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# CULVERT/STORM DRAIN EVALUATION TECHNOLOGIES

**Prepared For:**

Utah Department of Transportation
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**Final Report**
**April 2024**

RESEARCH

UDOT
Keeping Utah Moving
Utah Department of Transportation - Research Division
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# TECHNICAL REPORT ABSTRACT

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16. Abstract

While LiDAR (light detection and ranging) is not a new technology to UDOT, mobile LiDAR has not been used to enhance culvert inspections. The study reviewed two types of mobile scanning technologies for testing culverts, Pocket LiDAR (iPhone 12 Pro based laser emitter that is used to improve accuracy of photogrammetry) and SLAM LiDAR (simultaneous location and mapping). The control was made with hand measurements or with Terrestrial LiDAR (which is a portable unit that scans an area with multiple static scans, similar to what UDOT uses for some of its surveying).

This testing was performed to see if new versions of LiDAR could be used to supplement and improve culvert inspections within the scope of UDOT's rating criteria. UDOT had an overall goal to be able to automate inspections so that a culvert inspection expert did not have to watch the video after the inspection to evaluate each defect that was found in a pipe. Culvert inspections offer challenges that are atypical to Terrestrial LiDAR surveying. While Terrestrial LiDAR had a lot of utility for its ability to gather large amounts of point cloud data from a distance with outdoor lighting, LiDAR in culverts is done over very small distances and with artificial lighting.

Finding appropriate testing culverts that were easy and safe to enter with varied pipe materials was a challenge as many of the larger culverts that could be walked through are not readily accessible. This is often due to traffic safety issues with locations along state highways, water within the pipe or with locations where entry is limited due to structures.

By coordinating with two groups that specialized in mobile LiDAR and determining a reasonable sample size that could be accomplished in two days, a group of 11 pipes was set. These pipes were: concrete, plastic and metal pipe types; had different diameters; were near enough that travel time was not a drain on resources; large enough for walk-thru mobile scanning; and the pipes exhibited varied defects.

The testing found that the mobile technologies did well with some aspects of pipe measurements, including diameter, deflection, grade and joint gaps. The current measurement refinement level of this technology does not allow for meeting the UDOT inspection criteria for smaller defects such as fractures, surface deterioration, localized buckling, corrosion, and infiltration/exfiltration.

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# UNIT CONVERSION FACTORS

## SI* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9<br>or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

### APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

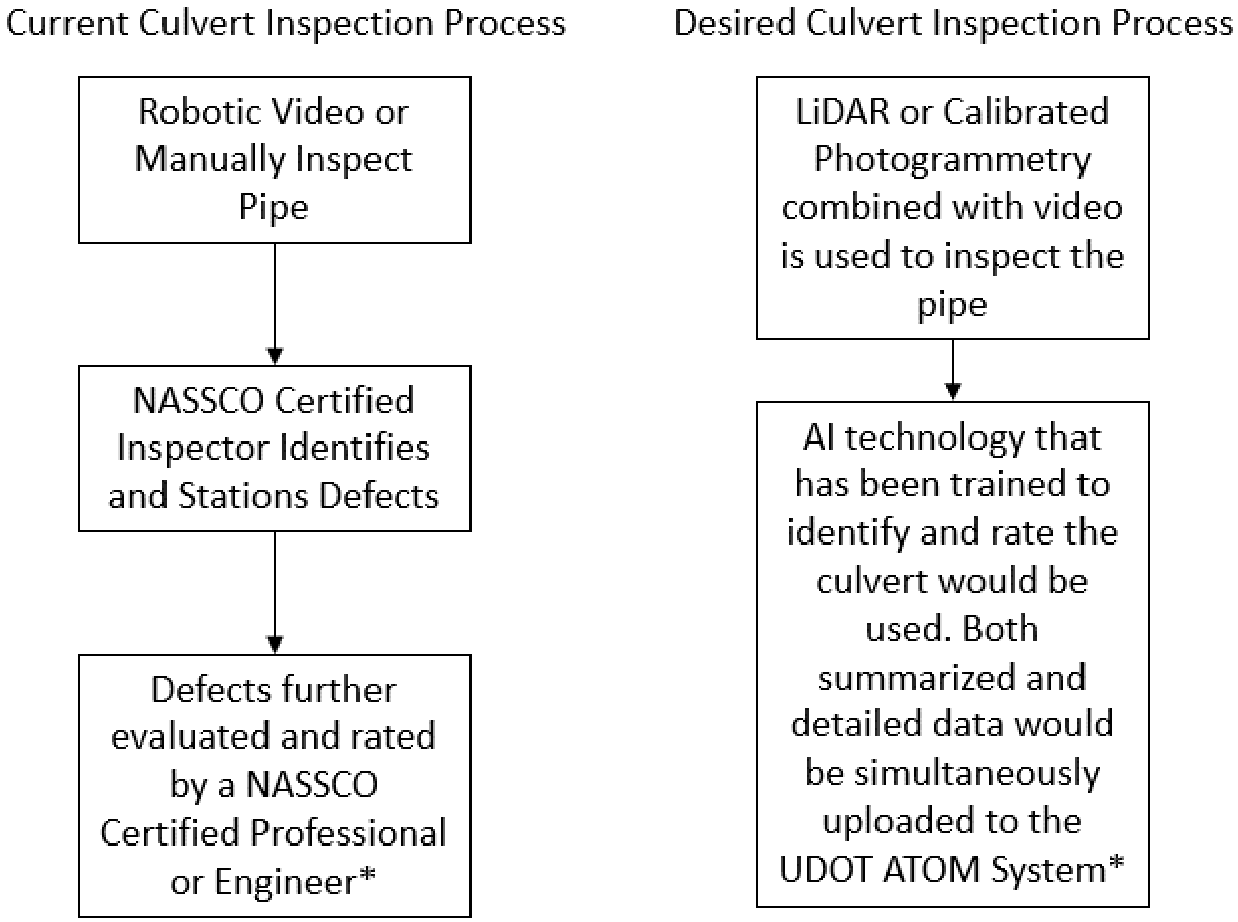
*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

# LIST OF ACRONYMS

| | |
|---|---|
| ATOM | Computerized Maintenance Management System by Google |
| BLK2GO | Leica BLK2GO – SLAM LiDAR Scanner |
| FHWA | Federal Highway Administration |
| LiDAR | Light Detection and Ranging |
| NASSCO | National Association of Sewer Service Companies |
| RTC360 | Leica RTC Terrestrial LiDAR Scanner |
| SLAM LiDAR | Simultaneous Location and Mapping LiDAR |
| UDOT | Utah Department of Transportation |

# EXECUTIVE SUMMARY

UDOT has thousands of pipes that are part of their infrastructure. Cleaning and inspecting all these pipes is an expensive proposition. UDOT has developed a detailed set of rating criteria for these inspections. Currently, robotic video cameras are used to inspect pipes for new construction, but the videos are not able to measure certain defects, and the defects need to be rated by a National Association of Sewer Service Company (NASSCO) trained professional. This process is labor intensive, costly, and subjective. The goal of this project was to determine if there were new technologies available to help automate the process. With advances in AI, if pipe defects could be accurately measured, there should be opportunities to automate the process. Figure ES.1 shows a summary of the current vs. desired culvert inspections. NASSCO certified inspectors are referenced because they are typically used by video inspection contractors that certify newly constructed pipes before paving is allowed. UDOT would have similar training for their maintenance employees that were inspecting existing pipes.



*This is often based on watching the video and looking for clues to determine scale (i.e., pipe diameter, stickers or stencils, leaves, etc). It is very subjective and 2D photos shouldn't be used to rate the pipe.

*The key improvement is to have an AI system trained to replace the Certified Professional or Engineer and limit human labor needs. It would also minimize the subjectiveness of human evaluation

**Figure ES.1 – Current vs. Future Desired Culvert Inspection Process**

The figure illustrates UDOT’s goals in this research. Unfortunately, the conclusions of this study are that the current state of LiDAR scans is not detailed enough to measure small defects, such as, fractures, joint gaps, surface deterioration, spalls, corrosion, infiltration/exfiltration, localized buckling, and bolts. LiDAR was effective in other measurements, such as shape and barrel alignment. If the data cannot be gathered accurately, then it’s **not** feasible to move on to an automated rating.

The study recommended that Pocket LiDAR was beneficial for inspecting large pipes that could be walked through. For example, if a pipe needed to be slip lined with another pipe, Pocket LiDAR could create an accurate enough 3D model for design of the slip lining pipe. It was recommended that Pocket LiDAR was easy to train inspectors to gather data, and the cost of the Pocket LiDAR made it readily available, as some of the inspectors may already have an iPhone that is LiDAR capable. It was recommended that Pocket LiDAR be processed centrally by the Survey Group as the process is very similar to the drone photogrammetric surveying that UDOT currently uses. Other potential non-pipe inspection applications were suggested as potentially practical applications for Pocket LiDAR, including ADA ramp inspections, culvert headwalls, excavations and key utilities during trenching activities, and private properties that may be impacted by construction.

It was recommended that the BLK2GO or other similar full LiDAR mobile scanners do not have the benefit-to-cost ratio necessary to justify widespread use for culvert inspection. There are currently several companies that use LiDAR combined with more traditional video inspection, but they were not willing to participate in the study as they were currently more focused on providing inspection services, or they were concerned that they did not want proprietary technology to be published.

AI technology for culvert inspection was also reviewed. The AI companies are very optimistic about their ability to improve defect finding and speed video inspections with the AI software. Yet, rating defects, especially those that needed small measurements, was not the current focus and they felt that a highly trained inspector or engineer would still be required to evaluate the defects. With the ongoing UDOT research on AI pipe inspection through the University of Utah, it is felt that this report should provide input to their projects so that they can further identify how AI culvert rating of measurement-sensitive defects could be accomplished.

# 1.0 INTRODUCTION

## 1.1 Problem Statement

Allocating labor to pipe inspection has become more difficult in recent years. The purpose of this research is to review current technologies to determine if there are techniques for more efficient pipe inspection. This includes both data collection and evaluation. AI techniques may be available that would eliminate the subjectivity of current processes.

UDOT faces a critical challenge in modernizing its culvert inspection processes to ensure the continued safety and functionality of its transportation infrastructure. Existing culvert inspection methodologies lack the efficiency, accuracy, and scalability required to meet the state's evolving infrastructure demands and needs, environmental considerations, and budget constraints.

To address these pressing issues, UDOT must explore and implement new technologies, such as LiDAR-based systems. LiDAR stands for light detection and ranging. "It uses lasers to ping off objects and return to the source of the laser, measuring distance by timing the travel, or flight, of the light pulse."[1] LiDAR is a methodology that uses laser technology.[2] LiDAR along with Artificial Intelligence (AI) analysis to automate culvert rankings should be considered. However, the adoption of these technologies requires a well-defined strategy, financial investment, workforce training, and the development of clear standards and guidelines.

## 1.2 Objectives

Most culvert pipe inspection relies on visual inspection of the pipe using various methods of video inspection for post-video evaluation in the office. This includes pole cameras and pipe video cameras on robotic deployment systems. This project will evaluate how to gather the appropriate data, as provided in the UDOT Pipe Rating system. The project will evaluate whether AI can be used to assess the data automatically. The goal will be to establish whether these newer technologies can be less labor intensive and whether the data/ratings can be seamlessly imported into the ATOM UDOT Maintenance Management system and meet the UDOT rating criteria.

AASHTO Culvert/Storm Drain Inspection Guide 2020 will be used as one of the main references for this project. As technologies are changing rapidly, our literature search will evaluate if new technologies that fit this guide are available.

Research tasks include:

- Review the state of practice of other state agencies including a survey of new technologies used for pipe condition and performance measures
- Determine alternative methodologies and technology review
- Develop test locations for methodology evaluation
- Provide evaluation of technology performance related to current pipe condition inspection
- Develop the data requirements and process needed to apply AI technology to pipe assessments
- A cost benefit of the implementation of new technology relative to existing pipe inspection techniques

## 1.3 Outline of Report

- Introduction – The scope, goals, and objectives of the study
- Research Methods – Includes both literature review and a survey of the current state of the technologies within the Western Association of State Highway and Transportation Officials. It also includes introductions to the technologies used to gather data: Terrestrial LiDAR, Pocket LiDAR, and SLAM LiDAR
- Data Collection (or analysis) – This chapter will include the following:
    - Determining test sites for case studies
    - Data collection process
    - A comprehensive listing of the sites surveyed
- Data Evaluation (or Analysis) – This chapter will focus on whether the LiDAR or AI technology can currently access the UDOT culvert rating criteria
- Conclusions
- Recommendations and Implementation
- References

Appendices

- Appendix A WASHTO Culvert Survey Questionnaire
- Appendix B Detailed Survey Responses
- Appendix C Leica RTC360 Product Specification
- Appendix D Leica BLK2GO Product Specification
- Appendix E Sample Overall Point Clouds
- Appendix F Pipe Video Cameras – Available Data, Brochures, etc.

# 2.0 RESEARCH METHODS

## 2.1 Overview

This chapter will address the literature search and how LiDAR and AI technologies became the focus of the report. The survey of 17 WASHTO states did not show that any DOTs had adopted either of these technologies. This chapter will provide an introduction to the function of currently used LiDAR systems, including: traditional LiDAR (for control), pocket LiDAR, and SLAM LiDAR (simultaneous localization and mapping). It will also document that there are other similar LiDAR systems already in use, but not available to this report. It will also summarize the discussions involving AI Pipe inspection systems that were found in searching out these pipe inspection technologies.

## 2.2 Literature Search

The literature search was based on studies and technologies suggested by UDOT and online search engines. The key literature and technologies in this section were the ones that were critical to focusing the study. Specifically, it was found that two entities already incorporated LiDAR into their video inspection services. While initial discussions with these entities were useful, they ultimately opted not to participate in the study as their focus is providing the service and they were concerned about proprietary technology being published and available for competitors.

### 2.2.1 Highway Infrastructure Inspection Practices for the Digital Age (2022)[3]

The goal of this synthesis was to identify various technologies used by state DOTs to inspect highway infrastructure. One of the sections was specific to Remote Sensing and Monitoring Technologies. Thirty-two percent of the 28 DOT respondents had used LiDAR and 3D Laser Scanning. The top inspection activities using LiDAR and 3D laser scanning during maintenance of highway infrastructure assets includes pavement management, assessment of slope stability and landslides, and location of material placement for performance tracking. The responses in this report did not indicate that any of the states had a comprehensive culvert inspection process using LiDAR.

### 2.2.2 Cues, SoLID FX: LIDAR, SONAR, and Live CCTV[4]

Cues Company was researched as they had typically been on the cutting edge of pipe inspection technologies. They initially provided the research team with PowerPoint slides for the presentation of the problem statement, but after the research was awarded, they became non-responsive and were unwilling to come perform testing outside of their regular service fees. From the brochure for their system, it was clear that they had LiDAR sensing that could measure pipe diameter and shape. It is also realized that they are gathering the data while moving at up to 4 ft/sec (likely SLAM LiDAR), but it was not clear what LiDAR scanner they were using or at what resolution the point clouds were created.

It is unfortunate that the study was unable to coordinate with them on whether they had overcome some of the limitations of LiDAR measurements. This includes what type of lighting they use; how small of measurements they make; and how they deal with crack measurements (LiDAR or manual measurements); accuracy of the LiDAR; size and usability of the point clouds; etc. That said, the BLK2GO SLAM LiDAR scanner that was used in the study should have similar accuracies with equivalent lighting. It might be possible to use Cues technology on a future UDOT project where the rehabilitation requirements mandated LiDAR culvert inspection is needed. With a paid service, Cues or one of the companies that uses their LiDAR-enhanced video might be more willing to discuss whether they have solved the limitations discussed in this study.

### 2.2.3 University of Texas at Arlington

The University of Texas at Arlington had performed some testing in Utah approximately 20 years ago. At the time, they had the ability to have a robotic camera video pipe, including the concept of laser profiling. The laser profiling was a simple process that recorded a spinning laser in the darkness of the pipe, with the laser clearly illuminating the pipe shape. For flexible pipes where deflection needed to be measured, this technology, when combined with proper calibration of the video could make accurate deflection measurements in pipes. Knowing this group of researchers, it was found that they had progressed the technology to include mobile LiDAR enhancement to their videos. In meeting with them, they seemed to have capabilities similar to Cues that was discussed previously. They were willing to come participate in the testing, but the cost suggested was much higher than the project budget. They quit responding to requests, even for the researchers to travel and view their technology on a current project. They did not want to have proprietary information published where their competitors could have access to it.

### 2.2.4 LiDAR Deployment Using ANYmal Robot

As part of the initial culvert testing, Kuker Ranken tested a fully equipped ANYmal Robot "Dog" (quadrupedal robot). This Robot was created by ANYbotics, a Swiss company. This robot can be controlled via wireless signals or deployed to inspect sites autonomously. This type of robot would be an alternative delivery mechanism to traditional tractor-based pipe video cameras or drones. The ANYmal is noted for its ability to enter dangerous atmospheres and operate autonomously, using SLAM LiDAR and cameras to monitor its path simultaneously and continuously. For example, the unit could autonomously travel through an unmapped mine, mapping the tunnel while avoiding obstacles. The ANYmal can be outfitted with various sensors in addition to the LiDAR and cameras, including acoustical, thermal, and gas. For example, the gas sensor would be useful for inspecting a potentially explosive or non-breathable atmosphere.

Kuker Ranken demonstrated one of these units as part of the initial culvert tests. They reported that the cost of the demo unit, as equipped, was $250,000. There were several findings:

- In a canal that used Utah Lake/Jordan River water for irrigation supply, the silt/sediment was very difficult (6" to 12" deep) for the ANYmal's feet to navigate as it almost became stuck. The suppliers determined that the robot would need to have something like a snowshoe to operate in silt and coordinated this information with the design/manufacturer.
- In a different 72" reinforced concrete pipe, there was 12" inches plus of ponded water. The ANYmal sensed this water and since it could not determine how deep the water was or whether the bottom of the hole was too uneven, the ANYmal stopped and refused to go on. This test was stopped so as not to damage the ANYmal.

- In the 60” triple wall polypropylene pipe in Little Cottonwood Canyon, near Lisa Falls, the ANYmal went through the pipe. While this was not a problem in rougher surface pipes, the plastic pipe was smooth enough that the ANYmal’s “feet” did not make good contact and the ANYmal would start to slip if it stepped up the wall, away from the flow line. While the suppliers were able to secure the ANYmal with a rope for safety, they would not be able to use the ANYmal autonomously in a plastic pipe of this size until they were able to address the slipping.
- It was difficult to get the ANYmal into the culvert in many cases. The slopes around the inlets were typically very steep, so the ANYmal had to be carried in with three people involved. The ANYmal weighs 65 – 75 lbs. based on attached sensors. This would not be practical for a single UDOT maintenance person to use, but future versions may be smaller and more adaptable to pipe inspection.

Based on the issues above, it was determined not to further use the ANYmal on this project. This is mainly because the project was focused on the viability of using LiDAR to rate the pipe, not the delivery mechanism of the LiDAR. As traditional pipe video cameras on a track driven system are much cheaper and more effective in a pipe, there was not a need to test delivery mechanisms further. With advances in robotics and drone technology, there may be new delivery methods that should be considered in the future. Figure 2.3.2 is a photograph of Kuker Ranken testing the ANYmal at Geneva Pipe’s yard in Salt Lake City.

While the ANYmal wasn’t ideal for culvert inspection, this robot or others that are being developed may have use within other areas of the department:

- There may be incident management applications where the ANYmal could enter a hazardous atmosphere and assess the situation.
- It could be used for incident management or mapping of landslides or avalanches.
- It is submersible for short periods of time, so it could be used in areas with standing water.

Figure 2.3.2 Photo of ANYmal Robot Testing at Geneva Pipe in Salt Lake City

## 2.3 Survey of WASHTO States

This study collected data about other states' culvert inspection tools and techniques by sending out surveys to western state DOTs that are part of the Western Association of State Highway and Transportation Officials (WASHTO). The states that were surveyed were: New Mexico, Colorado, Nebraska, Idaho, Oregon, South Dakota, Arizona, Nevada, Oklahoma, Wyoming, Montana, Alaska, North Dakota, Hawaii, Washington, and California. The survey included frequency of inspection, inspection techniques, culvert rating guides, databases, and new technologies. The raw data and a blank copy of the original survey are included in the appendices. Tables and Figures will be included in the report and will reference the data from Appendices A and B.

### 2.3.1 Inspection Programs

Figure 2.3.1 lists the proportion of states that have a culvert inspection program, out of the states that responded to the survey.

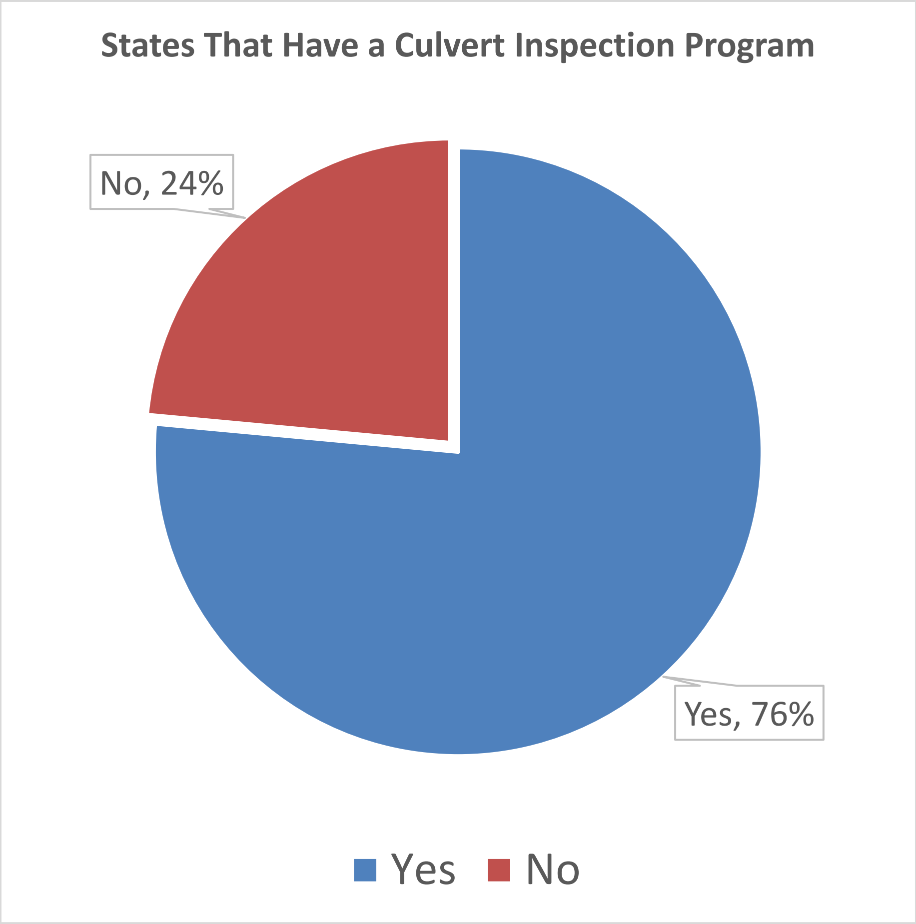


**Figure 2.3.1 Inspection Programs**

### 2.3.2 Inspection Frequency

Figure 2.3.2 lists the culvert inspection frequency for all of the states that responded to the survey.

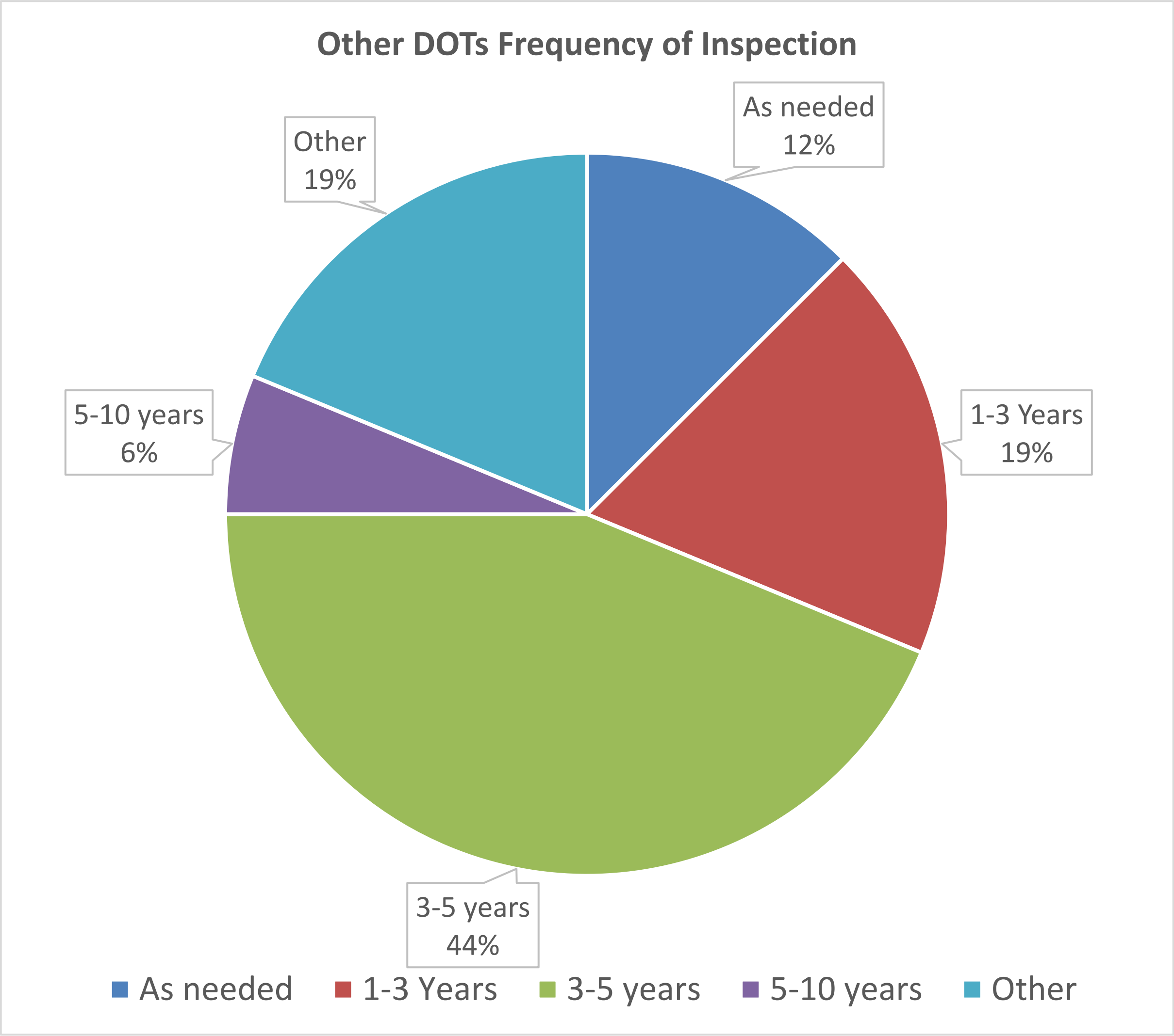


**Figure 2.3.2 Inspection Frequency**

### 2.3.3 Inspection Methods

This section contains the data collected regarding the different methods of culvert inspection that the surveyed states used. It also contains the data collected on technology types that surveyed states considered to help them in their culvert inspection programs.

Figure 2.3.3 shows the different types of culvert inspection that the surveyed states perform.

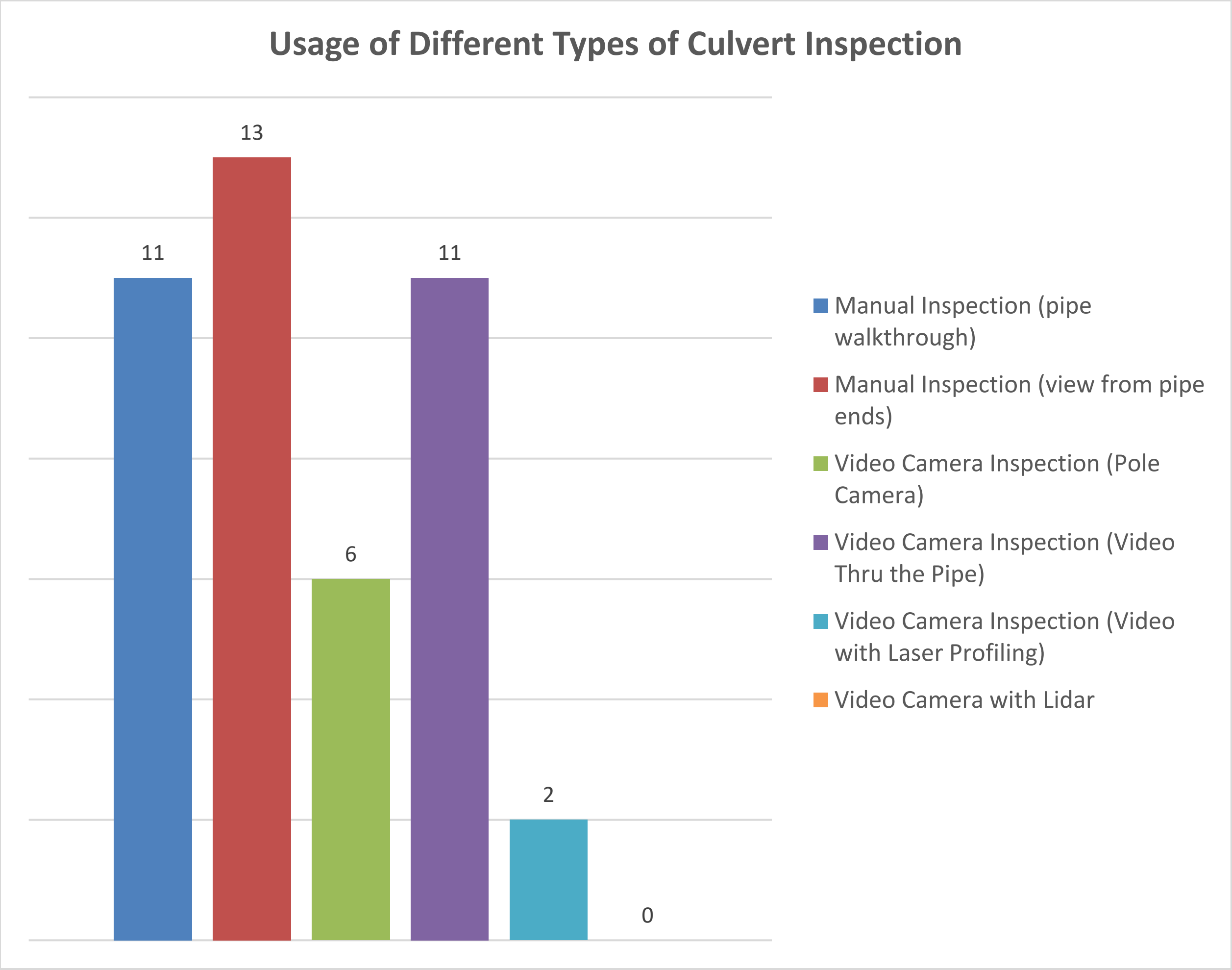


**Figure 2.3.3 Inspection Methods**

### 2.3.4 New Technologies

Figure 2.3.5 shows the types of new technologies that the surveyed states are considering or have considered.

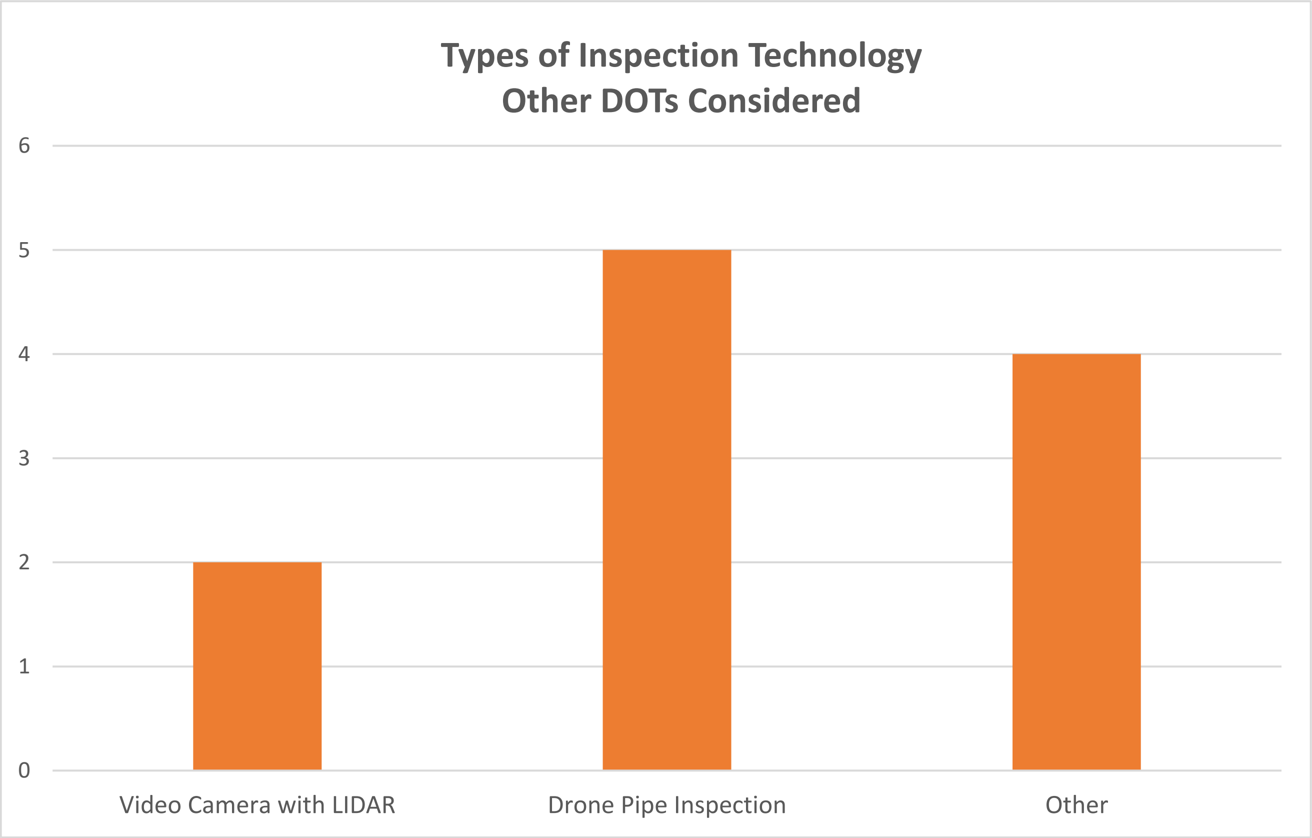


**Figure 2.3.4 Inspection Technologies**

### 2.3.5 Reviews and Databases

This section contains the surveyed states' responses about their internal reviews of their culvert inspection programs, as well as their responses about the databases they use to perform their inspections.

Figure 2.3.5 contains responses about Inspection Practice Reviews from the surveyed states.

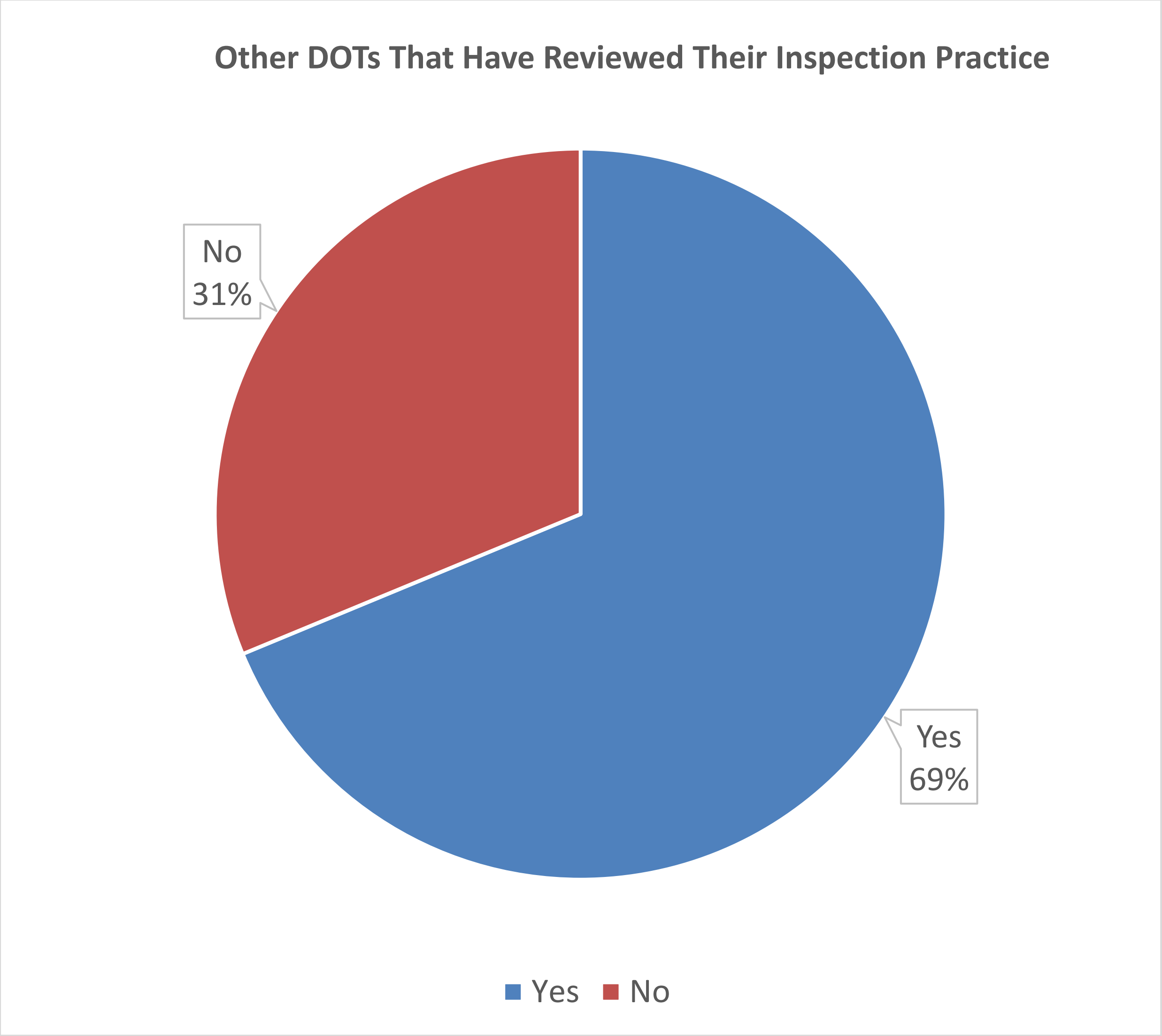


**Figure 2.3.5 Inspection Reviews**

### 2.3.6 Inspection Databases

Figure 2.3.6 contains information on the databases that the surveyed states use to house their culvert inspection data.

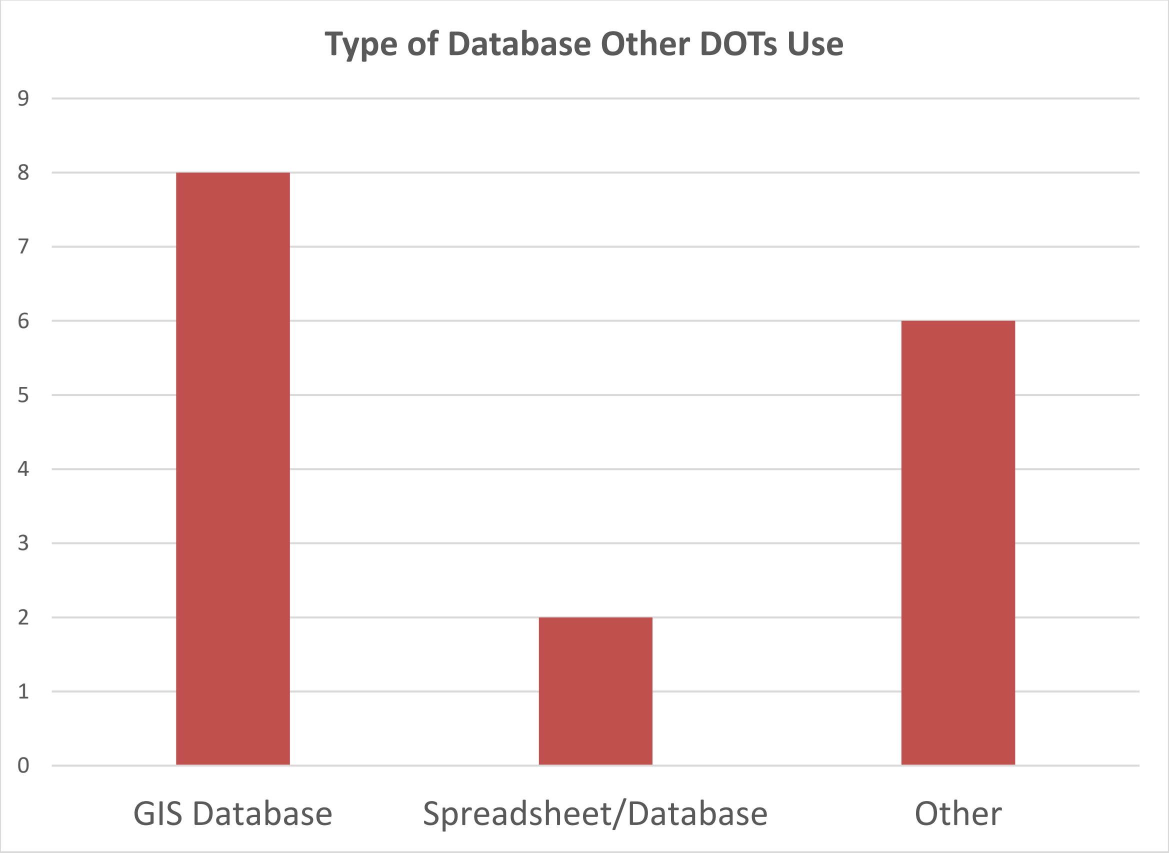


**Figure 2.3.6 Inspection Databases**

This survey primarily gathered information on the culvert inspection tools and techniques used by states adjacent to Utah. Of the states responding, 76% of these states have developed a culvert inspection plan, and a plurality of those states have an inspection frequency of 3-5 years. The most common inspection type was manual. The least common inspection type was a camera using LiDAR. Of the states responding, 69% have reviewed their inspection practices. In addition, most of the surveyed states use a GIS database to keep track of their inspection data. The survey data helped to identify that other western states had yet to adopt emerging technologies.

## 2.4 Terrestial LiDAR

LiDAR works on the same principles as radar and sonar. All three technologies emit waves of energy to detect and track objects. The difference is that while radar uses microwaves and sonar uses sound waves, LiDAR uses reflected light, which can measure distance faster, with greater precision and higher resolution than either radar or sonar.[5]

Terrestrial LiDAR is a ground-based LiDAR system frequently used for terrain and landscape mapping. Terrestrial LiDAR can be used to collect more localized and short-range data, making it ideal for mapping smaller areas with high precision.

While Terrestrial LiDAR played a key role in this study, it was used only for baseline comparisons. Some terrestrial LiDAR systems are static, fixed in one location and used for taking precise and repeated LiDAR scans of a single area. Static LiDAR is often used on archeological sites, construction projects, and for kinds of hazard assessment such as monitoring the ground surface of an active volcano, earthquake fault, or flood zone. In this study, our testers used a Leica RTC360 scanner, which is a portable unit that scans an area with multiple static scans. These setups, like traditional surveying, can tie in the setups and map control points. Terrestrial laser scanning (TLS), also referred to as terrestrial LiDAR (light detection and ranging) or topographic LiDAR, acquires XYZ coordinates of numerous points on land by emitting laser pulses toward these points and measuring the distance from the device to the target.[6] The RGB color value of each point is also acquired so that it can be used to create point clouds and meshes that look more photorealistic. Table 2.4.1 shows a summary of the scanner capabilities of the Leica RTC360. The Leica RTC360 is a high accuracy/high resolution and speed scanner with a current cost of approximately $80,000, and it typically requires survey supervisor-level training. In addition to the training, the Leica Cyclone processing software, approximately $5,000, and a high speed/capacity computer are recommended. Even though this LiDAR is simpler with 4 variables per point, at 2,000,000 points per second, the resolution of this scanner can be high enough that processing times can take multiple hours. Often the capture resolution is reduced in processing to decrease file sizes on scans where the level of detail is not as critical. Detailed product specifications are included in Appendix C with a summary in Table 2.4.1.

**Table 2.4.1**
**Leica RTC360 Specifications Summary[7]**

| | |
|---|---|
| **General** | |
| 3D Laser Scanner | High-speed 3D laser scanner with integrated HDR spherical imaging system and Visual Inertial System (VIS) for real-time registration |
| **Performance** | |
| Data Acquisition | < 2 min for complete full dome scan and spherical HDR image at 6mm @ 10m resolution |
| Real-time registration | Automatic point cloud alignment based on real-time tracking of scanner movement between setups based on Visual Inertial System (VIS) by video-enhanced inertial measurement unit |
| Double scan | Automatic removal of moving objects |
| **Scanning** | |
| Range | Min. 0.5 - up to 130 m |
| Speed | Up to 2,000,000 pts / sec |
| Resolution | 3 user-selectable settings (3/6/12mm @ 10m) |
| **Imaging** | |
| Camera | 36 MP 3-camera system captures 432 MPx raw data for calibrated 360° x 300° spherical image |

**Figure 2.4.1 Photo of Michael Olsen (EZDataMD), obtaining RTC360 Baseline Scan of Herriman Tunnel, August 7, 2023**

## 2.5 Pocket LiDAR

Pocket LiDAR is a new technology that became more prevalent with Apple's introduction of the iPhone 12 Pro in Fall 2020. Pocket LiDAR is similar to the traditional LiDAR methods. It utilizes a laser, seen as a dot near the camera lens grouping on the iPhone Pro or Pro Max, to gather point data and to measure the distance to the center of photos. Apple's initial interest in LiDAR appeared to be more related to virtual reality games and applications than engineering applications such as culvert ratings.

The various phone applications take photos to be used with Photogrammetric Stitching, with the laser helping to calibrate the photo's location. Photogrammetry is the practice of stitching 2D images from multiple angles into a 3D object.[9] Photogrammetric Stitching is a common way to create a 3D model based on triangulating common points that can be seen from different perspectives in different photos, by using AI to compare the features in the photos. The more triangulation between the photos that occurs, the more accurately the data can be processed. Pocket LiDAR technology attempts to improve the accuracy of the stitching by incorporating laser measurements. It appears that the technology relies more on the aspect of stitching photos than LiDAR data, depending on the software application used. Unlike 3D scanning, which uses structured laser light to measure the locations of points in a scene, photogrammetry uses actual images to capture an object and turn it into a 3D model.[10] Unlike traditional lasers, iPhone lasers use a Vertical Edge Surface Emitting Laser (VCSEL), which is convenient for mobile devices, as they can be constructed in small dimensions featuring a feasible ratio between laser power consumption and supplied power as well as a narrow wavelength bandwidth[11].

UDOT suggested that an ongoing Federal Highway Administration report "Leveraging Pocket LiDAR for Construction Inspection and Digital As-Builts" was research that might be valuable in relation to culvert inspections. After coordinating the potential culvert inspection case study to the FHWA project, the Pocket LiDAR researchers[12] identified a reasonable scoping of the culvert types and quantities that could be tested as part of their study. The Pocket LiDAR study has a limited scope to evaluate how well the pocket LiDAR can work in general. This study will show how the pocket LiDAR works on helping to more accurately identify defects that have been defined in UDOT's rating criteria.

The current cost of the iPhone 15 Pro is approximately $1,000 and the iPad Pro ranges between $800 and $1,100 based on screen size. While the low cost of this Pocket LiDAR is one of its draws, the software applications that are viable are starting to require paid subscriptions. Processing the data relies on a high-speed/capacity computer and the final processing time can take multiple hours.

Table 2.5.1 shows the general specifications for the iPhone 12.

**Table 2.5.1**
**iPhone 12 Pro Specifications Summary**[13]

| | |
|---|---|
| **General** | |
| LiDAR Sensor | The laser is emitted from a Vertical Cavity Surface Emitting Laser (VCSEL) in a near infrared spectrum in a 2D array[13] |
| **Performance** | |
| Data Acquisition | LiDAR sensor emitting an array of 8 x 8 points diffracted into 3 x 3 grids making a total of 576 points[13] |
| Data Processing | Apple, Inc. proprietary software platform ARKit triangulates the mesh internally based on the raw point measurements. During point cloud export … points are sampled from the mesh's surface and the points are not the raw point cloud collected with the iPhone's LiDAR sensor.[13] |
| **Scanning** | |
| Accuracy | Shapes of small objects are measured with an absolute accuracy of ± 1 cm 3D models of a scene that was 130 x 15 x 10 meters had an absolute accuracy of ± 10 cm.[13] |
| Precision | The error in precision is ± 1 cm. Precision decreases when scanning surfaces under 10 cm side length.[13] |
| **Imaging** | |
| Camera | 12 MP 2D camera and up to 4k video recording |

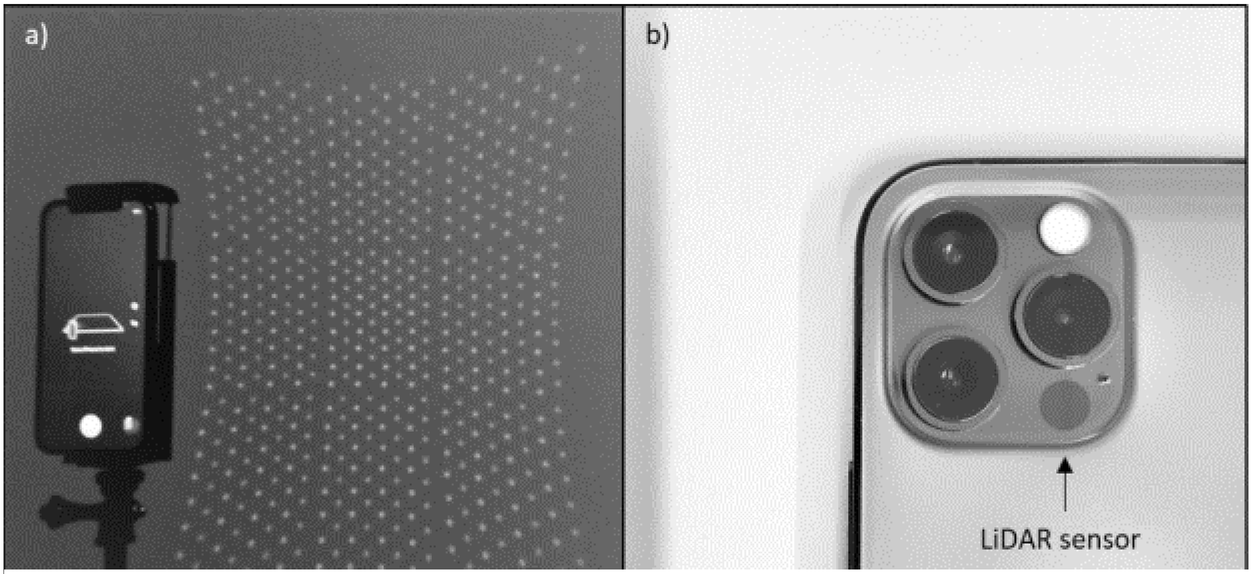


**Figure 2.5.1 The Apple iPhone 12 Pro mounted on a selfie stick with LiDAR sensor emitting an array of 8 x 8 points diffracted into 3 x 3 grids making a total of 576 points (a), Apple iPhone 12 Pro camera module (b)**

**Figure 2.5.2 Photo of John Caya using iPhone to create 3D scan of Lisa Falls Cross Culvert, Little Cottonwood Canyon, August 7, 2023**

## 2.6 Mobile Scanner System Using SLAM LiDAR, Leica BLK2GO

The Leica BLK2GO is a handheld imaging laser scanner that uses Simultaneous Location and Mapping LiDAR (SLAM) technology to capture images and point clouds in real time. SLAM LiDAR differs from Terrestrial LiDAR in that it allows data capture while in motion. Simplified, the SLAM LiDAR technology is using images to help coordinate its location in space and so that the LiDAR data can be captured while in motion. With this mobile package, a set base is not required, but it is suggested to add known control points or scaled targets to improve accuracy and creation of point clouds. The BLK2GO's technology combines LiDAR SLAM, Visual SLAM, and an IMU.[14] The best way to combat the uncertainty of a mobile scanner’s location in space at any time is with an additional sensor, normally an internal measurement unit, or IMU. This sensor detects any motion the scanner makes, making available a new data set to assist with real-time data collection and data post processing.[14]

The BLK2GO captures 420,000 points per second. It can capture 3D digital twins while in motion. The BLK2GO has a high-resolution 12-megapixel camera on the front for capturing detailed images. It weighs approximately 775g and has a battery that lasts around 45 minutes.

While it would not be practical to mount Terrestrial LiDAR to some type of robotic rover delivery mechanism, SLAM LiDAR is well adapted to multiple delivery systems.  While it is outside of the scope of this research to suggest a delivery system, inspections could include handheld inspection of larger pipe, drones, and autonomous robotics (either tracked or with walking capabilities). It should be mentioned that all of the LiDAR systems in this study had limitations of pipes smaller than 48” in diameter, as LiDAR was not currently feasible due to backscatter effects of LiDAR.

LiDAR SLAM is widely used in autonomous driving, robotics, and mapping applications.[1] It has several advantages over Vision SLAM, including the ability to operate in low-light or no-light conditions. Both Vision SLAM or LiDAR SLAM have their strengths and weaknesses and are better suited for different applications and environments.

**Vision SLAM** has the advantage of being less expensive and easier to implement, as it uses standard cameras that are widely available. It can also provide detailed visual information about the environment, such as texture and color, which can be useful in some applications. However, Vision-Based SLAM can be less accurate than LiDAR-Based SLAM, especially in low-light or dynamic lighting conditions, and can be more sensitive to visual occlusions or cluttered environments.[14]

**LiDAR-Based SLAM**, on the other hand, has the advantage of providing highly accurate and precise 3D maps of the environment, even in low-light or no-light conditions. It is also less sensitive to visual occlusions or cluttered environments and can be more robust to changes in lighting conditions. However, LiDAR sensors can be expensive and require significant computational resources to process the large amounts of data they generate.[14] There is currently not an option to use the BLK2GO with LiDAR SLAM only (without the Visual SLAM), but future versions will include this option.[16] For pipe inspections, a high strength, well-distributed external lighting source is critical for the Visual SLAM LiDAR.[16] In this study, some of the inaccuracy was likely due to the lack of an ideal 360 degree, adequate lighting source.

Like Terrestrial LiDAR scanning, SLAM LiDAR acquires XYZ coordinates of numerous points by emitting laser pulses toward these points and measuring the distance from the device to the target. The color of each point is also acquired through cameras so that it can be used to create point clouds and meshes that look more photorealistic. Table 2.6.1 shows a summary of the scanner capabilities of the Leica BLK2GO. The Leica BLK2GO is a high-resolution mobile scanner with a current cost of approximately $58,000[15] and it typically requires minimal training to collect data. In addition to the training, the Leica Cyclone processing software, approximately $2,500, and a high-speed/capacity computer are recommended. Processing the Visual SLAM, LiDAR SLAM, and IMU data can take multiple hours. The speed of the BLK2GO at 420,000 points per second is similar to the RTC360 at low resolution.

**Table 2.6.1**
**Leica BLK2GO Specifications Summary[15]**

| | |
|---|---|
| **General** | |
| 3D Laser Scanner | High-speed 3D laser scanner with integrated HDR spherical imaging system and Visual Inertial System (VIS) for real-time registration |
| **System Performance** | |
| Range | 0.5 m minimum to 25 m maximum |
| Range Noise | ± 3 mm - Environment Dependent |
| Accuracy Indoor | ± 10 mm - Controlled Environment (scan duration 2 minutes) |
| **Scanning** | |
| Range | Min. 0.5 - up to 25 m |
| Speed | 420,000 points/second |
| Field of View | 360° (horizontal) / 270° (vertical) |
| **Imaging** | |
| Camera | 12 Megapixel, 90° x 120°, rolling shutter |

**Figure 2.6.1 Photo of Brady Reisch using Leica BLK2GO Mobile LiDAR Scanner to create 3D scan of Lisa Falls Cross Culvert, Little Cottonwood Canyon, August 21, 2023**

## 2.7 Summary of Technologies

This chapter reviewed three types of point cloud generating technologies, including: their specifications; an overview of how they conceptually work; and the relative cost of each including software. The technologies included: the Leica RTC360 Terrestrial LiDAR, Pocket LiDAR – Mobile Scanner (Apple iPhone 12 Pro) and the Leica BLK2GO – Mobile Scanner. It found that Pocket LiDAR was relatively inexpensive and the BLK2GO was much more expensive as a mobile scanner. The RTC360 had capacity for point clouds that had 5 times more resolution that the BLK2GO.

# 3.0 DATA COLLECTION

## 3.1 Overview

This chapter will review how the data collection was planned to include the key factors in determining field locations. In the initial planning of the project, UDOT provided databases for locations and condition of pipe culverts: the Horrocks Data Base in the Salt Lake City area and the Region One database (which is in progress). The existing databases typically include the pipe diameter, pipe material, and location. The data related to the interior condition of the pipe and whether the pipe is showing defects in the UDOT Pipe Culvert Rating System are not often available. Much of this data was collected from outside the pipe or with pole cameras that are limited in rating individual defects. Hence the need to determine if emerging technologies would make data collection more efficient. One caution on pipe inspections is that many pipe culverts will have debris or sediment loads that limit pipe inspections until the pipe is cleaned.

One of the key but difficult components of the study was finding a variety of easily accessible pipes (without right-of-way or safety issues) that were in the same general vicinity (so that travel time between inspections was minimized) and exhibited different pipe types/defects. The Horrocks database shown in Figure 3.1.1 provided a good base. With that in mind, the research team contacted Salt Lake County and received internal proprietary data that had more information on the culverts in this area than the Horrocks Database.

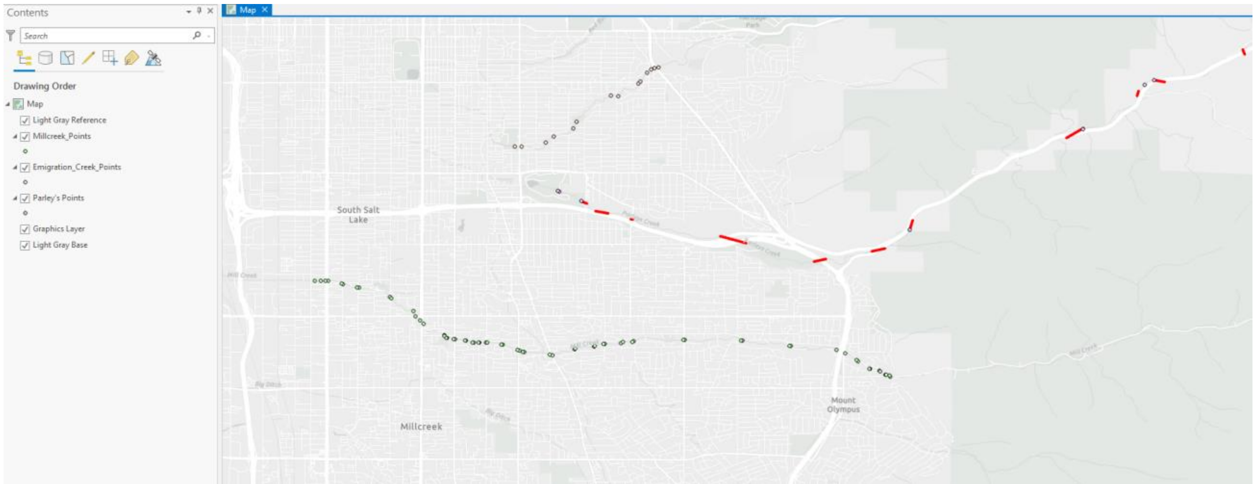


**Figure 3.1.1 Horrocks Pipe Culvert Database showing pipe culverts along Mill Creek, Emigration Creek and Parley's Creek**

The researchers started reviewing the Salt Lake County database at Red Butte Creek, Emigration Creek, Mill Creek, and Parley's Creek drainages.[17] The review criteria were looking for pipe at least 48" in diameter for full entry. Pipe culverts and road crossings were easily accessible and relatively safe in all of these drainages, but Parley's Creek had the best supply and variety of large enough culverts. Parley's Creek also had a benefit in that many of the pipes were underneath UDOT roads but had easier access than having to set up within UDOT right-of-way. ArcGIS was used to view and catalog culvert locations. Field visits were made to each of the pipes to see if access was feasible, safe, and whether the culvert exhibited features that should be considered in UDOT's Pipe Culvert Rating Criteria.

In working with the testing groups that were willing to participate in the field testing, it was determined that they had enough budget and time set aside to spend two days in the field doing pipe inspections. A portion of their time was spent doing short presentations of the technologies to UDOT personnel that were invited by the UDOT Pipe Culvert Committee. A detailed schedule of anticipated inspection time, travel time from site to site, and travel time to travel from parking to the culvert was developed. Figure 3.1.2 is a graphic of the testing locations. In the description of each pipe in the following sections, the pipe is listed by milepost, where appropriate, and by latitude/longitude so that the location can easily be searched on the internet.

The testers gathered point cloud data for each pipe. The data included full loops of the RTC360 in some pipes, but no RTC360 data in other pipes due to inaccessibility with this bulky survey grade instrument. Pocket LiDAR point clouds were gathered for all pipes. BLK2GO data included looping the scan for accuracy where possible, but there were pipes where the BLK2GO data was corrupted and unavailable. The BLK2GO testers and author have agreed that these pipes could be retested and an addendum added at a later date when pipe culverts are inspectable again.

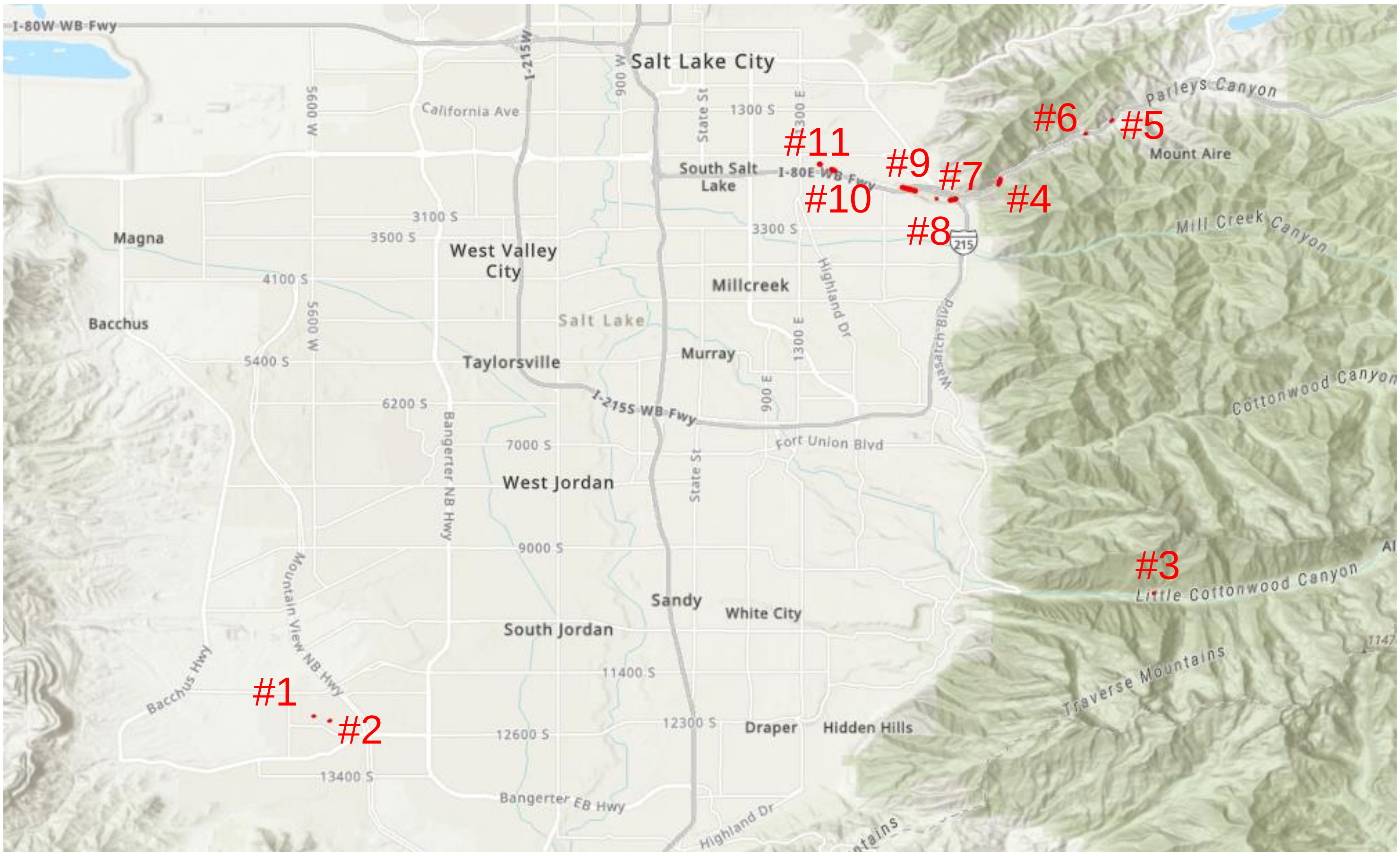


**Figure 3.1.2 Testing Locations that include, Herriman, Little Cottonwood Canyon and Parley’s Creek**

## 3.2 Test Pipe 1 - Midas Creek – Anthem Boulevard and Big Bend Drive, Herriman, UT

This 32 ft x 16 ft corrugated metal plate arch was selected as it would be a good location to include UDOT viewing the technologies because of its size. It was easy to access and has parking along Big Bend Drive. Each day of testing had an intro of the technologies at this location. The size and length of the pipe were also good for lighting. This was the most well-lit pipe.

### 3.2.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – This scan included multiple stations with a full loop across the road and back to the start of the scan. This looping was performed when possible as it helps to tie together the scan.
- Pocket LiDAR Scan – This scan was difficult as the range of the iPhone was sometimes exceeded while trying to walk through the center of the culvert.
- Leica BLK2GO – SLAM LiDAR – This scan included looping over the road and back to the start of the scan. This loop was performed to tie the scan together and avoid drift in the scan.

Figure 3.2.1 Herriman Midas Creek – Culvert with RTC360 Scanner Shown

## 3.3 Test Pipe 2 – Herriman Tunnel –- Miller Crossing and Ryeland Lane, Herriman, UT

This 72-inch Reinforced Concrete Pipe was selected as it was easily accessible and near Test Pipe 1. It was desirable to find concrete pipes, and obtaining easily accessible pipes of this size is difficult. It was determined that there was an elbow and manhole approximately 134 feet from the pipe inlet. The scans started 2-3 sections past the elbow. Since this pipe had limited external lighting, it was a good test of the lighting requirements.

### 3.3.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – This scan included multiple stations, but it was not possible to loop the survey above ground.
- Pocket LiDAR Scan and Leica BLK2GO – SLAM LiDAR – The graffiti in this pipe was actually a benefit for photogrammetric stitching as it gave additional points that could be triangulated in multiple photos.

Figure 3.3.1 Herriman Tunnel – John Caya, Scanning with Pocket LiDAR

## 3.4 Test Pipe 3 – Lisa Falls –- SR-210 and Lisa Falls (40.57204 N, 111.72968 W), Salt Lake County, Utah

This 60-inch Triple Wall, Polypropylene Pipe was selected as the research was trying to locate a smooth wall plastic pipe. The concern with these pipes is that they can have an extremely uniform surface with less recognizable points that can be triangulated by the software.

### 3.4.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – This scan included multiple stations with a full loop across the road and back to the start of the scan. This looping was performed when possible as it helps to tie together the scan.
- Pocket LiDAR Scan – This scan was difficult as the range of the iPhone was sometimes exceeded while trying to walk through the center of the culvert.
- Leica BLK2GO – SLAM LiDAR – This scan included looping over the road and back to the start of the scan. This loop was performed to tie the scan together and avoid drift in the scan.

**Figure 3.4.1 - Brady Reisch using Leica BLK2GO Mobile Lidar Scanner Lisa Falls Cross Culvert, Little Cottonwood Canyon, August 21, 2023**

## 3.5 Test Pipe 4 – Parley’s Creek –- I-80 Eastbound, Milepost 129.26 (40.71532 N, 111.78417 W), Salt Lake County, Utah

Even though the testing was conducted near the end of August, this 72-inch Reinforced Concrete Pipe had velocities that were too high to enter the pipe so only the outlet and headwall were scanned.

### 3.5.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – Not tested.
- Pocket LiDAR Scan – The outside of the culvert and headwall only.
- Leica BLK2GO – SLAM LiDAR – The outside of the culvert and headwall only.

**Figure 3.5.1 – Parley’s Creek, I-80 Parley’s Canyon, Salt Lake County, August 21, 2023**

## 3.6  Test Pipe 5 – Parley’s Creek –- I-80 Westbound, Milepost 131.96 (40.73740 N, 111.74481 W), Salt Lake County, Utah

This 84-inch Corrugated Metal Plate Arch crosses I-80 and this is the downstream outlet. The terrain to get to this pipe was rugged and therefore, the RTC360 was not feasible to use.  As this pipe was long without light from both sides, lighting was an issue.

### 3.6.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – Not tested.
- Pocket LiDAR Scan – Approximately 30 feet inside the outlet was tested.
- Leica BLK2GO – SLAM LiDAR – Approximately 30 feet inside the outlet was tested.

**Figure 3.6.1 – Parley’s Creek, I-80 Parley’s Canyon, Salt Lake County, August 21, 2023**

### 3.7 Test Pipe 6– Parley’s Creek –- I-80 Westbound, Milepost 130.2 (40.73324 N, 111.75326 W), Salt Lake County, Utah

This 84-inch Corrugated Metal Plate Arch crosses I-80 and runs parallel to I-80. It was not feasible to use the RTC360 as a control. This location is the upstream inlet. As this pipe was long without light from both sides, lighting was an issue.

#### 3.7.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – Not tested.
- Pocket LiDAR Scan – Approximately 30 feet inside the outlet was tested.
- Leica BLK2GO – SLAM LiDAR – Approximately 30 feet inside the outlet was tested.

**Figure 3.7.1 – Parley’s Creek, I-80 Parley’s Canyon, Aaron Mackliet and Randy Wahlen Scanning, Salt Lake County, August 21, 2023**

### 3.8 Test Pipe 7 – Parley's Creek –- I-215 Northbound, Milepost 1.05 (40.70961 N, 111.80125 W), Salt Lake County, Utah

This 90-inch Corrugated Metal Plate Arch crosses I-215, and the downstream outlet was surveyed due to its proximity to the Parley's Historic Nature Park. The pipe includes a concrete bottom which creates high velocities and slick conditions. It was not feasible to walk up the flowline of this pipe while scanning. Therefore, the RTC360 was not used to scan control. Testers walked along the concrete edge, just above flowline, but it was difficult to get good results with the equipment not more centered in the pipe.

#### 3.8.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – Not tested.
- Pocket LiDAR Scan and Leica BLK2GO – Slam LiDAR – Approximately 30 feet inside the outlet was tested. The testing was from the side of the pipe, so the results were not as good as walking up the middle of the pipe.

**Figure 3.8.1 – Parley's Historic Nature Park, Salt Lake County, August 21, 2023**

## 3.9 Test Pipe 8 – Cross Culvert Under the Trail, Within Parley's Historic Nature Park –- (40.71000 N, 111.80745 W), Salt Lake County, Utah

This 48-inch Corrugated Metal Pipe is a cross culvert under the trail. The pipe had a lot of damage, including: misalignment, buckling, debris, joint separation, corrosion. The size of the pipe made it difficult to traverse and scan.

### 3.9.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – This scan included multiple stations with a full loop across the trail and back to the start of the scan. This looping was performed when possible as it helps to tie together the scan. Looping outside the culvert was difficult due to vegetation cover. Scanning inside the culvert was difficult due to the diameter of the culvert.

- Pocket LiDAR Scan – The pipe was scanned from inlet to outlet. It was difficult to use the scanner correctly, while traversing the pipe and attempting to light the pipe.

- Leica BLK2GO – SLAM LiDAR – The pipe was scanned from inlet to outlet. 360-degree lighting was an issue in this small pipe that was difficult to crawl through, scan and manage lighting.

**Figure 3.9.1 – John Caya using Pocket LiDAR in Parley's Historic Nature Park, Salt Lake County, August 8, 2023**

## 3.10 Test Pipe 9 – Reinforced Concrete Pipe Under I-80, Within Parley's Historic Nature Park –- (40.71286 N, 111.81332 W), Salt Lake County, Utah

This 90-inch Reinforced Concrete Pipe under I-80 at this location, the inlet being in Tanner Park and the outlet being near the Salt Lake Country Club. It was desirable to test near the center of the culvert where the pipe transitions from concrete to corrugated metal, but the flows in the pipe were high enough and the pipe was slick enough that this was not feasible. In fact, the testers used a rope to stabilize themselves so that they did not slip and fall with expensive equipment in hand.

### 3.10.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – It was not feasible to take this unit into this culvert.
- Pocket LiDAR Scan and Leica BLK2GO – SLAM LiDAR – The pipe was scanned from inlet to outlet. It was difficult to use the scanner correctly, while traversing the pipe, holding onto a rope, and attempting to light/scan the pipe.

**Figure 3.10.1 – John Caya and Aaron Mackliet using Pocket LiDAR in Parley's Historic Nature Park, Salt Lake County, August 8, 2023**

### 3.11 Test Pipe 10 – Corrugated Metal Pipe in Sugarhouse Park, –- (40.72042 N, 111.84286 W), Salt Lake City, Utah

This 90-inch Corrugated Metal Plate Arch inlets to the east of 1700 East, crosses under the road, and outlets in Sugarhouse Park near Hidden Grove. It was not feasible to use the RTC360 as control as the pipe was in a very steep gully at the inlet and it was not possible to loop the survey. As with other long pipes without being able to see both ends, lighting was an issue.

#### 3.11.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – Not tested.
- Pocket LiDAR Scan and Leica BLK2GO – Mobile Scanner – The majority of the pipe was scanned.

**Figure 3.11.1 – Sugarhouse Park, Hidden Grove Pipe**

## 3.12 Test Pipe 11 – Concrete Pipe in Sugarhouse Park, –- (40.72218 N, 111.84686 W), Salt Lake City, Utah

This 60-inch Concrete Pipe crosses under Sugarhouse Park Road. It was difficult to scan this pipe as it was extremely limited at the inlet due to inlet control of the flow. The pipe increased, one joint from the inlet, which led to slick conditions near the outlet. All of the technologies entered through the inlet and did not exit the outlet. Both Leica scanners were looped and the outlet/headwall was scanned from the creek downstream.

### 3.12.1 Tests Conducted

- Leica RTC360 – Terrestrial LiDAR – This scan included multiple stations with a full loop over the road and to the outlet. Scanning inside the culvert was difficult due to water levels.
- Pocket LiDAR Scan – The pipe was scanned from inlet to outlet. It was difficult to use the scanner correctly in the area with little headroom and high water.
- Leica BLK2GO – SLAM LiDAR – The pipe was scanned from inlet to outlet, then from inlet over the road to the creek downstream from the outlet.

**Figure 3.12.1 – Sugarhouse Park, Reinforced Concrete Pipe, Michael Olsen, Aaron Mackliet and Daxton Nielson scan the outlet/headwall with the RTC360 Scanner, August 8, 2023**

## 3.13 **Summary**

Figure 3.13.1 shows an example of the types of point clouds that were gathered for each pipe. This Pocket LiDAR Point Cloud is from the Test Pipe 8 – Cross Culvert under the trail at Parley's Historic Nature Park. The point clouds from the various tests will be used to determine if the LiDAR provides usable data for the UDOT Pipe Defects that need to be rated.

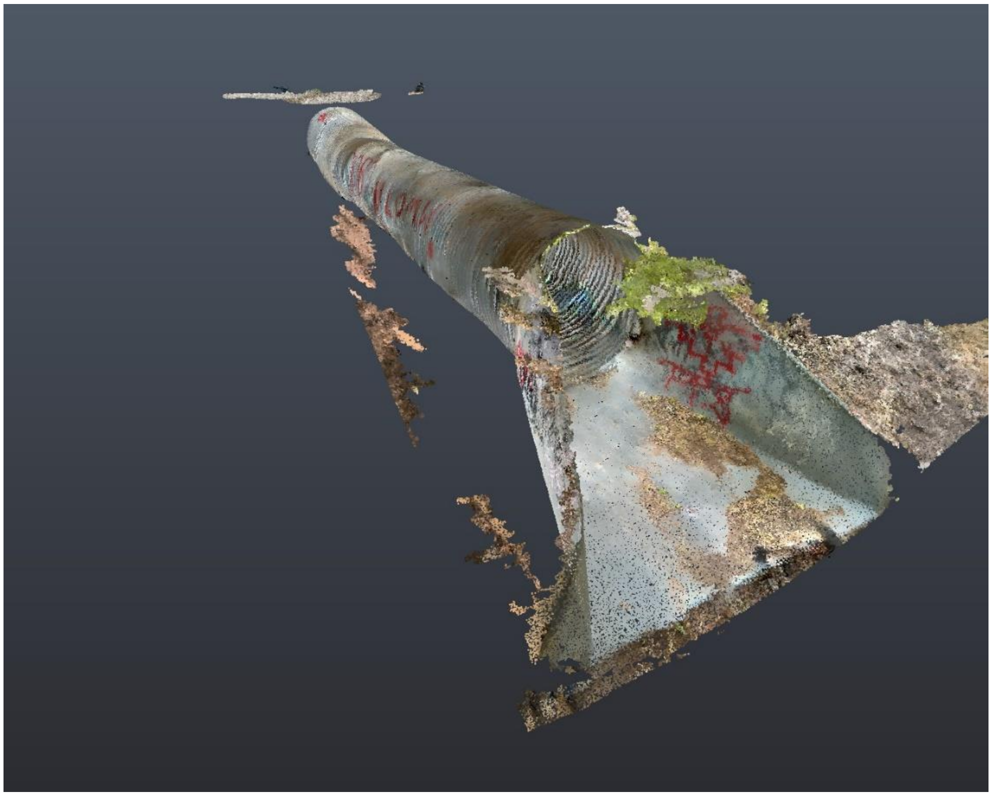


**Figure 3.13.1 – Pocket LiDAR Point Cloud in Parley's Historic Nature Park, Salt Lake County**

# 4.0 DATA EVALUATION

## 4.1 Overview

This chapter will review the technologies with respect to whether they can measure and rank culvert defects, according to the tolerances in the UDOT Culvert Rating System.[18] The following defects for the most common pipe types have been summarized from the UDOT Pipe Defect Rating Sheets in Table 4.1.1. This summary has taken 3 pages of instructions and abbreviated it, focusing on the minimum measurement that would need to be made:

**Table 4.1.1 – UDOT Pipe Defect Rating**

| | **Pipe Type/Defect Threshold** | | |
|---|---|---|---|
| **Defect** | | | |
| | **Concrete** | **Thermoplastic** | **Corrugated Metal** |
| Cracking/Fractures | > 0.05 inches | Any width of crack | Any width of crack |
| Spalling/Slabbing | ½ inches | N/A | N/A |
| Local Buckling (rippling in pipe wall) | N/A | No Measurement Specified | N/A |
| Shape (Deflection) | N/A | > 5.0% | > 5.0% |
| Deterioration or Surface Damage (Loss of Pipe Wall) | Abrasion > 0.25 inches | Erosion > 10% of pipe wall thickness | Visual Abrasion |
| Barrel Alignment | Change in Alignment >5% | Change in Alignment >5% | Change in Alignment >5% |
| Pipe Joints | Less than 1 wall thickness | Less than 1 wall thickness | Less than 1 wall thickness |
| Corrosion | N/A | N/A | Rusting |
| Infiltration/Exfiltration | N/A | N/A | Staining |
| Bolts/Seams | N/A | N/A | Missing Bolt |

All of these except Corrosion and Infiltration/Exfiltration will be evaluated as to whether the defect is visible with LiDAR. For Corrosion and Infiltration/Exfiltration, LiDAR is not an applicable technology currently. It is felt that these two defects have a general threshold requirement, so the accuracy of their measurement is not critical.

## 4.2 Cracking and Fractures

The research focused on what size of cracks could be evaluated with the aid of LiDAR-generated 3D models. Figure 4.2.1 shows an example of a crack in the Lisa Falls Polypropylene pipe. This pipe was chosen as it was found that smaller cracks were not identifiable with current mobile LiDAR technologies.

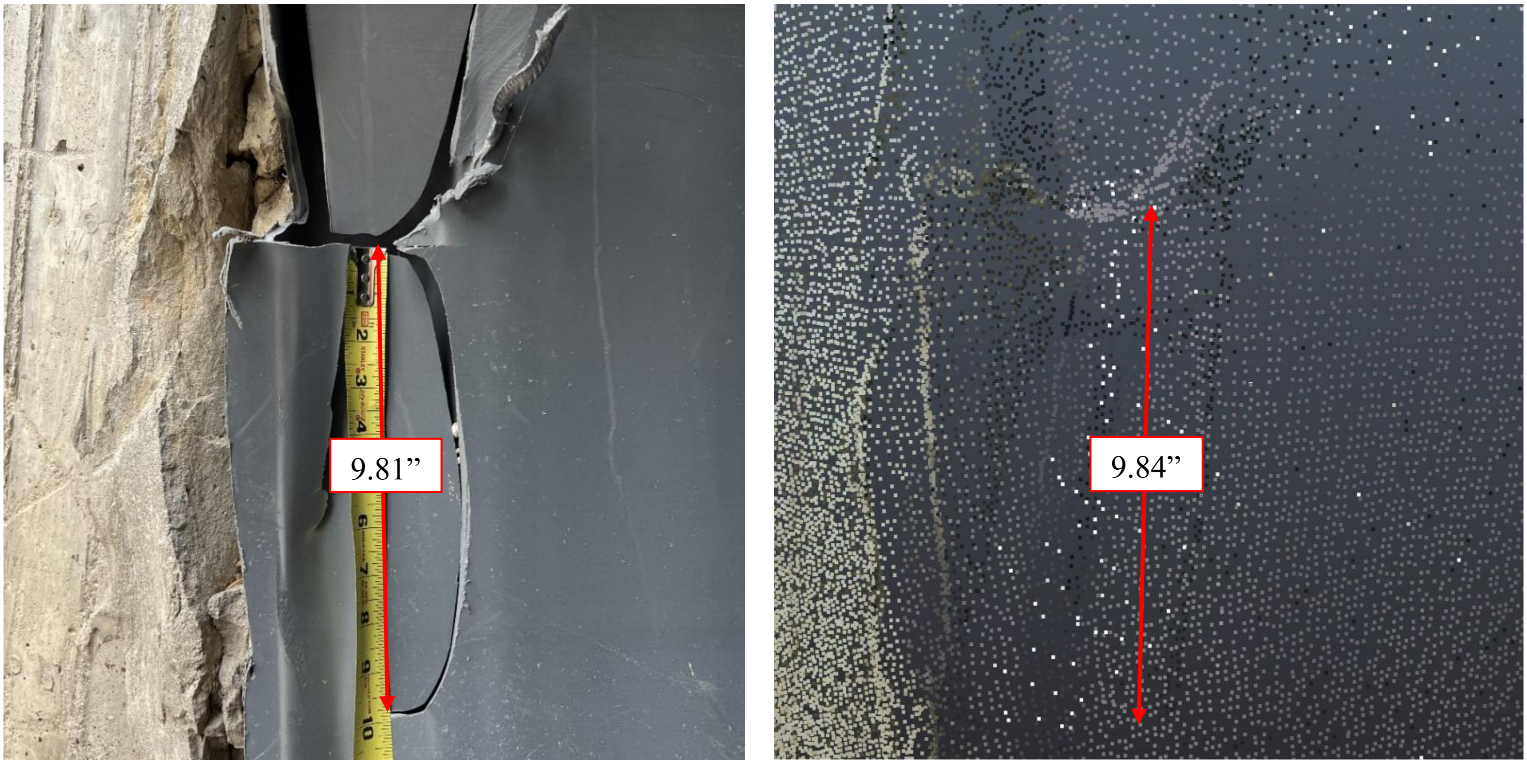
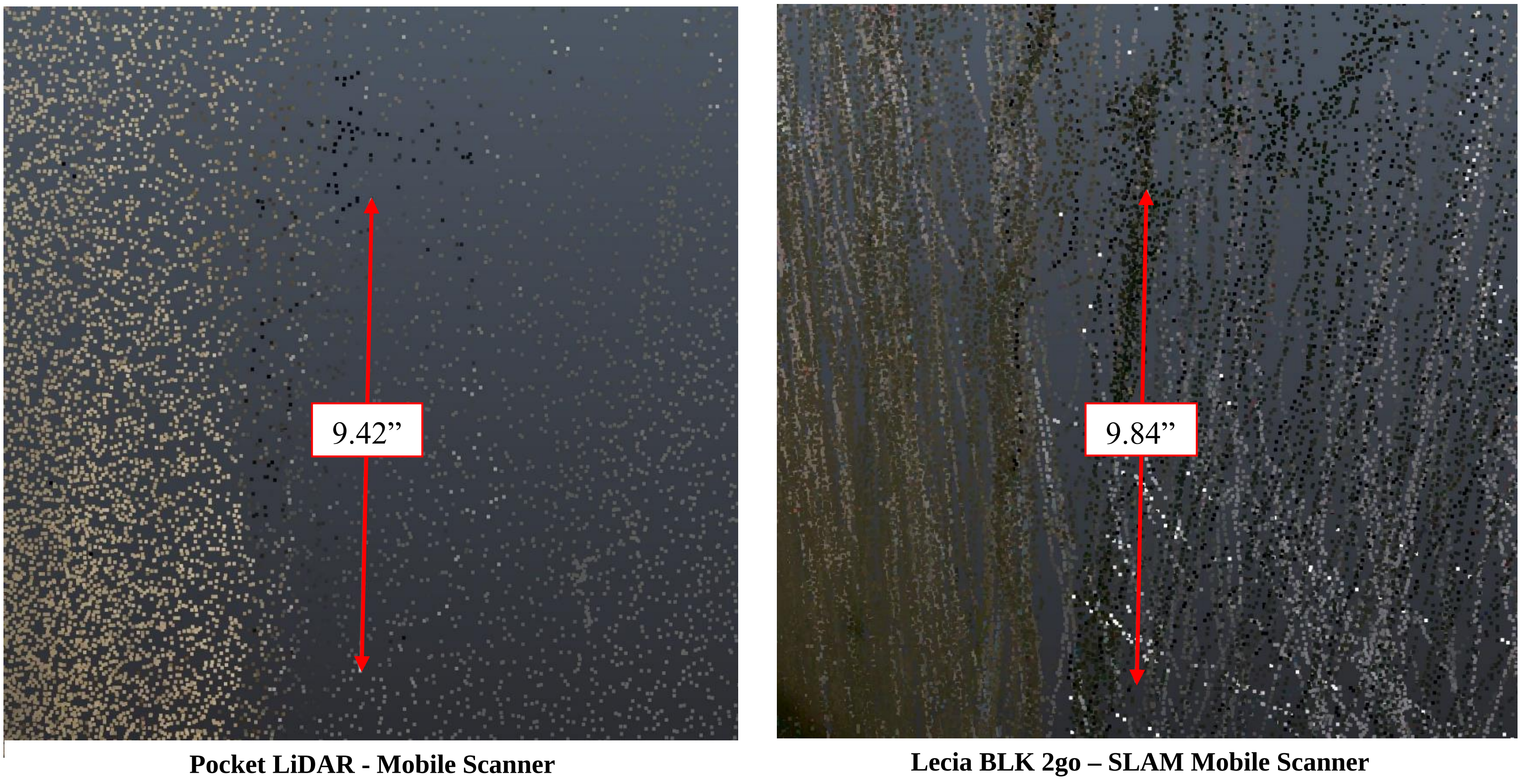


**Photo** **Leica RTC-360 – Terrestrial Scanner**



**Pocket LiDAR - Mobile Scanner** **Lecia BLK 2go – SLAM Mobile Scanner**

**Figure 4.2.1 – Cracking in Lisa Falls Polypropylene Pipe**

### 4.2.1 Results of Cracking/Fracture Defect Evaluation

Figure 4.2.1 shows the pipes were measured within the following accuracies, with the photo measurement as the base. Table 4.2.1 shows the measurement accuracies as compared to the photo with scale:

**Table 4.2.1 – Accuracy of Cracking Measurement with LiDAR**

| | Absolute Difference | Relative Difference |
|---|---|---|
| Leica RTC360 - Terrestrial Scanner | + 0.03” | + 0.30% |
| Pocket LiDAR – Mobile Scanner | - 0.39” | - 4.14% |
| Leica BLK2GO – Mobile Scanner | + 0.03” | + 0.30% |

It needs to be noted that the minimum rating measurement for concrete culverts was a defect threshold of fractures greater than 0.05 inches. None of the point clouds were dense enough to be able to capture a fracture of this width. From the figures it can be seen how difficult it was to identify this extremely large crack through point clouds only. In fact, identifying the crack required changing the orientation of the point cloud for a specific area until the crack became somewhat visible. Without a photo and location as a base condition, this crack would not have been measurable through LiDAR. It can also be seen that very few points in the point cloud fall within cavity of the crack. This shows that if crack widths in the 0.5-inch range are not measurable, that the UDOT threshold of 0.05 inches is not currently measurable.

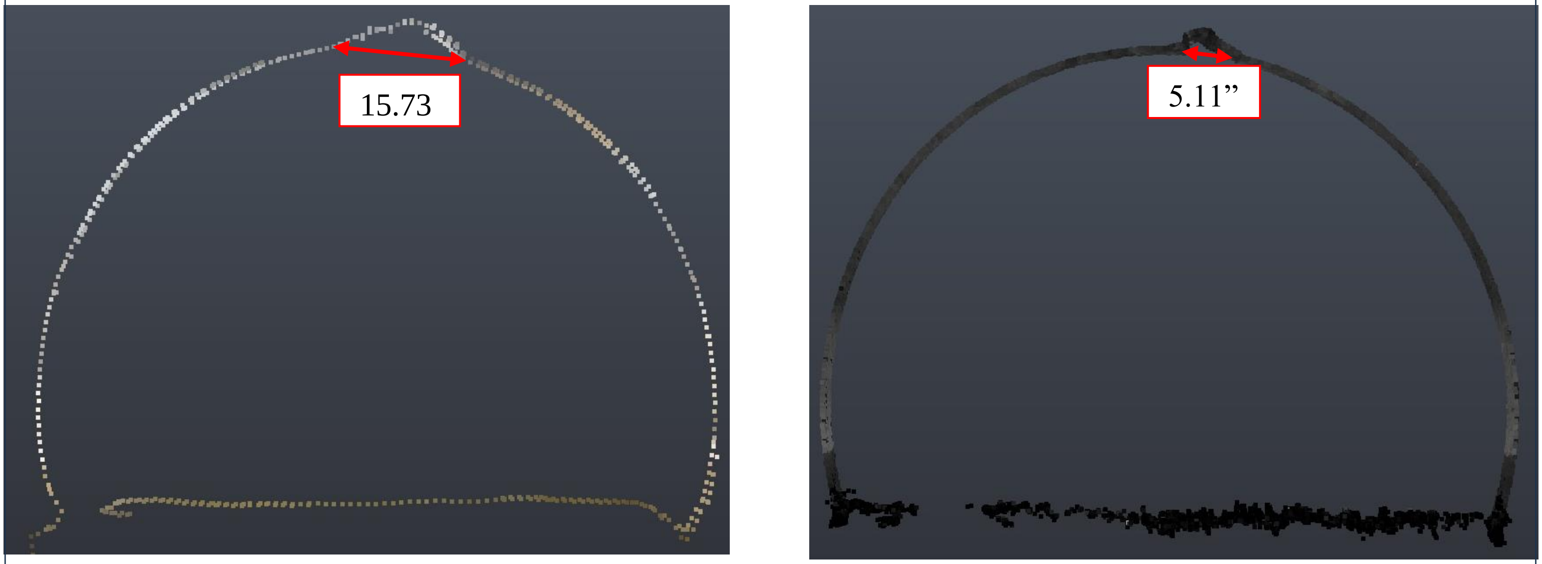
It is unclear whether LiDAR point cloud resolution will increase enough in the future to accomplish this type of small measurement, as LiDAR point clouds this dense would be extremely data intensive and most applications do not need this higher point density. In the case of Thermoplastic and Corrugated Metal pipes, where no measurement of the fracture is required, AI Technology should be able to be trained to identify a fracture.

### 4.3 Spalling Evaluation

The Sugarhouse Park, 60-inch Reinforced Concrete pipe was used because of the measurable spalling. This spalling likely occurred due to damage from connecting the storm drain inlets directly into the pipe with jack hammers, i.e., poor construction practices.

Figure 4.3.1 shows the results of the analysis. It was not possible to get a photo of this section that illustrated the full shape of pipe and spall as is seen with LiDAR. This is one of the benefits of LiDAR or Photogrammetry over traditional pipe video inspections. The RTC360 was stationed immediately under the spall, so there is confidence that the RTC360 measurements are accurate. The BLK2GO scan was made, but the file was corrupted in processing and is not available. The testers would like to retest the pipe and amend the document to include the results of the BLK2GO at a later date.

**Photo of Sugarhouse Concrete pipe where the spall was measured.**



**Pocket LiDAR - Mobile Scanner**

**Leica RTC-360 – Terrestrial Scanner**

**Figure 4.3.1 – Spalling in Sugarhouse Park Reinforced Concrete Pipe**

### 4.3.1 Results of Spalling Defect Evaluation

Figure 4.3.1 shows the pipes that the Pocket LiDAR did not have enough accuracy for. While it correctly shows the spall, the photogrammetric stitching did not recreate the 3D model with accurate measurements. It is likely that this inaccuracy is because the section was very difficult to light and use the phone to scan simultaneously. There is also a possibility that the sections from each scan are not exactly at the same station within the pipe. Every effort was made to overlay the scans correctly, so while the section location could have affected the measurements, it did not affect it to this degree.

### 4.4 Shape Evaluation

This test case focused on the Lisa Falls pipe as it was the only test pipe where deflection could be measured. In thermoplastic pipe, the flexibility of the pipe will typically yield vertical and horizontal deflections. Typically, the vertical reduction in diameter will be compensated by a similar horizontal deflection. The strength of the pipe comes from proper soil compaction around the pipe. Proper soil compaction allows this deflection to occur, but not to exceed established limits. The UDOT ranking criteria starts scrutinizing deflections greater than 5%. Figure 4.4.1 shows deflections taken at the same place in the Lisa Falls Culvert.

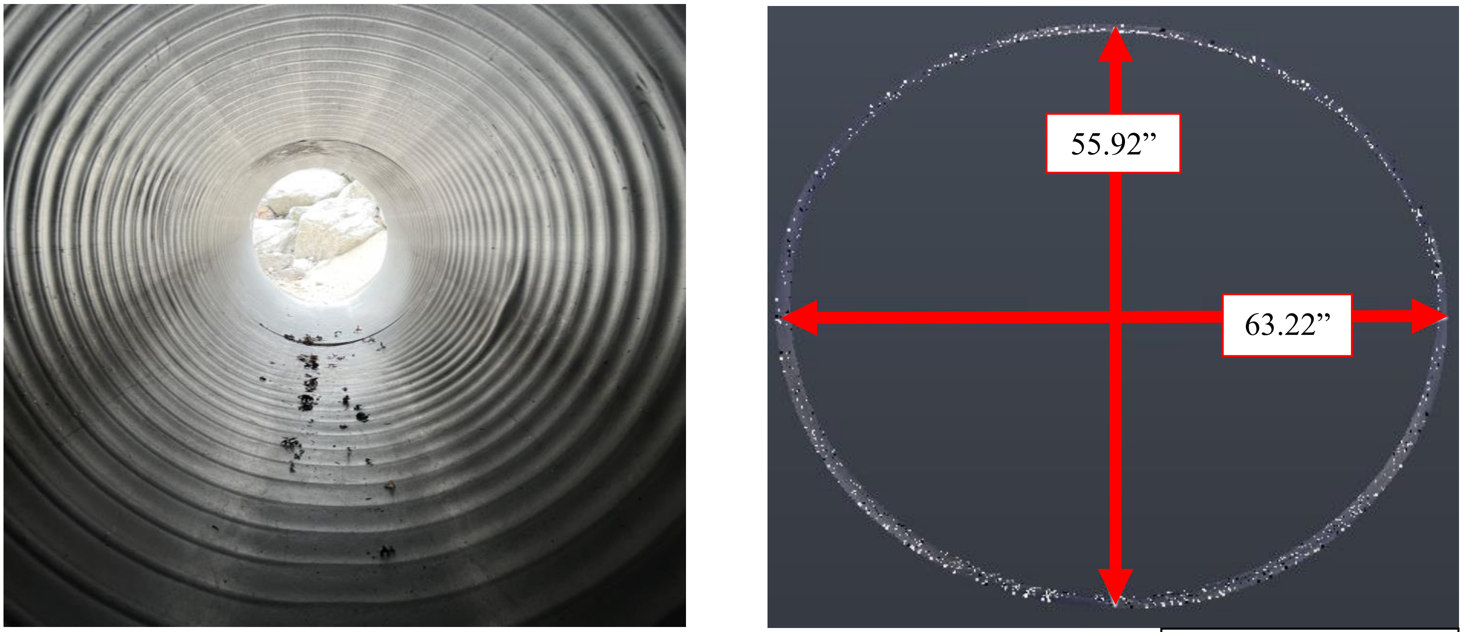
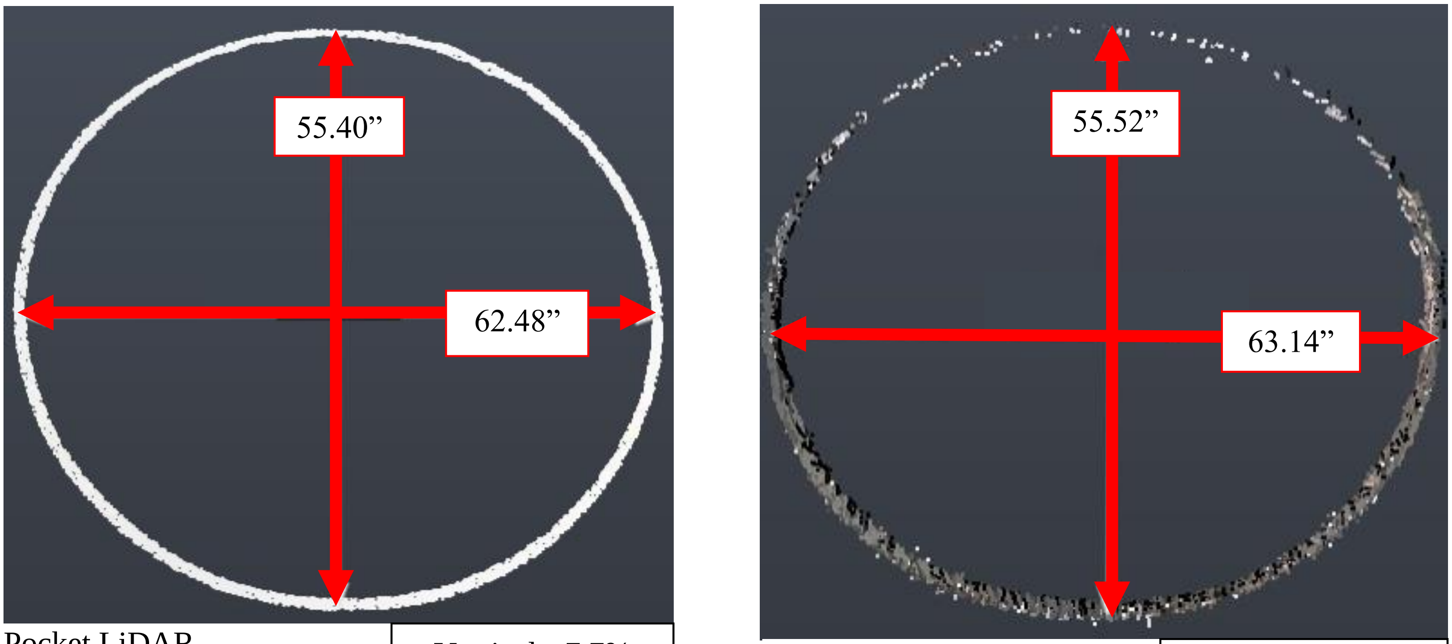


Photo of Pipe

RTC360 – Terrestrial

Vertical: -7.3%
Horizontal: +5.1%



Pocket LiDAR –
Mobile Scanner

Vertical: -7.7%
Horizontal: +4.1%

Lecia BLK2GO –
Mobile Scanner

Vertical: -8.1%
Horizontal: +5.2%

**Figure 4.4.1 – Shape Evaluation of Pipe, Lisa Falls 60” Polypropylene**

Figure 4.4.1 shows pipe deflection measurement accuracies, with the RTC360 as the base. The absolute difference in inches was calculated for each direction. Also, the absolute difference in deflection percentage, based on a 60-inch initial diameter, was calculated. Table 4.4.1 shows the measurement accuracies as compared to the photo with scale:

**Table 4.4.1 – Accuracy of Shape Measurement with LiDAR**

| | Absolute Difference Vertical | Absolute Deflection Vertical | Absolute Difference Horizontal | Absolute Deflection Horizontal |
|---|---|---|---|---|
| Pocket LiDAR – Mobile Scanner | -0.50” | -0.4% | -0.74” | +1.0% |
| Leica BLK2GO – Mobile Scanner | -0.40” | -0.8% | -0.08” | +0.1% |

It needs to be noted that the minimum rating measurement for deflection was 5%, with variations in rating occurring between 5% and 10% deflection. The results show that the deflections measurements of each technology are within reasonable tolerances and that this data would be useful for determining the shape/deflection of flexible pipes. This also shows that the Pocket LiDAR, while being the least costly alternative, is accurate enough to utilize.

It should be mentioned that the literature search found that deflection measurement technology already exists and is accurate, when properly calibrated. This technology uses a laser that is spun and pulled behind the pipe video camera. To accomplish this, the pipe video camera inspects the pipe with artificial lighting to access the condition of the pipe. In reversing the camera, the pipe is rerecorded without lights and the laser illuminating the shape of the pipe. A key to this technology is being able to calibrate the video for each pipe. It is also critical to have the pipe video centered in the pipe.

## 4.5 Localized Buckling/Rippling in Pipe Wall Evaluation

Localized Buckling or Rippling occurs when high stresses occur in plastic pipe walls. This section will review whether LiDAR can detect this small defect. Figure 4.5.1 shows a photo that illustrates the localized buckling and the sectioned point clouds for the different technologies at this location.

Photo with Localized Buckling Highlighted RTC360 - Terrestrial

Pocket LiDAR – Mobile Scanner BLK2GO – Mobile Scanner

**Figure 4.5.1 – Sections of Lisa Falls Pipe with Localized Buckling**

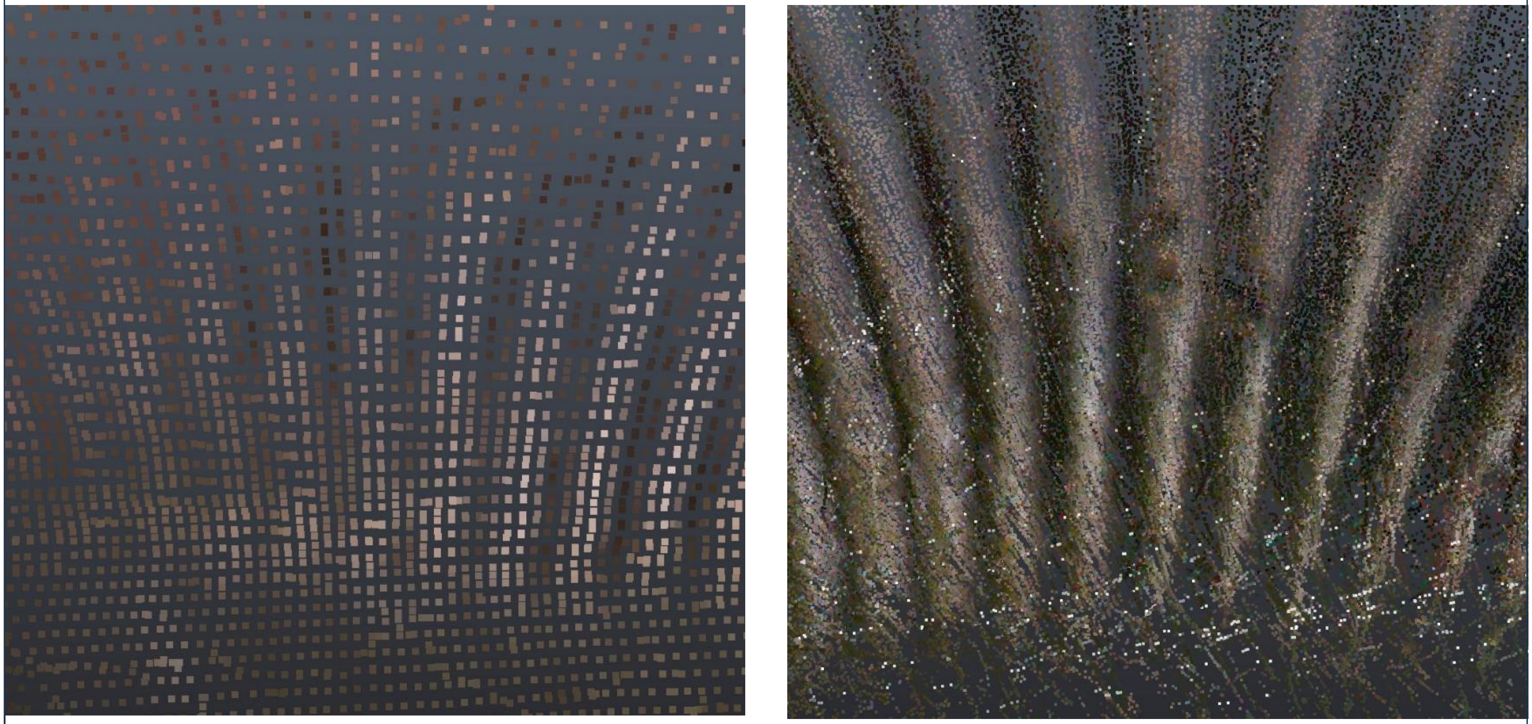
### **4.5.1 Results of Localized Buckling**

The graphics show that the localized buckling is not evident enough or large enough to make measurements. It also shows some shape deformation in the BLK2GO that is not consistent with the other technologies. This shows that LiDAR is not currently able to make reasonable measurements for localized buckling.

### 4.6 Deterioration or Surface Damage Evaluation

Surface damage was found in Test Pipe 5, the 84-inch Corrugated Metal Plate Arch, that goes under I-80 near the Mt. Aire Canyon exit. This section had corrosion fully through the pipe wall in multiple locations near the low flow line.  This area was chosen as it was near the entrance and had the best lighting.  Figure 4.6.1 shows the photo of the area with the Pocket LiDAR and BLK2GO scans. The RTC360 was not used as control for this pipe due to the steep conditions to access the inlet.

**Photo of Corrosion Damage**



**Pocket LiDAR - Mobile Scanner**

**Lecia BLK2GO – Mobile Scanner**

**Figure 4.6.1 – Corrosion Damage in Corrugated Metal Pipe**

### **4.6.1 Results of Deterioration or Surface Damage Evaluation**

The photo and scans in Figure 4.6.1 were not measured for accuracy as the RTC360 was unavailable for control at this location. The RTC360 was not used as control for this pipe due to the steep conditions to access the inlet. Yet, even without measurements, the scans yield some lessons learned and why LiDAR would not be a simple “plug and play solution.” In the Pocket LiDAR scan, it looks as if a mesh net were draped over it. That is because this location was not scanned densely and the dark gray spots are areas without data. In contrast, the BLK2GO scanner showed a reasonable 3D model for this location. That said, based on the spalling analysis with a much larger damage area, it is not currently feasible to measure small widths of surface deterioration. This type of damage would likely be better served using traditional video methods combined with AI learning and identification of the defect.

### 4.7 Barrel Alignment Evaluation

For this evaluation, the Lisa Falls pipe was chosen as it was installed as a “broken back” culvert, with the slope changing midway through the culvert. This is not uncommon in new construction if the grade the pipe is placed on is not consistent throughout. These grade breaks can often be seen through joint gaps that vary greatly from the top to the bottom of the pipe.

Figure 4.7.1 shows the Lisa Falls pipe from the downstream outlet. This photo shows how the first sections of pipe, in the background, are at a different slope than the rest of the pipe. Figure 4.7.2 shows the Lisa Falls pipe with lines indicating a straight grade from inlet to outlet. Slope measurements to the broken back point of inflection are shown.

**Figure 4.7.1 – Photo of Interior Grade Change, Lisa Falls 60” Polypropylene Pipe**

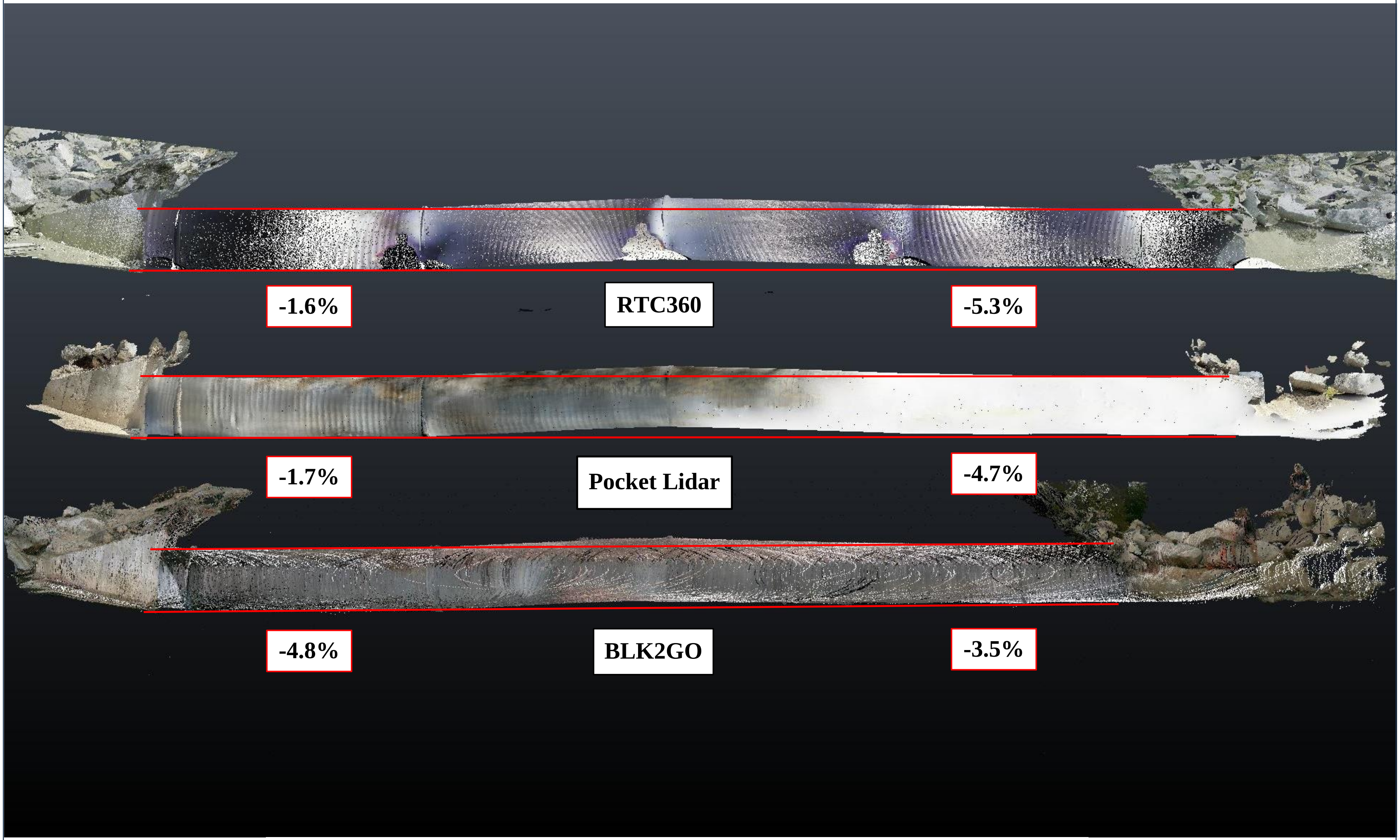


Figure 4.7.2 Comparison of Grade Change, Lisa Falls Polypropylene Pipe

### 4.7.1 Results of Barrel Alignment Evaluation

Figure 4.7.1 shows the pipe slopes were measured within the following accuracies, with the RTC360 as the base. Table 4.7.1 shows the measurement accuracies as compared to RTC360 as control:

**Table 4.7.1 – Accuracy of Barrel Alignment with RTC360 as Control**

| | Absolute Difference Upstream | Absolute Difference Downstream |
|---|---|---|
| Pocket LiDAR – Mobile Scanner | + 0.1% | - 0.6% |
| Leica BLK2GO – Mobile Scanner | - 3.2% | - 1.8% |

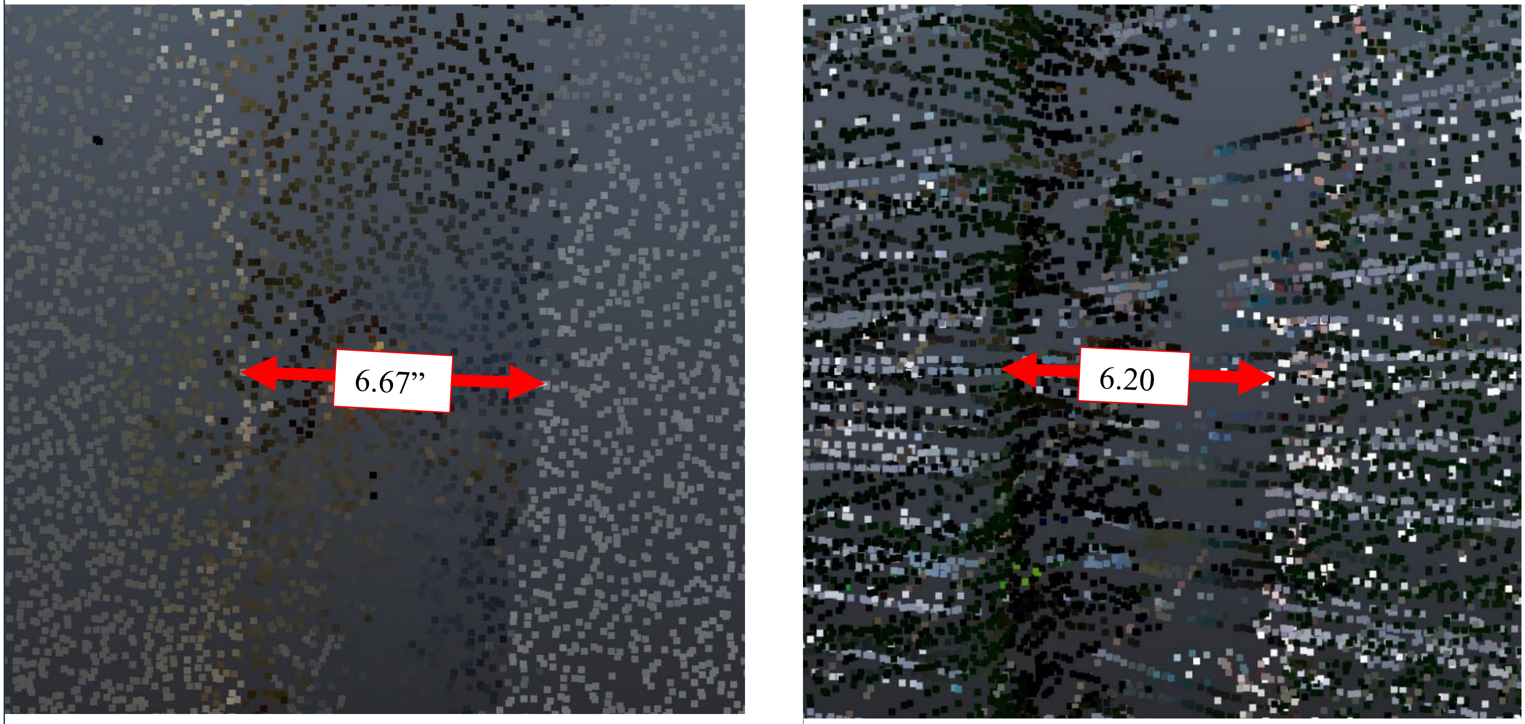
The above results were the opposite of what was encountered with section 4.2 Cracking. In that section, the Leica BLK2GO – Mobile Scanner was more accurate than the Pocket LiDAR – Mobile Scanner. As was discussed earlier, the mobile scans are highly sensitive to having evenly broadcast lighting within the culvert and Pocket LiDAR was more effectively lit during the testing than the BLK2GO scanner. We believe a fault in the BLK2GO Visual LiDAR caused the inaccuracies as there was not enough light to resolve the photogrammetric stitching. It was observed that one of the central pipe sections was shortened significantly and this affected the overall length and slopes of the pipe. This is even with adding scaled targets and looping the survey over the road for the BLK2GO scanner.

The Pocket LiDAR scanning was accurate enough to determine slopes to within the UDOT criteria of 5 percent. For the BLK2GO scanner, it’s not known if the lighting issue or the dependance on Visual SLAM over LiDAR SLAM would have enough impact to make the BLK2GO scans as accurate as Pocket LiDAR or better.

## 4.8 Pipe Joints Evaluation

Joint Gap requirements are based on pipe wall thickness, the smallest measure being 1 wall thickness. Therefore, the minimum thresholds for a 24-inch diameter pipe, the smallest UDOT Standard, were 3 inches for concrete pipe[19], 2 inches for HDPE dual wall pipe[20] and ½ inch for a Corrugated Metal Pipe[21]. Therefore, this research should focus on whether LiDAR is accurately able to measure the smallest joint gap, which would be ½ inch. As it was difficult to find and measure smaller joint gaps, the following 7” gap was measured for accuracy.

**Photo** **Leica RTC-360 – Terrestrial Scanner**



**Pocket LiDAR - Mobile Scanner** **Lecia BLK2GO – Mobile Scanner**

**Figure 4.8.1 – Joint Gaps in Lisa Falls Polypropylene Pipe**

### 4.8.1 Results of Joint Gap Defect Evaluation

Figure 4.8.1 shows the pipes were measured within the following accuracies, with the photo measurement as the base. Table 4.8.1 shows the measurement accuracies as compared to the photo with scale:

**Table 4.8.1 – Accuracy of Joint Gap with LiDAR**

| | Absolute Difference | Relative Difference |
|---|---|---|
| Leica RTC360 - Terrestrial Scanner | 0.0” | 0.0% |
| Pocket LiDAR – Mobile Scanner | - 0.33” | - 4.95% |
| Leica BLK2GO – Mobile Scanner | - 0.8” | - 12.90% |

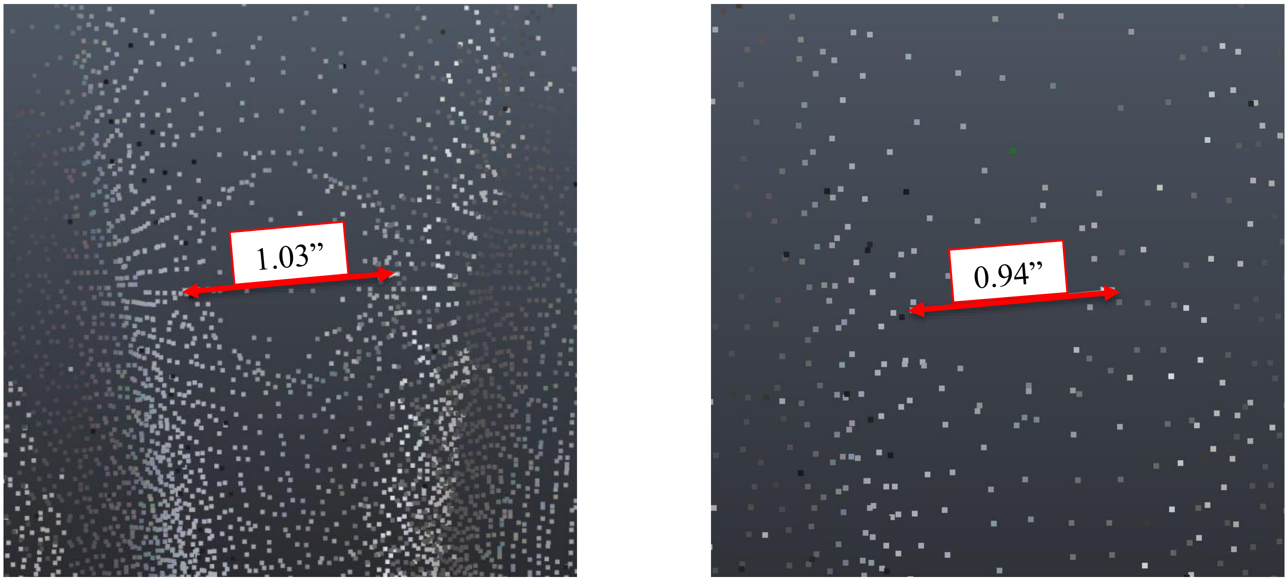
The above results were completely opposite to what was encountered with section 4.2 Cracking. In that section, the Leica BLK2GO – Mobile Scanner was more accurate than the Pocket LiDAR – Mobile Scanner. The reasons for this inaccuracy related to this single joint gap were theorized and then confirmed with the testing groups. For the mobile scans of section 4.2 Cracking, the area of the crack was at the end of the pipe, therefore, good, even lighting was consistent between the three scanning technologies. The mobile scans are highly sensitive to having evenly broadcast lighting within the culvert. The Pocket LiDAR was easier to keep lighting consistent as it needed 180-degree lighting. For the BLK2GO, it needs 360-degree lighting, so it was prone to problem spots during the test. It could be seen that the lighting brightness and consistency varied throughout the pipe scans. For this section of the report, the inaccuracy of the BLK2GO was based on inadequate lighting and the current practice that the BLK2GO relies more on photogrammetry than LiDAR. In essence, uneven lighting makes it more difficult to stitch together photos for the 3D model.

It needs to be noted that the minimum rating measurement for joint gaps in culverts was ½ inch for a Corrugated Metal Pipe. With even lighting, joint gaps should be able to be viewed down to +/- 0.2 inches based on the accuracy found in the cracking analysis. Automating this process would be difficult as processing these data-intensive point clouds requires high effort for the data gleaned.

AI Technology **can** be trained to identify joint gaps and to flag those that are out of specification.

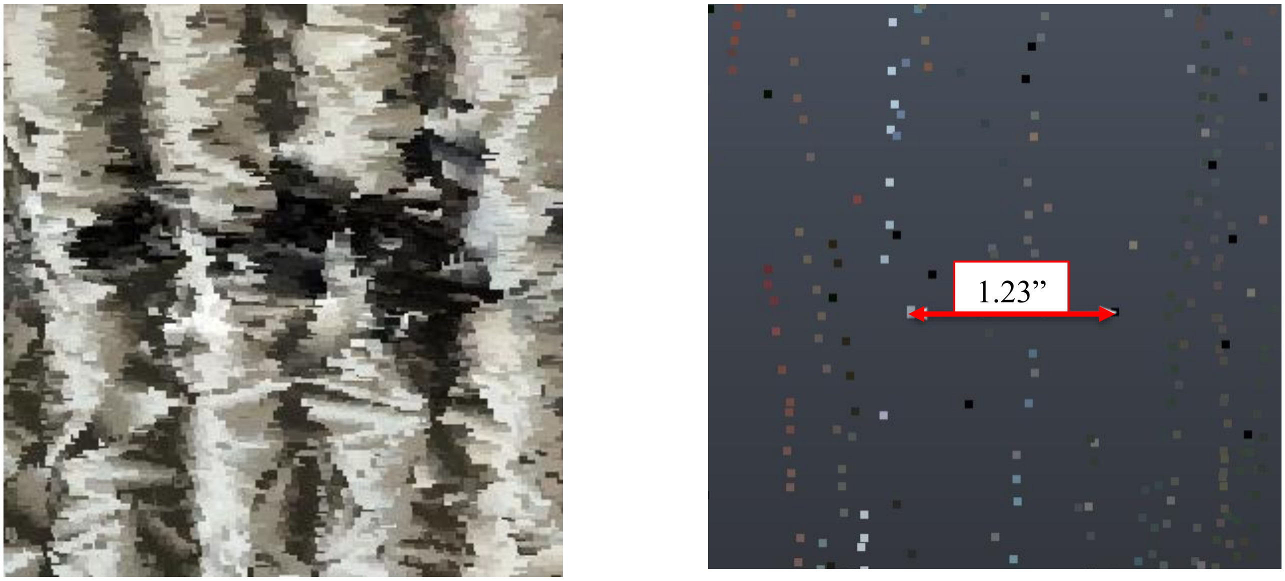
### 4.9 Bolts/Seams Evaluation

The threshold for the Bolts defect is a missing bolt. Measurements are not critical for this, so it might be better accomplished by a traditional video camera with AI learning for missing bolt detection. At the same time, bolts in the Corrugated Metal Plate Arch were a good test of the LiDAR capabilities as these approximately 1-inch bolts would be thought to be readily recognizable in a scan. Figure 4.9.1 shows a bolt in the Herriman Midas Creek 32’ x 16’ Corrugated Metal Plate Arch.  This bolt was scanned with the RTC360 in both high and medium resolution, Pocket LiDAR and the BLK2GO.  Pocket LiDAR was not measurable due to the width of this culvert being near the end of the range of the Pocket LiDAR laser. Table 4.9.1 shows the results of the bolt measurements with the RTC360 High Resolution as the control.



**RTC360 set at High Resolution**

**RTC360 set at Medium Resolution**



**Pocket LiDAR – Mobile Scanner**
**Not Measurable**

**BLK2GO – Mobile Scanner**

**Figure 4.9.1 – Bolt Measurements at Herriman Midas Creek Culvert**

**Figure 4.9.1 – Results of Bolt Measurement**

Figure 4.9.1 is illustrative of several issues that are important to the study. Using the RTC360 on high resolution is not typical as the file size makes it extremely difficult to use these files. While processing speed and data management should improve over time, high resolution is currently an option for only small sections. The data also shows how the BLK2GO scanner has a resolution that is less than the RTC360 medium resolution. This is one of the reasons that the BLK2GO had difficulty resolving small measurements, it simply does not have enough resolution.

**Table 4.9.1 – Accuracy of Bolt Measurements**

| | Absolute Difference | Relative Difference |
|---|---|---|
| Leica RTC360 - Terrestrial Scanner – High Resolution | 0.0” | 0.0% |
| Leica RTC360 - Terrestrial Scanner – Medium Resolution | - 0.09” | - 8.7% |
| Leica BLK2GO – Mobile Scanner | + 0.2” | + 19.4% |

The above table illustrates that LiDAR is currently not able to distinguish small measurements due to the point cloud resolution. This impacts measuring seams, bolts, fractures, joint gaps, surface deterioration and smaller spalls.

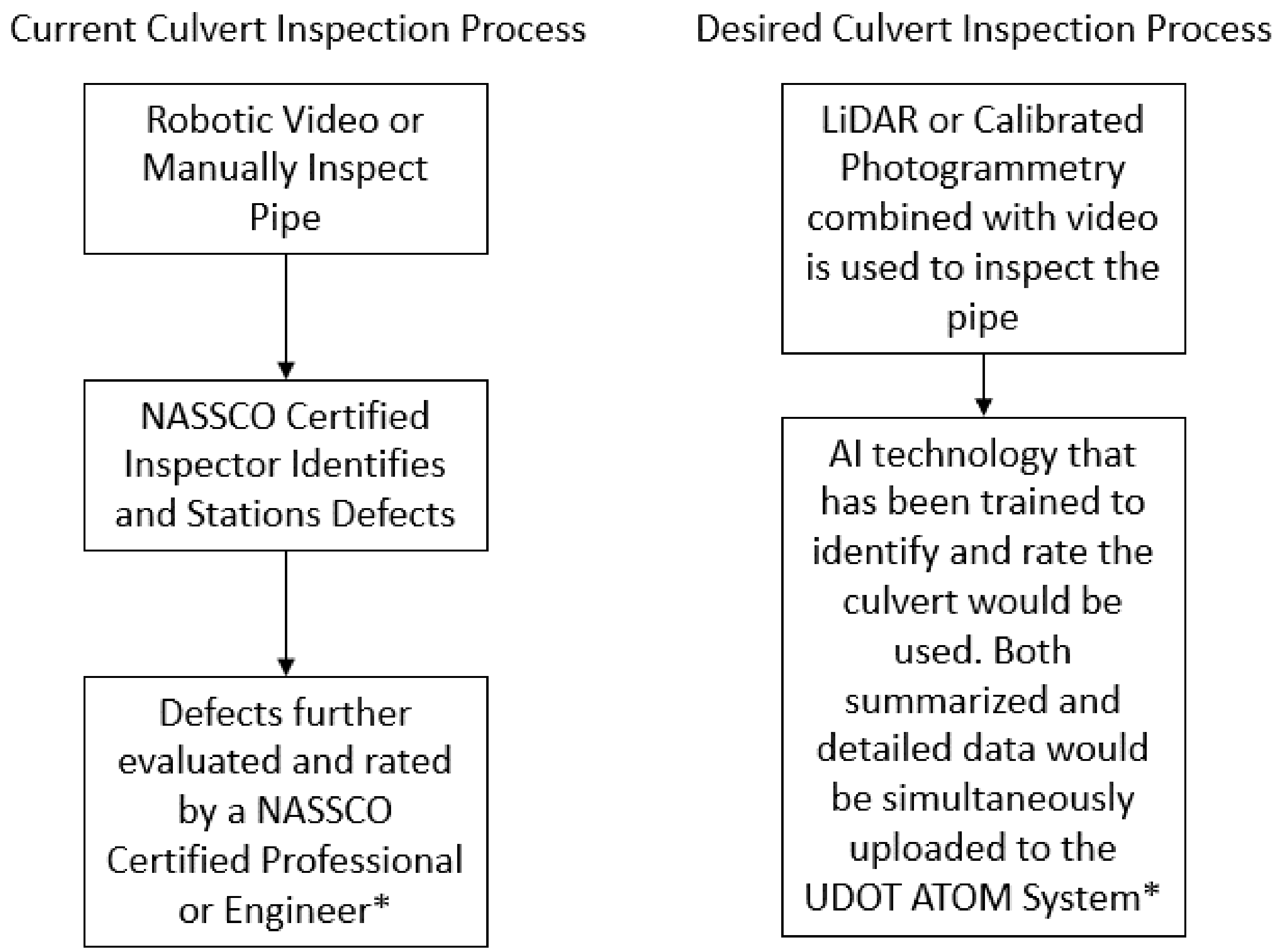
## 4.10 Summary

The results were mixed. Larger measurements such as shape, deflection and barrel alignment were reasonably accurate. Smaller measurements like fractures, spalling, surface deformation, joint gaps, bolts, etc., were not very accurate. Some of the accuracy could be resolved through better lighting and other improvements, but it is unlikely that LiDAR will improve sufficiently to have dense enough point clouds to measure small cracks.

# 5.0 CONCLUSIONS AND FINDINGS

## 5.1 Summary

This research was to evaluate if there was currently a technology that could rate culvert inspections independent of the need for reviewing the videos manually. There were several existing technologies that were marketed adding LiDAR to pipe video camera technology. While there was some initial collaboration with these technologies, they opted not to participate in the research so they would not have to explain their proprietary technology. Figure 5.1.1 shows a flow chart of how the culvert inspection process currently works and the desired process NASSCO certified inspectors reference because they are typically used by video inspection contractors that certify newly constructed pipes before paving is allowed. UDOT would have similar training for their maintenance employees that were inspecting existing pipes.



*This is often based on watching the video and looking for clues to determine scale (i.e., pipe diameter, stickers or stencils, leaves, etc). It is very subjective and 2D photos shouldn't be used to rate the pipe.

*The key improvement is to have an AI system trained to replace the Certified Professional or Engineer and limit human labor needs. It would also minimize the subjectiveness of human evaluation

**Figure 5.1.1 – Current vs. Future Desired Culvert Inspection Process**

The research found several LiDAR technologies to evaluate to see if LiDAR could evaluate pipes per the UDOT ranking criteria. LiDAR data was collected in 11 culverts throughout the Salt Lake valley. UDOT's Pipe Culvert Ranking was used as a template to compare defects in the pipe with the two LiDAR technologies with survey-grade LiDAR used as a control.

### Overall Testing

The testing was performed with manual walking inspections of the pipe. It was determined that if a technology was found to be effective it could be attached to some type of rover or drone that fit its capabilities. Therefore, the LiDAR testing was independent of a delivery method.

- With all the technologies, having adequate lighting in a culvert was an issue. Bright enough lighting with a uniform projection is critical to having accurate point clouds. The SLAM LiDAR with a 360-degree field of view suffered the most due to inadequate lighting.
- Both technologies, Pocket LiDAR, and SLAM LiDAR, rely on photo capture to assist in creating a 3D model. It was found that "drift" occurs in these technologies. In essence, the point cloud becomes more inaccurate as the length of the culvert increases. This is due to a compounding of small errors as the 3D model is stitched together based on recognizable points. This is especially difficult to avoid in culverts as the uniformity of the surface provides less recognizable points. This drift can be seen as changes in horizontal or vertical curvature or length of the culvert. Culverts longer than 50 feet are more prone for drift to occur. To minimize drift, it is recommended that the culvert inlets/outlets be mapped, and that the inspection be "looped" (by crossing back to the start point by an above ground route). Attempting to minimize drift is not practical in real-world inspections as it would result in additional inspection time, processing time and traffic safety issues.

### Terrestrial LiDAR

Terrestrial LiDAR, with its multiple setups, was only used as a control. While Terrestrial LiDAR is very accurate, the point clouds are based on the line of sight from the fixed unit to the point being captured. In pipe culverts, there are obstructions such as corrugations that prevent line of sight within corrugations as the distance from the unit increases. Therefore, the Terrestrial LiDAR's 3D models can be seen to be more detailed (with realistic impressions) around areas of the setup with less detail in areas in between setups. For example, the corrugation pattern of the pipe varies from realistic to questionable depending on the location of the setup. The Terrestrial LiDAR was used for control only and is not practical for wide use in culvert inspection.

### Pocket LiDAR

The Pocket LiDAR is simple to learn and use to gather data. The amount of data is limited due to the capacity of an iPhone. The processing of the data is more difficult to learn and time consuming. The cost of the hardware is relatively inexpensive, with the software/computer processing needs being slightly expensive. The Pocket LiDAR performed well given the low cost and portability. It is more than adequate for measurements such as diameter, ovality, and length. For defects such as cracks, spalls, and localized buckling, the point cloud was not dense enough to be effective. It was difficult to find, see, or accurately measure the boundaries of these smaller defects. Therefore, this technology is not currently addressing the problem statement. It was also found that LiDAR will likely not have dense enough point clouds to measure these small defects.

### SLAM LiDAR

SLAM Lidar was simple to learn and convenient to use. The cost of the handheld LiDAR and processing software is significant. It was found that the current density of the SLAM LiDAR point clouds is relatively equivalent to the lowest resolution density of Terrestrial LiDAR. SLAM LiDAR point clouds are not currently dense enough to use for measurements of small defects, such as cracks, spalls, or localized buckling. It is not clear if the SLAM LiDAR point cloud densities will increase significantly as the current resolution is typically adequate for fast, mobile mapping of complex buildings or other spaces not well suited for Terrestrial LiDAR. While Terrestrial LiDAR is typically mapped at the highest resolution, it is often processed in a lower resolution as the high-resolution point cloud does not provide enough critical information to justify the processing and data management issues.

## 5.2 Limitations and Challenges

The report showed various challenges that resulted in limitations currently:

- Culverts less than 36” are not currently a candidate for LiDAR inspection due to the back scatter effect. A more traditional method of 2D inspection with a video or a spinning laser is more accurate and practical than LiDAR for measuring deflection for these smaller pipes.[22] Due to these limitations, smaller pipe culverts and storm drains were not inspected in this study.

- Except for extremely large culverts, greater than 10 feet in diameter with short lengths, effective lighting is a challenge with LiDAR systems that rely on photogrammetry. In the study, the SLAM LiDAR lost accuracy due to the difficulty in lighting the culvert evenly in 360 degrees during the mobile inspection. In the large Midas Creek Culvert in Herriman, the culvert was nearly 24 feet wide and 15 feet high. As the culvert was just over 100 feet long, the lighting within the culvert was relatively uniform and the SLAM LiDAR performed much better. In smaller pipe culverts, the variation in lighting could be seen in the point cloud and it affected the 3D point cloud. While Pocket LiDAR fared much better, due to needing even lighting over roughly 130 degrees, keeping the lighting consistent was still a challenge while trying to navigate through the culvert.

- Pipes that are extremely uniform with little variation, such as plastic pipes, are difficult to use photogrammetry techniques, as there are sometimes not enough common points in the photos, which leads to drift and inaccuracy. This could be seen in the Lisa Falls 60” diameter SaniTite HP triple-wall pipe. This polypropylene pipe is gray in color, smooth, and extremely uniform (except for interior corrugations that are induced from compacting the pipe). Black plastic pipes are likely to be even more difficult based on uniformity and difficulty in adequate lighting.

- AI pipe inspections are currently focused on making the inspection process more accurate and effective, but they are not as focused on being able to make accurate measurements that would allow for automated pipe ratings. While there might be some benefit from using AI, the systems reviewed used photogrammetry which would be like Pocket LiDAR but without a laser measurement for improving accuracy. The AI technology will still require manual ranking of the defects which is inconsistent with the goals of this study.

# 6.0 RECOMMENDATIONS AND IMPLEMENTATION

## 6.1 Recommendations

The study identified that the emerging technologies of LiDAR and AI are not developed to a point where the technologies could be incorporated into an automated pipe inspection ranking system. LiDAR was found to be helpful for larger measurements of shape, slope, and joint gaps. Yet, it was determined that LiDAR does not have dense enough point clouds to measure smaller features that are critical to ranking pipes: fractures, localized buckling, and loss of wall thickness. Therefore, for the short term, rating culvert defects may be better performed using photogrammetry, videos, and human verification rather than with LIDAR and AI which are still emerging technologies.

## 6.2 Implementation Plan

### 6.2.1 SLAM LiDAR

While it was hoped that this study might find an interim plan to gather data that could be used in the future when a more automated AI ranking system is developed. SLAM LiDAR has limitations that won’t allow it to accurately capture the measurements of all the defects needed in the ranking criteria. This along with the current cost of the systems (in excess of $50,000) makes it impractical to recommend its use in culvert inspections currently. The cost of LiDAR is in flux with new, less expensive LiDAR technologies being developed for autonomous vehicles, but even with cost reductions, there may be similar limitations to point cloud densities. SLAM LiDAR may have other applications within the department and in areas where lighting is not an issue. For example, the maximum range of 25 meters may allow for 3D mapping under bridges, although a high payload drone would likely be required to transport the LiDAR safely. The pipe culvert committee should revisit this technology in several years to see if data acquisition/processing has improved enough to accurately identify the UDOT defect criteria.

### 6.2.2 Pocket LiDAR

It is recommended that Pocket LiDAR could be used as it was in the study for large pipes available for safe manual inspections where the goals were to identify the varying dimensions of the pipe diameter and grade. For example, if using a deteriorated pipe as the host pipe for slip lining were the project goal, proper use of Pocket LiDAR would be a good application to find the maximum outer diameter of the pipe that could be used as a slip liner. It would also be helpful in calculating a final grade for the slip liner, for hydraulic purposes, and in calculating the volumes of annular space that would need to be filled with grout. This is a relatively infrequent rehabilitation project so it is felt that the ease of use and cost effectiveness of Pocket LiDAR would be well suited for this. Pocket LiDAR has several potential non-culvert-related inspection capabilities, so developing the technology in a centralized department would be beneficial to other applications. These could include 3D mapping of: ADA ramp inspections, culvert headwalls, excavations and key utilities during trenching activities, and private properties that may be impacted by construction. There are certainly more applications for Pocket LiDAR that would be applied as the technology becomes more widely used in the department. It is recommended that this technology should exist with the survey department (particularly drone surveyors) as they likely already have similar training, software, and adequate computers for processing the data. It would be possible to easily train inspectors and maintenance personnel to gather the data and send it to a central department for processing. It is likely that some employees have also purchased Pocket LiDAR technology as part of their UDOT-subsidized phone allocation.

### 6.2.3 Other Pipe Video Inspection Systems with LiDAR Capability

There were two other pipe video inspection services that reported advances in LiDAR. Unfortunately, they were unable to participate in the study due to concerns about sharing proprietary technologies. These companies also appeared to be more interested in providing inspection services than in developing technologies that UDOT could purchase and use their own personnel to conduct the inspections. It might be possible to find example projects where their technology could be used and tested. For example, if a slip lining project needed 3D mapping of the existing culvert, they could be contracted to map the culvert and provide the data to UDOT.

In this scenario, they might be more willing to answer questions about the accuracy and development of the technology, especially if their answers were not being displayed in a readily viewed research report. It should be mentioned that paying for these technologies to test the example pipes in this study was discussed, but their initial estimates were higher than the budget of this research project. Without the ability to have them answer questions about the limitations and accuracy of their technologies, it was determined that their use in this project was not currently feasible. Also, the SLAM LiDAR and Pocket LiDAR tests showed that without significant advances in the technologies that ranking defects through LiDAR will be outside the capabilities of typical SLAM LiDAR or photogrammetric technologies.

### 6.2.4 AI Video Inspection Technologies

As part of the project, we reached out to two AI pipe video companies that are developing software and training the AI system. They are very optimistic about their ability to improve defect finding and speed video inspections with the AI software. Yet, in questioning them about their ability to accurately measure and rate defects, this was not a current focus and they felt that a highly trained inspector or engineer would still be required to evaluate the defects. With the ongoing UDOT research on pipe inspection AI through the University of Utah (UofU), it is felt that this report should provide input to their projects so that they can further identify how AI culvert rating could be accomplished. This report showed that using only uncalibrated photogrammetry to create a 3D pipe model would not likely be accurate enough to measure defects such as cracking, spalling, and other defects where tolerances require a measurement. It is recommended that the pipe culvert committee investigate whether more efficient inspections warrant the cost of using AI technology. Recent UDOT presentations have affirmed that there may not be enough funding made available to clean and inspect all culverts. As the UDOT approach has focused on identifying the culverts with more risk, and as these culverts are in the hundreds instead of the overall tens of thousands, the benefits of more efficient inspections and automated ranking through AI is not as beneficial in the short term. The pipe culvert committee should revisit the AI technology through the University of Utah report and future evaluation of the improvements of the technology.

### 6.2.5 Directions of Future Research

This study showed benefits from creating a 3D model if the technologies can be improved. From the research, LiDAR point clouds may never be dense enough to evaluate small defects such as cracking and spalling. When including AI into the discussion, it was concluded that a combination of LiDAR-based point clouds where photogrammetric models could be draped would be the best approach for developing accurate photogrammetric models. With this combination AI could then accurately measure cracking and spalling based on a highly calibrated visual model. Therefore, after the UofU AI pipe study is completed, there should be a discussion at the pipe committee as to whether further research is warranted and whether the existing pipe video systems with LiDAR are progressing on an approach that would ultimately allow for automated ranking of the pipe through AI.

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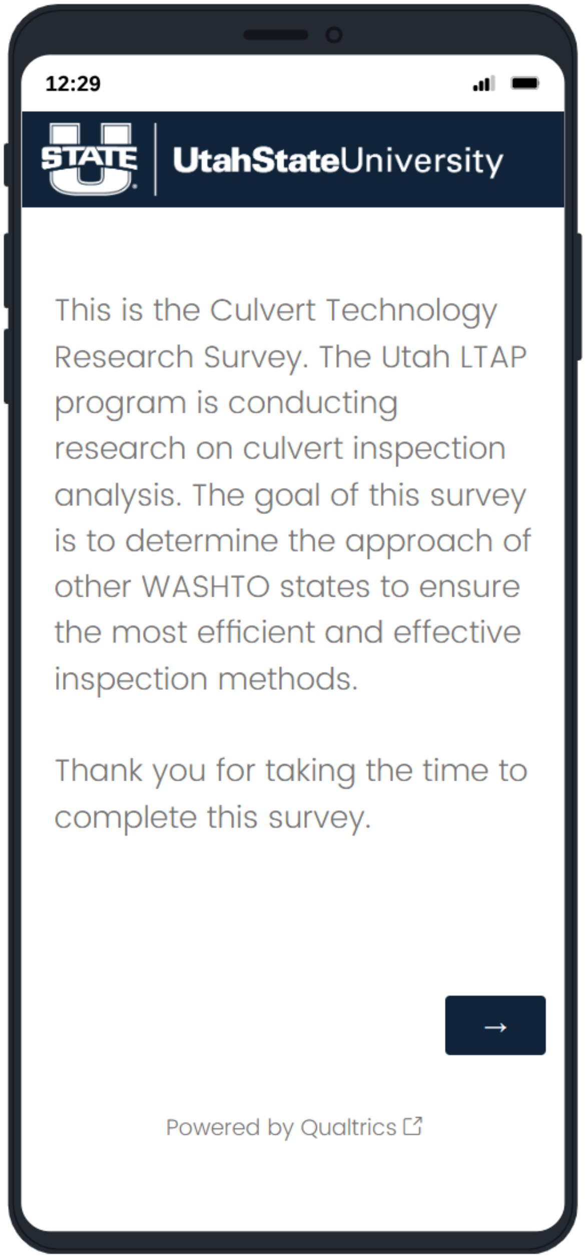
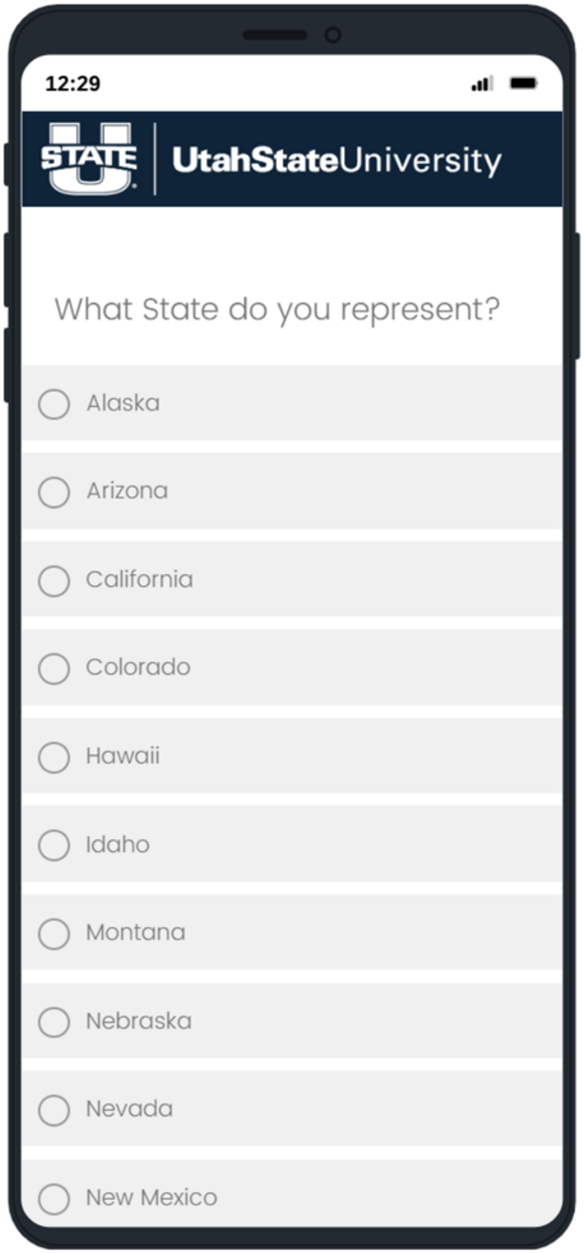
# APPENDIX A:  WASHTO CULVERT SURVEY QUESTIONAIRE

To survey 17 of the states in the Western Association of State Highway and Transportation Officials (WASHTO), Qualtrics Database was used.  The survey questions as shown on a cell phone follow in the following 10 graphics:



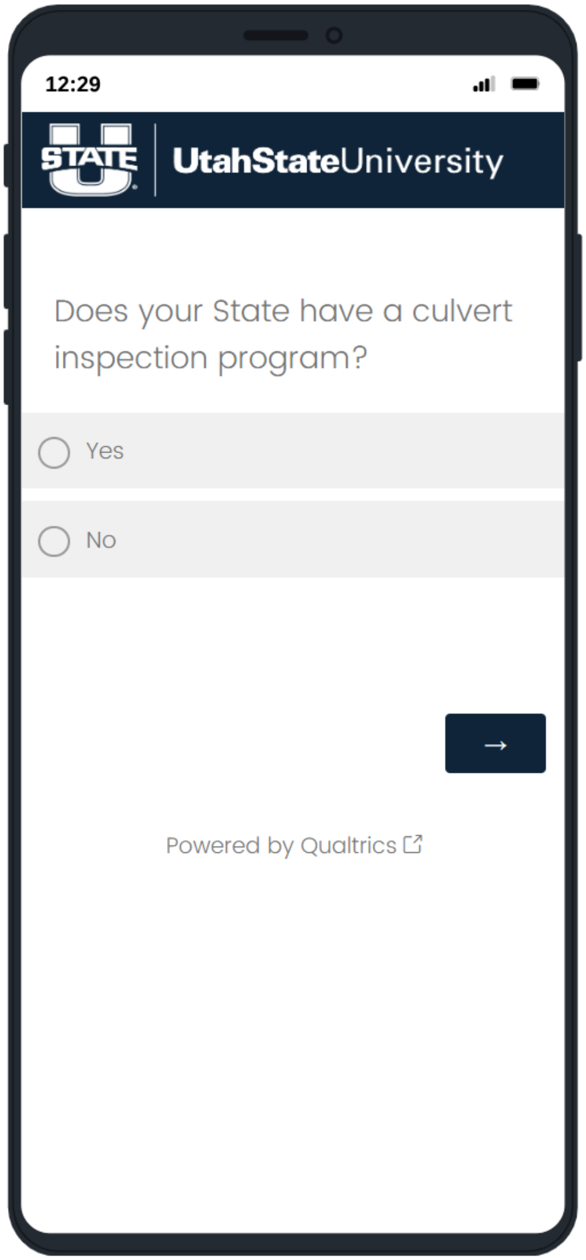
This is the Culvert Technology Research Survey. The Utah LTAP program is conducting research on culvert inspection analysis. The goal of this survey is to determine the approach of other WASHTO states to ensure the most efficient and effective inspection methods.

Thank you for taking the time to complete this survey.



What State do you represent?

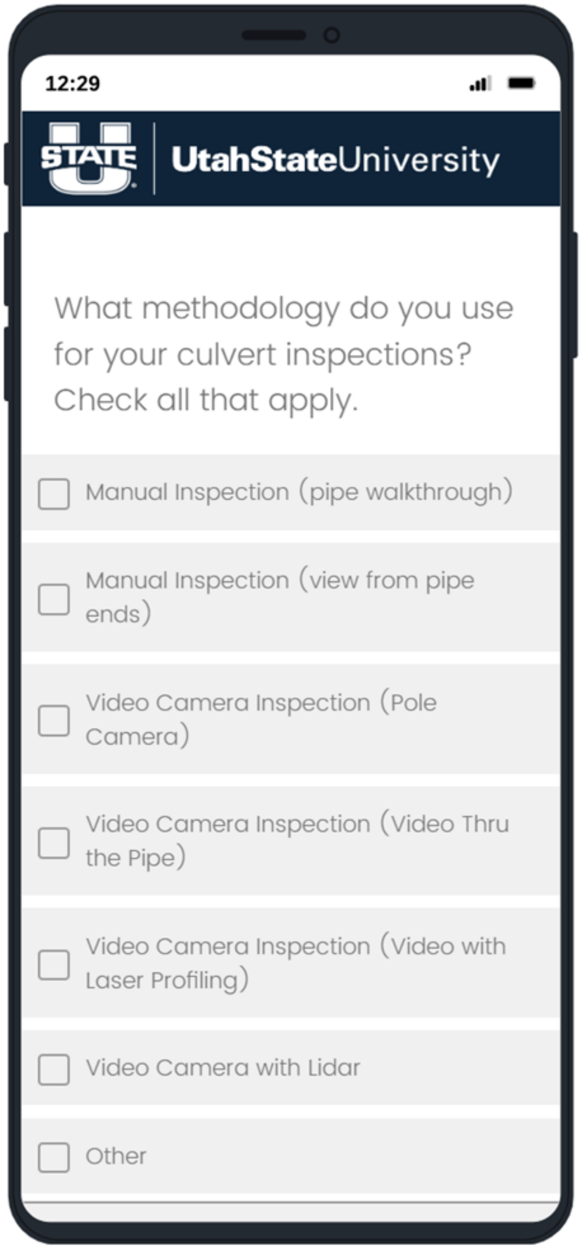
- ○ Alaska
- ○ Arizona
- ○ California
- ○ Colorado
- ○ Hawaii
- ○ Idaho
- ○ Montana
- ○ Nebraska
- ○ Nevada
- ○ New Mexico



Does your State have a culvert inspection program?

○ Yes

○ No



What methodology do you use for your culvert inspections? Check all that apply.

☐ Manual Inspection (pipe walkthrough)

☐ Manual Inspection (view from pipe ends)

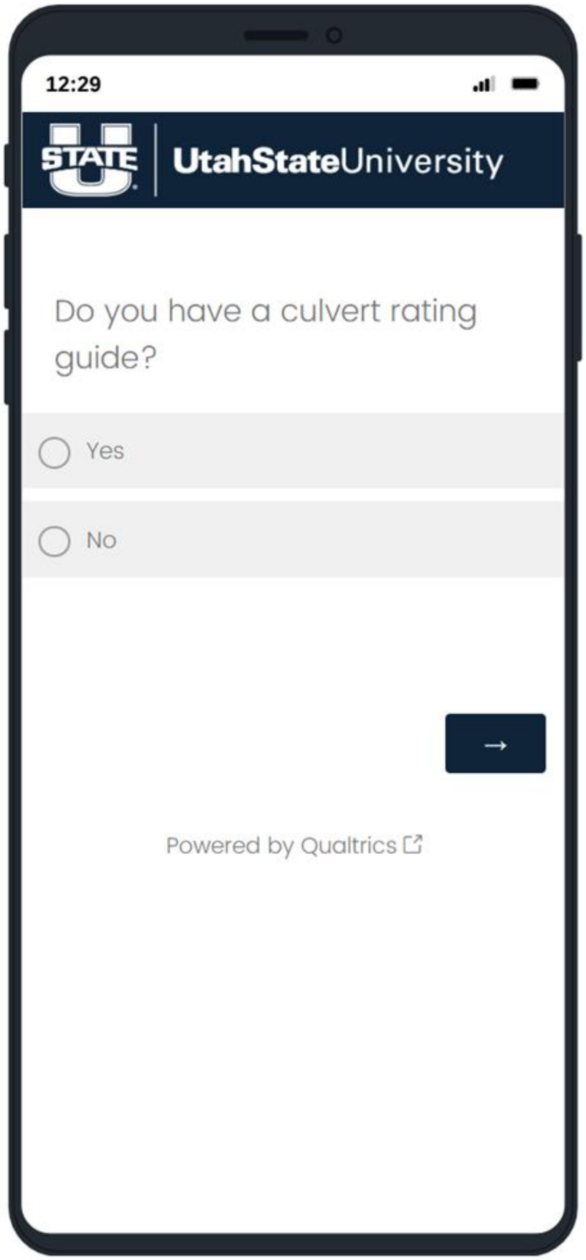
☐ Video Camera Inspection (Pole Camera)

☐ Video Camera Inspection (Video Thru the Pipe)

☐ Video Camera Inspection (Video with Laser Profiling)

☐ Video Camera with Lidar

☐ Other



12:29

UtahStateUniversity

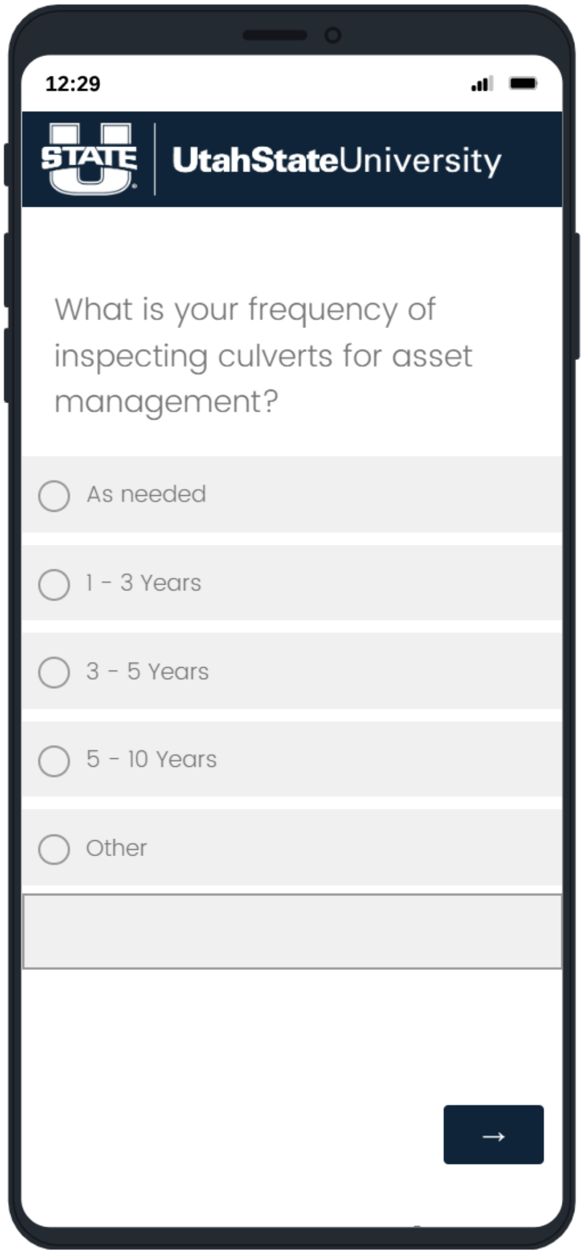
Do you have a culvert rating guide?

○ Yes

○ No

→

Powered by Qualtrics



12:29

UtahStateUniversity

What is your frequency of inspecting culverts for asset management?

○ As needed

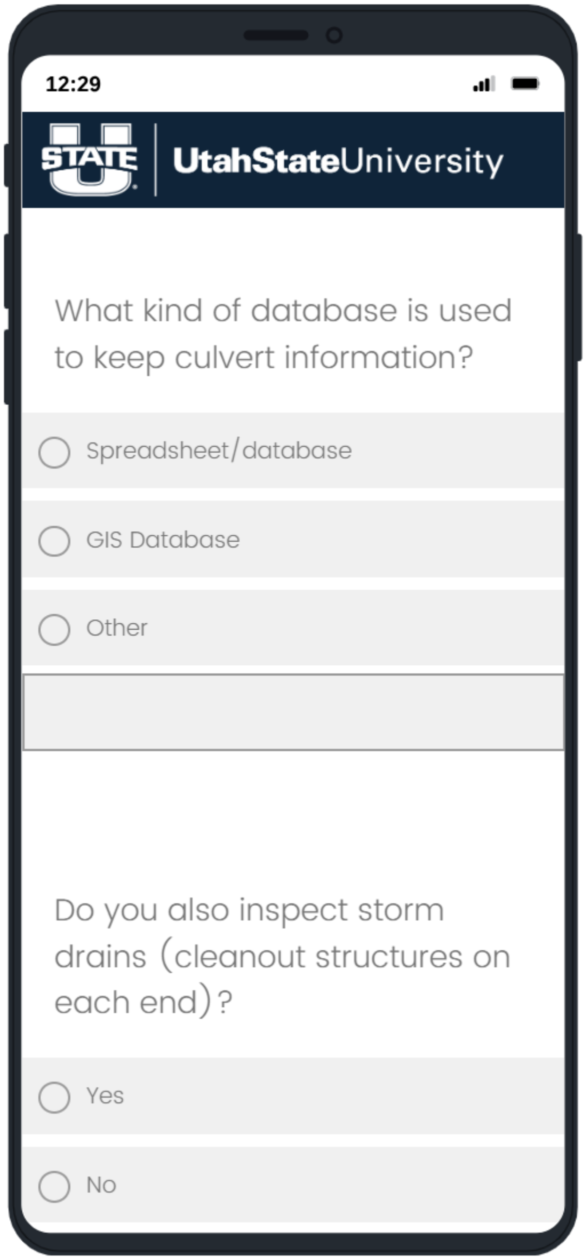
○ 1 - 3 Years

○ 3 - 5 Years

○ 5 - 10 Years

○ Other

→



What kind of database is used to keep culvert information?

○ Spreadsheet/database

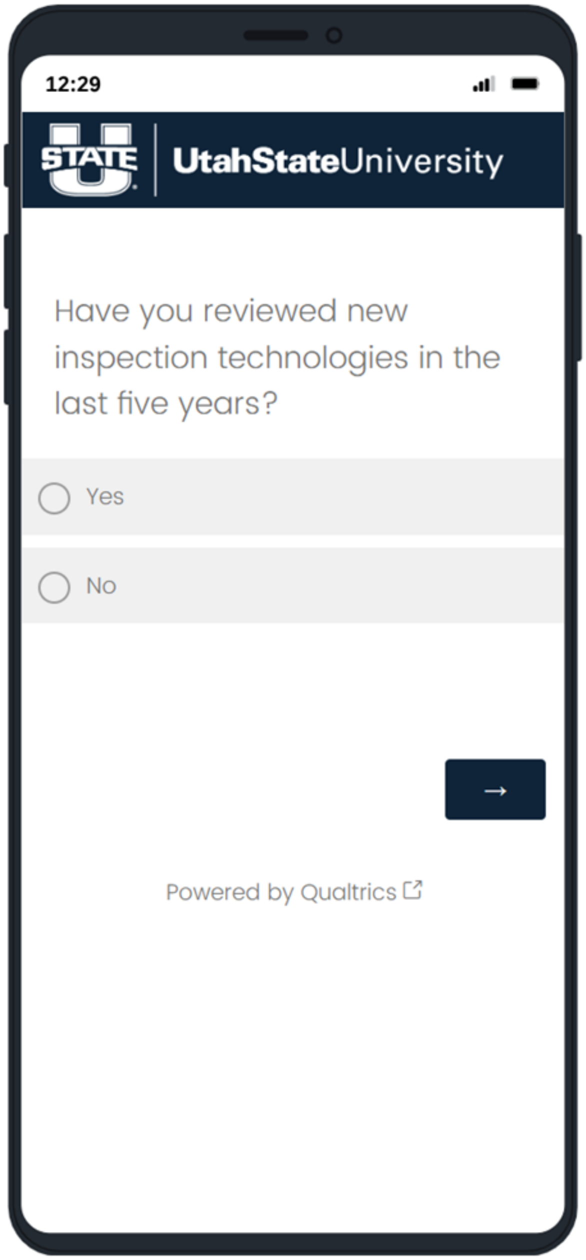
○ GIS Database

○ Other

Do you also inspect storm drains (cleanout structures on each end)?

○ Yes

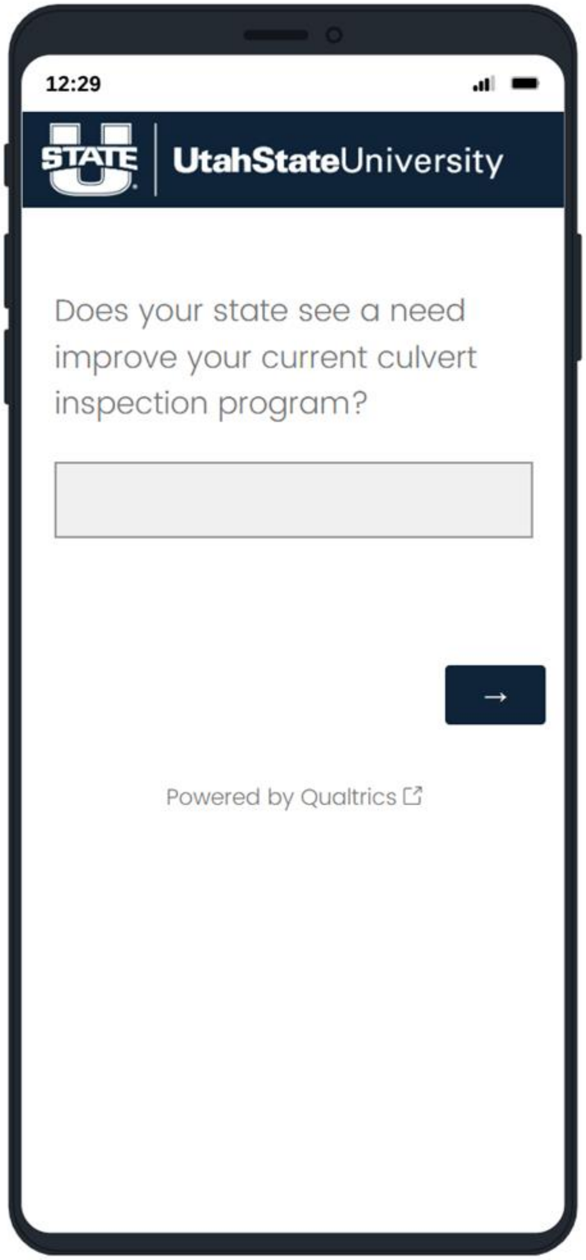
○ No



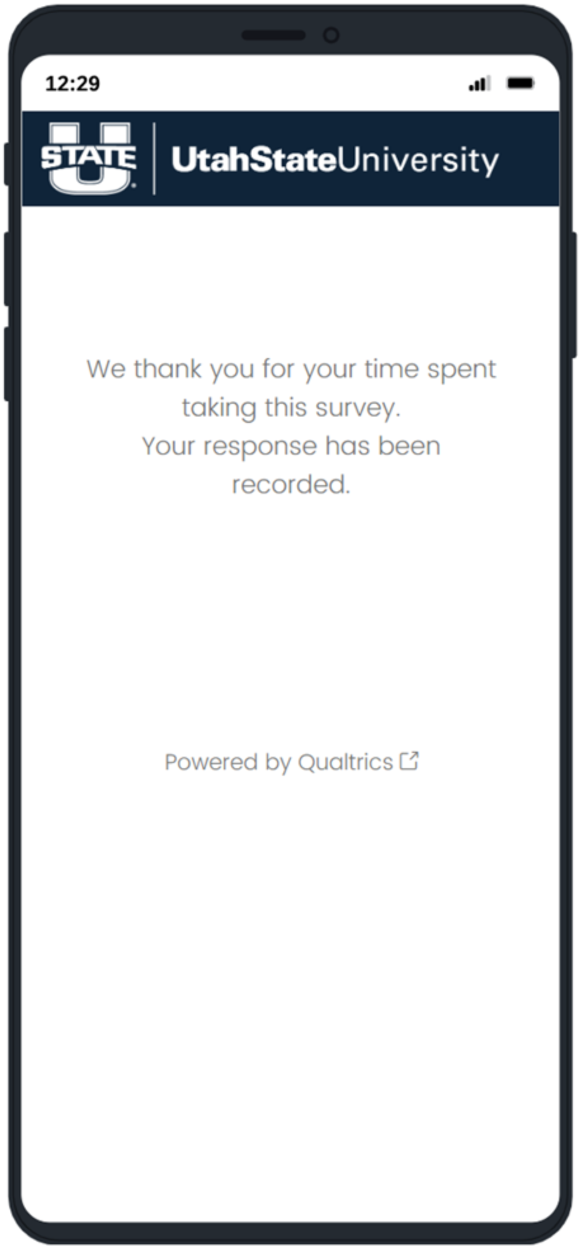
Have you reviewed new inspection technologies in the last five years?

○ Yes

○ No



Does your state see a need improve your current culvert inspection program?



We thank you for your time spent taking this survey.
Your response has been recorded.

# APPENDIX B:  DETAILED SURVEY REPONSES

The following printout includes the detailed responses to each question from all participants:

| Q0<br>What State do you represent? | Q1<br>Does your State have a culvert inspection program? |
|---|---|
| New Mexico | Yes |
| Colorado | Yes |
| Nebraska | No |
| Idaho | No |
| Oregon | Yes |
| South Dakota | Yes |
| Arizona | Yes |
| Nevada | Yes |
| Oklahoma | No |
| Wyoming | No |
| Montana | Yes |
| Juneau, Alaska | |
| North Dakota | Yes |
| Hawaii | Yes |
| Washington | Yes |
| Sacramento, California | Yes |
| Sacramento, California | Yes |
| Washington | Yes |
| | |
| | |

| Q0<br>What State do you represent? | Q1.5<br>IF your State has a culvert inspection program, input a link to your procedures. |
|---|---|
| New Mexico | |
| Colorado | https://www.codot.gov/programs/bridge/bridge-manuals/inspection-code- |
| Nebraska | |
| Idaho | |
| Oregon | contact Rob Trevis: robert.e.trevis@odot.oregon.gov |
| South Dakota | |
| Arizona | https://azdot.gov/sites/default/files/media/2022/10/ADOT-SWMP-Sept-2022.pdf |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | * See Footnote 1 |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | https://maintenance.onramp.dot.ca.gov/maintstormenvcomp/culvert-inspection-program-cip |
| Washington | |
| | |
| | |

| Q0<br>What State do you represent? | Q2<br>What methodology do you use for your culvert inspections? Check all that apply. - |
|---|---|
| New Mexico | Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe) |
| Colorado | Manual Inspection (pipe walkthrough) |
| Nebraska | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Video Thru the Pipe) |
| Idaho | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Video Thru the Pipe) |
| Oregon | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Video Thru the Pipe),Video Camera Inspection (Video with Laser Profiling) |
| South Dakota | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Video Thru the Pipe) |
| Arizona | Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe) |
| Nevada | Manual Inspection (view from pipe ends),Video Camera Inspection (Video Thru the Pipe) |
| Oklahoma | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe) |
| Wyoming | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends) |
| Montana | Manual Inspection (view from pipe ends) |
| Juneau, Alaska | |
| North Dakota | Video Camera Inspection (Video Thru the Pipe) |
| Hawaii | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe) |
| Washington | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe) |
| Sacramento, California | Video Camera Inspection (Video with Laser Profiling) |
| Sacramento, California | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe) |
| Washington | Manual Inspection (pipe walkthrough),Manual Inspection (view from pipe ends),Video Camera Inspection (Pole Camera),Video Camera Inspection (Video Thru the Pipe),Other |
| | |
| | |

| Q0<br>What State do you represent? | Q2_7_TEXT<br>What methodology do you use for your culvert inspections? Check all that apply. - |
|---|---|
| New Mexico | |
| Colorado | |
| Nebraska | |
| Idaho | |
| Oregon | |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | Rover for underwater video |
| | |
| | |

| Q0<br>What State do you represent? | Q2_7_TEXT<br>What methodology do you use for your culvert inspections? Check all that apply. - |
|---|---|
| New Mexico | |
| Colorado | |
| Nebraska | |
| Idaho | |
| Oregon | |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | Rover for underwater video |
| | |
| | |

| Q0<br>What State do you represent? | Q3<br>What is your frequency of inspecting culverts for asset management? - |
|---|---|
| New Mexico | 3 - 5 Years |
| Colorado | 3 - 5 Years |
| Nebraska | 3 - 5 Years |
| Idaho | As needed |
| Oregon | Other |
| South Dakota | 3 - 5 Years |
| Arizona | 3 - 5 Years |
| Nevada | 1 - 3 Years |
| Oklahoma | 1 - 3 Years |
| Wyoming | |
| Montana | Other |
| Juneau, Alaska | |
| North Dakota | As needed |
| Hawaii | Other |
| Washington | 1 - 3 Years |
| Sacramento, California | 3 - 5 Years |
| Sacramento, California | 5-10 |
| Washington | 3 - 5 Years |
| | |
| | |

| Q0<br>What State do you represent? | Q3_5_TEXT<br>What is your frequency of inspecting culverts for asset management? - |
|---|---|
| New Mexico | |
| Colorado | |
| Nebraska | |
| Idaho | |
| Oregon | depends on condition |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | twice yearly |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | Varies |
| Washington | |
| Sacramento, California | |
| Sacramento, California | 5-7 years |
| Washington | |
| | |
| | |

| Q0<br>What State do you represent? | Q4<br>Do you have a culvert rating guide? |
|---|---|
| New Mexico | Yes |
| Colorado | Yes |
| Nebraska | Yes |
| Idaho | No |
| Oregon | Yes |
| South Dakota | Yes |
| Arizona | Yes |
| Nevada | Yes |
| Oklahoma | Yes |
| Wyoming | |
| Montana | Yes |
| Juneau, Alaska | |
| North Dakota | Yes |
| Hawaii | No |
| Washington | Yes |
| Sacramento, California | Yes |
| Sacramento, California | Yes |
| Washington | Yes |
| | |
| | |

| Q0<br>What State do you represent? | Q5<br>If you do have a culvert rating, please input a link. |
|---|---|
| New Mexico | |
| Colorado | https://www.codot.gov/programs/bridge/bridge- |
| Nebraska | It's based on AASHTO but has been customized for Nebraska. We are still working on our inspection manual so it isn't available to the public yet. |
| Idaho | |
| Oregon | contact Rob Trevis: robert.e.trevis@odot.oregon.gov |
| South Dakota | not available externally - contact me for a copy |
| Arizona | https://azdot.gov/sites/default/files/2019/09/1803BridgeInspectionGuidelines.pdf |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | In our Maintenance Management System we have input fields that are filled out by our inspectors |
| Juneau, Alaska | |
| North Dakota | We use the AASHTO Guide |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | https://maintenance.onramp.dot.ca.gov/downloads/maintenance/Inspection_Manual_September_Update_2021.pdf#overlay-context=node/546/draft |
| Washington | we use the Culvert Assessment and Decision-Making Procedures Manual for Federal Lands Highway |
| | |
| | |

| Q0<br>What State do you represent? | Q6<br>What kind of database is used to keep culvert information? - |
|---|---|
| New Mexico | GIS Database |
| Colorado | Other |
| Nebraska | GIS Database |
| Idaho | Other |
| Oregon | Other |
| South Dakota | GIS Database |
| Arizona | GIS Database |
| Nevada | Other |
| Oklahoma | Spreadsheet/database |
| Wyoming | |
| Montana | Other |
| Juneau, Alaska | |
| North Dakota | GIS Database |
| Hawaii | Spreadsheet/database |
| Washington | GIS Database |
| Sacramento, California | GIS Database |
| Sacramento, California | GIS Database |
| Washington | Other |
| | |
| | |

| Q0<br>What State do you represent? | Q6_3_TEXT<br>What kind of database is used to keep culvert information? - |
|---|---|
| New Mexico | |
| Colorado | BrM |
| Nebraska | |
| Idaho | Some Districts are using a spreadsheet and others are using a GIS database |
| Oregon | cold fusion/oracle tables |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | Maintenance Management System developed by agile assets |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | no sure, my be sql |
| | |
| | |

| Q0 What State do you represent? | Q7 Do you also inspect storm drains (cleanout structures on each end)? - |
|---|---|
| New Mexico | Other |
| Colorado | No |
| Nebraska | Other |
| Idaho | Yes |
| Oregon | Other |
| South Dakota | No |
| Arizona | Yes |
| Nevada | Yes |
| Oklahoma | Other |
| Wyoming | |
| Montana | No |
| Juneau, Alaska | |
| North Dakota | Other |
| Hawaii | Yes |
| Washington | Yes |
| Sacramento, California | Yes |
| Sacramento, California | Yes |
| Washington | Other |
| | |
| | |

| Q0<br>What State do you represent? | Q7_3_TEXT<br>Do you also inspect storm drains (cleanout structures on each end)? - |
|---|---|
| New Mexico | planned future effort |
| Colorado | |
| Nebraska | Outfalls are inspected for Municipal Separate Storm Sewer Systems (MS4s) |
| Idaho | |
| Oregon | If you mean for maintenance, yes. But not for structural. |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | Random Sampling |
| Wyoming | |
| Montana | |
| Juneau, Alaska | |
| North Dakota | As needed. |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | yes but inspected separatlly |
| | |
| | |

| Q0<br>What State do you represent? | Q8<br>Have you reviewed new inspection technologies in the last five years? |
|---|---|
| New Mexico | Yes |
| Colorado | Yes |
| Nebraska | Yes |
| Idaho | No |
| Oregon | Yes |
| South Dakota | Yes |
| Arizona | No |
| Nevada | No |
| Oklahoma | No |
| Wyoming | |
| Montana | No |
| Juneau, Alaska | |
| North Dakota | Yes |
| Hawaii | Yes |
| Washington | Yes |
| Sacramento, California | Yes |
| Sacramento, California | Yes |
| Washington | Yes |
| | |
| | |

| Q0<br>What State do you represent? | Q9_3_TEXT<br>If you have reviewed new inspection technologies in the last five years, which technologies? - |
|---|---|
| New Mexico | |
| Colorado | |
| Nebraska | Remote Car with Gopro |
| Idaho | |
| Oregon | video camera with laser profile |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | video inspection |
| | |
| | |

| Q0<br>What State do you represent? | Q10<br>Does your state see a need improve your current culvert inspection program? |
|---|---|
| New Mexico | yes - increase scope and level of detail of inspections, add inspection elements needed for future design, improve rating system to enhance capital planning |
| Colorado | Yes, for culverts &lt;48" in diameter |
| Nebraska | Yes |
| Idaho | YES. We are actively engaged in creating asset management plans for multiple asset types. Our current effort is geared towards signs. That will be followed by Guardrail Terminal Ends. I'm expecting culverts to be after that. |
| Oregon | yes |
| South Dakota | continuous improvement |
| Arizona | Overall mapping improvements are needed as far as state and city connections and contributions. |
| Nevada | yes |
| Oklahoma | Always room for improvement. |
| Wyoming | |
| Montana | not at this time |
| Juneau, Alaska | |
| North Dakota | Yes |
| Hawaii | |
| Washington | Yes |
| Sacramento, California | |
| Sacramento, California | not currently |
| Washington | perhaps |
| | |
| | |

| Q0<br>What State do you represent? | |
|---|---|
| New Mexico | |
| Colorado | |
| Nebraska | |
| Idaho | |
| Oregon | |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | |
| | |
| | |

| Q0 | |
|---|---|
| What State do you represent? | * Footnote 1 |
| New Mexico | Activity Description Activity 3100 Culvert Inspection includes performing Routine Maintenance Culvert Inspections. including providing traffic control and mobilization and/or operation of equipment. The inspection of culverts, box culverts, and similar drainage structures is done under this activity. The main purpose of the Routine Culvert Inspections is to catch any major problems or changes that have arose since the last Inspection was performed. Any major problems or changes that are discovered during the inspections would generally be considered urgent. They may affect the safety or integrity of the structure and should be addressed as soon as possible with some type of repair or remedial action. Culvert Inspection Program 1. Inspections performed by MDT Maintenance personnel. These Routine Maintenance Culvert Inspections are an “in-house” MDT program and should to be performed biannually. They are not meant to be very detailed, but to be quick and simple, focusing only on major structural components and any major changes in their condition. Serious deficiencies requiring emergency attention that are discovered during the Culvert Inspections (or at any other time) are reported through the Maintenance Area/Division office. 2. Extreme Event Structure Inspections Inspection may be required during or immediately after an extreme event such as an earthquake, flooding, or other event with the potential to cause widespread damage. Frequency of Culvert Inspections Maintenance inspections on all culverts should be performed by maintenance personnel twice a year, once during the fall and again in the spring. Culverts should be inspected if they are involved in a major event such as an earthquake, flood, or high-water runoff event. Possible actions that may be required following a routine maintenance culvert inspection include: • Immediately remove materials threatening the integrity of the structure • Immediately cleaning culverts that are plugged or schedule replacement or sleeving/lining of pipes that are threatened structurally by deterioration • Prioritizing the cleaning or repair of culverts based on funding availability and other maintenance priorities • Scheduling labor and equipment to assist in making structure repairs |
| Colorado | |
| Nebraska | |
| Idaho | |
| Oregon | |
| South Dakota | |
| Arizona | |
| Nevada | |
| Oklahoma | |
| Wyoming | |
| Montana | |
| Juneau, Alaska | |
| North Dakota | |
| Hawaii | |
| Washington | |
| Sacramento, California | |
| Sacramento, California | |
| Washington | |
| | |
| | |

# APPENDIX C: LEICA RTC360 PRODUCT SPECIFICATION

## Leica RTC360 3D Reality Capture Solution

Fast. Agile. Precise.

**Fast**

The Leica RTC360 laser scanner makes 3D reality capture faster than ever before. With a measuring rate of up to 2 million points per second and advanced HDR imaging system, the creation of coloured 3D point clouds can be completed in under 2 minutes. Plus, automated targetless field registration (based on VIS technology) and the seamless, automated transfer of data from site to office reduce time spent in the field and further maximise productivity.

**Agile**

Small and lightweight, the Leica RTC360 scanner's portable design and collapsible tripod mean it's compact enough to fit into most backpacks, ready to be taken anywhere. Once on-site, easy-to-use one-button operation makes for fast, hassle-free scanning.

**Precise**

Low noise data allows for better images, resulting in crisp, high-quality scans that are rich in detail and ready for use in a range of applications. Combined with Cyclone FIELD 360 software for automated registration in the field, the Leica RTC360 scanner offers outstanding precision that can be checked on-site.

PART OF HEXAGON

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Leica Geosystems

# Leica RTC360 Product Specifications

| | |
|---|---|
| GENERAL | |
| 3D laser scanner | High-speed 3D laser scanner with integrated HDR spherical imaging system and Visual Inertial System (VIS) for real time registration |
| PERFORMANCE | |
| Data acquisition | < 2 mins for complete full dome scan and spherical HDR image at 6mm @ 10 m resolution |
| Real time registration | Automatic point cloud alignment based on real time tracking of scanner movement between setups based on Visual Inertial System (VIS) by video-enhanced inertial measurement unit |
| Double scan | Automatic removal of moving objects |
| SCANNING | |
| Distance measurement | High-speed, high dynamic time of flight enhanced by Waveform Digitising (WFD) technology |
| Laser class | 1 (in accordance with IEC 60825-1:2014), 1550 nm (invisible) |
| Field of view | 360° (horizontal) / 300° (vertical) |
| Range | Min. 0.5 - up to 130 m |
| Speed | Up to 2,000,000 pts / sec |
| Resolution | 3 user selectable settings (3/6/12 mm @ 10 m) |
| Accuracy* | Angular accuracy 18"<br>Range accuracy 1.0 mm + 10 ppm<br>3D point accuracy<br>1.9 mm @ 10 m<br>2.9 mm @ 20 m<br>5.3 mm @ 40 m |
| Range noise* ** | 0.4 mm @ 10 m, 0.5 mm @ 20 m |
| IMAGING | |
| Camera | 36 MP 3-camera system captures 432 MPx raw data for calibrated 360° x 300° spherical image |
| Speed | 1 minute for full spherical HDR image at any light condition |
| HDR | Automatic, 5 brackets |
| NAVIGATION SENSORS | |
| Visual Inertial System | Video enhanced inertial measuring system to track movement of the scanner position relative to the previous setup in real time |
| Tilt | IMU based, Accuracy: 3' for any tilt |
| Additional sensors | Altimeter, Compass, GNSS |

| | |
|---|---|
| OPERATION | |
| On scanner | Touch-screen control with finger touch, full colour WVGA graphic display 480 x 800 pixels |
| Mobile devices | Leica Cyclone FIELD 360 app for iPad or Android tablets including:<br>- Remote control of scan functions<br>- 2D & 3D data viewing<br>- Tagging<br>- Automatic alignment of scans |
| Wireless | Integrated wireless LAN (802.11 b/g/n) |
| Data storage | Leica MS256, 256 GB exchangeable USB 3.0 flash drive |
| DESIGN & PHYSICAL | |
| Housing | Aluminium frame and sidecovers |
| Dimensions | 120 mm x 240 mm x 230 mm / 4.7" x 9.4" x 9.1" |
| Weight | 5.35 kg / 11.7 lbs, nominal (without batteries) |
| Mounting mechanism | Quick mounting on 5/8" stub on lightweight tripod / optional tribrach adapter / survey tribrach adapter available |
| POWER | |
| Internal battery | 2 x Leica GEB361 internal, rechargeable Li-Ion batteries.<br>Duration: Typically up to 4 hours<br>Weight: 340 g per battery |
| External | Leica GEV282 AC adapter |
| ENVIRONMENTAL | |
| Operating temperature | -5° to +40°C |
| Storage temperature | -40° to +70°C |
| Dust/Humidity*** | Solid particle/liquid ingress protection IP54 (IEC 60529) |


Leica Cyclone
FIELD 360


Leica Cyclone
REGISTER 360


Leica ScanStation
P50

**active» Customer Care**

Your Trusted Active Customer Care

Active Customer care is a true partnership between Leica Geosystems and its customers. Customer Care Packages (CCPs) ensure optimally maintained equipment and the most up-to-date software to deliver the best results for your business. The myWorld @ Leica Geosystems customer portal provides a wealth of information 24/7.

All specifications are subject to change without notice.

All accuracy specifications are on a level of confidence of 68% according to the Guide of the Expression of Uncertainty in Measurement (JCGM100:2008) unless otherwise noted.

* At 89% albedo.

** For single shot measurements.

*** For upright and upside down setups with a +/- 15° inclination

Scanner: Laser class 1 in accordance with IEC60825:2014

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+41 71 727 31 31

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# APPENDIX D: LEICA BLK2GO PRODUCT SPECIFICATION

| | |
|---|---|
| **DESIGN & PHYSICAL** | |
| Housing | Black anodized aluminium |
| Dimensions | Height: 279 mm / Diameter: 80 mm |
| Weight | 650 g (775 g including battery) |
| Transport cover | BLK2GO transportation case |
| **OPERATION** | |
| Stand-alone operation | One-button operation |
| Mobile device | BLK Live app for iOS and Android including: live 2D and 3D while scanning, device status and data management.<br>iOS 12.1 or higher recommended devices: iPhone series 8, X, 11, 12 Android 9 or higher. Recommended devices: Samsung Galaxy series S10, S20, S21 |
| Communication | Wireless (app connection) |
| Internal memory | 24 hours of scanning (compressed data) / 6 hours (uncompressed data) |
| Battery | Exchangeable, rechargeable Li-Ion battery (Leica GEB821) 45-50 minutes |
| **LiDAR & IMAGING** | |
| Laser class | 1 (in accordance with IEC 60825-1) |
| Wavelength | 830 nm |
| Field of view | 360° (horizontal) / 270° (vertical) |
| Range | Min. 0.5 - up to 25 m |
| Point measurement rate | 420,000 pts/sec |
| High resolution camera | 12 Mpixel, 90° x 120°, rolling shutter |
| Panoramic vision system | 3-camera system, 4.8 Mpixel 300° x 135°, global shutter |
| **SYSTEM PERFORMANCE (GRANDSLAM BASED)** | |
| Range noise * ** | +/-3 mm |
| Accuracy indoor *** | +/-10 mm |
| **ENVIRONMENTAL** | |
| Robustness | Designed for indoor and outdoor use |
| Operating temperature | 0 to +40 °C |

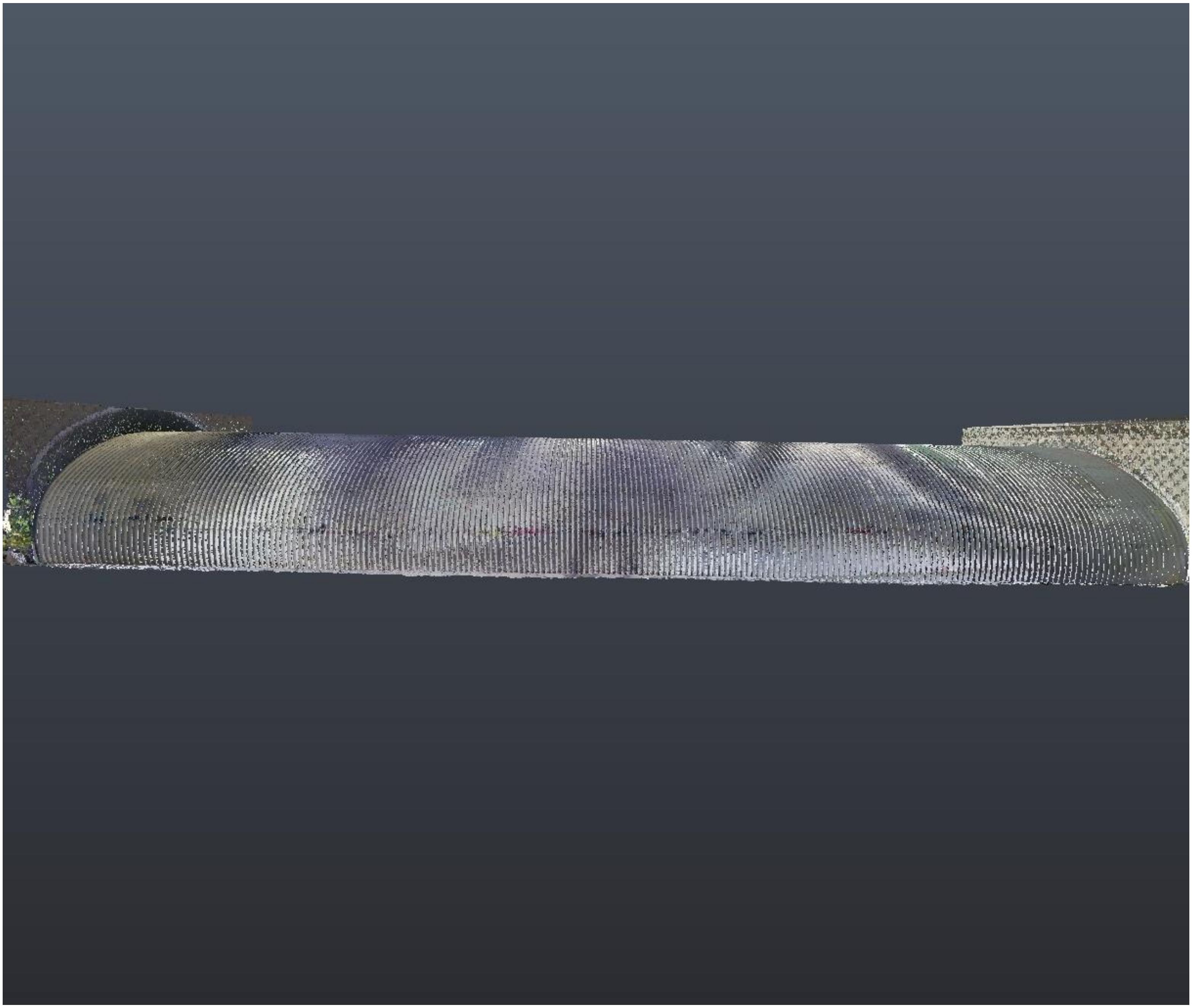
| | |
|---|---|
| Dust & humidity protection | IP54 (IEC 60529) |
| **DATA PROCESSING** | |
| Data transfer | Wireless and USB 3.0 |
| Desktop software | Leica Cyclone REGISTER 360 PLUS and Cyclone REGISTER 360 PLUS (BLK Edition) |

All specifications are subject to change without notice.
All accuracy specifications are one sigma unless otherwise noted.
*at 78% albedo
**environment dependent
***controlled environment (scan duration 2 minutes)

## APPENDIX E: SAMPLE OVERALL POINT CLOUDS

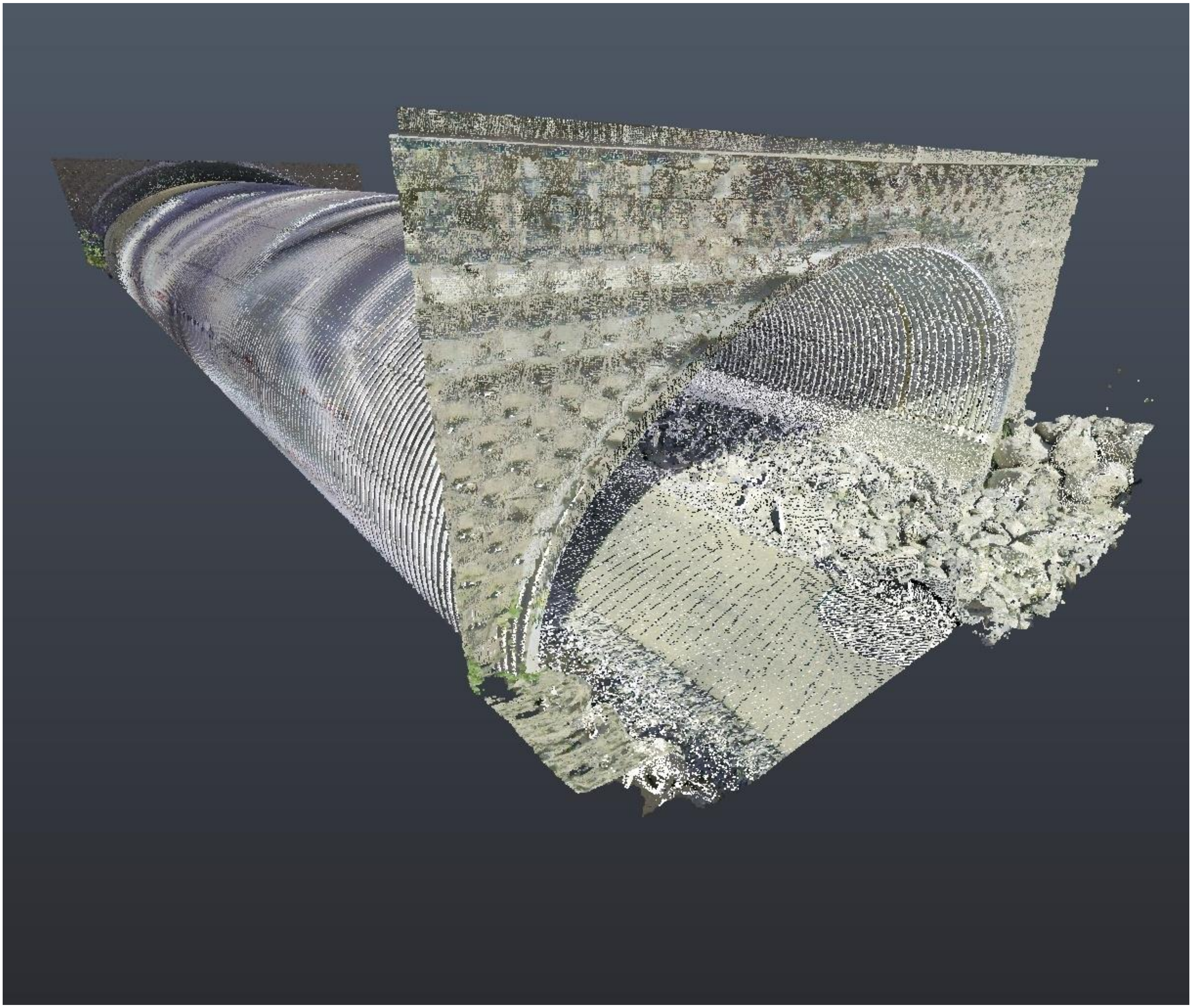
Test Pipe 1 – Midas Creek – Elevation View

Lecia RTC360 – Terrestrial LiDAR



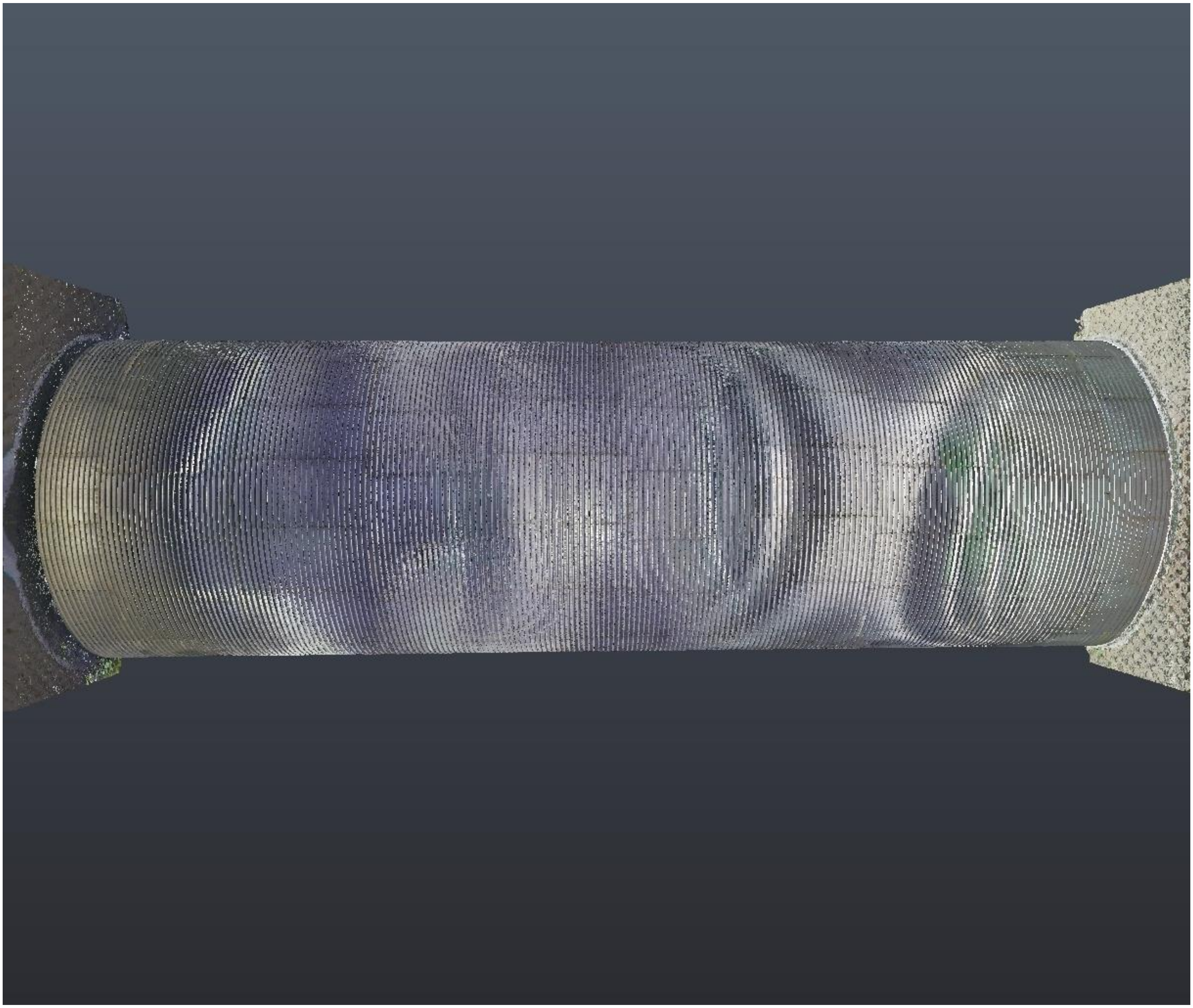
Test Pipe 1 – Midas Creek – Isometric View

Lecia RTC360 – Terrestrial LiDAR



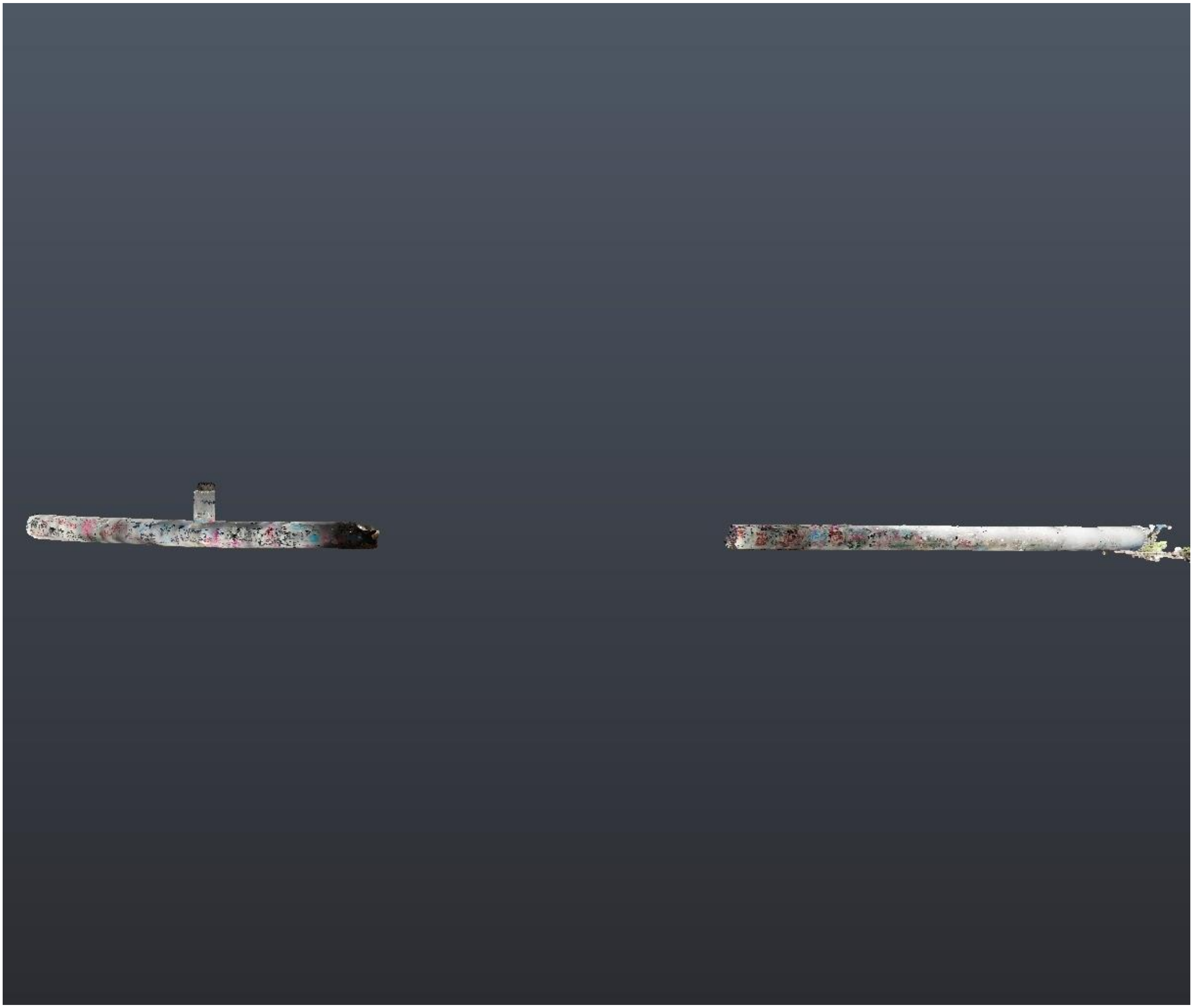
Test Pipe 1 – Midas Creek – Plan View

Lecia RTC360 – Terrestrial LiDAR



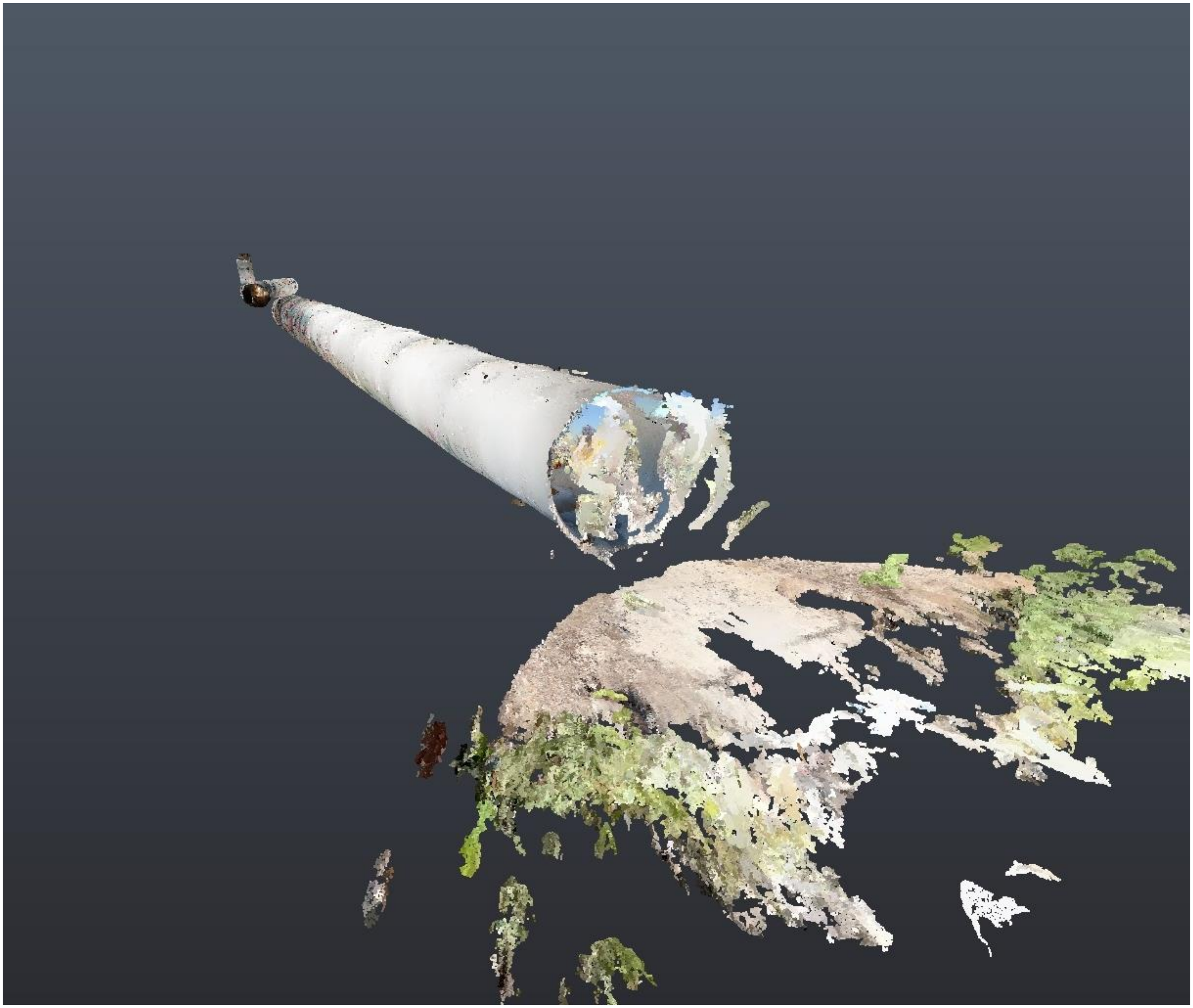
Test Pipe 2 – Herriman Tunnel – Elevation View

Pocket LiDAR Scan



Test Pipe 2 – Herriman Tunnel – Isometric View

Pocket LiDAR Scan



Test Pipe 2 – Herriman Tunnel – Plan View

Pocket LiDAR Scan

Test Pipe 3 – Lisa Falls – Elevation View

Lecia BLK2GO – SLAM LiDAR

Test Pipe 3 – Lisa Falls – Isometric View

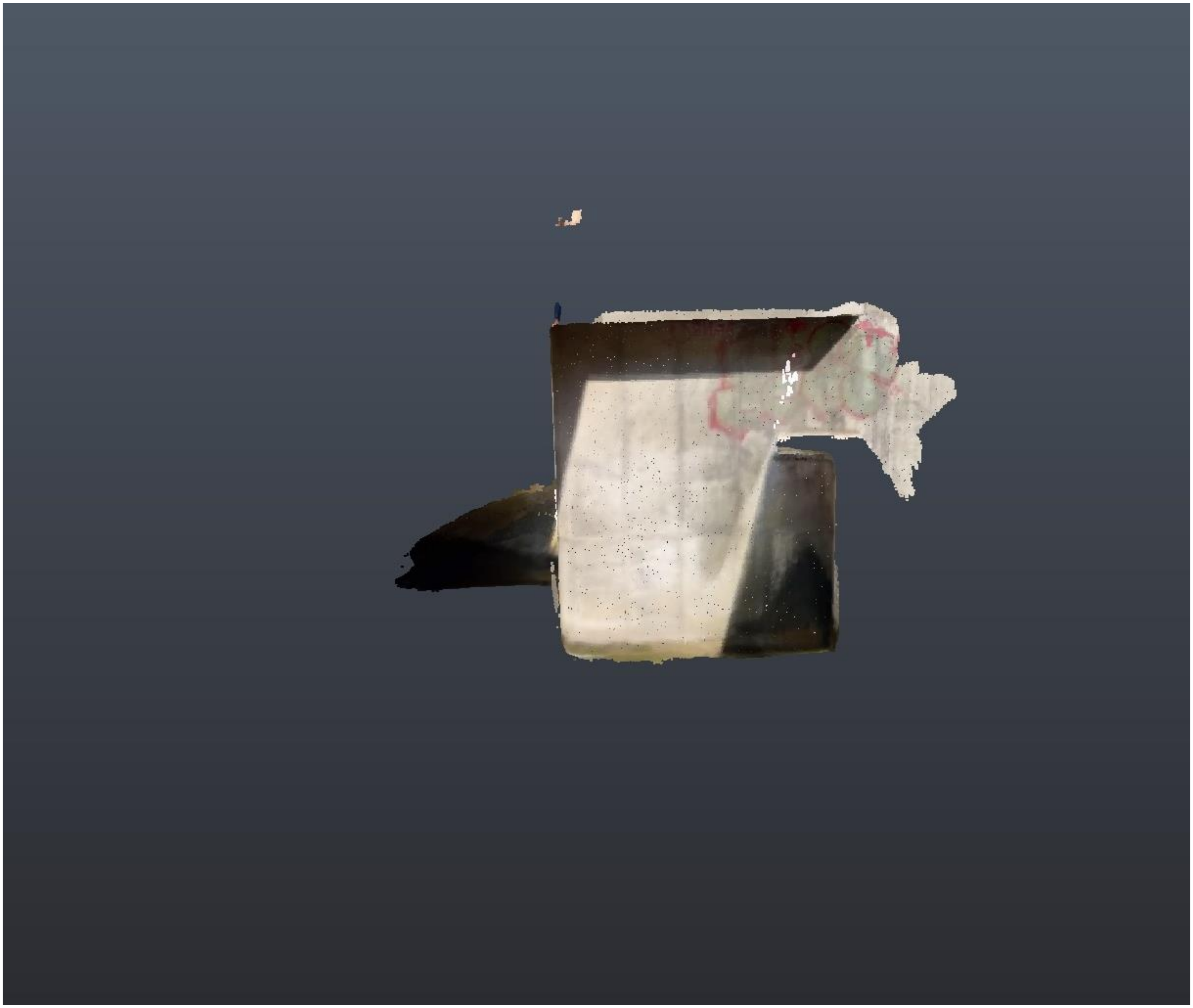
Lecia BLK2GO – SLAM LiDAR

Test Pipe 3 – Lisa Falls – Plan View

Lecia BLK2GO – SLAM LiDAR

Test Pipe 4 – Parley’s Creek - I-80 Eastbound, Milepost 129.26 - Elevation View

Pocket LiDAR Scan

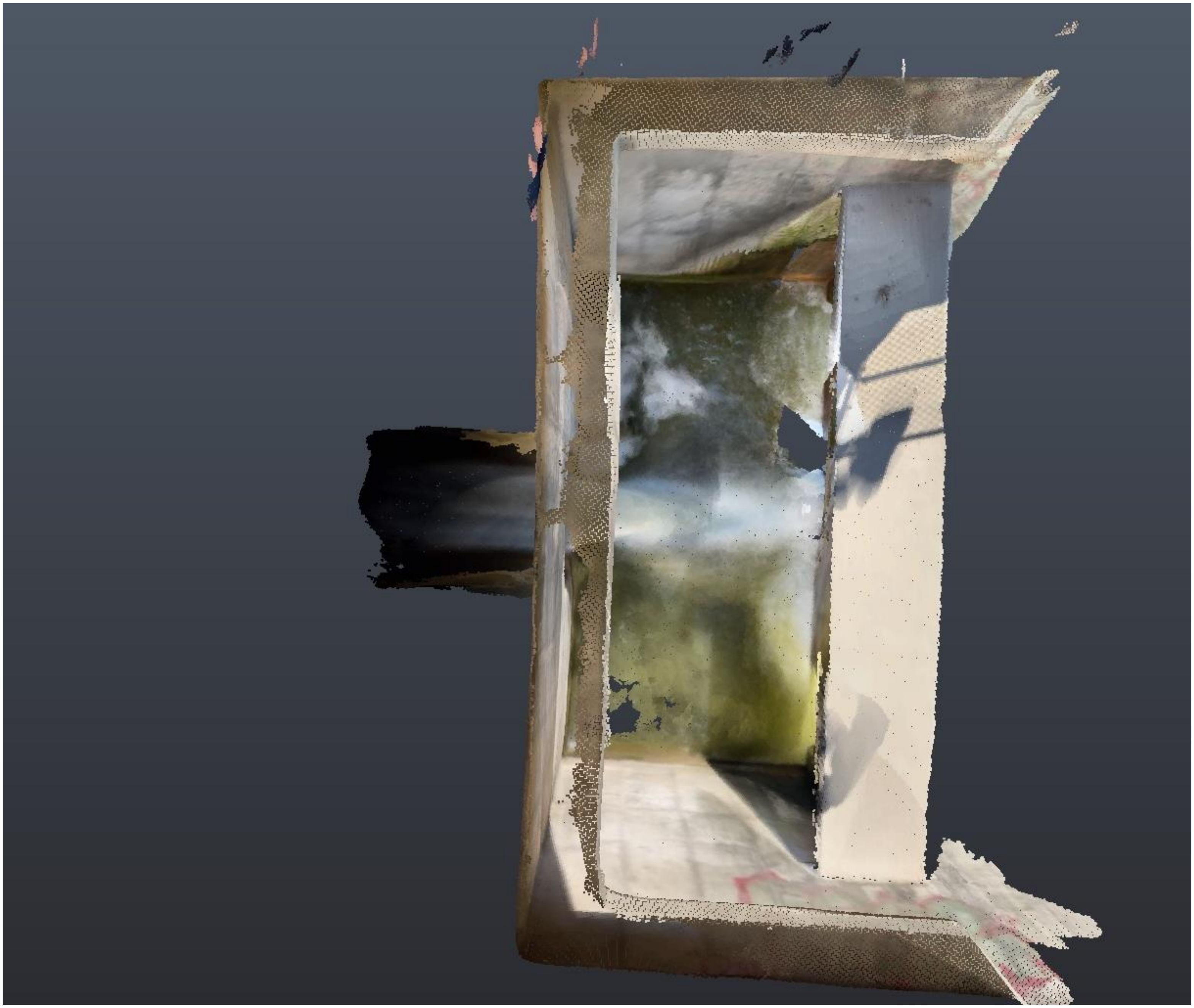


Test Pipe 4 – Parley’s Creek - I-80 Eastbound, Milepost 129.26 – Isometric View

Pocket LiDAR Scan

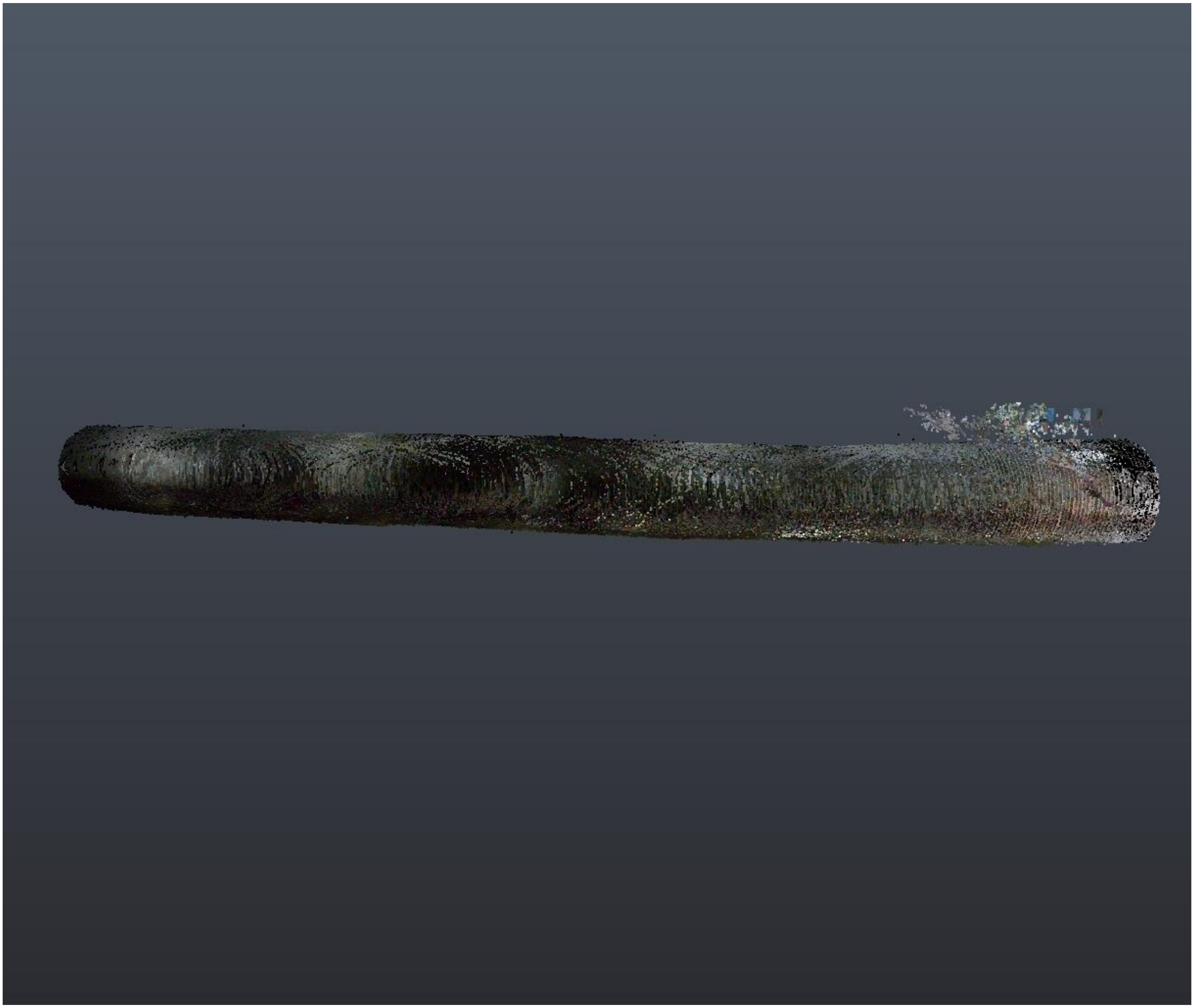
Test Pipe 4 – Parley's Creek - I-80 Eastbound, Milepost 129.26 – Plan View

Pocket LiDAR Scan



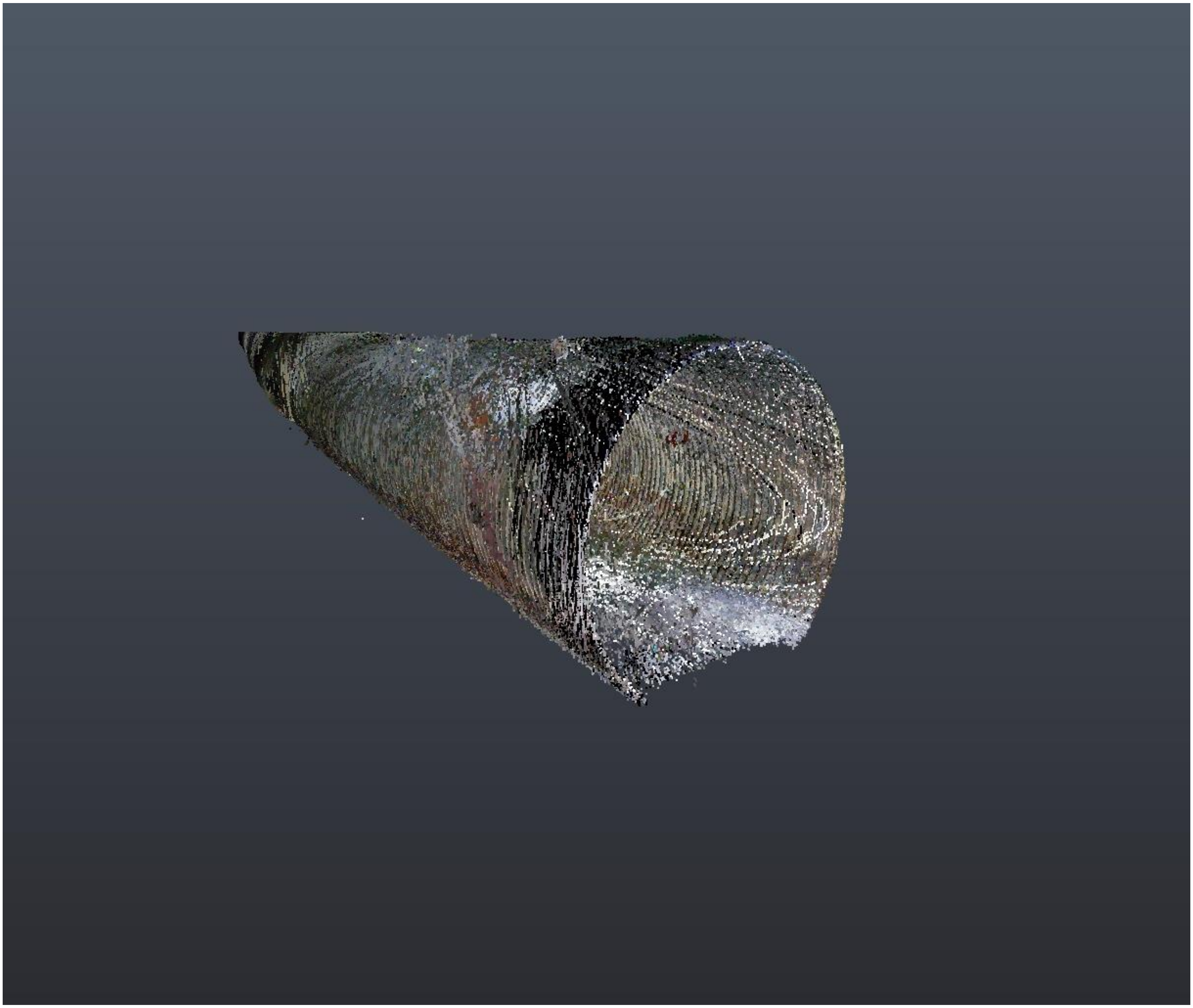
Test Pipe 5 – Parley’s Creek - I-80 Westbound, Milepost 131.96 - Elevation View

Lecia BLK2GO – SLAM LiDAR



Test Pipe 5 – Parley’s Creek - I-80 Westbound, Milepost 131.96 - Isometric View

Lecia BLK2GO – SLAM LiDAR



Test Pipe 5 – Parley’s Creek - I-80 Westbound, Milepost 131.96 - Plan View

Lecia BLK2GO – SLAM LiDAR

Test Pipe 6 – Parley’s Creek –- I-80 Westbound, Milepost 131.39 - Elevation View

Pocket LiDAR Scan

Test Pipe 6 – Parley's Creek – I-80 Westbound, Milepost 131.39 - Isometric View

Pocket LiDAR Scan

Test Pipe 6 – Parley’s Creek – I-80 Westbound, Milepost 131.39 – Plan View

Pocket LiDAR Scan

Test Pipe 7 – Parley’s Creek, I-215 Northbound, Milepost 1.05 – Elevation View

Pocket LiDAR Scan

Test Pipe 7 – Parley’s Creek, I-215 Northbound, Milepost 1.05 – Isometric View

Pocket LiDAR Scan

Test Pipe 7 – Parley’s Creek, I-215 Northbound, Milepost 1.05 – Plan View

Pocket LiDAR Scan

Test Pipe 8 – Cross Culvert Under the Trail within Parley's Historic Nature Park – Elevation View

Lecia RTC360 – Terrestrial LiDAR

Test Pipe 8 – Cross Culvert Under the Trail within Parley's Historic Nature Park – Isometric View

Lecia RTC360 – Terrestrial LiDAR

Test Pipe 8 – Cross Culvert Under the Trail within Parley’s Historic Nature Park – Plan View

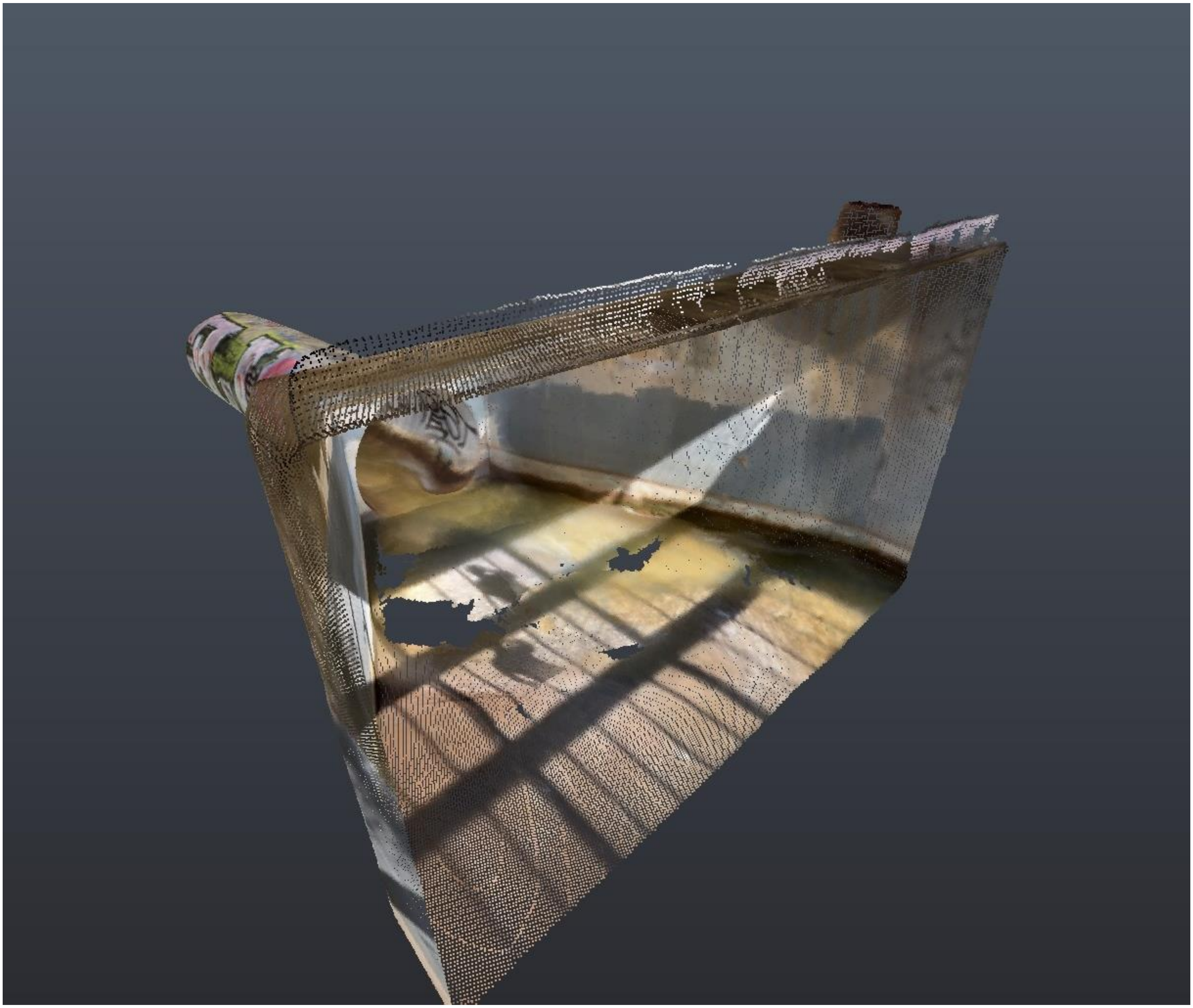
Lecia RTC360 – Terrestrial LiDAR

Test Pipe 9 – Reinforced Concrete Pipe under I-80, within Parley’s Historic Nature Park– Elevation View

Pocket LiDAR Scan

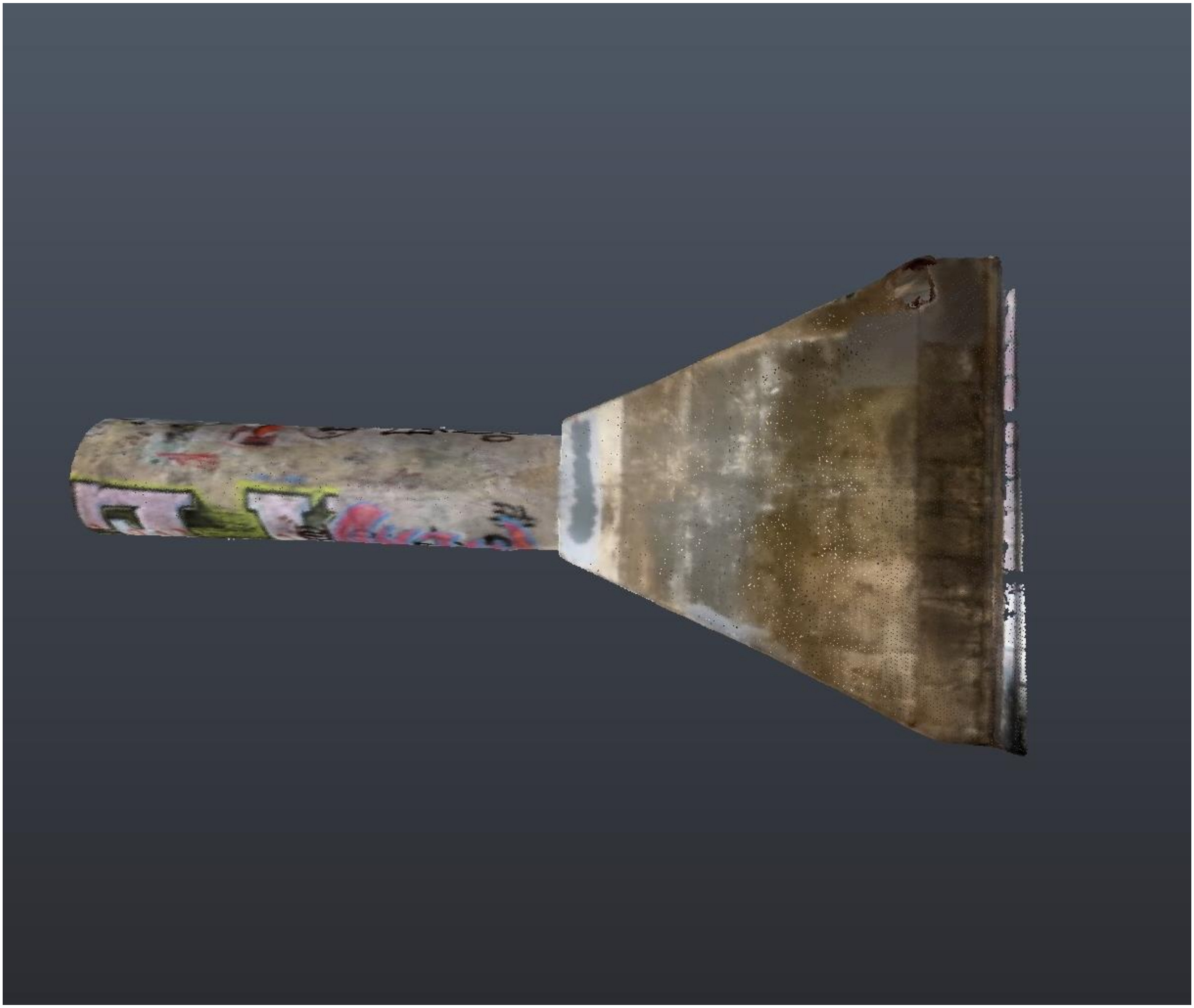
Test Pipe 9 – Reinforced Concrete Pipe under I-80, within Parley's Historic Nature Park– Isometric View

Pocket LiDAR Scan



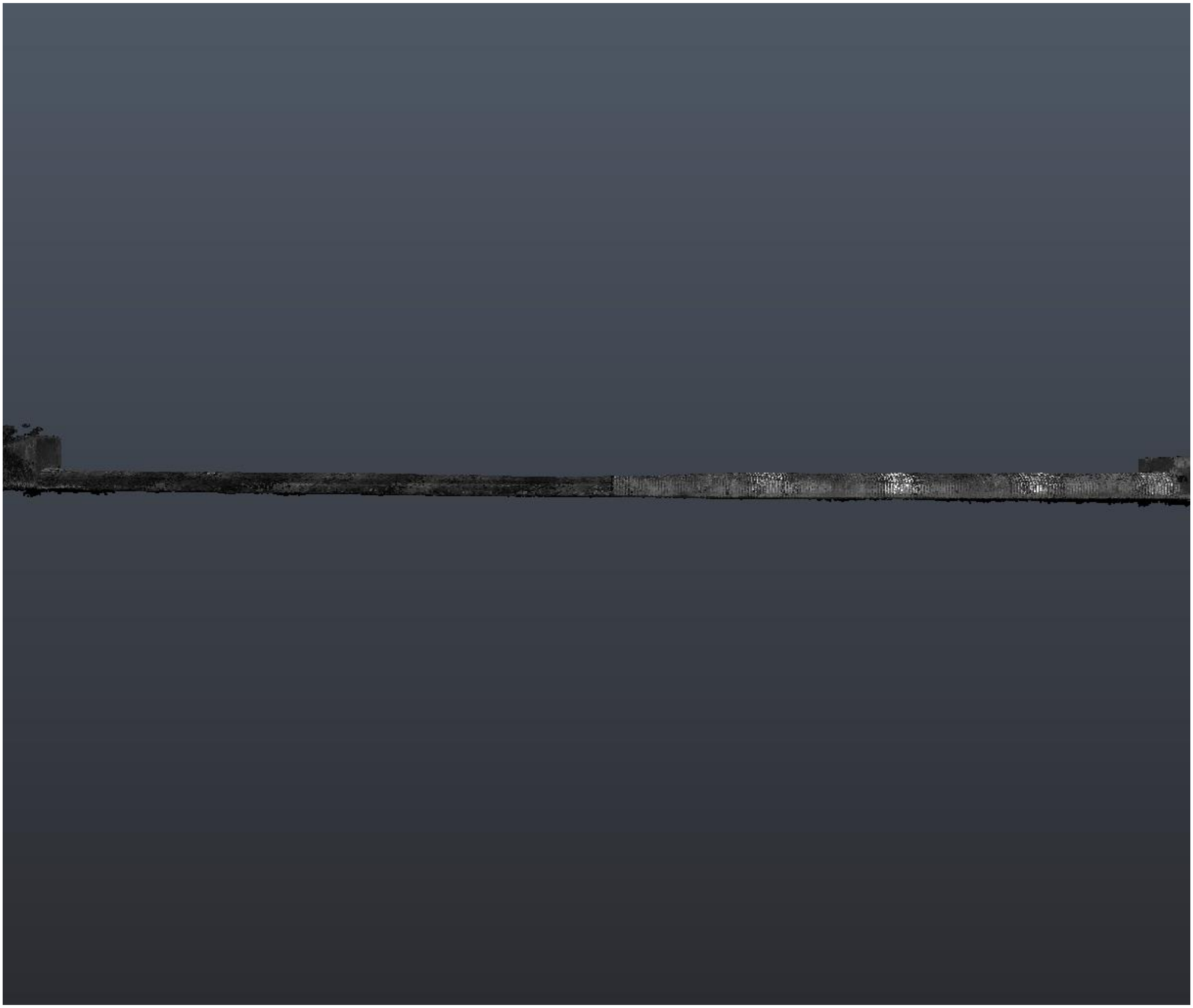
Test Pipe 9 – Reinforced Concrete Pipe under I-80, within Parley's Historic Nature Park– Plan View

Pocket LiDAR Scan



Test Pipe 10 - Corrugated Metal Pipe in Sugarhouse Park – Elevation View

Leica RTC360 Terrestrial LiDAR



Test Pipe 10 - Corrugated Metal Pipe in Sugarhouse Park – Isometric View

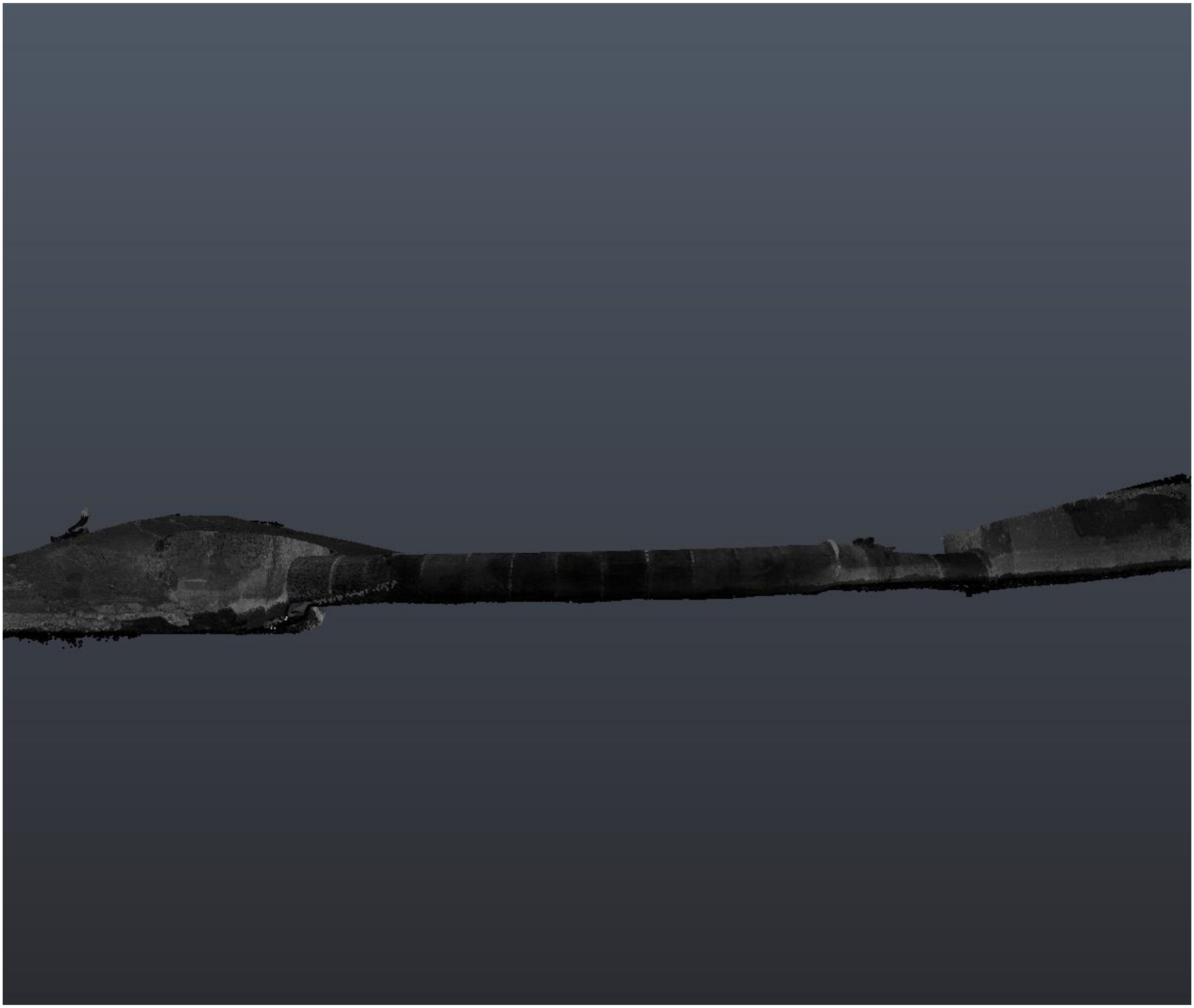
Leica RTC360 Terrestrial LiDAR

Test Pipe 10 - Corrugated Metal Pipe in Sugarhouse Park – Plan View

Leica RTC360 Terrestrial LiDAR

Test Pipe 11 – Concrete Pipe in Sugarhouse Park – Elevation View

Leica RTC360 Terrestrial LiDAR



Test Pipe 11 – Concrete Pipe in Sugarhouse Park – Isometric View

Leica RTC360 Terrestrial LiDAR

Test Pipe 11 – Concrete Pipe in Sugarhouse Park – Plan View

Leica RTC360 Terrestrial LiDAR