracy
	GENERAL		
1	State, City, Location		
2	Structure Name		
3	Personnel Performing Inspection		
4	Date of inspection		
5	Start Time		
6	End Time		
7	Transverse Origin Location (x,y)		
8	Longitudinal Origin Location		
9	Transverse Sampling Spacing		
10	Longitudinal Sampling Spacing		
11	Temperature		
12	Device		
13	Manufacturer		
14	Data Acquisition System		
15	System Model		
16	System Serial Number		
17	Sensor Name		
18	Sensor Model		
19	Sensor Serial Number		
20	Spectral Range		
21	Detector Type		
22	Detector Pitch		
23	Resolution		
24	Frame Rate		
25	Time Constant		
26	Standard Temperature Range		
27	Accuracy		
28	Lense used		
29	Zoom		
30	Fusion		
31	Operating Temperature Range		
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INFRARED THERMOGRAPHY			
	RAW DATA		
37	Time Stamp		
38	Data Acquisition System		
39	Antenna Model		
40	Gain		
41	Range		
42	Word Size		
43	Pulse repetition rate		
44	Samples/scan		
45	Scans/second		
46	Spatial Mode		
47	Distance Units		
48	Scans/Unit		
49	Vertical Filters		
50	Vertical Filter Values		
51	Horizontal Filters		
52	Horizontal Filter Values		
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INFRARED THERMOGRAPHY			
	CONDITIONED DATA		
75	Date File		
76	ASCII File		
77	Scan #		
78	Longitudinal Location		
79	Transverse Location		
80	Target		
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Appendix A.4 – Ultrasonic Tomography Testing Protocol

TP006A

ULTRASONIC TOMOGRAPHY

Introduction

Scope:

The ultrasonic technique encompasses all methods that employ the use of acoustic waves over 20 kHz. The principle of operation is the same regardless of the type of UST system: a sensor or group of sensors emits a stress pulse (typically a P- or S-wave) into the specimen. As the waves propagate, areas with changes of impedance reflect portions of the wave, and these reflections are captured by sensors. Through time-of-flight measurements and frequency/amplitude characteristics, defects and/or discontinuities can be determined. Ultrasonic techniques have shown a promising future for detecting and locating internal defects in concrete structures, including concrete thickness, internal duct locations, material layers, reinforcement presence, elastic modulus, cracks, voids, delamination, and corrosion.

The ultrasonic tomography (UST) technique described here uses a linear array of dry-point-contact transducers that generate shear waves at a center frequency of 55 kHz.

Terminology:

- *Shear waves*. S-waves cause the material to oscillate in a direction perpendicular to the direction of propagation and cannot travel through air or water
- *DPC transducers.* Dry-point-contact transducers do not require couplant as do conventional ultrasonic transducers
- *SAFT algorithm.* Synthetic Aperture Focusing Technique is an algorithm developed to reconstruct time of flight (TOF) measurements into B-, C-, and D-scans for imaging
- *A-scan.* This scan shows amplitude of the received wave vs time
- *B-scan.* This two dimensional scan is a SAFT reconstruction image that shows width of scan vs depth of scan (profile or elevation view)
- *C-scan.* This two dimensional scan is a SAFT reconstruction image that shows width of scan vs length of scan (plan view)
- *D-scan.* This two dimensional scan is a SAFT reconstruction image that shows width of scan vs depth of scan (profile or elevation view perpendicular to the B-scan)

Significance and Use:

The UST method is best used to measure the depth of subsurface layer interfaces. Since shear waves are highly reflected by air or water, this method can typically easily locate such anomalies such as delamination, cracking, member thickness, and voids. Additionally, any material with an impedance mismatch compared to the tested media will cause reflections. This means UST can be used to locate and detect reinforcement,

ULTRASONIC TOMOGRAPHY

embedded beams, dowels, pipes, etc within the penetration limit. The limitations of the system include the inability to test non-flat surfaces, to determine the specific type of anomaly located, and depth limitations associated with the scanning frequency.

Interpretation of UST scans may require a high level of experience and education with this method.

Capabilities and Limitations:

- *Duct location.* Acceptable for both internal and external ducts, depending on device used. Linear arrays are typically limited to testing on smooth concrete surfaces, while pulse echo or through transmission can possibly be used on external ducts.
- *Duct type.* As long as sufficient bonding between the duct lining and surrounding grout is maintained (no shrinkage cracks or air gaps present), this method is applicable to any duct type. Metal ducts do tend to reflect acoustic waves more than non-metal, so internal inspection may not be possible.
- *Effect of concrete cover.* Typical low frequency (approximately 50 kHz) UST devices perform better when the concrete cover is between 2-12 inches. Deeper cover may be acceptable provided there is not heavy reinforcement congestion.
- *Effect of layered ducts.* Ducts behind other ducts cannot be discerned using UST.
- *Effect of reinforcement congestion.* Surrounding reinforcement will strongly affect any investigation since the presence of steel highly reflects acoustic waves. This makes any object directly beneath the reinforcement undiscernible and areas in between reinforcement visible. Densely spaced reinforcement will therefore hide any investigation beyond the bars' location.
- *Accessibility requirements.* For linear arrays, the area required for scanning is device dependent. For the A1040 MIRA, 3D images typically require a 2 ft x 2 ft or larger (depending on scanning increments) accessible testing surface. Testing within the anchorage region is generally assumed not possible using UST due to the highly reflective steel used in the anchorages. Pulse echo techniques can, however, be used on individual strands for near-anchorage defects.

Referenced Documents:

1. ASTM C597 – 09, Standard Test Method for Pulse Velocity Through Concrete

2. SHRP2 Report S2-R06(G)-RW, Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings

3. Ultrasonic Low-Frequency Tomograph A1040 MIRA Operation Manual (www.acsys.ru)

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ULTRASONIC TOMOGRAPHY

Procedure

Data Collected:

- TOF measurements for transmitted and received acoustic signals
- Amplitude of received acoustic signals
- Wave speed measurements

Apparatus:

- Transducer matrix
- Data Acquisition System (DAQ)
- Computer with appropriate software
- Appropriate power source/charged batteries
- Appropriate connecting cables
- DMI attached to rolling systems
- Appropriate marking system (landscaping paint, permanent markers, welder's soapstone, or pre-made grid systems)

Process Description/Data Collection Principle:

A marking system or other form of data collection management is used to perform testing and relate findings to the physical structure. UST tests are used to detect concrete cover, as well as location and depth (within reflector and depth limitations) for reinforcement, structural components, conduits, cables, prestressing steel, post-tensioned ducts, voids, honeycombing, surface layers, member thickness, and other anomalies.

After performing the appropriate manufacturer's calibration (typically involving wave speed calculation), the transducer matrix is moved along the inspected area and transmits/receives data at discrete locations. An attached DMI (if appropriate) records distance traveled for post-analysis. The transducer matrix receives and transmits data at a selected scan rate/density.

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ULTRASONIC TOMOGRAPHY

Photo:

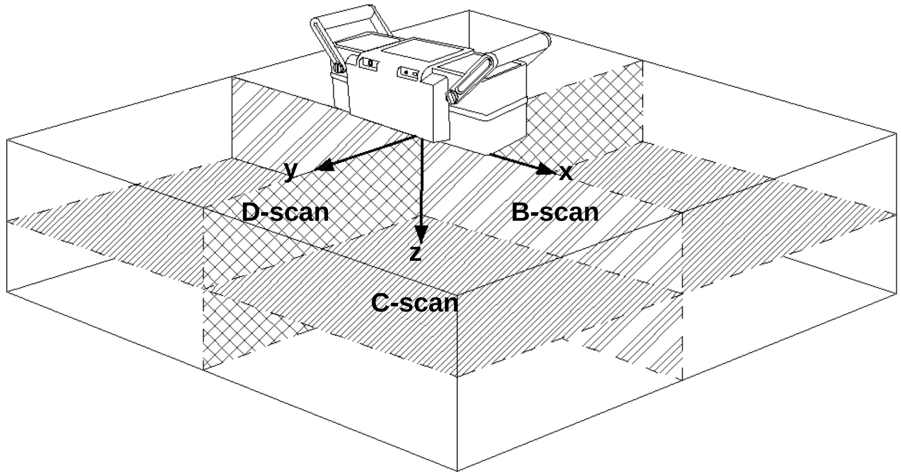

Figure A.4-1: UST device on inspection element showing B-, C-, and D-scans (from SHRP2).

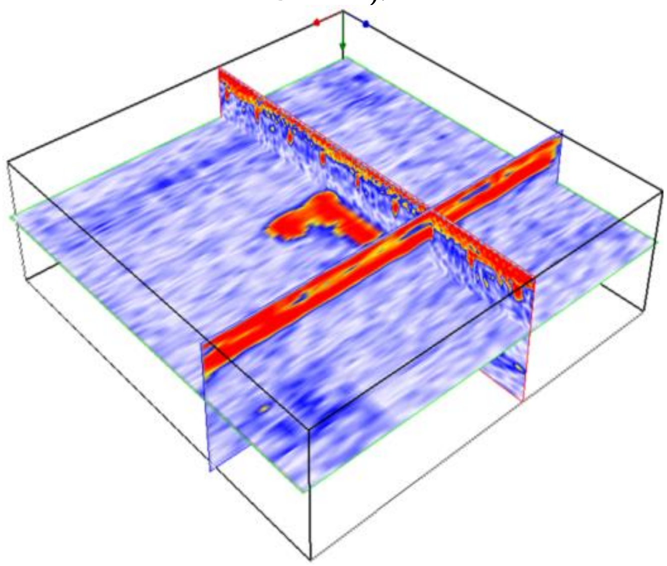

Figure A.4-2: Typical UST scan showing B-, C-, and D-scans per Figure 1 (from SHRP2).

ULTRASONIC TOMOGRAPHY

Data Collection Procedure:
All manufacturer's manuals and procedures should be strictly adhered to in addition to the following data collection procedures.

PREPARATION:

Step 1 – Collect bridge structure files.

Step 2 – Gather all required apparatuses named above.

Step 3 – Ensure proper working order of all system components.

Step 4 – Determine appropriate parameters for the type of inspection required (central frequency, desired coupling, scan density and rate, testing paths, etc).

Step 5 – Enter span under inspection and ensure appropriate marking system is in place

Step 6 – At a minimum, record all data specified in the section "Necessary Information for Data Collection". Keep this data updated for each span/section under inspection, noting any significant changes (particularly in temperature or humidity) during testing.

Step 7 – Perform preliminary walk-through of testing site, noting any damage indicators

Step 8 – Once a specific site is chosen for testing, ensure all surfaces are clean and free of debris.

Step 9 – Use appropriate marking system for reference.

Step 10 – Calibrate UST unit (if required) as specified in the manufacturer's manual.

Step 11 – (RECOMMENDED) Create a sample file to ensure proper working order of all system components.

DATA COLLECTION:

Step 1 – Use the appropriate testing lines or paths and scan the selected area, making sure to note start and end time and location and other relevant data.

Step 2 – Continue to scan selected lines or paths until all areas are scanned, being diligent to name the saved data according to testing location. After each area is tested,

ULTRASONIC TOMOGRAPHY

repeat Steps 4-11 under “Preparation” as necessary before additional continuing data collection.

DATA REPORTING:

Step 1 – Follow guidelines under “Reporting” section below in creating an inspection report.

Step 2 – Submit completed inspection report to inspection program manager.

Criteria for Data Validation:
Ground truth data is typically collected by using the DMI locations from the scans or otherwise relating the scan dimensions to the area under investigation. All ground truth data should be properly recorded (precise location, photos, ambient temperature, humidity, etc.).

Note: For the NCHRP 14-28 mock-up specimens located at Texas A&M Transportation Institute, no ground truth data collection is allowed!

Calculation or Interpretation of Results:
All calculations or interpretation of results should be performed by experienced and educated personnel. System software often makes data interpretation easier, but care should be taken that interpretation is overseen by properly qualified personnel.

Reporting

Subdivision of the Structure for Inspection & Recordkeeping:
Investigators should always record the appropriate subdivisions of the structure for analysis, recordkeeping, and future tests. Every testing location should be clearly identified.

Next Process:
All final reports describing the test and visual representation of results are to be given to the owner of the structure or file manager. All key features noted from the investigation should be clearly identified and labeled with respect to the structures start and/or end locations.

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ULTRASONIC TOMOGRAPHY			
Necessary Information for Data Collection			
#	**Description**	**Units/format**	**Values/Accuracy**
	GENERAL		
1	State, City, Location		
2	Structure Name		
3	Personnel Performing Inspection		
4	Date of inspection		
5	Start Time		
6	End Time		
7	Transverse Origin Location (x,y)		
8	Longitudinal Origin Location		
9	Transverse Sampling Spacing		
10	Longitudinal Sampling Spacing		
11	Temperature		
12	Device		
13	Manufacturer		
14	Data Acquisition System		
15	System Model		
16	System Serial Number		
17	Sensor Name		
18	Sensor Model		
19	Sensor Serial Number		
20	Pulse length		
21	Center Frequency		
22	Bandwidth		
23	Pulse Delay		
24	Wave Speed		
25	Analog Gain		
26	Color Gain		
27	Period		
28	Time Corrected Gain		
29	Measured Wave Speed		
30	Manual Wave Speed		
31	Horizontal Scanning Step		
32	Vertical Scanning Step		
33	Pulse Delay		
34	Wave Speed		
35	Analog Gain		
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ULTRASONIC TOMOGRAPHY			
	RAW DATA		
37	Time Stamp		
38	Data Acquisition System		
39	Antenna Model		
40	Gain		
41	Range		
42	Word Size		
43	Pulse repetition rate		
44	Samples/scan		
45	Scans/second		
46	Spatial Mode		
47	Distance Units		
48	Scans/Unit		
49	Vertical Filters		
50	Vertical Filter Values		
51	Horizontal Filters		
52	Horizontal Filter Values		
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ULTRASONIC TOMOGRAPHY			
	CONDITIONED DATA		
75	Date File		
76	ASCII File		
77	Scan #		
78	Longitudinal Location		
79	Transverse Location		
80	Target		
81	Depth		
82	Amplitude		
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Appendix A.5 – Sounding Testing Protocol

TP008A

SOUNDING

Introduction

Scope:

For the inspection of external PT ducts, a sounding inspection is generally performed to identify the existence of voids in ducts. In the regular inspection of PT bridges, the sounding inspection is executed by tapping an impactor or coin and inspectors document tendons for further inspection using a borescope when tendons have "irregular sounding" by tapping (Corven 2001; Trejo et al. 2009). Although the sounding inspection might contain errors, it is easy to execute in the field and is a relatively rapid method for detecting voids in ducts. Also, this inspection is particularly effective in the field because it can be applied without a power supply.

Terminology:

- *Impactor*. Any object with a blunt edge used for tapping duct walls.

Significance and Use:

The effectiveness of the sounding method was assessed in an external tendon mock-up specimen using transparent acrylic ducts (Im et al. 2010; Im and Hurlebaus 2012). After blindly applying the sounding method, it was then compared with the visual inspection through the transparent ducts (Figure 1). The sounding inspection method was difficult to identify a tiny void and required experience for the assessment, but it was capable of identifying relatively large voids, which may be a cause of corrosion. Thus, the sounding method can be a promising tool to identify voids in the field if a new instrument using microphone can be developed and assessed in future research.

Interpretation of sounding by ear may require a low level of experience but can be highly subjective

.

Capabilities and Limitations:

- *Duct location.* Acceptable for external ducts only.
- *Duct type.* Acceptable for non-metal ducts only.
- *Effect of concrete cover.* Not applicable for internal ducts.
- *Effect of layered ducts.* Not applicable for internal ducts.
- *Effect of reinforcement congestion.* Not applicable for internal ducts.
- *Accessibility requirements.* Sounding only requires physical accessibility to allow manual tapping on the pipes.

Referenced Documents:

1. Corven, J. 2001. "Mid Bay Bridge Post-Tensioning Evaluation." Final Report, Florida Department of Transportation

2. Im, S. B., S. Hurlebaus and D. Trejo. 2010. "Inspection of Voids in External Post-tensioned Tendons." Transportation Research Record: Journal of the Transportation Research Board Vol. 2172, No., pp. 115-122.

3. Im, S. B. and S. Hurlebaus. 2012. "Non-Destructive Testing Methods to Identify Voids in External Post-Tensioned Tendons." KSCE Journal of Civil Engineering Vol. 16, No. 3, pp. 388-397.

4. Trejo, D., S. B. Im, R. G. Pillai, M. B. D. Hueste, P. Gardoni, S. Hurlebaus and M. Gamble. 2009d. "Effect of Voids in Grouted Post-Tensioned Concrete Bridge Construction: Inspection and Repair Manual for External Tendons in Segmental, Post-Tensioned Bridges", Texas Transportation Institute, Texas A&M University System.

Procedure

Data Collected:

- Void image mapping (Figure 1)
- Audio files (if used)

Apparatus:

- Impactor
- Image maps
- Recorder (if used)

Process Description/Data Collection Principle:

A marking system or other form of data collection management is used to perform testing and relate findings to the physical structure. Use of void image mapping is strongly encouraged.

SOUNDING

Photo:

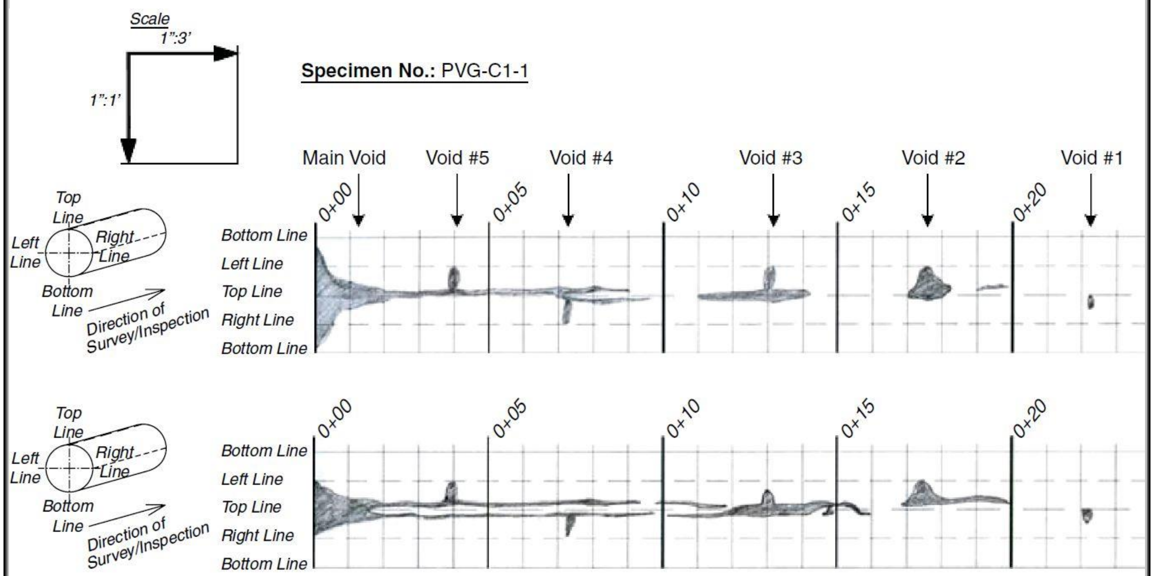

Figure A.5-1. Void image of specimen (from Im and Hurlebaus 2012).

Data Collection Procedure:
All manufacturer's manuals (for automated sounding methods) and procedures should be strictly adhered to in addition to the following data collection procedures.

PREPARATION:

Step 1 – Collect bridge structure files.

Step 2 – Gather all required apparatuses named above.

Step 3 – Ensure proper working order of all system components.

Step 4 – Determine appropriate parameters for the type of inspection required (testing paths, etc).

Step 5 – Enter span under inspection and ensure appropriate marking system is in place

Step 6 – At a minimum, record all data specified in the section "Necessary Information for Data Collection". Keep this data updated for each span/section under inspection, noting any significant changes (particularly in temperature or humidity) during testing.

SOUNDING

Step 7 – Perform preliminary walk-through of testing site, noting any damage indicators

Step 8 – Once a specific site is chosen for testing, ensure all surfaces are clean and free of debris.

Step 9 – Use appropriate marking system for reference.

DATA COLLECTION:

Step 1 – Use the appropriate testing lines or paths and sound the selected area, making sure to note start and end time and location and other relevant data.

Step 2 – Continue to sound selected lines or paths until all areas are sounded, being diligent to record the anomalous areas according to testing location. After each area is tested, repeat Steps 4-11 under "Preparation" as necessary before additional continuing data collection.

DATA REPORTING:

Step 1 – Follow guidelines under "Reporting" section below in creating an inspection report.

Step 2 – Submit completed inspection report to inspection program manager.

Criteria for Data Validation:
Ground truth data is typically collected by using the marking system in conjunction with the void image maps. All ground truth data should be properly recorded (precise location, photos, ambient temperature, humidity, etc.).

Note: For the NCHRP 14-28 mock-up specimens located at Texas A&M Transportation Institute, no ground truth data collection is allowed!

Calculation or Interpretation of Results:
All interpretation of results should be performed by experienced and educated personnel. System software often makes data interpretation easier, but care should be taken that interpretation is overseen by properly qualified personnel.

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SOUNDING

Reporting

Subdivision of the Structure for Inspection & Recordkeeping:
Investigators should always record the appropriate subdivisions of the structure for analysis, recordkeeping, and future tests. Every testing location should be clearly identified.

Next Process:
All final reports describing the test and visual representation of results are to be given to the owner of the structure or file manager. All key features noted from the investigation should be clearly identified and labeled with respect to the structures start and/or end locations.

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SOUNDING			
Necessary Information for Data Collection			
#	**Description**	**Units/format**	**Values/Accuracy**
	GENERAL		
1	State, City, Location		
2	Structure Name		
3	Personnel Performing Inspection		
4	Date of inspection		
5	Start Time		
6	End Time		
7	Transverse Origin Location (x,y)		
8	Longitudinal Origin Location		
9	Transverse Sampling Spacing		
10	Longitudinal Sampling Spacing		
11	Temperature		

Appendix A.6 – Borescope Testing Protocol

TP009A

BORESCOPING

Introduction

Scope:

Borescope inspection of PT ducts can be used to identify and provide visual information with respect to the condition of the grout and the prestressing steel within the duct. This inspection is performed by inserting the flexible borescope into the duct being inspected, either by opening a grout inlet/outlet or drilling a small hole. Borescope inspections are relatively slow but they provide the user with the ability to visually see the conditions that exist within the duct (Corven 2001; Trejo et al. 2009). Although this is a useful method in determining the extent of voids and corrosion, a void must be present in order for the camera to be able to physically enter the duct.

Terminology:

-

Significance and Use:

The significance of the borescope inspection method is that it has the ability to provide very useful qualitative data on voids, corrosion, or other defects within ducts. Data for this method is pictures and videos, no quantitative data is provided. This method does not have the ability to locate detrimental conditions so it is typically used after another method of inspection, typically visual or sounding, locates a void. Borescoping also requires access for the camera lens, making it a very useful in anchorage regions where the grout inlet/outlets can be opened for inspection and closed afterwards.

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Capabilities and Limitations:

- *Duct location.* Acceptable for internal and external ducts.
- *Duct type.* Acceptable for all duct types.
- *Effect of concrete cover.* Data from inside a duct is unaffected, provided camera access is available.
- *Effect of layered ducts.* No effect.
- *Effect of reinforcement congestion.* No effect.
- *Accessibility requirements.* Small hole or opening required for the flexible camera to be inserted into the duct.

Referenced Documents:

1. Corven, J. 2001. "Mid Bay Bridge Post-Tensioning Evaluation." Final Report, Florida Department of Transportation

2. Trejo, D., S. B. Im, R. G. Pillai, M. B. D. Hueste, P. Gardoni, S. Hurlebaus and M. Gamble. 2009d. "Effect of Voids in Grouted Post-Tensioned Concrete Bridge Construction: Inspection and Repair Manual for External Tendons in Segmental,

BORESCOPING

Post-Tensioned Bridges", Texas Transportation Institute, Texas A&M University System.

Procedure

Data Collected:

- Photographs
- Video files (if used)

Apparatus:

- Image maps
- Recorder (if used)

Process Description/Data Collection Principle:

Using a labeling system on the camera cord is very useful to determine the length of cord that has been inserted into the duct, providing the user with the approximate location of the camera at all times.

TP009A

BORESCOPING

Photo:

Figure A.6-1. Boroscope image of void (from Corven 2001).

Data Collection Procedure:
All manufacturer's manuals and procedures should be strictly adhered to in addition to the following data collection procedures.

PREPARATION:

Step 1 – Collect bridge structure files.

Step 2 – Gather all required apparatuses named above.

Step 3 – Ensure proper working order of all system components.

Step 4 – Determine appropriate parameters for the type of inspection required (testing paths, etc).

Step 5 – Enter span under inspection and ensure appropriate marking system is in place

Step 6 – At a minimum, record all data specified in the section "Necessary Information for Data Collection". Keep this data updated for each span/section under inspection, noting any significant changes (particularly in temperature or humidity) during testing.

BORESCOPING

Step 7 – Perform preliminary walk-through of testing site, noting any damage indicators

Step 8 – Once a specific site is chosen for testing, ensure all surfaces are clean and free of debris.

Step 9 – Use appropriate marking system for reference.

Step 10 – If necessary, drill access hole(s) where voided regions have been previously determined.

DATA COLLECTION:

Step 1 – Use the appropriate testing lines or paths, insert the borescope camera while keeping careful track of the length of cord inserted into the duct to ensure the location of data is documented.

Step 2 – Continue to borescope selected entry points until all areas are inspected, being diligent to record the anomalous areas according to testing location. After each area is tested, repeat Steps 4-10 under "Preparation" as necessary before additional continuing data collection.

DATA REPORTING:

Step 1 – Follow guidelines under "Reporting" section below in creating an inspection report.

Step 2 – Submit completed inspection report to inspection program manager.

Criteria for Data Validation:
Ground truth data is typically collected by using the marking system in conjunction with the void image maps. All ground truth data should be properly recorded (precise location, photos, ambient temperature, humidity, etc.).

Note: For the NCHRP 14-28 mock-up specimens located at Texas A&M Transportation Institute, no ground truth data collection is allowed!

BORESCOPING

Calculation or Interpretation of Results:
All interpretation of results should be performed by experienced and educated personnel. System software often makes data interpretation easier, but care should be taken that interpretation is overseen by properly qualified personnel.

Reporting

Subdivision of the Structure for Inspection & Recordkeeping:
Investigators should always record the appropriate subdivisions of the structure for analysis, recordkeeping, and future tests. Every testing location should be clearly identified.

Next Process:
All final reports describing the test and visual representation of results are to be given to the owner of the structure or file manager. All key features noted from the investigation should be clearly identified and labeled with respect to the structures start and/or end locations.

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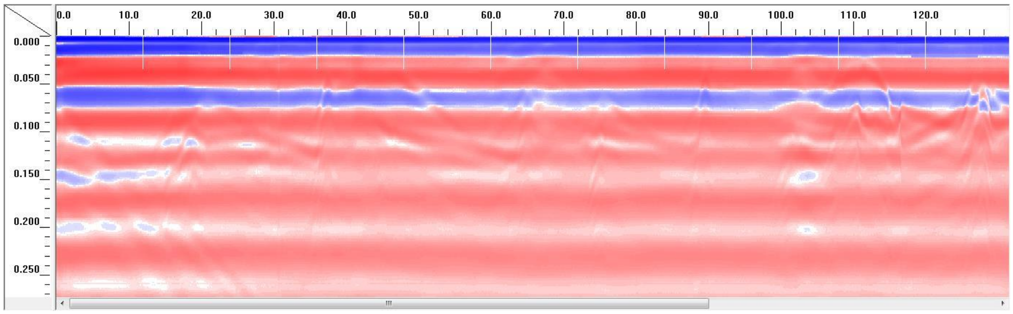
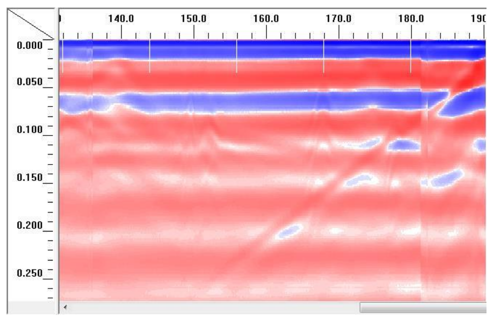
BORESCOPING			
Necessary Information for Data Collection			
#	**Description**	**Units/format**	**Values/Accuracy**
	GENERAL		
1	State, City, Location		
2	Structure Name		
3	Personnel Performing Inspection		
4	Date of inspection		
5	Start Time		
6	End Time		
7	Transverse Origin Location (x,y)		
8	Longitudinal Origin Location		
9	Transverse Sampling Spacing		
10	Longitudinal Sampling Spacing		
11	Temperature		

APPENDIX B – NDE TESTING RESULTS

Appendix B.1 – Ground Penetrating Radar Results

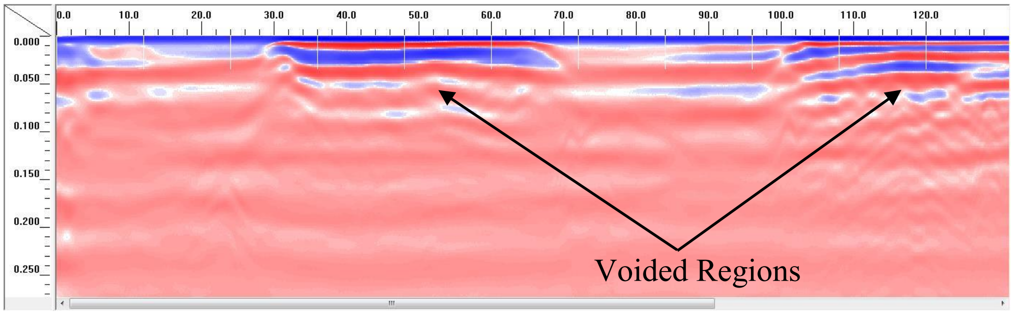


(a)

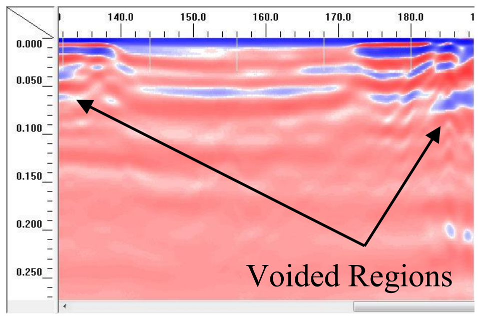


(b)

Figure B.1-1: Specimen 1 GPR Results (a) 1 – 130 in. (b) 130 – 190 in.

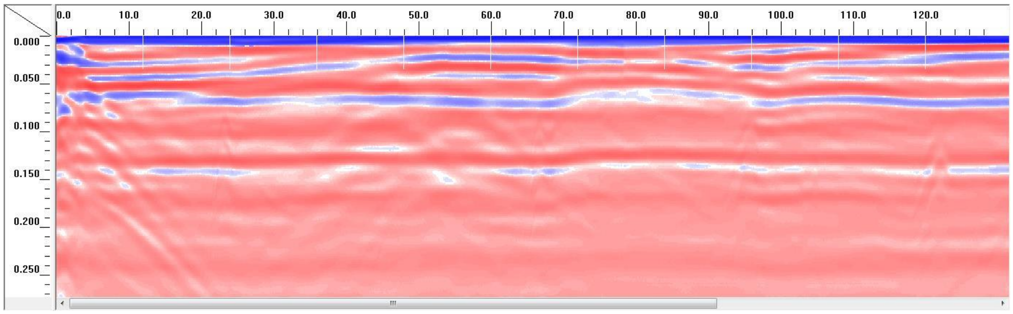


(a)

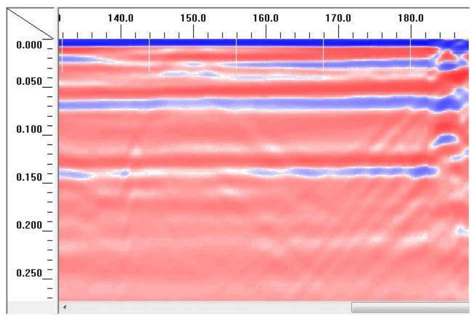


(b)

Figure B.1-2: Specimen 2 GPR Results (Test 2) (a) 1 – 130 in. (b) 130 – 190 in.

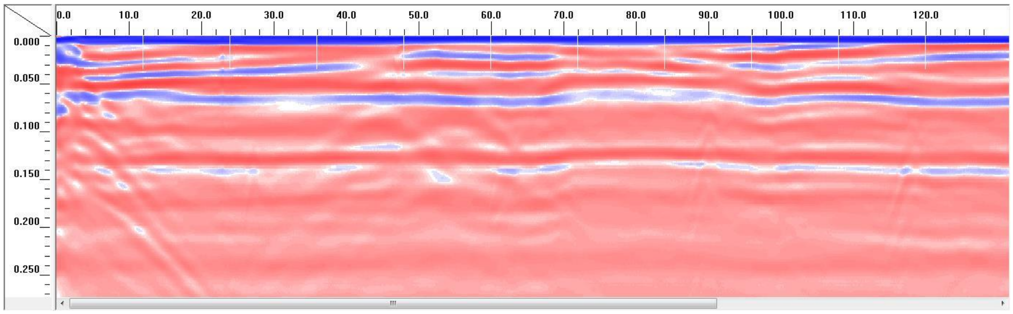


(a)

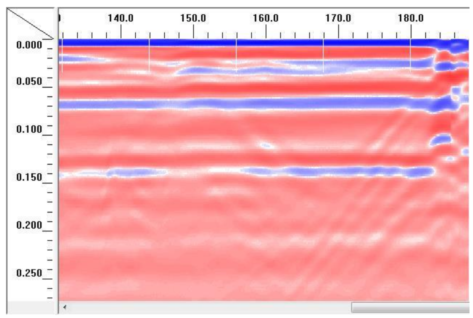


(b)

Figure B.1-3: Specimen 3 GPR Results (Test 1) (a) 1 – 130 in. (b) 130 – 190 in.

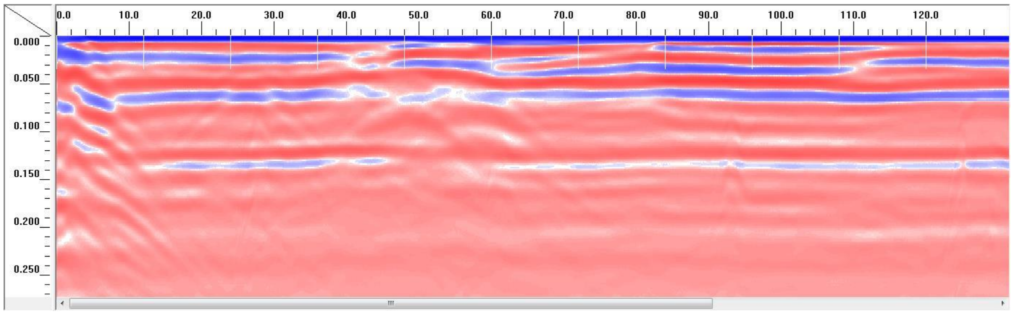


(a)

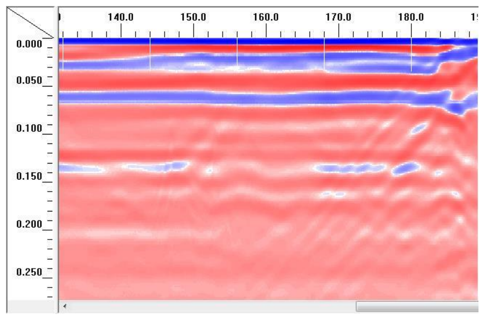


(b)

Figure B.1-4: Specimen 3 GPR Results (Test 2) (a) 1 – 130 in. (b) 130 – 190 in.

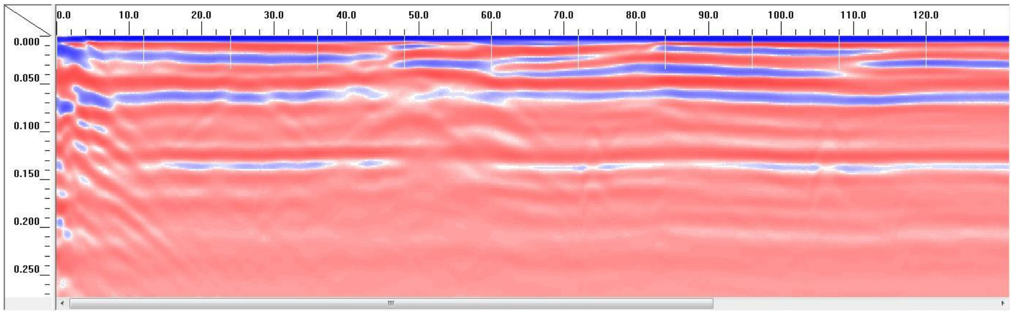


(a)

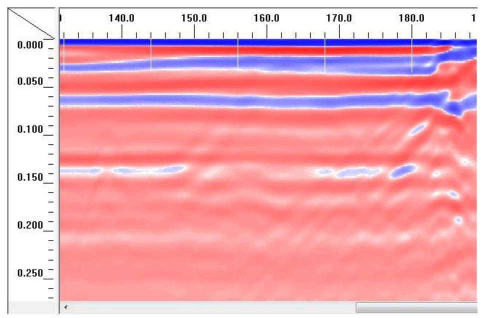


(b)

Figure B.1-5: Specimen 4 GPR Results (Test 1) (a) 1 – 130 in. (b) 130 – 190 in.



(a)



(b)

Figure B.1-6: Specimen 4 GPR Results (Test 2) (a) 1 – 130 in. (b) 130 – 190 in.

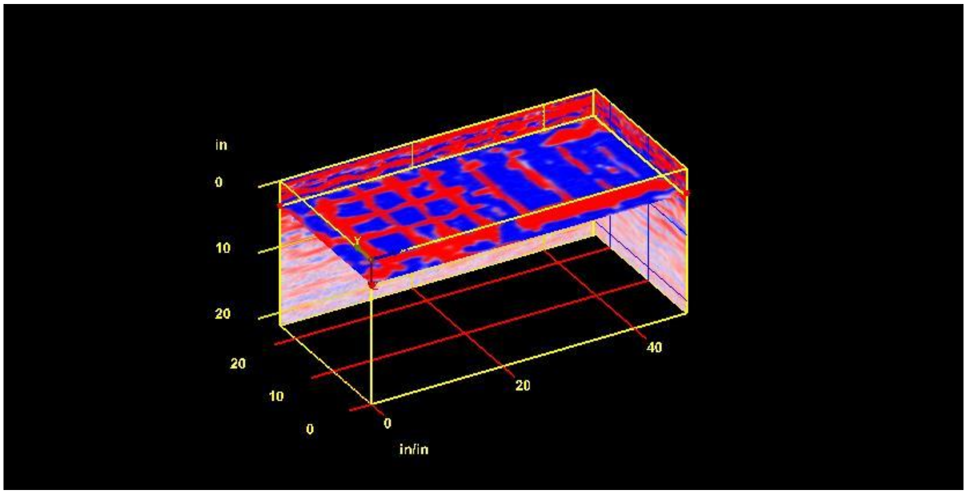


Figure B.1-7: GPR Map Showing Reinforcing Grid For Deck Anchorage

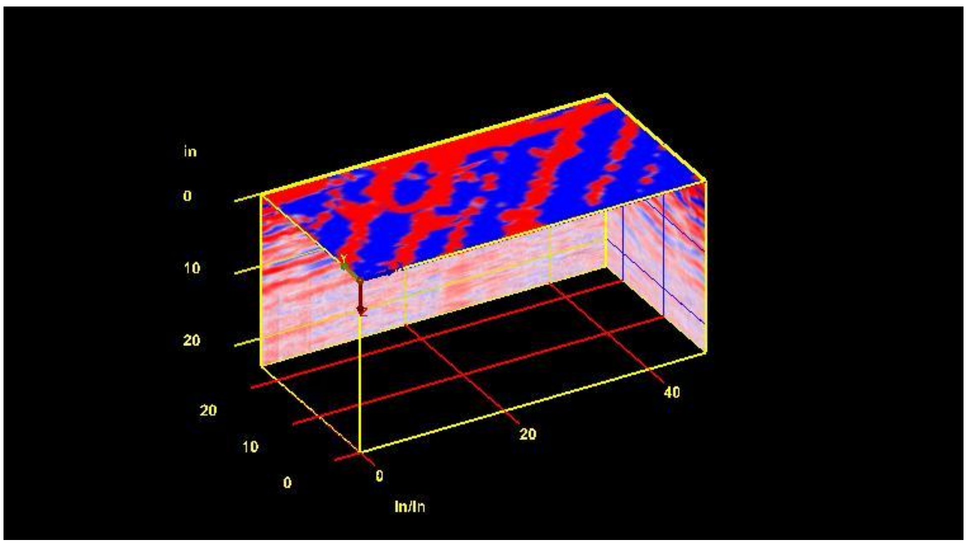


Figure B.1-8: GPR Map Showing Reinforcing Grid For Deck Anchorage

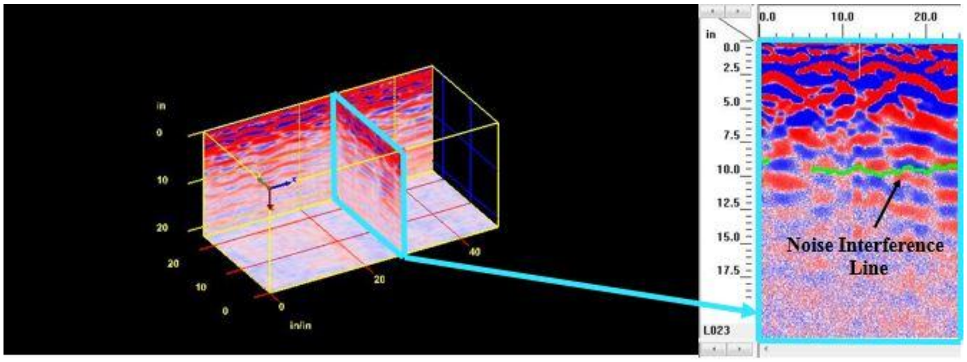


Figure B.1-9: GPR Map and D-Scan Showing Noise Interference Level For Deck Anchorage

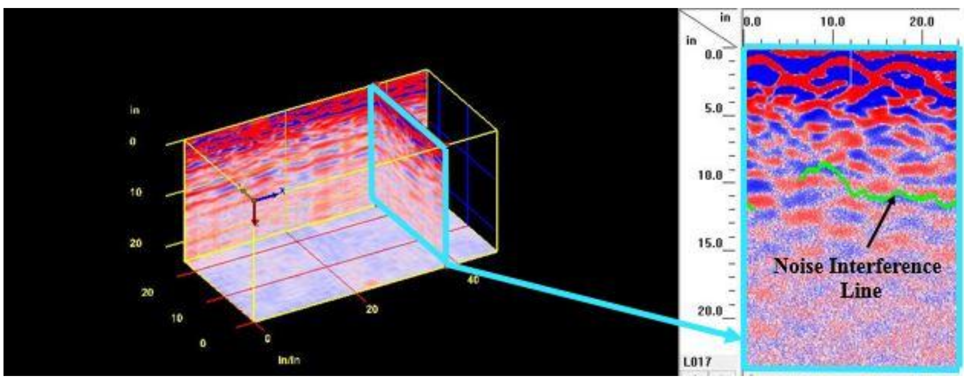


Figure B.1-10: GPR Map and D-Scan Showing Noise Interference Level For Pylon Anchorage

Appendix B.2 – Magnetic Flux Leakage Results

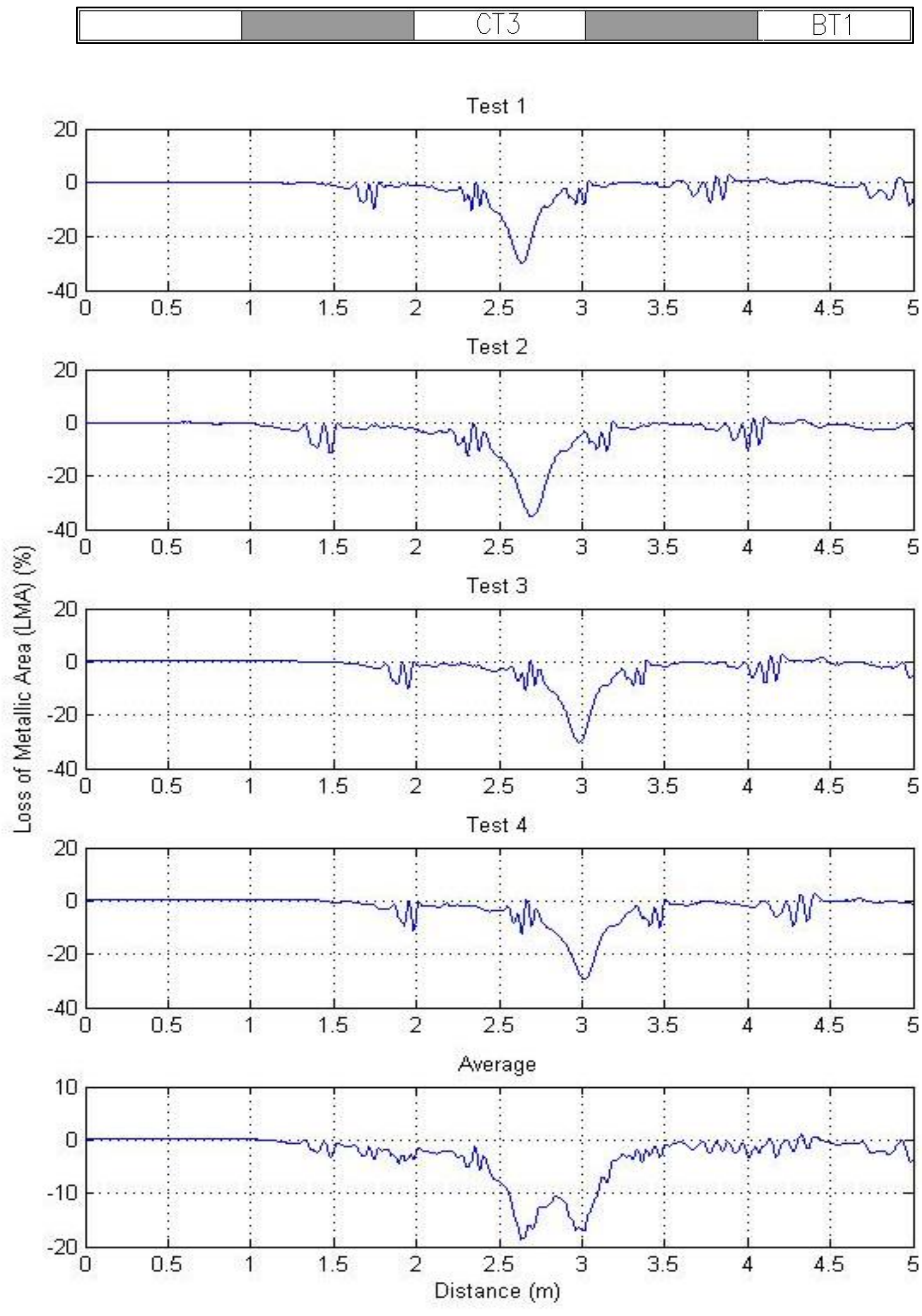


Figure B.2-1: Specimen 1 MFL Results

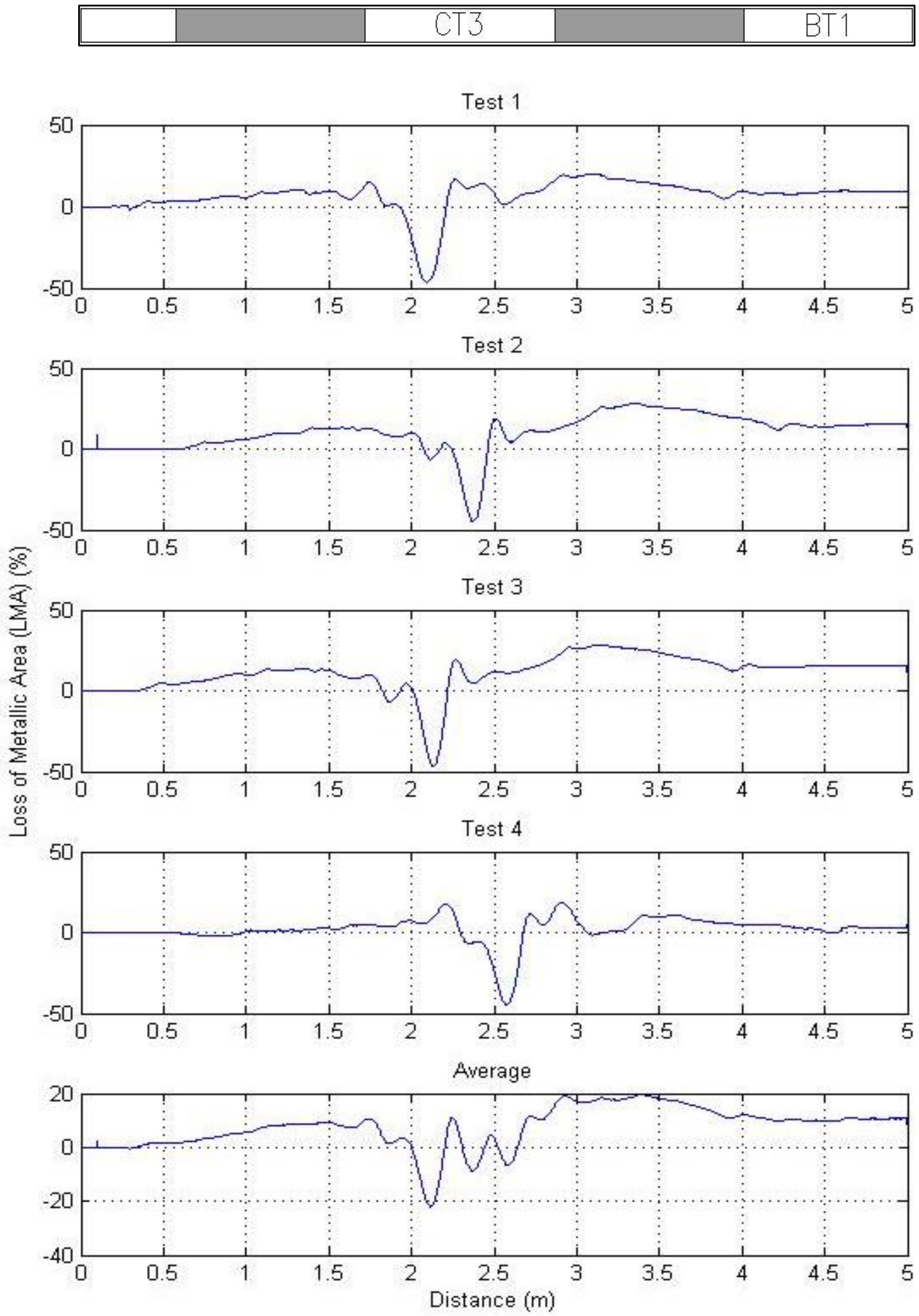


Figure B.2-2: Specimen 2 MFL Results

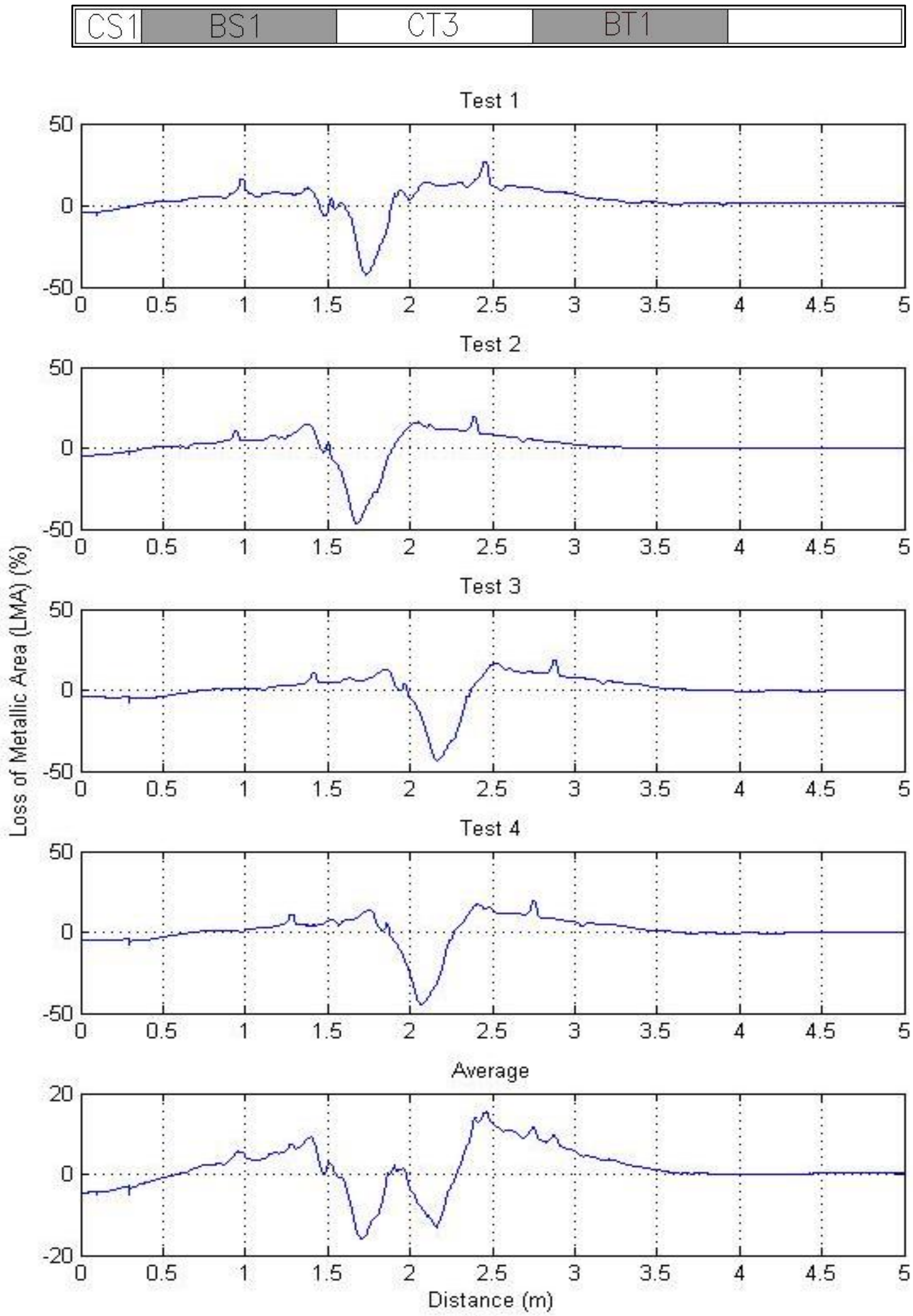


Figure B.2-3: Specimen 3 MFL Results

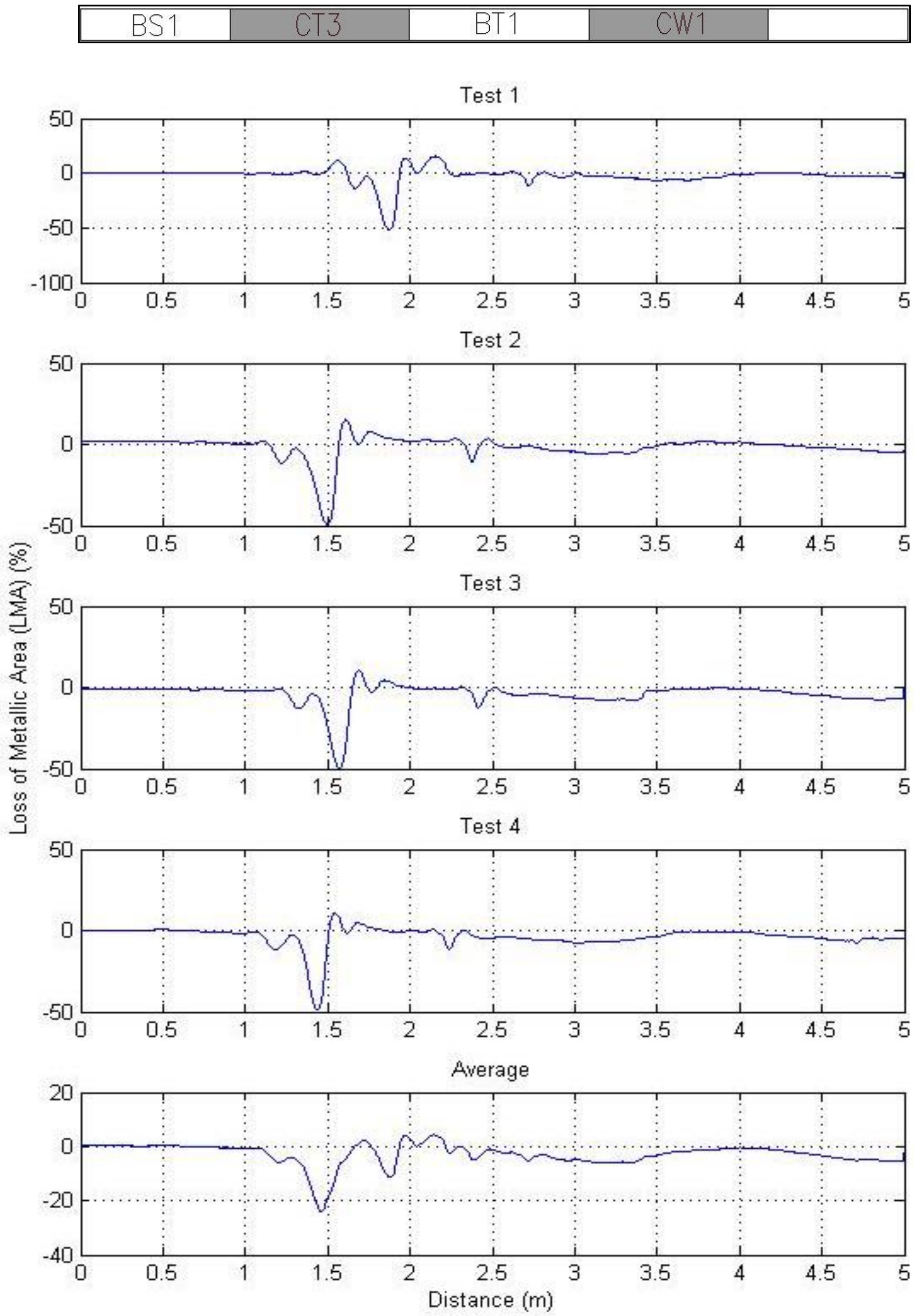
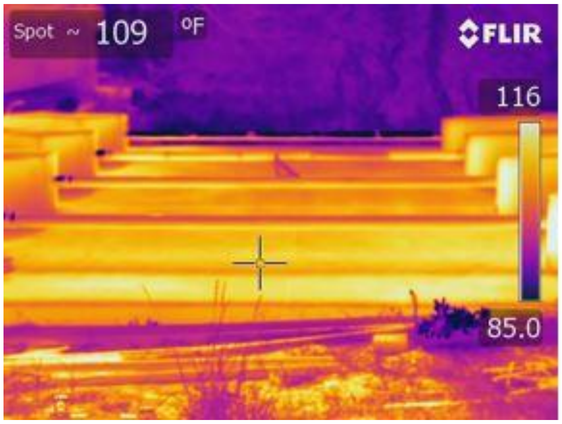
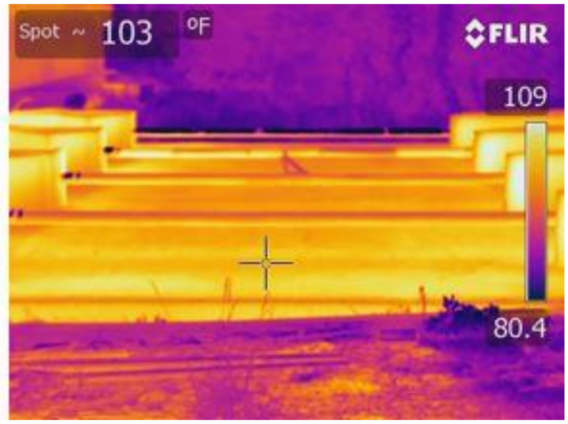


Figure B.2-4: Specimen 4 MFL Results

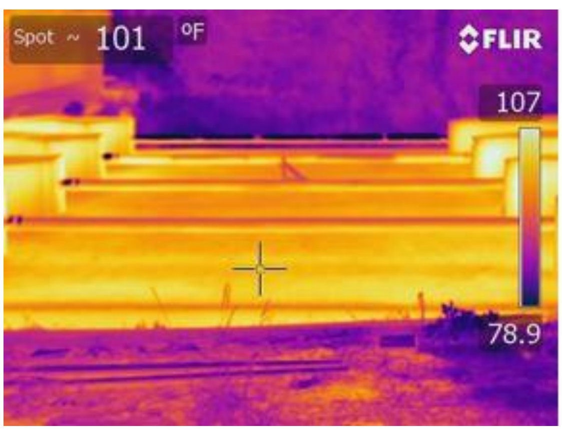
Appendix B.3 – Infrared Thermography Results



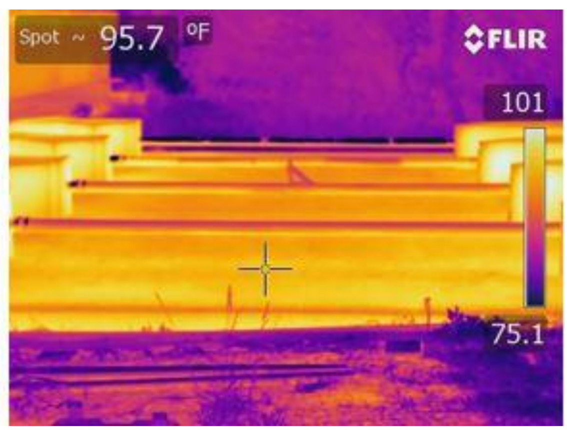
(a)



(b)

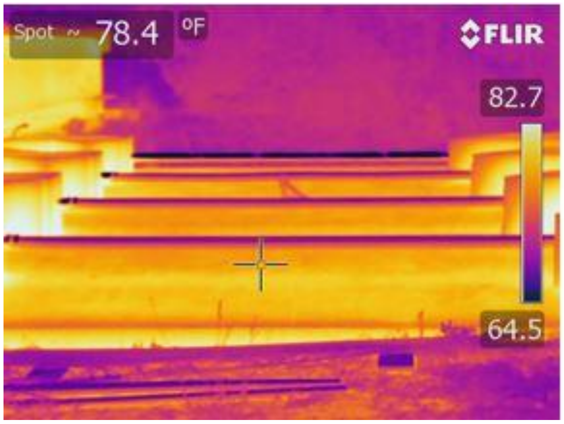


(c)

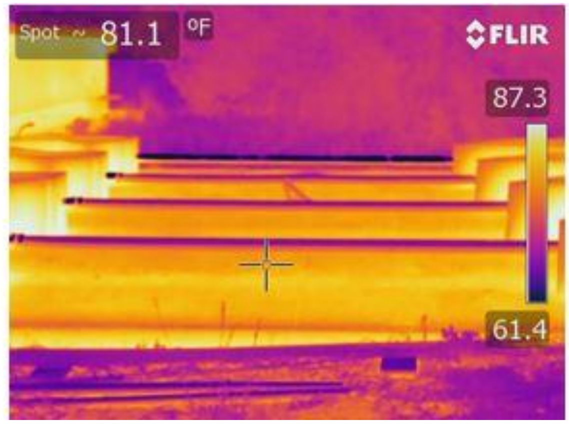


(d)

Figure B.3-1: Infrared Images of Mock-Up Specimens During Cooling Off Period

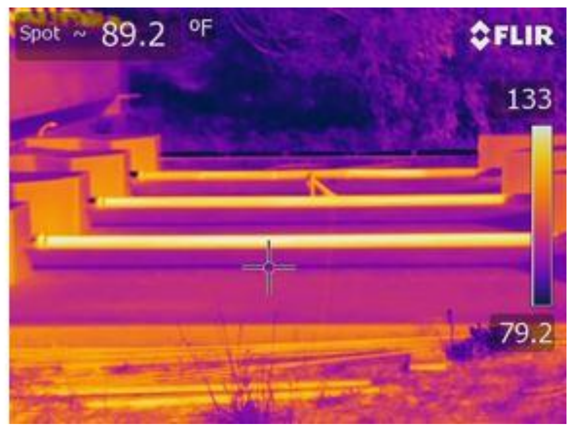


(a)



(b)

(c)



(d)

Figure B.3-2: Infrared Images of Mock-Up Specimens During Heating Up Period

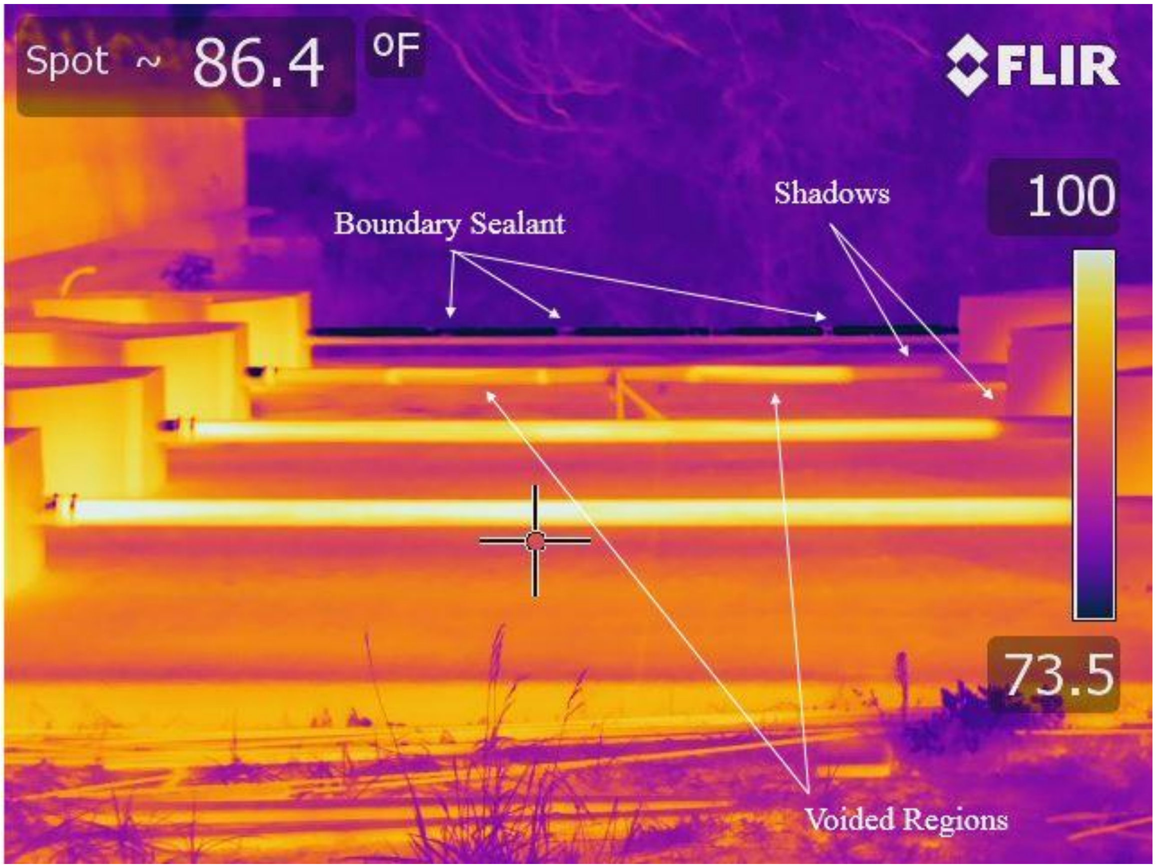
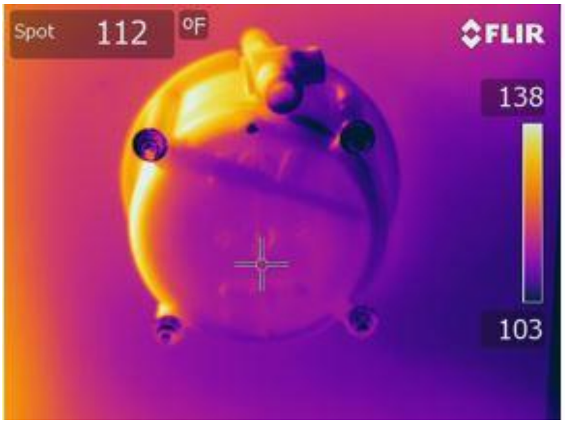
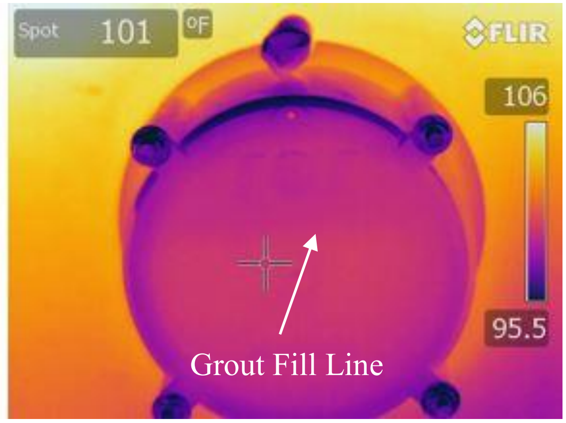


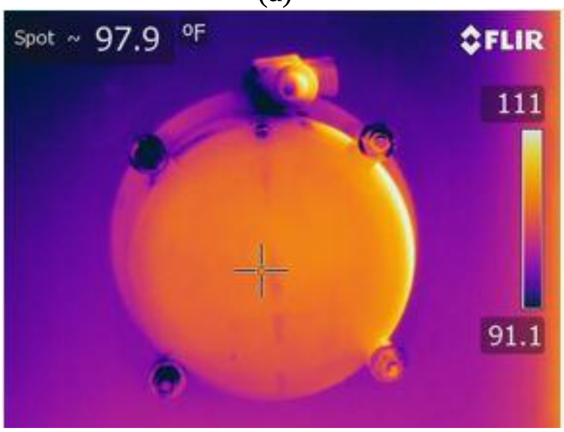
Figure B.3-3: Enlarged Infrared Images of Mock-Up Specimens During Heating Up Period



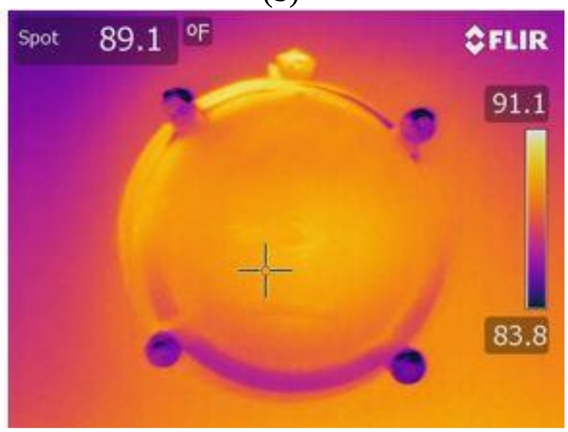
(a)



(b)



(b)



(d)

Figure B.3-4: Infrared Grout Cap Images of Specimen 1 (a) Gridline A During Cool Down (b) Gridline K During Cool Down (c) Gridline A During Heating Up (d) Gridline K During Heating Up

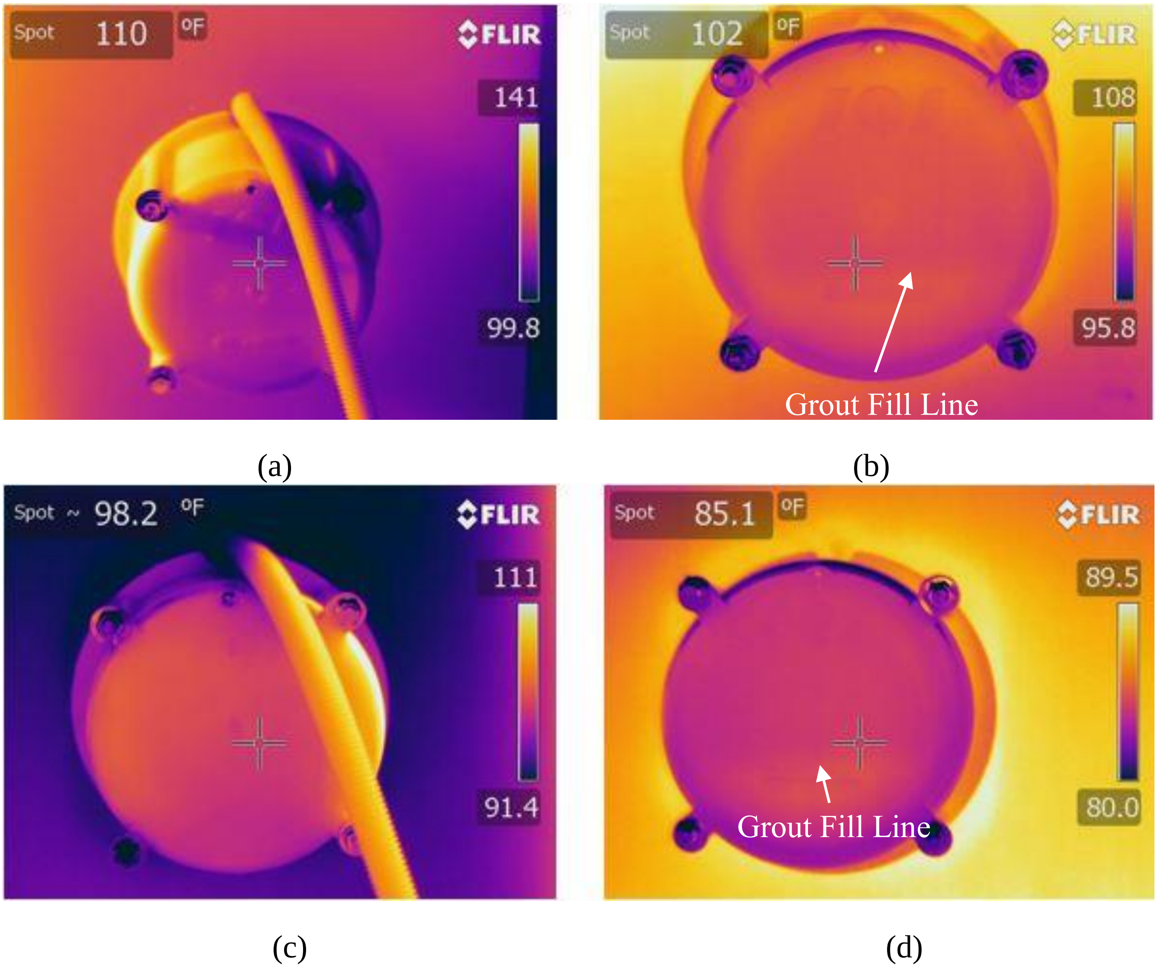
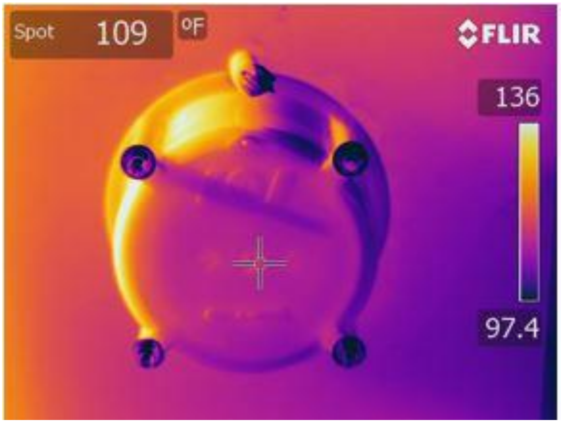
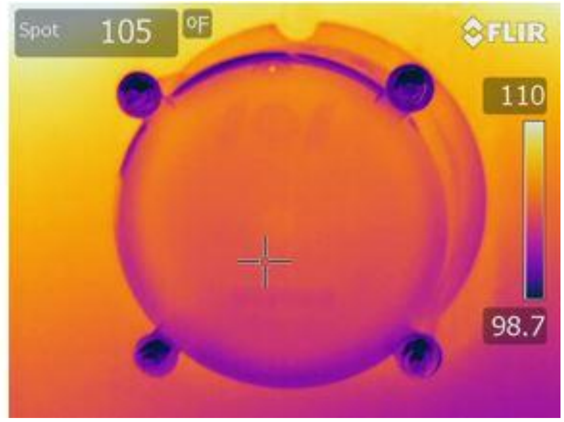


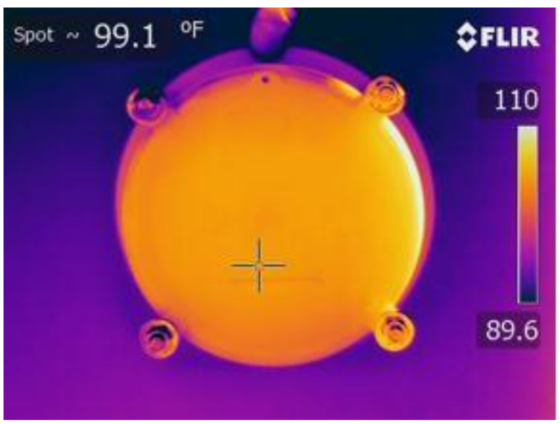
Figure B.3-5: Infrared Grout Cap Images of Specimen 2 (a) Gridline A During Cool Down (b) Gridline K During Cool Down (c) Gridline A During Heating Up (d) Gridline K During Heating Up



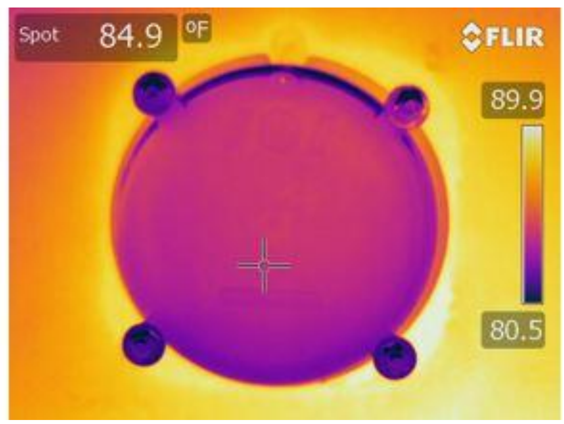
(a)



(b)

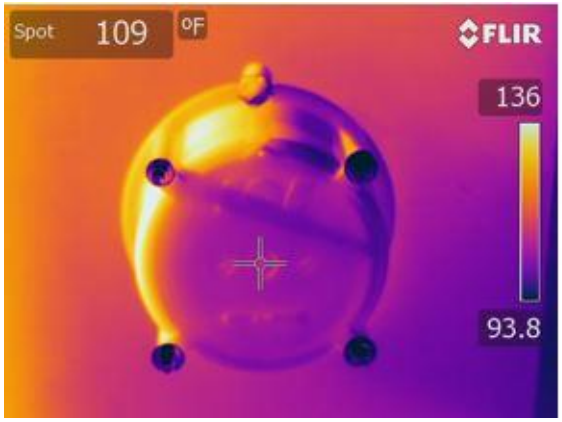


(c)

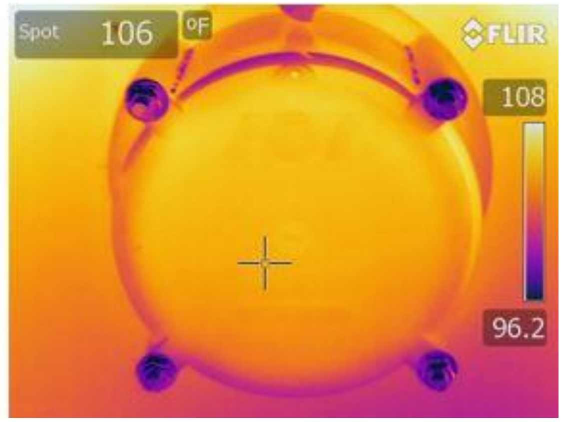


(d)

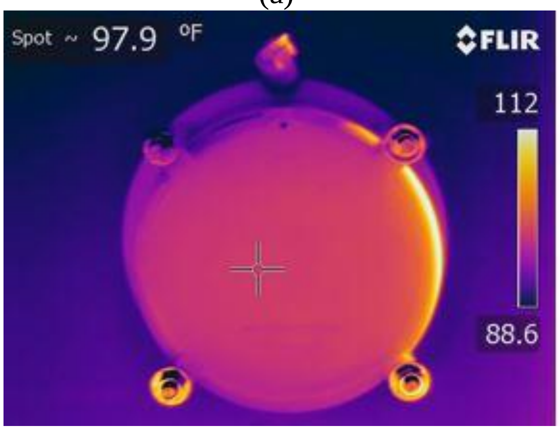
Figure B.3-6: Infrared Grout Cap Images of Specimen 3 (a) Gridline A During Cool Down (b) Gridline K During Cool Down (c) Gridline A During Heating Up (d) Gridline K During Heating Up



(a)



(b)



(c)

(d)

Figure B.3-7: Infrared Grout Cap Images of Specimen 4 (a) Gridline A During Cool Down (b) Gridline K During Cool Down (c) Gridline A During Heating Up (d) Gridline K During Heating Up

Appendix B.4 – Ultrasonic Tomography Results

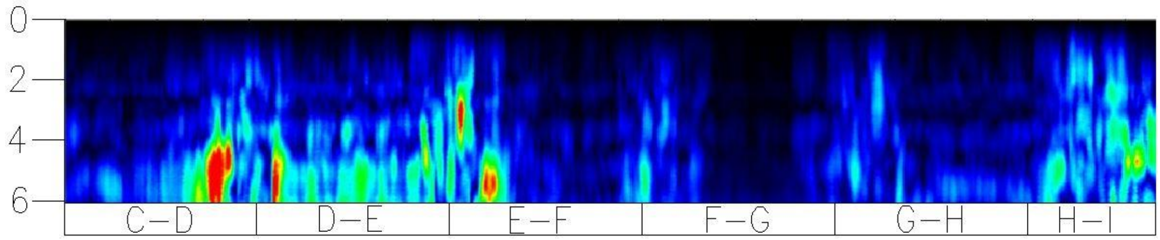


Figure B.4-1: B-scan Results of Specimen 1 (Test 1)

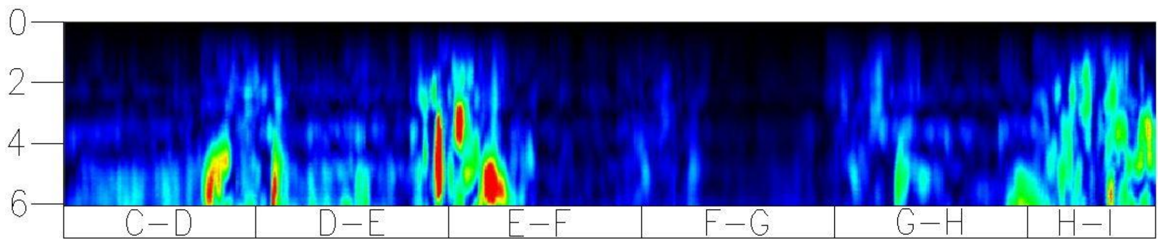


Figure B.4-2: B-scan Results of Specimen 1 (Test 2)

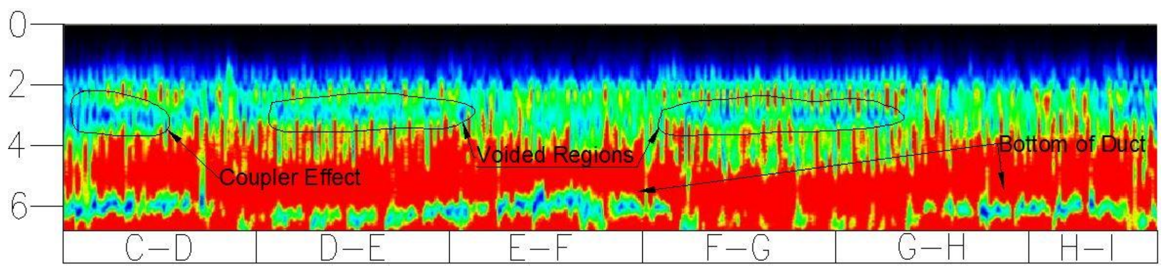


Figure B.4-3: B-scan Results of Specimen 2 (Test 2)

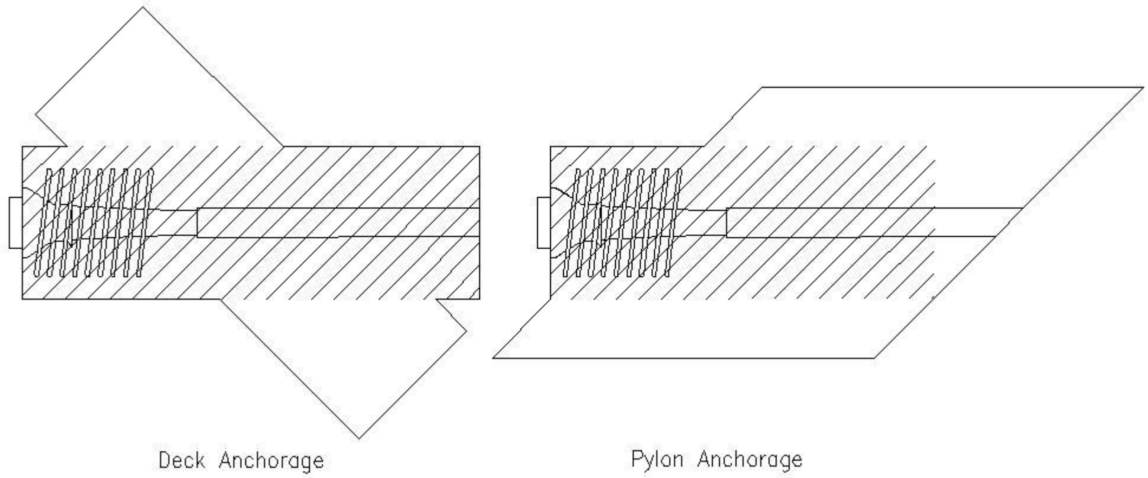
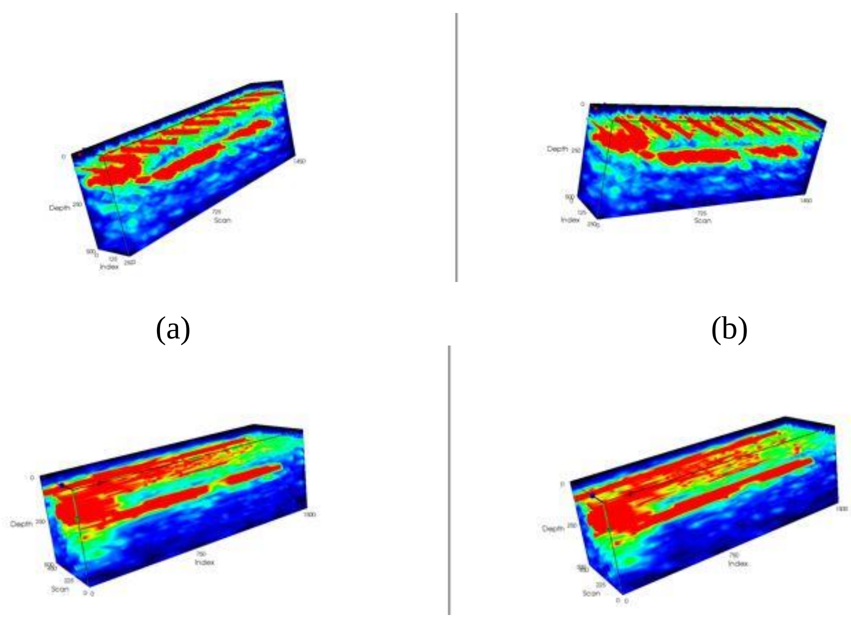


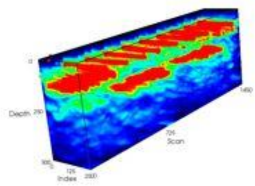
Figure B.4-4: UST Testing Areas for Top Scans



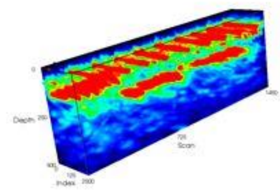
(a) (b)

(c) (d)

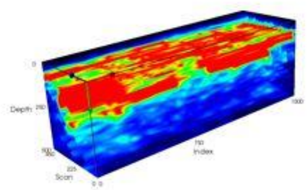
Figure B.4-5: UST 3-D Maps from Specimen 1 Deck Anchorage Top Scans (a) I (b) I (c) II (d) II



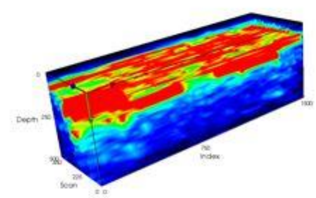
(a)



(b)

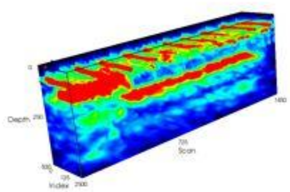


(c)

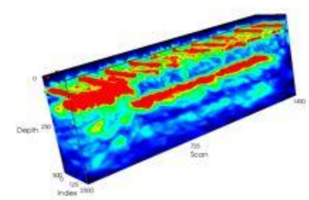


(d)

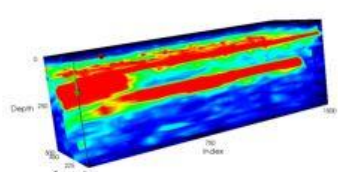
Figure B.4-6: UST 3-D Maps from Specimen 2 Deck Anchorage Top Scans (a) I (b) I (c) II (d) II



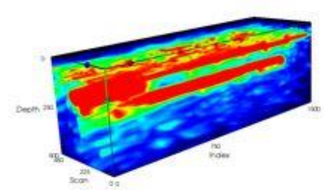
(a)



(b)

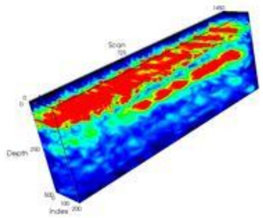


(c)

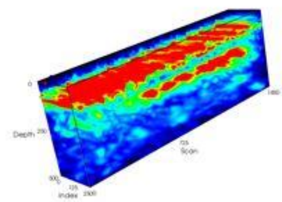


(d)

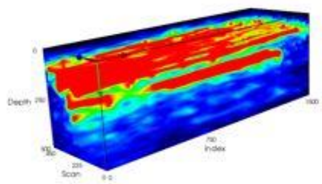
Figure B.4-7: UST 3-D Maps from Specimen 3 Deck Anchorage Top Scans (a) I (b) I (c) II (d) II



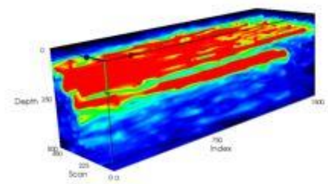
(a)



(b)

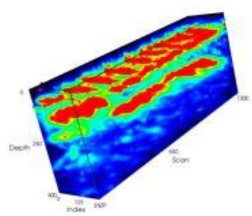


(c)

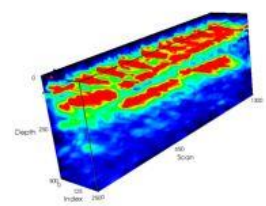


(d)

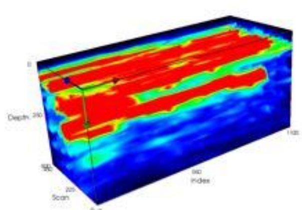
Figure B.4-8: UST 3-D Maps from Specimen 4 Deck Anchorage Top Scans (a) I (b) I (c) II (d) II



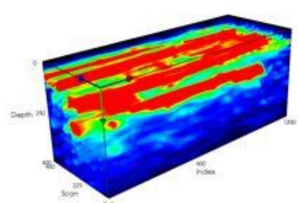
(a)



(b)

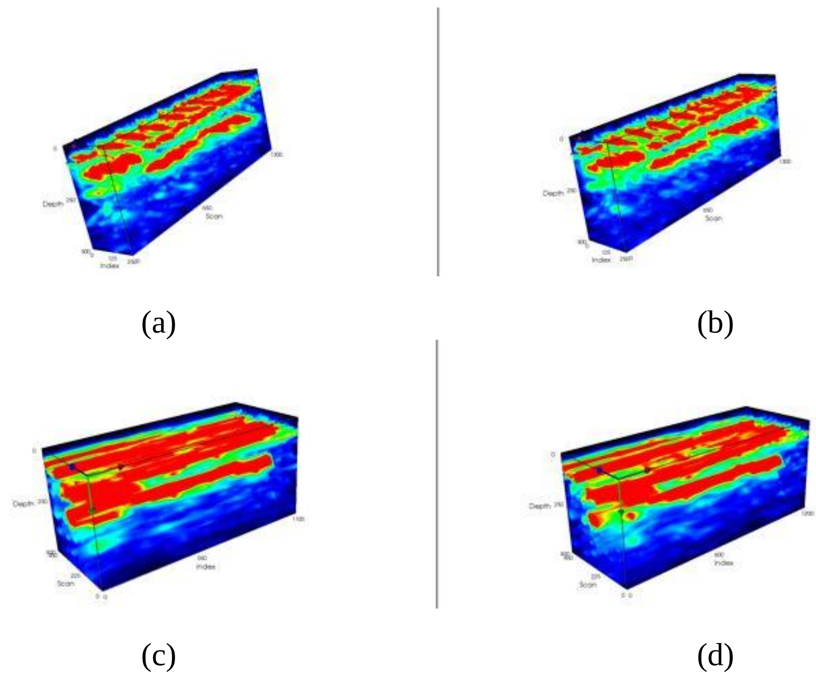


(c)



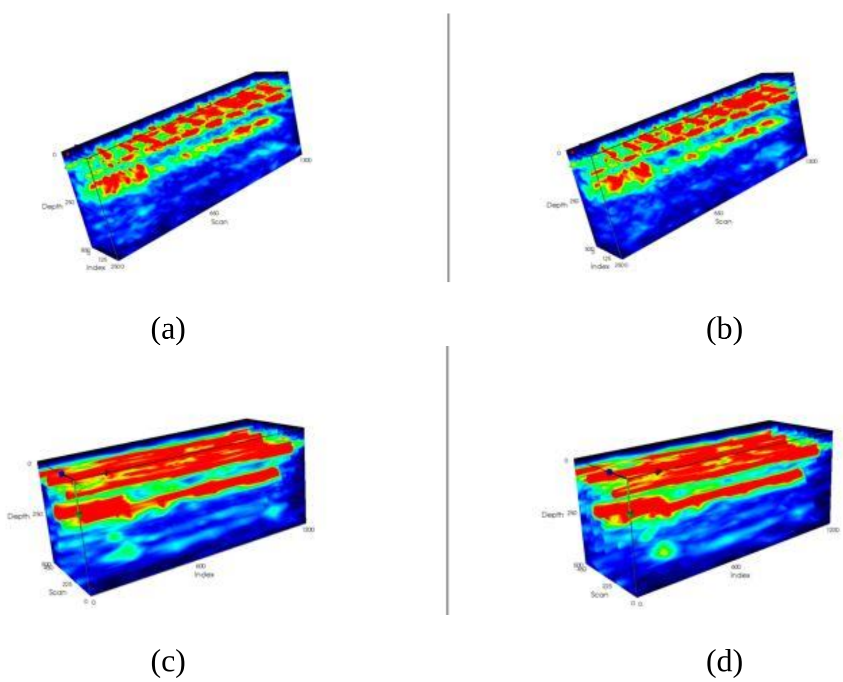
(d)

Figure B.4-9: UST 3-D Maps from Specimen 1 Pylon Anchorage Top Scans (a) I (b) I (c) II (d) II



(a) (b) (c) (d)

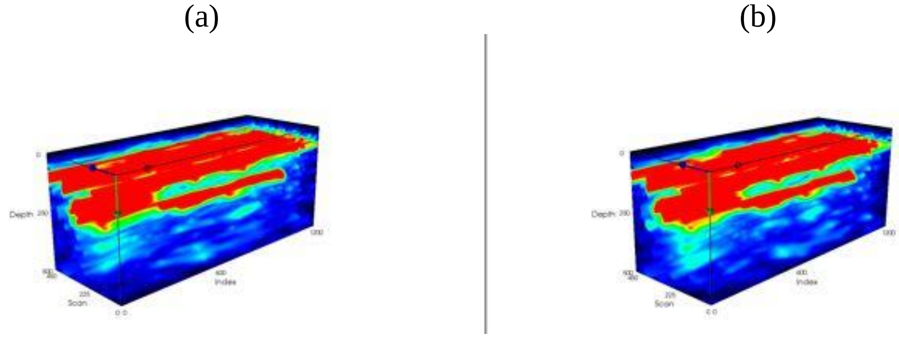
Figure B.4-10: UST 3-D Maps from Specimen 2 Pylon Anchorage Top Scans (a) I (b) I (c) II (d) II



(a) (b) (c) (d)

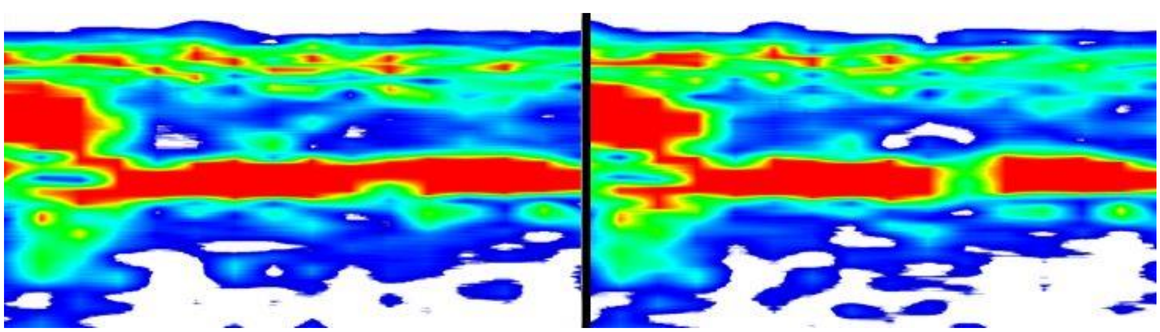
Figure B.4-11: UST 3-D Maps from Specimen 3 Pylon Anchorage Top Scans (a) I (b) I (c) II (d) II

(a) (b)



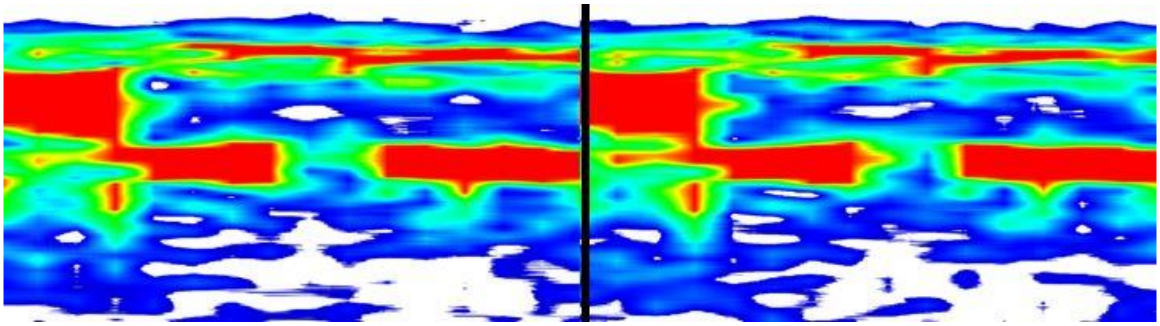
(c) (d)

Figure B.4-12: UST 3-D Maps from Specimen 4 Pylon Anchorage Top Scans (a) I (b) I (c) II (d) II



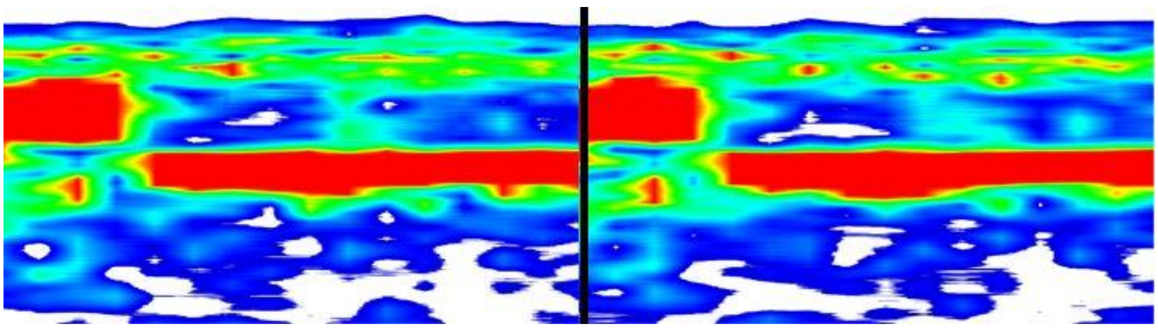
(a) (b)

Figure B.4-13: UST D-scans Through Duct from Specimen 1 Deck Anchorage Top Scans (a) II (b) II



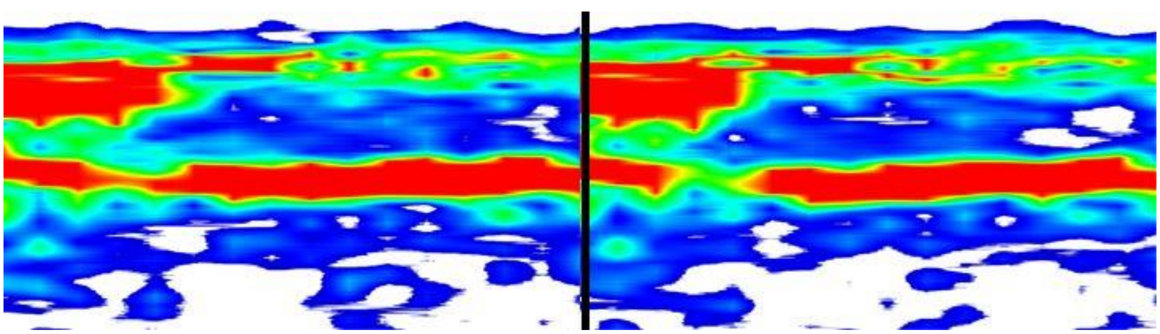
(a) (b)

Figure B.4-14: UST D-scans Through Duct from Specimen 2 Deck Anchorage Top Scans (a) II (b) II



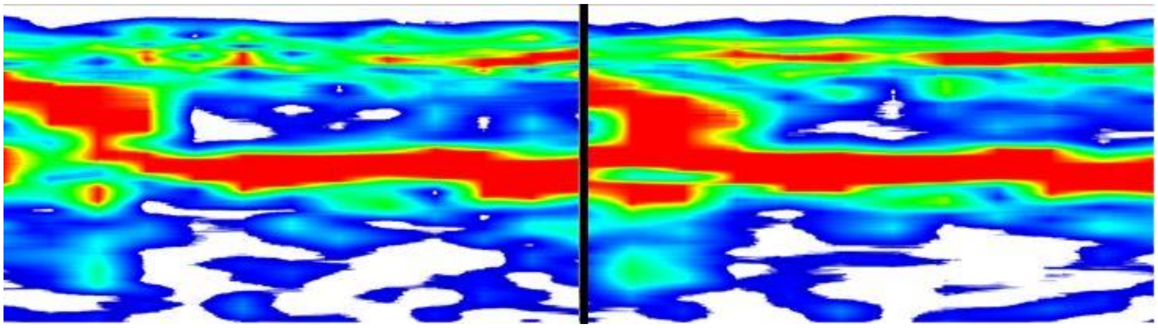
(a) (b)

Figure B.4-15: UST D-scans Through Duct from Specimen 3 Deck Anchorage Top Scans (a) II (b) II



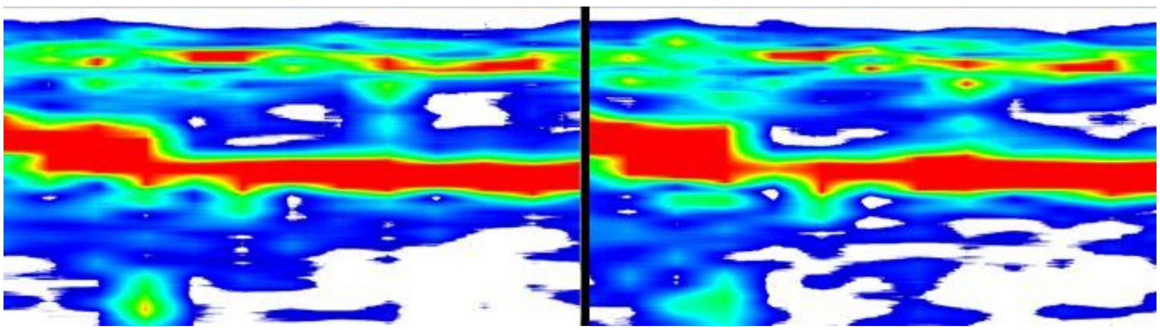
(a) (b)

Figure B.4-16: UST D-scans Through Duct from Specimen 4 Deck Anchorage Top Scans (a) II (b) II



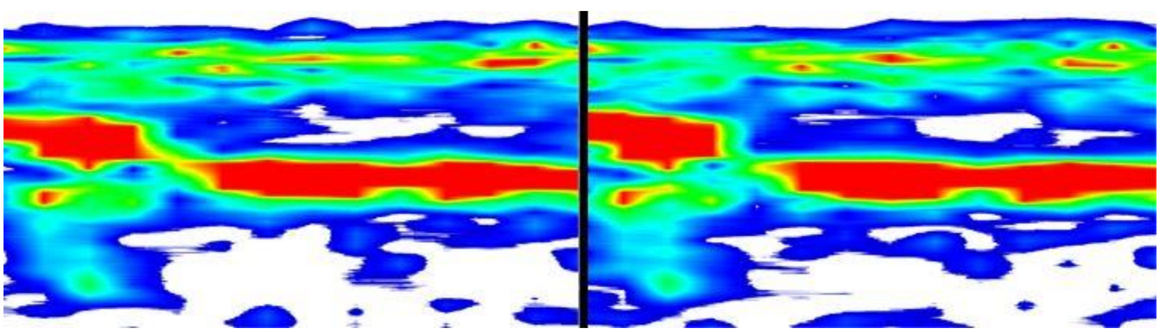
(a) (b)

Figure B.4-17: UST D-scans Through Duct from Specimen 1 Pylon Anchorage Top Scans (a) II (b) II



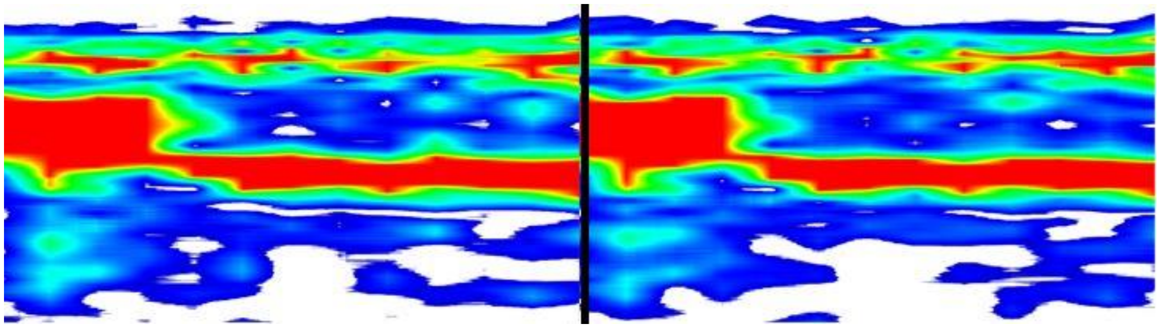
(a) (b)

Figure B.4-18: UST D-scans Through Duct from Specimen 2 Pylon Anchorage Top Scans (a) II (b) II



(a) (b)

Figure B.4-19: UST D-scans Through Duct from Specimen 3 Pylon Anchorage Top Scans (a) II (b) II



(a) (b)

Figure B.4-20: UST D-scans Through Duct from Specimen 4 Pylon Anchorage Top Scans (a) II (b) II

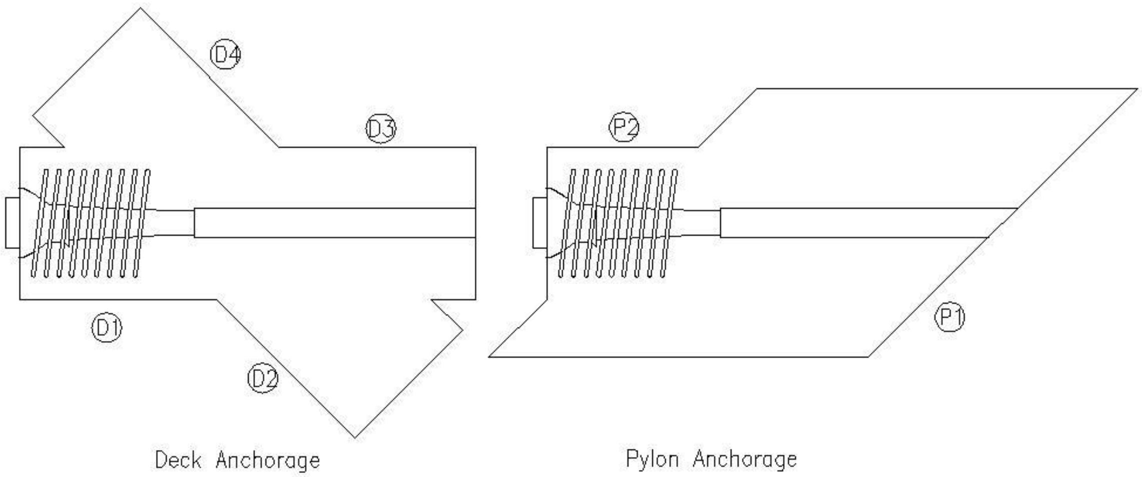
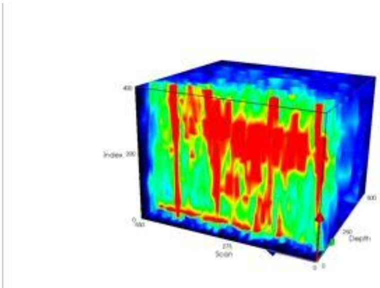
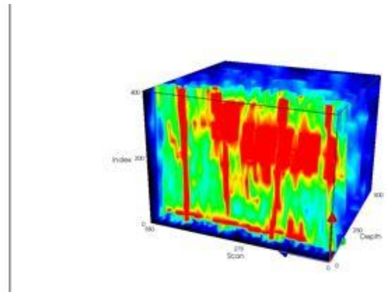


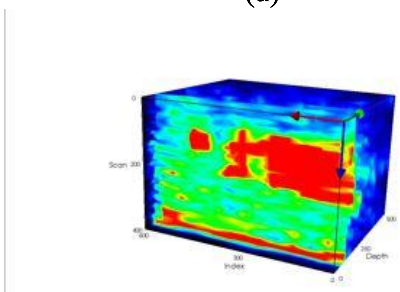
Figure B.4-21: Labels for UST Side Scans



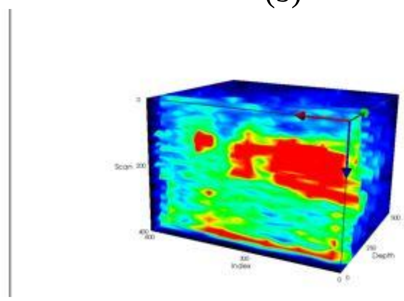
(a)



(b)

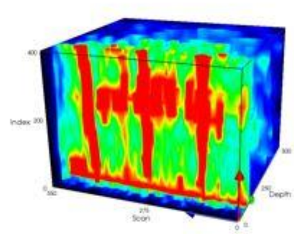


(c)

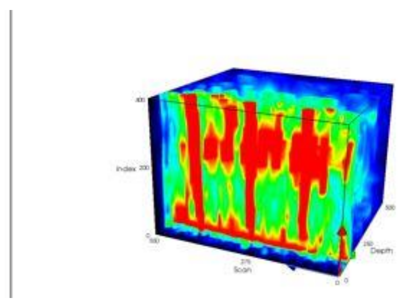


(d)

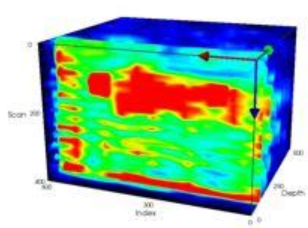
Figure B.4-22: UST 3-D Maps from Specimen 1 D1 Scans (a) I (b) I (c) II (d) II



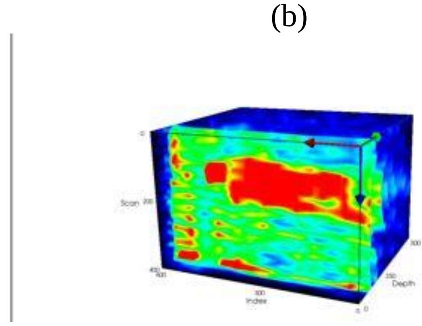
(a)



(b)

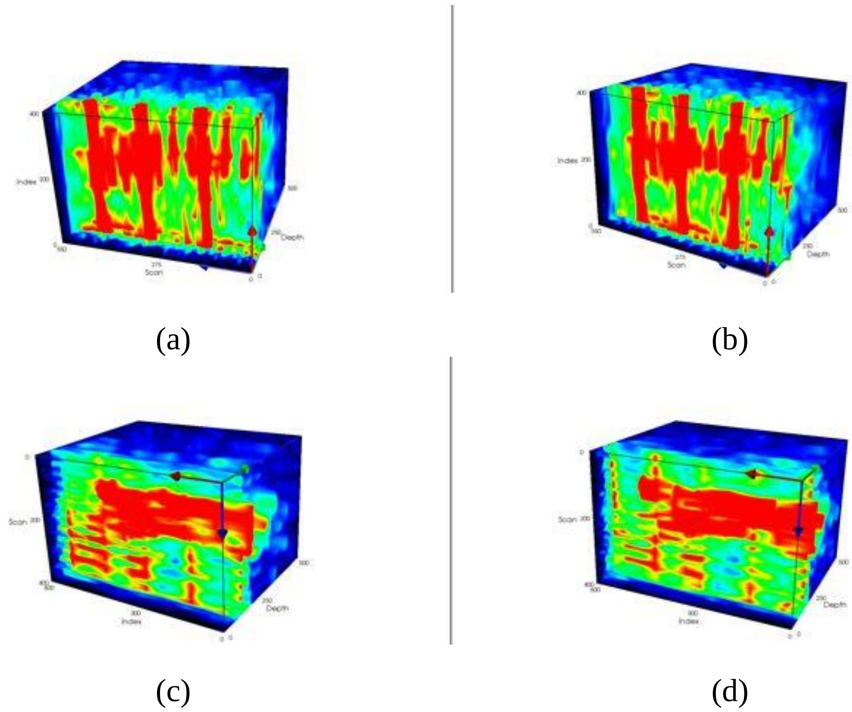


(c)



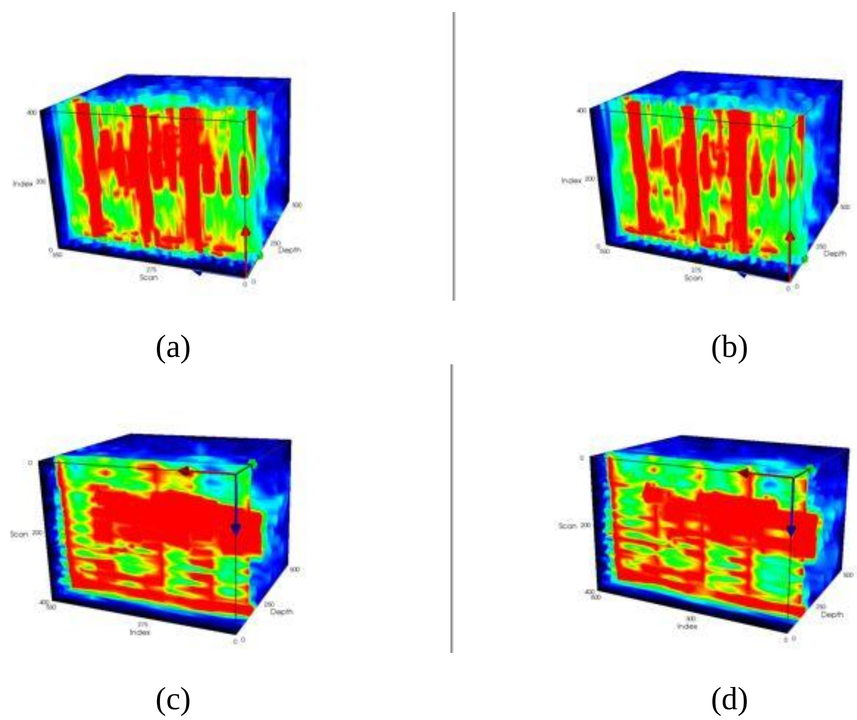
(d)

Figure B.4-23: UST 3-D Maps from Specimen 2 D1 Scans (a) I (b) I (c) II (d) II



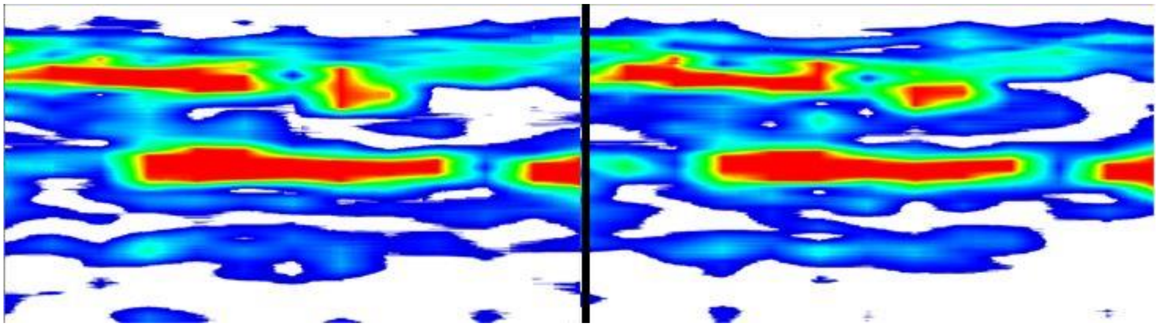
(a) (b) (c) (d)

Figure B.4-24: UST 3-D Maps from Specimen 3 D1 Scans (a) I (b) I (c) II (d) II



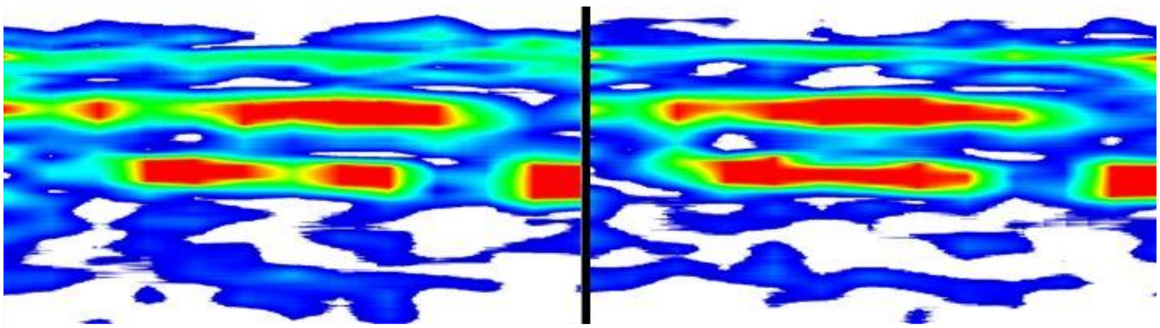
(a) (b) (c) (d)

Figure B.4-25: UST 3-D Maps from Specimen 4 D1 Scans (a) I (b) I (c) II (d) II



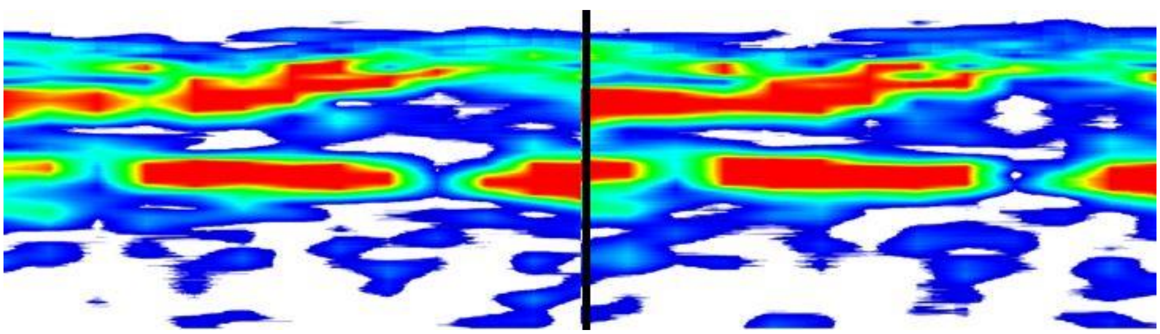
(a) (b)

Figure B.4-26: UST C-scans Through Duct from Specimen 1 D1 Scans (a) II (b) II



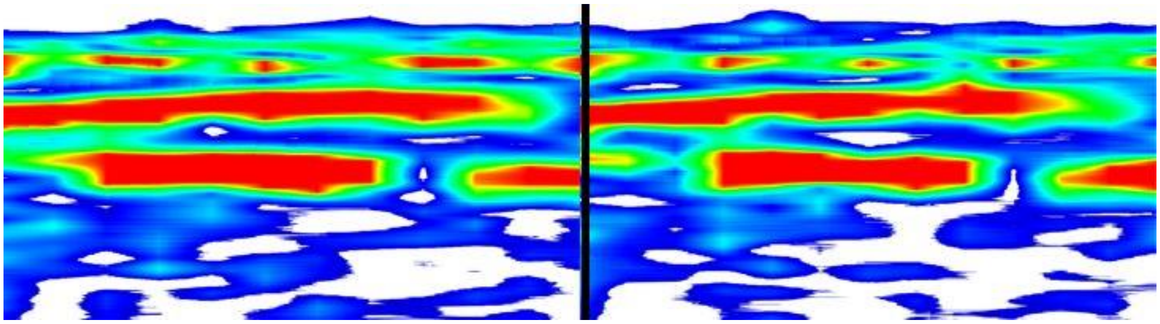
(a) (b)

Figure B.4-27: UST C-scans Through Duct from Specimen 2 D1 Scans (a) II (b) II



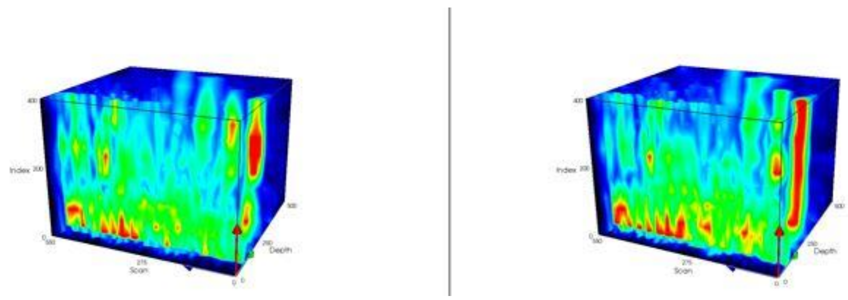
(a) (b)

Figure B.4-28: UST C-scans Through Duct from Specimen 3 D1 Scans (a) II (b) II

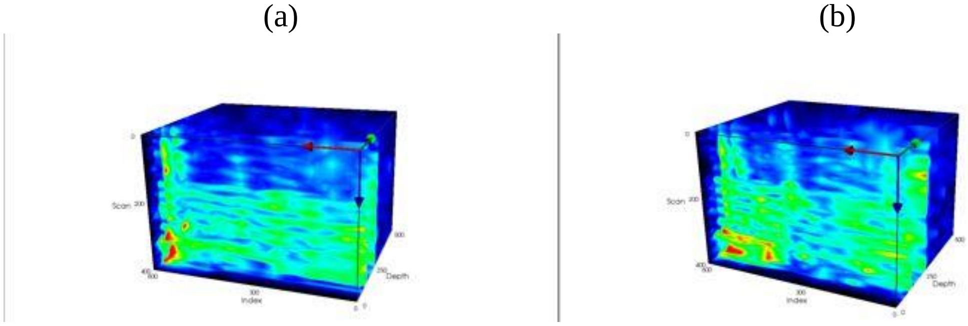


(a) (b)

Figure B.4-29: UST C-scans Through Duct from Specimen 4 D1 Scans (a) II (b) II

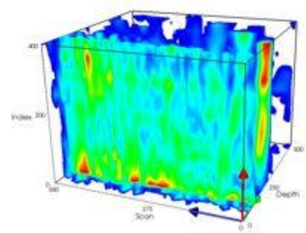


(a) (b)

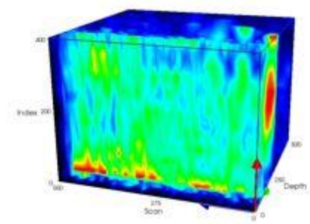


(c) (d)

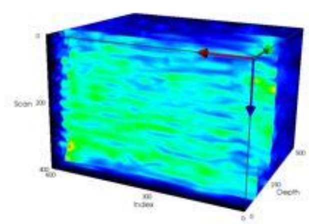
Figure B.4-30: UST 3-D Maps from Specimen 1 D2 Scans (a) I (b) I (c) II (d) II



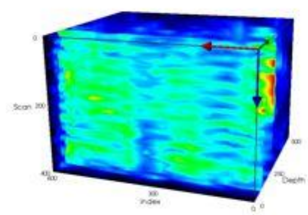
(a)



(b)

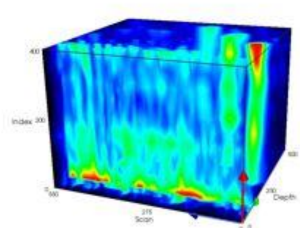


(c)

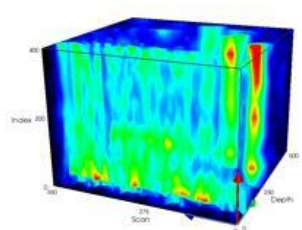


(d)

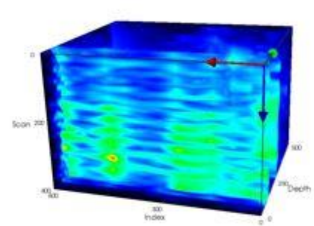
Figure B.4-31: UST 3-D Maps from Specimen 2 D2 Scans (a) I (b) I (c) II (d) II



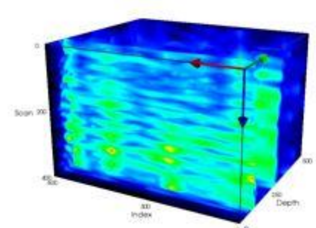
(a)



(b)

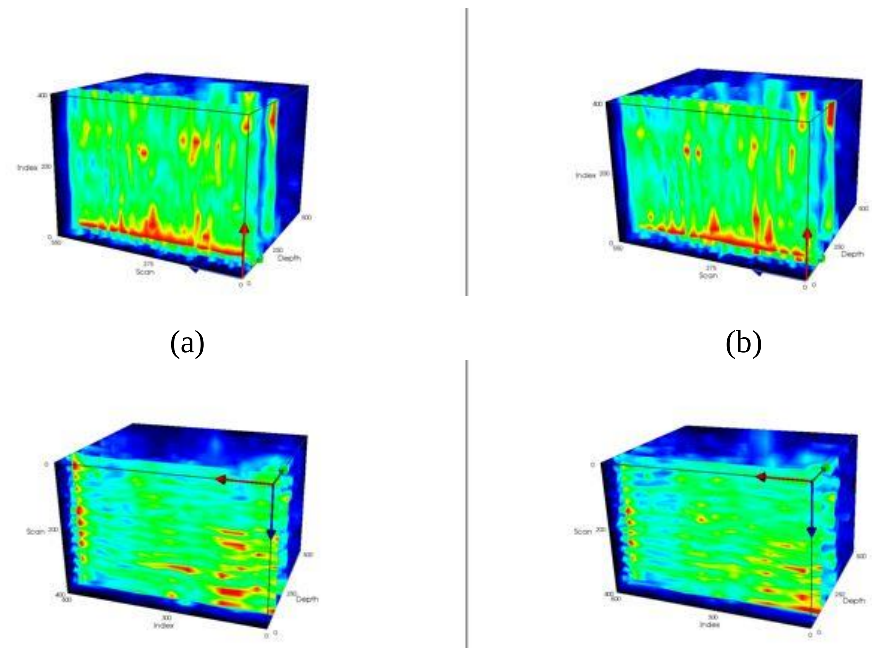


(c)



(d)

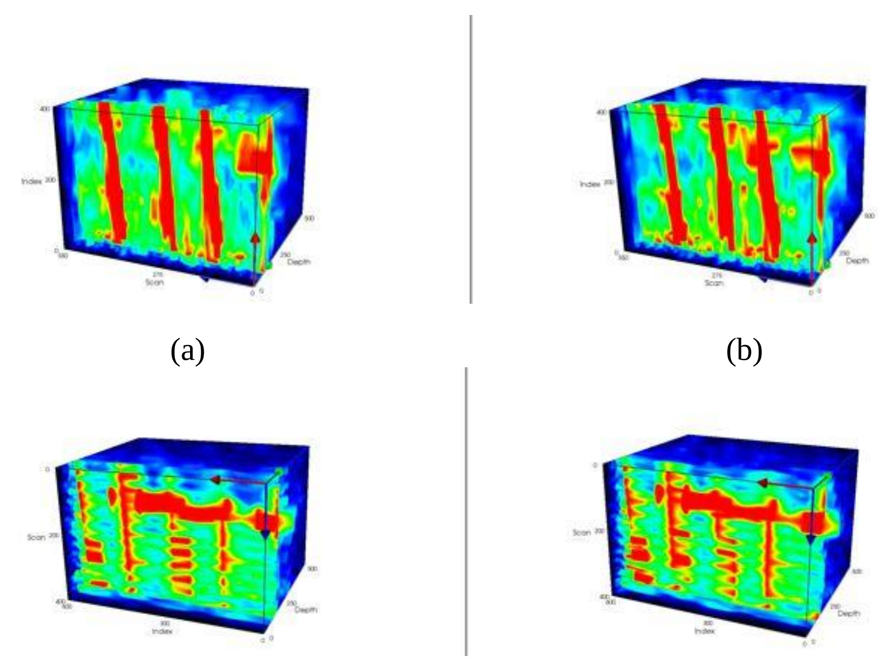
Figure B.4-32: UST 3-D Maps from Specimen 3 D2 Scans (a) I (b) I (c) II (d) II



(a) (b)

(c) (d)

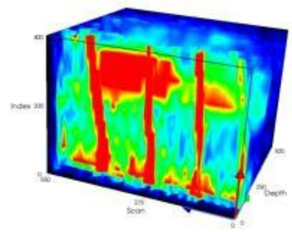
Figure B.4-33: UST 3-D Maps from Specimen 4 D2 Scans (a) I (b) I (c) II (d) II



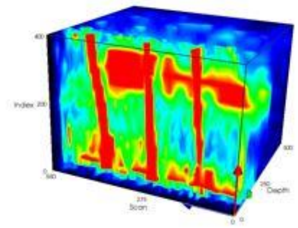
(a) (b)

(c) (d)

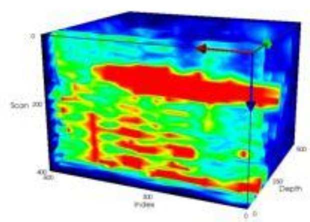
Figure B.4-34: UST 3-D Maps from Specimen 1 D3 Scans (a) I (b) I (c) II (d) II



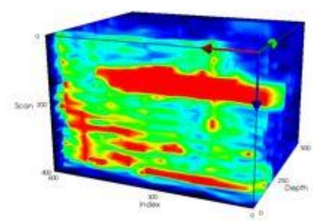
(a)



(b)

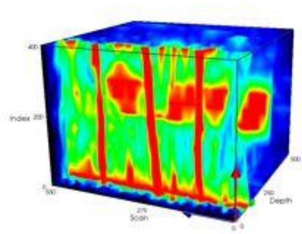


(c)

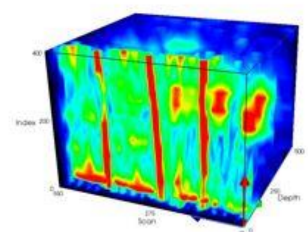


(d)

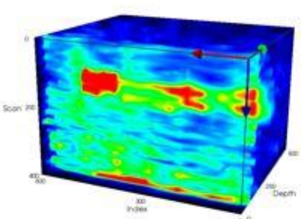
Figure B.4-35: UST 3-D Maps from Specimen 2 D3 Scans (a) I (b) I (c) II (d) II



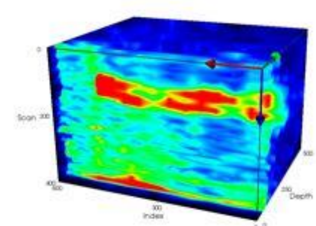
(a)



(b)

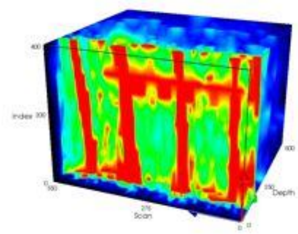


(c)

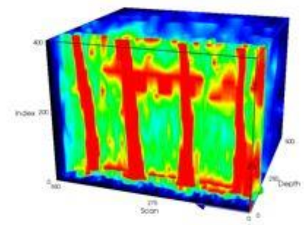


(d)

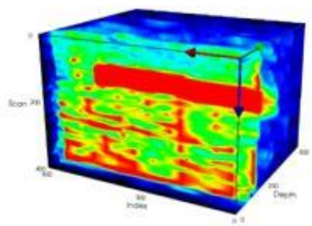
Figure B.4-36: UST 3-D Maps from Specimen 3 D3 Scans (a) I (b) I (c) II (d) II



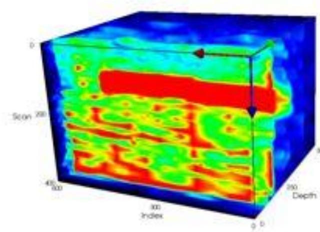
(a)



(b)

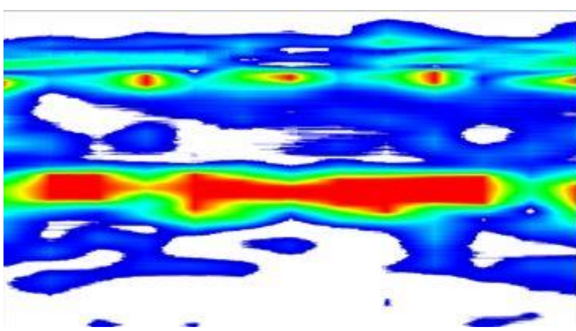


(c)

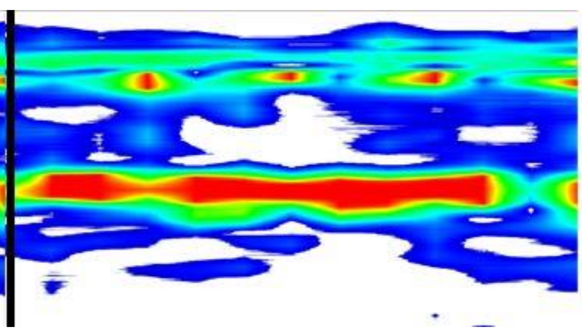


(d)

Figure B.4-37: UST 3-D Maps from Specimen 4 D3 Scans (a) I (b) I (c) II (d) II

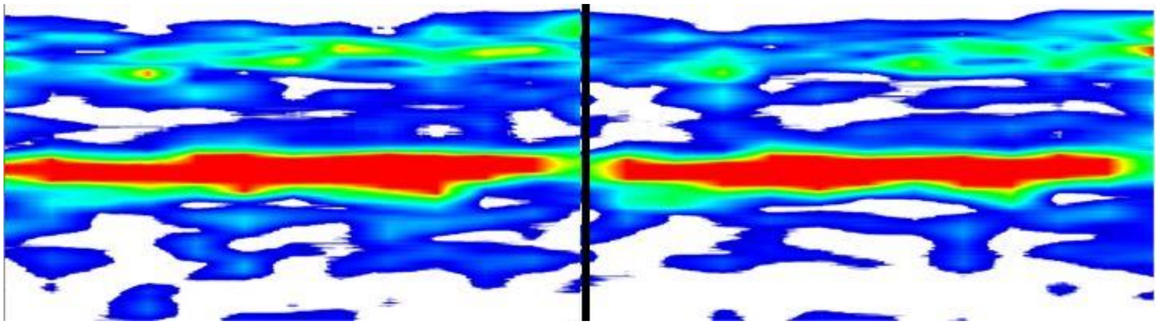


(a)



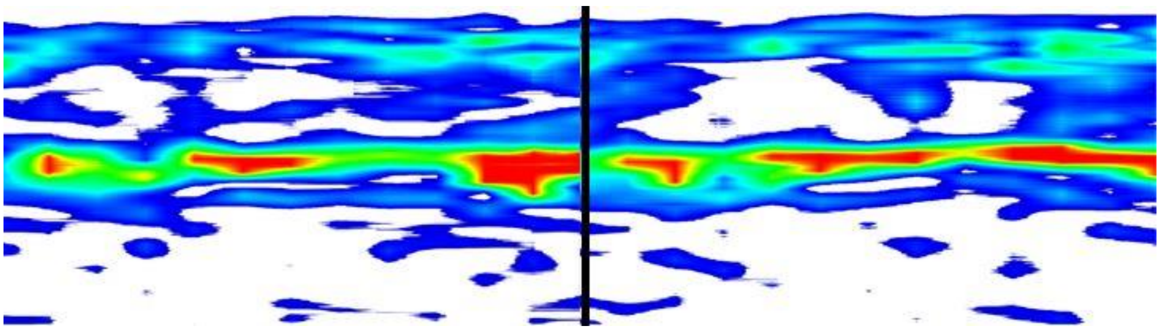
(b)

Figure B.4-38: UST C-scans Through Duct from Specimen 1 D3 Scans (a) II (b) II



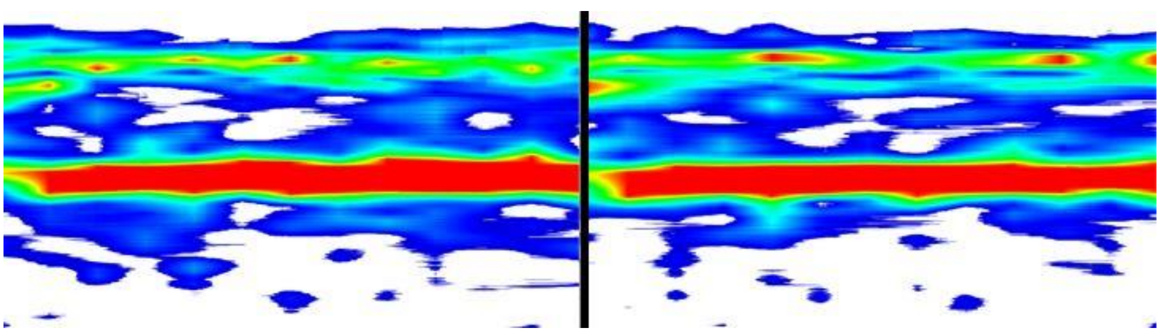
(a) (b)

Figure B.4-39: UST C-scans Through Duct from Specimen 2 D3 Scans (a) II (b) II



(a) (b)

Figure B.4-40: UST C-scans Through Duct from Specimen 3 D3 Scans (a) II (b) II



(a) (b)

Figure B.4-41: UST C-scans Through Duct from Specimen 4 D3 Scans (a) II (b) II

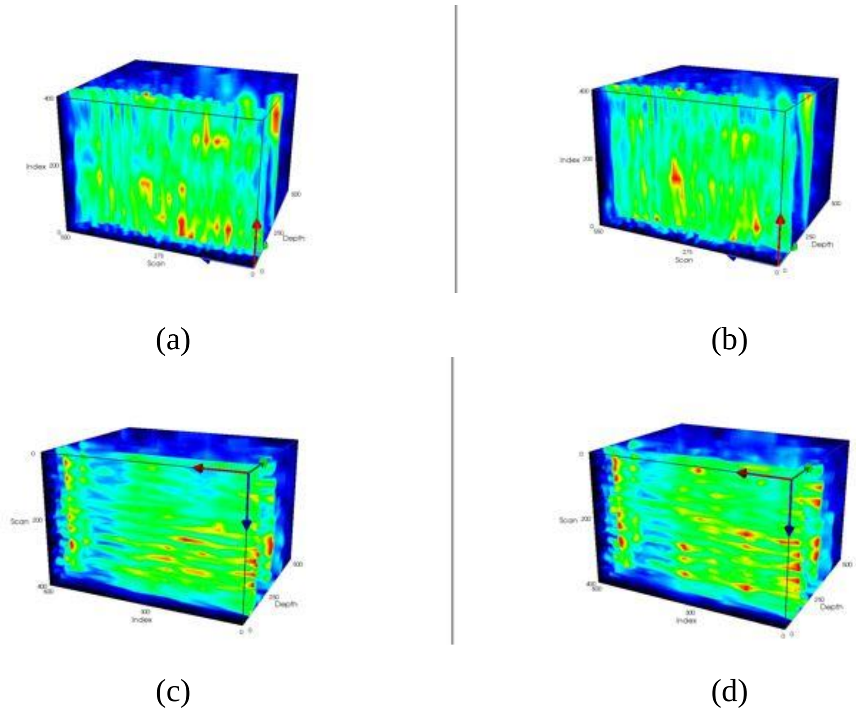


Figure B.4-42: UST 3-D Maps from Specimen 1 D4 Scans (a) I (b) I (c) II (d) II

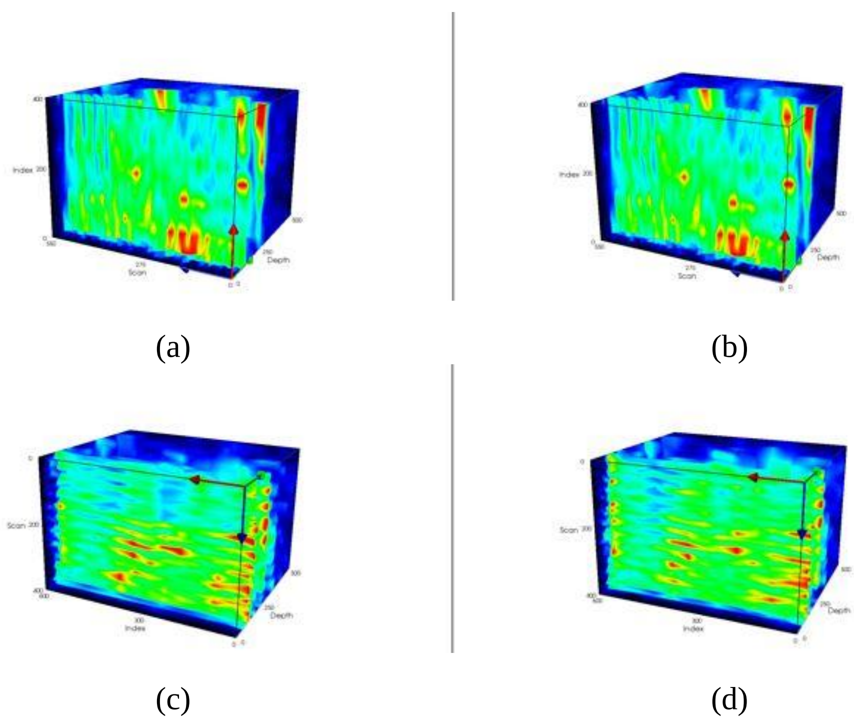
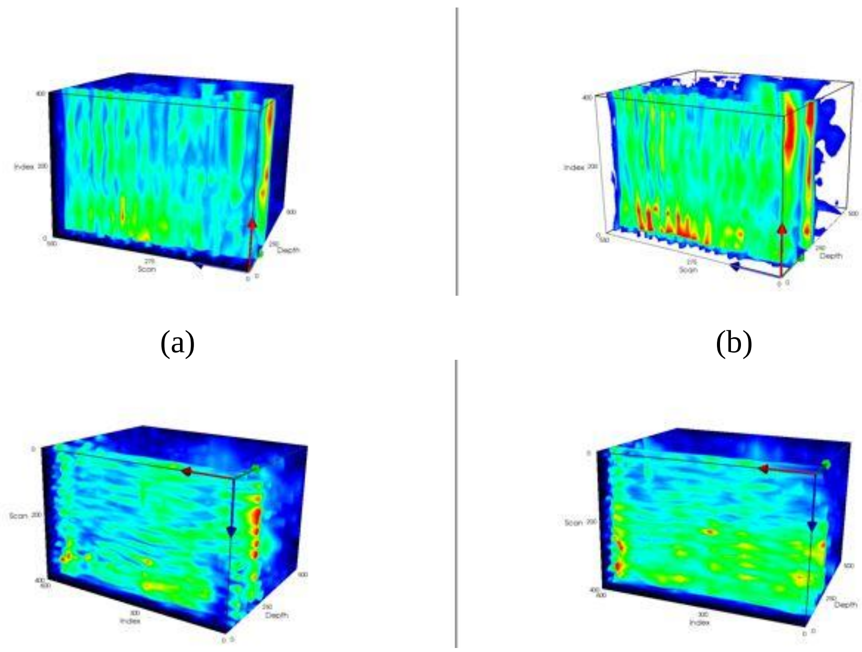
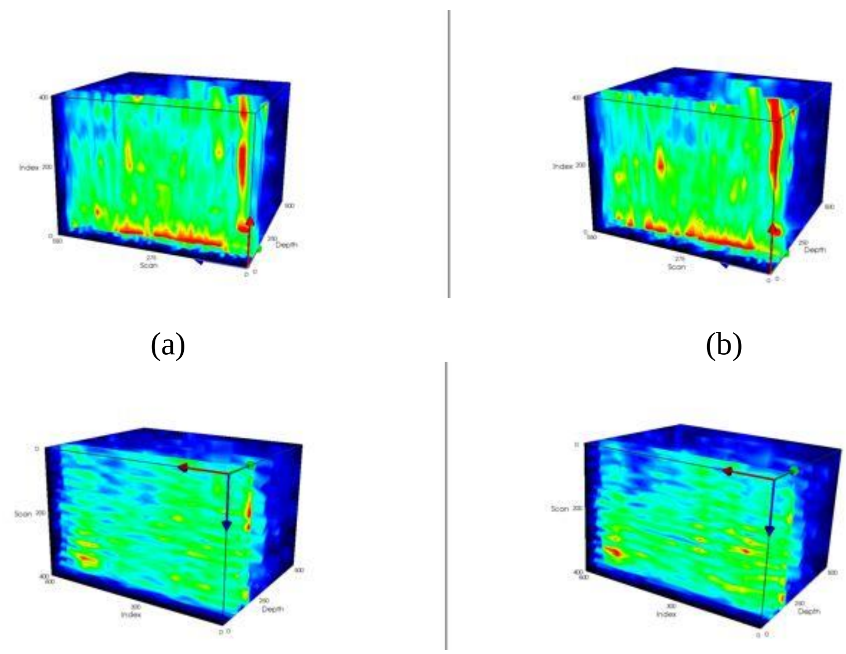


Figure B.4-43: UST 3-D Maps from Specimen 2 D4 Scans (a) I (b) I (c) II (d) II



(a) (b) (c) (d)

Figure B.4-44: UST 3-D Maps from Specimen 3 D4 Scans (a) I (b) I (c) II (d) II



(a) (b) (c) (d)

Figure B.4-45: UST 3-D Maps from Specimen 4 D4 Scans (a) I (b) I (c) II (d) II

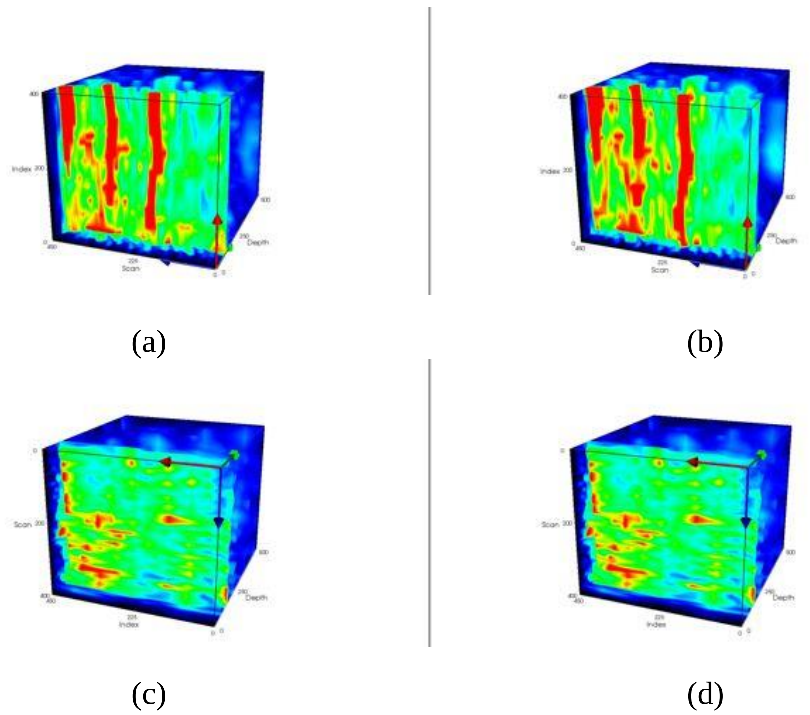


Figure B.4-46: UST 3-D Maps from Specimen 1 P1 Scans (a) I (b) I (c) II (d) II

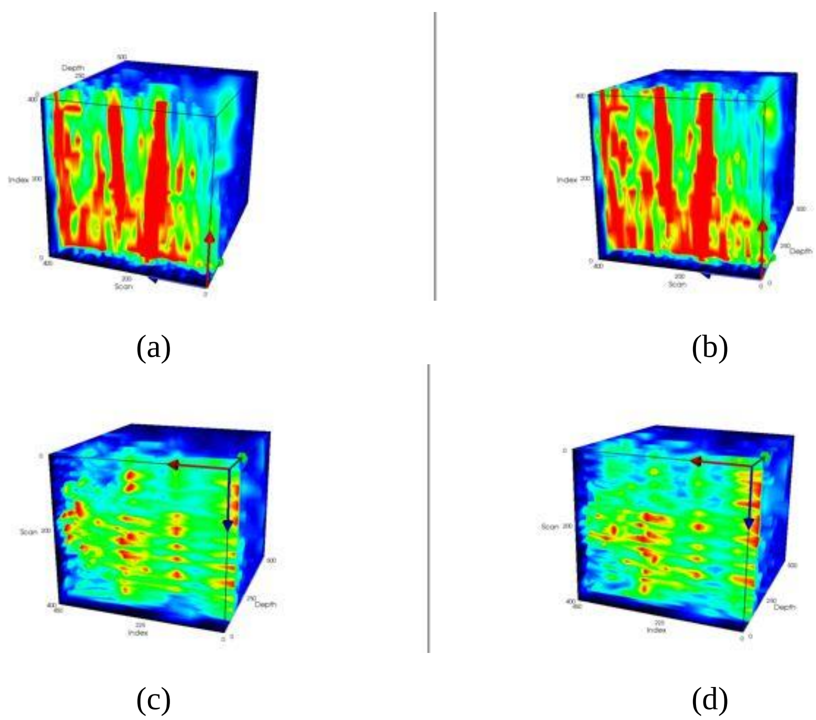
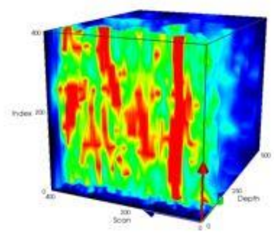
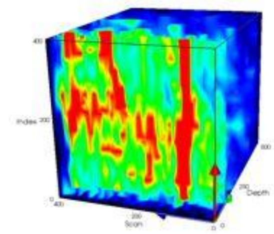


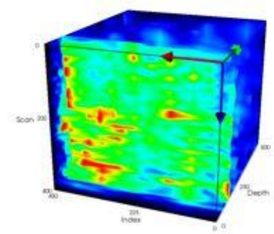
Figure B.4-47: UST 3-D Maps from Specimen 2 P1 Scans (a) I (b) I (c) II (d) II



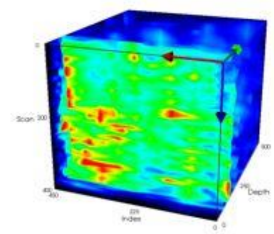
(a)



(b)

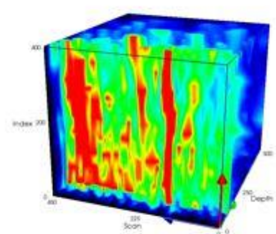


(c)

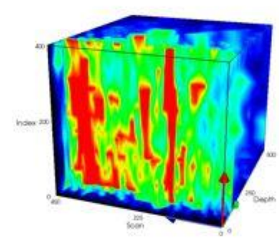


(d)

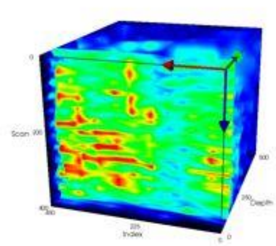
Figure B.4-48: UST 3-D Maps from Specimen 3 P1 Scans (a) I (b) I (c) II (d) II



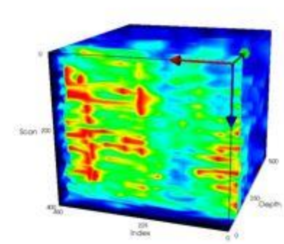
(a)



(b)

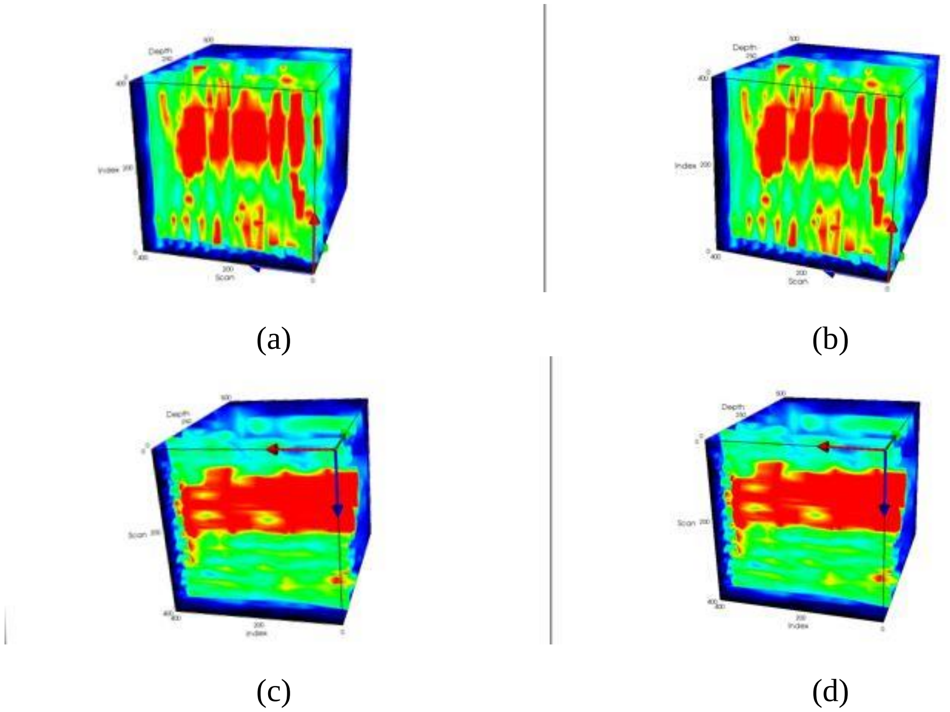


(c)



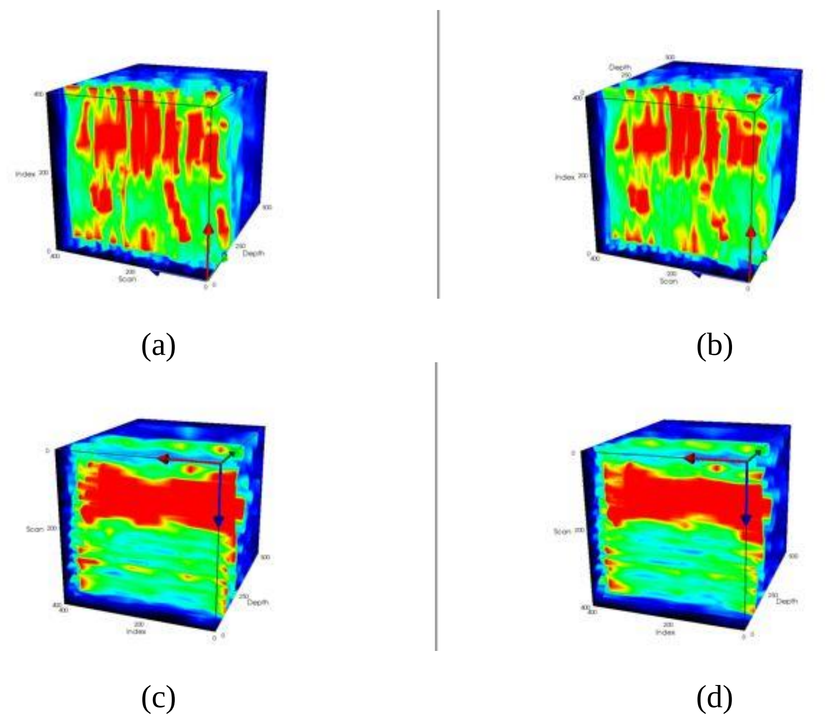
(d)

Figure B.4-49: UST 3-D Maps from Specimen 4 P1 Scans (a) I (b) I (c) II (d) II



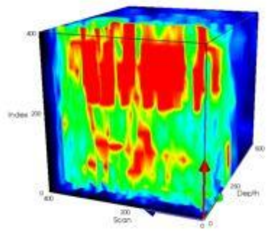
(a) (b) (c) (d)

Figure B.4-50: UST 3-D Maps from Specimen 1 P2 Scans (a) I (b) I (c) II (d) II

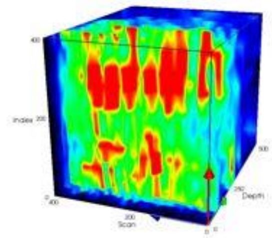


(a) (b) (c) (d)

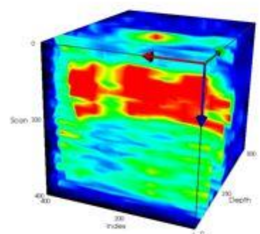
Figure B.4-51: UST 3-D Maps from Specimen 2 P2 Scans (a) I (b) I (c) II (d) II



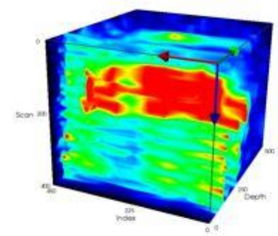
(a)



(b)

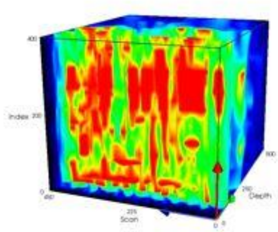


(c)

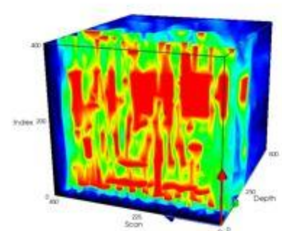


(d)

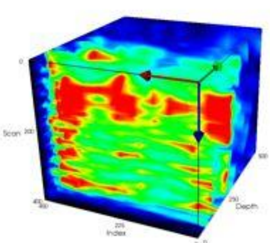
Figure B.4-52: UST 3-D Maps from Specimen 3 P2 Scans (a) I (b) I (c) II (d) II



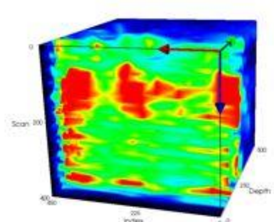
(a)



(b)

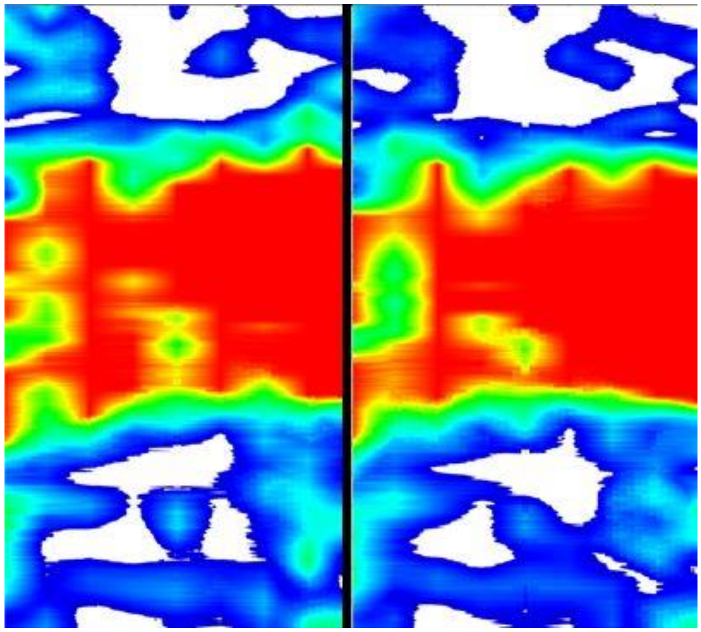


(c)



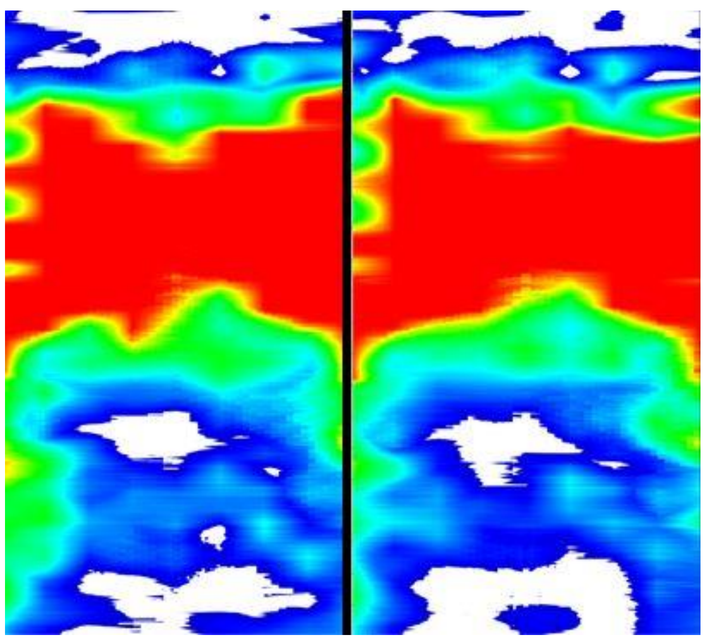
(d)

Figure B.4-53: UST 3-D Maps from Specimen 4 P2 Scans (a) I (b) I (c) II (d) II



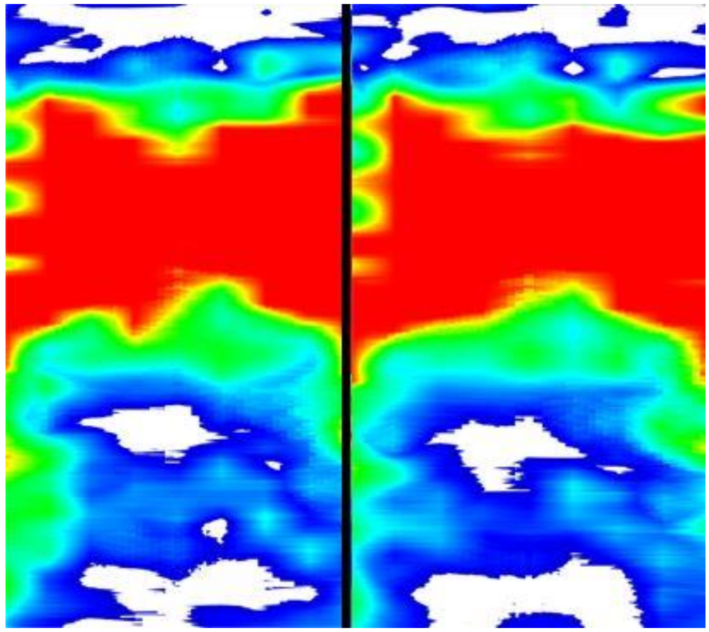
(a) (b)

Figure B.4-54: UST D-scans Through Duct from Specimen 1 P2 Scans (a) II (b) II



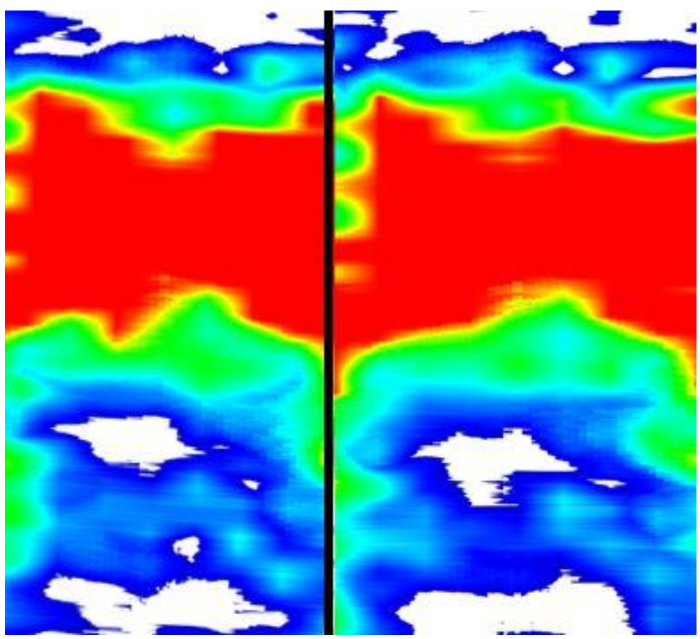
(a) (b)

Figure B.4-55: UST D-scans Through Duct from Specimen 2 P2 Scans (a) II (b) II



(a) (b)

Figure B.4-56: UST D-scans Through Duct from Specimen 3 P2 Scans (a) II (b) II



(a) (b)

Figure B.4-57: UST D-scans Through Duct from Specimen 4 P2 Scans (a) II (b) II

Appendix B.5 – Sounding Results

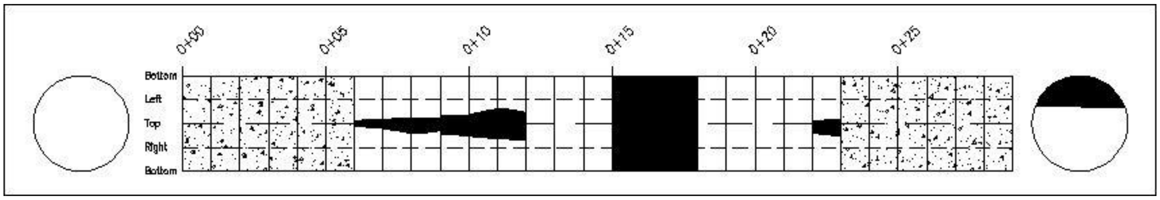


Figure B.5-1: Sounding Map 2 of Specimen 1

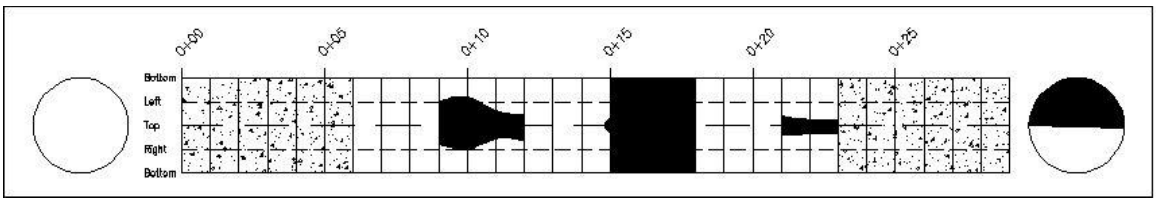


Figure B.5-2: Sounding Map 1 of Specimen 2

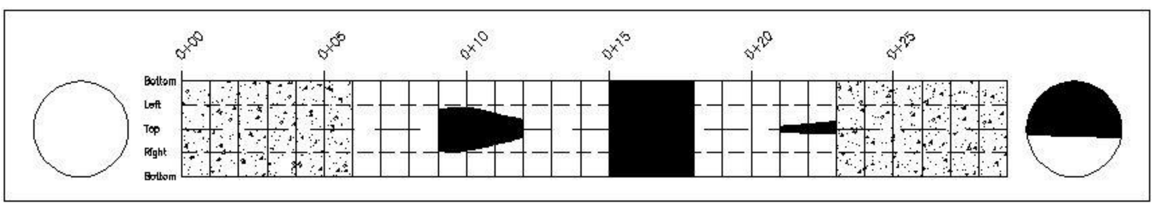


Figure B.5-3: Sounding Map 2 of Specimen 2

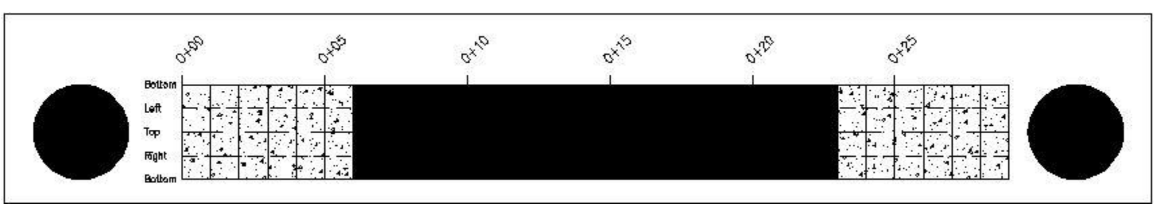


Figure B.5-4: Sounding Map of Specimen 3

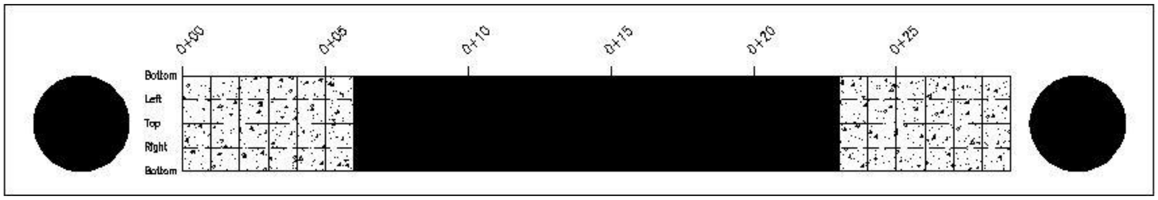


Figure B.5-5: Sounding Map of Specimen 4

Appendix B.6 – Borescope Results

Specimen 1

A-B: No entry access

B-C: No entry access

C-D: No entry access

D-E:

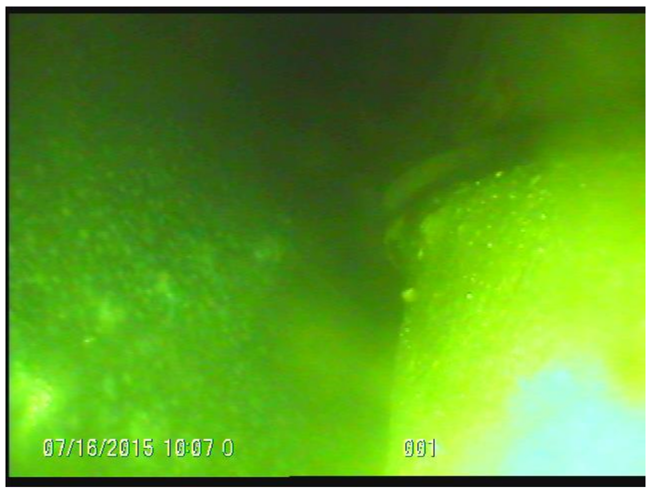


Figure B.6-1: Borescope Photo of Water Infiltration in Specimen 1 Grid D-E

E-F: No entry access

F-G:

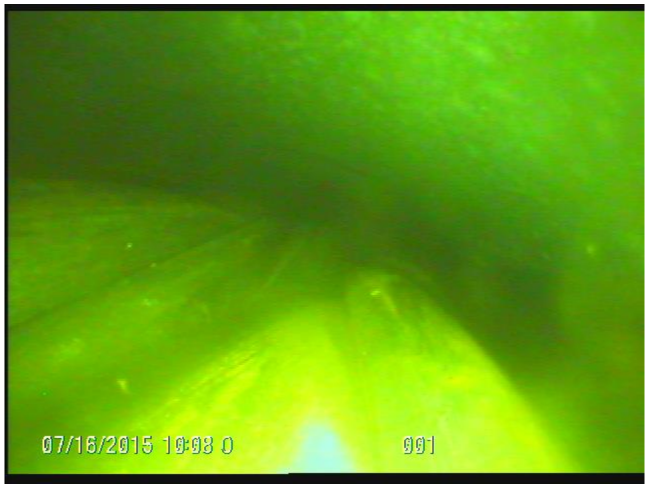


Figure B.6-2: Borescope Photo of Voided Region in Specimen 1 Grid F-G

G-H: No entry access

H-I: No entry access

I-J: No entry access

J-K:

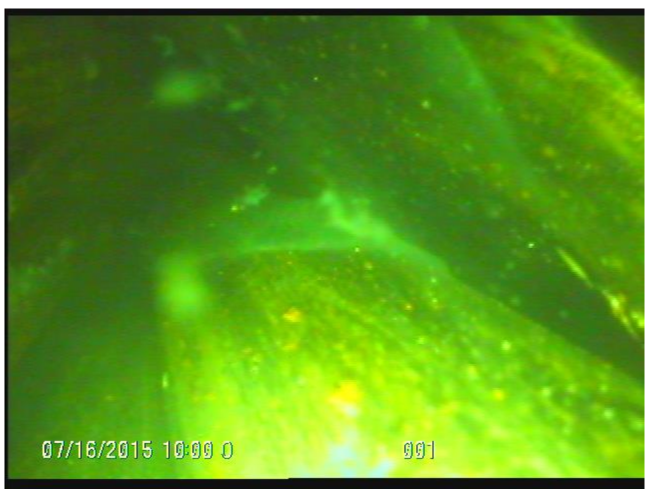


Figure B.6-3: Borescope Photo of Water Infiltration in Specimen 1 Grid J-K

Specimen 2

A-B: No entry access

B-C: No entry access

C-D: No entry access

D-E:

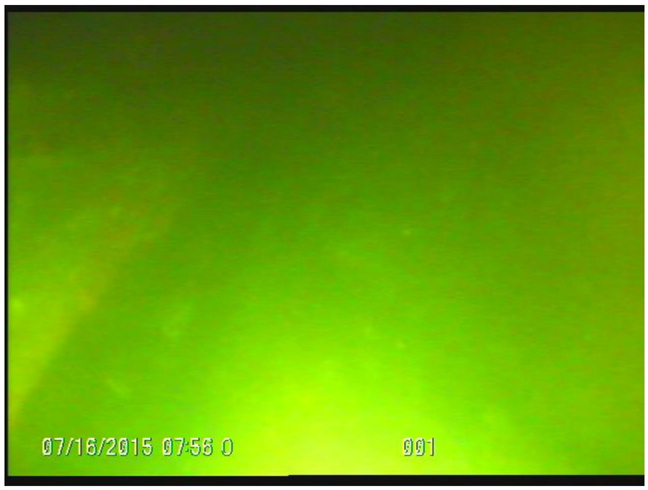


Figure B.6-4: Borescope Photo of Water Infiltration in Specimen 2 Grid D-E

E-F: No entry access

F-G:

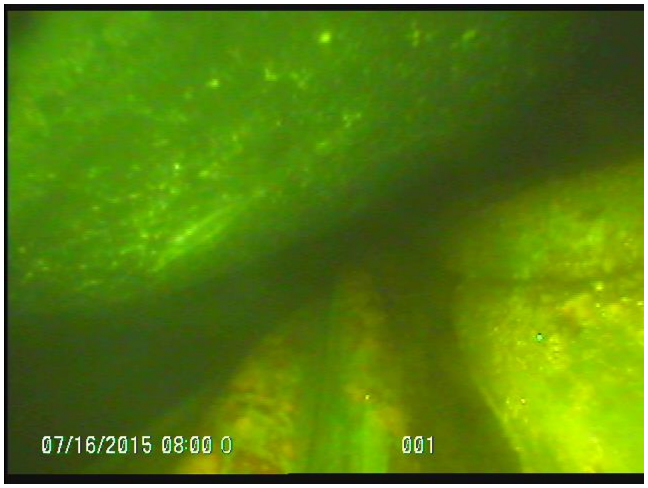


Figure B.6-5: Borescope Photo of Voided Region in Specimen 2 Grid F-G

G-H: No entry access

H-I:

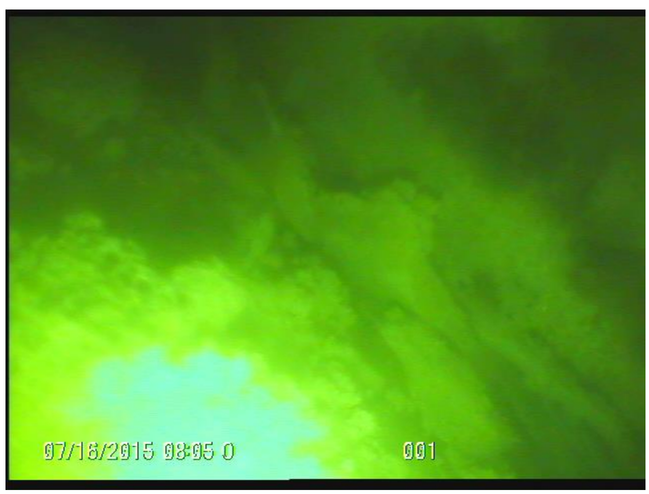


Figure B.6-6: Borescope Photo of Grout Segregation in Specimen 2 Grid H-I

I-J: No entry access

J-K: No entry access

Specimen 3

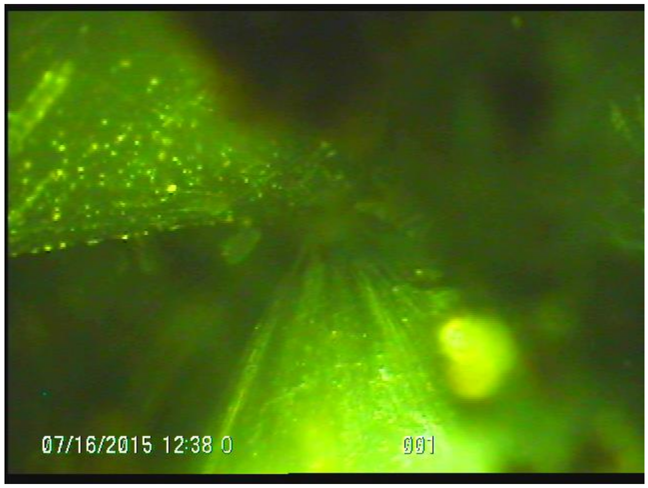


Figure B.6-7: Borescope Photo of Intact Strands in Specimen 3 Grid D-E

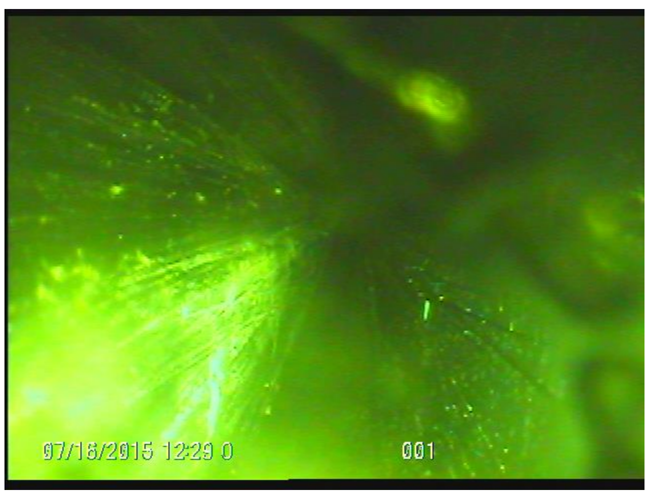


Figure B.6-8: Borescope Photo of Intact Strands in Specimen 3 Grid E-F

Specimen 4

Figure B.6-9: Borescope Photo of Intact Strands in Specimen 4 Grid F-G

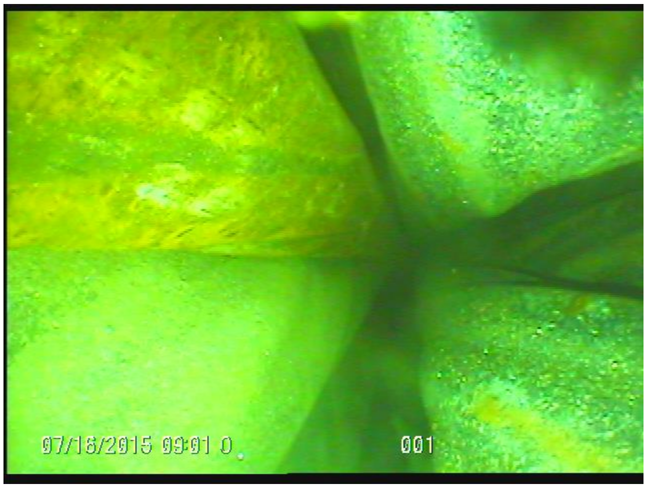


Figure B.6-10: Borescope Photo of Exposed Strand in Specimen 4 Grid C-D

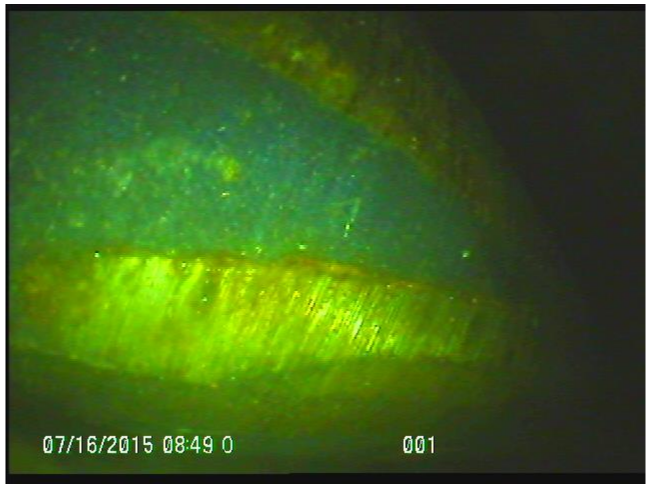


Figure B.6-11: Borescope Photo of Exposed Strand in Specimen 4 Grid E-F

Figure B.6-12: Borescope Photo of Sheathing Stripping in Specimen 4 Grid I-J

APPENDIX C – DEFINITION OF SCORING GUIDELINES

Appendix C outlines the definitions of each metric category's ranking system. Note that these guidelines were adapted from Appendix A of Revised Interim Report No. 2 for the NCHRP on Project 14-28 (Hurlebaus et al., 2014).

Ranking / Category	1	2	3	4	5	6	7	8	9	10
Precision										
Repeatability (correlation)	x < 0.1	0.1 ≤ x < 0.2	0.2 ≤ x < 0.3	0.3 ≤ x < 0.4	0.4 ≤ x < 0.5	0.5 ≤ x < 0.6	0.6 ≤ x < 0.7	0.7 ≤ x < 0.8	0.8 ≤ x < 0.9	≥ 0.9
Reproducibility (correlation)	x < 0.1	0.1 ≤ x < 0.2	0.2 ≤ x < 0.3	0.3 ≤ x < 0.4	0.4 ≤ x < 0.5	0.5 ≤ x < 0.6	0.6 ≤ x < 0.7	0.7 ≤ x < 0.8	0.8 ≤ x < 0.9	≥ 0.9
Accuracy *(correlation)*	x < 0.1	0.1 ≤ x < 0.2	0.2 ≤ x < 0.3	0.3 ≤ x < 0.4	0.4 ≤ x < 0.5	0.5 ≤ x < 0.6	0.6 ≤ x < 0.7	0.7 ≤ x < 0.8	0.8 ≤ x < 0.9	≥ 0.9
Ease of Use										
Power Demand	Requires direct power, high voltage (≥220 V)				Requires low voltage, extension cord (110 V)			Not handheld but battery operated	Handheld, 4-8 hour battery life	Handheld, ≥ 8 hour battery life
No. of Personnel	Large crew (≥ 20)	15-20 personnel	10-15 personnel	5-10 personnel	3-5 personnel	1-2 personnel, manual data collection	1 personnel, manual data collection	3-5 to set-up, data acquisition is automated	1-2 to set-up, data acquisition is automated	1 to set-up, data automated acquisition
Inspection Requirements										
Operator Qualification	Extensive prior knowledge, experience, or operator certification required				Moderate prior knowledge, experience, or operator certification required				Minimal prior knowledge, experience, or operator certification required	

Ranking / Category	1	2	3	4	5	6	7	8	9	10
Inspection Requirements, Continued										
Operator Training (in USD per person)	≥ 2000	2000 ≥ x > 1750	1750 ≥ x > 1500	1500 ≥ x > 1250	1250 ≥ x > 1000	1000 ≥ x > 750	750 ≥ x > 500	500 ≥ x > 250	250 ≥ x > 100	100 ≥ x > 0
USD per Hour (Operator costs only)	≥150				150 ≥ x > 75					75 ≥ x > 0
Complexity of Data Interpretation	Extensive prior knowledge, experience, or certifications of operator(s) required				Moderate prior knowledge, experience, or certifications of operator(s) required					Minimal prior knowledge, experience, or certifications of operator(s) required
Cost										
Cost of Equipment (in thousands USD)	≥ 200	200 ≥ x > 150	150 ≥ x > 100	100 ≥ x > 75	75 ≥ x > 50	50 ≥ x > 20	20 ≥ x > 10	10 ≥ x > 5	5 ≥ x > 1	≤ 1
Labor Costs for Inspection (in USD per ft of stay cable or external PT and per ft^2 of cover surface for internal PT)	≥5				5 ≥ x > 1					≤ 1

APPENDIX D – METRICS TABLES

Ground Penetrating Radar (External Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Non-Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Non-Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability										x	10
Reproducibility										x	10
Accuracy											
					x						5
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Non-Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability										x	10
Reproducibility										x	10
Accuracy											
									x		9
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability										x	10
Reproducibility										x	10
Accuracy											
							x				7
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (External Non-Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (Anchorage Regions)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (Anchorage Regions)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (Anchorage Regions)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Ground Penetrating Radar (Anchorage Regions)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications						x					6
Operator Training						x					6
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						x					6
Labor Costs for Inspection					x						5

Magnetic Flux Leakage (External Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability									x		9
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability									x		9
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability									x		9
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Non-Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability									x		9
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability									x		9
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Non-Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability									x		9
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Non-Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Magnetic Flux Leakage (External Non-Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand								x			8
No. of Personnel								x			8
Inspection Requirements											
Operator Qualifications		x									2
Operator Training	x										1
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment			x								3
Labor Costs for Inspection	x										1

Infrared Thermography (External Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (External Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (External Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (External Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (External Non-Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection											

Infrared Thermography (External Non-Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability						x					6
Reproducibility						x					6
Accuracy											
				x							4
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (External Non-Metal Ducts)

Voids

Ranking / Category	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability								x			8
Reproducibility								x			8
Accuracy											
										x	10
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Water Infiltration

Ranking / Category	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability						x					6
Reproducibility						x					6
Accuracy											
						x					6
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (External Non-Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (Anchorage Regions)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection											

Infrared Thermography (Anchorage Regions)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability						x					6
Reproducibility						x					6
Accuracy											
				x							4
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (Anchorage Regions)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability						x					6
Reproducibility						x					6
Accuracy											
								8			8
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability						x					6
Reproducibility						x					6
Accuracy											
						x					6
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Infrared Thermography (Anchorage Regions)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	9
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications						x					6
Operator Training		x									2
USD per hour					x						5
Complexity of Data Interpret.					x						5
Cost											
Cost of Equipment						6					6
Labor Costs for Inspection										10	10

Ultrasonic Tomography (External Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Non-Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Non-Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability										x	10
Reproducibility							x				7
Accuracy											
					x						5
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Non-Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability										x	10
Reproducibility							x				7
Accuracy											
									x		9
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability										x	10
Reproducibility							x				7
Accuracy											
						x					6
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (External Non-Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (Anchorage Regions)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (Anchorage Regions)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (Anchorage Regions)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Ultrasonic Tomography (Anchorage Regions)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand									x		9
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications		x									2
Operator Training			x								3
USD per hour	x										1
Complexity of Data Interpret.	x										1
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection										x	10

Sounding (External Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Metal Ducts)

Breakage

Ranking / Category	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Grout Conditions

Ranking / Category	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
			x								3
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
							x				7
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
			x								3
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Non-Metal Ducts)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Non-Metal Ducts)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
			x								3
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Non-Metal Ducts)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
							x				7
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
			x								3
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (External Non-Metal Ducts)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (Anchorage Regions)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (Anchorage Regions)

Breakage

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Grout Conditions

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
		x									2
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (Anchorage Regions)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
					x						5
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability							x				7
Reproducibility					x						5
Accuracy											
		x									2
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Sounding (Anchorage Regions)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability	x										1
Reproducibility	x										1
Accuracy											
	x										1
Ease of Use											
Power Demand										x	10
No. of Personnel							x				7
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment										x	10
Labor Costs for Inspection										x	10

Boroscope (External Metal & Non-Metal Ducts / Anchorage Regions)

Corrosion

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability			x								3
Reproducibility			x								3
Accuracy											
		x									2
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5

Section Loss

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability			x								3
Reproducibility			x								3
Accuracy											
		x									2
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5

Boroscope (External Metal & Non-Metal Ducts / Anchorage Regions)

Breakage

Ranking / Category	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability			x								3
Reproducibility			x								3
Accuracy											
		x									2
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5

Grout Conditions

Ranking / Category	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability			x								3
Reproducibility			x								3
Accuracy											
		x									2
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5

Boroscope (External Metal & Non-Metal Ducts / Anchorage Regions)

Voids

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability					x						5
Reproducibility					x						5
Accuracy											
				x							4
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5

Water Infiltration

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability			x								3
Reproducibility			x								3
Accuracy											
		x									2
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5

Boroscope (External Metal & Non-Metal Ducts / Anchorage Regions)

General Tendon Deterioration in the Anchorage System

Category \ Ranking	1	2	3	4	5	6	7	8	9	10	Rating
Precision											
Repeatability			x								3
Reproducibility			x								3
Accuracy											
		x									2
Ease of Use											
Power Demand					x						5
No. of Personnel						x					6
Inspection Requirements											
Operator Qualifications										x	10
Operator Training										x	10
USD per hour										x	10
Complexity of Data Interpret.										x	10
Cost											
Cost of Equipment					x						5
Labor Costs for Inspection					x						5