INSTRUMENTATION AND DEFORMATION MEASUREMENT OF CHARLOTTE COUNTY CULVERT NO. 2. USING SHAPEARRAY TECHNOLOGY

by

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ABSTRACT

DE03 (Route 127) Culvert No. 2, is an existing corrugated steel pipe (CSP) culvert in Charlotte County, southwest New Brunswick, chosen for load test, field instrumentation with ShapeArray and LiDAR monitoring in this project. In this study, ShapeArray (SAA), was mounted inside the pipe in a circular orientation and utilized to record displacement in the middle of the culvert. Field work consisted of performing static and dynamic loading tests using NBDTI standard test vehicle, with only static loading test results presented in this study. Twenty static load tests were completed, ten times in each traffic direction. In addition to the SAA data, Laser Scanning survey method (LiDar) was used to assess culvert deformation along the culvert.

The tests showed that the culvert's crown deflected more than other locations along the circumference of the pipe, with a maximum displacement of 0.04 mm, which is extremely small. Both SAA and LiDar showed good agreement with respect to the pipe performance and the data from these two different independent approaches was internally consistent.

DEDICATION

This project report is dedicated to all people who didn’t give up on me finishing my Master of Engineering degree. Especially to my loved ones who at least did their part to help me finish it. A special feeling of gratitude to my loving parents, Gholamhassan and Minoo whose words of encouragement and push for tenacity ring in my ears. Special thanks to my wife Shirin Dehgahi that did not leave me alone during my program and my sisters Mehrnoosh and Mahsa have never left my side and are very special to me. I also dedicate this project report to my many friends who have supported me throughout the program. I will always appreciate all they have done.

ACKNOWLEDGEMENTS

I wish to thank my supervisors who were more than generous with their expertise and precious time. A special thanks to Dr. Othman Nasir, for his countless hours of reflecting, reading, encouraging, and most of all patience throughout the entire program. I would like to acknowledge and thank my co-supervisor Dr. Arun Valsangkar for allowing me to conduct my research and providing any assistance requested. Special thanks to the members of the Department of Transportation and Infrastructure staff who helped me throughout my research.

Table of Contents

List of Tables

List of Figures

1.0. INTRODUCTION

1.1. Preface

For more than a century, corrugated steel pipe (CSP) has been the preferred option for engineers and used in many projects. With its wide variety of coatings, corrugation patterns, and steel thicknesses, CSP offers dependable durability. The flexibility and value of CSP are unmatched by any other pipe material on the market today [2].

Regular applications for corrugated steel pipe include:

- Culverts
- Storm sewers
- Stream enclosures
- Detention and Retention systems
- Power plant cooling lines
- Conveyor tunnels
- Utility conduits
- Foundation structures

Corrugated steel pipe offers a variety of environmental advantages, such as less greenhouse gas emissions, decreased pollution, less acid rain, and a reduction in the depletion of resources required in manufacturing, such as water and electricity.

Many of the large-diameter CSP constructed decades ago are corroded today and need rehabilitation or replacement. Such large-diameter pipes and culverts used to be repaired by dig and replace technology in the past. To repair or replace deteriorating pipes and culverts in whole or in part while minimizing the impact on traffic, numerous technologies have been developed recently. Different techniques have developed in the last decade such as: Slip lining, Spiral wound lining, Cured-In-Place-Pipe (CIPP) and Geopolymer structural lining. Geopolymer structural lining is one of the most used methods. In order to restore lost structural integrity, cementitious ingredients are centrifugally sprayed on the internal surface of a damaged host pipe. Sprayed materials thickness depends on the design requirements and life span. Geopolymer materials consist of epoxy, shotcrete, polyester, silicone, urethane, and vinylester. This method's benefits include being adaptable to any form and diameter without requiring a modification to the spraying equipment, seamless and solid repair with a minimum thickness, low cost, and quick application [2].

There are many benefits to rehabilitating existing CSPs structures versus replacement of the whole pipe or structure, especially economically. In addition, greater flexibility in scheduling the project and crew, less traffic control costs and lower environmental effects at the job site are other benefits of rehabilitating the structure in place. Also, the cost of rehabilitation has been found to be about one fifth to one fourth of replacement cost and would extend the service life of the structures by approximately 25 to 50 years.

1.2. Project objectives

The main objective of this research was to determine the effectiveness of using SAA and LiDAR survey methods to monitor the performance of a Geospray lined CSP. The Following activities were undertaken to achieve the project objectives:

- Installing field instrumentation.
- Running static and dynamic tests before and after geospray application.
- Collecting SAA and LiDAR data.
- Data interpretation to determine culvert deformation.

1.3. Scope of work

The existing CSP culvert, DE03 (Route 127) Culvert No. 2 in Charlotte County, was selected for field instrumentation and monitoring in this study. The culvert is in the southwest New Brunswick region, which is approximately 100 km southwest of the City of Fredericton, New Brunswick. This culvert, subject of present research was rehabilitated with a mortar lining system, and geopolymer application was done to achieve an approximate thickness of 60 mm in three coats, with one coat applied per day.

In this project ShapeArray (SAA) is used to record displacements of the culvert. ShapAarray is installed in circular orientation inside the pipe. Each segment of SAA records a specific coordinate as a signal and the data is transferred to the data acquisition system (DAS). In addition to the SAA data, Laser Scanning survey method (LiDar) was used to assess culvert deformation and determine cross-sectional shapes at certain intervals (30 Centimeters) along the culvert before and after lining application.

In this field project two types of load tests were done. Static loading tests were done before and after GSL application. The test vehicle, a dump truck with specific weight was supplied by NBDTI and was used to conduct load testing.

This report evaluated the performance of rehabilitated culvert, especially culvert deformation under different static loading conditions.

1.4. Reader's guide

First chapter is introduction to the project, Chapter 2 summarizes similar studies related to the topic of this study, Chapter 3 explains the field condition, instrumentation procedures, static testing methodologies, and results, and Chapter 4 presents conclusion of this study.

2.0. LITERATURE REVIEW

In this chapter, several research and studies that have been conducted in the past to assess the performance of CSP are reviewed.

2.1. Corrugated Steel Pipe

Modern drainage system engineering continues to rely heavily on corrugated steel pipe (CSP). CSP was created in 1896 and has been used successfully for more than a century. CSP is produced in a variety of forms and sizes, with diameters ranging from 15 centimeters to more than 15 meters. Steel-soil interaction structures have practically limitless strength and integrity [2]. More than 30 meters of fill height can be accommodated by CSP structures. CSP is offered with a wide range of protective coatings which have been shown to fulfill the needs of demanding environments. Using the appropriate coating, specific to the area and application, service life can exceed 100 years. CSP is a reasonably priced product that can be installed quickly these days. CSP can be installed even during extreme weather conditions because it is not much susceptible to climatic variability or moisture. Engineers can use equipment more effectively because of quick installation and steel's inherent strength. Contractors and project owners who are concerned about costs choose CSP because it combines a strong, long-lasting product with simple installation. A material's durability refers to its ability to resist against deterioration brought on by corrosion, abrasion, applied loads, and installation techniques. A number of factors, such as soil resistivity, acidity (pH), moisture content, soluble salts, and oxygen content, affect how long steel pipe will last in soil. The majority of soils have a pH between 6.0 and 8.0, which is recognized as neutral and is an acceptable range for steel pipe durability, but acidic soils, which are more frequently found in areas with considerable rainfall, have lower pH values and tend to be more corrosive. The amount of moisture in the soil can also have an impact on CSP's durability. Moreover, Granular soils that allow the culvert’s backfill to drain quickly increase durability, and low moisture content soils are often not corrosive to CSP. High clay content soils are more corrosive than well-drained soils because they tend to hold water for longer periods of time [2]. All these factors cause the CSP to degrade and deform.

2.2. General Culvert Rehabilitation Methods

The rehabilitation methods discussed here are intended to restore the culvert to its initial structural integrity. The common methods are as following:

- Paved invert
- Cured-in-place pipe liner
- Sliplining
- Centrifugally cast liner

The focus in this research is on the centrifugally cast liner inside the CSP. Table 1. Shows the details of various methods listed above.

Table 1. Culvert Rehabilitation Methods details [2].

Methods	Design	Material	Construction
Paved invert	Structural integrity assessment (partially or completely deteriorated)	Welded wire fibric and ready-mix concrete	• Removal of damaged parts • Surface preparation • installation of paved invert • installation of protective systems • quality control.
Cured-in-place pipe liner	Design based on the loads including soil, live and hydrostatic loads.	flexible needled felt layers (nonwoven or woven material with ability to carry resin)	• Removal of damaged parts • Surface preparation and External Void Filling • Liner insertion • Curing (hot water, steam, or Ultraviolet light) • quality control.
Sliplining	Design based on the structural capacity, hydrostatic capacity, and associated loads.	High-density polyethylene fibres and grout	• Surface preparation • Liner installation with bulkhead • Grouting the annular space • End Treatments • quality control.

Centrifugally Cast Liner	Design based on the structural capacity, liner thickness and hydraulic capacity	Cementitious materials containing fibers	• Surface preparation • Joint repairs and fill all gaps • Lining application • Curing and quality control.

2.3. Centrifugally Cast Liner (Culvert Rehabilitation Method Investigated in this Study)

As seen in Figure 2.1, centrifugally cast liners are liners that are installed in the interior of the culvert by a spinning head that is powered by air or electricity. Liner's material can be cementitious mortars, polymers etc. These materials are typically used on CSP culverts to increase structural strength and give corrosion protection. Pipes with diameters of 75 to 300 centimeters can be lined with this method. The thickness depends on the speed of cast and how fast the machine is moving through the culvert.

Figure 2.1. Centrifugally Cast Liner Installation [2].

By assuming that the liner is a thin tube that is subjected to a uniform radial external pressure, the buckling capacity of these liners is calculated. The estimate is conservative in that it assumes that the present culvert has no structural capacity. However, the Engineer will need to evaluate the assumption of uniform radial external pressure for each individual project. The minimum flexural strength required needs to be determined and approved. The lined culvert has smaller diameter, and adequate hydraulic capacity should be taken into consideration.

The specific mix result in a finished product should be abrasion and corrosion resistant. The materials properties of the liner should be:

Minimum flexural strength of 7.5 MPa, Minimum 28 days compressive strength of 55 MPa, and no damage after 300 cycles of freeze and thaw [2].

Surface of the pipe should be clean and without any debris to guarantee the liner material bonds with the host pipe. It could be better to fill in any irregularities or sudden changes in culvert shape to create more gradual transitions. The liner can be applied more evenly in this manner. Alternatively, after the liner installation is finished, these areas can be repaired using mortar.

It is recommended to pave the culvert invert before installing the liner if it is very uneven or corroded. In addition to giving the machine's skids a flat surface to travel on, this also fills voids. High strength and free flow are required for the selected mortar.

The mortar supplier normally use high-speed rotating applicator. The provider of the mortar may specify typical commercial models and other equipment including pumps, compressors, and mortar mixers. The spinning applicator, which is dragged through the culvert, places the liner inside the culvert. Coordination between rotational speed and withdrawal rate results in the desired thickness. For the specified thickness to be achieved, it can take several passes.

To ensure the quality and control of work, the following should be monitored during construction:

• Visual inspection: The liner should be examined visually for issues such dropouts, uneven, and irregular surfaces.

• Liner thickness: Using a laser profiler that is connected to a pipeline camera, a survey is the best technique to determine liner thickness. On the inside of the pipe, a ring of laser light is projected at a perpendicular angle to the direction of camera's movement. The surface of the pipe can then be represented in charts and cross sections using software. Surveys should be conducted to check the thickness before and after lining is installed.

• Compressive strength: Two-inch cubes samples should be taken out from casted materials during the application to assess compressive strength for QC and QA [3].

Regular inspections should be carried out. It is advised to do more frequent checks to make sure the liners are functioning as intended [2].

2.3.1 Canadian Research in Centrifugally Cast Liner and Geopolymer Liners

In 2013, research conducted by Moore and García (2) at the Queen's University at Kingston, Ontario, Canada describe large-scale testing of geopolymer liner application to corrugated metal pipe (CMP). Three damaged and deteriorated CMP culverts were excavated from the E407 Toll Road in Ontario. Two culverts with 1200 mm in diameter and 7 meters long, were assembled out of three deteriorated corrugated steel pipe segments and buried in the laboratory under controlled soil fill conditions. The assembled culverts were tested under Canadian Highway single axel loads standards under a burial depth of 1200 mm. The 2 culverts were then repaired with GeoSpray geopolymer mortar lining with target thickness of 50.8 mm and 76.2 mm and were allowed to cure for 28 days. Testing of the culverts was performed under single and tandem axel loads with buried depths of 1200 mm and 2100 mm respectively. The burial configuration and elevation is shown in Figure 2.2 [4].

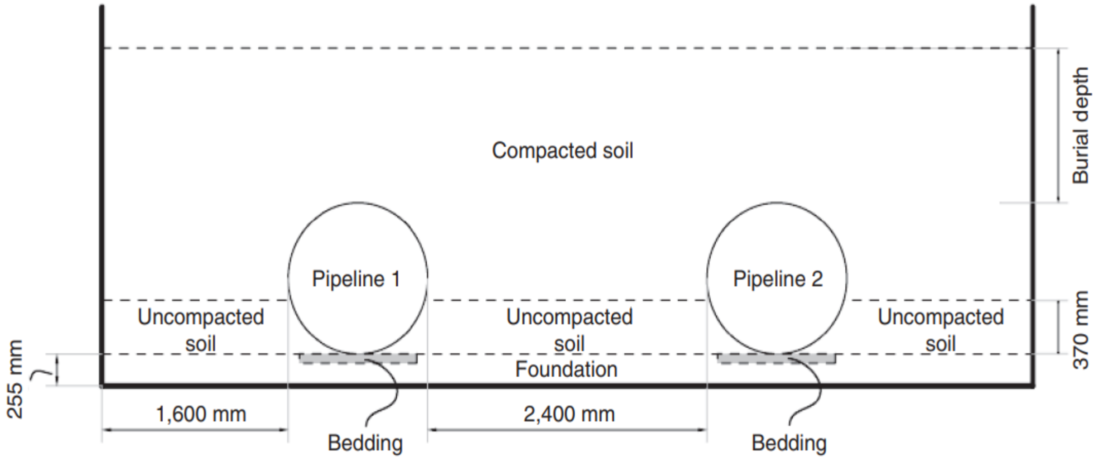


Figure 2.2. Burial configuration [4].

Sprayed material was geopolymer nano-ceramic mortar and water and was applied to the culverts through a spinning head. The liner application was done in two days in stages. Two passes for each pipe on day 1, one additional pass for Pipeline 2 and two additional passes for Pipeline 1 were performed on day 2. Figure 2.3. shows the pipelines after liner application [4].

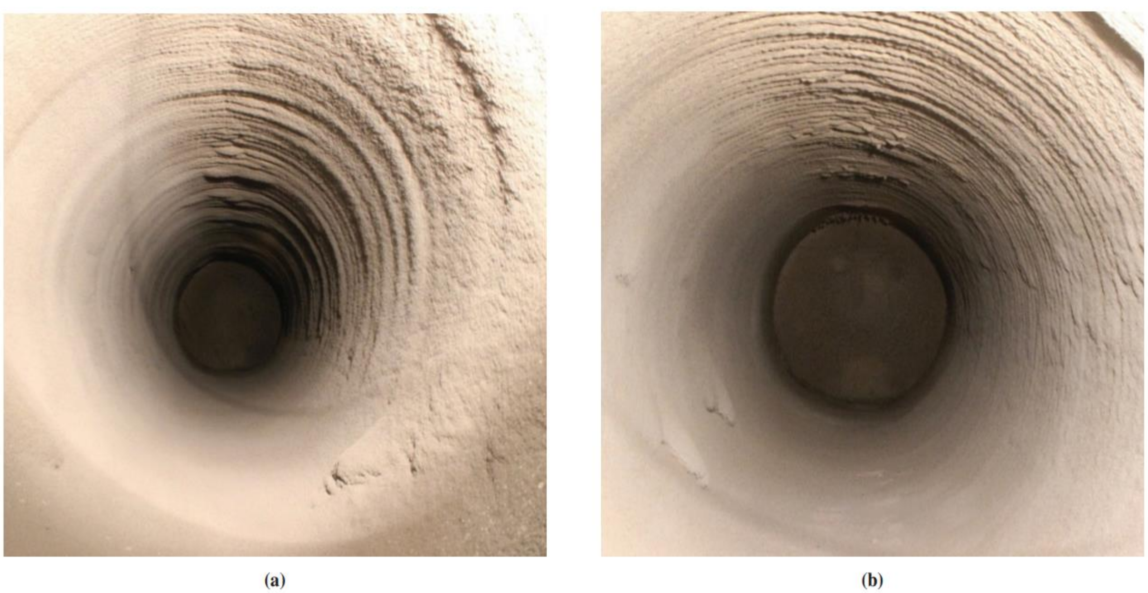


Figure 2.3. Pipelines after liner application, (a) Pipeline 1 and (b) Pipeline 2 [4].

During load testing of culvert 1, the first signs of liner cracking occurred at a tandem axle load of approximately 800 kN, 45% higher than the fully factored load of 552 kN for the culvert. The first crack was circumferential and additional signs of cracking then occurred at loads of 850 kN and 900 kN. For culvert 2, signs of initial cracking occurred at 650 kN, 18% higher than the fully factored load of 552 kN for the culvert. Furthermore, major signs of cracking were shown at loads of 750 kN and then 800 kN. By exhumation of culverts after testing, liner thickness distribution around the pipe circumference was measured. The liner in culvert 1 had a target thickness of 76.2 mm and was observed to have a mean thickness of 64 mm or 84% of the target thickness, with a crown thickness of 73 mm, 96% of the target, invert thickness of 57 mm, 75% of the target, and spring line thicknesses of 60 and 71 mm, 79% and 93% of the target respectively. The liner in culvert 2 had a target thickness of 50.8 mm, with a mean thickness of 44 mm, 87% of the target thickness, crown thickness of 58 mm, 114%, invert thickness of 43 mm, 85%, and spring line thicknesses of 37 and 47 mm, 73% and 93% of the target thickness respectively [4].

The findings of the research done at the Queen’s University are considered the most significant and subsequent practice and research is based on this work.

2.3.2 Field Case Studies of Centrifugally Cast Liner

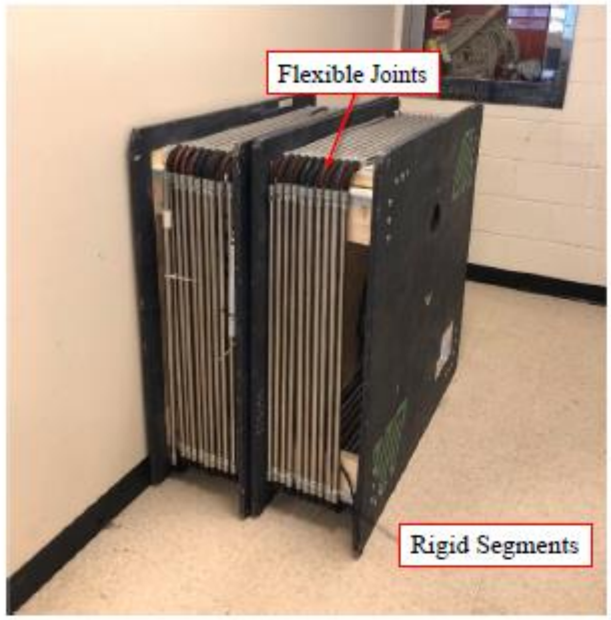
Recently, Haixue et al. [5] presented Canadian Case studies where geospray liner methodology was used to rehabilitate two culverts in Ontario. The lessons learned from the construction activities are provided which are similar to discussion presented in sub-section 2.3.1. The paper also reports that the design methodology of distributed beam across a partial ring is conservative in comparison to the finite element analysis performed by the authors. It is worth noting that no instrumentation or field monitoring consisting of load testing was performed in this research [5].

2.4. Monitoring system of CSP.

2.4.1. ShapeArray sensors (Horizontally installed).

ShapeArray sensors (SAA) is an instrumentation that can measure small deformations by monitoring the structure continuously. A site with ground's soft spots, located in Sarnia, Ontario, Canada, at Mile 13.75 of the CN Rail St Clair Subdivision, was monitored with two methods of instrumentational monitoring, SAA and LIDAR scans. Track settlements have been investigated by both methods and results have compared to each other to evaluate methods performance and accuracy. The data gathered from The SAA was comparable to that from LIDAR with the additional advantage of measuring settlement of the track. Long-term rail settlements at this location were discovered to depend on seasonal and climatic factors, with slower rates during the winter and higher rates during the summer [6]. Figure 2.4. shows the SAA rolls and dimensions and configuration of ShapeArray instrumentation.

(a)



(b)

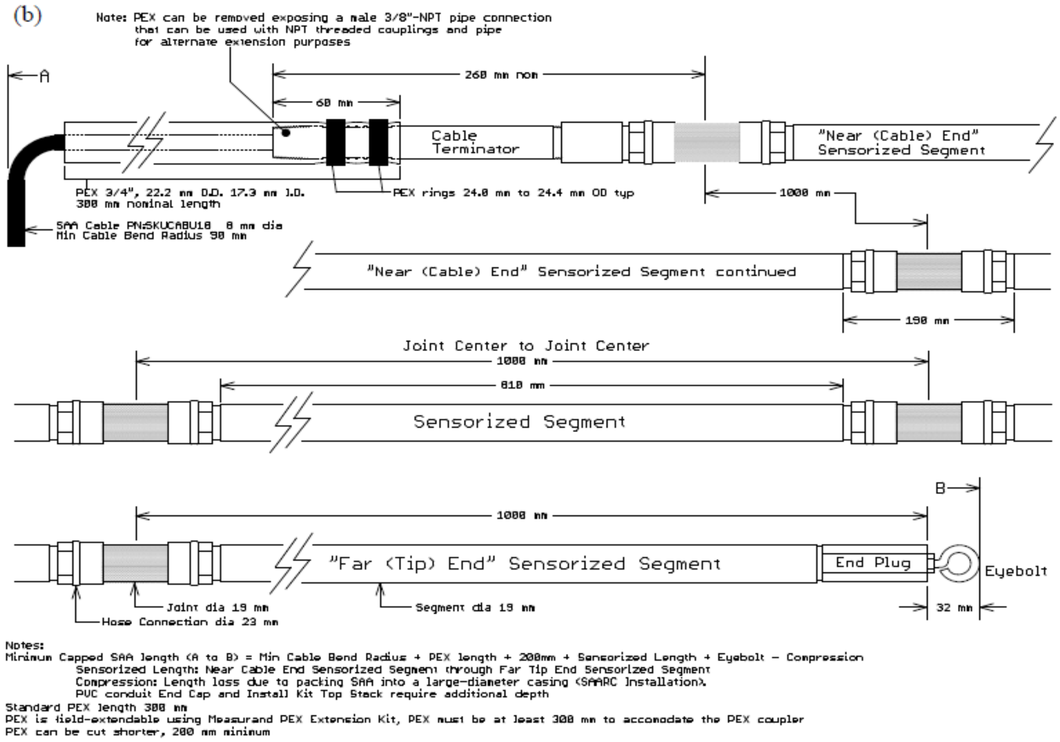


Figure 2.4. Horizontal SAA (a) On rolls for transportation and (b) Dimensions and configuration [6].

The field site is an industrial facility access line in Sarnia, Ontario, Canada, at Mile 13.75 of the CN Rail St Clair Subdivision. In order to evaluate sensor performance against the complete range of vertical deformations anticipated to be encountered in rail measurement applications, it is crucial that this site has a track rating that is comparable with substantial track deformations.

Two 40 m long SAA sensors were installed on the sleepers on each side of the track and deformation was measured under environmental loading and revenue service loading with two trains travelling daily through the monitored section over the nine-month monitoring period (August 2018 to May 2019). Full LIDAR scans of the track were conducted at the time of the SAA installation (baseline data), after small deformations (~5–10 mm), and after large deformations (~100 mm). Figure 2.5. shows the site and SAA installation details [6].

Figure 2.5. Sarnia test site (a) monitored track depression and (b) installation detail of the SAAs enclosed in steel conduits attached to the ties [6].

The following conclusions can be made from the field trial:

- A 40 m long SAA sensor determined the measurements of vertical track settlement at the site zone that were consistent with the results of LIDAR.
- Improvement of the SAA technique performance was observed when:

  1) the reading of the sensors was taken under low thermal gradients (i.e., at midnight rather than during daylight hours when the steel conduit and track were influenced by solar radiation), and

2) both ends of the SAA sensor were assumed fixed (i.e., zero displacement) rather than just one end.

- Installation of two SAA sensors on each side of the track enabled changes at both sides of the track to be identified. The calculation of the absolute cross-level of the track requires additional measurements besides SAA, e.g., LIDAR system, to determine the change in data during the time of SAA installation.
- In this study, recording period of 1 h was used to optimize battery use during the winter season. Rates of vertical settlement were observed at the field site varying from 43 mm/year during early fall (September to November), to 254 mm/year following the spring rainfall (mid-March to May).
- The differential LIDAR scan results indicate that the failure mechanism is combination of vertical and lateral deflection. While the SAA is designed to measure vertical displacement, the combined nature of the vertical and lateral deflection with this asymmetrical bearing capacity mechanism indicates how ShapeArray sensors could be used where the vertical settlement is the only component of track geometry change [6].

2.4.2. Monitoring Displacement versus Depth Using Shape Accelerometer Arrays (Vertically installed)

For establishing horizontal displacement against depth profiles during lateral pile load tests, SAA give engineers information that is relatively similar to that provided by inclinometer probes. These arrays typically consist of triaxial chip-based accelerometers located at different intervals (0.3 m intervals in this case) within flexible waterproof tubing.

These ShapeArray can provide a continuous and precise readout of displacement, velocity, acceleration, and rotation at each accelerometer location. The performance of the ShapeArray was compared to that of conventional inclinometer probes during a full-scale lateral pile load test. The test findings show that the ShapeArray can provide accuracy for static loadings in this study that is comparable to that from an inclinometer.

When doing lateral load testing, the horizontal displacement versus depth profiles on deep foundations are important. In the past, downhole inclinometer probes or strings were utilized to obtain these profiles. Typical inclinometer probes call for the user to measure slope inside a pipe that is normally concreted into place inside the pile at 600 mm intervals. The displacement of the pile must be held constant over a 15 to 20 minutes period while the inclinometer measurements are made. It is also possible to insert strings of down-hole inclinometers inside the inclinometer pipe at varied spacings. Although this option is more expensive, it enables faster and simultaneous measurement collection. Nevertheless, the displacement of the foundation must be held relatively constant for a period of several seconds so that the inclinometers can stabilize and provide an accurate reading. SAA consists of joint-connected rigid segments covered by a waterproof conduit, each containing triaxial chip-based accelerometers located at different intervals depending on the project. Along the length of the pile, arrays can be put into the concreted pipe. This device is capable of continuously displaying rotation, displacement, velocity, and acceleration. Also, array can monitor lateral pile behavior during dynamic loading as well as static loading tests. A field test was conducted as part of this study to assess SAA's performance and compare it with conventional inclinometer probes [7]. Figure 2.6. shows the configuration of the pile cap and instrumentations.

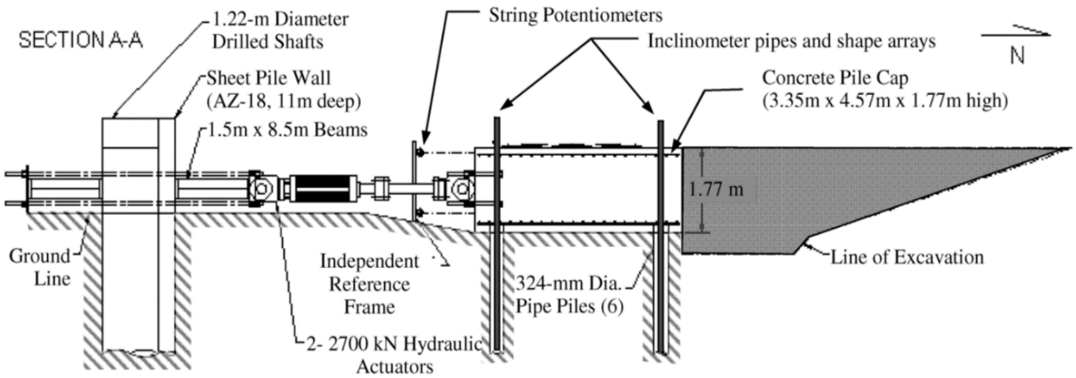


Figure 2.6. Configuration of pile cap, piles, and instrumentation for lateral load test [7].

Pile cap displacement was measured using three methods of instrumentation: string potentiometers, inclinometers, and SAA.

Enhanced results of the field testing and the analysis of the test findings are:

- For lateral pile load testing conducted under static conditions, the shape accelerometer array system can provide reasonably accurate and precise displacement versus depth profiles.
- The inclinometer and ShapeArray displacement differences were frequently less than 2 mm, demonstrating equal measurement precision.
- The ShapeArray system has the advantage of offering practically continuous displacement data at each sensor position throughout a test as opposed to traditional inclinometer measurements. By doing this, extended delays in the load test schedule and creep displacement are removed, both of which have the potential to negatively affect the pile head load-displacement curve.

- To increase accuracy during static loading, particularly at small displacements, and to enable usable measurements during dynamic loading, improved techniques of attaching the array to the PVC pipe are required [7].

2.5. Load Test

A common technique for determining the structural strength of CSP is to load test the culverts using a loaded truck that is moving or stationary. For static loading, this approach requires positioning a truck with a known load on top of the culvert at specific spots, and for dynamic loading tests, it involves moving the truck over the culvert at a predetermined speed. The performance of the culvert in responding to the moving load is then evaluated using a variety of tools, like SAA or LIDAR cameras. Based on research, Alderman [8] in 2012 for the field testing of the rehabilitated Kelly Creek No. 2 corrugated steel culvert, loaded truck spots for this project were selected. Figure 2.7. shows the loaded truck positions at both directions (north and south) [8]. (NF1: North direction, Front axle and position 1, NR: North direction, Rear axle, SF: South direction, Front axle, SR: South direction, Rear axle)

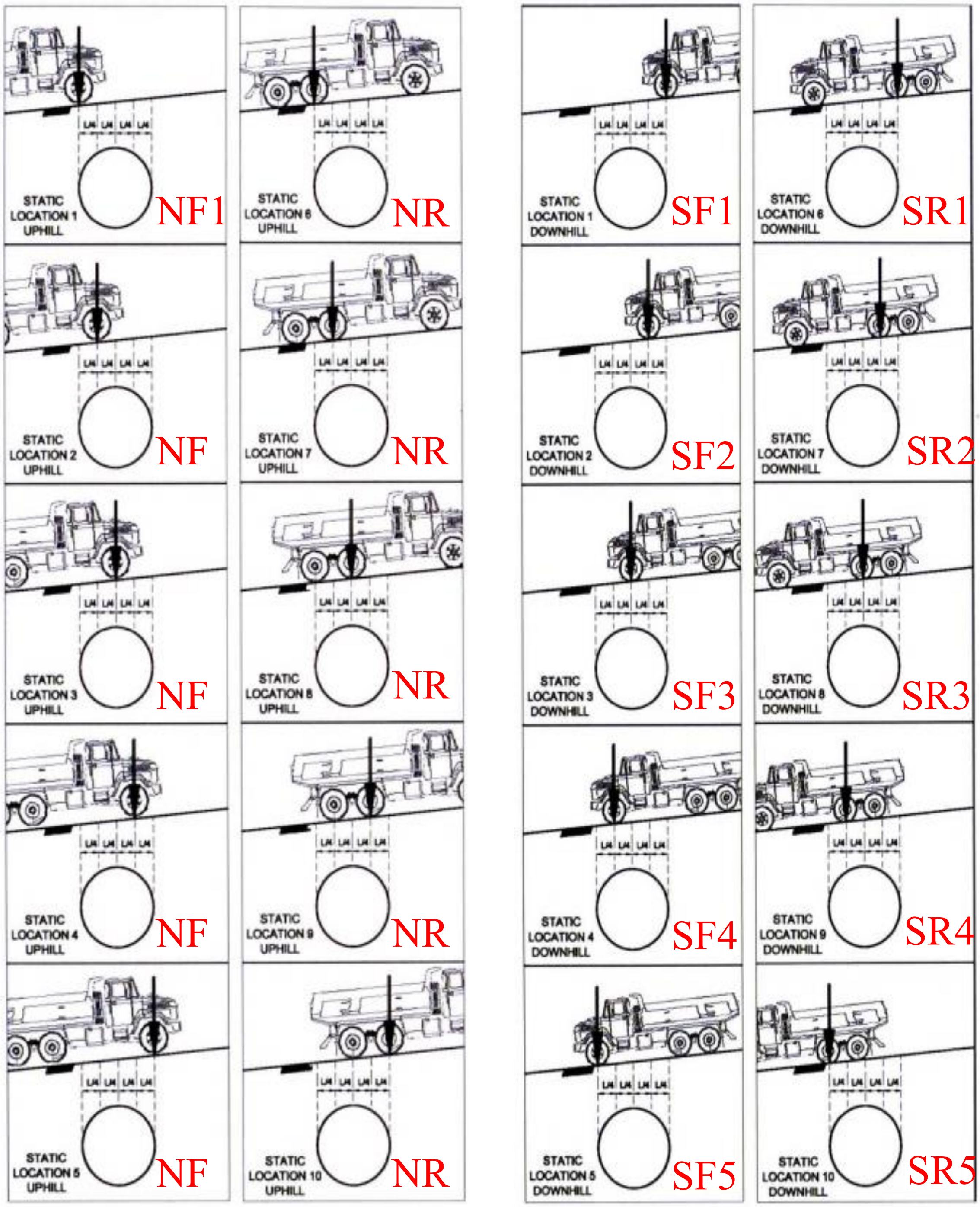


Figure 2.7. Truck locations for the static loading tests [8].

3.0. FIELD INSTRUMENTATION AND TESTING METHODOLOGIES

3.1. Description of the culvert and project

The existing corrugated steel pipe (CSP) culvert, DE03 (Route 127) Culvert No. 2 in Charlotte County, was selected for field instrumentation and monitoring in this study. The culvert is in the southwest New Brunswick region, which is approximately 100 km southwest of the City of Fredericton, New Brunswick and is shown in Figure 3.1.

The invert of the culvert were deteriorated and needed to be fixed to avoid culvert failure that could result in road failure and put traveling public at danger. Charlotte County Culvert No. 2 (DE03) was selected for this study as the culvert was proposed for rehabilitation with a mortar lining system, and geopolymer application was done to achieve an approximate thickness of 60 mm in four coats, with one coat applied per day. The culvert has a diameter of 1.55 m and an invert length of approximately 34 m and a slope of 4.1% (north to south). The corrugate steel plate thickness is 5 mm, and the corrugations are defined by a pitch of 125 mm (5″) and a depth of 25 mm (1″). Streambed to roadbed depth is 4 meters, so the depth of soil above the culvert is 2.2 meters. Liner applications were performed on November 23rd and 24th, 2021. Figure 3.2. shows the culvert plan and site details.

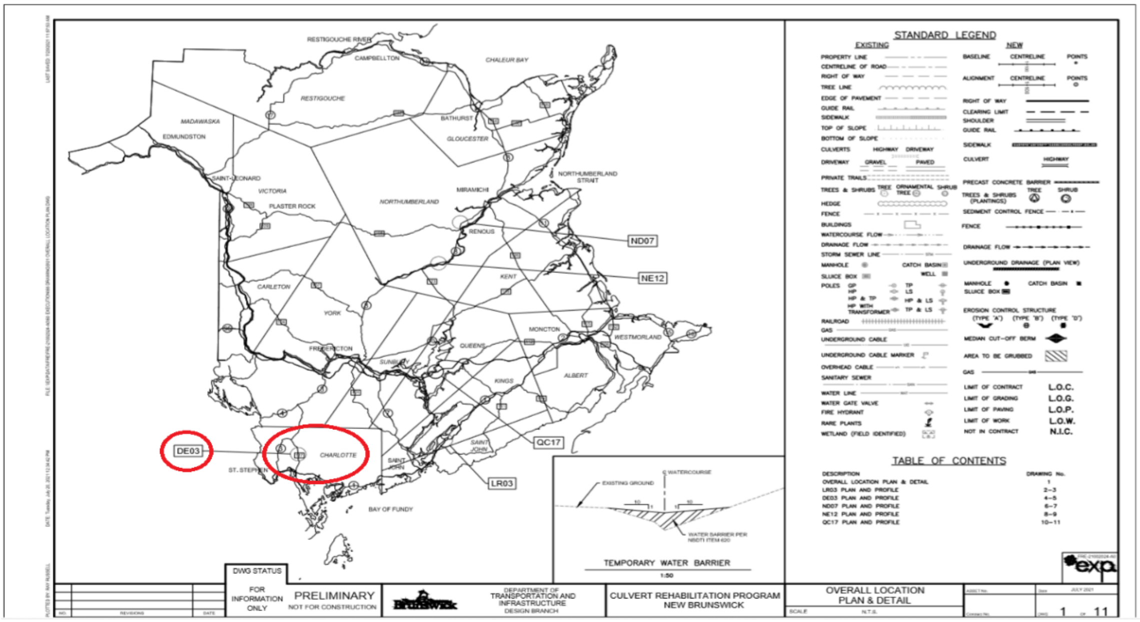


Figure 3.1. Location of the subject culvert in New Brunswick province.

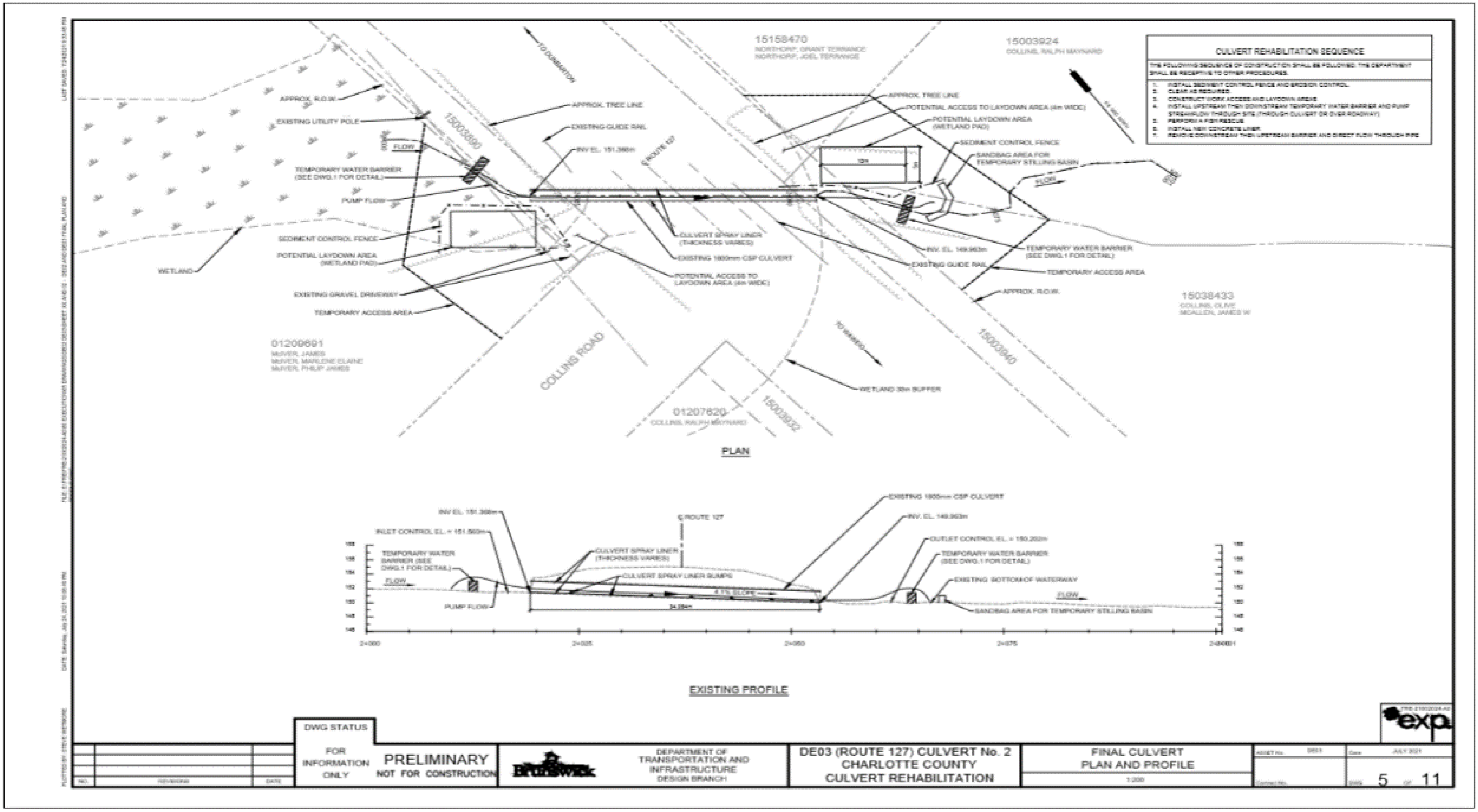


Figure 3.2. Culvert plan and profile provided by NBDTI.

Figure 3.3. CSP, view from the northern entrance

The invert, crown, or sidewalls of the pipe are examined throughout the cleaning process, and deteriorated sections were repaired to create a constant slope to the pipe. Prior to lining the pipe, all open joints are filled with grout or the geopolymer lining material. The pipe's interior walls and floor were thoroughly cleaned and clear of any dirt, rocks, sediment, or other objects that could prevent the geopolymer from bonding to the host pipe. Active leaks were fixed before the lining material was applied. For the purpose of stopping active leaks, the use of quick-setting mortars or grouts is recommended. Mortar laboratory properties is shown in Table 2. Geopolymer Pipe Lining Mortar manufactured by GeoTree Solutions (formerly Milliken Infrastructure Solutions, LLC) and conform to the following properties under laboratory conditions for quality assurance [10].

Table 2. Geopolymer pipe lining mortar laboratory properties provided by NBDTI [10].

Compressive Strength	ASTMC39 or C109	1 Day	17 MPa
		28 Day	55 MPa
Flexural Strength	ASTM C78	7 Day	5 MPa
		28 Day	9 MPa
Tensile Strength	ASTM C496	28 Day	6 MPa
Shrinkage RH	ASTM C1090	28 Day	0% at 65%
Modulus of Elasticity	ASTM C469	1 Day	20,000 MPa
		28 Day	35,000 MPa
Bond Strength	ASTM C882 Type II	1 Day	6 MPa
		28 Day	17 MPa
Freeze Thaw Durability	ASTM C666	300 Cycles	Zero Loss
Set Time	ASTM C807	Initial	< 75 min
		Final	< 120 Min

To control and stop water flow inside the CSP and discharge the collected water in the open area at the southern side of the CSP, a pumping station was constructed at the northern entrance of the culvert as shown in Figure 3.4.

Figure 3.4. Southern side of CSP before pumping (top left), Southern side of CSP after pumping (top right), northern entrance of CSP during pumping (bottom left) and stopped flow culvert and cleaning process (bottom right).

3.2. Instrumentation

In this study, ShapeArray (SAA) is used to record displacement at center of the culvert (under the right lane of the road, from north to south). ShapeArray was installed in circular orientation inside the pipe (before cleaning process). All segments and conduit contain extended cable of SAA, tightened to the culvert by pipe strap and wall screws. Conduits contain extended cable of ShapeArray , tightened to the crown of the culvert and extended to the data acquisition system (DAS) box. SAA had twenty-two segments, with the first segment shown with pink color and last segment has blue color as is shown in Figure 3.5.

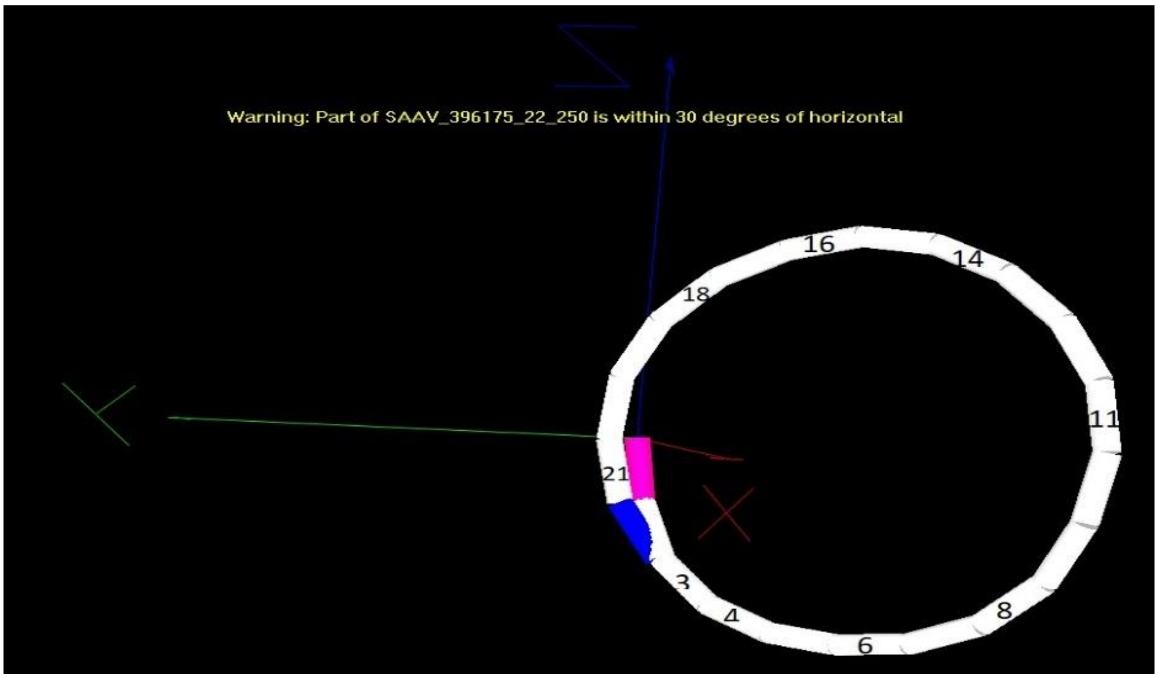


Figure 3.5. ShapeArray segments orientation.

Each segment of SAA records a specific coordinate as a signal and the data is transferred to DAS (segments 10, 11 20 and 21 are springline, segments 4 to 8 are invert and 14 to 17 are culvert crown). The data logger contains a sensor to receive the information and a computer chip to store it. The information stored in the data logger is transferred to a computer for analysis. In this study DAS is powered by a car battery and solar panel. In addition to the SAA data, Laser Scanning survey method (LiDAR) is used to assess culvert deformation before and after lining application. A 5-meter section of the culvert's length was used for the whole scan (2.5-metres on either side of the Centre of the culvert). Each complete scan started at the eastern end of the 5-meter section and moved toward the culvert's upstream side. A 360-degree 2D LiDAR scan was taken along the 5-meter section in increments of 30 centimeters, producing 18 cross-sectional scans that were used to determine cross sections along the culvert's central section. Along a sliding rail system, the LiDAR scanner was moved through the 5-metre segment. To make sure each full scan was in the same Z axis location for each full scan, a tripod was set next to the CSP's inlet and utilized as a reference point. The pull rods made of fiber glass were marked and stopped at intervals of 30 centimeters. On November 3, 2021, scans were taken before applying the lining. After the CSP had been spray lined, the same LiDAR scanning procedure was conducted on December 3, 2021.

LiDAR scanning work was done by Atlantic Data Acquisition Services Inc. that was hired directly by NBDTI and the details of LIDAR report are presented in appendix 1.

Table 3 and Table 4 present the coordinate of SAA segments. X coordinates refer to horizontal displacement of the segments and Z coordinates refer to vertical displacement of the segments.

	X0	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22
SF1	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.5
SF2	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
SF3	0.0	3.8	-72.8	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
SF4	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
SF5	0.0	3.8	-72.8	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
SR1	0.0	3.8	-72.8	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
SR2	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.0	-467.1	-373.1	-289.6	-221.1	-156.6	-97.1	-65.8	-53.6
SR3	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.5
SR4	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.5
SR5	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NF1	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NF2	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NF3	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NF4	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.1	-289.6	-221.1	-156.6	-97.1	-65.8	-53.6
NF5	0.0	3.8	-72.7	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NR1	0.0	3.8	-72.8	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.3	-652.6	-566.0	-467.1	-373.0	-289.6	-221.0	-156.6	-97.1	-65.8	-53.5
NR2	0.0	3.8	-72.8	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NR3	0.0	3.8	-72.8	-165.9	-274.1	-394.9	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.0	-467.1	-373.1	-289.6	-221.0	-156.6	-97.1	-65.8	-53.6
NR4	0.0	3.8	-72.8	-165.9	-274.1	-395.0	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.1	-467.1	-373.1	-289.6	-221.1	-156.6	-97.1	-65.8	-53.6
NR5	0.0	3.8	-72.8	-165.9	-274.1	-395.0	-513.8	-623.3	-709.4	-790.0	-799.3	-774.3	-713.4	-652.6	-566.0	-467.1	-373.1	-289.6	-221.1	-156.6	-97.1	-65.8	-53.6
Baseline	0.0	3.7	-73.4	-167.1	-275.9	-397.4	-516.8	-626.2	-712.0	-792.3	-801.5	-776.4	-715.6	-654.7	-567.9	-468.2	-373.2	-288.5	-218.9	-153.8	-94.0	-62.8	-50.8

Table 3. X coordinates of segment's tip based on the first segment's sensor's coordinate (0,0)

	Z0	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15	Z16	Z17	Z18	Z19	Z20	Z21	Z22
SF1	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
SF2	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	611.0	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
SF3	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
SF4	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
SF5	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
SR1	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
SR2	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
SR3	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
SR4	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
SR5	0.0	-247.8	-467.1	-628.2	-718.2	-744.7	-724.0	-639.3	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10/9	-255.0	-469.5
NF1	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NF2	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NF3	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-11.0	-255.0	-469.5
NF4	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NF5	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NR1	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NR2	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.3	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NR3	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.4	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NR4	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.3	-479.6	-265.5	-19.9	226.1	439.0	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
NR5	0.0	-247.8	-467.1	-628.2	-718.3	-744.7	-724.0	-639.3	-479.6	-265.5	-19.9	226.1	439.1	610.9	717.0	751.4	707.1	604.8	440.7	229.2	-10.9	-255.0	-469.5
Baseline	0.0	-247.8	-466.6	-627.3	-717.4	-743.9	-723.3	-639.0	-479.4	-265.4	-19.7	226.2	439.2	611.0	717.2	751.6	705.9	604.9	440.8	229.4	-10.7	-254.8	-469.1

Table 4. *Z* coordinates of segment's tip based on the first segment's sensor's coordinate (0,0)

Figure 3.6. ShapeArray before unboxing (top left and right), ShapeArray tightened to the culvert by pipe strap and wall screws (middle left and right), All segments installed ShapeArray orientation (bottom left) and DAS box (bottom right).

3.3. Field testing

The static load testing was undertaken on Wednesday November 3rd, 2021. The test vehicle was a dump truck weighing 14,340 kg which was supplied by NBDTI and was used to conduct static load testing. The truck was loaded with 6,420 kg of gravel bringing the total weight of the truck to 20,760 kg. The test truck is shown in Fig. 3.7.

Twenty static load tests were completed, ten times in each traffic direction before and after lining application. The test locations (five spots) for the truck over the culvert during the static tests was the exact middle spot of the culvert under the right lane of the road from north to south (14.75 meters away from northern entrance of the culvert). The truck was positioned over each location for approximately 20 seconds before moving to the next location as shown in Figure 3.8.

Figure 2.7. in previous chapter shows loaded truck locations for static load testing.

Figure 3.7. Loaded test truck.

Figure 3.8. Test location over the culvert and truck position.

3.4. Test results

3.4.1. Dynamic load testing

ShapeArrays can be used to measure dynamic acceleration or vibration. Twelve dynamic load tests were also completed, six in each direction before and after lining application. The speed of the truck for the dynamic tests was increased from 10 km/hr to 50 km/hr, at 20 km/hr intervals. However, dynamic tests data were collected in order to evaluate relevant contribution of liner under different acceleration or vibration that applied by loaded truck or the worst-case scenario through traffic, but interpreting the dynamic tests data was not within the present scope of study.

3.4.2. Static load testing

The most critical segments regarding vertical displacement are the segments that are mounted on the crown of the culvert (segment 14, 15, 16 and 17) considering Figure 3.9 and Figure 3.11, and the segments that mounted at the bottom of the culvert (segment 5, 6 and 7) shown in Figure 3.5. However, the most important segments for horizontal displacement are the segments which are mounted close to the springline along both sides (segment 3, 10, 11 and 20) considering Figure 3.10 and Figure 3.12. For calculating vertical and horizontal displacements under static loading, displacements, Segment 1 was assumed to have a displacement of zero as the main objective was to determine relative deformations of the culvert before and after rehabilitation. For instance, the maximum vertical displacement in south direction static loading test were measured as 0.013 mm at SR4 position and -0.013 mm at SR5 position at segments 20 and 15 respectively.

South direction

Displacement data gathered from SAA in the south direction of the road over the culvert is presenting in Figs. 3.9. and 3.10.

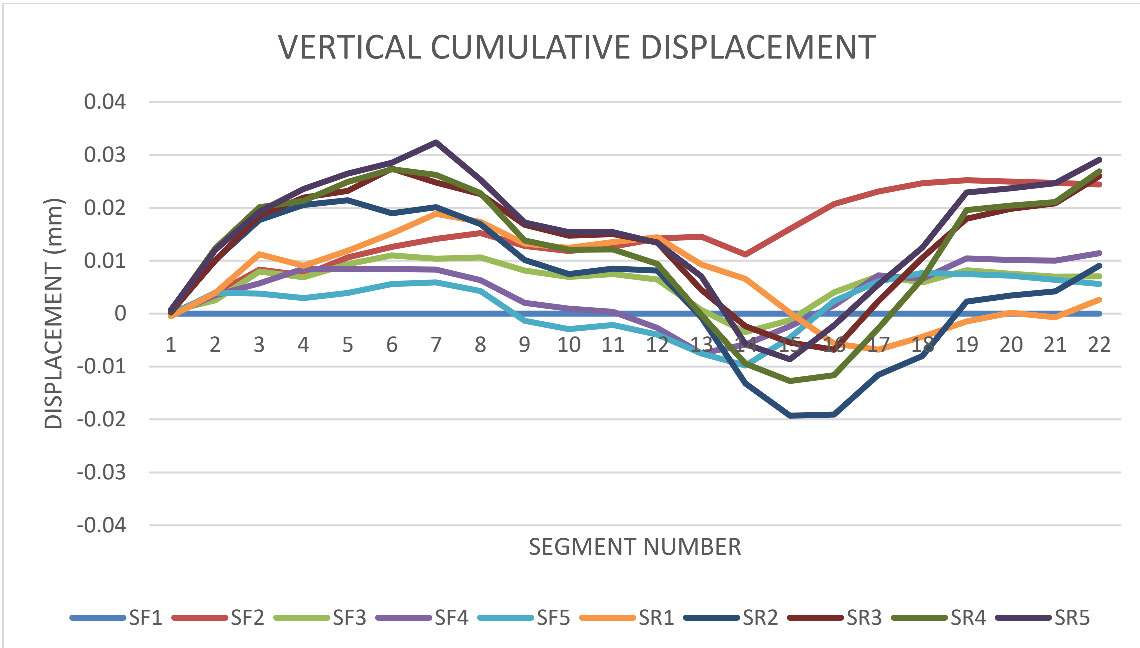


Figure 3.9. Vertical cumulative displacement in south direction before lining application.

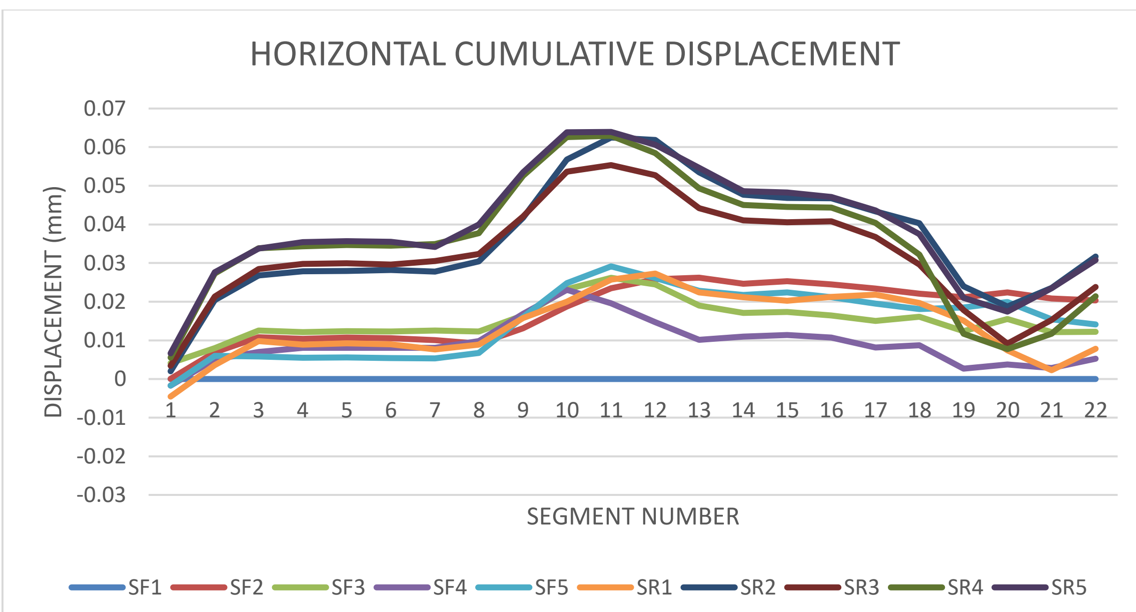


Figure 3.10. Horizontal cumulative displacement in south direction before lining application.

North direction

Displacement data gathered from SAA in the north direction of the road over the culvert are presenting in Figure 3.11. and Figure 3.12.

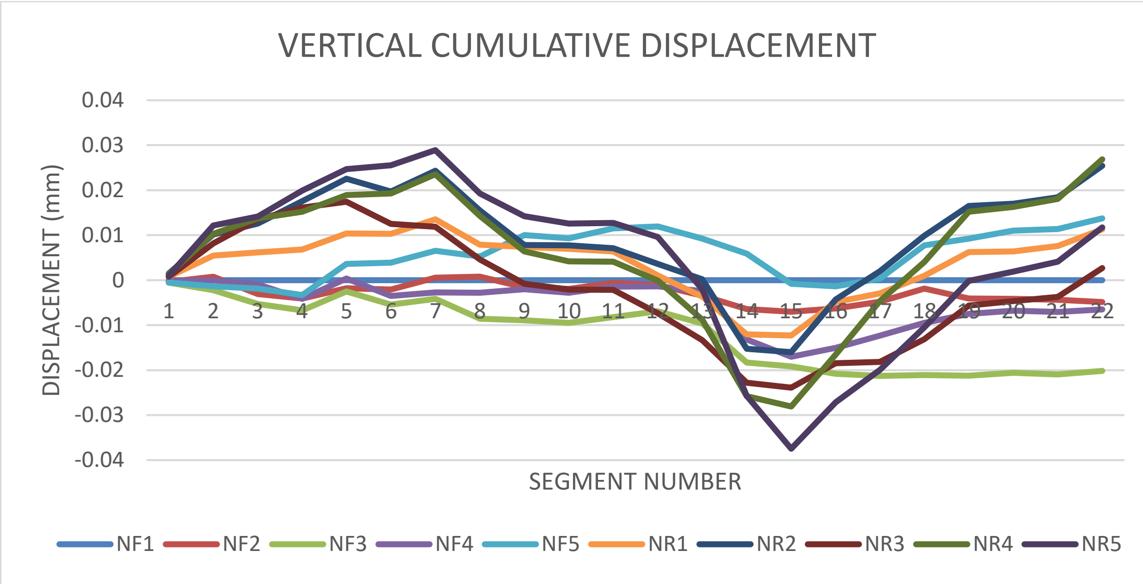


Figure 3.11. Vertical cumulative displacement in north direction before lining application.

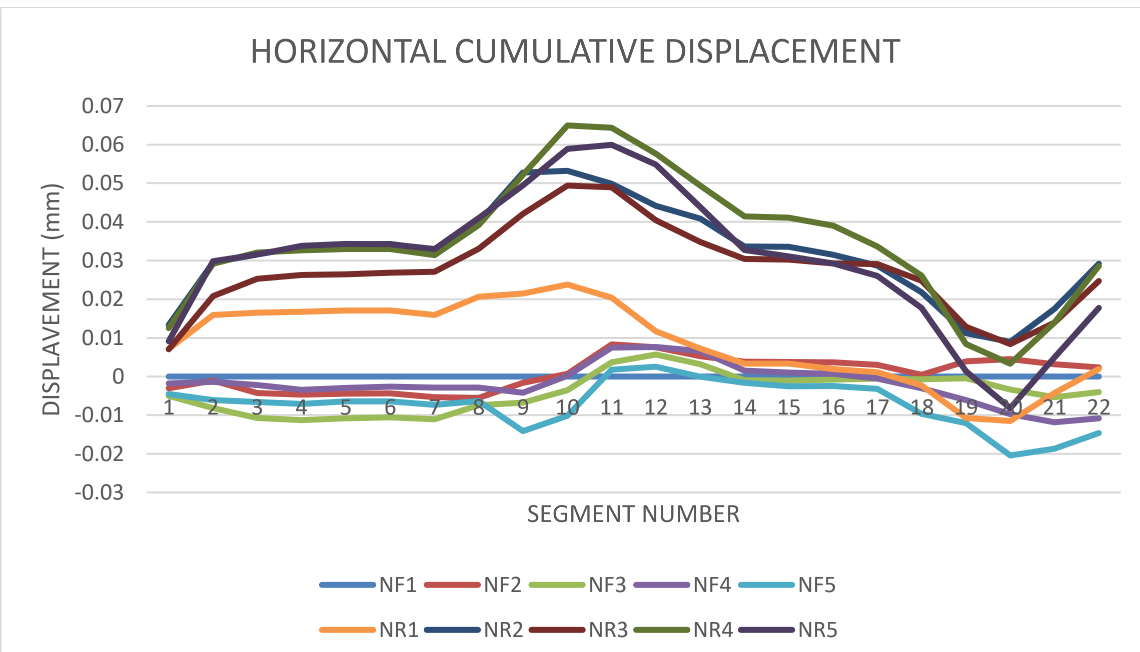


Figure 3.12. Horizontal cumulative displacement in north direction before lining application.

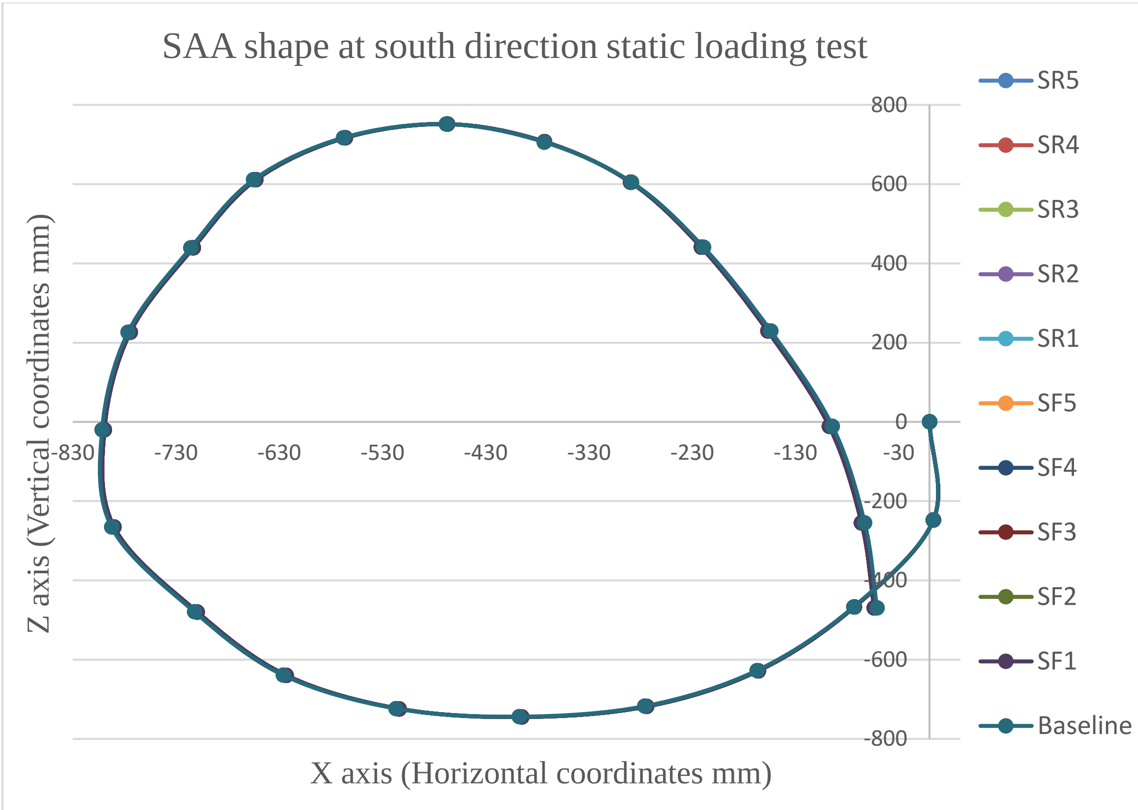


Figure 3.13. shape of culvert based on recorded coordinate by ShapeArray. Baseline (without loading) and 10 loading positions in south direction before lining application.

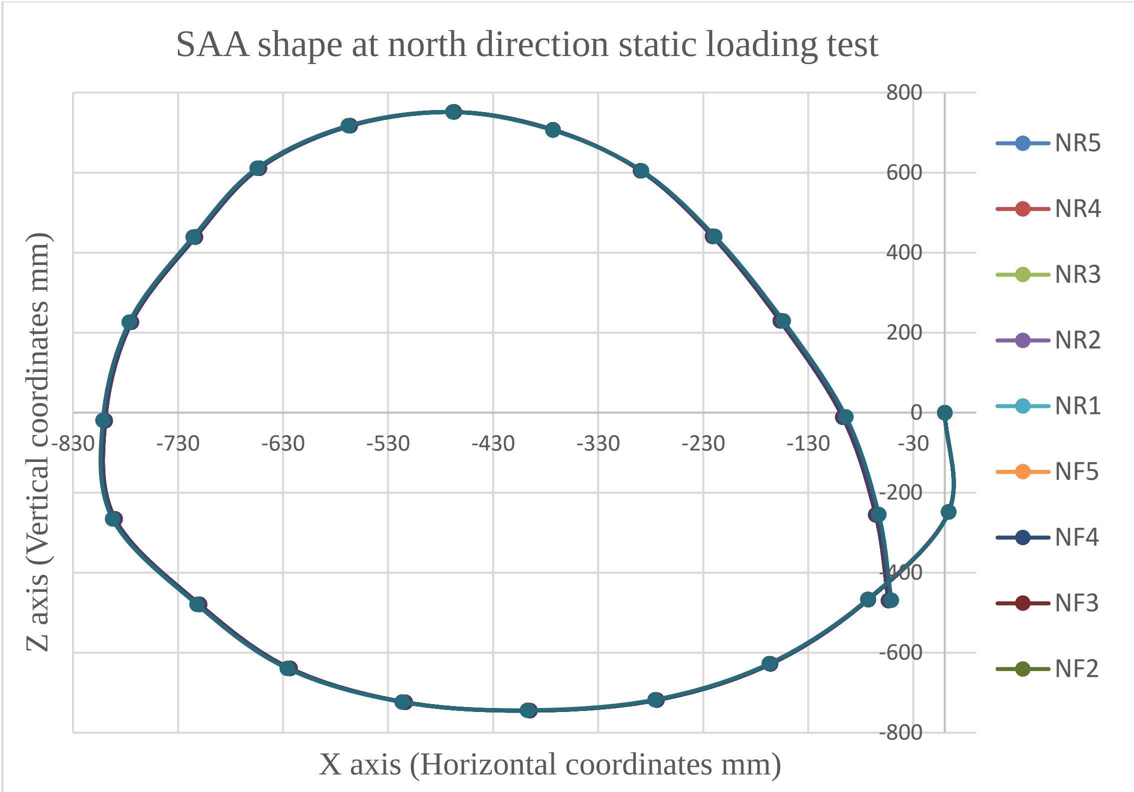


Figure 3.14. shape of culvert based on recorded coordinate by ShapeArray. Baseline (without loading) and 10 loading positions in north direction before lining application.

The baseline data and the additional 10 loading positions after lining application differ slightly in both the north and south directions, as seen in Figures 3.13 and 3.14, and all of the displacement readings are practically identical.

4.0 CONCLUSIONS

The field testing was successfully accomplished in line with the project's criteria, which included measurements of the culvert deformation using SAA. The following conclusions of the field testing are presented:

- The segments positioned near the springline along both sides are the most important in terms of horizontal cumulative displacement (segment 3, 10, 11 and 20).
- Maximum vertical displacement for north and south lane loading is 0.04 mm at NR5 position and 0.03 mm at SR5 position, respectively. For north direction loading, the maximum horizontal displacement is 0.06 mm at NR5 and NR4 positions, while it is slightly larger than 0.06 mm at SR5 and SR4 positions in south direction. Maximum vertical displacement in the aforementioned positions occurred in both directions at segments 7 and 15. Maximum horizontal cumulative displacement at those positions happened at segments number 10 and 11 in both directions.
- The key finding of this report was that the SAA technology is capable of measuring a continuous deformation profile of culverts.
- The static loading tests with a loaded truck did not result in any noticeable deformation at any CSP spots, but ShapeArray technology has demonstrated that even the smallest deformations can be continuously recorded by this device.

- ShapeArray instrumentation results are very accurate and reliable by comparing them to LiDAR data, and that there is good agreement in deformation measurements between SAA and LiDAR.

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APPENDIX I

ROLLINGDAM, NB

December 26, 2021

ABSTRACT:
LiDAR scanning of unlined and post lined Culvert along NB Route 127 using a 2D 360-degree LiDAR scanner.

Atlantic Data Acquisition Services Inc.

December 26, 2021

Joe MacDonald, P.Eng.
NBDTI
Kings Place
440 King Street
Fredericton, NB E3B 5H8

Dear Mr. MacDonald,

Atlantic Data Acquisition was assigned to perform 360-degree Two-Dimensional (2D) Light Detection and Ranging (LiDAR) scans of a Corrugated Steel Pipe (CSP). The scans were to be conducted along NB Route 127 at Rollingdam as located in **Figure 1** below.

LiDAR scans were conducted on November 03rd and December 03rd of 2021.

Figure 1. *Site location.*

The assignment consisted of two parts: "Unlined" culvert scans and post "Lined" culvert scans. The Unlined scans were to set a baseline and was conducted on November 03rd. Four complete scans were conducted on November 03rd, consisting of an unloaded scan and then continuing to loaded scans. The unloaded scan was conducted without any additional loading of the crown of the culvert. Then a loaded vehicle (**Picture 1.**) was statically placed at three predetermined positions seen in **Picture 2**, **Picture 3**, and **Picture 4** below. A full scan of the culvert consisted of a 5-metre section of the length of the culvert. This 5-metre section was located 2.5-metres on either side of the Centre of the West (south bound) lane of Route 127. Each full scan began at the eastern end of the 5-metre section moving towards the inlet end of the culvert. At 30 centimetre increments a 360 degree 2D LiDAR scan was captured along the 5 metre section resulting in 18 cross-sectional scans as seen in **Figure 2 & 3** below.

Picture 1. *NBDTI Vehicle - Loaded Plow Truck.*

Picture 2. *NBDTI Vehicle - Loaded Plow Truck at Static Location 8 – Front Rear Tandem Axle over Crown.*

Picture 3. *NBDTI Vehicle - Loaded Plow Truck at Static Location 9 – Rear Tandem Axles Centred over Crown.*

Picture 4. *NBDTI Vehicle - Loaded Plow Truck at Static Location 10 – Rear Tandem Axle over Crown.*

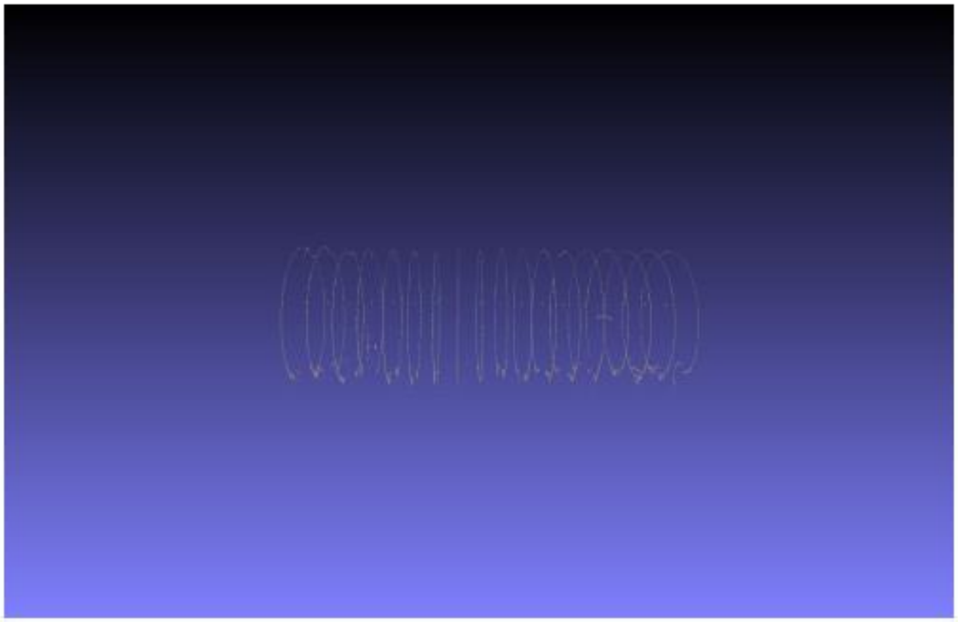


Figure 2. *18 LiDAR scanned cross-sections of a 5-metre section of CSP.*

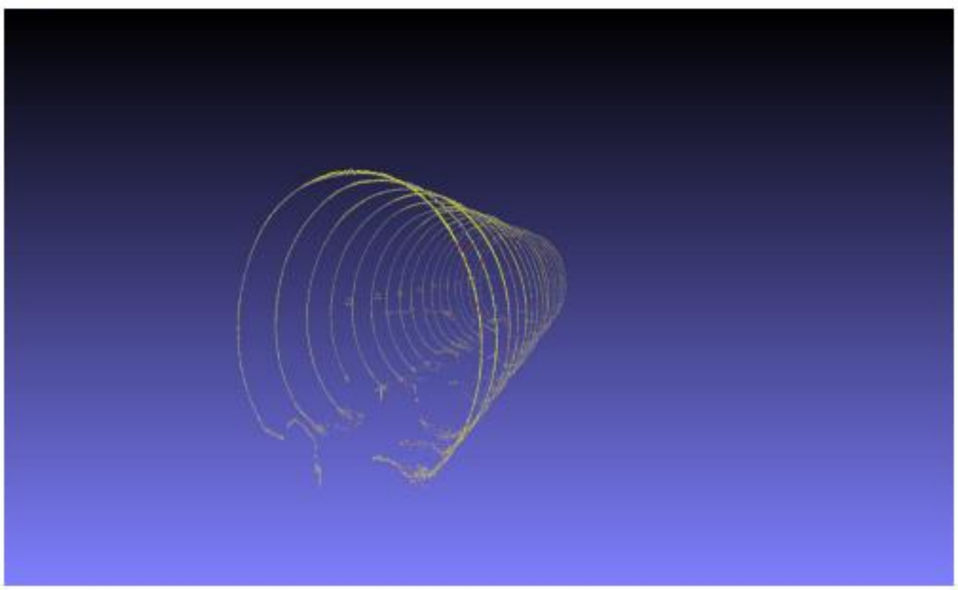
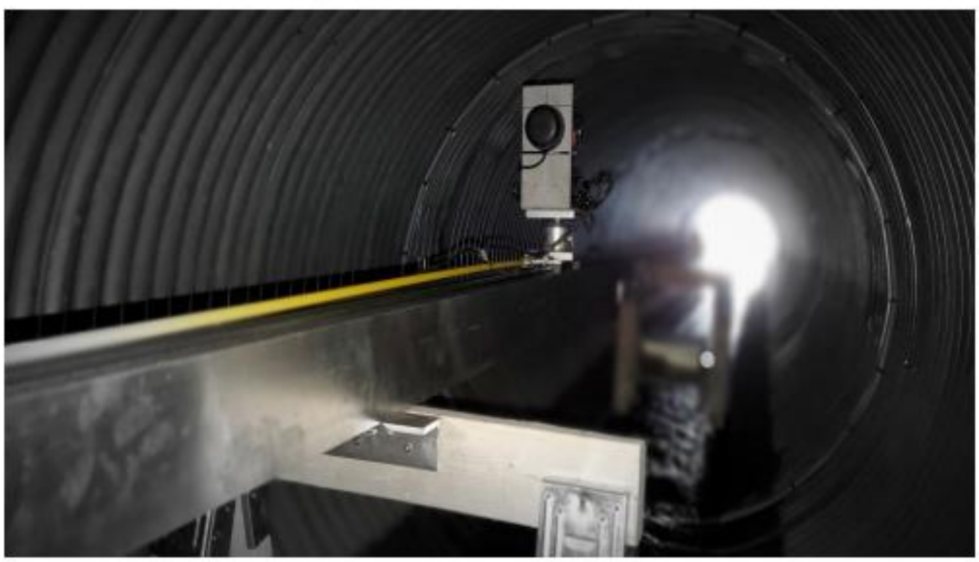


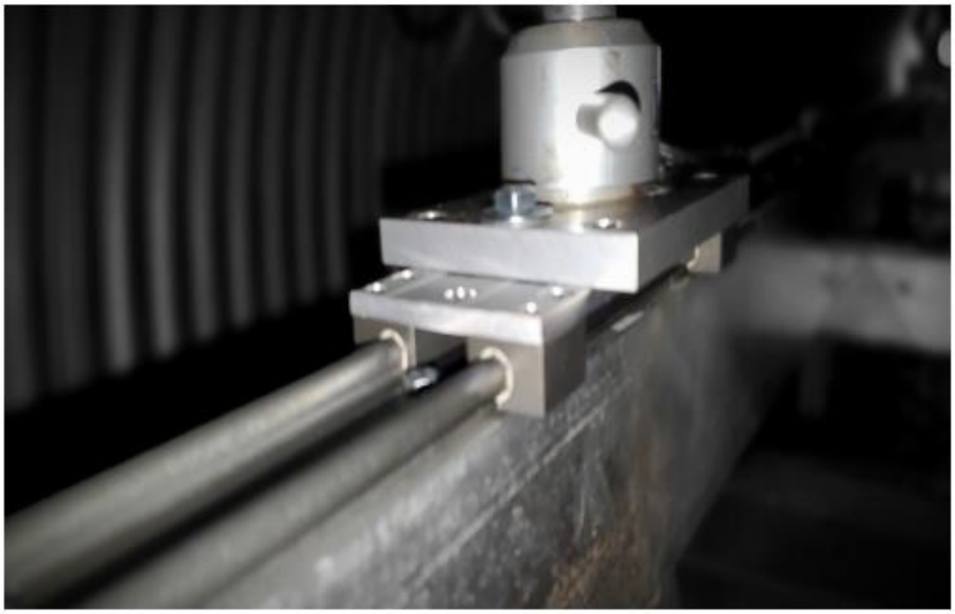
Figure 3. *18 LiDAR scanned cross-sections of a 5-metre section of CSP.*

The LiDAR scanner was pulled through the 5-metre section along a sliding rail system as seen in **Picture 5, 6, 7** and **Picture 8** below. The rail system was bolted to a rectangular aluminum tube and then fastened to two sawhorses. The two sawhorses had plastic containers with approximately 30 kilograms of water on each platform stabilizing them.

Picture 5. *LiDAR mounted to railing system.*



Picture 6. *LiDAR mounted to railing system.*



Picture 7. *LiDAR mounted to railing system.*

Picture 8. *LiDAR mounted to railing system.*

A tripod was affixed near the inlet to the CSP (**Picture 9.**) and used as a reference point to ensure each full scan was at the same Z axis location. The fibre glass pull rods were marked and stopped at 30 centre increments (**Picture 10.**).

Picture 9. *Tripod near the inlet of the CSP as a reference for incrementing the LiDAR between full scans.*

Picture 10. *Tripod near the inlet of the CSP as a reference for incrementing the LiDAR between full scans. Marking along the fibre glass pull rod to make Z axis locations.*

The same LiDAR scanning proceedure as described above was again conducted on December 03, 2021 after the CSP had been spray lined with a protective structural coating.

Examples of the LiDAR crosssectional scans are seen below in Figures 3 and Figure 4 below.

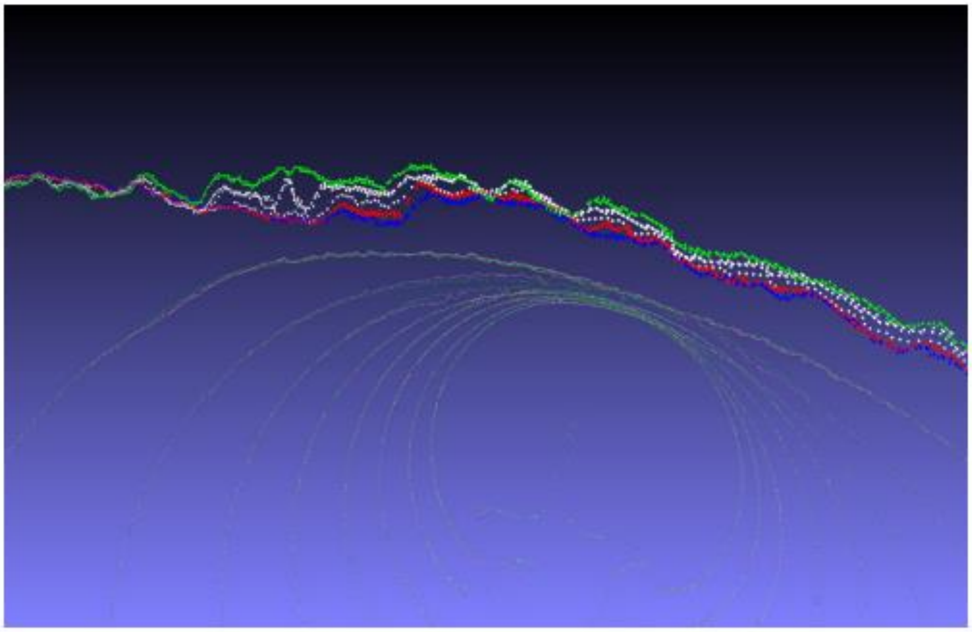


Figure 4. *Cross-sectional LiDAR scan of "Lined" CSP – The Green points are the unloaded baseline scan while the other coloured points represent the three statically loaded positions described above in* ***Pictures 2, 3*** *and* ***4****.*

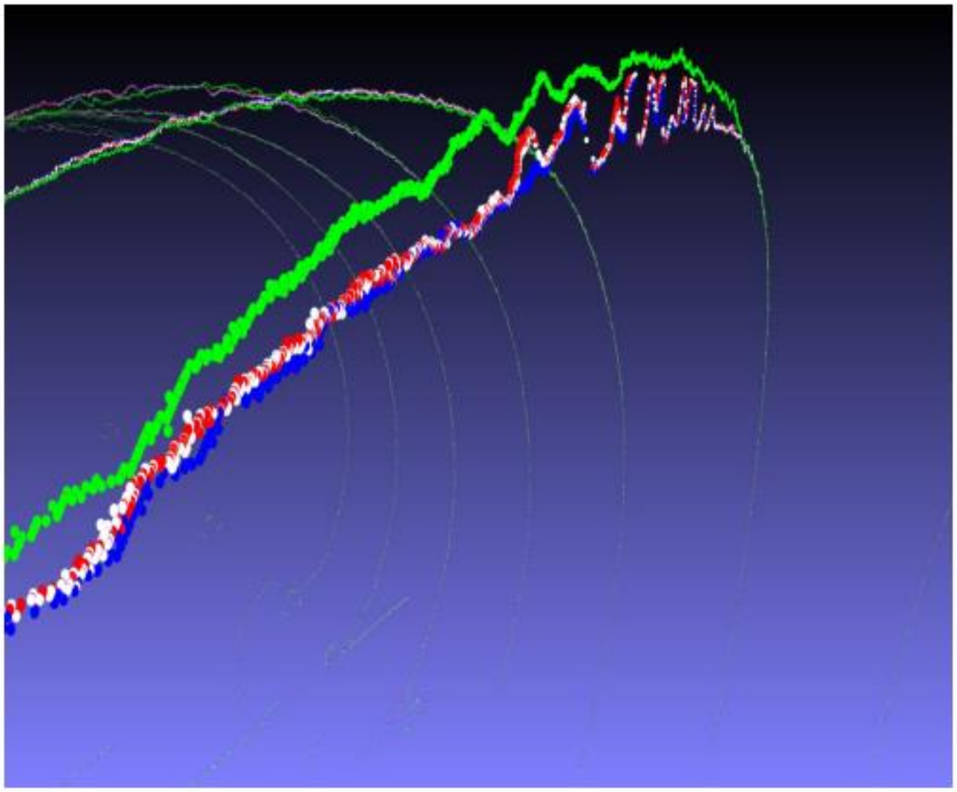


Figure 5. *Cross-sectional LiDAR scan of "Lined" CSP – The Green points are the unloaded baseline scan while the other coloured points represent the three statically loaded positions described above in* ***Pictures 2**, **3** and **4**.*

Eight post processed PLY file extensions will be provided for further point cloud data manipulation techniques. Of the eight post processed PLY files, four are processed from the "Unlined" CSP and the remaining four are for the "Lined" CSP LiDAR scans.

Kind regards,

Andrew Sutherland, P.Tech.

Owner / Atlantic Data Acquisition Services Inc.

APPENDIX II

CURRICULUM VITAE

Mohammad Rezania

Universities attended:

Master of Engineering, Geotechnical Engineering, September 2021- Ongoing.
University of New Brunswick, Fredericton, NB.
Project: Field measurements and data collection of the performance of rehabilitated Culvert.

Master of Science, Geotechnical Engineering, September 2011- April 2014.
Arak University, Arak, Iran
Thesis: Study of nano-carbon black effect on cut off wall in earth dam.

Bachelor of Science, Civil Engineering, September 2006- August 2011.
Islamic Azad University, Isfahan, Iran
Project: Design of seven floors concrete structure with shear wall.

Publications:

Conference Paper (International)

- M. Rezania, 2018, Effect of carbon black on concrete structure, 2nd international congress on world contemporary in civil engineering architecture and urban development, UAE-Dubai/24-27 Feb 2018.
- M. Rezania, 2018, Effect of Ethanolamines on Portland cement loading time, international congress on science and engineering, Hamburg-Germany, 12 March 2018.

Conference Paper (Iran)

- M. Rezania, 2013, Experimental study on nano-carbon black effect on cut off wall in earth dam, first national conference of geotechnical engineering, University of Mohaghegh Ardabili, 2013.
- M. Rezania, 2013, Experimental Study of the Simultaneous Effect of Nano-Silica and Nano-Carbon Black on Concrete, first national conference of geotechnical engineering, University of Mohaghegh Ardabili, 2013.

Journal Paper

- M. Rezania, M. Panahandeh, S.M.J. Razavi, F. Berto, 2019, Experimental Study of the Simultaneous Effect of Nano-Silica and Nano-Carbon Black on permeability and mechanical properties of the Concrete, Theoretical and Applied Fracture Mechanics, Volume 104, December 2019, 102391.
- M. Rezania, H. Moradnezhad, M. Panahandeh, M. J. Rahimpoor Kami, A. Rahmani, B. Vosough Hosseini, 2020, Effects of Diethanolamine (DEA) and Glass Fiber Reinforced polymer (GFRP) on setting time and mechanical properties of shotcrete, Journal of Building Engineering, Volume 31, September 2020, 101343.