# FORMAL PROCESSES FOR INSPECTING BRIDGE DECK DRAINS USING LIDAR AND PHOTOGRAMMETRY

By

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DISSERTATION

Submitted in partial fulfillment of the requirements

for the degree of Doctor of Philosophy at

The University of Texas at Arlington

May 2023

Arlington, Texas

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This page is dedicated to my mother “Dr. Golzar Saber”. I am certain you see me from above and are happy with my accomplishments.

## Disclaimer

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author.

**Acknowledgements**

First and foremost, I would like to thank my supervising professor, Dr. Mohsen Shahandashti. I could spend the rest of my career life thanking him, but it wouldn't come close to doing him justice. I thank him for all the times he has guided me and been a fatherly backbone to me, especially when times were tough. He mentored me and equipped me with a large library of skills that I will always attribute to him during future endeavors. I am also very thankful to Prof. Abolmaali for believing in me and allowing me many opportunities to grow into the engineer I was always meant to be. I wouldn't be where I am today without his constant support. I am also grateful to Dr. Ryu, Dr. Tsung, and Dr. Zhou for taking the time out of their busy schedule to be in my PhD supervising committee and for supplying me with insightful comments that allowed my research to progress.

I would also like to thank my lab mates, who were always there for me and helped me when needed. I am glad to have met the genius minded people whom I can call my friends and will always be there to give their support.

I also want to thank my family for supporting me through my pursuit of greatness and education. Specifically, I want to thank my father "Dr. Kamal Bani Hani" for believing in me and encouraging me. I also want to thank my mother, who never showed me anything except support and love. I cannot wait to see you again someday.

Lastly, I am grateful to the Texas Department of Transportation. This material is based upon the work supported by TxDOT for project 0-7092.

**Abstract**

FORMAL PROCESSES FOR INSPECTING BRIDGE DECK DRAINS USING LIDAR AND PHOTOGRAMMETRY

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Poor-performing bridge deck drains result in water standing on the bridge deck. The standing water threatens the safety of bridge users and deteriorates bridge structural elements. Bridge deck drains are only inspected biennially, and they do not impact the bridge rating established from inspections. Furthermore, literature shows that visual inspection results are sometimes skewed due to human errors. In this regard, a part of this research was conducting a survey study to help identify the problems with deck drains to help transportation agencies minimize the consequences of poor drainage. Another part of this research was to create a convolutional neural network (CNN) to classify the problems found in bridge deck drains through images in order to improve inspections on deck drains. The results of the survey study shed light on many bridge deck drain problems that were absent in literature. Furthermore, it also highlighted a major issue: most transportation agencies do not keep track of bridge deck drain assets on bridges. Therefore, as-is models were created based on 3D scenes reconstructed from images and a LiDAR sensor.

The results of this research show the advantages of tracking bridge deck drain assets through as-is 3D models created based on acquired imagery and laser scans. The advantages lie in the ability to compare the as-is models with as-built models and track future inspections and maintenance operations. Moreover, as-is models allow designers to analyze the hydraulic properties of drains,

and easily modify and improve the design should the need arise. The results of the survey also helped in listing all the major and minor problems. The created as-is model accurately resembled the drain on the inspection site. The resemblance includes the different parts of the drain system, their quantities, and their sizes. As-is models provide the opportunity of exporting spreadsheets containing systems' components with attached images, which enables office teams to conduct a thorough inspection without going through the inconveniences of on-site inspections. The results also showed that using a pretrained CNN model, it was possible to classify problems found in images taken of bridge deck drains. The model reached 96% accuracy in classifying the condition of grate inlets after being trained on a very small dataset.

The outcomes of this research offer transportation agencies a robust way of keeping track of bridge deck drain assets and current conditions. The research also provides the basis for automating the inspection of deck drains using images acquired on site, which promotes safer inspections and decreases time spent on inspections.

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# CHAPTER I: INTRODUCTION

Recent rainfall induced crashes have been observed on bridges, such as the crash on a bridge located on the I-10 West in Louisiana that occurred in July 2022. The rain caused a pickup truck to impact an 18-wheeler, causing the 18-wheeler to collide with the guard rails and fall off the bridge (Romero, M., 2022). Another crash on a California bridge occurred on the 4$^{th}$ of December in 2019, where the bridge runoff caused a semi-truck to teeter over the embankment. It took three tow trucks to remove the semi-truck (Cota-Robles, M., 2019). On December 2$^{nd}$ of 2022, a bridge in Santa Clarita, California, experienced rain induced crashes; while first responders were at the scene of an SUV that fell and crashed from a bridge, a box truck experienced the same rain caused crash and fell on top of the SUV. Luckily, the first responders were not harmed, however, the persons involved in the two crashes were transported to a hospital (Firehouse, 2022). Moreover, in 2014, investigators discovered that despite having holes drilled on The Bay Bridge in San Francisco, California, water was still seeping through the deck and causing the underlying steel to corrode (Bay Area News Group, 2014). The Bay Bridge spokesman, Andrew Gordon, stated that it wasn't possible to assess the effectiveness of the open systems without rainfalls, mentioning that it's impossible to acquire permits that allow for dumping of water on the bridge deck to test the deck drains (Bay Area News Group, 2014). Those were only a handful of examples showing how poor bridge drainage threatens the safety of bridge users and the structural integrity of bridges, as well as why transportation agencies spend millions on bridge repairs. Those examples highlight the need for better deck drain inspections that ensure peak performance of these systems are achieved, in order to minimize the dangerous effects of poor deck drainage. Despite the efforts made by transportation agencies to remove runoff from bridge decks, there is little understanding of the challenges bridge deck drains encounter, and what drain configurations should be used to minimize the effects of bridge deck runoff.

Hence, this research was conducted to grasp the full extent of problems and challenges encountered with bridge deck drains, then utilizing the information gathered to improve the inspections done on bridge deck drains through classifying images illustrating different problems of deck drains. This inspection method helps eradicate the errors resulting from visual observations, where a neural network would conduct the inspection based on acquired images, and an office team could oversee the inspection process. Moreover, this research provides a method for creating as-is information models of bridge deck drains that assist transportation agencies in analysis and future maintenance of deck drains.

Chapter 2 offers a thorough literature review. The chapter first reviews the current state of knowledge and practice regarding bridge deck drains and problems found in the literature, then introduces newly applied systems, including data collection and processing, in order to model and inspect bridges. Chapter 3 explains the methodologies used for conducting a survey study that aimed to capture the state of practice regarding bridge deck drains across the states, as well as for creating formal approaches that explain the processes involved in creating as-is information models and inspecting bridge deck drains, based on the data acquired from a camera and a laser scanner. Chapter 4 contains the results acquired from two surveys, for both Texas and other states respectively. The surveys addressed the challenges found in the design, construction, and maintenance of bridge deck drains. The surveys also shed light on many problems observed in bridge deck drains. Chapter 5 presents an accurate as-is model of elevated drains, created based on images acquired from a phone camera. Chapter 6 presents two neural networks used to classify the condition of grate inlets that appear in images (broken and not broken grates). The first model was a regular Convolutional Neural Network, and the second model was based on Transfer Learning. The second model achieved high accuracy, even though the dataset used to train the network was small. Finally, Chapter 7 presents the conclusions and future work.

# CHAPTER II: LITERATURE REVIEW

## 2.1 Bridge Deck Drainage System

Bridge deck drainage is an integral component of the bridge system, helping in the fast and effective removal of runoff from bridges. Bridge drain inlets receive runoff from the decks and gutters, and through pipes and downspouts, the runoff is conveyed to ground drainage structures (Hammons and Holley, 1995). Bridge deck drainage maintenance is one of the major contributors to the overall bridge maintenance cost (Vlcek & Koncicky, 2012). The rainfall-runoff carries debris that causes frequent clogging in bridge deck drains. Poor bridge drainage results in water standing on the bridge pavements. Standing water deteriorates bridge structures and significantly increases the cost of bridge deck maintenance (Hammons and Holley, 1995; Brown et al., 2009). Bridge deck drains that can operate with minimum maintenance are essential to improve the traffic operation, enhance safety, and minimize deterioration of bridge deck structures. However, the drain types that can be used in bridges are limited due to the restrictions imposed by bridge aesthetics, elevation, structural integrity, and maintenance requirements (Young et al., 1993; Qian et al., 2013).

Bridge deck drainage systems can either be (FHWA, 2015; SCDOT, 2006):

- Open deck drainage system.
- Closed deck drainage system.

### 2.1.1 Open Bridge Deck Drains

Open deck drainage systems are horizontal or vertical penetrations through the bridge structures. Horizontal penetrations (Fig 2.1, a) are the drainage slots that are constructed as a part of the bridge barriers and curbs. Vertical penetrations (Fig 2.1, b) are the drainage slots in a bridge deck. The pipe in the vertical penetration extends through the bridge deck and receives the runoff from a grate inlet or a scupper inlet. Extension pipes may be used to avoid wind driven sprays that cause scour (Young et al., 1993).

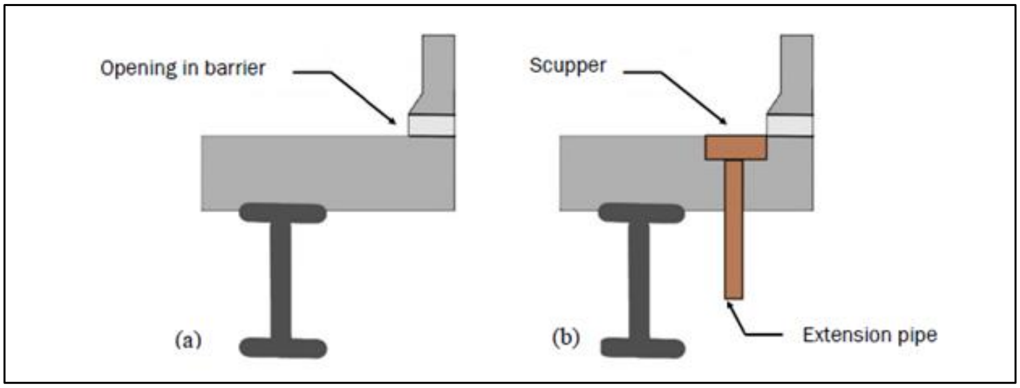


**Figure 2.1.** Open bridge deck drain (a) Horizontal penetration (b) Vertical penetration (Modified from FDOT, 2018)

The open deck drainage system allows the runoff contaminated with chemicals and chlorides to come in direct contact with the bridge structural components (NDOT, 2008). This contact results in premature spalling of concrete or corrosion of steel as later will be shown in Figure 2.6 (FDOT, 2018; Young et al., 1993). Drain extensions may be used for open systems to prevent the runoff from coming in contact with superstructure and substructure elements of the bridge (FDOT, 2018). Scour pads might need to be considered at ground level to prevent soil erosion (e.g., riprap, precast concrete pad) (FDOT, 2018). If runoff freefalls from a height higher than 25 ft, water will disperse enough that no erosion protection is needed unlike falls smaller than 25 ft (SCDOT, 2006). Figure 2.2 displays an open deck drainage (horizontal openings) used in Houston, Texas. The openings discontinue when the bridge passes over a lane below it.

**Figure 2.2.** Horizontal openings on a bridge in Houston (Source: GoogleEarth, 2021)

### 2.1.2 Closed Bridge Deck Drains

Closed deck drainage systems comprise grate inlets with a closed piping system affixed to bridge substructures for transporting runoff to a ground drainage inlet. Figure 2.3 contains the basic components for a typical bridge deck drain. Closed deck drainage systems are required when there are environmental concerns, such as contamination due to runoff, flooding, or soil erosion immediately below the bridge structure (SCDOT, 2006). Grate inlets have different designs and orientations making them suitable for different grades (Brown et al., 2009). Pipes in the closed deck drainage system are susceptible to corrosion and clogging due to the debris and sand carried by rainfall runoffs (SCDOT, 2006).

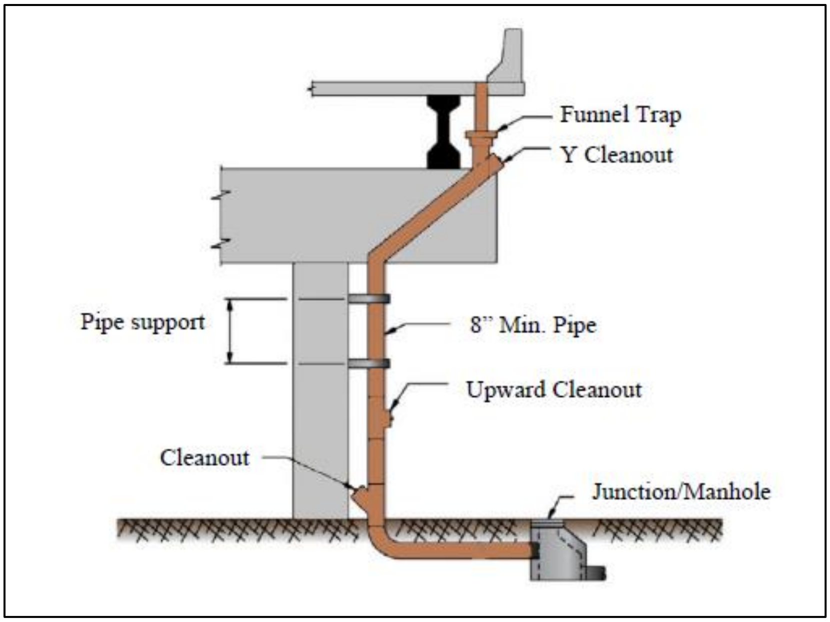


**Figure 2.3.** Closed deck drainage system (Modified from FDOT, 2018)

Drainpipes in closed systems can either be embedded within a bridge structure (Figure 2.4, a) or run down the exterior of the bridge. The drainpipes that are embedded within a bridge structure are challenging to maintain through cleaning and flushing (Young et al., 1993). Drainpipes in hung systems can either go downward at piers or bents (Figure 2.4, b) (common for overpasses) or long pipes that discharge at bridge ends (Figure 2.4, c) (flow in pipes combined from multiple inlets) (FDOT, 2019).


**Figure 2.4.** Closed bridge deck drain (a) Drain embedded within bridge structure (GoogleEarth, 2022) (b) Drain running down the exterior of the bridge (GoogleEarth, 2022) (c) Combined drains which discharge at bridge ends (Hennegan and Associates, 2020)

Properly designed bridge deck drains must (1) limit the water spreading into traffic lanes; (2) prevent significant water depth accumulation to reduce hydroplaning (Qian et al., 2013). Poor bridge deck drainage does not directly contribute to the structural failure of bridges. However, properly designed bridge deck drains will improve bridge safety, maintenance schedule, and structural integrity (Qian et al., 2013). Although the water film depth determines whether hydroplaning occurs or not, pavement texture, tire pressure, and tire tread depth influence the speeds at which hydroplaning occurs (Young et al., 1993).

Although bridge deck drains have similar components as typical pavement drainage systems, bridge deck drains less efficient than typical pavement drainage systems because (Brown et al., 2009; Young et al., 1993):

1. Bridge decks have flatter cross slopes.
2. Bridge decks have uniform cross slopes.
3. Inlets and scuppers used with bridge deck drains are significantly less efficient that typical pavement drainage.
4. Drainage inlets and piping are relatively small.
5. Bridge deck drains clog frequently due to debris (e.g., soda cans, water bottles) and sand.
6. Bridges do not have clear zones.

Bridge decks with zero grades and sag vertical curves have poor hydraulic performance and should be avoided (SCDOT, 2006). Qian et al. identified six factors that influence the amount of flow entering deck drains (Qian et al., 2013):

1. Drain size and geometry.
2. Flow regime.
3. Manning's roughness coefficient.
4. Approach discharge.
5. Cross slope.
6. Longitudinal slope.

**2.2 Bridge Deck Drain Problems**

Stormwater runoff must be quickly removed from bridge decks to maintain vehicle and pedestrian safety on bridges (Qian et al., 2013). When bridge deck drains are unable to intercept water efficiently, standing water will start appearing on the roadway (Hammons and Holley, 1995). Standing water causes vehicles to hydroplane (Hammons and Holley, 1995). Hydroplaning on bridges occurs at shallower depths than highway pavement because of the reduced surface texture

(Brown et al., 2009). Figure 2.5 illustrates how hydroplaning develops with increased speeds and water depths. Standing water also deteriorates the structure and significantly increases the cost of bridge deck maintenance (Brown et al., 2009; Hammons and Holley, 1995).

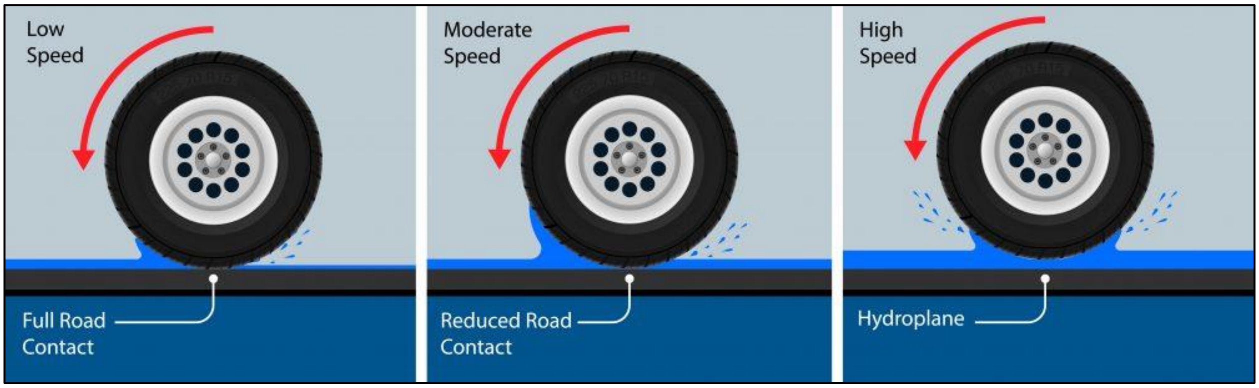


**Figure 2.5.** Tire hydroplaning at different speeds and water depth (left) No hydroplaning occurs (middle) Tires start losing contact with road (right) Tire no longer has contact with road (Smartmotorist, 2022)

The Florida Department of Transportation identified 7 items to look for when conducting basic preventative maintenance on bridge deck drains (FDOT, 2018):

1. Debris.
2. Clogged elements.
3. Evidence of ponding.
4. Leaks.
5. Broken frame.
6. Broken pipe fittings.
7. Loose hardware.

Bridge deck drains that are not working properly will result in reinforcing steel corroding at locations where water remains or flows down (Yashima and Huang, 2021). Water retaining from bridge construction often causes defects (Vlcek & Koncicky, 2012). Layered rust on steel girders must be removed immediately when found as the water in the layers would accelerate corrosion

(Yashima and Huang, 2021). Steel and concrete corrosion on bridges is usually the result of improper outflow of water or water retaining in some bridge parts (Vlcek & Koncicky, 2012). Figure 2.6 shows corroded concrete and steel below a bridge deck. The chloride ions from deicing salts are considered the main reason for the corrosion of reinforcing bars (Lee at al., 2005).

**Figure 2.6.** Underdeck concrete spalling and reinforcement corrosion (Evans and Oats, 2010)

Each drain requires periodic maintenance to ensure adequate performance regardless of the drain configuration (Young et al., 1993). Hopwood and Courtney inspected different sized inlets ranging from 9” X 9” to 1’-9” X 2’-2” (Hopwood and Courtney, 1989). They concluded that although all drains were susceptible to clogging, larger ones performed better (Hopwood and Courtney, 1989). Pipes in the closed deck drainage system are susceptible to corrosion and clogging due to the debris and sand carried by rainfall runoffs (SCDOT, 2006). Rust stains around drainpipes (Figure 2.7) indicate loose joints or fractures due to the trapped water freezing in drainpipes (Hopwood and Courtney, 1989). Pipe bends reduce the hydraulic capacity of bridge deck drainage systems and debris accumulates and collects at those bends (FDOT, 2019; SCDOT, 2006). Clogged bridge deck drains allow water ponding on bridge decks. Ponded water eventually attacks critical bridge elements (MnDOT, 2019).

**Figure 2.7.** Rust stains may indicate fracture or a loose joint (Dreamstime, 2022)

Clogging of bridge deck drains is local; amount of debris varies from one location to another (Iowa DOT, 2022). Figure 2.8 illustrates how clogging differs from one area to another. The bridge in Dallas containing debris is in a densely populated area unlike the other two drains in El Paso.

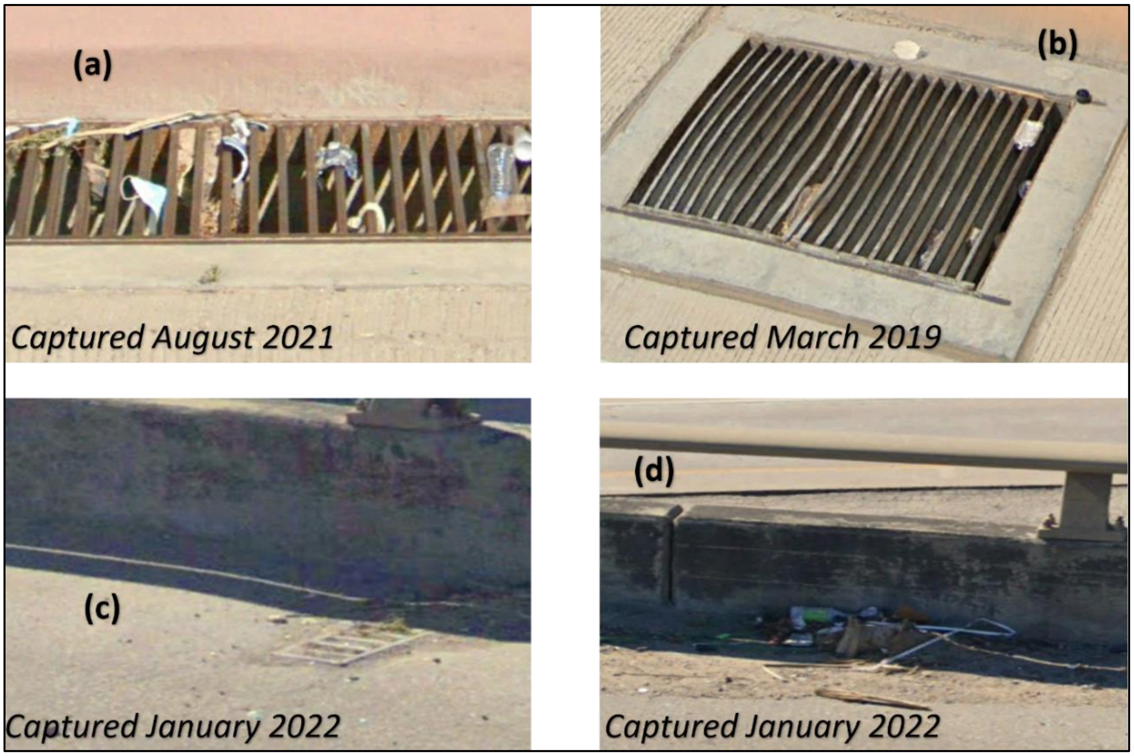


**Figure 2.8.** Debris accumulation on bridge decks (a) Clogged inlet in Las Tierras, El Paso (b) Deformed inlet in Borderland, El Paso (c) Inlet clogged and contains vegetation in Dallas (d) Heavy amounts of debris and sand the same bridge deck as image c (GoogleEarth, 2022)

### 2.3 Bridge Deck Drain Inspections

Bridge deck drain design is often one of the last items listed in the scope of a bridge design project (Boedecker et al., 2011). On-site visual inspections are how bridge drains are typically inspected; human errors create many uncertainties in the inspection results (Bian et al., 2017). Inspection of bridge deck drains do not affect the bridge rating as they do not have their own rating scale within the National Bridge Inspection (NBI) standards (fully dependent on inspection notes) (MDOT, 2016). However, some states may still choose to rate the conditions of bridge drainage elements such as Minnesota. MnDOT inspects the condition, function, and adequacy of each drainage system on the bridge deck (including components of deck drains) (MnDOT, 2020).

Two to Four weeks prior to bridge inspection, the bridge is checked for debris, vegetation, or water that may affect the safety and access of inspectors (DelDOT, 2020). Equipment, personnel, and access needs are also evaluated during this period by the Delaware Department of Transportation (DelDOT, 2020).

Visual based inspections are time consuming and may lead to infrequent inspections (Cross et al., 2020). Infrequent inspections can create inspection gaps that may lead to incorrect information about assets' actual conditions (Cross et al., 2020). Inspections are laborious and may be subject to the inspector's opinions (Cross et al., 2020). If the inspection data was found to be inaccurate, additional on-site inspections may be required (Puri and Turkan, 2020).

Conducting bridge inspections visually has several disadvantages (Belloni et al., 2020; Bolourian et al., 2017; Cross et al., 2020; Popescu et al., 2019):

1. Costly.
2. Time consuming.
3. Labor intensive.
4. Subjective reports.
5. Only visible defects are detected.
6. Limited to accessible areas.
7. Color vision, visual acuity, and fear of traffic may affect inspectors.
8. Highly dependent on the knowledge and expertise of inspectors.

Civil infrastructures including bridges are becoming older around the globe (Belloni et al., 2020). Advanced monitoring systems are essential for determining the health and safety of infrastructures (Belloni et al., 2020). Inspection data accuracy can be improved by using new inspection techniques (Popescu et al., 2019). Data acquired from new inspection methods are more reliable that visual based inspections (Popescu et al., 2019). Accurate data collection using sensors reduces errors originating from subjective opinions and inspection lapses (Cross et al., 2020).

The use of optical sensors (e.g., LiDAR, camera) is rapidly replacing visual based inspections in civil engineering (Popescu et al., 2019). Prior to data collection, the parts that need to be inspected, as well as the locations of the sensors should be identified (Bian et al., 2017). Once data is acquired, 3D models can be made available to different parties (e.g., bridge managers, structural engineers) to aid in decision making without having to mobilize from the office (Cross et al., 2020; Popescu et al., 2019). Figure 2.9 displays a colored 3D point cloud of an elevated drain reconstructed from images captured using an iPhone camera.

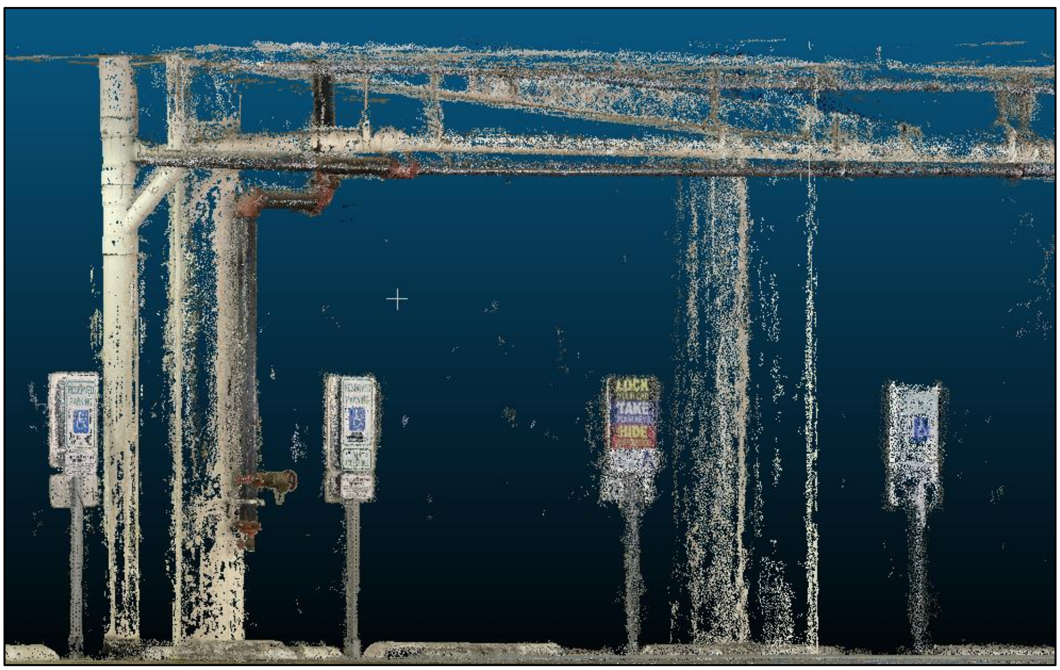


**Figure 2.9.** RGB point cloud reconstructed from iPhone images

3D models are easily maintainable and accessible making them ideal for reconstruction and renovation projects (Kushwaha et al., 2018). 3D models must be detailed enough to allow for visual inspections to be performed off site (detailed enough to identify certain defects) (Popescu et al., 2019).

The use of contactless sensors for inspections offers several advantages (Popescu et al., 2019):

1. Reduces or eliminates lane closure.
2. Avoids traffic delays.
3. Ensures people's safety.
4. Eliminates human errors.

**2.4 Light Detection and Ranging (LiDAR)**

Light Detection and Ranging (LiDAR) is a remote sensing technology that detects range and provides 3D point clouds that represent the scanned surfaces without physical contact (Liu et al., 2011). Point cloud is the most primitive type of 3D models containing many points that accurately represent different scenes to allow measurements and drawings (Popescu et al., 2019).

Points in a point cloud can be described as shown in Figure 2.10 (Bian et al., 2017):

$$P = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_n & y_n & z_n \end{bmatrix}$$

$$R = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{bmatrix}$$

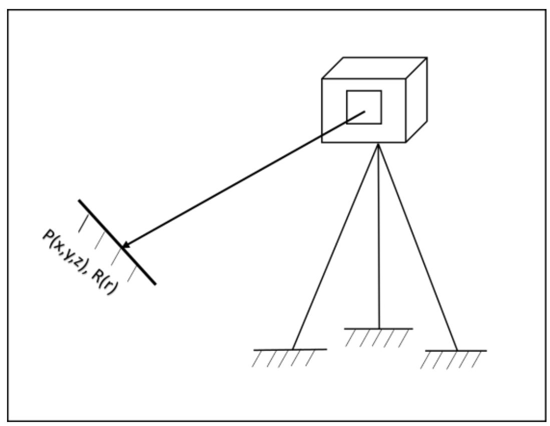


**Figure 2.10.** Light Pulse Representation (Adopted from Bian at al., 2017)

Where P represents the cartesian coordinates that provide the distance between the sensor and each point, and R represents the reflectivity value; brighter objects have higher reflectivity.

LiDAR sensors measure distances using one of two techniques (Liu et al., 2011):

- Time-of-Flight (TOF): The distance of an object is calculated through utilizing the time for the beam to reach an object and reach the sensor again, and the known speed of the beam.
- Phase-Based: The distance of an object is calculated by comparing the reflected light's phase shift to a reference beam phase.

Although TOF is widely used in civil engineering projects (Riveiro and Solla, 2016)**,** Phase-based technique offers denser point clouds (higher accuracy) and faster data acquisition compared to TOF (Liu et al., 2011).

A single LiDAR scan can acquire all the surface information of a bridge contained within the field of view of the scanner (Liu et al., 2011). The evaluation of the points in point clouds is the basis for bridge inspections using LiDAR sensors (Liu et al., 2010). The quality of the points when scanning bridges are affected by (1) Angle; (2); Range; (3) Edge effects (causes scattered points and presents details from being scanned); and (4) Surface reflectivity issues (Bian et al., 2017). Figure 2.11 displays a LiDAR point cloud of an elevated drainage structure with no RGB information, which makes it harder to interpret and visualize compared to colored point clouds.

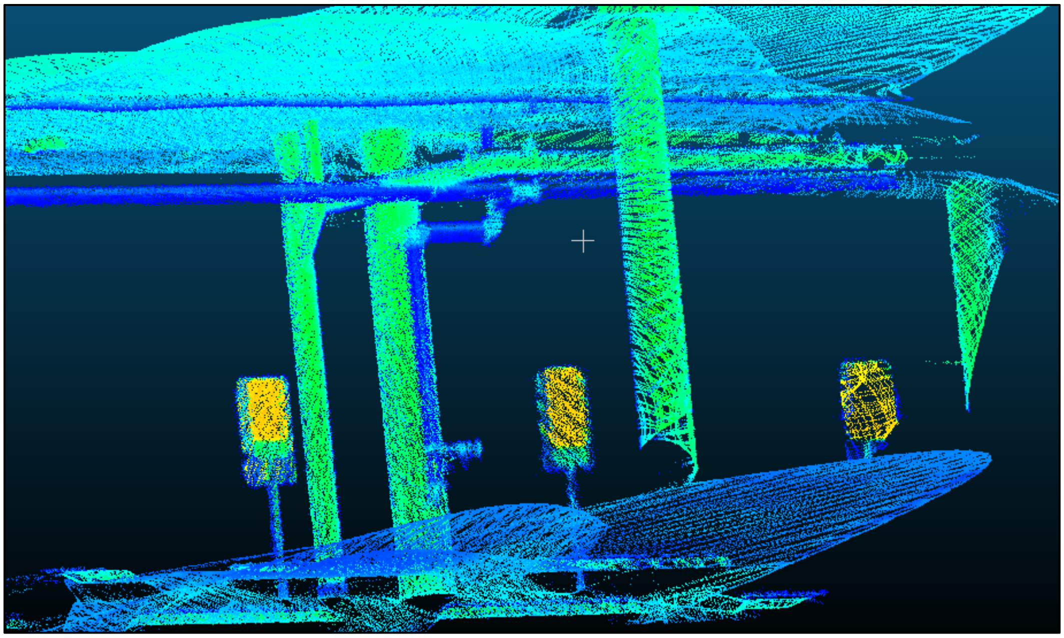

**Figure 2.11.** Point cloud of elevated drain structure captured with Livox MID-40

### 2.4.1 LiDAR Data Collection and Processing

LiDAR data collection can be (Congress, 2018):

1. Stationary; known as Terrestrial Laser Scanning (TLS).
2. Mobile; known as Mobile Laser Scanning (MLS).
3. Aerial; known as Aerial Laser Scanning (ALS).

During stationary scans, changes in temperature can deform the scanner's hardware mount which results in large errors especially for distant objects (Lee et al., 2019). Temperature change is not the only environmental effect to consider; dust in the atmosphere, lighting conditions, and passing traffic can also produce errors in the scans (Bian et al., 2017). Moreover, to guarantee maximum reflectance, scanned objects need to be reflective and perpendicular to the laser pulse (Lee et al., 2019).

Coordinate system of LiDAR scans will be different at different locations. The different coordinate systems may create measurement errors (Lee et al., 2019). Strategically placed reflectors (Figure

2.12) may be used on site to serve as references when changing the LiDAR position between stationary scans (Lee et al., 2019). Reflectors help minimize errors and inaccuracies of the scan registration (Lee et al., 2019).

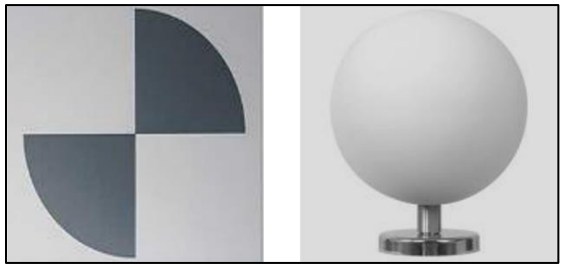

**Figure 2.12.** On-site marker (left) and reflector (right) to improve scan accuracy (Berntsen, 2022)

Point clouds acquired from LiDAR scans can be further processed using Global Navigation Satellite Systems (GNSS) and Inertial Measurement Unit (IMU) data thus increasing the accuracy of geometries in point clouds (Puri and Turkan, 2020). GNSS data help account for errors emerging from ionospheric disturbance and different systematic errors (Puri and Turkan, 2020).

A full 3D model of the scene can be generated by aligning (registering) multiple LiDAR scans together. This process is called unification of point cloud coordinate system (Popescu et al., 2019). Mobile and terrestrial (stationary) LiDAR scans may also be combined, depending on the requirements of the project (Puri and Turkan, 2020). To unify the point clouds into one coordinate system (scan registration), algorithms are used (Cao et al., 2020). Scan registration mainly consists of coarse and fine registration (Puri and Turkan, 2020). Coarse registration is done by manually identifying and selecting corresponding points in different scans to be aligned, thus unifying the scans into a single coordinate system. Fine registration can be done using two algorithms (Nearest Neighbor algorithm and Iterative Closest Point (ICP) algorithm) (Puri and Turkan, 2020).

### 2.4.2 LiDAR Applications on Bridges

Table 2.1 below describes four LiDAR applications already implemented on bridges.

**Table 2.1.** LiDAR applications on bridges (Liu et al., 2011; Lee et al., 2019; Cao et al., 2020; Puri and Turkan, 2020)

| Application/Description | Comments |
|---|---|
| Bridge structure defect detection:<br><br>- Quantification of material mass losses by comparing scans taken at different dates using an algorithm that references the flatness of the surface. | - The algorithm for detecting surface damage is called Light Detection and Ranging-Based Evaluation (LIBE).<br>- Algorithm can quantify material mass losses from concrete corrosion and steel erosion.<br>- Over repeated scans, deterioration rate prediction models can be generated or updated. |
| Long-term displacement measurement of bridges:<br><br>- Obtaining long-term deflection measurements.<br>- For the success of the algorithm, the scanner was placed perpendicular to strategically placed highly reflective objects. | Many algorithms were tested for short-term displacement measurements:<br>- 3D modeling for bridge maintenance by cabaleiro et al.<br>- Measuring changes in a concrete girder bridge due to truck load by Fuchs et al.<br>- Analyzing the relationship between bridge clearance and traffic by Watson et al. |
| Ancient arch bridge reconstruction:<br><br>- Identifying detailed geometric features of an ancient bridge to help combat bridge deterioration. | - Non-Uniform Rational B-Spline (NURBS) algorithm was utilized for bridge reconstruction.<br>- Preprocessing was done before using the NURBS algorithm.<br>- Unifying the scans using geometric feature based splicing method.<br>- Noise removal using curvature reduction method. |
| LiDAR and 4D models for monitoring progress of bridge construction:<br><br>- Data collection during construction was conducted to compare percent of completion (POC) between as-built 3D- models with as-planned 3D-models at any time during construction. | - Preprocessing was done before modeling the as-built point cloud.<br>- A nearest neighbor algorithm was used to align the as-built point cloud with the as-planned 3D model to achieve 1 to 1 point matching and discard points outside a set threshold.<br>- Iterative Closest Point (ICP) algorithm was used to improve the alignment to assist in object recognition. |

## 2.5 Photogrammetry

Photogrammetry is the process of reconstructing 3D models using 2D images (Pixao et al., 2018). The acquired images are processed using software that utilize Structure-from-Motion (SFM) technique and Multi View Stereo (MVS) algorithm (Pan et al., 2019; Pepe et al., 2019). The SFM technique obtains the camera locations and orientations in all taken images to produce a sparce point cloud of the scene (Pepe et al., 2019). MVS algorithm significantly increases the density of the point cloud generated from SFM technique (Pepe et al., 2019).

Although point clouds generated in photogrammetry have no scale, they are easier to visualize and interpret than LiDAR generated point clouds because they contain RGB data (Popescu et al., 2019). Photogrammetric point clouds can be scaled by referencing acquired laser scans or known GPS coordinates on the site. Targets like in Figure 2.13 installed on site can also be used as references to scale the point cloud if the distances between them is known (e.g., 12-bit coded targets) (Pepe et al., 2019; Popescu et al., 2019). The quality of the photogrammetric results depends on the (1) experience of the person conducting the scan; (2) quality of images (camera settings, overlap, resolution); (3) experience of the person processing the scans; and (4) lighting conditions (under exposure and excess brightness cause issues in the point cloud) (Popescu et al., 2019; Riveiro et al., 2012).

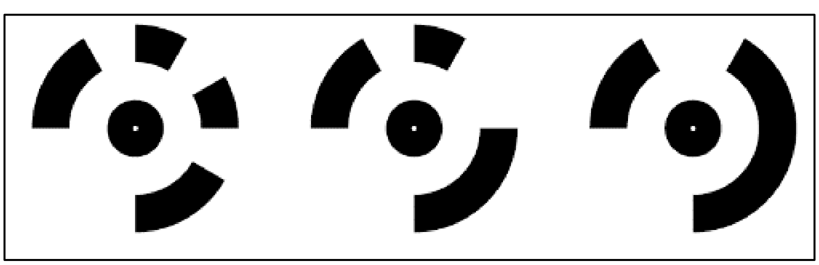

**Figure 2.13.** 12-bit Coded Targets (Modified from Agisoft, 2014)

The image resolution directly affects the point cloud density; low resolution images make it impossible to detect damage on structural members (Popescu et al., 2019). The structure to be modeled must take up most of the space in each image (adequate framing) (Riveiro et al., 2012). Sequential images must have at least 60% overlap for SFM technique to work properly (Popescu et al., 2019). Images captured must have adequate exposure level (Riveiro et al., 2012). If the required shutter speed is more than 1/30 of a second and the area does not have enough natural light, a tripod should be used (Riveiro et al., 2012).

### 2.5.1 Photogrammetry Data Collection and Processing

Photogrammetry involves identifying key points in images using key point detection algorithms (e.g., Scale Interval Feature Transform (SIFT)) (Puri and Turkan, 2020). Scaling and orientation of the point cloud can be done after the SFM technique by entering known ground control point data into the pixels of different images (Morgan and Brogan, 2016). Figure 2.14 displays the features matched between two images. The SFM technique is then used directly after feature matching (Robineau, A., 2020).

**Figure 2.14.** Feature matching between 2D images using SIFT descriptors

The workflow for creating dense point clouds using photogrammetry can be summarized as four simple steps (Pepe et al., 2019):

1. Acquire the set of images.
2. Align photos by detecting key points (features).
3. Generate a sparse point cloud using SFM technique.
4. Generate a dense point cloud using MVS algorithm.

Targets can be used if the scanned objects lacked distinguishable features (e.g., sharp edges, discoloration, bolts) (Popescu et al., 2019). After generating scaled photogrammetric point clouds, the unification of different point clouds into one coordinate system is done similarly to that of the LiDAR point clouds (coarse and fine registration). It is worth noting that some LiDAR scanners require specific software, while the software used with photogrammetry are either cheap or opensource (Cross et al., 2020). Combining aerial and terrestrial photogrammetry can also further improve photogrammetric models (Popescu et al., 2019).

### 2.5.2 Photogrammetry Applications on Bridges

Table 2.2 below describes four photogrammetry applications already implemented on bridges.

**Table 2.2.** Photogrammetry applications on bridges (Belloni et al., 2020; Kushawa et al., 2018; Pepe et al., 2019; Riveiro et al., 2012)

| Application/Description | Comments |
|---|---|
| Photogrammetry and deep learning for monitoring cracks:<br><br>- Combining photogrammetry and deep learning algorithms for automatic crack detection and measurement. | - The developed algorithm computes the changes in cracks over time by comparing images captured at different times.<br>- Most errors were a false positive resulting from the algorithm classifying wires and cables as cracks.<br>- Risk assessment for different types of cracks was done through numerical simulations based on Finite Element Method. |
| Bridge 3D modelling for structural analysis:<br><br>- Generation of 3D models based on terrestrial and aerial photogrammetric techniques to be used in qualitative and quantitative analysis. | - Qualitative analysis was done by mere visual inspections of the point clouds.<br>- Quantitative analysis was done by inserting the structural elements into a Finite Element Method software.<br>- Objects that were covered by vegetation were reconstructed in Rhino before being inserted into the structural analysis software. |
| Bridge vertical clearance measurement during bridge inspections:<br><br>- Measuring the vertical clearance during routine bridge inspections using a MATLAB algorithm.<br>- Estimation of beam curve mathematical expression based on 3D curve fitting. | - Prior to data collection, the intrinsic values of the camera were obtained (lens distortion parameters) and camera stations were identified.<br>- A reference measurement was taken to be used to scale the generated point cloud.<br>- Overlap and framing requirements were considered.<br>- Ideal monitoring beam shape periodically. |
| Bridge deck deformation and thickness measurements:<br><br>- Combining terrestrial laser scans with photogrammetric point clouds to:<br>- Measure bridge deck deformation based on traffic loads.<br>- Validate deck thickness measurement to be used for construction and maintenance purposes. | - Bridge deck thickness measurement can be used to monitor the construction of the bridge deck or a new deck layer.<br>- Photogrammetry and LiDAR generated point clouds were both processed then merged to produce a dense point cloud which was used for 3D documentation, and deck thickness and deflection measurements. |

## 2.6 Gaps in Knowledge

The literature indicates that bridge deck drainage systems can be challenging to maintain. With that in mind, improper performance of bridge deck drains will mainly decrease the safety of the users on the bridge as well as increase the bridge maintenance costs due to accumulated water damage in the superstructure and substructure of the bridge. Although it is undeniable that bridge deck drains are not in good condition, no formal study was conducted to understand the true extent of bridge deck drains' problems. A study is needed to evaluate past failures and provide guidance for inspecting bridge deck drains and recognizing common problems accompanied with bridge deck drains.

Optical sensors (e.g., camera, LiDAR, IR) have been used in many civil engineering and construction (horizontal and vertical construction) projects. Many State Departments of Transportation (DOTs) carry out the inspection of their bridges using optical sensors mounted on a UAV (e.g., Minnesota, Utah, North Carolina). However, bridge deck drains are often overlooked, and no formal approach was developed for using optical sensors for inspecting bridge deck drains.

# CHAPTER III: METHODOLOGY

This research has two goals to bridge the gaps in knowledge stated in the previous chapter. The first goal is to understand and grasp the extent of bridge deck drains' problems, which can be accomplished by creating and distributing structured surveys that address the problems, designs, construction, and maintenance and inspection of bridge deck drainage systems.

The second goal is to develop formal approaches for inspecting bridge deck drains using two different systems:

1. Terrestrial Laser Scanning (TLS).
2. Camera (Photogrammetry).

By the end of this research, the performance of the two systems for the inspection of bridge deck drains will be assessed and compared in order to recommend the most suitable system for inspecting deck drains.

## Task 1 – Structured Surveys

Two survey questionnaires were developed (Texas and out-of-state surveys) based on the literature review of current problems related to bridge deck drains, as well as their design, construction, and maintenance practices. Most questions included a set of predefined answers to assist in making the surveys brief and concise. Questions containing predefined answers also allowed participants to provide unique answers and additional details separately. Two draft surveys were submitted to the review panel selected by the Texas Department of Transportation's (TxDOT) Research and Technology Implementation Division (RTI). Based on the received feedback, the two surveys were finalized and made ready for distribution. The surveys were structured to present a description of bridge deck drains after a participant fills out their contact information. The Texas and the out-of-state surveys included 25 and 29 questions, respectively, organized into the five sections below:

A. Contact information (5 questions);
B. Bridge deck drain failure (3 questions)
    1. Frequency of bridge deck drain caused floods
    2. Duration of bridge deck drain caused floods
    3. Bridge deck drain problems;
C. Bridge deck drain design (6-10 questions)
    1. Reasons for choosing closed deck drains
    2. Reasons for choosing hung closed systems
    3. Reasons for choosing embedded closed systems
    4. Preference for type of closed system
    5. Drainpipe material (out-of-state)
    6. Reasons for choosing specific materials for drainpipes (out-of-state)
    7. Problems observed with different drainpipes (out-of-state)
    8. Components prioritization for design improvements
    9. General design recommendations
    10. Existing innovative designs (out-of-state)
D. Bridge deck drain construction (2 questions)
    1. Bad construction practices
    2. Drain installation recommendations;
E. Bridge deck drain maintenance and inspection (9 questions)
    1. Bridge deck drain maintenance agency
    2. End location of bridge runoff
    3. Types of bridge deck drain inspections
    4. Inventory data collection
    5. Maintenance approach
    6. Criteria involving method and schedule of maintenance
    7. Methods used for determining remainder service life
    8. Service life recommendations
    9. Maintenance equipment

Before distributing the surveys, the contents and protocols of the surveys were approved by the University of Texas at Arlington's (UTA) Institutional Review Board (IRB). The questionnaires were distributed through the online platform 'QuestionPro' (https://www.questionpro.com/). The research team distributed the Texas survey among TxDOT personnel across all 25 TxDOT districts. The out-of-state survey was sent to members from different Transportation Research Board (TRB) committees and select staff of state DOTs across the United States.

Finally, based on the results, the direct and indirect causes of bridge deck drain problems were identified. Task 2 involves the use of optical sensors to inspect deck drains to identify certain problems in a timely manner, thus improving bridge safety and lowering maintenance costs.

### Task 2 – Modeling Formal Processes for Inspecting Bridge Deck Drains Using LiDAR and Photogrammetry

The process of inspecting bridge deck drains using optical sensors requires a team comprising different skills (e.g., survey engineer, bridge engineer, software engineer). Therefore, it is ideal to design flowchart diagrams that clearly present all the activities that take place, the relationships between them, as well as the person responsible for each activity.

The Integrated DEFinition (IDEF) methodology is made up of different methods that are capable of modeling enterprises and their business areas (Hanrahan, 2022). The IDEF family of methods allows modelers to capture organizations' operations and information architecture, which are considered to be the foundation for process reengineering and improvement (Hanrahan, 2022).

### IDEFØ Method

The IDEFØ method can be used to model an organization's decisions and activities, hence this method is considered to be one of the first tasks when developing a system (IDEF, 2022). The IDEFØ is a type of flowchart diagram used to model the processes of an organization for better understanding and future improvements (Microsoft, 2022). Each process in a diagram can be further deconstructed into subprocesses that reveal more details until the required level of detail is reached (IDEF, 2022; Syque, 2022).

IDEFØ diagrams only contain one type of box that represents an activity, process, or function as shown in Figure 3.1 (Syque, 2022). But what makes the method unique are the different uses of arrows entering and exiting the boxes (Syque, 2022). The modeler has the freedom to portray a view of the processes and the inputs, outputs, controls, and mechanisms (ICOMs) that act on these processes (Hanrahan, 2022).

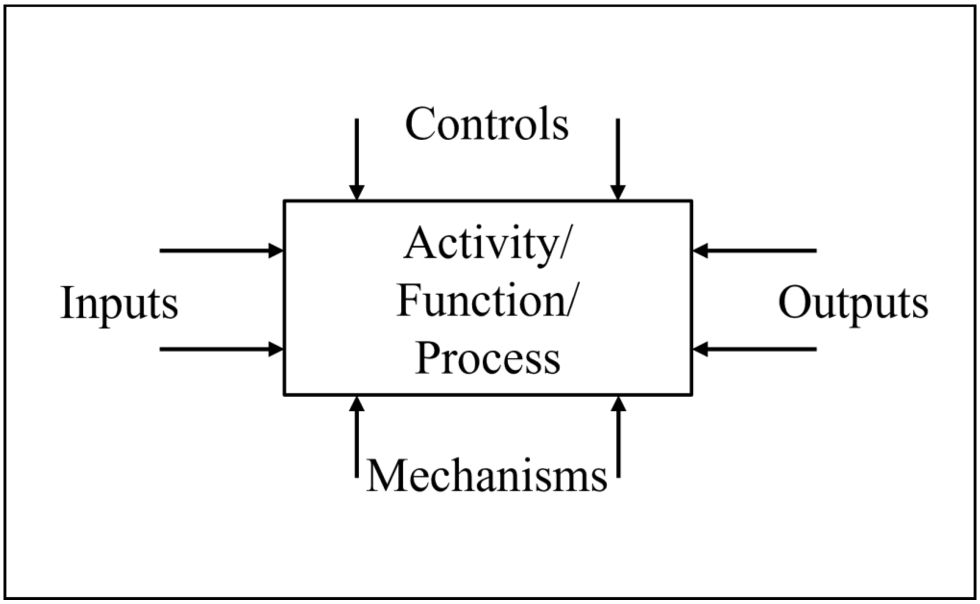


**Figure 3.1.** Basic IDEFØ syntax (Modified from IDEF, 2022).

Controls may be considered a type of input; they constrain and drive the different activities in a system (Syque, 2022). Mechanisms are considered the tools and resources necessary to complete the process of a model (e.g., machines, software) (Syque, 2022). It is not uncommon to classify a control as an input, therefore it is important to remember that inputs are the parts that will be transformed to outputs (Syque, 2022).

Although the purpose of IDEFØ models is to describe the activation of activities rather than their sequences (Hanrahan, 2022), it is easy to incorporate the sequences of activities into the model

(IDEF, 2022). Because of that, the reader might still interpret a non-sequential model as a sequence of activities (IDEF, 2022).

**IDEFØ Model Components**

A typical IDEFØ model is made up of 3 types of diagrams: a context diagram, parent/child diagrams, and a node tree (Microsoft, 2022). The modeler can also add a 'Glossary' section to the model to describe the model in more detail (Syque, 2022). The glossary section contains the definitions of the inputs, controls, outputs, and mechanisms (ICOMS) (Al-Tamimi, A., 2022).

The topmost diagram in an IDEFØ model is called the 'context diagram' (Microsoft, 2022). The context diagram is also referred to as the A-0 (A minus zero) diagram (Syque, 2022). Context diagrams only contain a single box bonded by ICOM arrows (Al-Tamimi, A., 2022). The purpose and viewpoint of a model is also included in the context diagram to set the overall context and scope of the model (Al-Tamimi, A., 2022; Syque, 2022).

Single processes in parent IDEFØ diagrams can be decomposed into subprocesses and modeled in a child diagram (Al-Tamimi, A., 2022). Child (decomposed) diagrams are also referred to as constraint diagrams (UNICOMSI, 2022). Decomposing a single process into subprocesses establishes the parent/child relationship, where the first diagram would be considered the 'parent' diagram to the decomposed diagram (child diagram) (Al-Tamimi, A., 2022).

The decomposition of an entire IDEFØ model can be presented in a single node tree diagram (Microsoft, 2022). Node trees illustrate the hierarchical relationships between functions nested in a parent/child diagram (UNICOMSI, 2022). Node trees are useful for indexing from the hierarchical structure of the diagrams (IDEF, 2022).

# CHAPTER IV: SURVEY RESULTS

This chapter contains the relevant results and the statistical analysis of responses from the two distributed surveys. The out-of-state survey had four questions in addition to the questions presented in both surveys. The purposes of the additional questions were to investigate the different materials used for bridge deck drainpipes and to capture any innovative bridge drainage designs across the United States. The questionnaires and detailed results can be found in Appendices A, B, and C at the end of this document. They can also be found in the TxDOT report 0-7092-1.

## 4.1 Survey Responses

The survey results in this chapter are arranged to match the order of the questionnaires. The blue graphs represent the results acquired from the Texas survey. The graphs in green represent the out-of-state survey results. This section summarizes information about the locations and positions of the participants (contact information). It is worth noting that the surveys were distributed to engineering staff and scholars with knowledge and expertise related to the different aspects of bridges and bridge deck drains (design, construction, inspection, and maintenance). This is advantageous because it promotes better communication and coordination between structural and hydraulic engineers. During drain installation, coordination between structural and hydraulic engineers is crucial; not only does it ensure the compatibility of drains with the structural elements of the bridge, but coordination will also guarantee that the designed hydraulic capacity is reached as well (Young et al., 1993).

The Texas survey received forty-five responses from TxDOT staff located in 17 different TxDOT districts. The districts are Abilene, Amarillo, Atlanta, Austin, Beaumont, Bryan, Dallas, El Paso, Fort Worth, Houston, Lufkin, Odessa, Paris, Pharr, San Angelo, San Antonio, and Tyler. Figure 4.1 contains the locations and positions of the survey respondents in Texas.

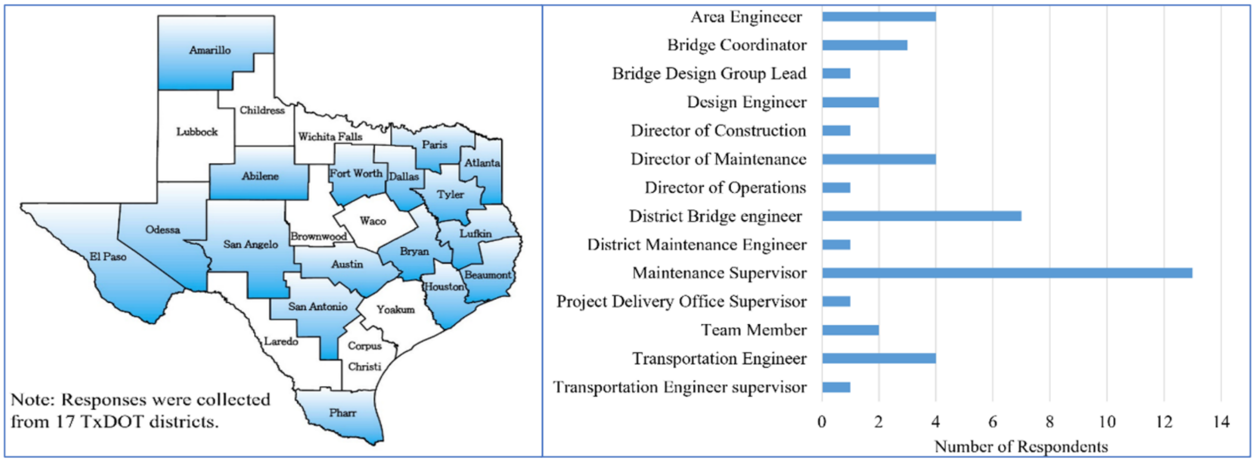


**Figure 4.1.** Texas survey responses (left) Respondents' locations (right) Respondents' positions

The out-of-state survey (Texas excluded) received thirty-four responses from 21 different states, the District of Columbia (DC), and the Quebec province in Canada. The states are Colorado, Florida, Georgia, Indiana, Kansas, Louisiana, Maine, Michigan, Nebraska, New Hampshire, New Jersey, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, Virginia, and Washington. Figure 4.2 displays the positions of the thirty-four respondents, as well as the location of the 21 states.

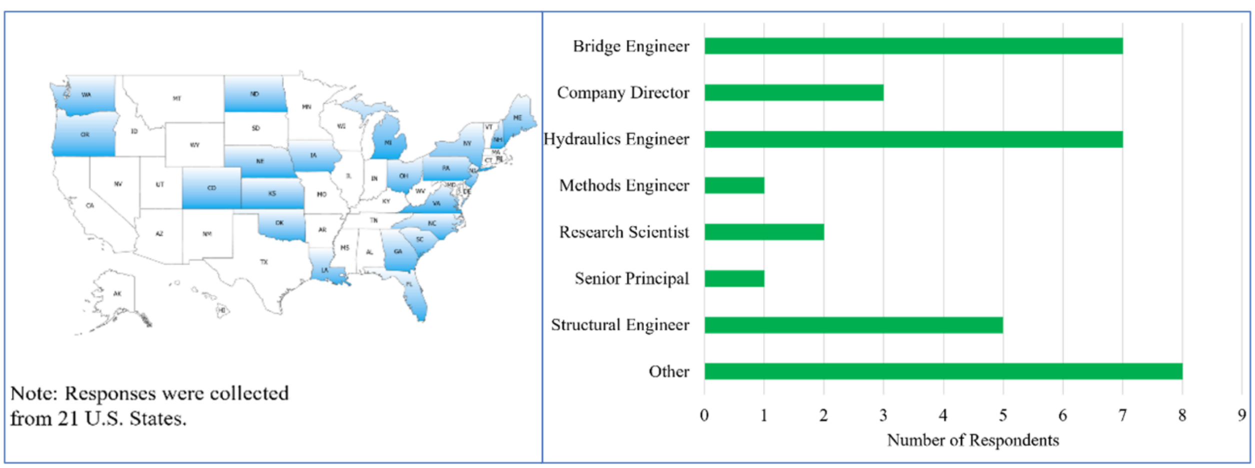


**Figure 4.2.** Out-of-state survey responses (left) U.S. States where respondents in America are located in (right) Positions of all respondents

The next section (survey results) contains the results related to the failure, design, construction, and maintenance and inspection of bridge deck drains.

### 4.2 Survey Results

A description of bridge deck drainage systems was provided after the contact information section. After reading the description, the participant was granted gradual access to the survey questions related to the failure, design, construction, and maintenance and inspection of bridge deck drains, in that order.

#### 4.2.1 Failure of Deck Drains

Identifying the common problems observed with bridge deck drains is a key first step to improving the performance of these systems. Figure 4.3 summarizes the statistical results related to the problems often found with bridge deck drains.

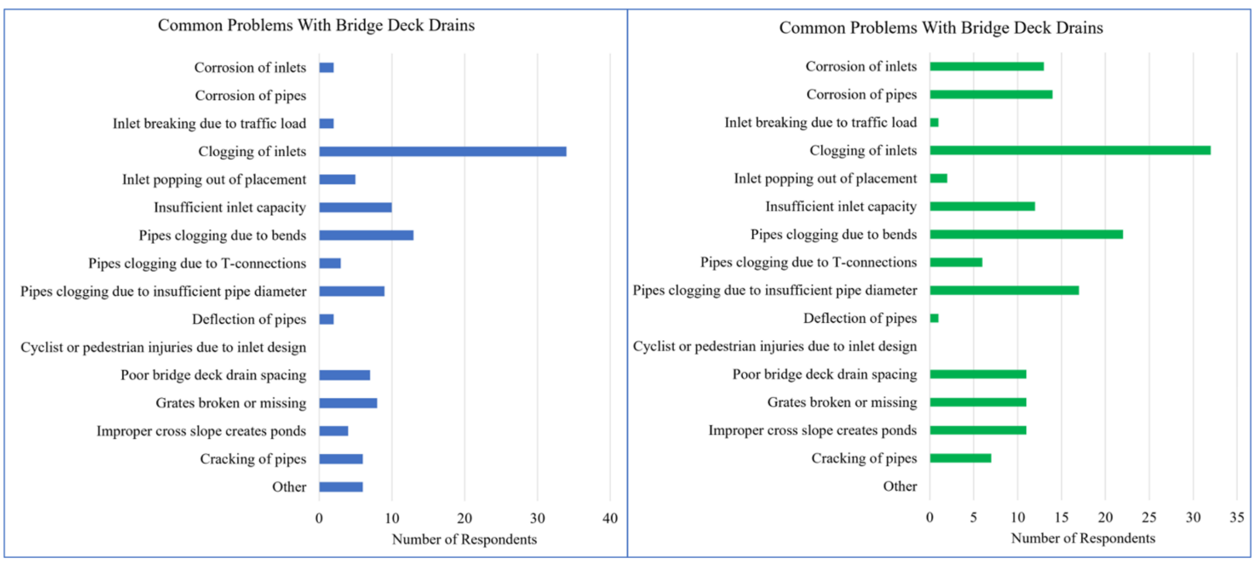


**Figure 4.3.** Common bridge deck drain problems (left) Texas (right) out-of-state

Clogging seems to be a prevalent issue with inlets and pipes in both surveys. 76% of the respondents in Texas answered with inlets clogging being the most common problem. Clogging of inlets was selected by 94% of the out-of-state participants as the most common problem, followed by clogging of pipes due to bends (64%).

A few participants from Texas identified other problems observed with bridge deck drains. These problems include the corrosion of pipe hanger connections, the overlaying of inlets by asphalt, and insufficient outlet capacity.

### 4.2.2 Design of Deck Drains

The participants were asked to prioritize different bridge deck drain components according to each component's need for design improvements. Figure 4.4 displays the results collected from the Texas and out-of-state surveys.

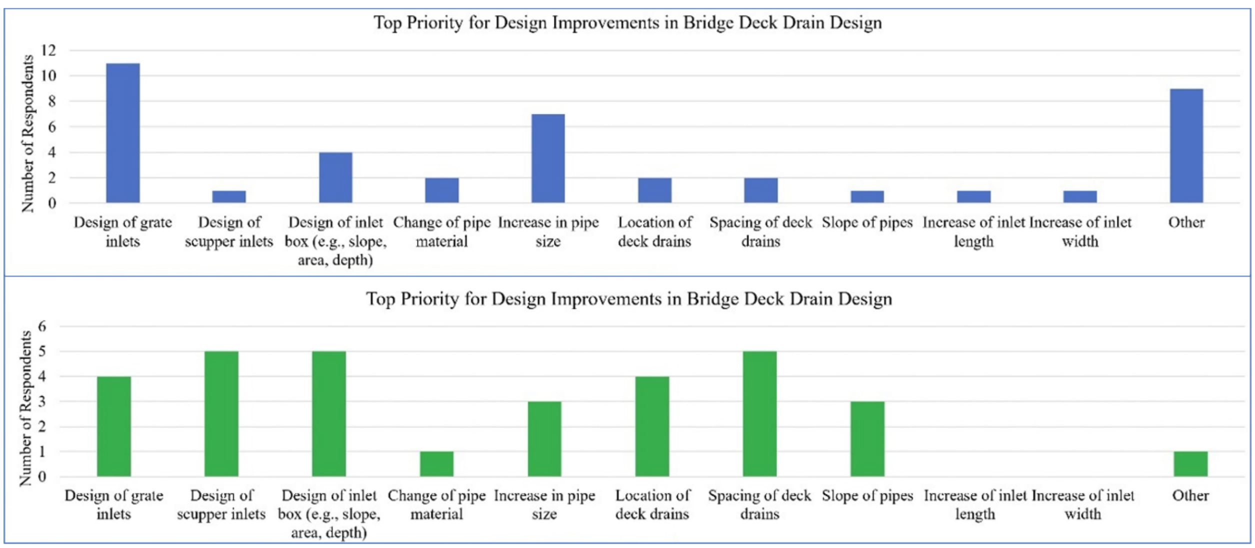


**Figure 4.4.** Priorities for improving the design of different bridge deck drain components (top) Texas (bottom) out-of-state

The clogging issue discussed in the failure section can be reflected in the figure above (Figure 4.4). The majority of the respondents from Texas have prioritized improving the design of grate inlets and increasing pipe sizes. It is in the author's opinion that the Texas participants that selected "Design of grate inlets" have encompassed scupper inlets in their answer as well. That is because of the TxDOT developed rectangular deck drain. The design combines a rectangular inlet (scupper) with a drain pan covered by grates (Qian et al., 2013).

The out-of-state results were not so different from the Texas results; out-of-state respondents have also prioritized improving the design of inlets. However, a few respondents also emphasized the possibility of improving standard pipe slopes. Increasing the slope would ensure self-cleansing velocities are reached, which in turn would act as a preventative or delaying measure for clogging. However, the designer must keep in mind that the vertical clearance of the bridge would impose a constraint on pipe slope values.

Other priorities were identified from the Texas survey. These priorities included standardizing the design of bridge deck drains and improving the connections between the pipes and the structure to prevent future pipe settlements. One out-of-state respondent has also recommended the elimination of bridge deck drains in the US, adding that bridge deck drains are underperforming because they can only handle smaller runoff events than the events they were designed for.

### 4.2.3 Maintenance and Inspection of Deck Drains

Properly functioning bridge drains promote safety and prolong a bridge’s service life, yet it was not clear how state agencies were conducting their inspection and maintenance practices on bridge deck drains. This section sheds light on how deck drains are maintained in Texas and other states after installation. Figure 4.5 contains the results obtained from the respondents when asked about the types of inspections their agency conducts on bridge deck drains.

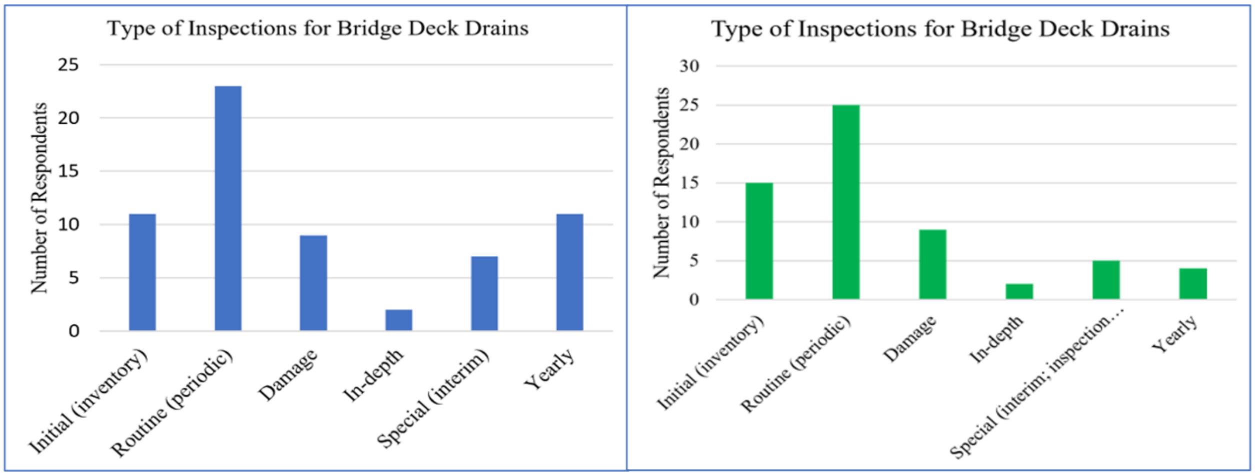


**Figure 4.5.** Types of inspections conducted on bridge deck drains (left) Texas (right) out-of-state

Results received from both surveys indicate that after conducting an inventory inspection, the majority of deck drains only go through routine inspections (every 24 months). Although in-depth and special inspections are not typically associated with bridge deck drains, they could be found suitable.

After asking about the types of inspections conducted on deck drains, the surveys moved on to the maintenance aspects of deck drains. Figure 4.6 presents the responses collected from participants when asked about factors that affect the method and schedule of bridge deck drain maintenance.

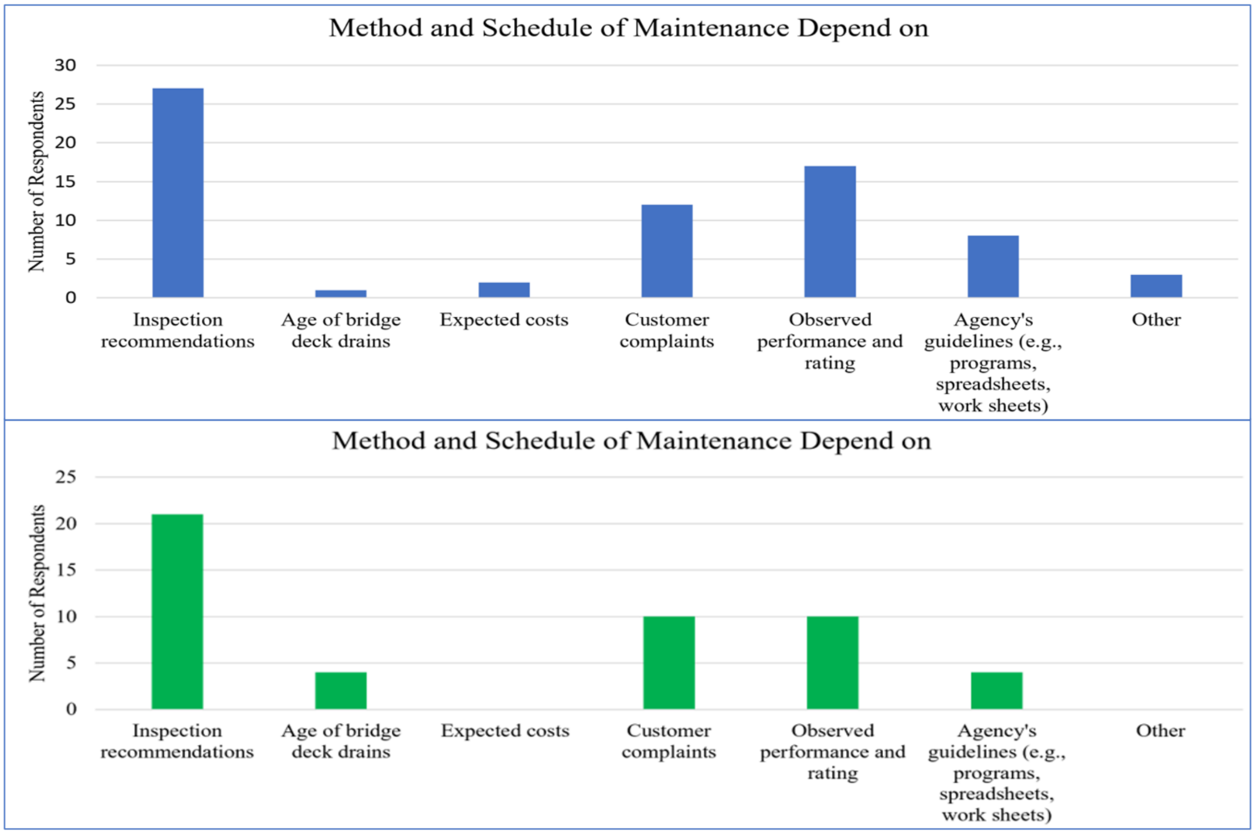


**Figure 4.6.** Factors that affect the method and schedule of maintenance (top) Texas (bottom) out-of-state

Both surveys point at "Inspection recommendations" being the dominant factor that drives the method and schedule of deck drain maintenance. It is worth noting that a respondent from Texas added that almost no maintenance operations are done on deck drains in their district. Inspection recommendations (notes) can be subjective and contain errors, as previously discussed in Chapter 2.

Figure 4.7 contains the responses collected from respondents when asked about their agency's maintenance approach for bridge deck drains.

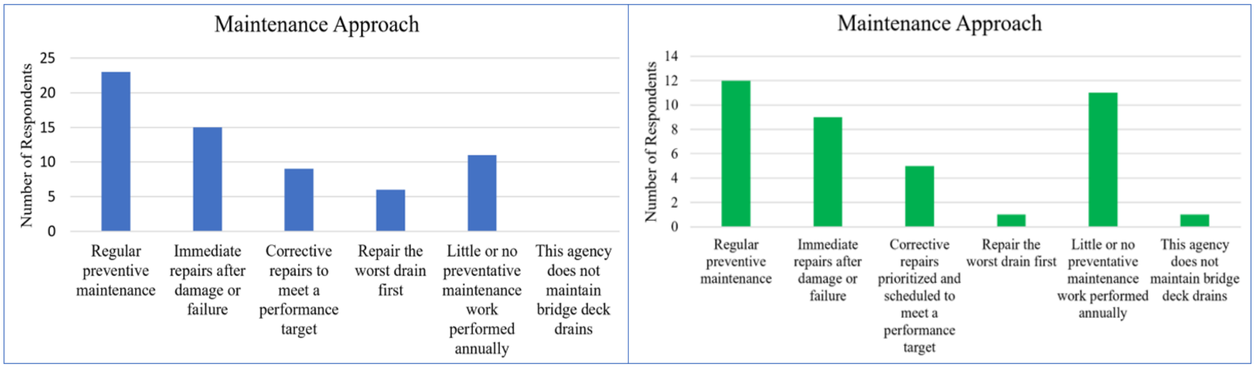


**Figure 4.7.** Maintenance approach for bridge deck drains (left) Texas (right) out-of-state

The same contradiction was observed in both surveys. "Regular preventative maintenance" and "Little or no preventative maintenance work" options were both chosen by many respondents. This may indicate poor inspections or inspection recommendations for bridge deck drains. Furthermore, the results of the following question (Figure 4.8) may be another indicator of poor inspections conducted on deck drains. Figure 4.8 contains the results obtained from participants when asked to provide recommendations for improving the service life of deck drains.

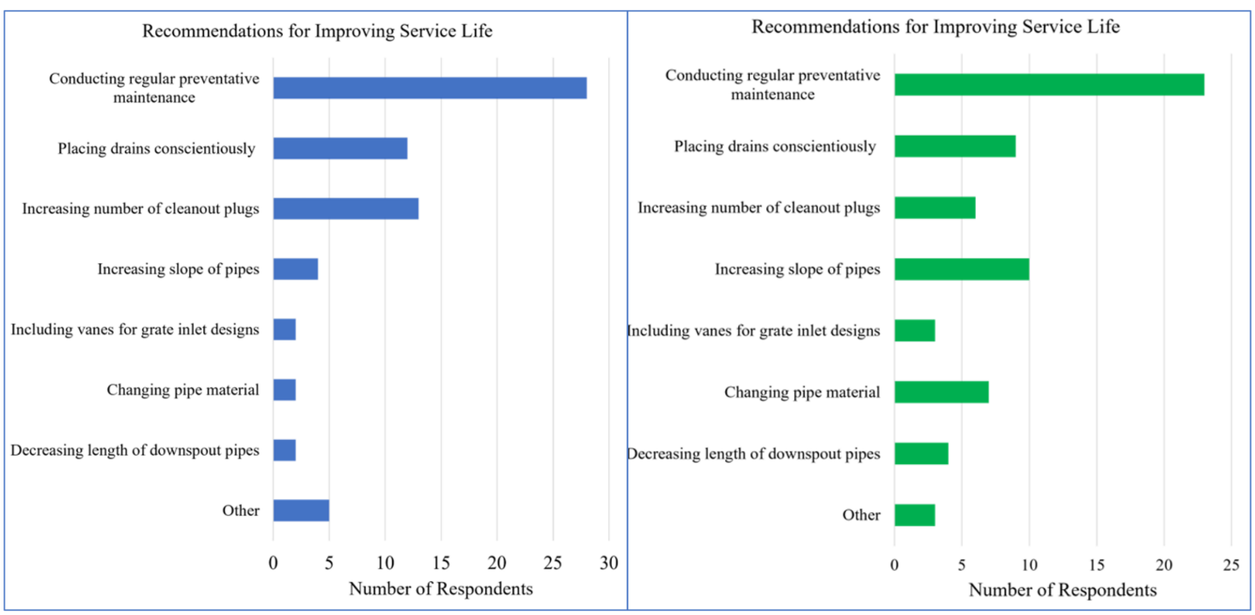


**Figure 4.8.** Recommendations for improving the service life of bridge deck drains (left) Texas (right) out-of-state

Although the method and schedule of maintenance are highly dependent on the inspector's recommendations (Figure 4.6), the number one recommendation received from the respondents was "Conducting regular preventative maintenance". This could indicate existing bridge deck drain problems that are not documented during inspections.

Finally, the participants were asked about the methods their agencies use to determine where bridge deck drains are in their service life. The results are in Figure 4.9 below.

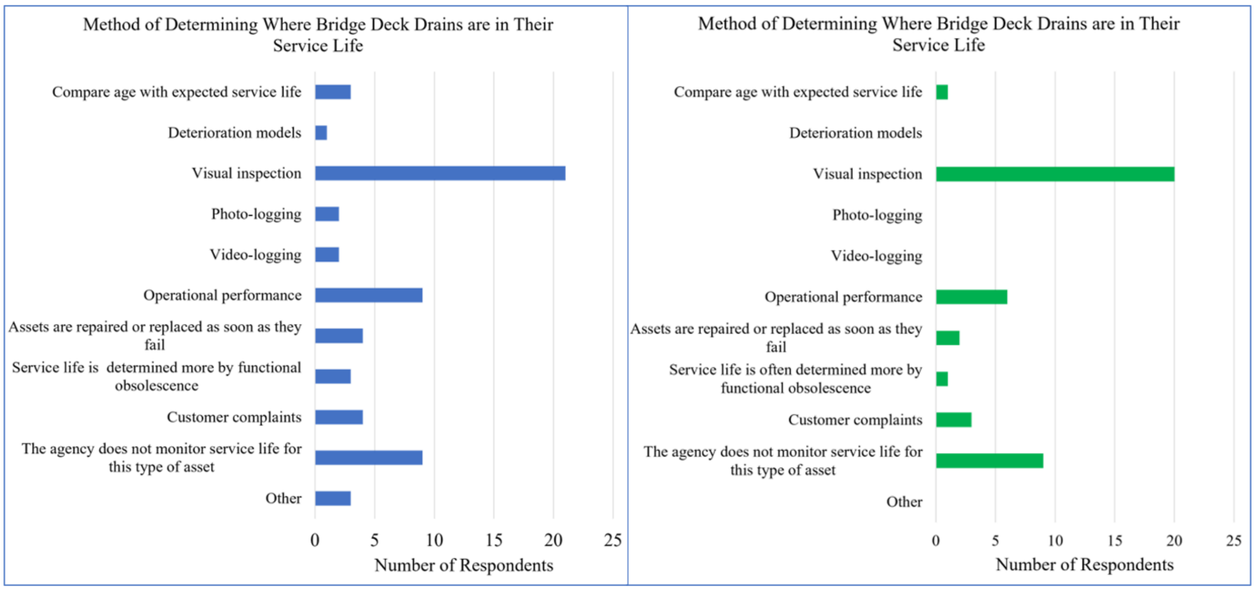


**Figure 4.9.** Methods used for determining where bridge deck drains are in their service life (left) Texas (right) out-of-state

Visual inspections were found to be the general answer in both surveys.

### 4.3 Summary

Clogging of deck drains will result in water standing on the bridge. Water standing on the bridge threatens the safety of drivers and pedestrians, and deteriorates bridge structural elements, thus increasing maintenance costs. Bridge deck drainage systems experience clogging on a much higher frequency than typical highway drains, especially in cities. This higher frequency can be attributed to the geometric nature of bridges. Bridges have flatter cross-slopes than typical highway pavement. It is also important to note that no clear zones exist on bridges, so the design spread must begin at the shoulder of the bridge. Furthermore, a closed system made up of multiple drains attached to a single horizontal piping system should be considered carefully when designing a bridge. This type of closed system can clog fast depending on the slope of the horizontal piping system. Clogging in pipes can be prevented if their slope was large enough to allow the runoff to reach self-cleaning velocities. Horizontal piping systems are typically constrained by the bridge's vertical clearance. In other words, their slope is the same as the longitudinal slope of the bridge.

Accurate and timely inspections of bridge deck drains are required to maintain driver and pedestrian safety and prolong the service life of bridges. Visual inspections are typically conducted on bridge deck drains every 24 months. Furthermore, the maintenance of deck drains is only dependent on inspection notes, but it has been established that inspection notes can be subjective at times or contain errors. It is also vital to mention that bridge ratings are not affected by bridge deck drains.

The importance of accurate bridge inspections is now greater than ever, considering that almost 10% of the bridges in the United States are considered to be structurally deficient. Using optical sensors for inspecting bridge deck drains can produce accurate, non-subjective, inspection results. Errors originating from subjective opinions and delayed inspections will be significantly reduced because the actual inspection would be conducted by a team in an office. Furthermore, optical sensors can detect defects that would otherwise be difficult to detect (e.g., newly developing stains). Sensors offer a much faster way for inspecting bridges when compared to visual inspections. The time saved because of these sensors prevents other scheduled inspections from being delayed. After sensor data processing, a team can create as-is 3D information models, with images and inspection notes attached on components that have problems.

# CHAPTER V: FORMAL REPRESENTATION OF CAMPUS ELEVATED STRUCTURE MODEL

This chapter contains six sections related to the inspection of an elevated drainage structure on UTA campus. The first section contains the devices and sensors used during data collection. The second section introduces the information requirements for developing a system for inspecting bridge deck drains. Section three introduces two IDEFØ models that represent the entire process of acquiring data using TLS and photogrammetry, all the way to having as-is models with inspection sheets and images. Each model is made up of a context diagram, parent/child diagrams, and a node tree. The fourth and fifth sections represent the processing tools used on the collected data using photogrammetry and TLS, respectively. Finally, section six illustrates the point cloud modeling process and a sheet containing element level inspection notes acquired using Autodesk Revit.

## 5.1 Devices and Sensors

The laser scanner used for this research is the ‘Livox Mid-40 LiDAR’ sensor by LivoxTech (Figure 5.1). The Mid-40 sensor can detect objects as far as 850 feet, provided that they reflect over 80% of light (LivoxTech, 2022). Darker objects require shorter distances to the sensor for laser detection to take place. For example, an object with 20% reflectivity can be detected by the Mid-40 from 425 feet away (LivoxTech, 2022).


**Figure 5.1.** Livox MID-40 laser scanner (LivoxTech, 2022)

The LiDAR sensor functions in temperatures between -4° F to 149° F and only weighs 760 grams (1.67 lb.), making the sensor suitable for most inspection operations. The sensor also provides a field of view (FOV) of 38.4° circular (Livox Tech, 2022).

The camera used for photogrammetry is the iPhone 12 Pro Max digital camera. The phone camera can capture 12 Megapixel images with 120° FOV (Apple, 2022). The portrait mode in the camera application offers an important advantage. This mode allows the photographer to control the depth of field by adjusting the aperture size (f-stop). The aperture size limits the amount of light (photons) reaching the internal chip of the camera. Smaller aperture sizes (higher f-stop numbers) increase the depth of field, which prevent background objects in images from being blurred.

## 5.2 Information Requirements

Requirements are a fundamental part of software systems, even if they were not made explicit during systems development (Bennaceur et al., 2019). In fact, Requirements Engineering (RE) is required at the beginning of every product development, where the set of requirements act as the basis for all subsequent development activities (Satzger et al., 2014; Jin. Z., 2017). RE is the part of software engineering that deals with developing digital world solutions for real life problems (Zave and Jackson, 1997; Jin. Z., 2017).

RE involves understanding people's needs from a computer system and knowing how to use these needs in system design (Sutcliffe and Gulliksen, 2012). All industry standards need requirements engineering (e.g., aerospace, automotive, railways), yet industry standards do not define what a requirement is (Boulanger, J., 2016). Good requirements engineering helps ensure that the developed system meets the needs of stakeholders (Hersman and Fowler, 2010). Any individual or organization that stands a gain or loss from a system being constructed is a stakeholder (Nuseibeh and Easterbrook, 2000). Requirement engineers must identify and communicate with stakeholders because they are important in acquiring unstated knowledge and hidden needs, as well as extracting system requirements (Bennaceur et al., 2019).

The requirements for developing a system for inspecting bridge deck drains vary. For example, environmental requirements may be something that needs to be considered when developing a system that uses cameras. With this consideration in mind, a software engineer may incorporate automatic pixel brightness adjustments to the system, depending on the lighting conditions during the capturing of images.

In this research, the scope of work is limited to the information requirements needed for inspecting bridge deck drains. In particularly, the problems that are found with bridge deck drain components. Table 5.1 below provides the list of information requirements needed for inspecting bridge deck drains (Brown et al., 2009; Hopwood & Courtney, 1989; Iowa DOT, 2022; SCDOT, 2006; VTRAN, 2007; and Zealand, T. N., 2001):

**Table 5.1.** Information requirements for inspecting bridge deck drains (Brown et al., 2009; Hopwood and Courtney, 1989; Iowa DOT, 2022; SCDOT, 2006; VTRAN, 2007; and Zealand, T.N., 2001).

| | | **Variable Value** | |
|---|---|---|---|
| **Component** | **Variable** | **1** | **0** |
| **Inlet** | Clogging | Inlet Clogged | Inlet Not Clogged |
| **Inlet** | Vegetation | Inlet Vegetated | Inlet Not Vegetated |
| **Inlet** | Broken Grates | Grates Broken | Grates Not Broken |
| **Inlet** | Deformed Grates | Grates Deformed | Grates Not Deformed |
| **Inlet box** | Debris Buildup | Debris Buildup | No Debris Buildup |
| **Drainpipe** | Clogging | Pipe Section Clogged | Pipe Section Not Clogged |
| **Drainpipe** | Exterior Stains | Stained Exterior | Clean Exterior |
| **Drainpipe** | Internal Stains | Stained Interior | Clean Interior |
| **Drainpipe** | Cracked Pipe | Pipe Cracked | Pipe Not Cracked |
| **Drainpipe** | Broken Pipe | Pipe Broken | Pipe Not Broken |
| **Drainpipe** | Observed Rust Stains | Rust Stains Observed | Rust Stains Not Observed |
| **Drainpipe** | Damaged Pipe Hanger | Damaged Hanger | Not Damaged Hanger |
| **Cleanout** | Absence at Bends | No Cleanout Provided | Cleanout Provided |
| **Cleanout** | Damaged Plug | Damaged Plug | Not Damaged Plug |
| **Outlet** | Clogging | Outlet Clogged | Outlet Not Clogged |
| **Outlet** | Vegetation | Outlet Vegetated | Outlet Not Vegetated |
| **Outlet** | Soil Erosion | Surface Erosion | No Surface Erosion |

Chapter six of this dissertation discusses an implementation of a binary classification neural network. The network classifies images based on one of the information requirements, in particular, broken grates.

## 5.3 Formal Processes for TLS and Photogrammetry

This section contains the two IDEFØ models for inspecting bridge deck drains using stationary LiDAR scanner (TLS) and Photogrammetry, respectively. The two models share many similarities, but they mainly differ in the data collection and processing functions.

### 5.3.1 IDEFØ Model for a TLS System

As previously mentioned, the topmost diagram in an IDEFØ model is the context diagram. The context diagram which sets the context of how bridge drains can be inspected using a TLS is presented in Figure 5.2. Most ICOMs used in the following diagrams are presented in the context diagram.

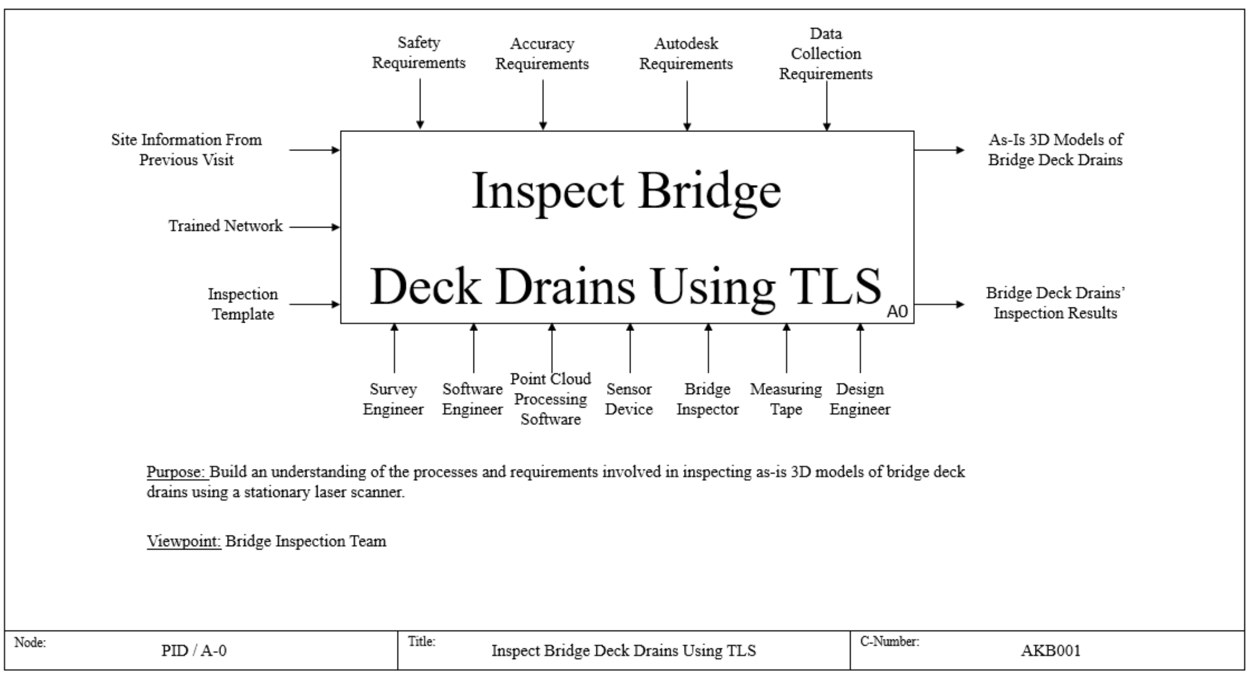


**Figure 5.2.** Context diagram for inspecting bridge deck drains using TLS

The next diagram (A0) in Figure 5.3 contains the four processes for inspecting deck drains using a TLS system. The first process (A1 – Collect Site Data) can be made more efficient if the site was previously visited and paper sketches for the locations of scanning were made. It is also preferred to take notes regarding any obstructions found on site that could negatively impact the scanning process. Having a strategy in place to deal with obstructions saves time and effort. The second process (A2 – Preprocess Collected Data) is done on the raw data collected in A1. After that, the third process (A3 – Create As-Is 3D Information Models) can take place. Finally, the drains are inspected in the fourth process (A4 – Inspect Bridge Deck Drain Models) by using a trained neural network and attaching the results to the as-is 3D model. The four processes in the A0 diagram are decomposed to a reveal the subprocesses of each one.

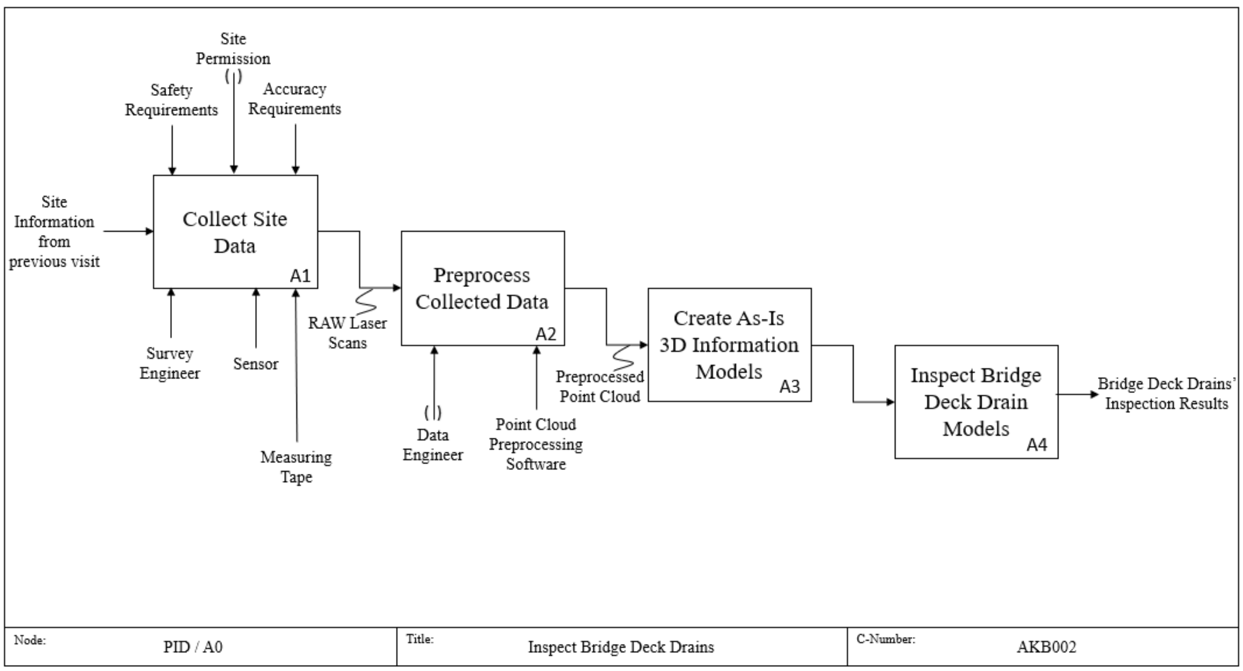


**Figure 5.3**. Parent diagram for TLS model – A0 – Bridge drains' inspection

The diagram in Figure 5.4 (A1 – Collect Site Data) contains the subprocesses for collecting data using a TLS system. Firstly, the scan locations are defined (A1-1), then the sensor could be connected to a computer (A1-2) and data collection can start (A1-3). For accuracy and validation, on-site measurements should be acquired (A1-3) to be compared with the measurements extracted from laser point clouds.

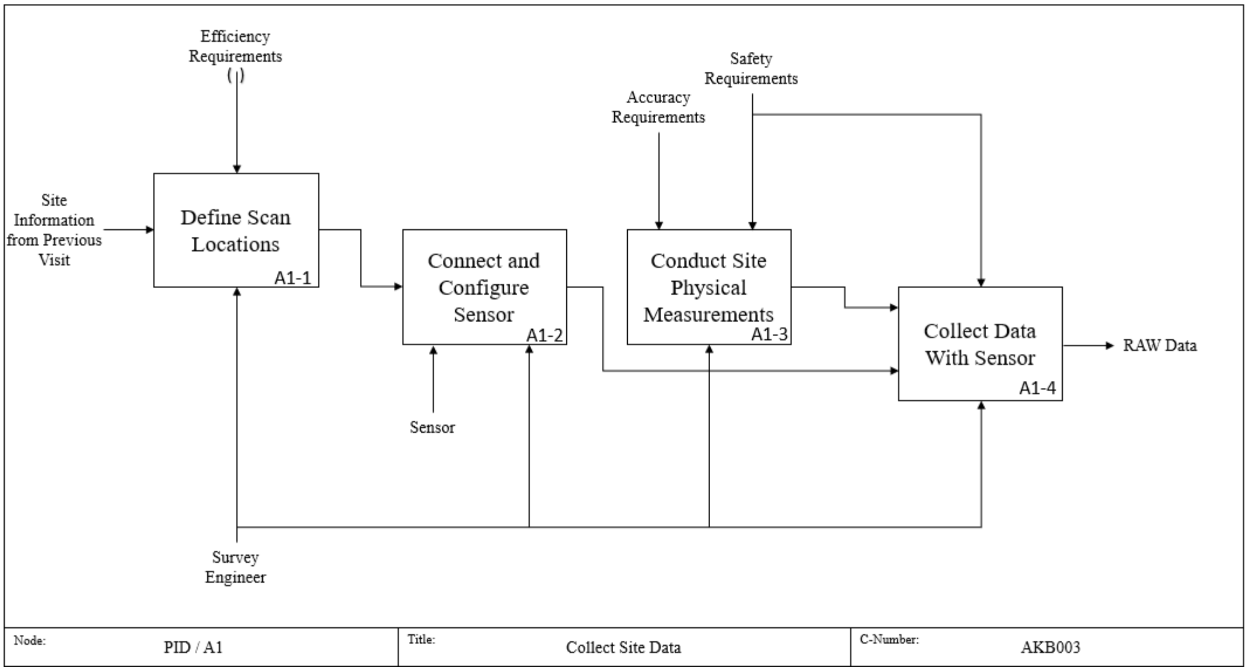


**Figure 5.4.** Child diagram for TLS model – A1 – Data collection

The point clouds acquired in A1 should be cleaned and registered to acquire a single unified point cloud representing the entire 3D scene of the scanned objects. Figure 5.5 (A2 – Preprocess Collected Data) contains the pipeline for preprocessing LiDAR point clouds. Normal estimation is done on all obtained point clouds (A2-1). Then coarse (A2-2) and fine registration using ICP algorithm (A2-3) are done on two point clouds, respectively. The two point clouds can then be merged, and the registration process is repeated with the third point cloud, and so on. Finally, after registering all the point clouds, it should be exported in PTS format (A2-4) so that it can be imported into Autodesk Recap.

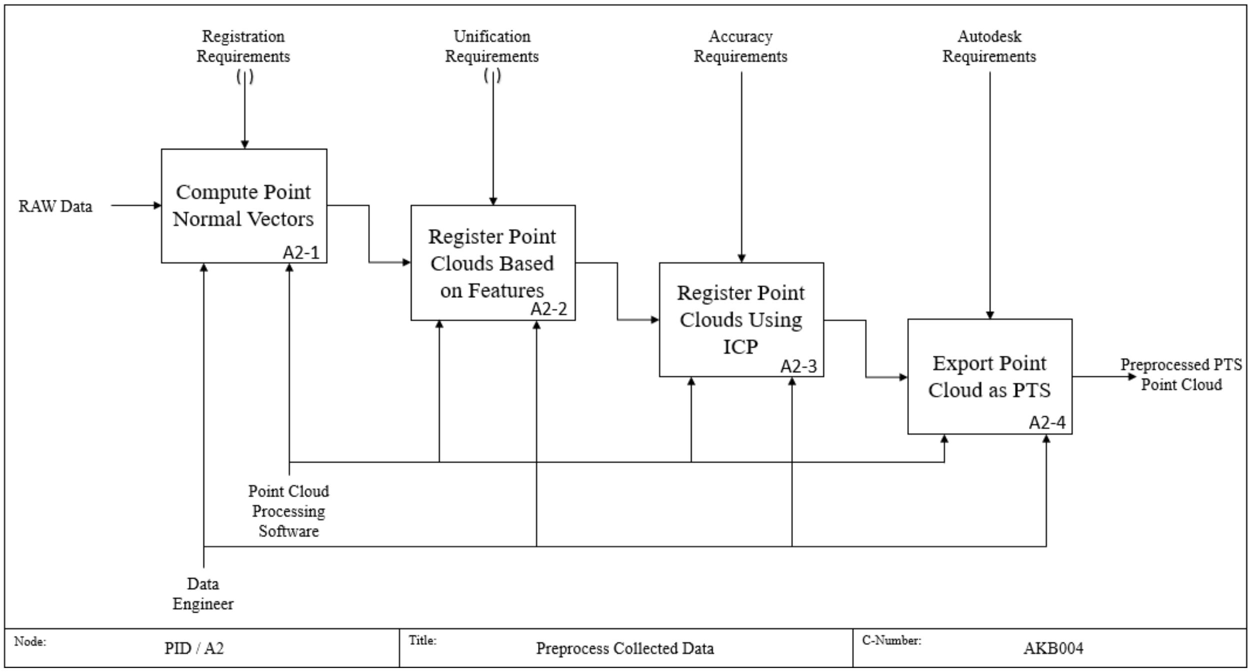


**Figure 5.5.** Child diagram for TLS model – A2 – Point cloud preprocessing

Using Autodesk Recap, the PTS point cloud file acquired from A2 is converted to RCP format (A3-1), which is the type of point cloud format that can be imported into Autodesk Revit (A3-2). The points in Revit are then modeled accurately by tracing the points that exist on planar surfaces (A3-3). Figure 5.6 (A3 – Create As-Is Information Model) contains the subprocesses mentioned for acquiring a 3D information model.

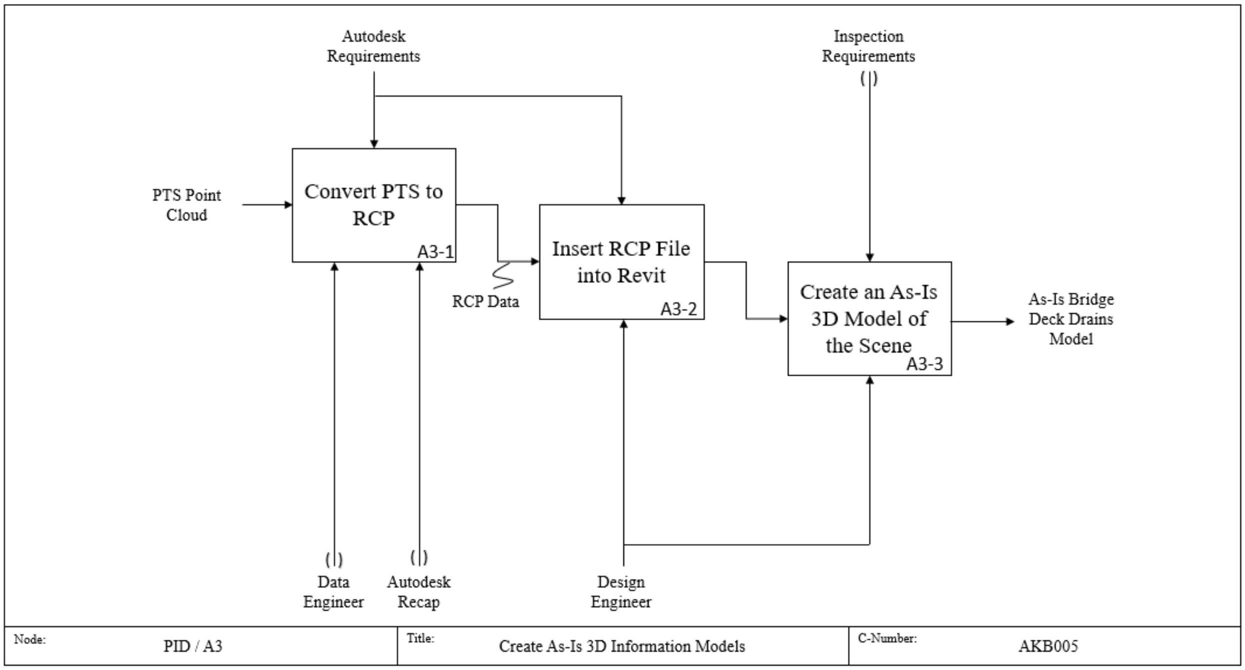


**Figure 5.6.** Child diagram for TLS model – A3 – Information modeling

The inspection process relies on acquired images of parts that need to be inspected. The images will be passed through a trained neural network for obtaining a classification report. Figure 5.7 (A4 – Inspect Bridge Deck Drain Models) illustrates the subprocesses required to acquire a classification report based on images acquired on the inspection site. The implementation of A4 is presented in Chapter 6 of this dissertation.

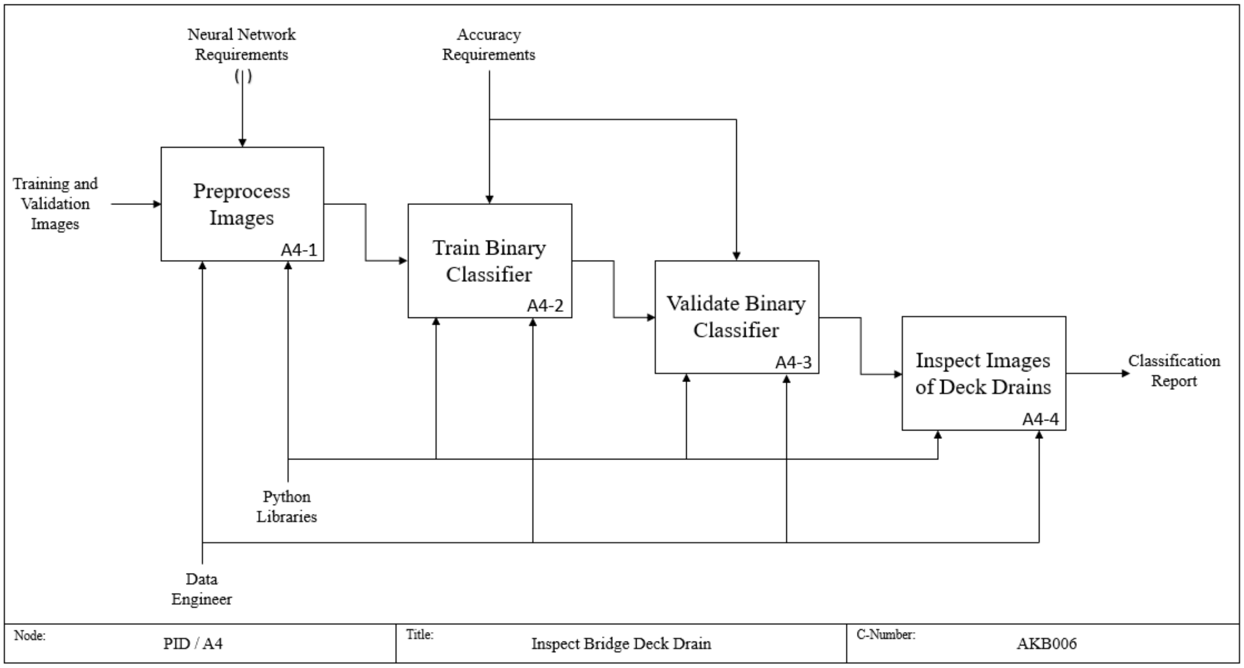


**Figure 5.7.** Child diagram for TLS model – A4 – Acquisition of inspection results

Figure 5.8 (Inspect Bridge Deck Drains Using TLS – Node Tree) displays the decomposition of the IDEFØ diagram for inspecting bridge deck drains using TLS.

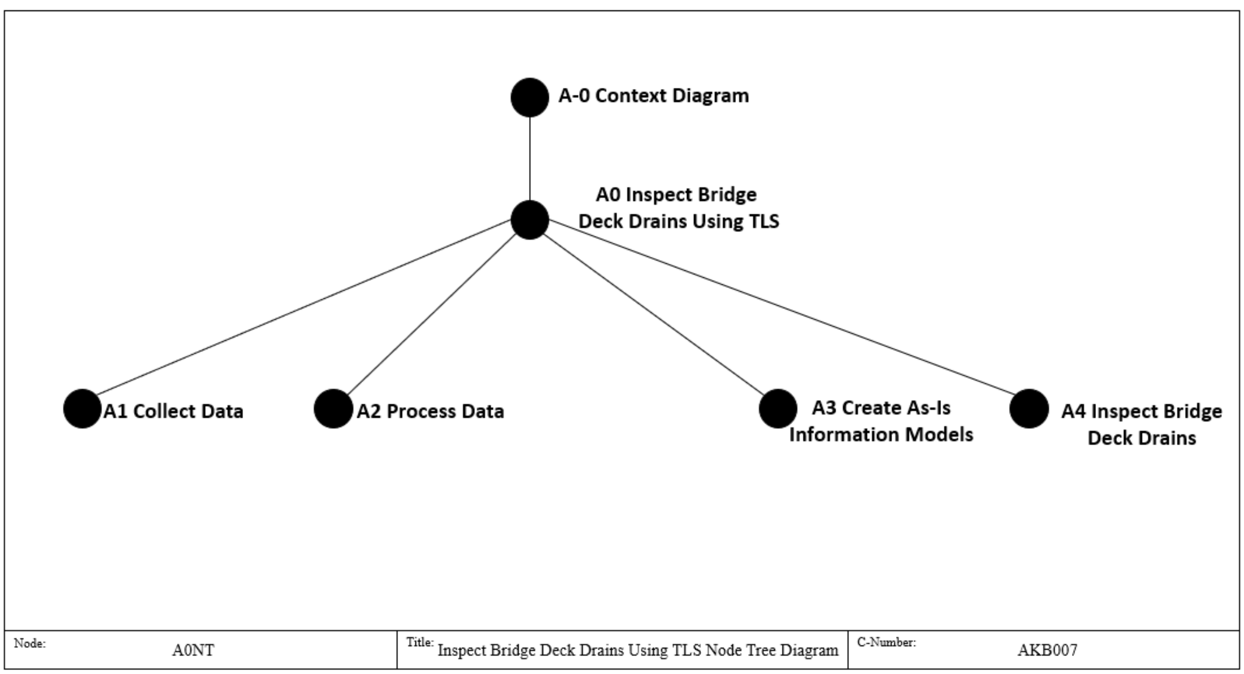


**Figure 5.8.** Node tree for TLS model – A0NT – IDEFØ diagrams

### 5.3.2 IDEFØ Model for Photogrammetry

The context diagram showing how bridge deck drains can be inspected using photogrammetry can be seen in Figure 5.9 (B-0 – Inspect Bridge Deck Drains). For photogrammetry, a camera sensor is used rather than a LiDAR sensor. The following diagrams display the processes and subprocesses involved in inspecting bridge deck drains using photogrammetry.

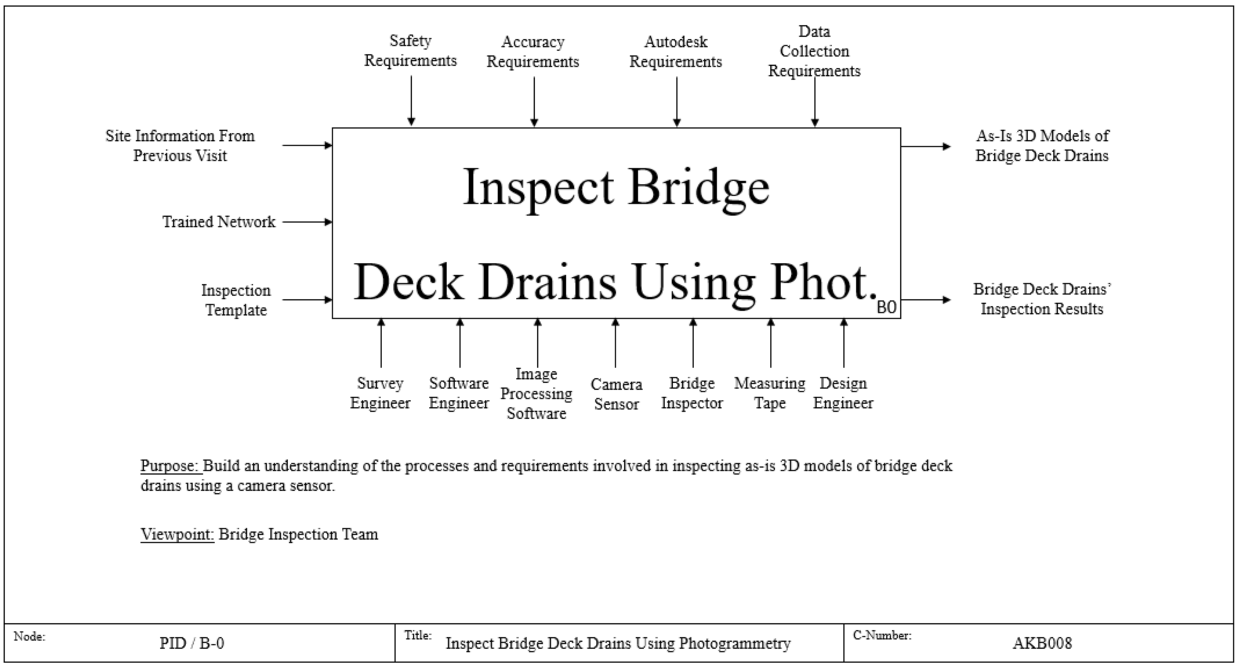


**Figure 5.9.** Context diagram for inspecting bridge deck drains using photogrammetry

Similar to using a TLS, it is highly recommended to visit the site and be sure incorporate any site obstructions within the image collection plan. Figure 5.10 (B0 – Inspect Bridge Deck Drains) contains the processes that go into inspecting bridge deck drains using photogrammetry. The first process is to collect images (B1). Images must be sequential with a high enough overlap for SFM to work. The collected images are then processed (B2) using SFM and MVS to acquire a dense non-scaled colored point cloud. The point clouds are then modeled intro Revit (B3) after converting the point cloud format to RCP. Finally, the inspection results from the neural network (B4) could be attached to the information model.

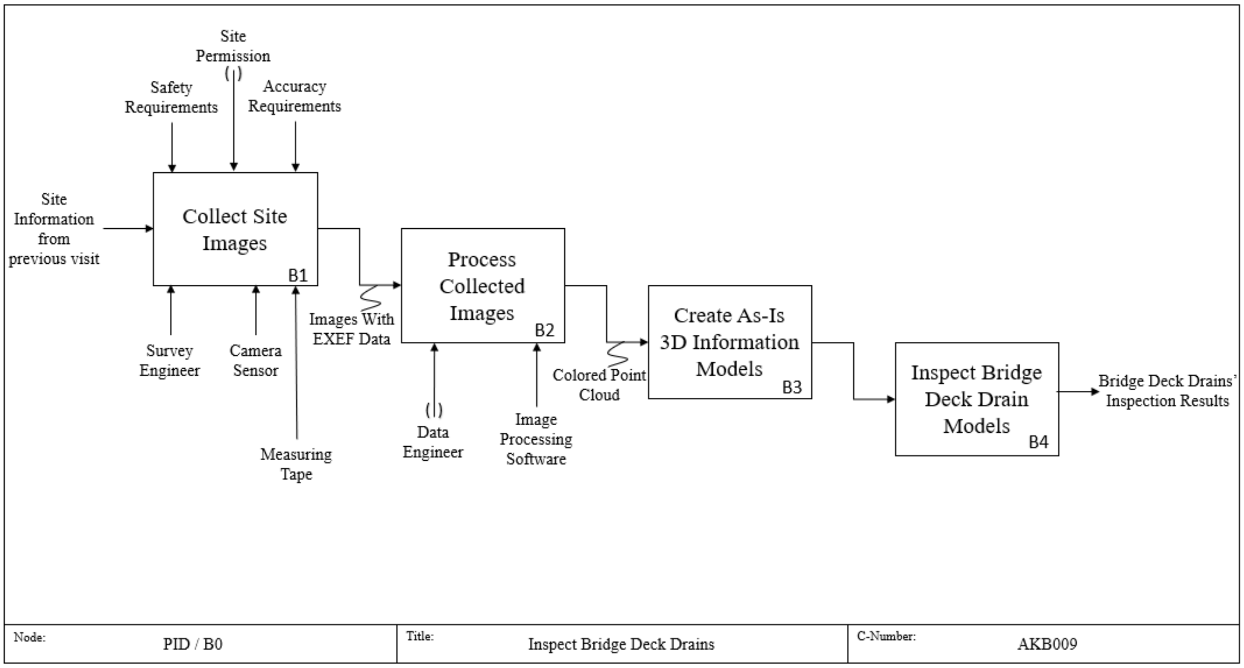


**Figure 5.10.** Parent diagram for Photogrammetry model – B0 – Bridge drains' inspection

Each process in the B0 parent diagram is decomposed below to reveal the subprocesses that make up each process. Figure 5.11 (B1 – Collect Site Images) shows the subprocesses that make up the process of collecting site images. Since it is important to have sequential images, it is important to know which route you are taking for image collection (B1-1). In other words, there may be obstructions that can be avoided if a route is planned. Images (B1-2) and site measurements (B1-3) are then acquired.

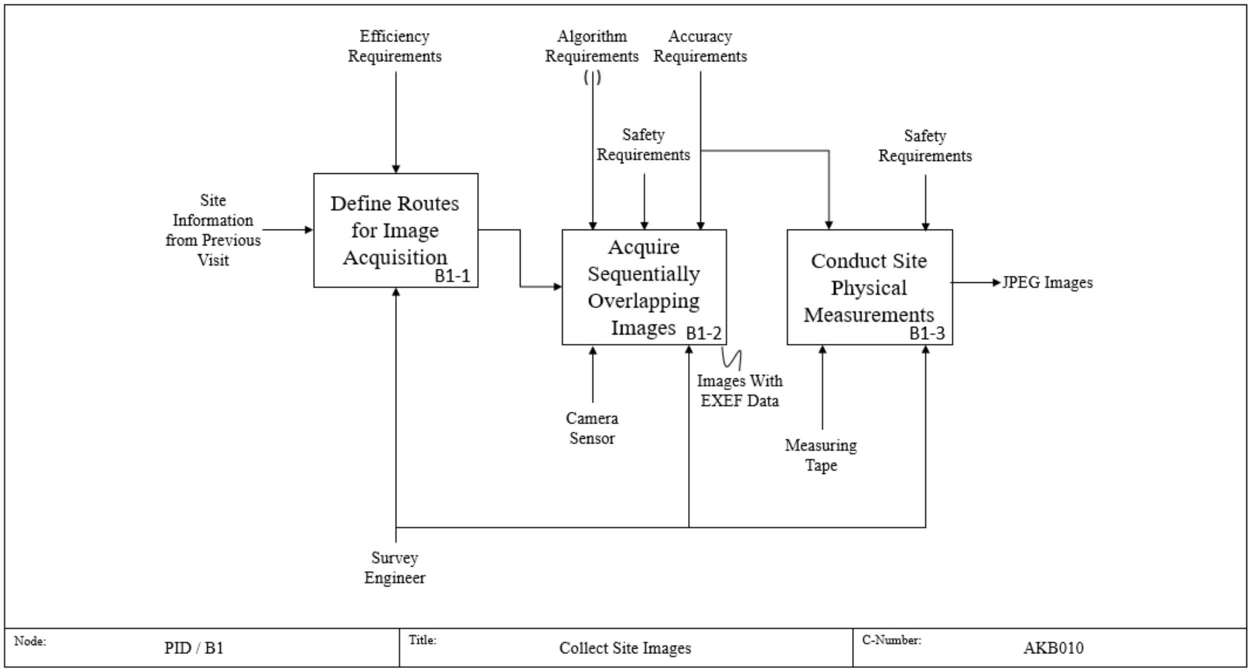


**Figure 5.11.** Child diagram for Photogrammetry model – B1 – Image collection

Figure 5.12 (B2 – Process Collected Images) contains the workflow for creating point clouds from images. Upon inserting the images into the processing software (B2-1), feature matching between images can be done (B2-2). SFM technique (B2-3) and MVS (B2-4) algorithm can be used after matching features, respectively. The output of MVS will be an unscaled point cloud. Scaling the point cloud (B2-5) can be done in multiple ways:

1. Scale based on acquired site measurements.
    a. By referencing pixels in images.
    b. By referencing the point cloud.
2. Scale by registering the colored point cloud.
    a. By registering it with a LiDAR point cloud while allowing the scale to be adjusted.

The scaled point cloud can finally be exported as PTS (B2-6) and converted through Autodesk Recap.

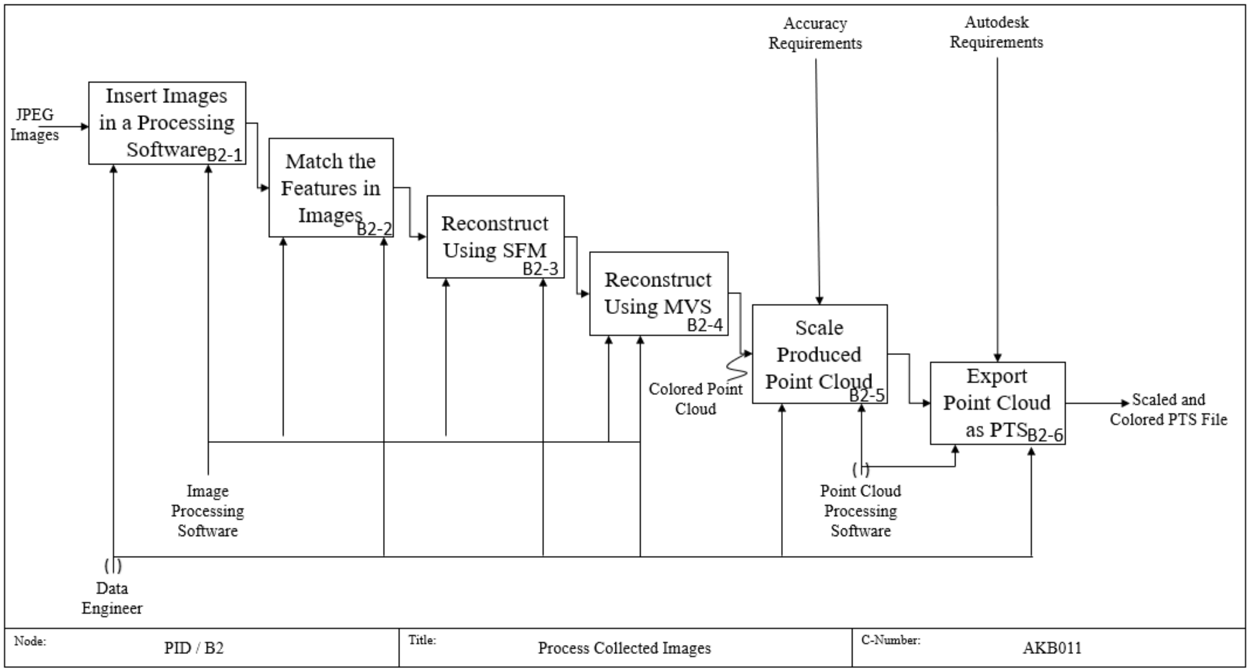


**Figure 5.12.** Child diagram for Photogrammetry model – B2 – Image processing

The acquired PTS file from B2 is inserted into Autodesk Recap to be converted to RCP (B3-1). The RCP file can be inserted in Revit (B3-2) to model the point cloud (B3-3). Figure 5.13 (B3 – Create As-Is 3D Information Model) displays the subprocesses for creating a 3D model from point clouds in Revit.

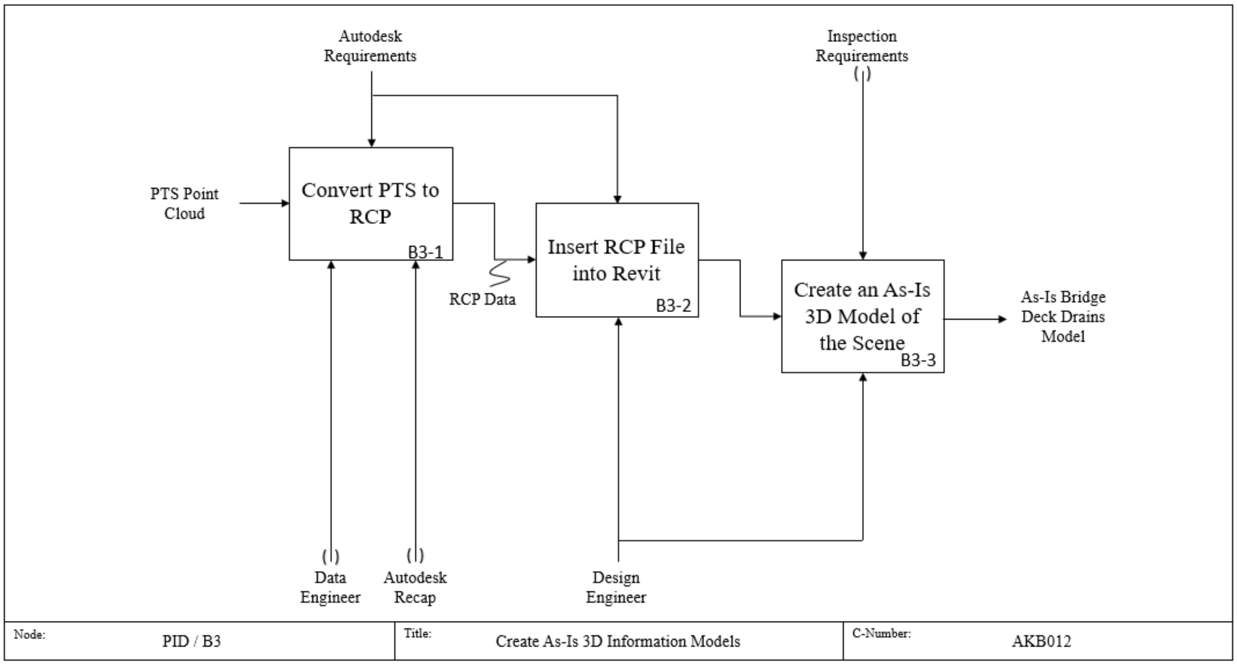


**Figure 5.13.** Child diagram for Photogrammetry model – B3 – Information modeling

The inspection process for inspecting bridge deck drains in Figure 5.14 (B4 – Inspect Bridge Deck Drains) is the same one used in A4 since they both rely on acquired images. A simple implementation of the binary classifier used for classifying the condition of grate inlets (broken vs. non-broken) can be found in Chapter 6.

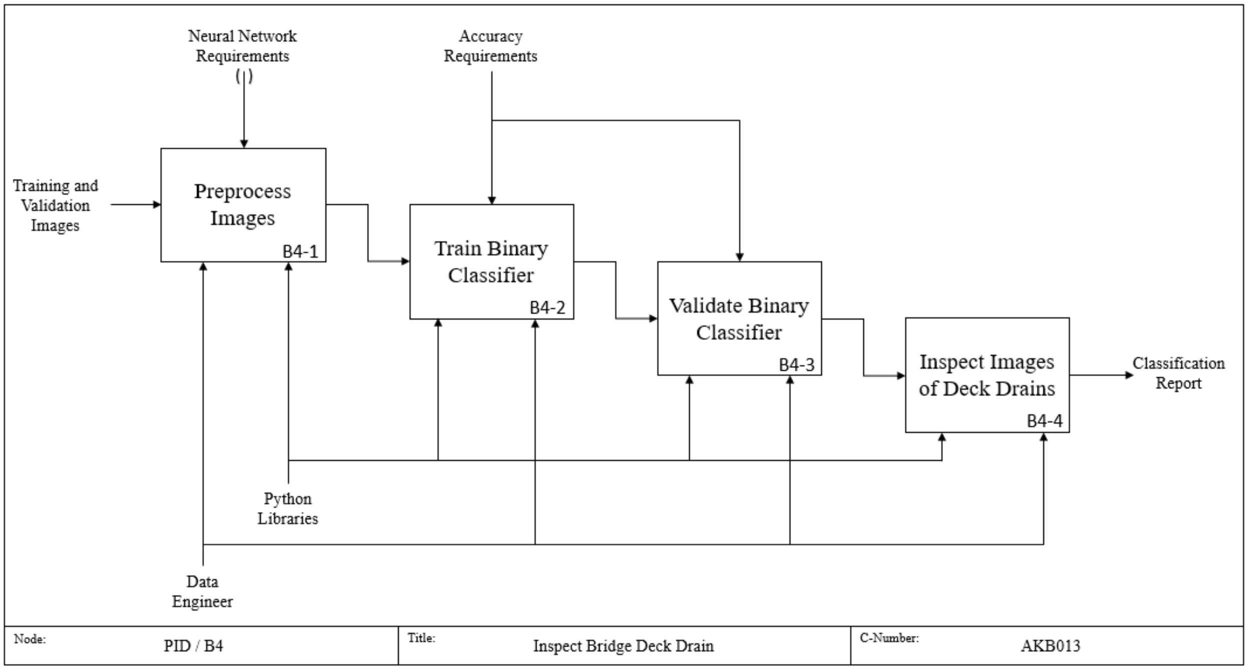


**Figure 5.14.** Child diagram for Photogrammetry model – B4 – Acquisition of inspection results

Figure 5.15 (Inspect Bridge Deck Drains Using Photogrammetry – Node Tree) displays the decomposition of the IDEFØ diagram for inspecting bridge deck drains using photogrammetry.

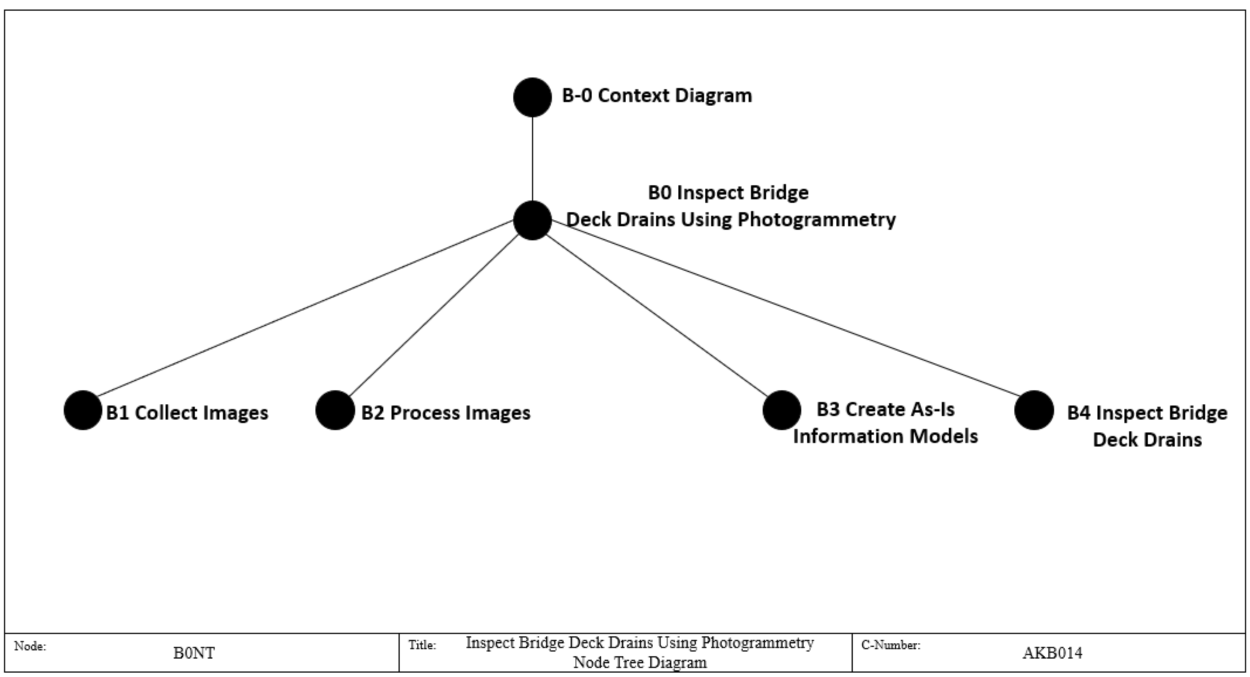


**Figure 5.15.** Node tree for Photogrammetry model – B0NT – IDEFØ diagrams

### 5.4 Photogrammetry

This section discusses image collection and processing for photogrammetry, as well as the advantages and disadvantages observed when using an iPhone camera for photogrammetry.

#### 5.4.1 Image Collection and Processing

A high-resolution depth camera would be ideal for photogrammetry applications. The capabilities of the phone's digital camera are limited compared to a professional camera. Another challenge found on the site was the large similarities and repetition in the drainage structure. To make things worse, the lack of reference points around the large structure made the reconstruction process difficult. Another disadvantage was the bright ceiling lights on site, which created a lot of noise in the point clouds. To address these challenges, multiple sets of images were taken so that the 3D scene is adequately captured. A video in 4K resolution was also collected. A python script was created to extract 4 frames per second from the video using Computer Vision's OpenCV library. A set of 583 images was extracted from the video and was used for dense reconstruction using COLMAP software. Additionally, 21 images of a circular grate inlet were taken. Figure 5.16 is a sketch that illustrates some routes taken for image collection.

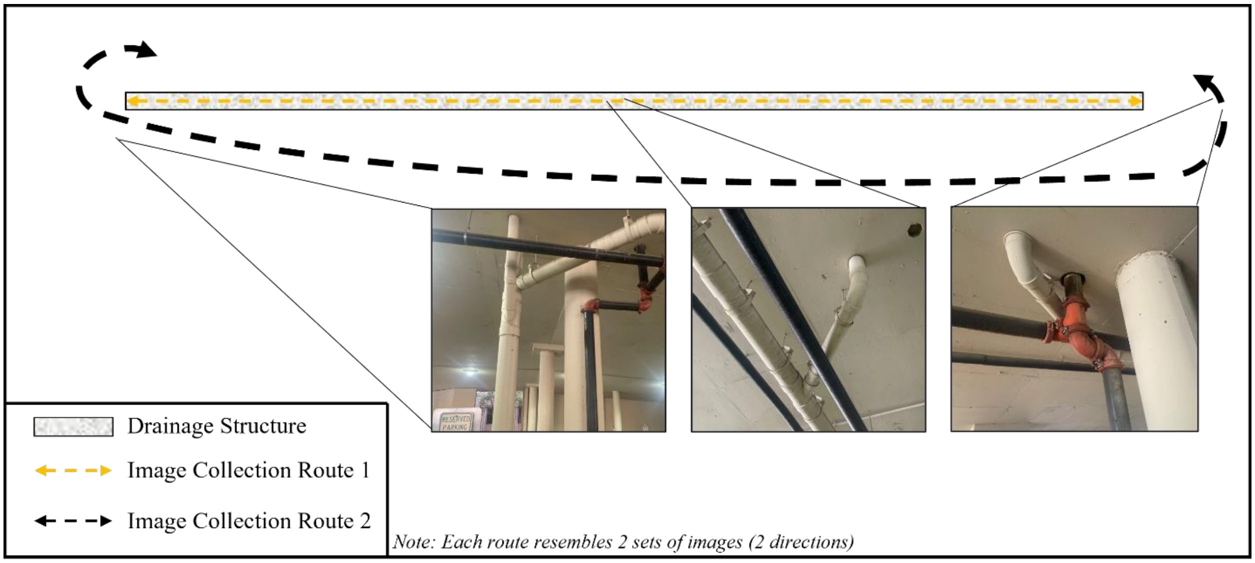


**Figure 5.16.** Sketch illustrating drainage structure image collection routes

The advantages found from using a phone camera were convenience and the fact that the EXIF data embedded in images contain the camera intrinsic parameters for automatic calibration. Additionally, iPhones have an advantage that is not found in other phones: Frames extracted from videos also contain EXIF data. The reconstructed scene was adequate to be modeled in Autodesk Revit. Figure 5.17 displays part of the reconstructed scene (point cloud) of the drains after removing most of the noise around the drains.

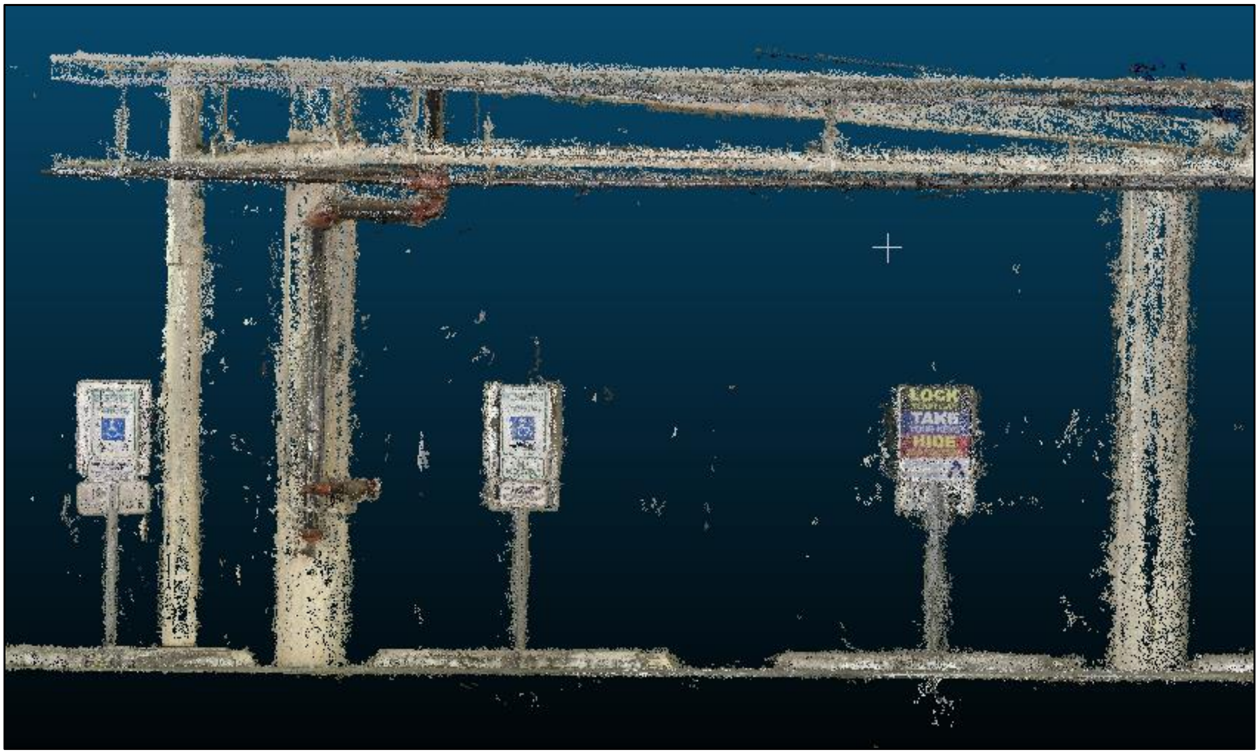


**Figure 5.17.** Unified RGB point cloud reconstructed from images and video frames

Due to similarities in drain segments, coupled with the fact that reference points were not installed prior to image collection, each set of images was divided into smaller sets for reconstruction. By using subsets, the errors produced by SFM, specifically feature matching between images, were minimized. The process was mainly trial and error in nature and chosen point clouds were finally registered for unification and filtered for noise removal (Figure 5.17). The reconstruction process in COLMAP is straightforward; after initializing the software for reconstruction, point clouds in the format of object files were outputted in the working space.

### 5.5 Terrestrial Laser Scanner

This section discusses the acquisition and processing of laser scans. It also mentions the challenges and limitations for using the MID-40 laser scanner.

### 5.5.1 TLS Data Collection

Two sets of laser scans were captured for the drains. The first set contains one laser scan of an inlet. The second set contains 54 laser scans taken from 13 locations. While one scan was captured at some locations (locations 1, 2, 3, 4, and 13), the scanner was rotated at other locations (locations 5, 6, 7, 8, 9, 10, 11, and 12) to capture multiple overlapped scans to assist in the registration process. Figure 5.18 shows a sketch of the drainage structure scan locations.

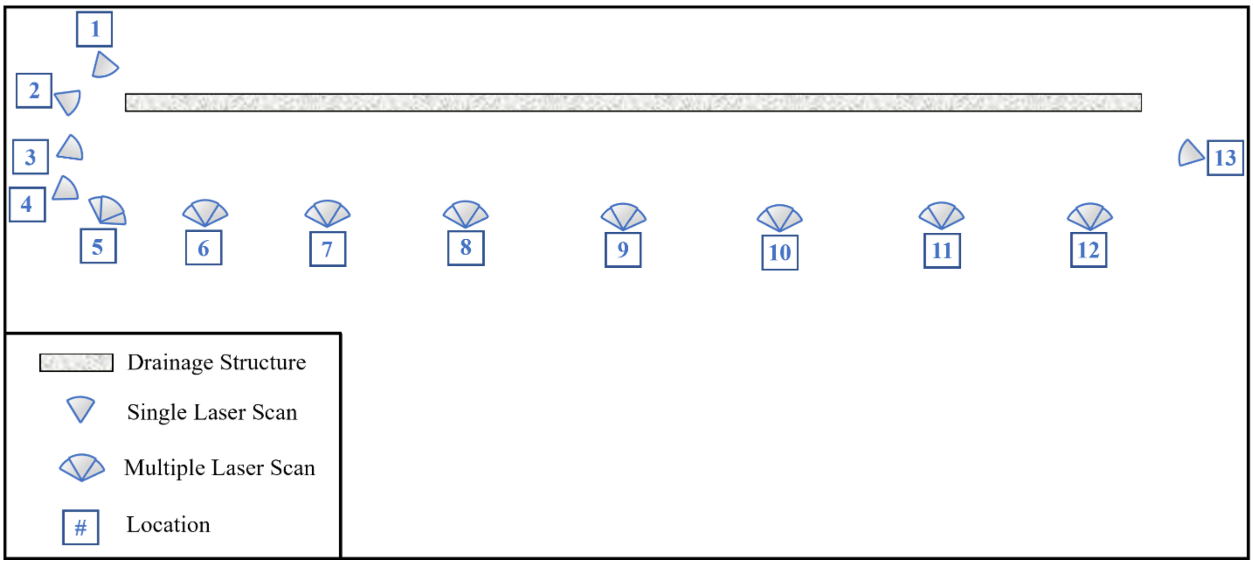


**Figure 5.18.** Sketch illustrating the 13 scan locations for the drainage structure

The data collection process took only 33 minutes to complete. Figures 5.19 and 5.20 respectively contain the point clouds acquired from the first 4 locations (one scan per location) and the point clouds acquired in location 5 (4 scans taken at location 5).

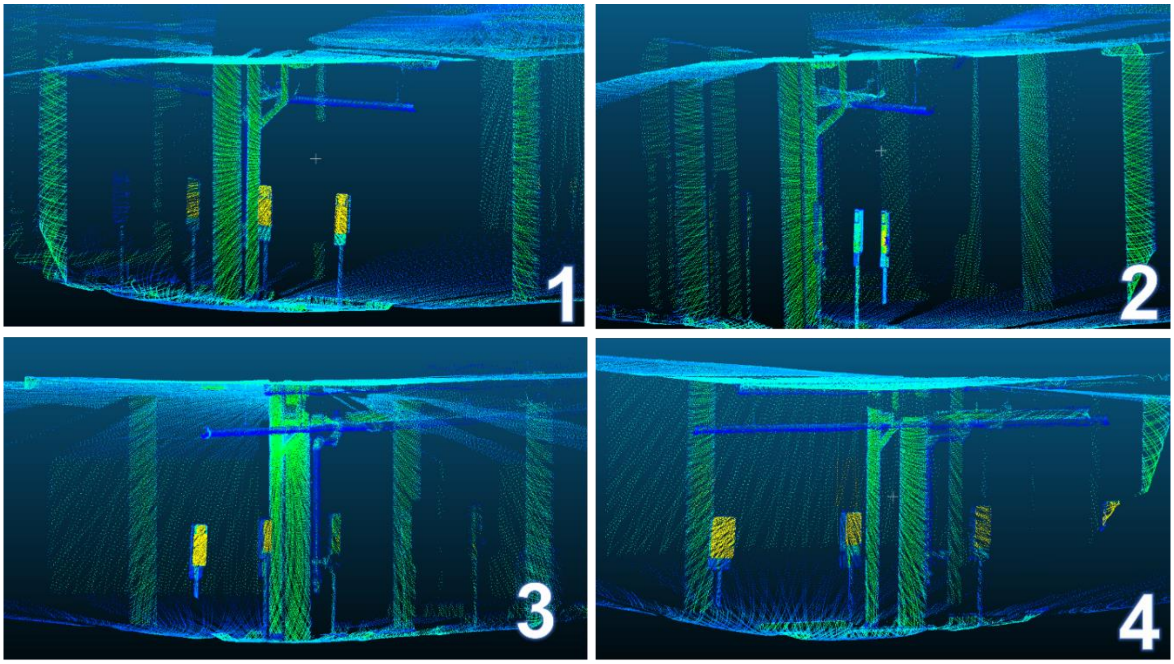


**Figure 5.19.** LiDAR point clouds obtained from positions 1, 2, 3, and 4

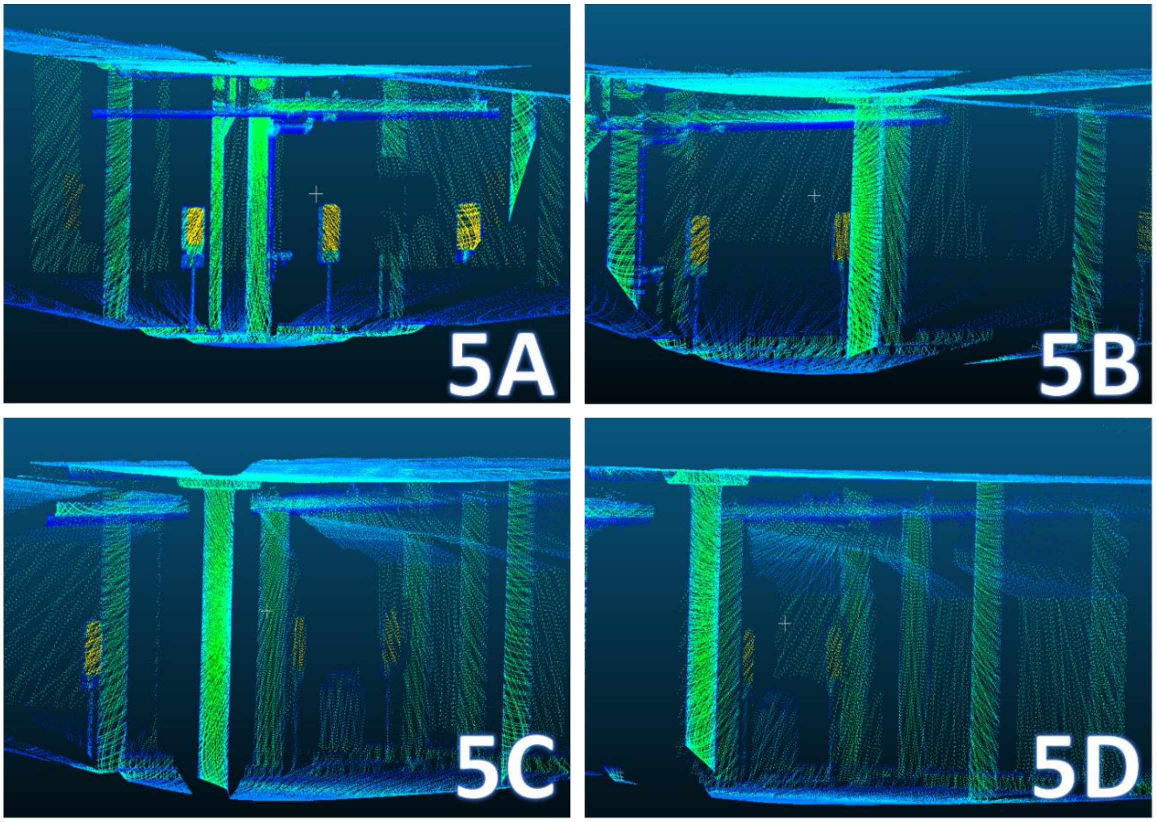


**Figure 5.20.** LiDAR point clouds acquired from rotating the scanner at position 5 (5a, 5b, 5c, and 5d)

Next section introduces the preprocessing steps to acquire a unified point cloud from the laser scans.

### 5.5.2 TLS Data Preprocessing

Preprocessing comprises normal estimation, coarse and fine registration, then finally merging the point clouds together. The workflow is repeated for each additional point cloud.

Normal estimation is first done on two sequential point clouds (e.g., 5a and 5b). Figure 5.21 displays the point cloud at location 5a. The top image represents the original point cloud, while the bottom image represents the computed normals.

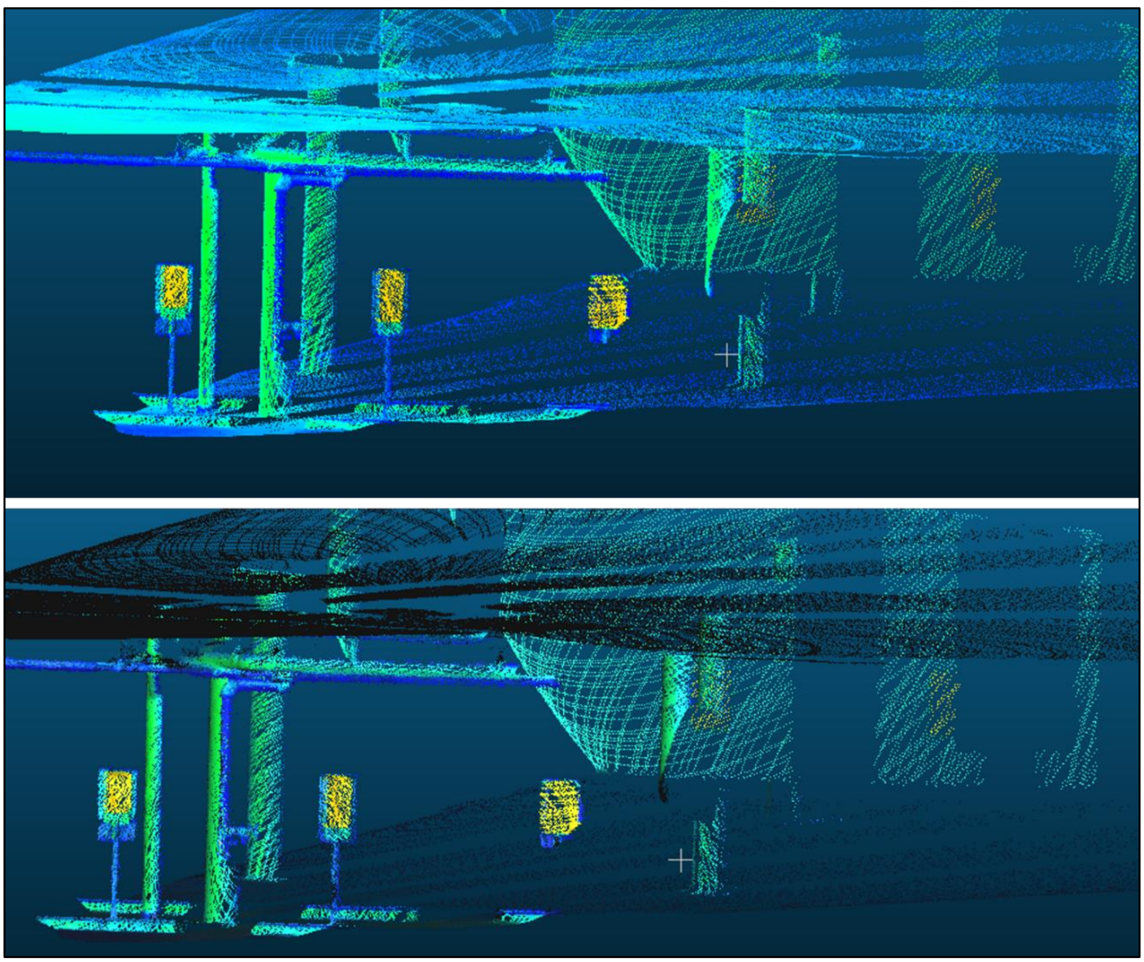

**Figure 5.21.** LiDAR point cloud of location 5a (top) represents the original point cloud (bottom) represents the computed normals

When computing normal vectors for a point cloud using CloudCompare, the user has the ability to change the algorithm's hyperparameters. Figure 5.22 presents the hyperparameters for computing normals. The only hyperparameter that was changed from the default in this research is the neighborhood size (k). Neighborhood size was changed from 100 to 10 for more accurate results.

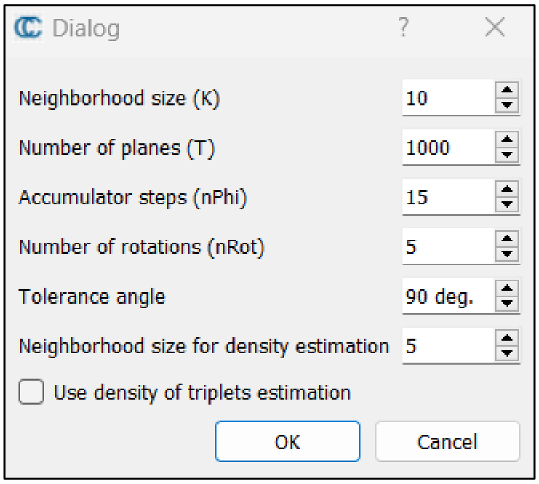


**Figure 5.22.** Normal vectors estimation parameters on CloudCompare

The reason normal vectors were estimated is to minimize the errors during the registration process. Figure 5.23 contains the error values of registering 5b with 5a. The left figure contains the error values without normal estimation. The right figure displays the error values for registration after obtaining normal.

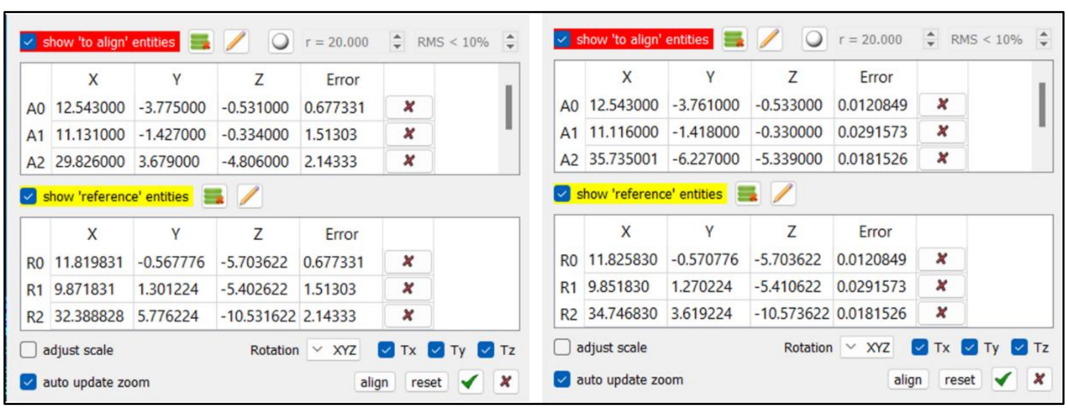


**Figure 5.23.** Error values for coarse registration (left) error values without normals (right) error values after normal estimation.

After coarse registration, fine registration is done using Iterative Closest Point (ICP) algorithm in CloudCompare. Figure 5.24 displays the fine registration parameters. The number of iterations was set to 10 (more iterations can be added if necessary) and the theoretical overlap between the clouds was set to 20%.

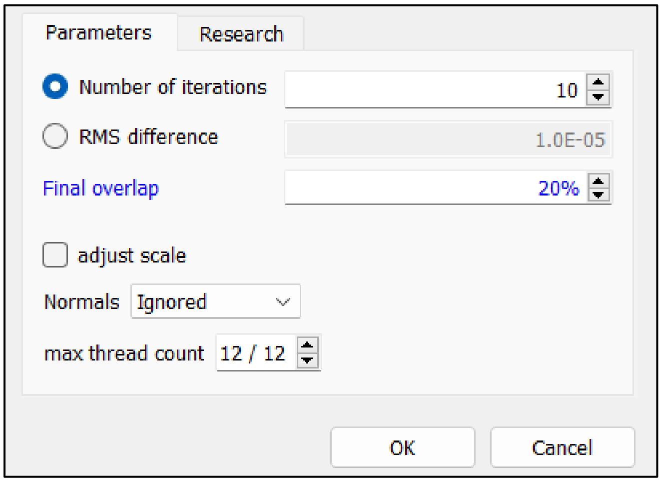


**Figure 5.24.** LiDAR point clouds fine registration parameters

Figure 5.25 contains the resultant of finely registering the four clouds acquired at location 5.

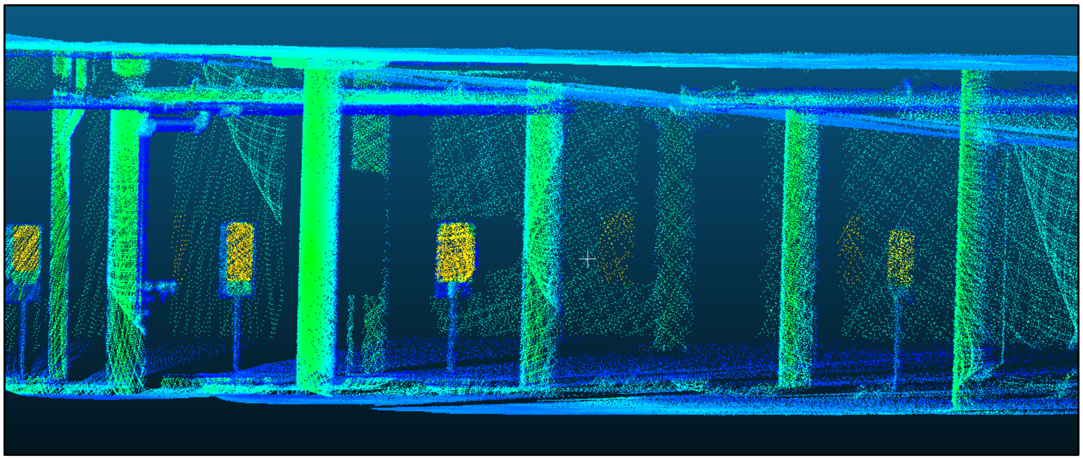

**Figure 5.25.** Full point cloud scene of location 5 (5a, 5b, 5c, and 5d)

The same process is repeated for all point clouds. Figure 5.26 contrasts between an image acquired on the site (left) and registered point clouds (right).

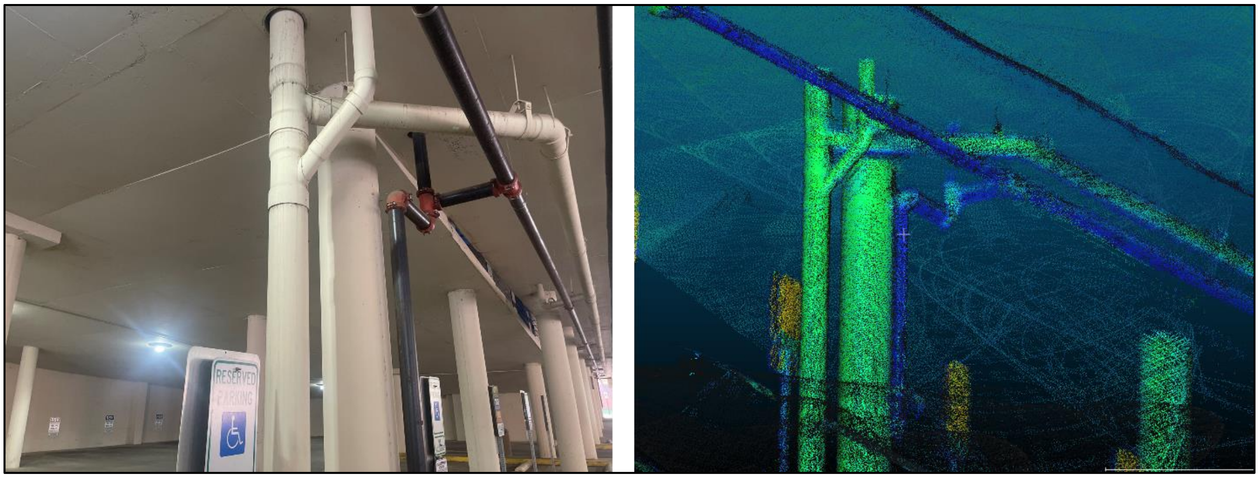

**Figure 5.26.** Drainpipes (left) site image (right) registered point clouds

Most of the downspouts were non-existent in the point cloud; registering the point clouds prior to filtering did not solve this issue but made it worse; it created a significant amount of noise and outliers, which made it impossible to detect the locations of the downspouts. It might be worth investigating the MID-40 results in mobile mapping to overcome this challenge. Due to the issue, the modeling process was limited to the photogrammetric point cloud.

### 5.6 As-Is 3D Modeling

The obtained unified RGB point cloud can now be converted to RCP format using Autodesk Recap in order to be imported into Revit. However, prior to conversion, the point cloud was scaled based on the point cloud acquired from TLS. That ensured correct geometric measurements. The scaled point cloud was then converted to RCP format and imported into Revit, as shown in Figure 5.27.

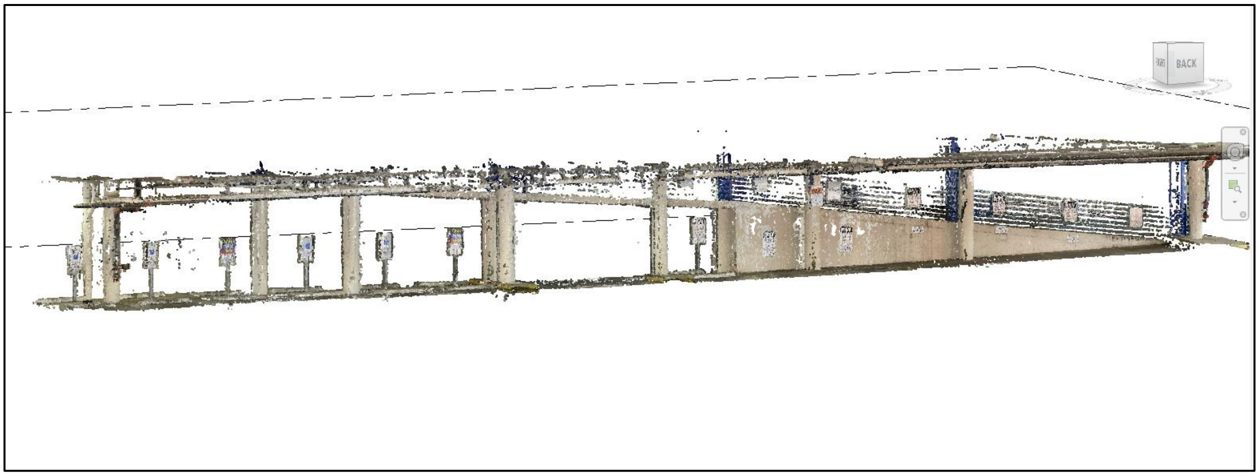

**Figure 5.27.** RCP point cloud in Revit

The components that made up the drainage system are inlets, PVC pipes, bends, T- and Y-connections, hangers, and a pipe reducer. The details of these components are listed in Table 5.2. No cleanout access is provided for the drainage system.

**Table 5.2.** Summary of the drainage system's components

| Component | Inlet | PVC Pipes | | | Bends | | Connections | | Hangers | | Reducer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Size/Type | 12" Circ. Grate | 8" | 6" | 3" | 5" | 3" | T | Y | 6" | 3" | 5-3" |
| Count | 6 | 2 | 6 | 14 | 1 | 8 | 1 | 5 | 19 | 15 | 1 |

Revit libraries contained all the necessary components except for hangers and the circular inlet. The inlet and hanger elements were found and downloaded from the website, BIM Object (www.bimobject.com). The components' amounts, sizes, and locations were modeled according to the images and point cloud, which resulted in a near perfect overlap. Figure 5.28 illustrates how modeling was done based on the points in the point cloud.

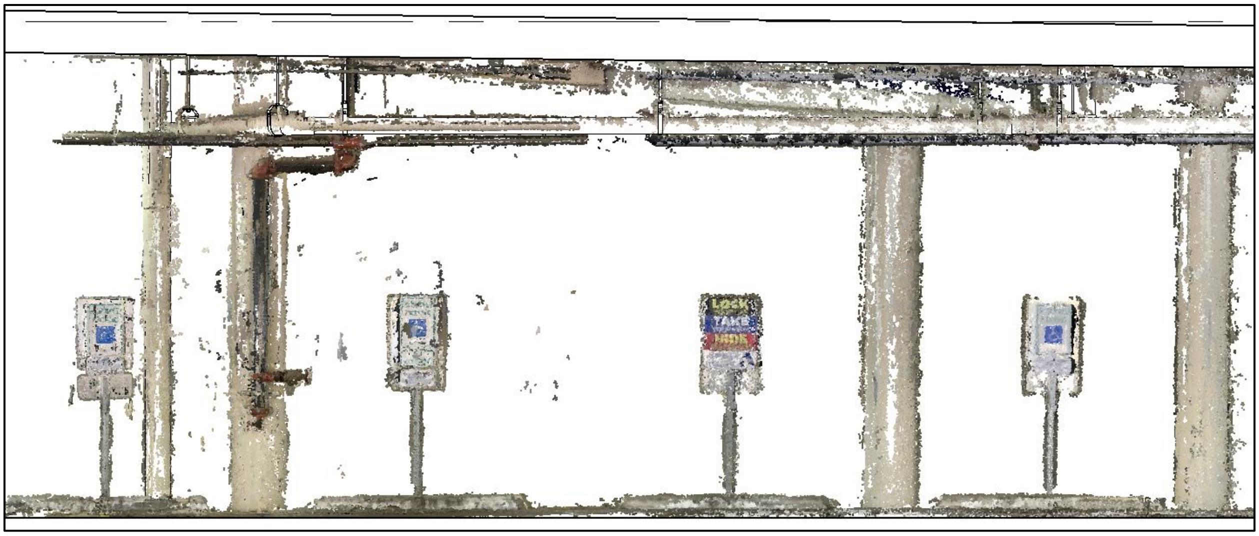

**Figure 5.28.** Modeling drains in Revit based on a point cloud.

Figure 5.27 illustrates the modeling process for one of the downspouts extending below an inlet. Different views in Revit were used for modeling; the figure below displays a 3D view (top right) and a ceiling view (bottom right). All the pipes were modeled along the points in the point cloud. A Y-connection, bend, and four hangers can be seen in Figure 5.29 below.

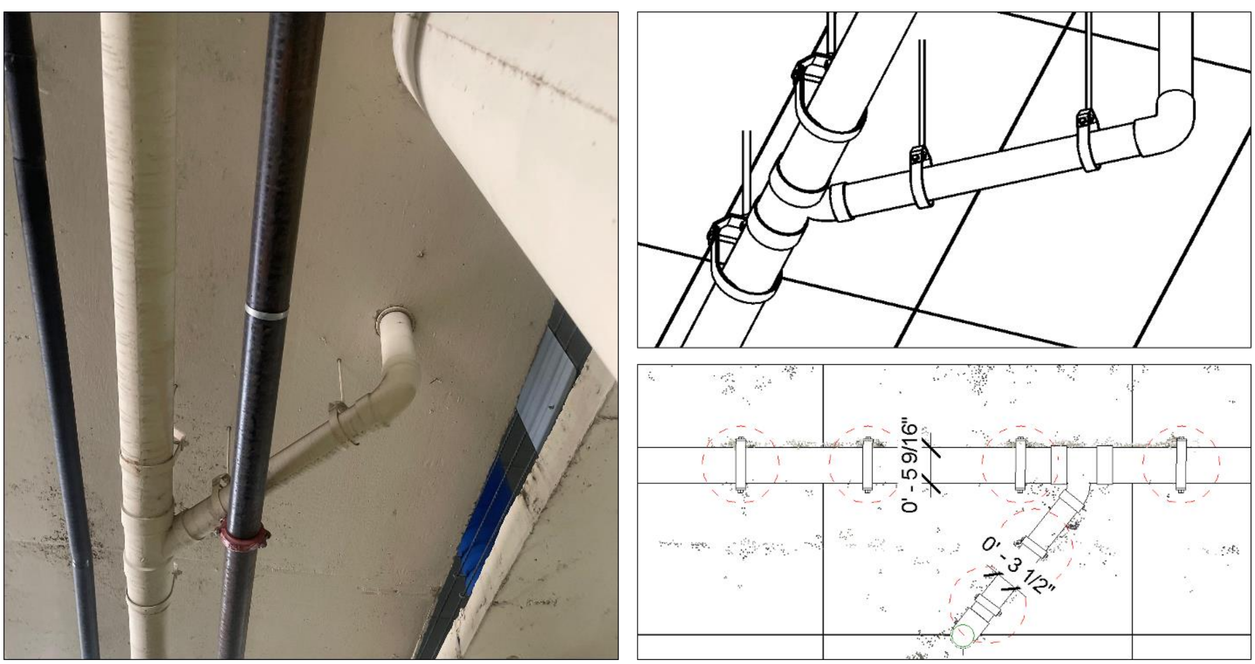


**Figure 5.29.** Downspout modeling in Revit: (left) image of the downspout (top-right) 3D view of the modeled downspout (bot-right) ceiling view of the modeled downspout

### 5.6.1 Circular Grate Inlets

The six inlets above the downspouts that are extending from the ceiling were also modeled in Revit. Figure 5.30 below shows how the inlet is represented in four different ways: Image, TLS point cloud, photogrammetric point cloud, and in Revit. The inlet in the TLS point cloud can barely be seen probably because of the similar low reflectivity of the floor.

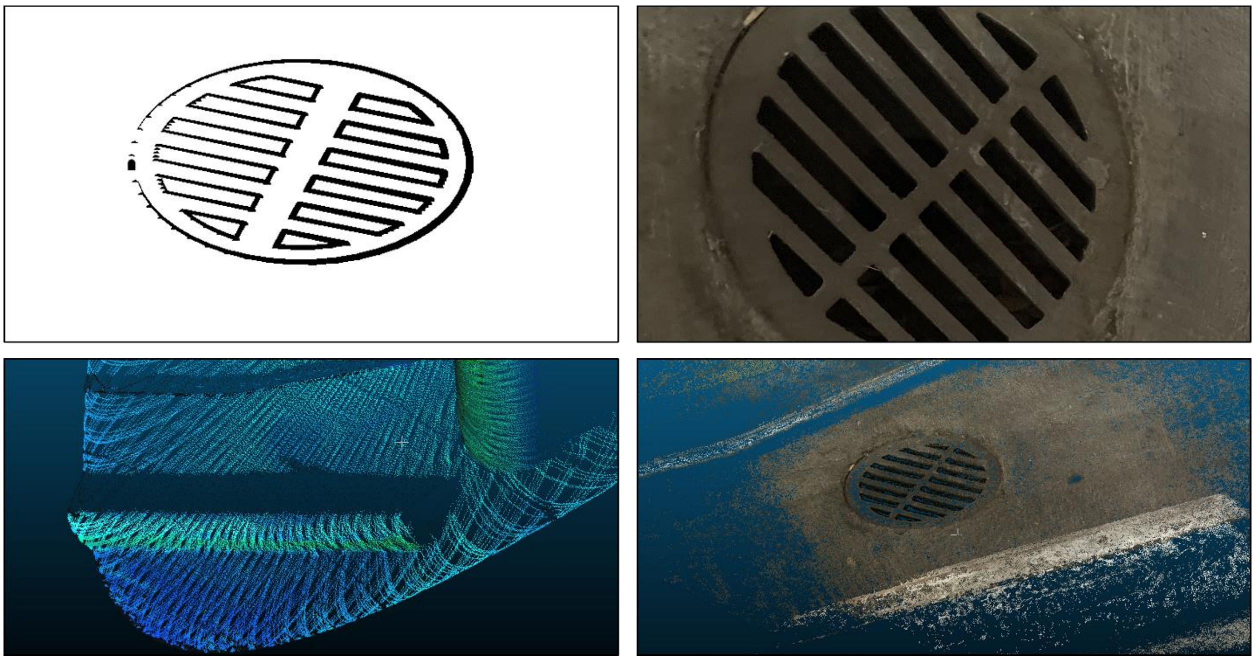

**Figure 5.30.** Circular grate inlet: (top right) inlet image (bottom right) inlet RGB point cloud (bottom left) inlet barely visible in TLS point cloud (top left) Revit element of the inlet

Figure 5.31 presents a part of the model showing two inlets along with their underlying downspouts.

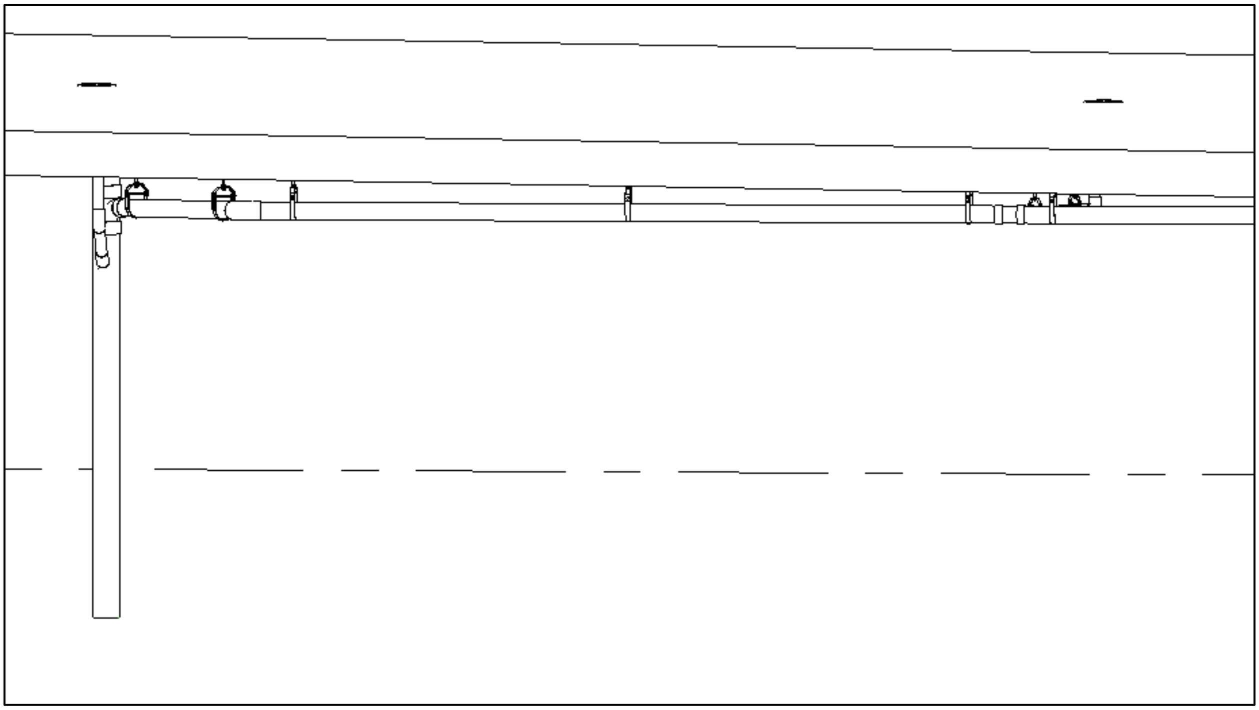

**Figure 5.31.** Revit model of inlets and downspouts

### 5.6.2 Illustration of Campus Elevated Structure

This section contains final discussion of the Revit model. Figure 5.32 below presents a part of the drainage structure in four different ways: Image, TLS point cloud, photogrammetric point cloud, and in Revit. The RGB information were found to be a huge advantage of photogrammetry in modeling drainage systems; different connected components were complete, easily differentiated and their edges were effortlessly observed.

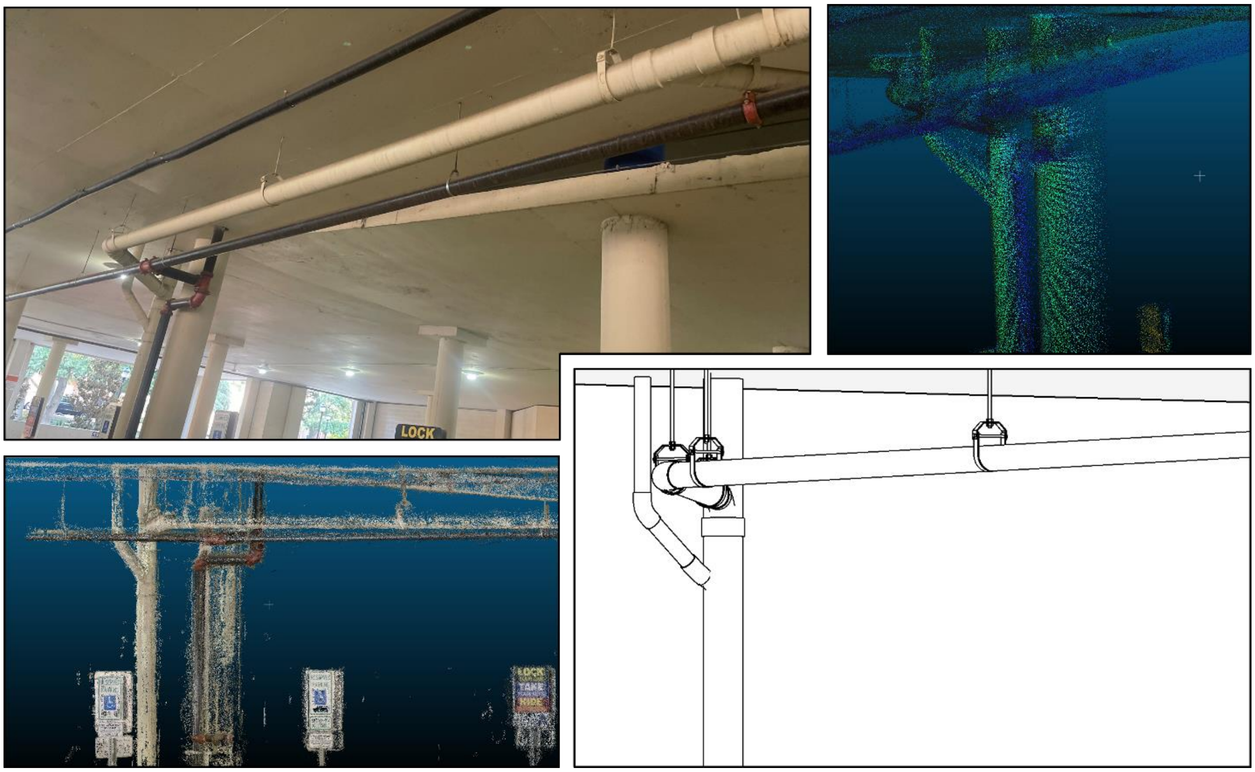


**Figure 5.32.** Drainage system: (top left) drainage image (bottom left) RGB point cloud of drains (top right) TLS point cloud of drains (top left) Revit element of the inlet

Another great geometric feature acquired during point cloud modeling is the slope of the above slab. Considering the difference in the ceiling distance to pipes presented in Figure 5.33 (far right and far left), modeling along the slope of the pipes alone does not showcase this difference. The slope of the above slab in the point cloud was taken into consideration and was found to be approximately 1.22%. Modeling the slope resulted in the overlap between the drains model and point cloud.

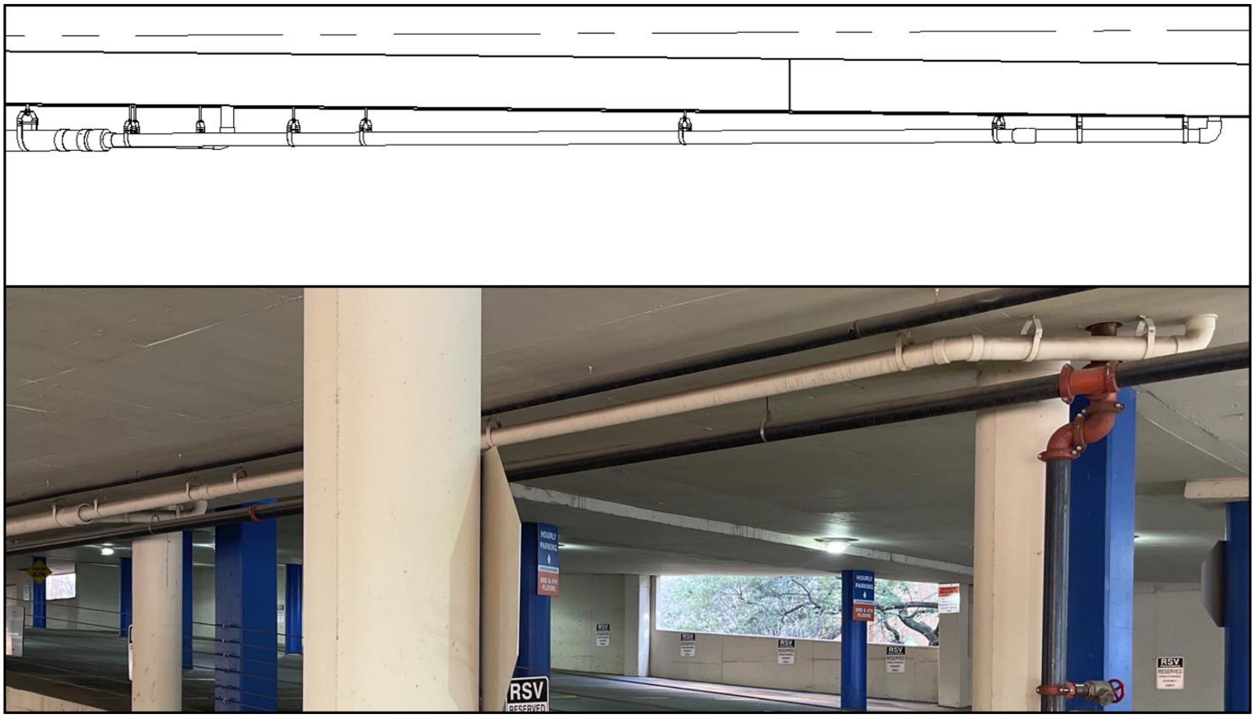


**Figure 5.33.** Final two downspouts on opposite ends and pipe reducer on the far left

Now the model can be compared with as-built or as-planned models to detect any changes that were not previously documented. Additionally, the model will serve as a great foundation for tracking the system's assets and future maintenance operations.

Finally, the model is ready for an element level inspection. The next section discusses how that can be done using Revit Schedules.

### 5.6.3 Inspection Summary

The schedule function in Revit allows the user to have all the elements that belong to a category (e.g., pipe) be listed in a sheet. The user has the flexibility to include all necessary information related to the elements. Revit also allows the user to upload an image related to each element. Figures 5.34 and 5.35 present examples of how schedules can be used. Figure 5.34 lists all the pipes used in the model and some of their properties. Those properties are type, diameter, top elevation, and bottom elevation. The user, or office team, can add inspection notes under the comment section and attach images should any issue be found. The model and the inspection sheet can be shared and updated after future periodic inspections.

<Pipe Schedule>

| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| Image | Mark | Type | Diameter | Top Elevation | Bottom Elevation | Comments |
| Pipe 1.png | Pipe #01 | PVC Pipe | 3" | 13' - 1" | 10' - 11 13/16" | |
| | Pipe #02 | PVC Pipe | 3" | 10' - 6 3/4" | 9' - 7 29/32" | |
| | Pipe #03 | PVC Pipe | 3" | 9' - 7 3/32" | 9' - 3" | |
| | Pipe #04 | PVC Pipe | 5" | 11' - 3 31/32" | 10' - 8 21/32" | |
| | Pipe #05 | PVC Pipe | 3" | 11' - 3 1/8" | 10' - 11 5/8" | |
| | Pipe #06 | PVC Pipe | 3" | 11' - 3 1/8" | 10' - 11 5/8" | |
| | Pipe #07 | PVC Pipe | 3" | 12' - 8 3/8" | 11' - 5 3/8" | |
| | Pipe #08 | PVC Pipe | 3" | 12' - 11" | 11' - 5 1/32" | |
| | Pipe #09 | PVC Pipe | 3" | 11' - 3 1/16" | 10' - 11 9/32" | |
| | Pipe #10 | PVC Pipe | 5" | 11' - 4 5/32" | 10' - 10 19/32" | |
| | Pipe #11 | PVC Pipe | 3" | 13' - 0 9/16" | 11' - 4 19/32" | |
| | Pipe #12 | PVC Pipe | 3" | 11' - 3 1/16" | 10' - 10 27/32" | |
| | Pipe #13 | PVC Pipe | 5" | 11' - 4 5/32" | 10' - 10 19/32" | |
| | Pipe #14 | PVC Pipe | 3" | 13' - 0 9/16" | 11' - 4 19/32" | |
| | Pipe #15 | PVC Pipe | 3" | 11' - 3 1/16" | 10' - 10 27/32" | |
| | Pipe #16 | PVC Pipe | 5" | 11' - 4 5/32" | 10' - 10 19/32" | |
| | Pipe #17 | PVC Pipe | 3" | 13' - 0 9/16" | 11' - 5 1/16" | |
| | Pipe #18 | PVC Pipe | 3" | 11' - 3 1/16" | 10' - 11 5/16" | |
| | Pipe #19 | PVC Pipe | 5" | 11' - 4 5/32" | 10' - 10 19/32" | |
| | Pipe #20 | PVC Pipe | 5" | 11' - 4 5/32" | 10' - 10 19/32" | |
| | Pipe #21 | PVC Pipe | 8" | 10' - 2 23/32" | 0' - 0" | |
| Pipe 22.png | Pipe #22 | PVC Pipe | 8" | 13' - 1" | 11' - 6 3/8" | Staining and Discoloration |

**Figure 5.34.** Revit produced pipe schedule with images and inspection note attached

Similar to the above figure, Figure 5.35 shows the schedule for pipe fittings (bends, connections, and reducer). An inspection note and image are attached to the T-connection element.

<Pipe Fitting Schedule>

| A | B | C |
|---|---|---|
| Image | Mark | Comments |
| | Bend #1 | |
| | Y-connection #1 | |
| | Pipe reducer 5"-3" | |
| | Bend #2 | |
| | Bend #3 | |
| | Y-connection #2 | |
| | Bend #4 | |
| | Bend #5 | |
| | Y-connection #3 | |
| | Bend #6 | |
| | Y-connection #4 | |
| | Bend #8 | |
| | Y-connection #5 | |
| | Bend #9 | |
| T-connection #1. | T-connection #1 | Staining and Discoloration |

**Figure 5.35.** Revit produced pipe fitting schedule with image and inspection note attached

Transportation agencies maintain thousand or tens of thousands of bridges each year. That means a much larger number of images will be taken during inspections. It is probably time consuming and infeasible to look through tens or hundreds of thousands of images each year for inspecting different systems. One solution is to automate the inspection process using pretrained Convoluted Neural Networks (CNNs) to classify different problems found in different components. Next chapter presents a neural network implementation for binary classifying one of the previously mentioned information requirements: Broken grates.

# CHAPTER VI: MODELING NEURAL NETWORKS FOR BINARY CLASSIFICATION OF THE CONDITION OF GRATE INLETS (BROKEN VS. NOT BROKEN)

This chapter introduces two models to classify the condition of grate inlets based on acquired images: a Convolutional Neural Network (CNN) model, and a pretrained CNN model (transfer learning). The tested condition was whether the inlet had broken grates or not. A set of 59 images were acquired from online sources. The images went through an augmentation process that transformed the dataset into 677 images. The images were classified as “Broken” and “Not Broken”, then divided into 3 sets: training, validation, and testing sets. Figure 6.1 below summarizes the ratios taken for creating the 3 sets. The pretrained model produced the highest accuracy, as one would expect.

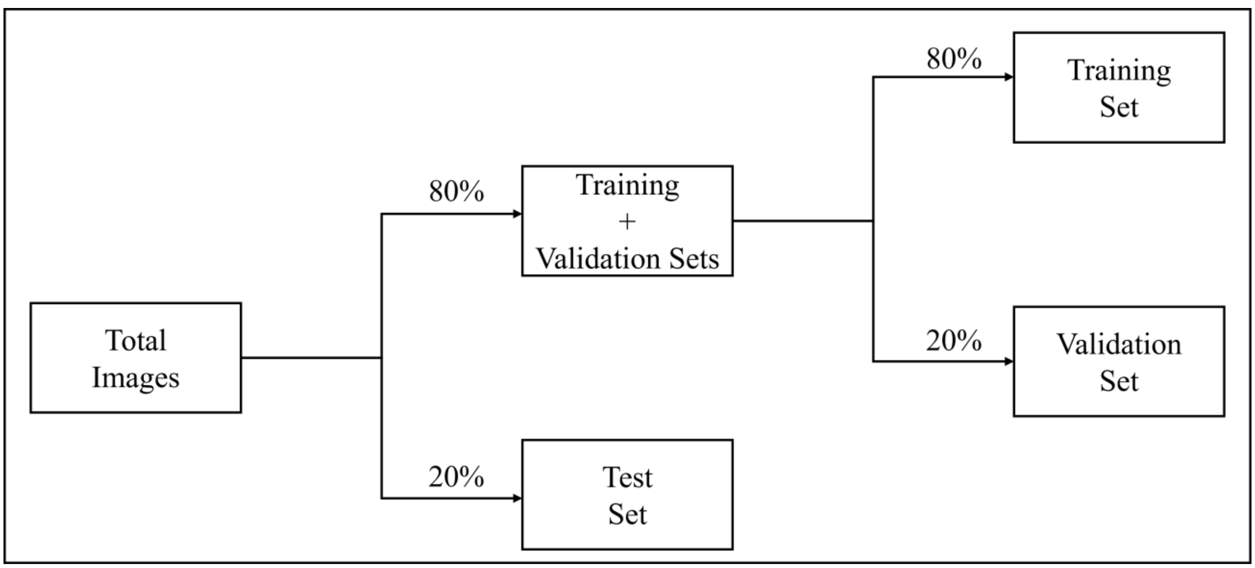


**Figure 6.1.** Distribution of total images for classification

## Image Augmentation

The fifty-nine images acquired are not nearly enough to train a classification model. Typical classification models should be trained on thousands, or even tens of thousands of images to achieve a desired accuracy. Hence, the 59 images must go through an augmentation process.

Augmentation is simply making minor alteration to a set of images to create a larger set. Using the OpenCV library in Python, the following augmentation operations were done on images: blurring, color inversion, contrast adjustment, darkening (lowering brightness), flipping, grayscaling, 90° rotation, 180° rotation, and translation. Figure 6.2 presents the results of the aforementioned operations done on a grate inlet image.

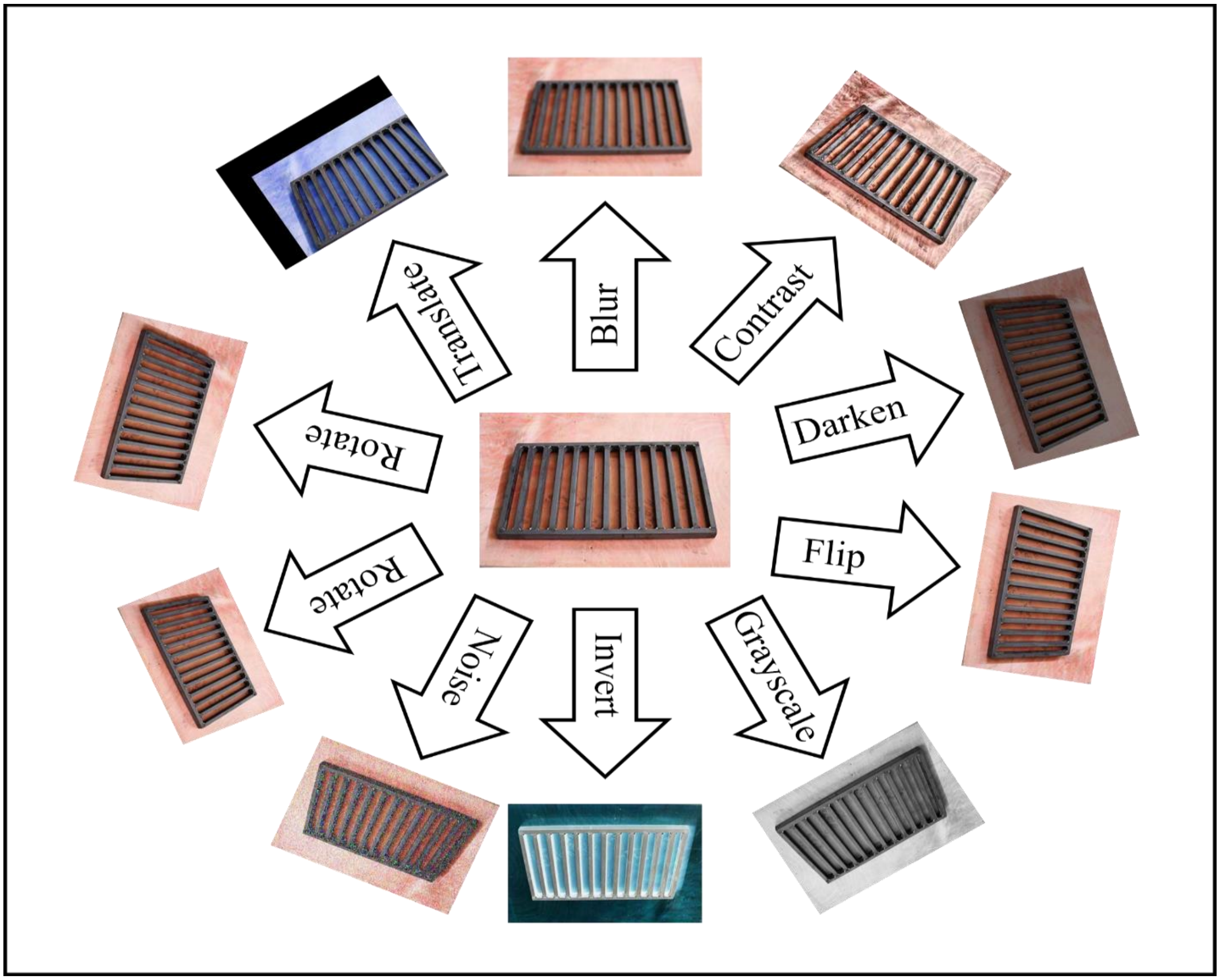


**Figure 6.2.** Example of augmentation of a grate inlet image (image taken from Primagem, 2020)

Post augmentation, 677 total images were accumulated. The images were resized to a resolution of 256 X 256, to unify their sizes (important for neural networks), as well as make training the models faster. Table 6.1 summarizes how the image set was divided into a training, validation, and testing sets based on the ratios shown in Figure 6.1.

**Table 6.1.** Distribution of image datasets

| Category | Total images | Training Set | Validation Set | Test Set |
|---|---|---|---|---|
| Broken | 336 | 215 | 67 | 54 |
| Not Broken | 341 | 218 | 68 | 55 |

The next two sections briefly go through the training and validation processes for binary classification models, and model evaluation metrics, respectively. After that, the results of the two models are discussed.

### Training and Validation

The model used cannot be too simple nor too complex (GeÌron. A., 2019). When the model is too complex, it will most probably overfit, meaning the model will perform great on the training data but performance will be bad on a test set (GeÌron. A., 2019). When a model is too simple, it will probably underfit the model. After training a model, evaluation must be done, as well as fine-tuning of the model to get an idea on how it will generalize to new cases (GeÌron. A., 2019). A validation set is passed during model training. Keras measures training accuracy and loss during each epoch, and validation accuracy and loss at the end of each epoch. If the training set showed much better performance, it usually means that the model is overfitting (GeÌron. A., 2019).

### Evaluation Metrics

This section introduces different metrics used to evaluate the classification model. These metrics are accuracy, confusion matrix, precision, recall, and $F_1$ score.

Starting with accuracy, it is simply the ratio of correct predictions. However, accuracy might not always be the best evaluation metric, especially for skewed data. Skewed data in the context of image classification means some classes are represented more than others (GeÌron. A., 2019). Thankfully, that is not the case for the grate inlets dataset.

The confusion matrix is another way to evaluate a classifier model. The basic idea is to count the times broken grates were classified as non-broken. It is done by comparing predictions with their actual values. Below is the form of a confusion matrix for a binary classifier:

$\begin{bmatrix} TN & FP \\ FN & TP \end{bmatrix}$, where:

TN: True negative

FP: False positive

FN: False negative

TP: True positive

A more concise metric is the precision, which is the accuracy of the positive predictions (GeÌron. A., 2019).

$$Precision = \frac{TP}{TP + FP}$$

Another metric that is usually used along with precision, is the recall. It is also called sensitivity. Recall is the ratio of the correctly detected positive instances (GeÌron. A., 2019). Below is the recall equation.

$$Recall = \frac{TP}{TP + FN}$$

Lastly, if two or more classification models are to be compared, the $F_1$ score is a suitable metric for that. The $F_1$ score refers to the harmonic mean between precision and recall (Canedo and

Mendes, 2020). The regular mean does not consider the variation between values, while the harmonic mean assigns higher weights to lower values (GeÌron. A., 2019). A high $F_1$ score means that both the precision and recall are high (Canedo and Mendes, 2020).

$$F_1 = \frac{2}{\left(\frac{1}{Precision}\right) + \left(\frac{1}{Recall}\right)} = \frac{TP}{TP + \left(\frac{FN + FP}{2}\right)}$$

Conveniently, Keras and SkLearn libraries take care of calculating all the previously mentioned metrics. The following sections discuss the models' results and metrics.

**Model 1: CNN**

Deep neural networks tend to breakdown when using large images (e.g., 128 X 128) for classification problems (GeÌron. A., 2019). The breakdown occurs because the large number of pixels and neurons will result in millions of connections at each layer (GeÌron. A., 2019). However, CNNs use partially connected layers and weight sharing which solves this problem (GeÌron. A., 2019).

The CNN architecture, at the first hidden layer, focuses the network on low-level features (Taweelerd et al., 2021). At the following layers, the features are at higher levels (Taweelerd et al., 2021). After going through 2 or 3 convolutional layers, the layers are pooled (inputs aggregation) (GeÌron. A., 2019). Pooling limits overfitting and reduces the computational load. Overfitting is further reduced by using dropout layers (GeÌron. A., 2019).

The CNN model created had 3 convolutional layers, with each followed by a pooling layer. A dropout layer was added after the final pooling, then followed by a hidden layer and the output layer. Figure 6.3 displays the training accuracy and loss, as well as the validation accuracy and loss.

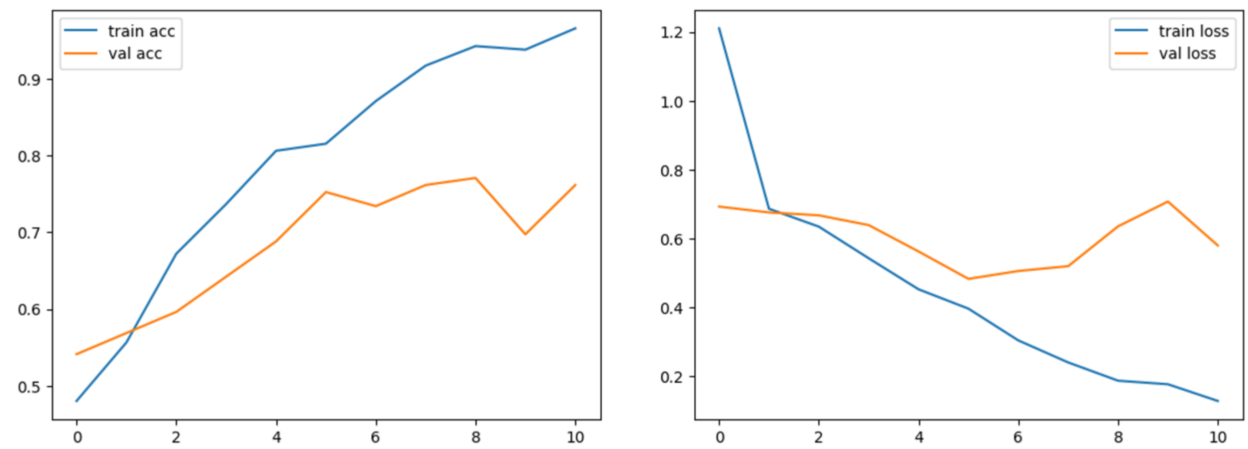


**Figure 6.3.** Training and validation accuracies and losses based on a CNN model: (left) accuracy values during each epoch (right) loss values during each epoch

Even though the training loss went down, the validation loss did not. The validation accuracy reached 76% and the training accuracy reached 96.5% after 11 epochs. This large difference entails that the model is probably overfitting. Furthermore, the test set was passed to the model and showed 87% accuracy and about 34% loss. The results in the confusion matrix showed that 13 of the 67 broken grate images were classified as not broken, and 4 out of the 68 non-broken grate images were classified as broken. The results don't seem promising. However, the additional evaluation metrics were examined as well. Precision, recall, and $F_1$ results are presented in Table 6.2 below:

**Table 6.2.** Precision, Recall, and F1 results of the CNN model

| | Precision | Recall | F1-Score |
|---|---|---|---|
| Broken | 0.81 | 0.93 | 0.86 |
| Not Broken | 0.94 | 0.83 | 0.88 |

The $F_1$ score for both classes were less than 90%, which is undesirable. The next section introduces transfer learning and how results can be significantly improved, especially for small datasets.

**Model 2: Transfer Learning**

Using the lower layers of a pretrained model is highly recommended when not enough training data is available (GeÌron. A., 2019). This technique is known as transfer learning. Some of the advantages of using transfer learning is the ability to use small datasets, as well as a higher speed of training (GeÌron. A., 2019).

In this section, the VGG-19 model pretrained on the ImageNet dataset was used. VGGNet architecture was created by Karen Simonyan and Andrew Zisserman at Oxford University. The architecture of the VGG-19 model is made up of multiple sets of 2 or 3 convolutional layers that are followed by a pooling layer. The layers are added to reach 19 convolutional layers. After the convolutional layers, 2 hidden layers and an output layer are added.

Images were resized to a resolution of 224 X 224, since the VGGNet model expects this resolution to be passed. Figure 6.4 presents the training accuracy and loss, as well as the validation accuracy and loss.

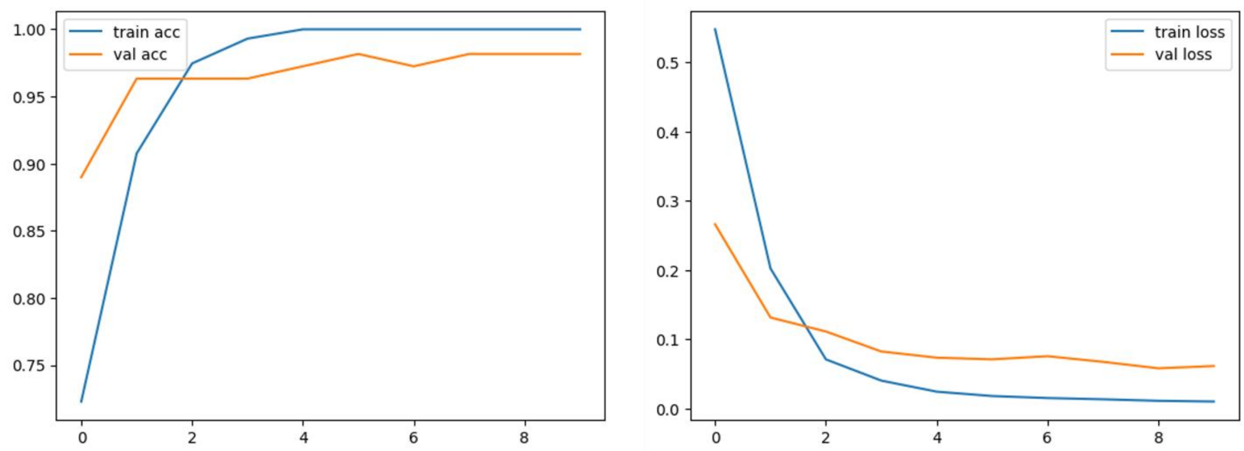


**Figure 6.4.** Training and validation accuracies and losses based on a VGG-19 model: (left) accuracy values during each epoch (right) loss values during each epoch

Significantly better results than the previous model can be observed in the above figure. The training loss went down to 1% and the validation accuracy reached 98.17% after 10 epochs, so barely any overfitting occurred. The test set was passed to the model and showed an accuracy of 95.5% with only 8% loss. The confusion matrix showed that out of the 67 images of broken grates, only 5 were classified as non-broken. Similarly, out of the 68 non-broken grate images, only 1 was classified as broken. The additional evaluation metrics are provided in Table 6.3.

**Table 6.3.** Precision, Recall, F1 results of the VGG-19 model

| | Precision | Recall | F1-Score |
|---|---|---|---|
| Broken | 0.93 | 0.98 | 0.95 |
| Not Broken | 0.99 | 0.93 | 0.96 |

Indeed, the results of this model are excellent. Even though the dataset was originally comprised of 59 images, overfitting was avoided, and high scores were achieved for all evaluation metrics thanks to the lower layers of the pretrained model.

# CHAPTER VII: CONCLUSIONS AND FUTURE WORK

## 7.1 Conclusions

It is impossible to find out if a pipe is experiencing clogging using LiDAR or photogrammetry. During rainfall events, the spread of water will exceed the design spread if the pipes were clogged, thus promoting hydroplaning and endangering bridge users. Additionally, the water remaining on the bridge deck can get through the deck and accelerate the corrosion of different bridge elements, such as steel girders.

The flexibility that 3D models provide present a great opportunity for transportation agencies to track assets and conduct element level inspections on different infrastructure systems. State DOTs may also include assessment scores as part of the inspection sheet produced in Revit. The scores allow state DOTs to build a strategy for prioritizing schedule and resources for maintenance operations.

In the case of modeling piping systems, photogrammetry was found to outperform laser sensors. The cost of a decent camera isn't nearly as high as a laser scanner. The camera also allows higher mobility on the site and less time spent on data collection. The dim light condition around the drains, especially the inlets, prevented the laser scanner from accurately distinguishing the inlets from the slab. In other words, both had close reflectivity values. The processing time for both systems was almost the same, although the time spent on reconstruction from images could have been cut down if a better camera and on-site references were used. The higher accuracy laser sensors provide was not found to be crucial for modeling piping systems. The accuracy from photogrammetry was more than adequate. Lastly, the RGB information in photogrammetry was very advantageous; different components and their edges were easily observable.

Transfer learning model acquired almost 96% accuracy for classifying the condition of grate inlets. The high accuracy was due to the layers of the pretrained networks that help in detecting various shapes and boundaries, despite the fact that a small dataset was used for training.

## 7.2 Future Work

The inspection approach implemented in this research was visually based. The conditions of visible elements could be assessed using cameras and LiDAR sensors. However, the aforementioned sensors were unable to provide information regarding clogging in pipes. Infrared Thermography may be used to provide internal information about pipes. Thermographic imagery can display the temperature differences in PVC pipes (Cheney, 2011). The locations with larger temperature deviations indicate clogging (Cheney, 2011).

Bridge deck drains lack a scoring system for conditional assessment. Perhaps one of the scoring systems used with other piping systems may be adopted or modified to be used for bridge deck drains. This would allow transportation agencies to better allocate time and resources by prioritizing maintenance operations for bridge deck drains.

Moreover, a multiclass classification neural network can be trained to detect additional problems that can be found in bridge deck drains. The neural network can be combined with OpenCV algorithms to be able to acquire inspection results in real time, thus saving valuable time and effort for classifying the conditions of different bridge deck drain components. Ideally, the classifier would be part of a software or phone app that directly feeds inspection results into a database.

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# APPENDIX A: TEXAS SURVEY QUESTIONS

Appendix A contains the questions presented in the Texas survey, distributed over 5 sections: (1) Contact information; (2) Bridge deck drain failure; (3) Bridge deck drain design; (4) Bridge deck drain construction; and (5) Bridge deck drain maintenance and inspection.

## A-1 Contact Information

- Name:
- Position:
- District:
- City/Town:
- E-mail:

## A-2 Bridge deck drain failure

1. How often does flooding occur on your bridges? (Select only one.)
    - o During rare severe rainfalls
    - o Once a year
    - o More than once a year
    - o During each rainfall

2. How long is the duration of typical floods on bridges due to drain failures? (Select only one.)
    - o Less than 30 minutes
    - o 30 minutes – 1 hour
    - o 1 – 2 hours
    - o More than 2 hours

3. Please select the common problems that occur with bridge deck drains in your district (Check all that apply.)
    - Corrosion of inlets
    - Corrosion of pipes
    - Inlet breaking due to traffic load
    - Clogging of inlets
    - Inlet popping out of placement
    - Insufficient inlet capacity
    - Pipes clogging due to bends
    - Pipes clogging due to T-connections
    - Pipes clogging due to insufficient pipe diameter
    - Deflection of pipes
    - Cyclist or pedestrian injuries due to inlet design
    - Poor bridge deck drain spacing
    - Grated broken or missing
    - Improper cross slope creates ponds
    - Cracking of pipes
    - Other:

**A-3 Bridge deck drain design**

4. What are the reasons for selecting closed bridge deck drains? (Check all that apply.)
    - Environmental regulations
    - Span of bridge
    - Type of road (e.g., highway, rural)
    - Level of service
    - Existing facilities or waterways underneath the bridge
    - Type of bridge (e.g., truss, arch, beam)
    - Expected service life of closed deck drains
    - Durability
    - Future construction on or underneath the bridge
    - Longitudinal slope
    - Roadway geometry
    - Transverse slope
    - Other:

5. What are the reasons for selecting hung on the exterior of the columns closed systems? (Check all that apply.)
    - Freeze and thaw damage resulted from embedded systems
    - Roadway geometry
    - Locations and spacing of inlets
    - Locations of outlets
    - Locations of cleanout plugs
    - Other:

6. What are the reasons for using embedded closed systems? (Check all that apply.)
    - Aesthetics
    - Roadway geometry
    - Locations and spacing of inlets
    - Locations of outlets
    - Locations of cleanout plugs
    - Scour prevention
    - Corrosion prevention
    - Other:

7. Based on experience, which type of closed system do you prefer? (Select only one.)
    - Hung on the exterior of the columns
    - Embedded in columns

8. What is your top priority for design improvements in bridge deck drain designs? (Select only one.)
    - Design of grate inlets
    - Design of scupper inlets
    - Design of inlet box (e.g., slope, area, depth)
    - Change of pipe material
    - Increase in pipe size
    - Location of deck drains
    - Spacing of deck drains
    - Slope of pipes
    - Increase of inlet length
    - Increase of inlet width
    - Other:

9. Do you have any recommendations for improving bridge deck drain designs? If yes, please explain.

### A-4 Bridge deck drain construction

10. Are there any construction practices that you have found to affect the service life or performance of bridge deck drains negatively? If yes, please explain.

11. Do you have any recommendations for improving bridge deck drain construction and installation? If yes, please explain.

### A-5 Bridge deck drain maintenance and inspection

12. Who maintains bridge deck drains after installation? (Check all that apply.)
    - o Your agency
    - o Outsourced to a private contractor
    - o Another government agency
    - o Other:

13. Where is the runoff typically drained to? (Select only one.)
    - o Junction box then transported to a storm sewer system
    - o Soil below the bridge
    - o Open channel
    - o Waterways below the bridge
    - o Other:

14. What types of inspections take place on bridge deck drains in your district? (Check all that apply.)

- Initial (inventory)
- Routine (periodic)
- Damage
- In-depth
- Special (interim: inspection scheduled at the discretion of the bridge owner) (e.g., monitor clogging.)
- Yearly

15. What inventory data does your agency have to help manage bridge deck drains? (Check all that apply.)

- Number of bridge deck drains
- Locations of bridge deck drains
- GPS coordinates of bridge deck drains
- Performance of bridge deck drains
- Photographs
- Videos
- Age of bridge deck drains
- Number of cleanout plugs
- Expected service life of bridge deck drains
- Inspection dates
- Material of pipes
- Sizes of pipes
- Material of inlets
- Size of inlets
- Areas of inlet openings
- No inventory exists
- Other:

16. What descriptions characterize your approach to preserving/maintaining bridge deck drains? (Check all that apply.)

- o Regular preventative maintenance
- o Immediate repairs after damage or failure
- o Corrective repairs prioritized and schedule to meet a performance target
- o Repair the worst drain first
- o Little or no preventative maintenance work performed annually
- o This agency does not maintain bridge deck drains

17. Method and schedule of maintenance in your agency depends on: (Check all that apply.)

- o Inspection recommendations
- o Age of bridge deck drains
- o Expected costs
- o Customer complaints
- o Observed performance and rating
- o Agency’s guidelines (e.g., programs, spreadsheets, work sheets)
- o Other:

18. How do you determine where a bridge deck drain is in its service life? (Check all that apply.)

- o Compare age with expected service life
- o Deterioration models
- o Visual inspection
- o Photo-logging
- o Video-logging
- o Operational performance
- o Assets are repaired or replaced as soon as they fail without regard to service life
- o Service life is often determined more by functional obsolescence than by wear-and-tear
- o Customer complaints
- o The agency does not monitor service life for this type of asset
- o Other:

19. Do you have any recommendations for improving the service life of deck drains? (Check all that apply.)

    - Conducting regular preventative maintenance
    - Placing drains conscientiously
    - Increasing number of cleanout plugs
    - Increasing slope of pipes
    - Including vanes for grate inlet designs
    - Changing pipe material
    - Decreasing length of downspout pipes
    - Other:

20. What equipment or machinery are used to clean and maintain bridge deck drains in your district? (Check all that apply.)

    - Hand or hand tools (e.g., snakes)
    - Compressed air
    - Flushing with water using low-pressure, high-volume water
    - Flushing with water using high-pressure, low-volume water
    - High-pressure power washer
    - Water jets
    - Water truck with power washer
    - Shovels
    - Maintenance and cleaning outsourced to a private contractor
    - Other:

# APPENDIX B: OUT-OF-STATE SURVEY QUESTIONS

Appendix B contains the questions presented in the out-of-state survey, distributed over 5 sections: (1) Contact information; (2) Bridge deck drain failure; (3) Bridge deck drain design; (4) Bridge deck drain construction; and (5) Bridge deck drain maintenance and inspection. The out-of-state survey contains the same questions as the Texas survey, as well as a few additional ones related to the pipes used on deck drains. Those questions can be found at the end of the design section.

## B-1 Contact Information

- Name:
- Agency:
- City/Town:
- State:
- E-mail:

## B-2 Bridge deck drain failure

1. How often does flooding occur on your bridges? (Select only one.)
    - o During rare severe rainfalls
    - o Once a year
    - o More than once a year
    - o During each rainfall

2. How long is the duration of typical floods on bridges due to drain failures? (Select only one.)
    - o Less than 30 minutes
    - o 30 minutes – 1 hour
    - o 1 – 2 hours
    - o More than 2 hours

3. Please select the common problems that occur with bridge deck drains in your state. (Check all that apply.)
    - Corrosion of inlets
    - Corrosion of pipes
    - Inlet breaking due to traffic load
    - Clogging of inlets
    - Inlet popping out of placement
    - Insufficient inlet capacity
    - Pipes clogging due to bends
    - Pipes clogging due to T-connections
    - Pipes clogging due to insufficient pipe diameter
    - Deflection of pipes
    - Cyclist or pedestrian injuries due to inlet design
    - Poor bridge deck drain spacing
    - Grates broken or missing
    - Improper cross slope creates ponds
    - Cracking of pipes
    - Other:

**B-3 Bridge deck drain design**

4. What are the reasons for selecting closed bridge deck drains? (Check all that apply.)
    - Environmental regulations
    - Span of bridge
    - Type of road (e.g., highway, rural)
    - Level of service
    - Existing facilities or waterways underneath the bridge
    - Type of bridge (e.g., truss, arch, beam)
    - Expected service life of closed deck drains
    - Durability
    - Future construction on or underneath the bridge
    - Longitudinal slope
    - Roadway geometry
    - Transvers slope
    - Other:

5. What are the reasons for selecting hung on the exterior of the columns closed systems? (Check all that apply.)
   - Freeze and thaw damage resulted from embedded systems
   - Roadway geometry
   - Locations and spacing of inlets
   - Locations of outlets
   - Locations of cleanout plugs
   - Other:

6. What are the reasons for using embedded closed systems? (Check all that apply.)
   - Aesthetics
   - Roadway geometry
   - Locations and spacing of inlets
   - Locations of outlets
   - Locations of cleanout plugs
   - Scour prevention
   - Corrosion prevention
   - Other:

7. Based on experience, which type of closed system do you prefer? (Select only one.)
   - Hung on the exterior of the columns
   - Embedded in columns

8. What pipe material does your agency often use for closed bridge deck drains? (Select only one.)
   - Polyvinyl Chloride
   - Steel
   - Fiberglass
   - Ductile iron
   - Other:

9. What are the reasons for using that material type? (Check all that apply.)
    - Flexibility
    - Lightweight
    - Ease of installation
    - Durability
    - Resistance to chemical attacks
    - Resistance to corrosion
    - Smooth inner walls
    - Low price
    - High availability
    - Low maintenance requirements
    - Ultraviolet light resistance
    - Other:

10. What are the common problems you found with this pipe material?

11. What is your top priority for design improvements in bridge deck drain designs? (Select only one.)
    - Design of grate inlets
    - Design of scupper inlets
    - Design of inlet box (e.g., slope, area, depth)
    - Change of pipe material
    - Increase in pipe size
    - Location of deck drains
    - Spacing of deck drains
    - Slope of pipes
    - Increase of inlet length
    - Increase of inlet width
    - Other:

12. Do you have any recommendations for improving bridge deck drain designs? If yes, please explain.

13. Are you aware of any innovative methods or systems in design that your DOT or other state DOTs have used? If yes, please explain.

**B-4 Bridge deck drain construction**

14. Are there any construction practices that you have found to affect the service life or performance of bridge deck drains negatively? If yes, please explain.

15. Do you have any recommendations for improving bridge deck drain construction and installation? If yes, please explain.

**B-5 Bridge deck drain maintenance and inspection**

16. Who maintains bridge deck drains after installation? (Check all that apply.)
    - Your agency
    - Outsourced to a private contractor
    - Another government agency
    - Other:

17. Where is the runoff typically drained to? (Select only one.)
    - Junction box then transported to a storm sewer system
    - Soil below the bridge
    - Open channel
    - Waterways below the bridge
    - Other:

18. What types of inspection take place on bridge deck drains in your state? (Check all that apply.)
    - Initial (inventory)
    - Routine (periodic)
    - Damage
    - In-depth
    - Special (interim: inspection schedule at the discretion of the bridge owner) (e.g., monitor clogging)
    - Yearly

19. What inventory data does your agency have to help manage bridge deck drains? (Check all that apply.)

- o Number of bridge deck drains
- o Locations of bridge deck drains
- o GPS coordinates of bridge deck drains
- o Existing conditions of bridge deck drains
- o Performance of bridge deck drains
- o Photographs
- o Videos
- o Age of bridge deck drains
- o Number of cleanout plugs
- o Expected service life of bridge deck drains
- o Inspection dates
- o Material of pipes
- o Sizes of pipes
- o Material of inlets
- o Types of inlets
- o Size of inlets
- o Areas of inlet openings
- o No inventory exists
- o Other:

20. What descriptions characterize your approach to preserving/maintaining bridge deck drains? (Check all that apply.)

- o Regular preventative maintenance
- o Immediate repairs after damage or failure
- o Corrective repairs prioritized and scheduled to meet a performance target
- o Repair the worst drain first
- o Little or no preventative maintenance work performed annually
- o This agency does not maintain bridge deck drains

21. Method and schedule of maintenance in your agency depends on: (Check all that apply.)

- o Inspection recommendations
- o Age of bridge deck drains
- o Expected costs
- o Customer complaints
- o Observed performance and rating
- o Agency's guidelines (e.g., programs, spreadsheets, work sheets)
- o Other:

22. How do you determine where a deck drain is in its service life? (Check all that apply.)

- o Compare age with expected service life
- o Deterioration models
- o Visual inspection
- o Photo-logging
- o Video-logging
- o Operational performance
- o Assets are repaired or replaced as soon as they fail without regard to service life
- o Service life is often determined more by functional obsolescence than by wear-and-tear
- o Customer complaints
- o The agency does not monitor service life of this type of asset
- o Other:

23. Do you have any recommendations for improving the service life of deck drains? (Check all that apply.)

- o Conducting regular preventative maintenance
- o Placing drains conscientiously
- o Increasing number of cleanout plugs
- o Increasing slope of pipes
- o Including vanes for grate inlet designs
- o Changing pipe material
- o Decreasing length of downspout pipes
- o Other:

24. What equipment or machinery are used to clean and maintain bridge deck drains in your state? (Check all that apply.)

- Hand or hand tools (e.g., snakes)
- Compressed air
- Flushing with water using low-pressure, high-volume water
- Flushing with water using high-pressure, low-volume water
- High-pressure power washer
- Vacuum trucks
- Water jets
- Water truck with power washer
- Shovels
- Maintenance and cleaning outsourced to a private contractor
- Other:

## APPENDIX C: SURVEY RESULTS

### C-1 TxDOT Participants

Appendix C presents the full list of results acquired and documented in TxDOT report 0-7092-1. The survey collected information about the locations and positions of respondents. Figure C.1 illustrates the locations and positions of Texas survey respondents. In total, forty-five people from 17 TxDOT districts responded to the survey.

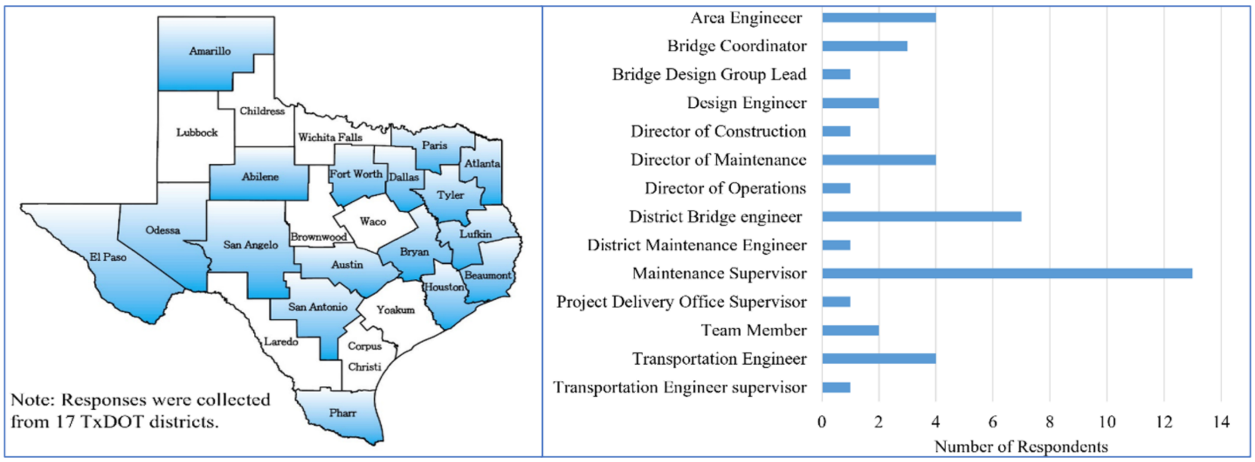


**Figure 11.1.** Districts (Left) and positions (Right) of survey participants (Texas)

### C-2 Out-of-State Participants

Figure C.1 illustrates the locations and positions of the out-of-state respondents. In total, thirty-four responses were collected from the District of Columbia (DC), Quebec province in Canada, and 21 states besides Texas

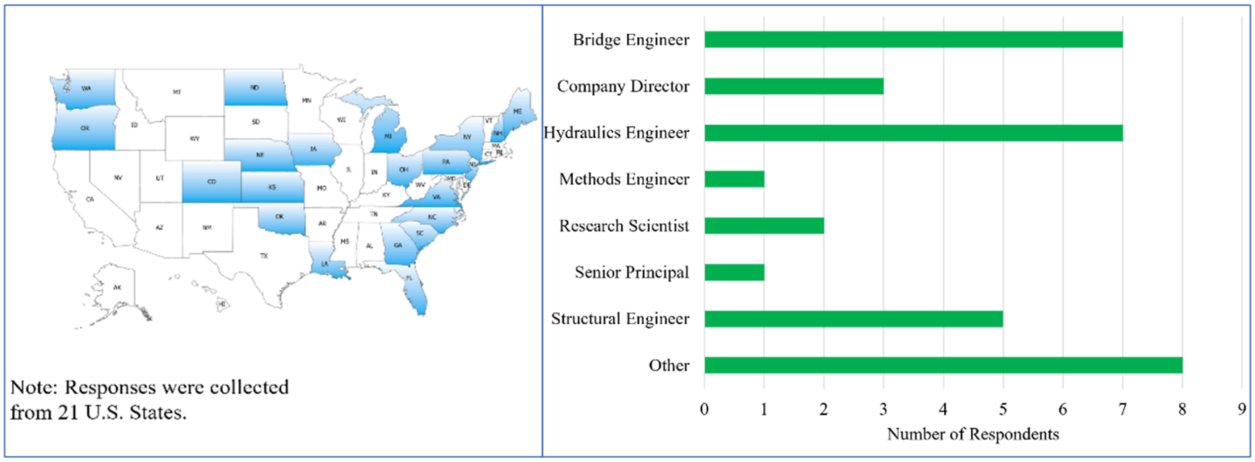


**Figure 11.2.** U.S. States (Left) and positions (Right) of survey participants (excluding Texas)

## C-3 Bridge Deck Drain Failure

### In-State Results

The TxDOT survey responses for the evaluation of bridge deck drain failures are summarized in Figure C.3. Most participants from Texas answered the bridge flooding only occurs during severe rainfalls and lasts less than 30 minutes. Additionally, most participants (76%) identified clogging of inlets to be the most common problem found in bridge deck drains.

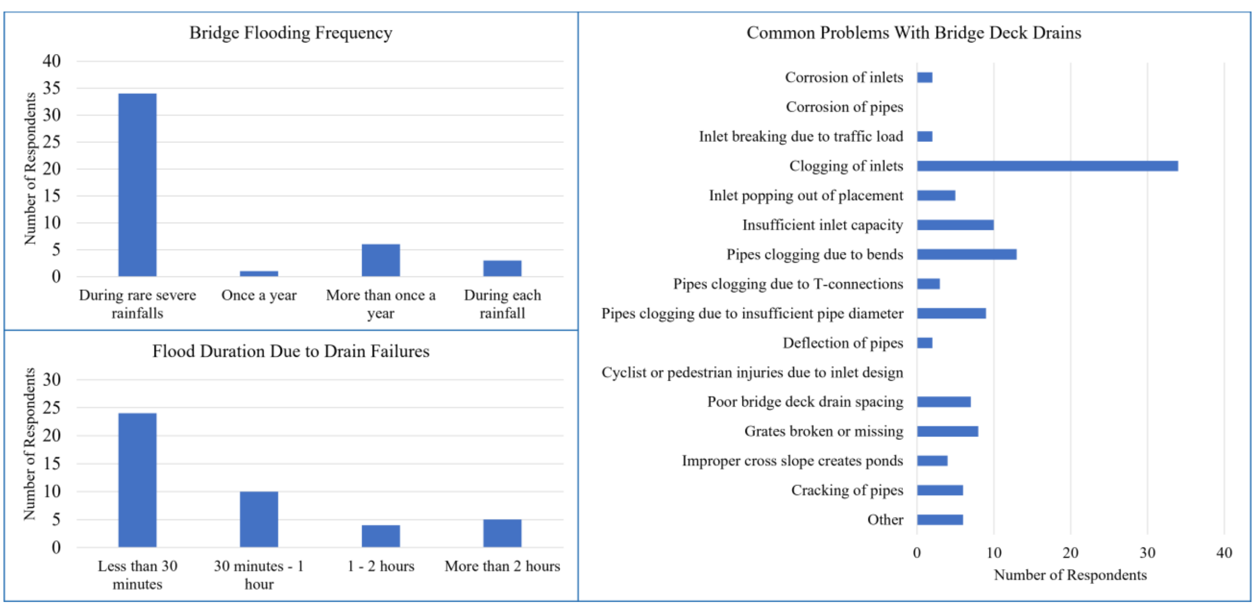


**Figure 11.3.** Summary of survey responses on bridge deck drain failure (Texas)

Other problems identified by the participants include the corrosion of pipe hanger connections, inlets overlayed by asphalt, and insufficient outlet capacity.

### Out-of-State Results

Similar to the above figure, the out-of-state responses regarding the failure section are summarized in Figure C.4. The results collected were similar to that of the Texas survey; bridge flooding usually only occurs during sever rainfall events and lasts less than 30 minutes. Some floods may last up to 2 hours in some states. 94% of out-of-state respondents selected clogging of inlets to be the most common problem, followed by pipes clogging due to bends (64%), pipes clogging due to insufficient pipe diameter (50%), corrosion of pipes (41%), and corrosion of inlets (38%).

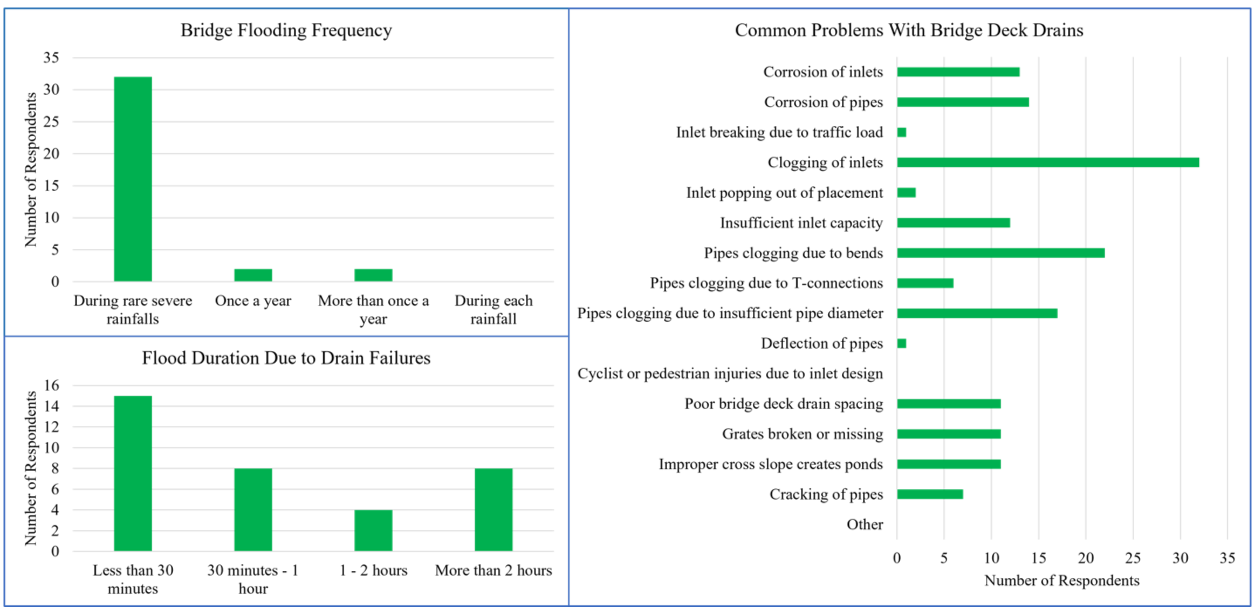


**Figure 11.4.** Summary of survey responses on bridge deck drain failure (outside Texas)

### C-4 Bridge Deck Drain Design

#### In-State Results

After the failure section, the surveys moved on to asking about the design of bridge deck drains. Figure C.5 summarize the results of most design questions received from Texas participants. When asked about the reasons for selecting closed deck drains as the bridge drainage system, twenty-one respondents considered existing facilities or waterways underneath the bridge as the main reason for selecting closed deck drains, followed by seventeen that considered the type of road as a contributing factor to choosing closed drains. The participants were also asked about system preference, where hung systems received the vote of twenty-six respondents. Eighteen respondents mentioned they prefer embedded closed systems. The survey also aimed to capture the reasons for selecting hung and embedded systems; embedded systems seemed to be mostly used for aesthetic reasons. On the other hand, deck drains hung on the exterior of the bridge were chosen based on available outlet locations. Additional reasons identified for selecting hung systems are: the ease of maintenance or replacement of inlets or pipes after clogging, lower associated risks (rupture detected easily), the convenience of post-construction installation, and the ease of replacement and repairs. One participant mentioned they preferred embedded systems because of lower lifecycle costs. When the participants were asked to select one component having the top priority to receive design improvement, design of grate inlets and increase in pipe size were chosen, respectively. Other priorities provided by the participants are provided at the bottom of Figure C.5.

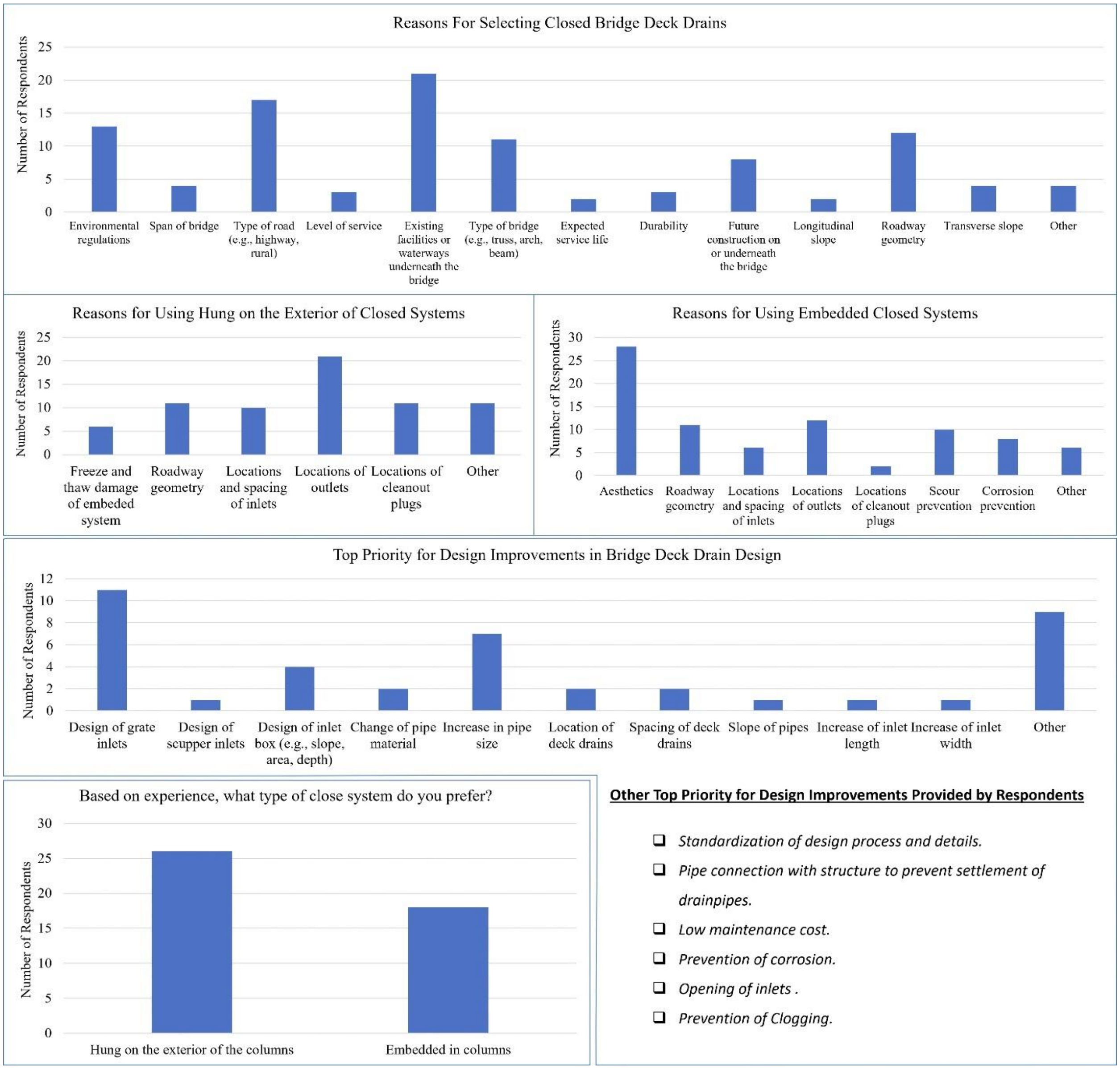


**Figure 11.5.** Summary of survey responses on bridge deck drain design (Texas)

The last question in the design section asked for recommendations to improve the designs of bridge deck drains. The recommendations from the respondents are summarized below:

- Design drains to have easy maintenance access for lower maintenance costs and higher service life.
- Standardize the design and detailing of closed bridge deck drains.
    - Two engineers may draft different details and drawings.
    - Generally, the drawn details are unclear, and poor drain performance can be partially due to how drawings are drafted.
- Develop a design method to calculate the capacity, flow, size, and spacing for the drainpipes at inlets and outlet locations.
- Use more embedded drains for aesthetic reasons.
- Use more robust, non-corrosive materials.
- Use inlets with higher capacities and conveyance.
- Design drains to achieve self-cleansing velocities.

**Out-of-State Results**

In the design section of the out-of-state survey, existing facilities underneath the bridge and environmental regulations were the main reasons for choosing closed systems (Figure C.6). Aesthetics were the deciding factor for choosing embedded systems. Three respondents from Tennessee, New Hampshire, and North Dakota mentioned that embedded systems are not used in their states. Locations and spacing of inlets followed by the freeze and thaw damage observed in embedded systems were the main reasons for selecting hung systems. Another provided reason for choosing hung systems is the ease of installation and maintenance compared to embedded systems. Twenty-eight respondents prefer hung systems to embedded ones, and only four respondents mentioned they prefer embedded systems. Three design improvement priorities were identified;

design of scupper and grate inlets, design of inlet boxes, and location of deck drains. A respondent from North Carolina recommended that states stop using bridge deck drains.


**Figure 11.6.** Summary of survey responses on bridge deck drain design (outside Texas)

The out-of-state survey contained additional questions asking about the pipe material used for deck drains and reasons for using them. The survey also enquired about problems found in these materials. Figure C.7. shows Polyvinyl Chloride (PVC) to be the most common pipe material used for bridge deck drains. The other pipe materials used are ductile iron, fiberglass, and steel. An additional pipe material was identified from a participant in New Hampshire. They mentioned that Fiberglass Reinforced Plastic (FRP) pipes are used for bridge deck drains.

| **Bridge Deck Drain Pipes** | | CO | FL | KS | LA | ME | MI | MN | NE | NJ | NY |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pipe Material** | PVC | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ |
| | Fiberglass | ✓ | | ✓ | | ✓ | | | | | |
| | Ductile Iron | ✓ | | | | | ✓ | | | | ✓ |
| | Steel | | | | ✓ | | | ✓ | | | |

| **Bridge Deck Drain Pipes** | | NC | ND | OK | OR | ON CANADA | PA | SC | TN | VA | WA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pipe Material** | PVC | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | |
| | Fiberglass | | | | | | ✓ | ✓ | | | |
| | Ductile Iron | | | | | | | | | ✓ | ✓ |
| | Steel | | ✓ | ✓ | ✓ | | ✓ | | | | |

**Figure 11.7.** Pipe materials used for bridge deck drains acquired from the survey (outside Texas)

After identifying pipe materials, the survey moved on to asking the participant about the reasons for selecting their chosen material, as well as about the problems found when using that material. Results showed that PVC pipes were preferred because of their resistance to corrosion, lightweight, and ease of installation. Fiberglass was selected because of its resistance to corrosion, and low maintenance requirements. Ductile iron also requires less maintenance and it is durable. Finally, steel pipes offer durability and corrosion resistance when galvanized. Figure C.8 below summarizes the responses regarding the reasons for selecting different pipe materials.


**Figure 11.8.** Reasons for selecting pipe materials (outside Texas)

Figure C.9 below presents the responses collected in regards to the problems found in pipe materials. A respondent from New Hampshire mentioned identified one disadvantage in FRP pipes: the high price of the material.

**PVC**

- Connections
- Cracking
- Durability
- Water hammer
- Aging
- Clogging
- Vandalism
- UV damage
- Joints
- Reaction to water forces
- Freeze and thaw cracks
- Joints can leak

**Fiberglass**

- Durability of fittings and joints
- Cracks and breaks easier than other types

**Ductile Iron**

- Corrosion
- Cracking
- Connection failures
- Heavy weight (difficult installation)

**Steel**

- Corrosion (includes galvanized steel)
- Clogging (plugs up)
- Cleanouts seize over time
- Surface rust discolors the concrete

**Figure 11.9.** Common problems with bridge deck drainpipes (outside Texas)

The participants were also asked to provide recommendations to improve the service life of bridge deck drains. The results are listed below:

- Eliminate the use of bridge deck drains.
  - They capture less runoff than what they are designed for.
  - The means to allow overflow in larger events should be considered.
  - Hung and exposed systems need to be eliminated.
- Make maintenance access easier and create a better maintenance routine.
- Use a more defined interface between structural design preferences for deck drain location and performance and hydraulic preferences.
- Incorporate stormwater treatment into the drain system.
- Restrict bypass flow at each bridge-end collector (catch basin or flume off the bridge).
- Use vertical pipes through openings instead of grate inlets.
- Use curb opening style inlets with improved throats.
- Design scuppers to be self-cleansing.
  - Pressure washing twice a year.
  - Inlets readily collect dirt and debris, and weed start growing on them.
- Improve shoulder width.
  - AASHTO allows for flexibility in shoulder width on long-spanned bridges.
- Remove the 90° turn at inlets.
  - Causes pipes to clog.

The last question in the design section of the out-of-state survey asked about innovative systems and designs of bridge deck drains. The recommendations from the respondents are summarized below:

- Use fiberglass-reinforced plastic (FRP) pipes.
- Use FRP scuppers and downspouts for durability.
- Consider an open “trough” type design to capture small flows.
  - Larger flows can overflow.
- Increase frequency of cleanout inspections.
- To the extent practicable, use slotted connections that allow overflow if the system get overwhelmed.

## C-5 Bridge Deck Drain Construction

### In-State Results

After the design section, the surveys moved on to ask about construction practices related to bridge deck drains. The construction section consisted of two questions that inquired about:

- Practices that negatively impact the performance or service life of drains.
- Recommendations for improving the installation of drains.

The practices that were found to negatively impact the performance or service life of bridge deck drains are:

- Lack of inspections.
- Improper design of pipe hangers and pipe expansion joints.
- Change of grade and alignment without engineers' approval.
- Improper installation of inlets by contractors according to the plans.
- Use of PVC for pipe runs.
- Difficulty accessing cleanouts.
- Use of small diameter pipes.
- Too many bends.
- Failure of weak hangers that creates handing drains.
- Hanger corrosion.
- Design of unsupported joints.

Recommendations for improving the construction and installation of bridge deck drains are summarized below:

- Designers need to pay more attention to drains, support, and expansion joints.
  - A lot of details are usually left for contractors.
- Inspection documentation should be added to the site manager sampling and testing requirements.
- Vegetation growth at the outlet must be considered.
- Supports for hung systems need to be improved.
- All sag points must have drain slots.
- Post-construction inspection should be performed to check if any sag points are created accidentally.
- A waffle-type opening at the deck drain could be helpful.
  - Prevents many types of debris from entering and clogging the pipes (e.g., 20 oz. water bottles).
- Standard designs with good and clear details must be developed.
- Durable materials need to be specified, and ample capacity for significant rainfall events needs to be provided.
- Robust inlets and grates should be used to prevent the infiltration of large materials that tend to clog the systems.

**Out-of-State Results**

The practices that were found to negatively impact the performance or service life of bridge deck drains are:

- Not cleaning out construction debris.
- Not extending drains below bridge decks.
- Not constructing at the correct slope or other design specifications.
- Not sealing correctly around the drains.
- Using materials that corrode (including galvanized steel).
- Using inappropriate connections.
- Using improperly constructed supports.
- Finishing work around the inlets improperly.
- Resurfacing decks improperly. That often affects the inlet flow performance negatively by changing the pavement depth to be exact.
- Setting grates against barriers improperly.
- Resurfacing decks improperly. That often affects the inlet flow performance negatively by changing the pavement depth to be exact.
- Setting grates against barriers improperly.
- Pouring concrete in embedded drains during the column pour.
    - Makes the drain unusable, so an external drain must be installed.
- Difficulty of cleaning embedded closed systems.

Recommendations for improving the construction and installation of bridge deck drains from the out-of-state survey are summarized below:

- Follow specifications.
- Use proper materials.
- Improve scupper designs.
- Use better details and inspection methods (they are not typical plumbing systems).
- Use exact coordinate tables in the plan set.
- Make sure space is small between grate inlets and curbs/barriers.
- Minimize the number of bends.
- Increase pipe slope, if possible.

## C-6 Bridge Deck Drain Maintenance & Inspection

### In-State Results

Finally, questions pertaining to the maintenance and inspection of bridge deck drains were presented after completing the construction section. Figure C.10 below illustrates the Texas results collected when asking about the party conducting maintenance, types of inspections, and method and schedule of maintenance. Results show that TxDOT primarily conducts maintenance operations on deck drains. Routine inspections are most common for these systems. Finally, method and schedule of maintenance highly depends on inspection recommendations followed by deck drains' performance observed. Additionally, a respondent mentioned that no maintenance is scheduled in their district.

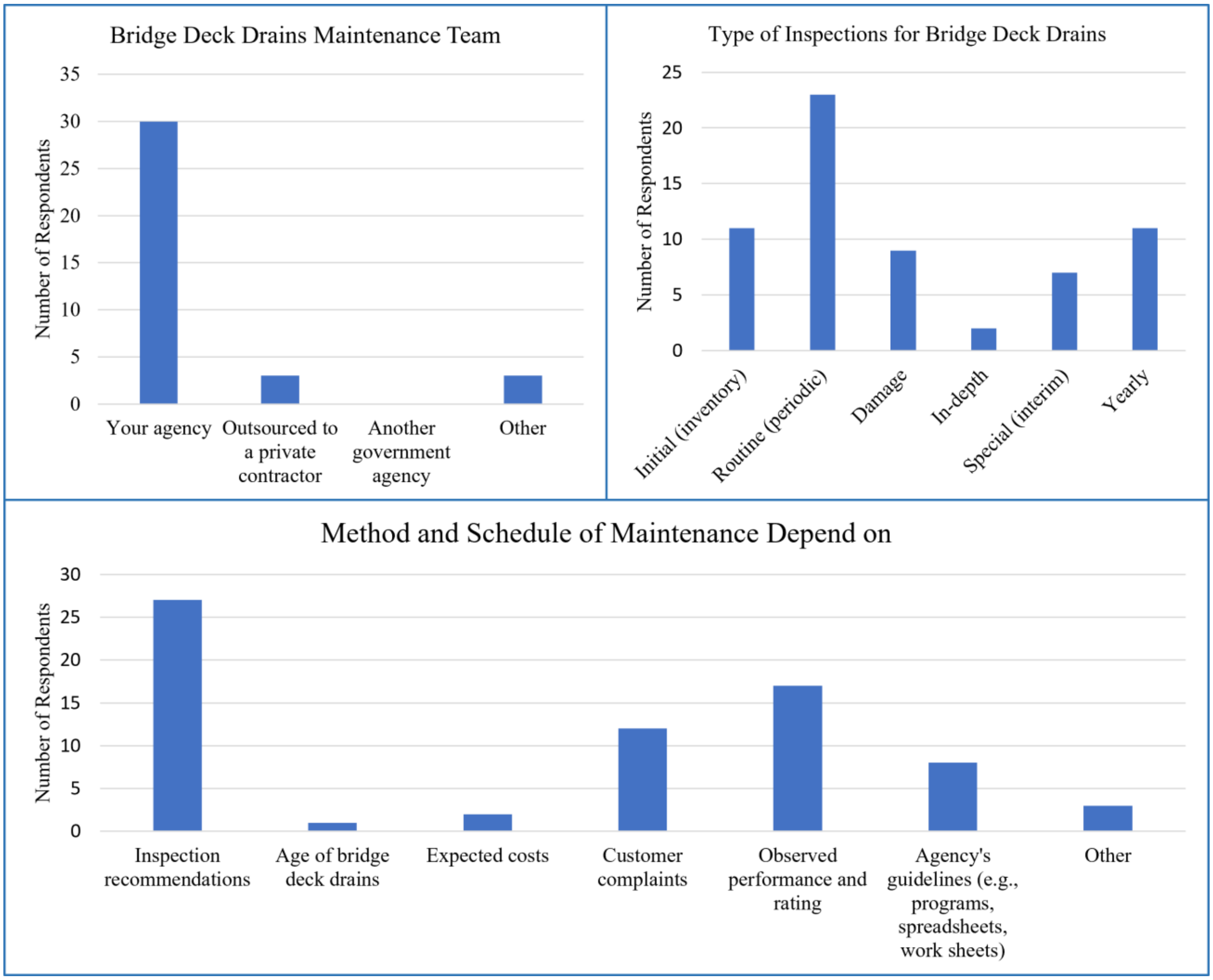


**Figure 11.10.** Bridge deck drains inspection and maintenance (Texas)

The survey then enquires about cleaning equipment, maintenance approach, as well as the end location of drained runoff. The results are presented in Figure C.11 below. In Texas, the most common cleaning method is using hand or hand tools, followed by low-pressure washing. Since closed systems require frequent regular preventative maintenance, it was selected as the main maintenance approach. Finally, most bridges in Texas drain the water to existing soil underneath the bridge.

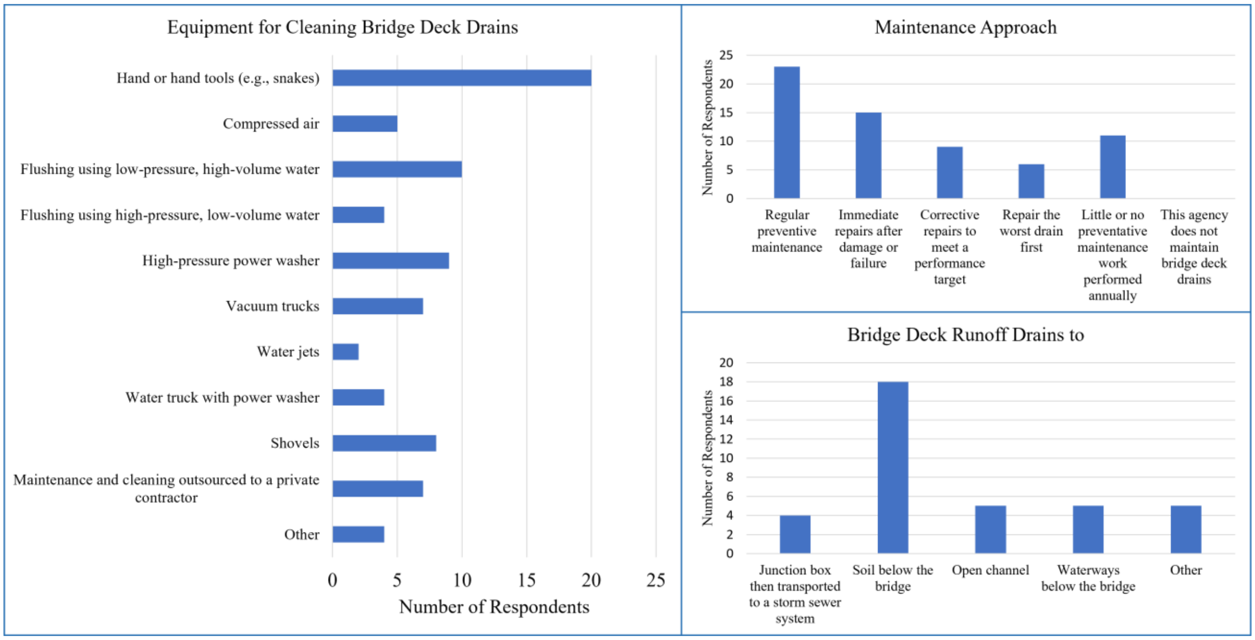


**Figure 11.11.** Cleaning equipment, maintenance approach, and runoff end location (Texas)

Moreover, the participants were asked to identify the inventory data collected on bridge deck drains. Figure C.12 below displays the deck drain data collected in Texas. Inspection dates, images, and existing conditions were the most collected data for bridge deck drains. One participant mentioned that bridge deck drains are rarely included in bridge inspections. Nine respondents mentioned that no inventory exists, which makes it seems that difficulties are currently found in regard to tracking the performance and maintenance of deck drains.

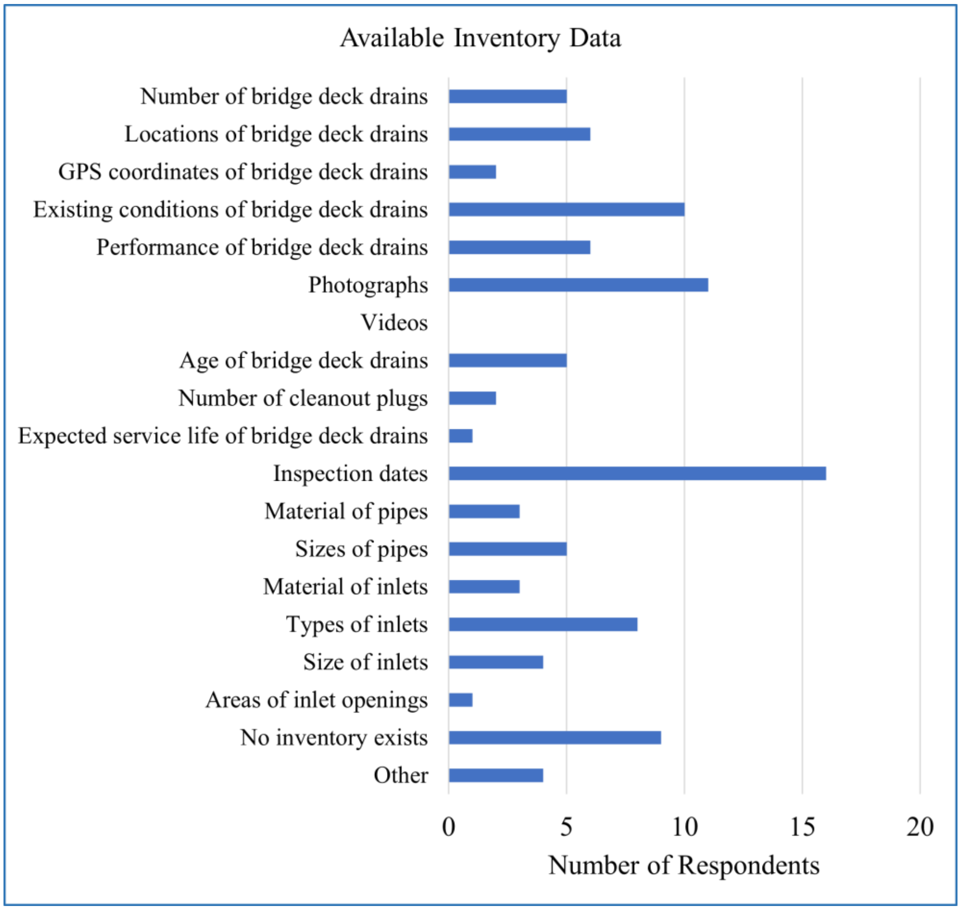


**Figure 11.12.** Available inventory data on bridge deck drains (Texas)

The last two questions in the survey ask about the methods for determining where deck drains are in their service life, as well as if the participants had recommendations for improving the service life of deck drains. The results are summarized in Figure C.13, where conducting regular preventative maintenance, increasing the number of cleanout plugs, and placing drains conscientiously were the top three recommendations for improving service life. Visual based inspections seemed to be the dominant method for determining where deck drains are in their service life.

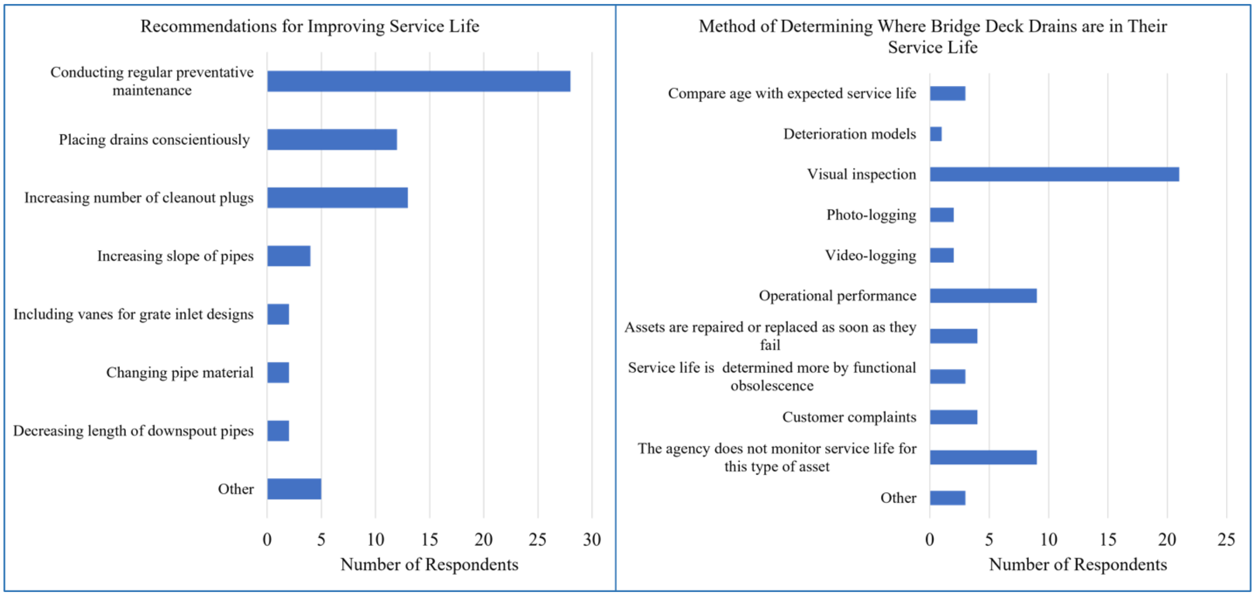


**Figure 11.13.** Recommendations for improving service life (Left) and determining where drains are in their service life (Right) (Texas)

### Out-of-State Results

The out-of-state survey had the same maintenance and inspection questions as the Texas survey. Figure C.14 below shows that most State DOTs are responsible for deck drain maintenance. Additionally, routine inspections were found to be the prevalent type of inspection done on deck drains. Method and schedule of maintenance highly depend on inspection recommendations. Observed performance and customer complaints also contribute to scheduling maintenance for deck drains.

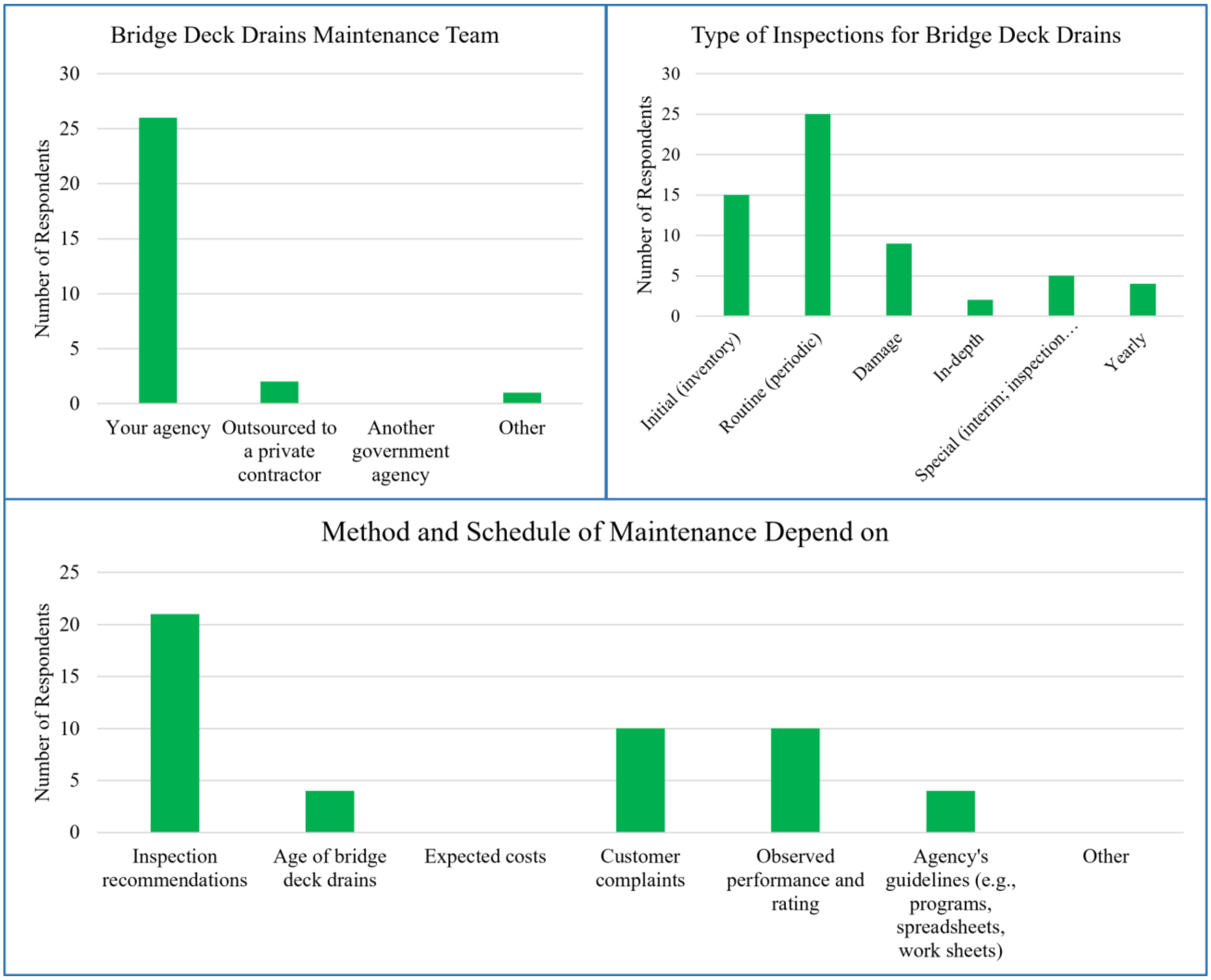


**Figure 11.14.** Bridge deck drains inspection and maintenance (outside Texas)

Since results show that clogging of inlets as the most common problem found, hand or hand tools were the most used cleaning method. Low-pressure flushing was also chosen as a common cleaning method. Twelve respondents chose regular preventative maintenance as the maintenance approach for drains, eleven mentioned that little or no maintenance is done on their states' deck drains. Most bridge runoff in the US is drained to soil underneath the bridge. One respondent mentioned that the runoff is drained to stormwater systems. Figure C.15 below presents the full set of results.

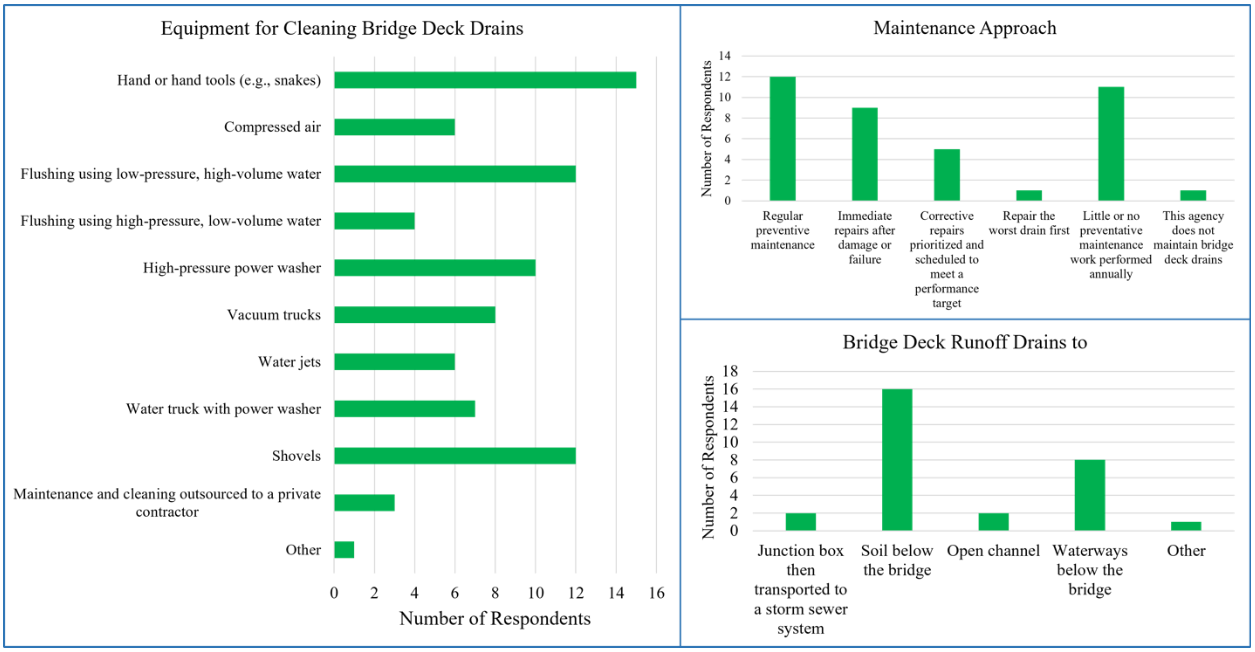


**Figure 11.15.** Cleaning equipment, maintenance approach, and runoff end location (outside Texas)

When asked about the type of inventory data collected, photographs and existing conditions were mostly chosen. Although other data is also collected, eleven participants claimed no inventory exists. Figure C.16 presents the results of inventory data collected on bridge deck drains.

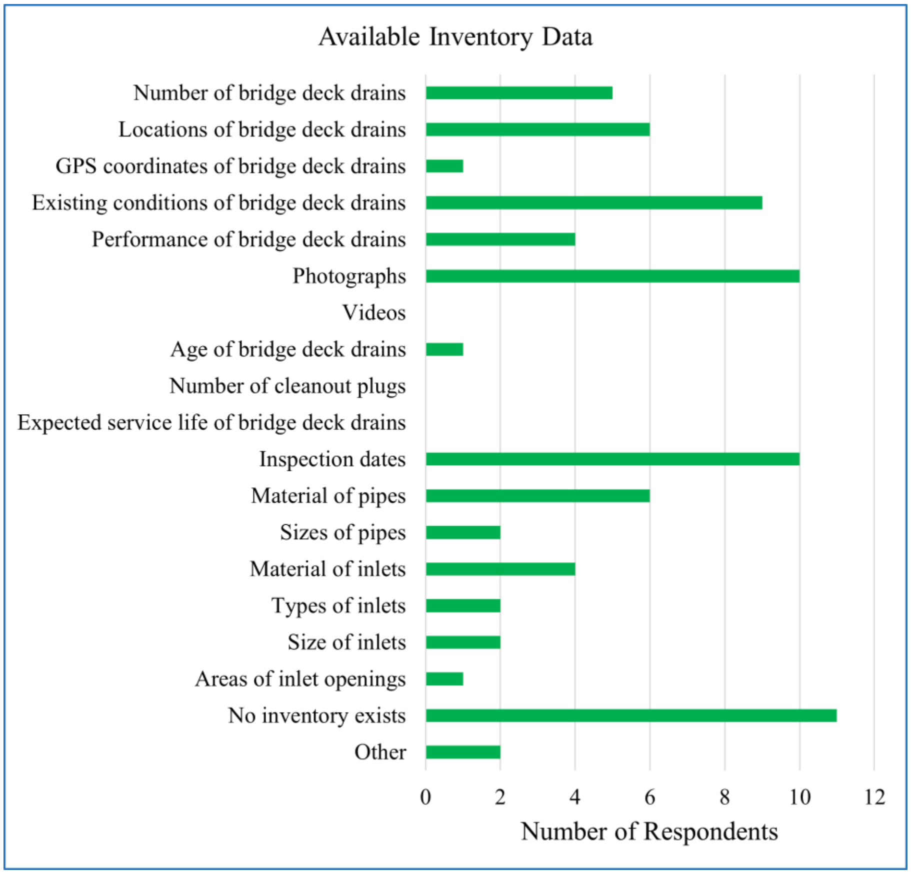


**Figure 11.16.** Available inventory data on bridge deck drains (outside Texas)

Similar to the Texas survey, regular preventative maintenance was the top recommendation chosen for improving the service life of bridge deck drains (Figure C.17). A few participants recommended increasing drain spacing and allowing higher spread through increasing shoulder width. The dominant method for determining where deck drains are in their service life was found to be visual inspection.

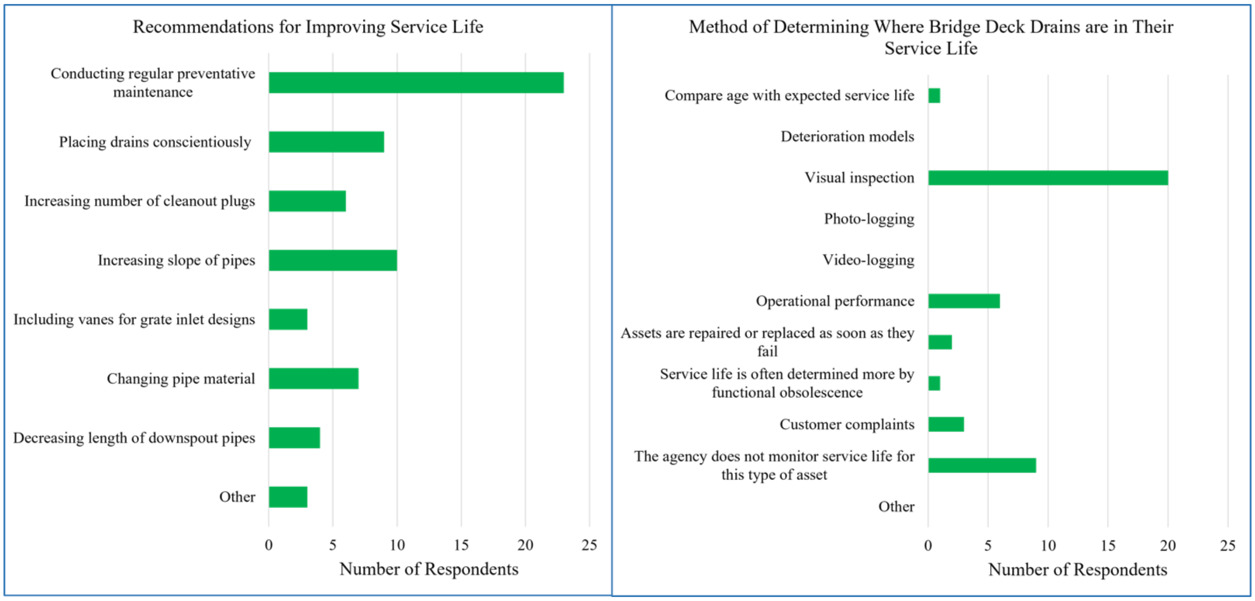


**Figure 11.17.** Recommendations for improving service life (Left) and determining where drains are in their service life (Right) (outside Texas)