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Synthesis Study:
Overview of Readily Available Culvert Inspection Technologies

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16. Abstract

Culverts, conduits that facilitate passage of water beneath roadways and other structures, represent important components of infrastructure systems, helping to drain, direct or divert surface water and prevent the disruption of roadways. Their efficient inspection and maintenance is thus critical to safe operation of Indiana's transportation infrastructure. Although approximately 25% of culverts associated with INDOT managed roadways are inspected each year, inspectors face many challenges determining the actual condition of culverts, which can vary substantially in material type, form, length, depth of cover, accessibility, and age. This study was therefore performed to understand and synthesize technical culvert inspection alternatives with a focus on identifying and prioritizing readily available solutions.

Research revealed that no standard inspection guidelines exist for small culverts, and that inspection practices vary significantly across states. DOT survey results indicate that DOTs primarily rely on visual examination conducted by field personnel, often from the open ends of the culvert, limiting the range of flaws and failure modes that can be identified, and the desired early warning benefits of inspection. While a range of technologies exist to facilitate inspection, most methods apply to only a limited set of culvert materials and operating conditions. This study thus provides a ranked recommendation of readily available culvert inspection solutions, segmented according to their applicability to varying culvert conditions and inspection needs. Techniques involving mobile visual camera systems and multi-sensing modes stand out for their potential to provide insight into the condition of a variety of culvert types at moderate cost.

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EXECUTIVE SUMMARY

SYNTHESIS STUDY: OVERVIEW OF READILY AVAILABLE CULVERT INSPECTION TECHNOLOGIES

Introduction

Culverts, conduits that facilitate passage of water through embankments or beneath roadways and other structures, represent important components of infrastructure systems, helping to drain, direct, or divert surface water and prevent the disruption of roadways by overtopping flows or erosion. According to the Indiana Department of Transportation, there are likely more than 80,000 culverts beneath Indiana roadways with a cross-sectional width between 10″ and 42″. Their efficient inspection and maintenance is thus critical to safe operation of Indiana's transportation infrastructure.

Approximately 25% of culverts associated with INDOT-managed roadways are inspected each year under INDOT Work Performance Standard 2320, with enhancements to the inspection procedure recommended and implemented as recently as 2014. Although inspection procedures have become more rigorous through these efforts, inspectors face many challenges in determining the actual condition of culverts, which can vary substantially in material type, form, length, depth of cover, accessibility, and age. This study was performed to understand and synthesize alternative culvert inspection methods, with a focus on identifying and prioritizing readily available solutions.

Findings

This study revealed that no standard inspection guidelines exist for small culverts and that inspection practices vary significantly across states. DOT survey results confirmed that most DOTs do not have a specific technical solution for small to medium culvert inspections and instead rely primarily on visual examination conducted by field personnel, often from the open ends of the culvert, which limits the range of flaws and failure modes that can be identified and the desired early warning benefits of inspection. The synthesis of available technical solutions demonstrates that a broad range of technologies are available to facilitate culvert inspection. However, many methods can only be employed for a limited set of culvert materials and operating conditions. As a result, more broadly applicable inspection methods such as visual camera-based and multi-sensing techniques stand out for their high potential to provide significant insight into the condition of a variety of culvert types at low to moderate cost.

Thus, the focus for DOTs such as INDOT should be developing and deploying a low-cost multi-sensing solution founded on visual techniques, with the added ability to navigate within a culvert via deployment on a remote-controlled mobile platform (e.g., a radio controlled (RC) vehicle)—a method broadly termed a visual-camera-on-crawler solution. Inspiration for this type of system can be derived by combining devices such as the Ultrasonic Culvert Inspection System developed by the Southwest Research Institute (SwRI) and FHWA, with additional capability to be mounted on a crawler for use in dry culvert conditions. Additionally, for visual-camera-on-crawler techniques, improvements such as the use of a side-scanning camera could greatly enhance efficiency and effectiveness by eliminating the need for stopping, panning, tilting, and zooming, thereby reducing the in-field time and effort of the system operator. Aside from adopting technology to facilitate inspection, a long-term goal should be developing a systematized phase-wise approach for issue detection and maintenance of culverts. Such a system would be particularly valuable when used in combination with the Esri Collector Application database that INDOT has commissioned for infrastructure maintenance. Furthermore, as data is collected via these systems, stochastic predictive models could be developed to provide INDOT asset managers with an informed rationale to schedule inspections and enhance overall resource utilization and efficiency in the inspection and maintenance of culvert infrastructure.

Implementation

The results of this synthesis study provide a ranked recommendation of readily available culvert inspection solutions. The recommendations are segmented according to their applicability to varying culvert conditions and inspection needs, including culvert material, flow condition, deployment constraints, and inspection time. Model numbers, vendor-related information, and, to the extent possible, general cost estimates are provided to assist in technology acquisition and development decision-making.

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REPORT STRUCTURE AND OVERVIEW

This report provides an overview of potential culvert inspection technologies and related recommendations for readily available solutions that can enhance the potential to increase the cost-effectiveness and efficiency of small culvert inspections. The opening of the report introduces the importance of culvert inspection and significance of related challenges, defines the scope and specific objectives of this research effort, and outlines the adopted research approach. Technical solutions are detailed in Chapter 5 based on an in-depth review of the inspection technology literature and related vendor offerings using the sources mentioned in Chapter 3. The evaluation framework described in Chapter 3 is then used to assess all of the technologies identified. The analysis is synthesized in Table 5.5 where the applicable technologies are organized based on their respective operating principle, extent of applicability to our problem, and whether or not a prototype or commercially available tool utilizing the technology exists. Figure 5.16, at the end of section 5.1 indicates the type of defect(s) that can be detected by various technologies for three primary culvert material types. Table 5.4 in section 5.2 covers specific vision-based tools that have been developed to inspect culverts so as to avoid human entry. It also categorizes them by usability in differing flow conditions. Separately, detailed information regarding the questionnaire developed for the nationwide survey of DOTs is included in Appendix A. Table 5.5 in section 5.3 categorizes technologies based on their deployment mode, applicability to culvert inspection based on material type, and provides vendor and model details including available cost data. It also includes reference links to technology vendor/model webpages. Furthermore, high potential technologies are distilled from the analysis, and a segmented solution prescription framework mapping technology to conditions of use is developed in Figure 7.3. Finally, a ranked recommendation of inspection technology options is also provided in Figure 7.4. In conclusion, a systematized phase-wise approach for issue-detection and maintenance is suggested as a possible mechanism for culvert (as well as other infrastructure) inspection and maintenance.

1. INTRODUCTION AND PROBLEM STATEMENT

Culverts, conduits that facilitate passage of water beneath roadways and other structures or through embankments, represent important components of infrastructure systems, helping to drain, direct or divert surface water and prevent the disruption of roadways by overtopping flows or erosion. According to the Indiana Department of Transportation, there are likely in excess of 80,000 culverts beneath roadways in Indiana within the size range of 10″ to 42″ in cross-sectional width. Their efficient inspection and maintenance is thus critical to safe operation of Indiana's transportation infrastructure. In addition, although rare, several culvert failures have occurred in Indiana. While only limited data exists on the costs of such failures, studies indicate that these costs include not only the installation and replacement of the culvert, but reconstruction of the failed roadway, potential costs associated with neighboring property damage, user delay costs, and, often, considerable political costs (Bowers, Magers, Pyrz, & Bullock, 2014). Specific cases of culvert failure and replacement noted in the report by Perrin and Jhaveri, which focused on interstate and state highways with 3% to 30% commercial vehicle traffic, described traveler delays of 20 minutes to 4 hours (e.g., due to detours) and total costs of $265,000 to $8 million per failure, highlighting the significance of proper culvert inspection and maintenance.

Under current practices, approximately 25% of culverts associated with INDOT managed roadways are inspected each year under INDOT Work Performance Standard 2320, with enhancements to the inspection procedure recommended and implemented as recently as 2014 (Bowers et al., 2014). Although inspection procedures have become more rigorous through these efforts, inspectors face many challenges determining the actual condition of the culvert which is typically evaluated on a qualitative scale from "excellent" to "critical". The installed base of culverts varies substantially in material type (e.g., precast concrete, varying formulations of plastic pipe, corrugated steel, and clay), form (e.g., circular pipe, three-sided structure, box structure), span (culverts are defined as "structures with a span length of 20 feet or less" in the 2013 Indiana Design Manual (Ch. 203)), length (e.g., some may exceed 300′ in length), depth of cover, accessibility, and age. Current inspection procedures rely upon manual visual examination performed from the ends of the conduit using simple tools such as flashlights, and handheld probes and mirrors. For culverts of small to medium diameter (10″ to 42″) which qualify as confined spaces, the effectiveness of these inspection procedures is very limited. Oftentimes culverts may only be accessible from one side and/or their lengths are such that only a cursory examination can be performed. In addition, many culverts contain water or soil at the time of inspection leading to an obstructed view of the actual conduit, which further inhibits determination of culvert integrity and function.

Culvert inspection may be performed for a variety of purposes ranging from general roadway/bridge inspections to locating them while conducting earthwork operations. Many INDOT projects also require locating or mapping existing culverts. Installation of thermoplastic culverts are followed by checks for ovality, which are also categorized as inspection. Yet another function of inspection is to generate CAD drawings for existing culverts that could aid in rehabilitation design decision making. With a focus on inspection for structural integrity, Table 1.1 highlights some of the common defects observed in different culvert material types.

TABLE 1.1
Common defects for different culvert materials/types (Yang & Allouche, 2009)

	Cementitious			Metallic	
Defects	**Cast-in-place**	**Pre-cast**	**Thermoplastic**	**Pipe**	**Structural plates**
Cracks	Yes	Yes	Yes	No	No
Spalls	Yes	Yes	No	No	No
Delamination	Yes	Yes	No	No	No
Joint misalignment	Yes	Yes	Yes	Yes	Yes
Internal/External corrosion	Yes	Yes	No	Yes	Yes
Invert erosion	Yes	Yes	Yes	Yes	Yes
Abrasion/wall thinning	Yes	Yes	Yes	Yes	Yes
Encrustation/debris	Yes	Yes	Yes	Yes	Yes
Pipe ovality	Yes	Yes	Yes	Yes	Yes
Footing defects	Yes	No	No	No	Yes
Slabbing (straightening of curved re-bars)	No	Yes	No	No	No
Defective joints	Yes	Yes	Yes	Yes	Yes
Lateral deflection	Yes	Yes	Yes	Yes	Yes
Crown sag	No	No	Yes	Yes	Yes
Corroded reinforcement bars	Yes	Yes	No	No	No
Dents and localized damage	No	No	Yes	Yes	Yes

2. OBJECTIVES AND SCOPE

The objectives of this Synthesis Study are twofold:

1. conduct a thorough review of technological solutions that are readily available to assess culvert structural integrity and function, and
2. develop recommendations for field trial of high potential technologies that could determine their appropriateness for culvert inspection settings in the State of Indiana, with a focus on examining and summarizing available off-the-shelf (OTS) solutions particularly suited to small to medium culvert inspection.

3. RESEARCH APPROACH

The synthesis presented herein encompassed a multipronged review of literature and databases including the following:

- INDOT/JTRP
- FHWA Database of Priorities, Market-Ready Technologies, and Innovations
- AASHTO's Technology Implementation Group
- Technology Transfer News of the NYDOT
- The Caltrans Division of Research and Innovation monthly videoconferences
- The TRB Research In Progress (RiP) Database
- The TRB TRIS database
- State-of-the-art and review articles in journals and trade publications
- Examination of commercial websites and vendor marketing literature

For each potential solution, information was gathered on the following parameters where available:

- Operating principle (e.g., visual stand-off inspection, contact-dependent non-destructive material evaluation)
- System performance (e.g., accuracy, precision, error)
- Deployment requirements/capabilities (e.g., field crew requirements, transport requirements, inspection time)
- Overall advantages and disadvantages
- Versatility across culvert types and settings (e.g., concrete vs. steel, empty vs. partially full of water)
- Potential to explore multiple culvert failure modes (e.g., hydraulic capacity, soil conditions, joint failure, corrosion/degradation, variations in wall thickness, deflection, cracking)
- Likely field performance (e.g., performance in rain, cold, snow)
- Reliability and maintenance requirements
- Cost (e.g., purchase, installation, maintenance)
- Compatibility with existing INDOT systems/procedures (to the extent available).

In addition to the sources cited above, a nationwide survey of DOTs was conducted to understand their experience with relevant technologies (if any) and/or their knowledge of potentially applicable inspection techniques. 100 valid responses were received from 32 DOTs, with an average of ~3 respondents per state. Collectively, the respondents covered a wide spectrum of roles including directors, engineers of various levels, chief unit leaders, designers, specialists, researchers, managers, and coordinators.

4. CULVERT INSPECTION PROCESS TREE FOR ISSUE DETECTION

A typical proactive culvert inspection system requires up-to-date and accurate asset condition data (Costello, Chapman, Rogers, & Metje, 2007). Specifically, a semi-automated, proactive system involves three key elements, namely a deployment decision process, a sensing inspection and analyses process, and when possible, a database updating process that can convey information about the status/history of the culvert installed base. Figure 4.1 provides a schematic example of a typical

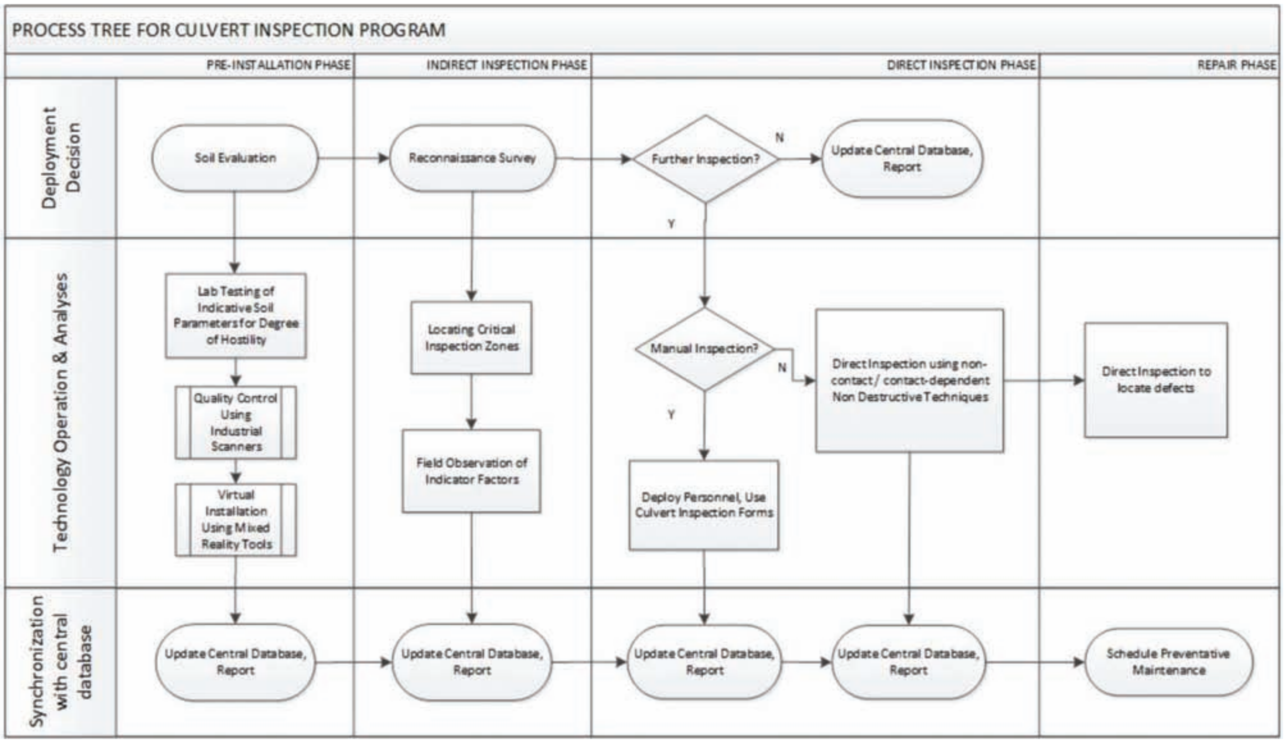


Figure 4.1 Schematic representation of culvert inspection system process tree.

inspection process tree. The figure shows three processes and cross linkages over four phases of a typical inspection. The process begins with a reconnaissance survey to locate any above threshold deviations in roads or drainage patterns near culverts over a large zone. The reconnaissance survey may be conducted using photogrammetric tools which are either terrestrial or aerial manned/unmanned vehicles fitted with 3D mapping tools passing through the zone under consideration. Reconnaissance can be done specifically for those areas that are already marked critical in the central database. Based on the result, a decision is made on further (direct) inspection. If the culvert is accessible, visual inspection may be carried out. Otherwise, one of the proposed techniques can be employed (as described in section 5). Finally, the diagram highlights a key message that calls for a system solution to tackle the issue of culvert inspection before damage occurs. This is necessary, as although rare, culvert failures lead to high cost delays and significant overall costs.

5. EXISTING AND POSSIBLE CULVERT MONITORING SOLUTIONS

A comprehensive literature review and database search was completed that encompasses perspectives on existing/commercially available culvert inspection technologies from the sources outlined in Chapter 3. This review led to the development of a fundamental taxonomy of available state-of-the-art inspection technologies (Table 5.1).

As illustrated in Table 5.1, the choice of technology for effective culvert inspection can be categorized as:

a. Methods applied indirectly that involve observing symptomatic conditions in either roadways, guide rails, embankments, drainage patterns or soil conditions, which are indicative of possible culvert damage and/or failures; and
b. Methods that can be directly applied to the damaged culvert at hand, to conduct a detailed inspection and eventually come to a solution decision. Non-OTS technologies that are yet to be realized by manufacturers have been noted from a technology obsolescence and upgrade perspective.

For currently market ready inspection technologies (i.e., those that are available off-the-shelf (OTS)), inspector education, training and integration with current management systems have been shown to be an effective component of any programmatic effort aimed at reducing culvert failures (Bowers et al., 2014; Youngblood, 2017).

For proactive asset management, large-scale photogrammetric surveys conducted by either terrestrial or unmanned aerial LiDAR can facilitate identification of potentially high-risk zones that may then be focused upon using more site-specific technologies. LiDAR based terrestrial / aerial inspection is recommended as it is a highly effective and versatile tool. Moderate days are best for LiDAR, and while there may be measurement difficulties in dense fog and heavy rain conditions, the advantage of these technologies is that no light is necessary, and that because they work on a GPS positioning signal, they work very well even in non-urban areas.

TABLE 5.1
Synthesis of potential state-of-the-art inspection technologies for various culvert material types

Deployment Mode	Inspection Technology	Availability	Applicability
Pre-installation			
Individual Culvert Pipe Inspection			
	3D Laser Scanning (portable)	OTS	M,C,P
	Coordinate Measuring Machines	OTS	M,C,P
	Micro-crack Testing—Liquid Penetrant Testing	OTS	M,P
	Smart Pipes (in-development)	Non-OTS	
	Smart Paints	Non-OTS	M,C,P
Soil/Soil-Culvert System Inspection			
	Soil Evaluation	OTS	M,C,P
	Mixed Reality (in-development)	Non-OTS	M,C,P
Pre-field visit			
	Stochastic Predictive Modeling	Non-OTS	M,C,P
In-field indirect inspection (primarily for priority determination)			
Solution deployed from within/inside/ close proximity to the culvert	Smoke Bomb & Leaf Blower Testing	OTS	M,C,P
Solution deployed at ground surface/outside the culvert	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either		
	- Terrestrial &/or	OTS	M,C,P
	- Non-terrestrial (unmanned aerial vehicle) for large scale surveys	OTS	M,C,P
	Electromagnetic—Ground Penetrating Radar	OTS	M,C,P
In-field direct inspection (for identified high-priority culverts)			
Solution Usable for Culverts 'In-Service'			
Solution deployed from within/inside/ close proximity to the culvert	Visual—Plain / Push-cameras	OTS	M,C,P
	Visual—CCTV Crawler	OTS	M,C,P
	Visual—CCTV Crawler with Side Scanning	OTS	M,C,P
	Electromagnetic—Magnetic Flux Leakage	OTS	M
	Electromagnetic—Ground Penetrating Radar	OTS	M,C,P
	Ultrasonic Scanning / Sonar Profiling (non-optimal)	OTS	M,C,P
	Multi-sensor Profiling—Laser & Sonar	OTS	M,C,P
	Multi-sensor Profiling—Laser & Sonar & Video	OTS	M,C,P
Solution deployed at ground surface/ outside the culvert	Optoelectronic—Laser Profiling (non-optimal)	OTS	M,C,P
	Electromagnetic—Ground Penetrating Radar	OTS	M,C,P
	Thermographic—Infrared Thermography (non-optimal)	OTS	C
Solution Best-Suited for Culverts Taken 'Out-of-Service'			
Solution deployed from within/inside/ close proximity to the culvert	Visual—Plain / Push-cameras	OTS	M,C,P
	Visual—CCTV Crawler	OTS	M,C,P
	Visual—CCTV Crawler with Side Scanning	OTS	M,C,P
	Optoelectronic—Laser Profiling	OTS	M,C,P
	Fully Automated Optoelectronic—Laser Profiling with CCTV and Neural Network Algorithm	Non-OTS	M,C,P
	Electromagnetic—Magnetic Flux Leakage	OTS	M
	Electromagnetic—Eddy Current Techniques (digging and exposing culvert surface is necessary)	OTS	M
	Electromagnetic—Ground Penetrating Radar	OTS	M,C,P
	Acoustic—Ultrasonic Scanning / Sonar Profiling	OTS	M,C,P
	Acoustic—Impact Echo Testing / SASW	OTS	C
	Radiographic—Backscatter Computer Tomography	OTS	M,C,P
	Radiographic—Gamma-gamma logging	OTS	C
	Re-bar Condition Testing—Magnetic Field Disturbance	OTS	C
	Micro-crack Testing—Liquid Penetrant Testing	OTS	M,P
Solution Best-Suited for Culverts Taken 'Out-of-Service'			
Solution deployed at ground surface/ outside the culvert	Optoelectronic—Laser Profiling	OTS	M,C,P
	Electromagnetic—Ground Penetrating Radar	OTS	M,C,P

OTS, off the shelf; M, metallic; C, cementitious; P, plastic.

In addition, foliage density challenges can often be mitigated, which could make this technology useful even for culverts in remote areas. A disadvantage of the method is its high cost, which may be a concern if the technology is used solely for culvert inspection purposes and not combined with other asset inspections that require geospatial surveys.

Besides photogrammetry, certain soil characteristics act as indicative parameters of potential for culvert deterioration. These characteristics include soil resistivity, pH value, redox potential, sulfate concentration, chloride content, moisture content, shrink/swell capacity, buffering capacity, linear polarization resistance, and the presence of contaminants. Table 5.2 highlights the relationships between individual parameters and potential for damage in culverts by material type.

5.1 Detailed Overview of Culvert Inspection Technologies and Operating Principles

Examination of the sources of information outlined in Chapter 3 indicates that currently available culvert inspection systems can be organized at a fundamental level by the *evaluation/sensing approach* employed in any given device or method and its specific operational configuration.

5.1.1 Probabilistic Approach

5.1.1.1 Predictive modeling. Culvert inlets often have trash screens installed on them to prevent the ingress of reasonably sized waste (see Figure 5.1). These screens need to be routinely cleared. However, the inspection must be done manually and there is no tool available to support the screen clearing decision. A 2012 publication in the ASCE Journal of Hydraulic Engineering (Streftaris, Wallerstein, Gibson, & Arthur, 2012) addressed this issue and developed a predictive model based on a Bayesian probability approach. The authors used data from a particular area in Belfast, UK that had 140 small, medium and large culverts and developed a stochastic-predictive model based on Markov chain probability. The model was built using seven variables including, climate and local meteorology

TABLE 5.2
Soil parameters relationship to damage potential in culverts

Soil Parameter	Relationship	Culvert Type
Resistivity	High corrosion rates if low resistivity	Metal
pH value	<4: corrosion of metal and deterioration of concrete stress cracking of polymers >8: corrosion of metal and corrosion of pre-stressed wire	Metal, Concrete & Thermoplastic
Reduction (Redox) potential	High microbial-induced corrosion potential in presence of sulfates and sulfides if high redox potential	Metal & Concrete
Sulfates concentration	Sulfate salts in solution cause sulfate attack on concrete	Concrete
Chloride content	Chloride ions cause corrosion in metal culverts as well as re-bar corrosion in concrete culverts	Metal & Concrete
Moisture content	High moisture relates to high corrosion potential	Metal & Concrete
Shrink/Swell capacity	High shrink/swell capacity soils tend to impart greater stresses	Metal, Concrete & Thermoplastic
Buffering capacity	High buffering capacity correlates with low damage potential	Metal & Concrete
Linear polarization resistance (LPR)	High LPR indicated low corrosion rates	Metal & Concrete
Contaminants	Contaminants can have damaging effects on polymeric materials	Thermoplastic

Source: Liu & Kleiner, 2013.

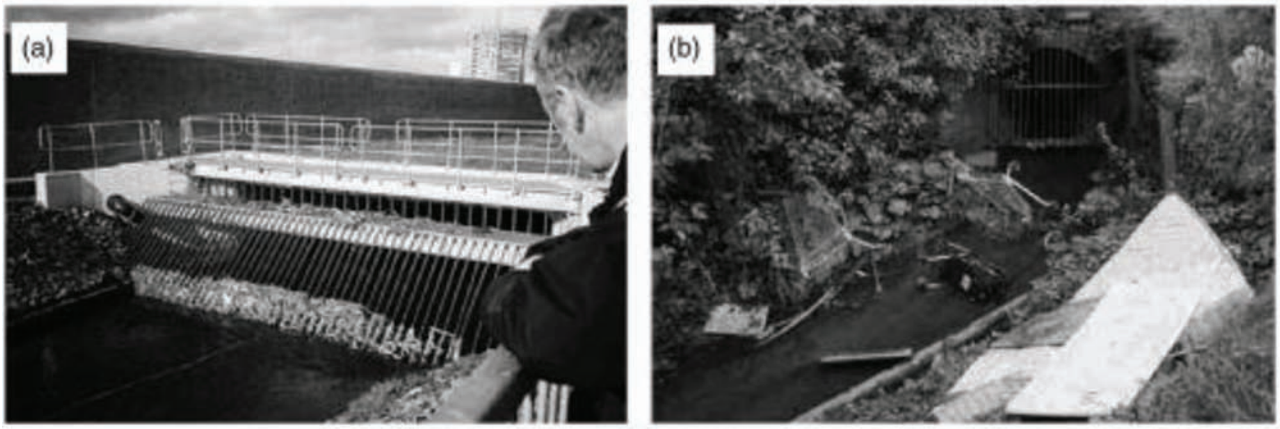


Figure 5.1 (a) Screen protecting inlet to large culvert with leaf-litter accumulation; (b) screen protecting culvert inlet on small channel with fly-tipped waste.

TABLE 5.3
Factors and significant variables defined in the predictive maintenance model of Streftaris et al. (2012)

Factor	Variable	Symbol	Unit	Description
Channel	Network length	L	m	Long-stream channel distance upstream of screen, including all tributaries extending to next upstream screen or to channel headwater if no intervening screens present
	Channel slope	S	m/mm/m	Slope measure adopted in Environment Agency (2009)[1]
Land use	Urban land use	U	%	Land use contributing to screens comprising, for example, industrial premises, urban wasteland, city centers, and shopping precincts
Meteorological	Rainfall	R	mm/day	Mean daily rainfall between inspections
Social deprivation	MDM	MDM	index	Northern Ireland Statistics and Research Agency Multiple Deprivation Measure (MDM)[2]

Source: Streftaris et al. (2012).

[1] Environment Agency. (2009). *Trash and security screen guide*. Flood and Coastal Erosion Risk Management Research and Development Programme. Bristol, UK: Environment Agency.

[2] See Northern Ireland Statistics, and Research Agency (NISRA). (2005). *Northern Ireland multiple deprivation measure: 2005*. Belfast, Northern Ireland: Northern Ireland Statistics and Research Agency.

(rainfall), land use pattern (percentage urban land use), neighborhood category (measure of social deprivation), and river parameters (network length, channel slope, combined-network length × channel slope). The analysis showed that six of the seven selected variables were statistically significant. The model results were then validated on the chosen area by omitting 250 actual observations and comparing observed values with the model predictions. Overall, the model accurately predicted the total number of blocked screens (101.5 as compared to 99 actually observed) thereby providing asset managers a reliable basis to make trade-off decisions and minimize maintenance resource deployment for inspection of culvert screens for trash accumulation. While this model is not commercially available as an off-the-shelf solution, development of a similar model for INDOT could help focus and optimize inspection and clearing operations.

Predictive variables used in the model in the referenced work are shown in Table 5.3.

5.1.2 Visual Approaches

5.1.2.1 Visual inspection-manual. This is the most basic form of culvert condition monitoring where a team of people physically go to the culvert and check it for any damage. The visual inspection involves qualitative examination and allocation of a specific 'quality state' to the conduit ranging from good to poor condition. It is generally conducted using hand tools such as flashlights and push cameras for culvert areas that are difficult to access. Using a push camera, the inspector is able to capture the inside condition of the culvert on video. This data can later be stored. Push cameras are ~2 inches in diameter, are waterproof (up to 2 bar), come with LED illumination, have pan and tilt feature, remote focus, and can also calculate distance. They currently tend to have 5.6-inch displays and the resolution is sharp for this display size (AIT Products, n.d.; see Figure 5.2). However, these are primarily meant for vertical deployment, as they do not have the rigidity required for easy viewing in the horizontal plane. They also do not possess side-scanning features and do not yield a point cloud (digitized) image.

The visual inspection is usually followed by noting the culverts that need attention and re-checking them on a more regular basis. The method is simple and effective in the sense that the system of inspection is well set in functional tasks and the culture for inspection crews. A review of multiple DOT culvert inspection forms highlights that this technique is adopted by many DOTs. However, this method quickly becomes impractical for small sized or inaccessible culverts.

For large as well as small culverts, a homegrown method to conduct a primary inspection on target culverts and specifically check for blockages is currently employed by the West Virginia DOT. As indicated by them, it consists of utilizing a smoke bomb, leaf blower and tarpaulin sheet. The working principle is simple in that the smoke from the smoke bomb is blown using the leaf blower from one end of the culvert. If smoke emerges in ample volume and discharge as expected on the other end, then there is no blockage or leak. Alternatively, the smoke may leak through a damaged section of the conduit or not emerge at the other end due to a complete blockage. This is then further inspected. The West Virginia DOT inspection team noted that they would get calls for inspections after conduits were significantly blocked and that some districts were likely to assume that the inspection team would inspect as well as clean out the blocked conduit. They also reported using this method as a preventative tool and observed significant cases of blocked conduits, as communicated by the West Virginia Highway Engineering unit. The simplicity, usability in low visibility conditions, applicability to culverts of any size, and low-cost requirements prompted inclusion of this method as a preliminary visual inspection approach to check for blockages. However, it does not yield detailed information regarding culvert damage and therefore can be used only as a

Figure 5.2 Pan and tilt push cameras and equipment. (Images from Advanced Inspection Technologies (AIT).)

preventative method or for preliminary inspection. In addition, to employ this method, a team of at least two inspectors must physically visit the culvert.

5.1.2.2 Visual inspection-using crawler mounted CCTV. This technique is considered the gold standard in inspection of sewer lines (Feeney, Thayer, Bonomo, & Martel, 2009). This is because sewer lines are inaccessible and subject to frequent clogging. The technique involves mounting a CCTV camera on a tethered robot that is introduced into the pipe from a manhole and has the capacity to run along a section of the pipe. The 360-degree pan and tilt type cameras generally used are remotely operated. The CCTV equipment may have a fish-eye lens or a normal wide-angle lens, and cameras may be at the front as well as back end of the probe. The setup should be able to produce a clear focused viewing image and video recording ranging from a minimum of 0.6m (2 feet) to about a distance of about ~3m (10 feet) from the lens. The CCTV camera/s send out recordings in real time to the inspection vehicle where the inspector manually assesses the pipe condition. This method is generally known as 'video inspection using crawler'; it is applicable to more than just sewer pipes, and could have potential use in culvert inspection. Crawler bots range in their applicability from 4-inch diameter pipes up to 96-inch diameter pipes (Envirosight, n.d.b). Mounted cameras dictate the image resolution; and certain models studied, offered by specific vendors, claimed resolution of 720 × 576 pixels, which is that of PAL (Phase Alternating Line), an analog standard resolution (Axis Communications, n.d.). The weight of the system (crawler bot and camera) varies with the size of bot employed. A 12.2″ × 4.4″ × 3.2″ bot may be used for pipe diameters 6″ and more (AIT, 2015) and would weigh ~8.2 kg (18 lbs.) for the system. A mechanized cable reel is used as the tether to the system and contains 6 cable conductors.

Although CCTV crawlers (see Figure 5.3) are very popular, they can pose certain usability challenges. These include time related issues such as frequent stopping to pan, tilt and zoom in on defects, and painstaking video reviewing; hardware issues such as high digital bandwidth requirement to share and store large video files; and possibility of human-error. A field inspector may come across a defect and decide to spend field time analyzing it, thereby making it difficult to

Figure 5.3 Crawler mounted CCTV cameras. (Images from CUES Inc.)

estimate culvert coverage over time. In order to overcome a few of these challenges, a technology known as side scanning may be employed (below).

5.1.2.3 Visual inspection-CCTV-cad combined—side scanning. Side Scanning Evaluation Technology (SSET) is deployed just like a CCTV crawler; however, it captures panoramic images at rapid speeds (Lygo, 2017). (See Figure 5.4.) With this data, offline personnel (superintendents, engineers, analysts) can quickly review the entire pipe interior as a flat image scan or navigate a virtual model of the pipe. Optical scanner and gyroscope technology provide the field engineer with the ability to see the total surface of the pipe interior along an entire length of pipe (Costello et al., 2007) and therefore, a side-scan captures greater detail than conventional video and presents it in a format that's easier to review and analyze. Rather than sit through hours of inspection footage, an analyst can view an entire length of pipe at once, quickly pinpointing problem areas and making annotations and measurements directly on them. This assessment can be done, at the office, after the scanning phase and consequently allows asset managers to predict field production rates. Side-scans can be acquired at up to 21.3m/minute (70 feet/minute) without stopping to pan, tilt or zoom (Envirosight, n.d.b). Being automated, side-scan technology relieves the operator from analyzing footage on the fly, thereby creating a potential to improve the speed and accuracy of inspection. The storage requirements for a side scan are lower than those for CCTV video. A single scan can store information on up to 914m/GB (3000 feet/GB) of memory. Other advantages include software capabilities such as automatic detection of joints, and quicker annotation during review. The side scan is essentially a camera and software improvement (varies with vendor product) and therefore can be added on as a replacement to existing cameras on traditional CCTV crawlers (Envirosight, n.d.b) for certain vendor products.

This highly powerful tool does have associated disadvantages. Some of these include the requirement for manual interpretation of scan results. This is so because multi-sensory data produced by the technology essentially is in the form of a digital image with color-coded defects. A neuro-fuzzy approach and digital imaging techniques have been researched to automate the interpretation process (Chae & Abraham, 2001; Iyer & Sinha, 2013) and eliminate potential for human error in identifying defects (Duran, Althoefer, & Seneviratne, 2007).

5.1.3 Optoelectronic Approaches

5.1.3.1 Laser profiling. Laser profiling systems are more advanced than CCTV/video systems and use one or more lasers arranged to emit and collect light in a diffuse scatter geometry to assess the distance from the laser source to the culvert surface based on either time of flight observations (beam source to culvert surface) or scatter intensity measurement using a position sensitive detector (PSD) to develop a complete profile of the inspected culvert. A laser profiling system is typically employed in combination with video sensing,

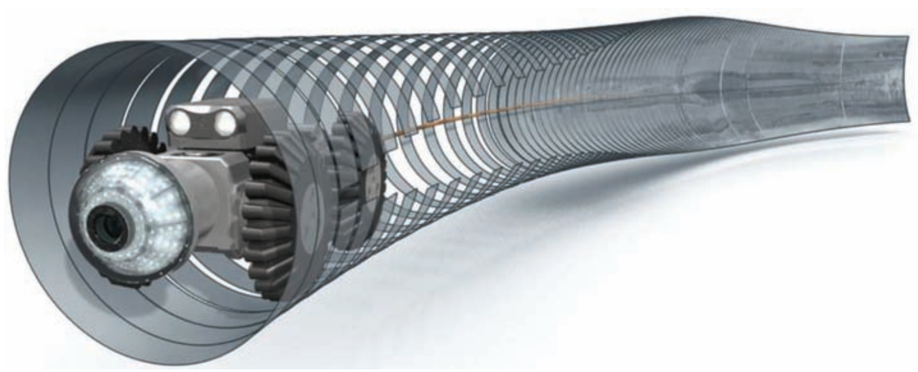


Figure 5.4 Crawler mounted CCTV with side-scanning and CAD capability. (Image from Envirosight Corp.)

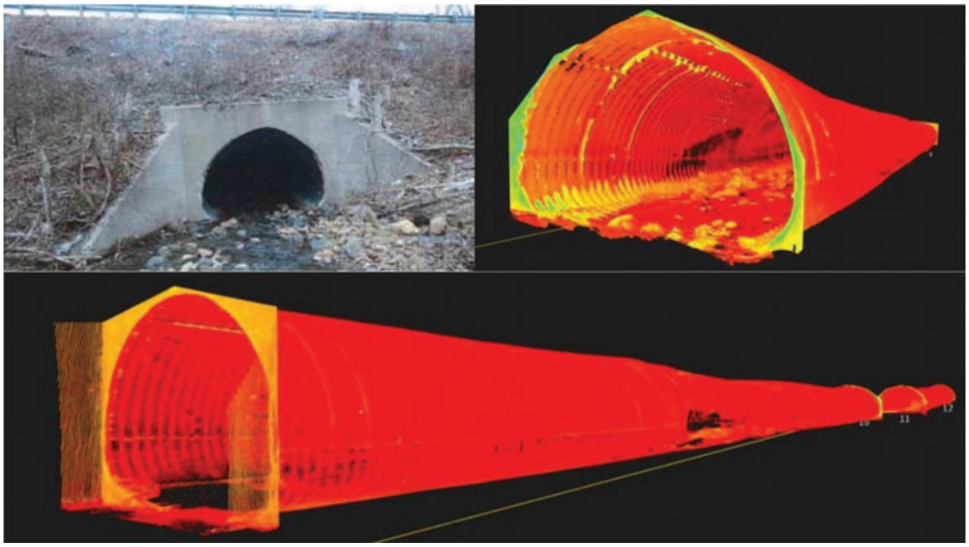


Figure 5.5 Laser profiling of two deteriorating culverts in Middletown, Connecticut. (Source: Mickel & Hagert, 2016.)

sonar sensing, and coordinate mapping. A system called the Pipe Inspection Real-time Assessment Technique (PIRAT) in which a laser sensor is mounted on a crawler has undergone field testing on 3.5 km of operating sewers in various operating conditions. The results were promising (Costello et al., 2007). The Connecticut DOT performed laser profiling on one of the culverts on I-91 (see Figure 5.5). Due to the high average daily traffic on this route and high fill height of the culvert, CTDOT considered multiple reinforcing treatments for the culvert. They employed the services of Close, Jensen & Miller, P.C., which used an instrument that combined 3D laser profiling, total station capabilities, high-resolution digital imagery and Global Navigation Satellite System (GNSS) connectivity. The images below show the laser profile 'point cloud' generated from this effort. The greatest advantage of a laser profiling exercise is its capability to be deployed without the need for daylight. Hence, it can be used in small and medium diameter culverts having considerable length.

While generally effective for anomaly detection, laser profiling requires an unobstructed path for inspection, and is thus typically performed in empty (i.e., air filled) conduits. Therefore, laser profiling cannot be performed on undrained culverts, without forfeiting view of some region of the culvert. They must be first taken out of service. The laser sensing method faces challenges of semi-automation and relies on human judgement for result interpretation. In 2007, Duran et al. developed a method to fully-automate the pipeline inspection analysis process where they coupled laser profiling with CCTV video and an evaluation algorithm based on artificial neural networks. They suggested that the only manual action to be performed should be that of introducing the laser profiling instrument into the pipeline. The suggested solution used the information of the intensity of reflected laser light as well as the light/ring position information generated by the laser profiler. Furthermore, they propose a two-stage classification algorithm using image processing and artificial neural networks to completely automate the analysis process and become independent of human analysis, thereby reducing the chances for error (Duran et al., 2007).

5.1.4 Electromagnetic Methods

5.1.4.1 Magnetic flux leakage (MFL). This in-line inspection (ILI) technique generally employed in pipeline maintenance operations for the oil & gas industry could potentially be employed to detect corrosion, pitting, cracks, and dents in metal culverts. MFL works on the principle of magnetizing a portion of the metal pipe and measuring the associated generated flux signals while the conduit is in use. The MFL tool is typically comprised of three components—the magnets, hall sensors and an eddy current sensor. The magnets create an elliptical magnetic flux between their two poles and a correctly placed 'hall-effect' sensor captures the access leakage-flux signal vectors. In the case of defects, the leakage-flux signal vectors show typical patterns. A separate eddy current vector needs to be employed alongside the setup to determine whether the location of the corrosion is on the internal pipe wall or external pipe wall surface (Clapman, Babbar, & Byrne, 2004). For oil and gas pipelines, depending on the resolution of the MFL tool employed, the accuracy of the method ranges from ± 5% to ± 1% of metal loss for high-resolution tools, and 40% losses for 13mm thick pipes with unclean surfaces (Drury & Marino, 2000). The speed of the tool ranges from 0.5~5m/s depending on the resolution. High-resolution MFL tools have been employed by large companies in the oil industry such as Petro China, Sinopec, and CNOOC for pipeline inspection (COSL, n.d.).

A limitation of the MFL is its obvious applicability to metal pipe culverts. In addition, the possibility of magnetic flux leak detection and therefore damage detection is completely dependent on the signal-to-noise ratio and may not be useful for corrugated metal pipes and others with surface roughness. It should however be noted that the MFL technique has been laboratory tested on twisted re-bars placed within a corrugated conduit, which produced a repeating pattern of minor peak and valley disturbances throughout the test length (DaSilva, Javidi, Yakel, & Azizinamini, 2009). This could be a potential workaround and further research can potentially throw light on this issue. Other reported disadvantages include the large amount of data that needs to be analyzed to quantify defects (Trenchless Technology, 2016) and the failure of detection when flow rates are too low or when the pipe surface is lined with epoxy coating, cement-mortar, HDPE, or when there is heavy internal deposits such as wax, scales, and tubercles. Logistical impediments include the size and weight of the tool, which can range from ~100 kg (1.85 m tool length) for 6″ diameter pipelines to ~1600 kg (3.30 m tool length) for 30″ diameter pipelines (COSL, n.d.). Russell NDE Systems Inc. developed a 105 kg, 4.4 m long ILI tool called Remote Field Technology (RFT) for inspecting unpiggable pipelines basing it on free-swimming operation, and claiming that the RFT could be used for any type of ferrous pipe with or without internal lining and/or disposition (Russell, 2013). Another similar tool called the RoboScan robot has been developed by Cutting Edge Solutions LLC (Torbin, 2006) and is applicable for gas pipelines having discharge rate of minimum ~3m (10 feet) per second. This could be a potential avenue for further enquiry.

5.1.4.2 Eddy current techniques (ECT). These non-contact non-destructive methods work on the principle of electromagnetism to detect surface and sub-surface defects such as pitting, corrosion, leaks and cracks in a conducive material. The root technology behind this is that a coil is excited by passing electricity through it, in turn when in proximity of the conductive culvert surface the coil induces 'Eddy' currents in the opposite direction in the pipe (see Figure 5.6). The presence of defects in the test material causes changes in the eddy currents and a corresponding change in phase and amplitude that can be detected by measuring the impedance changes in the coil (Buckley, 2003; Nelligan & Calderwood, n.d.). Various eddy current techniques include Full Saturation ECT, Remote Field ECT, Pulsed ECT, Eddy Current Array, and Lorentz Force ECT (see Figure 5.7). These vary slightly in their setup and have corresponding application specific advantages such as using Remote Field ECT to counter what is known as the 'skin-effect'—a phenomenon where the eddy current density reduces with the increase in conduit material thickness. A technological advancement from traditional Remote Field ECT is the use of orthogonal magnetic field excitation as compared to axial magnetic field excitation. The results indicate a large overall improvement in defect detection, specifically for axial cracks with depths less than 40% of wall thickness (Xu, Liu, Zhang, & Jia, 2014).

The basic technological limitation of these techniques is their applicability to metal culverts only, which limits their versatility. However, for metal culverts, they can be used for any type of flow condition, and may be used for large conduits as well as ones as small as 2 inches, if required. Pulsed eddy current probes enable using

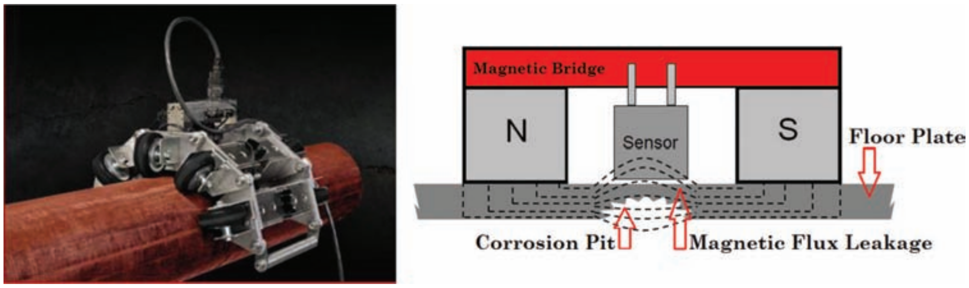


Figure 5.6 Magnetic flux leakage. (Image from MFE Enterprises Inc.)

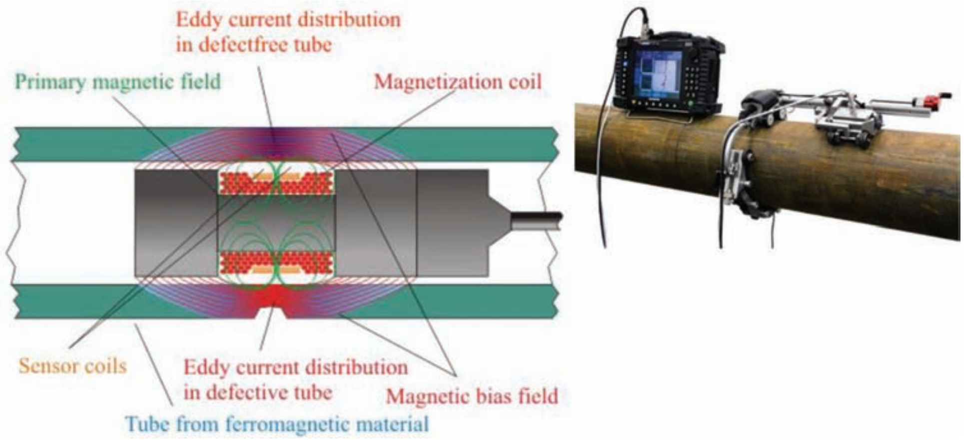


Figure 5.7 Eddy-current technique. (Image from kontroltechnik.com & Olympus-ims.com.)

the technique from the ground level as well as from within the pipe (Eddyfi Technologies, 2016). A May 2009 report by the US EPA succinctly describes OTS offerings by vendors and subtle differences in the individual offerings (Feeney et al., 2009).

5.1.4.3 Ground penetrating radar. Chen et al. published a paper in 2013 demonstrating the potential to employ Ground-Coupled Penetrating Radar as a non-destructive method of mapping anomalies and voids under roadways and pavements. Yet another report (Stelzer & Nichols, 2006) developed by the geotechnical services division of CDM at Clay County, FL., used GPR as a technique in their sub-surface exploration program. While the primary application of GPR in the utility industry is in locating buried pipes, GPR units with a 1GHz frequency antenna were reportedly used for concrete liner deterioration studies and anomaly detection from within the pipeline (Yang & Allouche, 2009).

A GPR system operates by transmitting short pulses of electromagnetic energy downward into the ground. These pulses are reflected back to a frequency-tuned antenna with amplitudes and arrival times that are related to the dielectric constant of the materials in the subsurface. Across the layer interfaces, part of the energy is reflected and part is absorbed, depending on the dielectric contrast of the materials. The time delays and the amplitude of reflected signals are used to evaluate subsurface conditions. Objects or areas in the subsurface with different electrical properties will reflect the pulse differently and appear as anomalies (Chen & Wimsatt, 2009) (see Figure 5.8). The versatility of the method allows the tool to be operated from the road surface as well as inside a culvert as discussed above. Additionally, the GPR can also detect soil structure around the culvert, the interface between the culvert and surrounding soil, as well as leakage through the culvert either by detection of underground voids in the soil that are created by the leaking water or by detecting anomalies in the depth of the pipe. This is because the radar propagation velocity changes due to variations in soil saturation caused by the leaking water (Liu & Kleiner, 2013).

A critical limitation of the GPR technique relates to concrete culvert scanning applications. In GPR applications, high frequency antennas are used, however, a critical limitation of the GPR technique relates to any moisture in the culvert or soil surrounding the culvert, which will likely inhibit the penetration of the radar signals (GPRS, n.d.). Therefore, in culverts with flowing or stagnant water, the portion of the culvert that is covered by the water cannot be scanned effectively using GPR. Additionally, cracking due to flexure is likely to occur on culvert bottoms and sides and the bottom cannot be scanned. However, cracking due to sheer forces is likely to occur on the sidewalls at 45-degree inclinations to the horizontal and cracking in general is likely to occur in multiple places. Other disadvantages include the reduced effectiveness of the GPR method, which is affected by soil conductivity, depth of the target, the presence and proximity of other buried objects, and environmental electromagnetic noise. The interpretation of the GPR sensing data requires trained personnel. Therefore, while GPR is a successful method to locate underground pipelines, inspecting damaged culverts from within may prove highly challenging.

5.1.5 Acoustic Methods

5.1.5.1 Ultrasonic Scanning. High frequency sound waves ranging between 50 kHz to 10MHz are able to provide information regarding the presence and location of boundaries within a pipe wall that result from the presence of delimitations, voids and excessively dense or highly corroded zones. The speed of ultrasound waves changes depending on the density of the medium through which they travel. When the propagating wave encounter reflecting surfaces such as the flaws, voids and boundaries between two different mediums, part of the acoustic energy is reflected back and received by a transducer, which also performs the signal transmitting function. The presence and location of various targets can be obtained from the raw data using a time domain based analysis. The results of

Figure 5.8 Ground penetrating radar: equipment, in-situ operation, and application output graph showing a detected void. (Images from envirophysics.com & alphageofisica.com.br.)

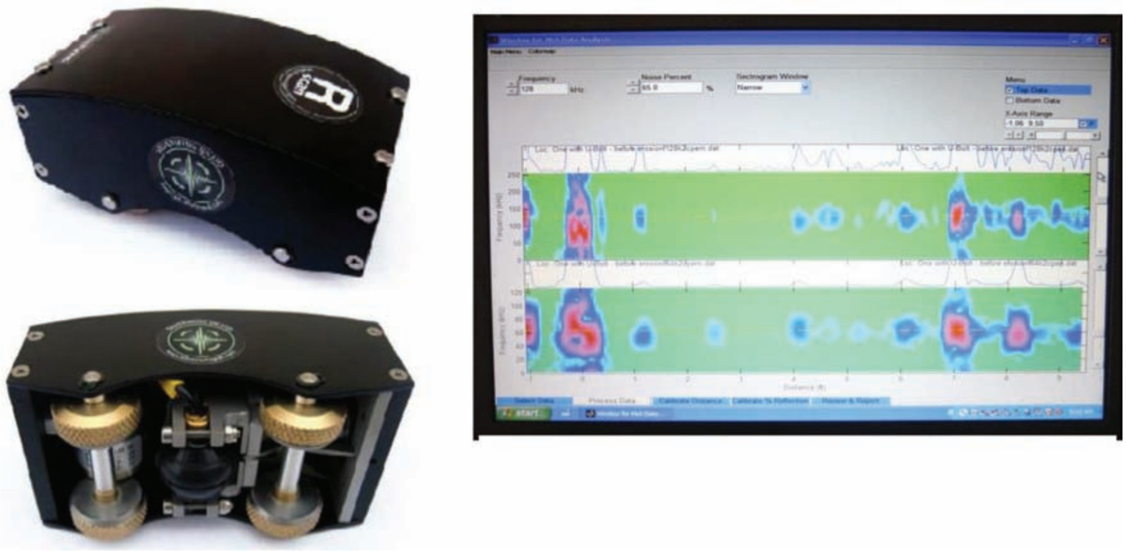


Figure 5.9 Ultrasonic scanning. (Images from http://www.worldoftest.com/r-scan-lite-ultrasonic-crawler-system and http://versaintegrity.com/service/guided-wave-ultrasonics-mss.)

inspection are presented in 2D or 3D formats (see Figure 5.9). The overall sensitivity of this method is very high, detecting between 1% to 5% loss of cross-section depending on operating conditions. This method is versatile and can be applied to culverts of any material, and of diameters larger than 4 inches.

Besides the culvert anomalies mentioned above, ultrasonic testing can reveal deflections in the pipe walls as well as the presence of debris and distinguish between hard and soft debris. The only disadvantage is that ultrasonic scanning can be performed either in air or in water but not both simultaneously. A method to overcome this is by coupling the sonar with a CCTV crawler or laser scanning CCTV crawler as has been described in section 5.1.6.1 below. As compared to the MFL method described in section 5.1.4.1, the ultrasonic method is rather slow. Also, as with MFL, the probability of anomaly detection varies with the equipment and technique used. Ideally, the ultrasonic sensing tool used should produce multiple scans (A, B & C). A-Scans present the amount of received ultrasonic energy as a function of time; B-Scans represent a cross-sectional view of the test specimen where the time-of-flight measurement is displayed as a function of transducer location. C-Scans are typically top-view type plans which display the location and size of the test target (NDT Resource Center, n.d.). Other specifics include facilitating a continuous coupling during the inspection (using water layer / surface gel), selecting the correct scanning technique (grid pattern / spot-checking), and correctly calibrating the tool. Employing such tools and techniques is likely to greatly enhance the likelihood of damage detection (Drury & Marino, 2000).

5.1.5.2 Sonar profiling. Similar in principle to laser profiling, sonar is a technique that uses sound wave propagation to interrogate objects on or under the surface of water (see Figure 5.10). This was originally used for navigation. However, active sonar has found profiling applications due to its ability to scan physical objects in its surrounding environment by emitting pulse signals and receiving them. Sonar uses acoustic frequencies ranging from infrasonic to ultrasonic. The choice of the frequency depends on the density of the liquid medium under investigation and required resolution of the scan. High frequencies are necessary when a high-resolution scan is desired. However, high frequencies have to be operated more slowly. The opposite is true as frequency is reduced for the same energy. A sonar profiling system typically travels in a pipeline at around ~0.1–0.2m/s and sends a pulse signal every 1.5 seconds. Sonars have been reported to detect pitting, cracks and debris defects greater than 3mm (Feeney et al., 2009), and share the advantages and disadvantages of ultrasonic scanning mentioned above.

Side scanning sonars may be used in culverts. However, a sonar's resolution along its track (azimuth) is angular and weaker as compared to the range resolution (Hansen, 2009). A surface mounted multi-beam 30 kHz sonar (EM300) was developed to test the limits of achievable spatial resolution and reported the ability of the technique to resolve <10m high targets in a 450m deep water body (considered low-resolution) (Clarke, Gardner, Torresan, & Mayer, 1998). High frequency sonars, such as JW Fishers' (n.d.) 1200 kHz side scanning sonar is able to produce very high-resolution images at 5m–50m ranges. These ranges are unsuitable for culverts which may typically need ~<1m range. As the sharpness of the produced acoustic image is directly proportional to scanning range, side-scanning sonars may produce less sharp acoustic images for culvert application.

5.1.5.3 Impact echo testing & spectral analysis of surface waves (SASW). Similar to ultrasonic testing, impact echo testing and SASW are two related acoustic techniques that can locate anomalies such as delamination, cracks, voids, and honeycombing in the culvert wall. These are typically applicable to culverts made of

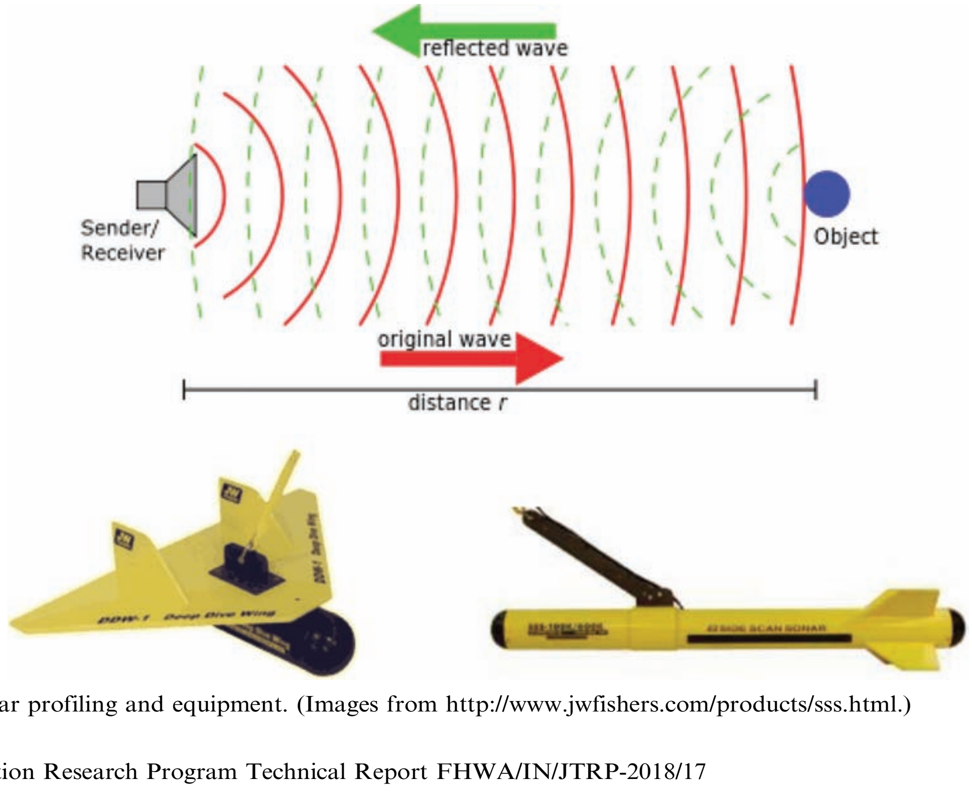


Figure 5.10 Sonar profiling and equipment. (Images from http://www.jwfishers.com/products/sss.html.)

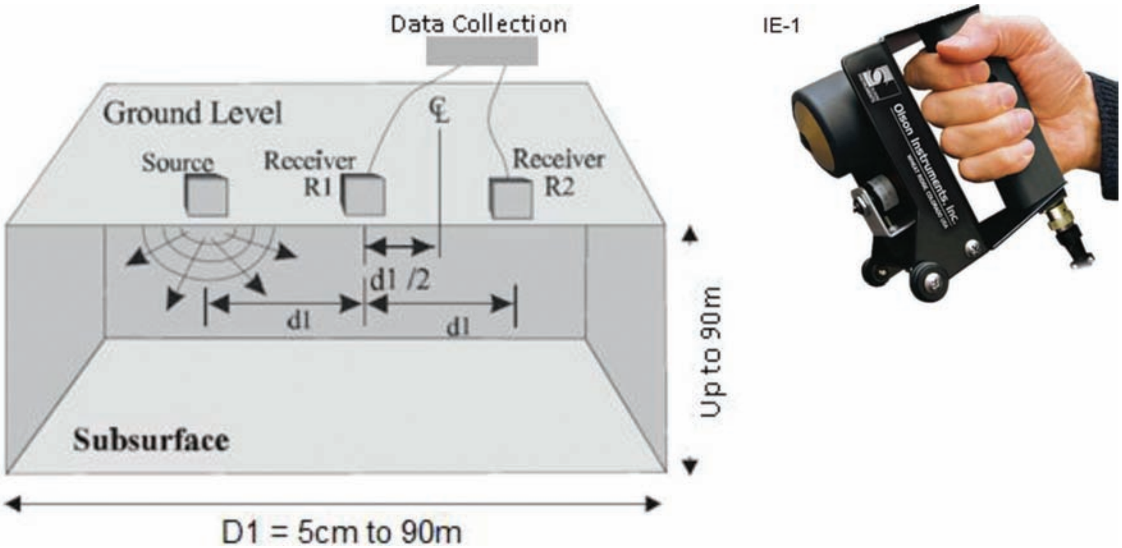


Figure 5.11 SASW. (Images from http://www.pcte.com.au/spectral-analysis-of-surface-waves-sasw; http://www.pcte.com.au/impact-echo.)

concrete, stone, plastic, and masonry materials greater than 6 inches in diameter. An instrumented impulse hammer or impactor hits the test surface (see Figure 5.11). The resulting echo (reflected sound wave) created is recorded with either a displacement or accelerometer sensor. The recording sensor is generally located adjacent to the impactor. While generating views of pipe thickness and geometry is relatively simple, frequency domain analysis is more complicated to infer other information pertinent to culvert inspection such as cracking, misalignment, or water ingress. Experience is required for accurate analysis and inspection. Advantages of the method include its applicability to concrete culverts of all sizes and its accuracy of ±2% of original conduit thickness at high-resolution operation (Sansalone & Streett, 1998).

5.1.6 Multi-Sensor Techniques

5.1.6.1 Culvert Profiling Using Sonar & Video. As briefly described in the sections above, multi-sensor methods often combine optoelectronic, visual and/or acoustic sensing to produce a single tool capable of inspecting in-service conduits in both wet and dry conditions. The Southwest Research Institute (SwRI) and the FHWA jointly created Ultrasonic Culvert Inspection System (UCIS) that uses sonar mapping and live video (see Figure 5.12). UCIS is a low-cost device that can map, monitor, and diagnose damage to roadway culverts. Sonar information produces a sufficiently resolvable three-dimensional representation of the culvert that can be viewed from many angles. The device is specially calibrated allowing it to be developed with inexpensive components, making this system appropriate for use in high-risk, flooded inspections (Hansen, Willden, Abbott, & Green, 2014). The authors report promising results with test equipment enabling meaningful evaluation of the status and integrity of culverts. The major advantages of the UCIS inspection system are its low-cost equipment (~$1000–$4000) and versatile applicability to culverts of all material types with diameters ranging between 0.3m and 1.5m. The tool has functionality in wet and dry conditions as well as limited visibility conditions. Its user-friendly design features (a sealed exterior, no external buttons, and easy cradle charging) and software interface on a ruggedized laptop that integrates easily with currently employed inspection practices make it attractive from an operations standpoint. A few disadvantages of the system include its inability to send data in real-time back to the software interface, and irregular antennae patterns that make use of inexpensive parts that are selected with a purpose to keep low overall cost. This particular tradeoff requires a custom manifold be built from known return signals at specific distances and angles for each new device so as to calibrate it correctly and is a major disadvantage.

The UCIS was able to sufficiently locate three test anomalies on a corrugated metal culvert—a dent intruding 3 to 5cm on the top surface, a large plastic piece inserted into the test culvert mimicking debris, and sand-gravel seated in the corrugations of the pipe.

The SwRI patented another sensor technology called the neutrally buoyant sensor, or the NBS (see Figure 5.13). This tool was designed with free-swimming operability to flow with karst aquifers (https://karst.iah.org/karst) to measure the size and morphology of caves. The NBS was assembled using commercially available components such as ultrasonic sensors and dual-axis magnetometers and accelerometers (Willden, Abbott, & Green, 2014). The wireless sensing tool was applied to a culvert conduit inspection project by the FHWA as an alternative to manual (visual and CCTV) inspection techniques currently in use. The NBS variant used in this

Figure 5.12 The UCIS device, parts, case in laboratory testing. Jointly developed by SwRI and FHWA.

project included a high-resolution ultrasonic sensor with a high-speed analog-to-digital converter, a 360-degree camera and lighting system for visual confirmation of the sensor results, and integrated Wi-Fi for live video streaming and data retrieval capability.

Advantages of the system include its capability to determine its real-time position with respect to the magnetic north (traversed path) and capability to determine motion dynamics (specifically periods of rapid motion) as a result of the magnetometer and accelerometer, respectively. The capacity to measure flow velocity as well as shape and size of the culvert. Disadvantages include deployment issues such as in situ buoyancy adjustments and waterproofing challenges for the equipment itself, and post scan analysis issues such as mandatory post-processing required to verify system functionality and large data storage requirements. The detailed design tradeoffs may be accessed here (Willden et al., 2014).

5.1.6.2 Smartball using acoustic, motion & thermo sensors. Developed and made commercially available by Pure Technologies, the SmartBall travels with the water flow and detects, locates, and estimates the magnitude of leaks as it rolls. This system is embedded with a range of acoustic sensors including ultrasonic transmitters, and motion sensors as well as thermosensors. As it travels in the pipe, it emits an acoustic pulse every 3 seconds for tracking and records acoustic data. The SmartBall uses the accelerometer, temperature and pressure sensors to detect air pockets and leaks. Furthermore, an above ground receiver can mark specific points where leaks are detected using the emitted pulse and tracking system with a location accuracy of less than 1 m. While the core technology has been developed specifically for application in pressurized pipes, certain technological elements and learning could be amalgamated with other methods to develop a technology specifically for culverts.

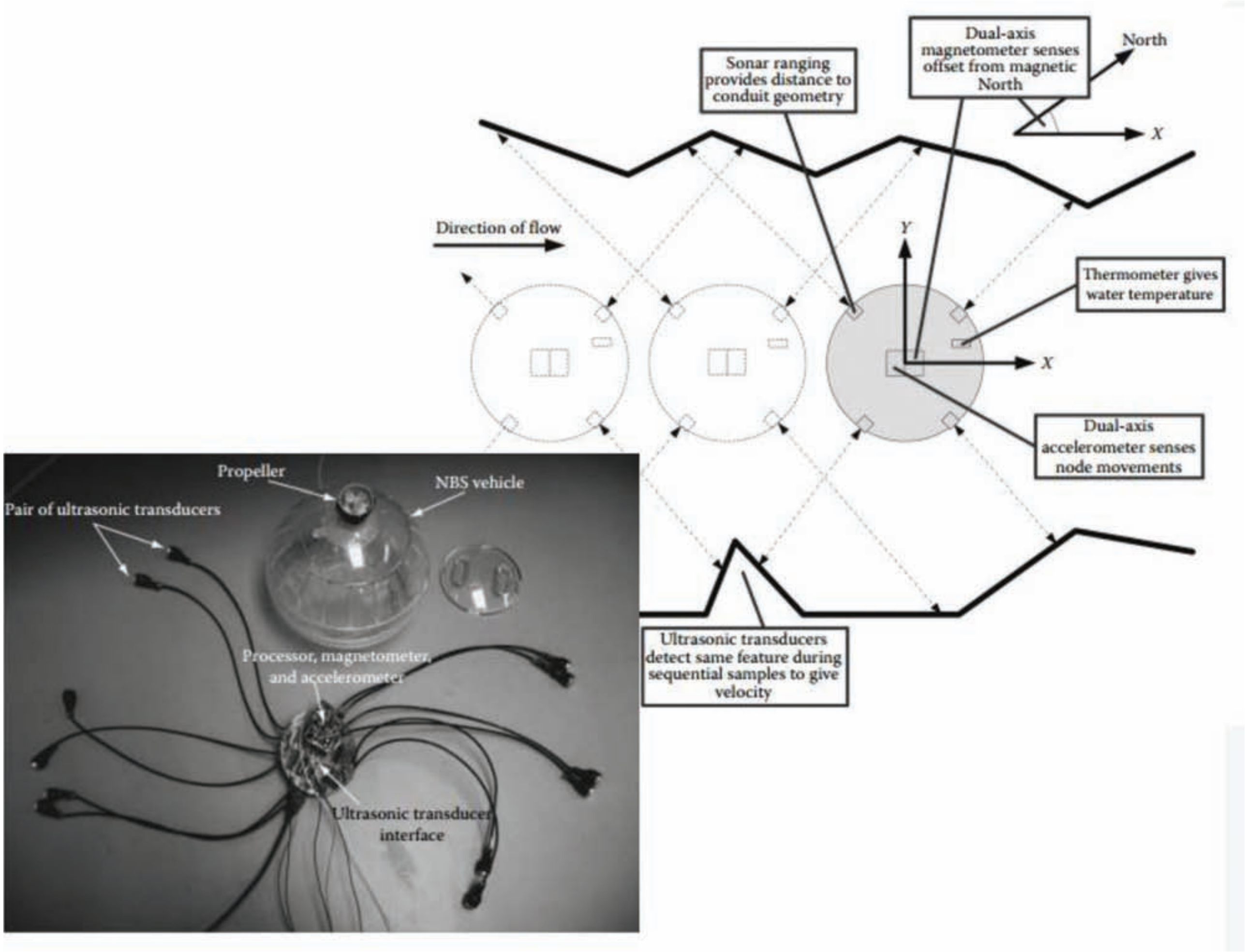


Figure 5.13 The neutrally buoyant sensor. (Image from http://www.crcnetbase.com/doi/pdf/10.1201/b15474-99.)

5.1.6.3 Sahara system using visual and acoustic sensors. The Sahara system is a free-swimming tethered hydrophone that is manually inserted into an existing in-service pipeline and can go through bends of up to 270-degree. The system consists of a probe embedded with acoustic sensors, lighting and a video camera that moves in the direction of flow. The acoustic sensor detects pulses at regular intervals that are received by a transmitter at the ground level (Pure Technologies, n.d.). As is with SmartBall, the core technology has been developed specifically for application in pressurized pipes; however, certain elements could potentially be amalgamated with other acoustic methods to develop a technology specifically for application in culverts.

5.1.7 Radiographic Testing

5.1.7.1 Backscatter computer tomography (BCT). The BCT method is used to map 'undermining' occurring in the soil supporting the culvert barrel. The method involves a non-medical application of the CT-scan technology used in medical sciences. Similar to CT scans, gamma rays are projected on to the target area and the backscatter radiation is measured. This tool was developed for specific application in culverts as a result of discussions between the New Brunswick DOT, Canada and Inversa Systems in a pilot project sponsored by the Ontario Good Roads Association (OGRA). The pilot tested the system developed by Inversa on three culverts in the city of Toronto based on a patented method devised by Arsenault and Hussein (2007) at the Laboratory for Threat Material Detection (LTMD) at the University of New Brunswick in 2004. The BCT equipment was able to provide snapshots through the culvert wall into the surrounding backing material (Anderson & Bowles, 2012). Major culvert failures occur due to 'undermining' or removal of backing material behind the culvert by leaking water or settlement, which leads to culvert collapse. The images generated by the BCT equipment were able to discern between solid back fills and those where undermining had occurred.

Another method known as gamma-gamma logging (see Figure 5.14) has been developed for use in cast-in-place concrete conduits to locate voids in the

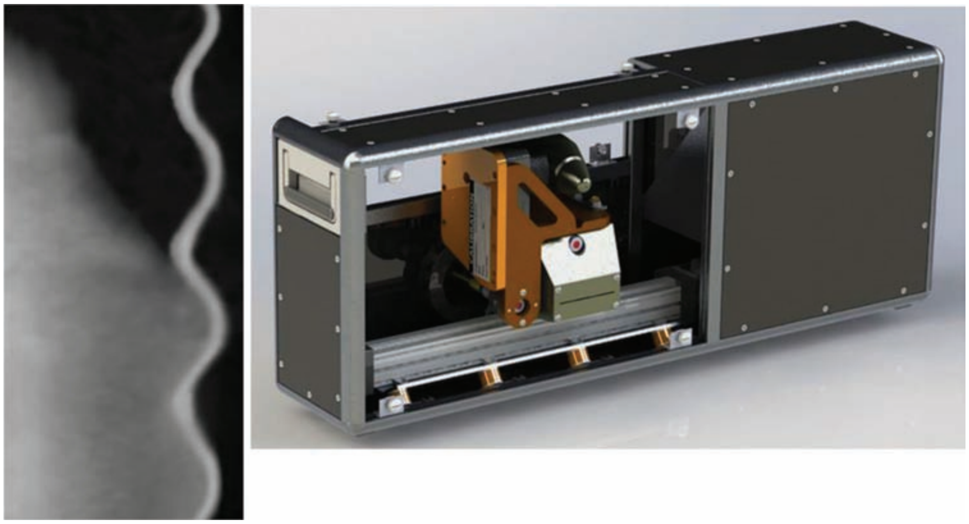


Figure 5.14 BCT and gamma-gamma logging equipment. (Images from http://inversasystems.com/technology.)

supporting soil bedding. This method is similar in principle to BCT in that a gamma-gamma probe—a source of gamma radiation and a gamma detector are used. The photons emitted react with the surrounding material based on density and are backscattered by the materials. Both the methods have substantial application issues such as personnel training and radioactive material disposal. While BCT can be applied to any material (Meemim, n.d.), gamma-gamma logging can only be used for concrete conduits. These methods are able to provide high-resolution (Henwood & McCain, 2006) information regarding the presence of voids in the backing soil behind the culvert. However, they are relatively high cost methods and therefore, it is recommended that they be used as a final step in the culvert inspection process tree, specifically to take better-informed decisions regarding whether the culvert needs replacement or rehabilitation and to mark out precise anomaly location.

5.1.8 Thermographic Testing—Infrared Thermography [IRT]

This is a non-contact method for detecting subsurface anomalies typically in concrete culverts. Any object at a temperature above 0 K radiates infrared energy and the amount of energy radiated is a function of its temperature and material emissivity. Therefore, in this method, the target surface is heated using a heat source such as an infrared tube light and the object's cooling characteristics are measured using an infrared camera. The infrared radiation is converted to a visible image. This method is categorized as active IRT. Alternatively, passive IRT requires no external heat source and is a preferred method. Thermal cameras are either hand held or fitted on to unmanned aerial vehicles and used in utility inspection (FLIR, n.d.; see Figure 5.15).

Sakagami and Kubo pioneered an NDT technique to map delamination defects in concrete structures in 2002, based on phase delay measurement using lock-in thermography by periodically heating the concrete. Later the technique was field tested on a concrete culvert that had delamination defects. The technique was successfully able to observe the delamination location and intensity (Sakagami & Kubo, 2002). Today, passive IRT systems are commercially available and include image analysis software usable on a handheld tablet such as the Apple iPad. The radiometric resolution of the system depends on the thermal camera used. Systems with standard resolution of 640 × 512 pixels are available. A notable disadvantage of the UAV fitted thermal inspection technique is the camera's incapability to conduct side-scanning. This may lead to limited scanning and/or require personnel entry into the culvert.

5.1.9 Other Innovative Methods Under Development

5.1.9.1 Smart pipes. This concept has been explored for some time. In 2006, a smart pipe project for deep-sea pipes was initiated in Europe and was slated for completion in 2012. Yet another project was initiated by ISPNET (Intelligent System for Pressure Networks) in 2015 that is currently in its testing phase. For both projects, the pipe under consideration is embedded with a number of sensors that allow real time monitoring of structural health conditions (ABN Pipe Systems).

5.1.9.2 Mixed reality. The massive investments by technology companies in the development of application software (Apps) for Virtual Reality—Augmented Reality (VR-AR) or Mixed Reality scenarios along with the introduction of platform technologies and cheap devices calls for special attention to the application of mixed reality applications for utilities in general and culvert inspection specifically. Mixed reality, at the broadest level, promises a state-of-the-art human-computer interface that can be used to visualize

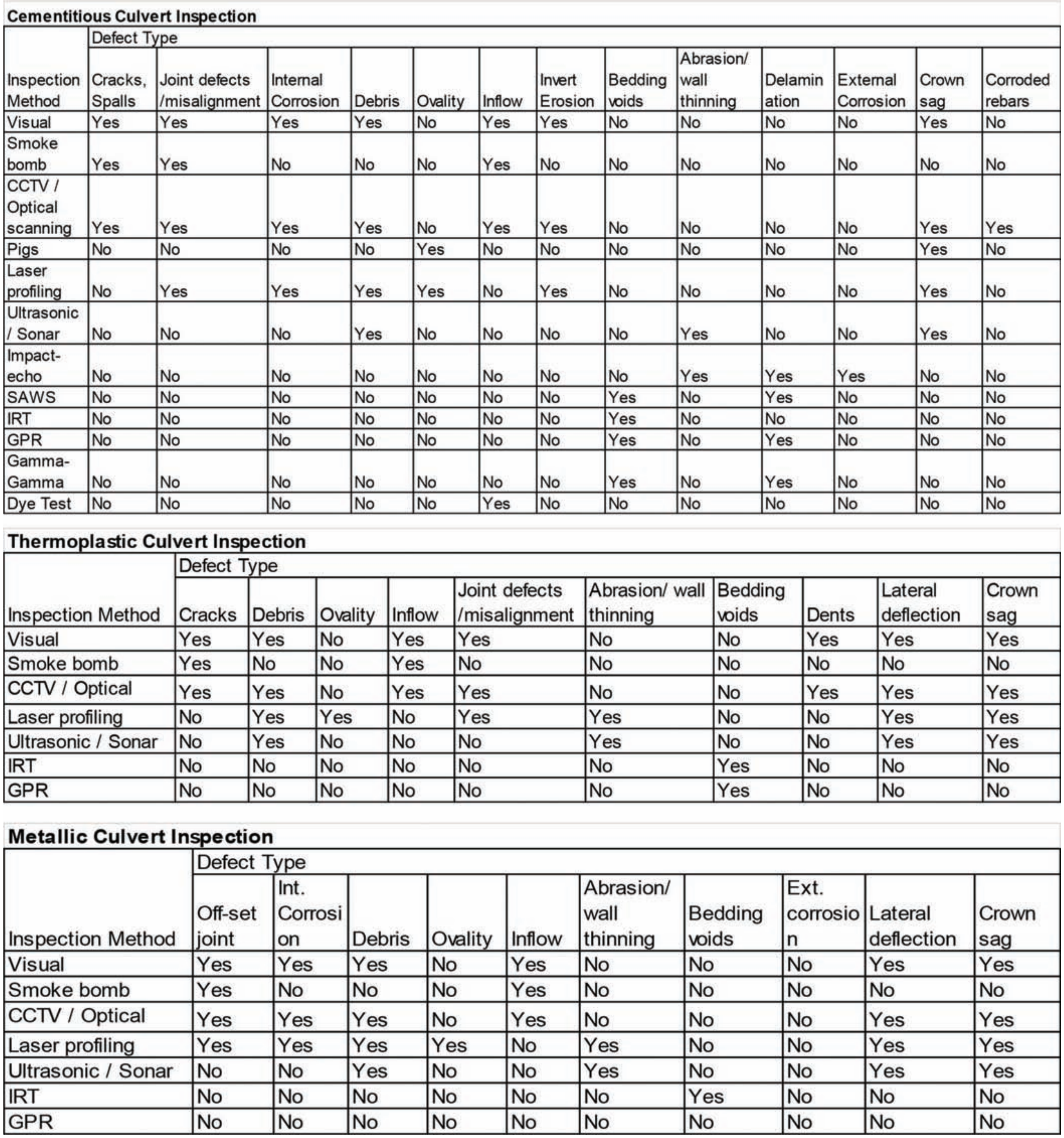
Figure 5.15 Infrared thermography using drones. (Images from http://www.flir.com/suas/aerial-thermal-imaging-kits/.)

culvert defects precisely without having to be present at the site of the inspection. A current solution involves a combination of mixed reality with geographic information system (GIS) mapping and document management that promises quicker and safer utility location applications (Meemim, n.d.).

5.1.9.3 Smart paints. Four smart paint technologies using distinct mechanisms have been proposed for application in culverts and pipes. One uses microencapsulated dye that can outline fatigue cracks, thereby highlighting potential critical areas in culverts and pipes that need attention. The other uses a resin layer attached to electrodes to monitor vibrations in the culverts and pipes caused by the overhead traffic flow. The vibrations can then be utilized to once again support fatigue calculations. The third technology proposes introducing a penetrating dye to detect the extent and size of surface flaws in steel members. For this method, the test area needs to be cleaned and separated from the structure and therefore is a pre-installation testing method rather than an existing culvert inspection method. The fourth is a patented technology called the Batelle Smart Corrosion Detector Capsule or simply 'smart bead'. The bead is a plastic that contains a healing agent. When mixed with a paint and applied to a metal pipe, the bead gets chemically activated (a state where the propensity to undergo a specific chemical reaction is high) (Wikipedia, n.d.a) and detects corrosion, cracking open itself allowing the healing agent to flow through the crack and patch the corrosion (Battelle Memorial Institute, 2015).

5.1.9.4 Methods to test the re-bar condition in RCC. A number of methods test re-bar condition in RCC. We have chosen those that may be performed in the field. The chloride test method is useful for testing concrete culverts that may have corroding re-bars. It consists of measuring the concentration of chloride ions in the concrete cover to the re-bar contained within (Fabianiak, 2012). Other methods include the magnetic field disturbance method, which evaluates the fatigue damage to steel reinforcement in the concrete member. The re-bars in the above methods must be located underneath the cover using a pachometer, colloquially known as a cover meter. The pachometer works on the principle of a pulse induction method as described in the acoustic methods section (Wikipedia, n.d.b). These are only applicable to testing re-bars in RCC conduits and are therefore limited to specific use cases.

5.1.9.5 Liquid penetrant testing. Liquid penetrant testing or dye penetrant testing is a widely applied, low-cost method that works on metallic and poly culverts. The principle is based on the capillary action between the hairline cracks of the culvert material and the low surface tension fluid that is applied. The fluid penetrates the cracks and the excess fluid is then removed. When viewed under an ultraviolet light, the dye shines and the cracks are



Cementitious Culvert Inspection

Inspection Method	Defect Type												
	Cracks, Spalls	Joint defects /misalignment	Internal Corrosion	Debris	Ovality	Inflow	Invert Erosion	Bedding voids	Abrasion/ wall thinning	Delamination	External Corrosion	Crown sag	Corroded rebars
Visual	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	No	Yes	No
Smoke bomb	Yes	Yes	No	No	No	Yes	No	No	No	No	No	No	No
CCTV / Optical scanning	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	No	Yes	Yes
Pigs	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No
Laser profiling	No	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No	Yes	No
Ultrasonic / Sonar	No	No	No	Yes	No	No	No	No	Yes	No	No	Yes	No
Impact-echo	No	No	No	No	No	No	No	No	Yes	Yes	Yes	No	No
SAWS	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No
IRT	No	No	No	No	No	No	No	Yes	No	No	No	No	No
GPR	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No
Gamma-Gamma	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No
Dye Test	No	No	No	No	No	Yes	No	No	No	No	No	No	No

Thermoplastic Culvert Inspection

Inspection Method	Defect Type									
	Cracks	Debris	Ovality	Inflow	Joint defects /misalignment	Abrasion/ wall thinning	Bedding voids	Dents	Lateral deflection	Crown sag
Visual	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
Smoke bomb	Yes	No	No	Yes	No	No	No	No	No	No
CCTV / Optical	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
Laser profiling	No	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes
Ultrasonic / Sonar	No	Yes	No	No	No	Yes	No	No	Yes	Yes
IRT	No	No	No	No	No	No	Yes	No	No	No
GPR	No	No	No	No	No	No	Yes	No	No	No

Metallic Culvert Inspection

Inspection Method	Defect Type									
	Off-set joint	Int. Corrosion	Debris	Ovality	Inflow	Abrasion/ wall thinning	Bedding voids	Ext. corrosion	Lateral deflection	Crown sag
Visual	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes
Smoke bomb	Yes	No	No	No	Yes	No	No	No	No	No
CCTV / Optical	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes
Laser profiling	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
Ultrasonic / Sonar	No	No	Yes	No	No	Yes	No	No	Yes	Yes
IRT	No	No	No	No	No	No	Yes	No	No	No
GPR	No	No	No	No	No	No	No	No	No	No

Figure 5.16 Map of the ability to detect defects in culverts of concrete, poly, and metal materials using specified technologies. (Source: Yang & Allouche (2009, pp. 28–29).)

exposed. The method may be supplemented with a magnetic-particle inspection for sub-surface crack detection (Wikipedia, n.d.c). This is a fairly simple, inexpensive and therefore common method. It is possible to use liquid penetrant testing as a quality control measure to check hairline cracks in piped culverts prior to installation. However, for existing culverts, it requires the culvert to be taken out of service and personnel to physically enter it and conduct the inspection making it a rather cumbersome process. In summary, Figure 5.16 indicates the type of defect(s) that can be detected by various

TABLE 5.4
A survey of currently used methods for culvert inspection

Inspection Method	Pipe Diameter Suitable for Inspection	Approximate Cost	Measurement Conditions		Optical Camera	Communication
			Mild	Flood		
SwRI/FHWA Ultrasonic Culvert Inspection System	0.3–1.5 m	$1,000–$4,000	✓	✓	✓	Relayed
CCTV	Up to 2 m, depending on lighting	$10,000s	✓	×	✓	Tethered
SSET	20–46 cm	$100,000–$150,000	✓	×	✓	Tethered
Everest VIT Rovver® 600	15–91 cm	$100,000–$150,000	✓	×	✓	Relayed
iPEK Rovver 125	10–152 cm	$100,000–$150,000	✓	×	✓	Relayed
Manned Entry (Visual Inspection) System	>1.2 m	Hourly wage	✓	×	✓	Written log

Source: Hansen et al. (2014).
✓= Feature is available; × = Feature is unavailable.

technologies for three primary culvert material types.

5.2 Visual Inspection Methods by Their Operational Suitability and Communication Method

Based on current technology, inspecting a culvert without physically visiting and examining it is not yet possible. Hence, some form of visualization, preferably one that allows operators to view inside-conduit condition without entering, is preferable. Therefore, a system that views culvert conditions and communicates the same to the operator is necessary. However, factors that influence operability include the suitability of the system to be inserted into the culvert, its suitability in various flow conditions, and the information communication mechanism (speed and detail). Table 5.4 is a comparison of such visual systems.

5.3 Technology Vendor and Cost Listing

See Table 5.5 for technology vendor and cost details.

TABLE 5.5

Vendor and cost details of technologies categorized based on their deployment mode and applicability to culvert type based on material

Deployment Mode	Inspection Technology	Applicability	Manufacturers & Vendors	Model	Cost (USD)	Link / Remarks
Pre-installation						
Individual Culvert pipe inspection						
	3D Laser Scanning (portable)	M,C,P	FARO	Focus S 350	30000	http://www.faro.com/products/3d-surveying/laser-scanner-faro-focus-3d/overview
	Coordinate Measuring Machines	M,C,P	FARO	Cobalt	50000	http://www.faro.com/en-us/products/metrology/faro-cobalt-array-imager/overview
			Creaform	MetraScan 3D + pipecheck 4.0 software	28000	https://www.creaform3d.com/en/metrology-solutions/optical-3d-scanner-metrascan
			Artec / Flir / Fluke / Lecia / Olympus Innov-X / Prodim / Sokkia / Thermo Niton / Topcon / Trimble		similar prices	Manufacturers besides FARO Technologies
	Micro-crack Testing—Liquid Penetrant Testing	M,P			-	Not available
	Smart Pipes (in-development)				-	Not available
	Smart Paints	M,C,P			-	Not available
Soillsoil-culvert system inspection						Not available
	Soil Evaluation	M,C,P			-	Not available
	Mixed Reality (in-development)	M,C,P			-	Not available
Pre-field visit						
	Stochastic Predictive Modeling	M,C,P			-	Special project—data model development
In-field indirect inspection (primarily for priority determination)						
'Solution deployed from within/inside/close proximity to the culvert	Smoke Bomb & Leaf-blower Testing	M,C,P			-	Not available
'Solution deployed at ground surface/outside the culvert	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either		Pheonix LiDAR systems			https://www.phoenixlidar.com/
	- Terrestrial &/or	M,C,P	Routscene	UAV-LiDARpod	160000	http://www.routescene.com/products/product/uav-lidarpod/
	- Non-terrestrial (unmanned aerial vehicle) for large scale surveys	M,C,P	LiDAR USA	A-series 32 channel	125000	
			Advanced Scientific Concepts / Alfa Photonics Sas / Cilas / Elbana Photonics / LusoSpace / Newport Corp. / Voxtel Inc.			Manufacturers
	Electromagnetic—Ground Penetrating Radar	M,C,P				

TABLE 5.5
(Continued)

Deployment Mode	Inspection Technology	Applicability	Manufacturers & Vendors	Model	Cost (USD)	Link / Remarks
In-field direct inspection (for identified high-priority culverts)						
Solution deployed from within/inside/ close proximity to the culvert	Visual—Plain / Push-cameras	M,C,P	Envirosight	Verisight Pro+	-	Not available
	Visual—CCTV Crawler	M,C,P	Aries Industries	Pathfinder	80000	https://www.ariesindustries.com/video-inspection/transporters/pathfinder/
			CUES		-	http://www.cuesinc.com/Products.html
			GoFAR USA		36000	http://www.gofarusa.com/
	Visual—CCTV Crawler with Side Scanning	M,C,P	CUES		-	http://www.cuesinc.com/Products.html
			Envirosight	Digisewer + ROVVERX	-	Not available
	Electromagnetic—Magnetic Flux Leakage	M	Eddify Corp / Silverwing		-	http://www.silverwingndt.com/contact/contact-details
	Electromagnetic—Ground Penetrating Radar	M,C,P	Geophysical Survey Systems Inc. (GSSI)	SIR-3000	20000	http://www.geophysical.com/sir3000.htm
			Geophysical Survey Systems Inc. (GSSI)	UtilityScan	20500	http://www.geophysical.com/utilityscan.htm
	Ultrasonic Scanning / Sonar Profiling (non-optimal)	M,C,P	Hydromax USA		7000	https://www.hydromaxusa.com/
	Multi-sensor Profiling—Laser & Sonar	M,C,P	National Plant Services (Carolyn Corporation Ltd.)		0	https://www.youtube.com/watch?v=wclmgVHTSAQ
	Multi-sensor Profiling—Laser & Sonar & Video	M,C,P	National Plant Services (Carolyn Corporation Ltd.)		0	https://www.youtube.com/watch?v=wclmgVHTSAQ
Solution deployed at ground surface/ outside the culvert	Optoelectronic—Laser Profiling (non-optimal)	M,C,P			-	Not available
	Electromagnetic—Ground Penetrating Radar	M,C,P	Geophysical Survey Systems Inc. (GSSI)	SIR-3000	20000	http://www.geophysical.com/sir3000.htm
			Geophysical Survey Systems Inc. (GSSI)	UtilityScan	20500	http://www.geophysical.com/utilityscan.htm
	Thermographic—Infrared Thermography (non-optimal)	C			-	Not available
Solution deployed from within/inside/ close proximity to the culvert	Visual—Plain / Push-cameras	M,C,P	Envirosight	Verisight Pro+	-	Not available
	Visual—CCTV Crawler	M,C,P	Aries Industries	Pathfinder	80000	https://www.ariesindustries.com/video-inspection/transporters/pathfinder/
			CUES		-	http://www.cuesinc.com/Products.html
			GoFAR USA		36000	http://www.gofarusa.com/
	Visual—CCTV Crawler with Side Scanning	M,C,P	CUES		-	http://www.cuesinc.com/Products.html
			Envirosight	Digisewer + RovverX	-	Awaiting quotations / Not available
	Optoelectronic—Laser Profiling	M,C,P			-	Not available
	Fully Automated Optoelectronic—Laser Profiling with CCTV and Neural Network Algorithm	M,C,P				Special project
	Electromagnetic—Magnetic Flux Leakage	M	Eddify Corp / Silverwing		-	http://www.silverwingndt.com/contact/contact-details

TABLE 5.5
(Continued)

Deployment Mode	Inspection Technology	Applicability	Manufacturers & Vendors	Model	Cost (USD)	Link / Remarks
	Electromagnetic—Eddy Current Techniques (digging and exposing culvert surface is necessary)	M	Eddify Corp / Sivlerwing		-	http://www.silverwingndt.com/contact/contact-details
	Electromagnetic—Ground Penetrating Radar	M,C,P	Geophysical Survey Systems Inc. (GSSI)	SIR-3000	20000	http://www.geophysical.com/sir3000.htm
	Acoustic—Ultrasonic Scanning / Sonar Profiling	M,C,P	Hydromax USA		7000	https://www.hydromaxusa.com/
	Acoustic—Impact Echo Testing / SASW	C				Not available
	Radiographic—Backscatter Computer Tomography	M,C,P				Not available
	Radiographic—Gamma-gamma logging	C				Not available
	Re-bar Condition Testing—Magnetic Field Disturbance	C				Not available
	Micro-crack Testing—Liquid Penetrant Testing	M,P				Not available
Solution deployed at ground surface/ outside the culvert	Optoelectronic—Laser Profiling	M,C,P			-	Not available
	Electromagnetic—Ground Penetrating Radar	M,C,P	Geophysical Survey Systems Inc. (GSSI)	SIR-3000	20000	http://www.geophysical.com/sir3000.htm

6. SURVEY OF DOTS AND FINDINGS FROM SURVEY

As part of the scope of this effort, a nationwide survey of DOTs was conducted in order to understand the current state of the art in culvert inspection among the DOTs. The survey questionnaire is attached in Appendix A. In summary statistics, we received 100 valid responses from DOT personnel in 32 states as shown in Figure 6.1. Appendix C reflects culvert inspection processes from participating DOTs, as well as their exposure to technological solutions for culvert inspection. Appendix D contains the names and contact information (where possible) of survey respondents; and It should be noted, that in most cases, the survey was sent out to a main contact who then distributed it to appropriate DOT personnel within their organization. Hence, appendices C & D cannot be directly correlated. As indicated by the respondents, the approximate number of existing small and medium sized culverts in the states range between 10,000 in certain smaller states to greater than 150,000 in larger ones. The average number of small and medium sized culverts reported was ~57,000. It is known that INDIANA has ~80,000 small and medium culverts. The respondents were also asked to indicate their designation within the DOT organization and the reported roles represent a wide spectrum spanning directors, engineers of various levels, chief unit leaders, designers, specialists, researchers, managers, and coordinators. Responders belonged to state, district and regional divisions of the DOTs. Responders also provided their position in the DOT. Overall 37 positions were mentioned. Positions were then categorized into roles as "engineer, specialist, maintenance, director, manager, coordinator, designer, unit leader" only if this keyword was mentioned in the roles indicated by the responders. The survey of the DOTs indicated that the most prevalent material types for culverts were metal, concrete, thermoplastic, metal with concrete lining, and clay in decreasing order of prevalence. This is captured in Figure 6.2.

Yet another finding from the survey was in regard to the frequency of inspection of the small and medium culverts among the DOTs. As captured in Figure 6.3, the majority (73%) of respondents from DOTs reported inspecting less than 30% of the culverts in their region on a regular basis. 22% believed that 30%–70% of the culverts in their regions were inspected on a regular basis, and only 5% of the respondents believed that more than 70% of the culverts in their region were inspected regularly. The frequency of inspections reported by DOTs varied and included annual, biennial, and once every 4 as well as 5 years. Although not specifically stated by respondents, it is suspected that the basis for this reported frequency is the NBIS guideline for large culverts. Overall, 61% of the respondents reported having an in-place system for culvert inspection, in general. Based on a follow-up question regarding the description of that method, it came to light that

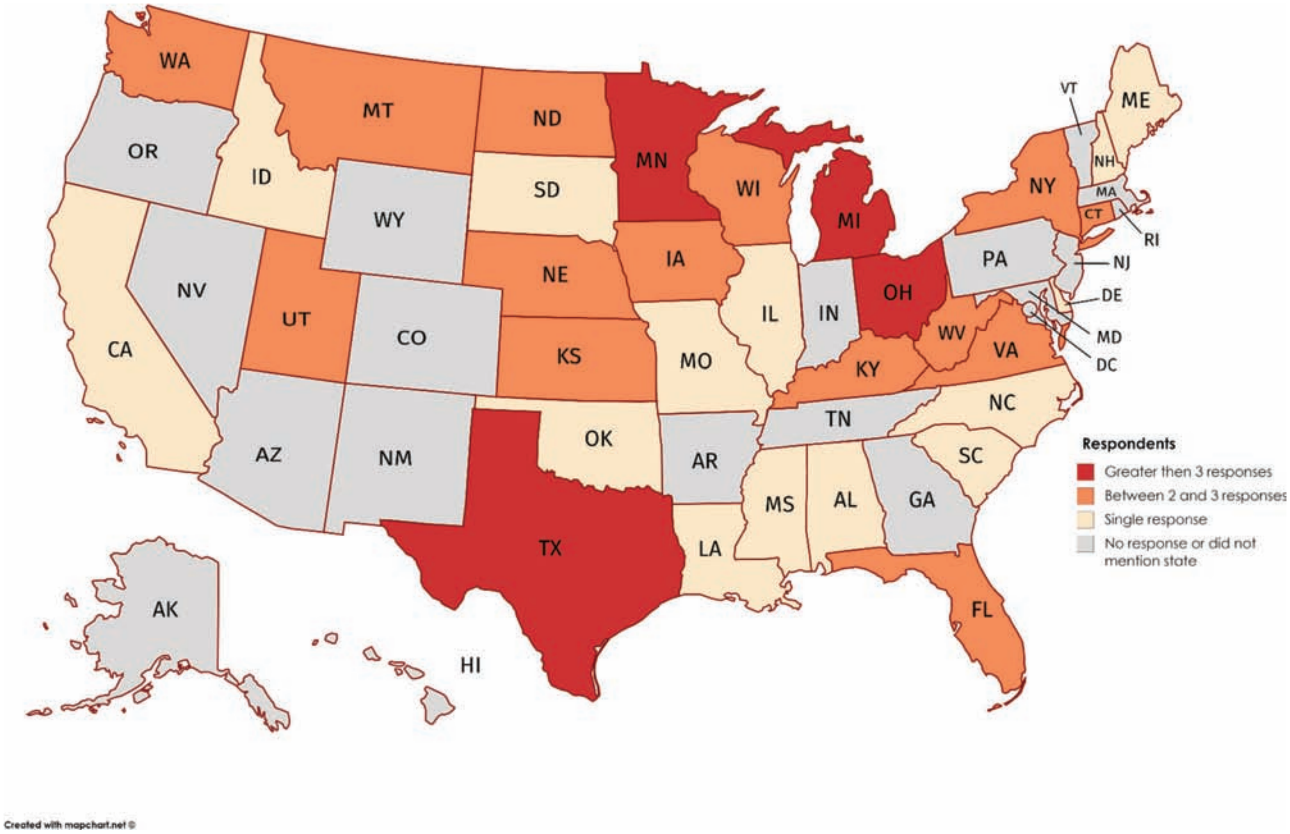


Figure 6.1 Map of state DOTs that responded to the survey and the number of respondents from each state.

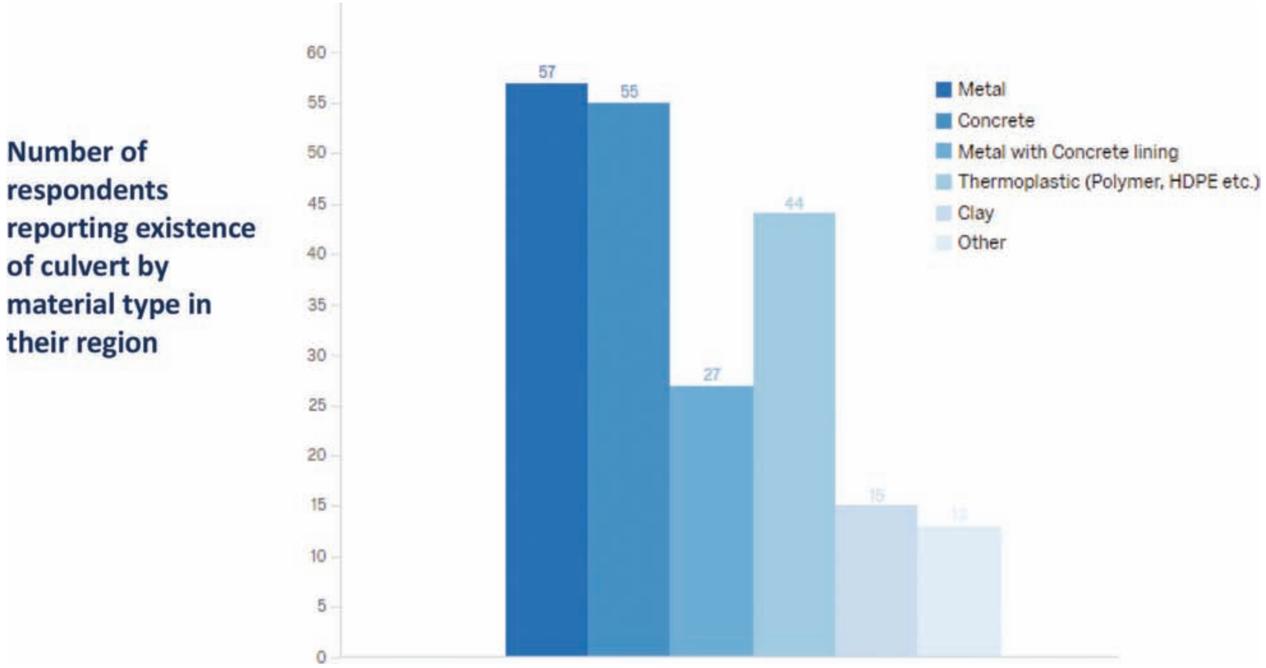


Figure 6.2 Culvert material type prevalence in DOTs.

the general inspection method and the recommended NBIS rating scale for large culverts was extended to small and medium culverts in a large number of DOTs (19 out of 32). The NBIS recommended rating scale is attached in Appendix B. In addition, a summary of the description of the system followed by the DOTs (Table 6.1) revealed that there is inconsistency in the inspection systems including inspection frequency among states

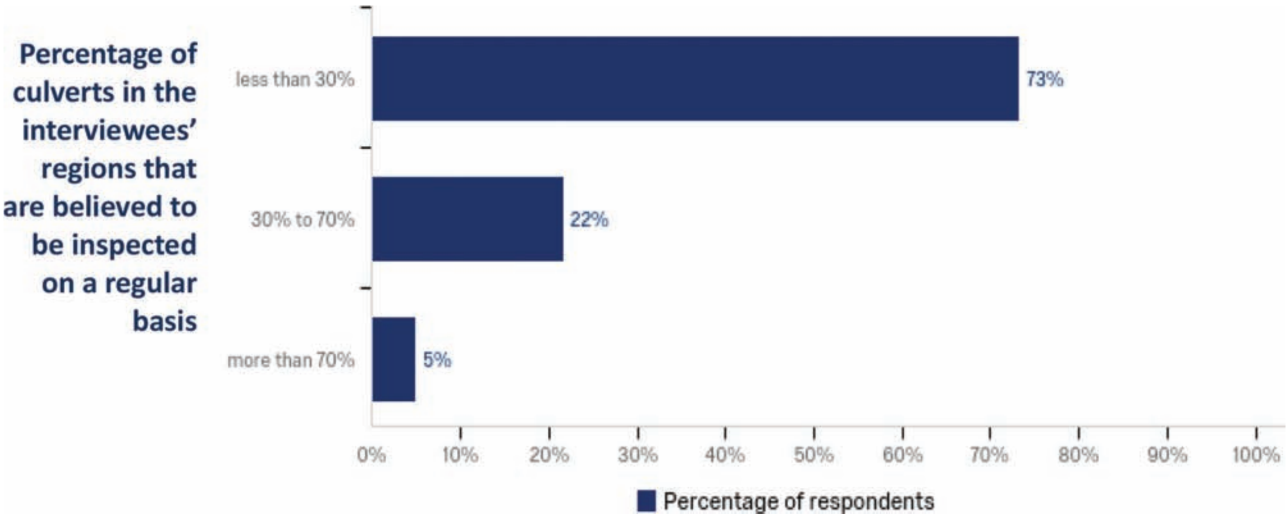


Figure 6.3 Culvert inspection frequency trend as reported.

TABLE 6.1
Inspection practices as reported by respondents from DOTs

Inspection practice reported	Description	States reporting such practice
Rating System	States that explicitly indicated using a rating scale 0–9 with less than 4 being generally monitored	NC, UT, OH, MI, MN, CT, ME
Frequency of inspections	States that explicitly indicated inspection frequency as annual, biennially, once every 4 years and once every 5 years	UT, IA, KS, CT, FL, SC, MS, NY, MI
NBIS Standards	States that explicitly mentioned following the NBIS standard	WI, VA, ID, NE
Reactive	States that explicitly indicated only monitoring culverts that are flagged by in-field teams	CA, ND, MI, FL, MT
Non-systematic inspections	States that explicitly indicated that no specific monitoring system was being followed	WI, VA, IA, NE

which highlights the need for a standard guideline for inspecting small and medium sized culverts. A 2016 study and subsequent report from the TRB database dated May 2016 develops a new rating scale and inspection frequency guideline (Beaver & Richie, 2016).

The survey also explored custom solutions that might have been developed by states to inspect culverts. 70% of states reported not having developed any custom build solutions. However, 15% of states reported having a custom-built solution for culvert inspection. A state-wise distribution is shown in Figure 6.4. The solutions include:

- Earth pressure monitoring
- Acquired equipment / assembled solutions
- The use of camera
- The use of drones
- The use of crawlers
- The use of HIVE (recently developed by MnDOT)
- The use of a 'GoPro'
- Solutions to enhance visibility from the pipe end

Out of the states that were surveyed, Ohio, Minnesota, Michigan, Florida, and Utah reported interest in using / developing solutions that are related to visual methods that include pole-cameras, videos using CCTV, and in certain cases, a crawler mounted CCTV. This is one of our recommended high potential technological solutions. No states reported awareness, use, or development of a multi-sensor solution such as the UCIS developed by SwRI and FHWA, and reported above in section 5.1.6.

The survey also explored the most important design features and solution characteristics that DOT personnel would like to see in a culvert inspection tool. The survey analysis revealed a gap in what is sought and what is known or being pursued by DOTs (Figure 6.5). For instance, it was found that usability while culvert is 'in-service' was rated critically important. However, awareness of multi-sensing solutions that offer high-potential to facilitate culvert monitoring while 'in-service' was limited (8% of respondents). Similarly, reduction of manual effort was rated high importance. However, all respondents' current technological solutions remain quite labor intensive. Cost effectiveness was also rated high importance. This is in congruence with DOTs search for new technical solutions as crawlers loaded with cameras are cost effective solutions as proven by the MnDOT's HIVE

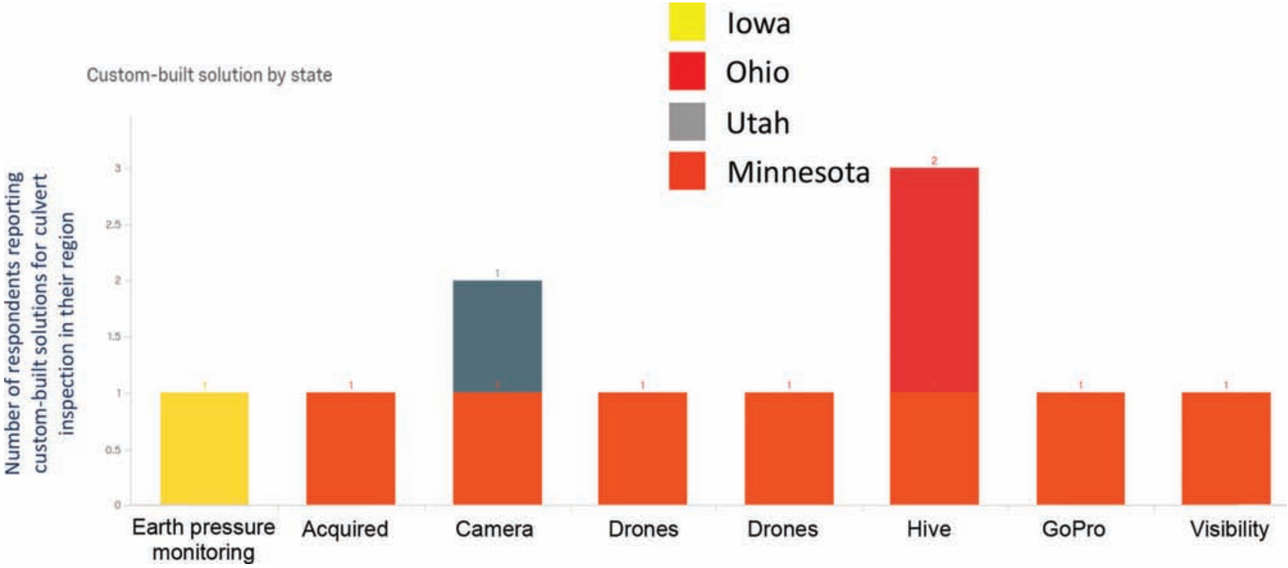


Figure 6.4 Custom-built solution by state.

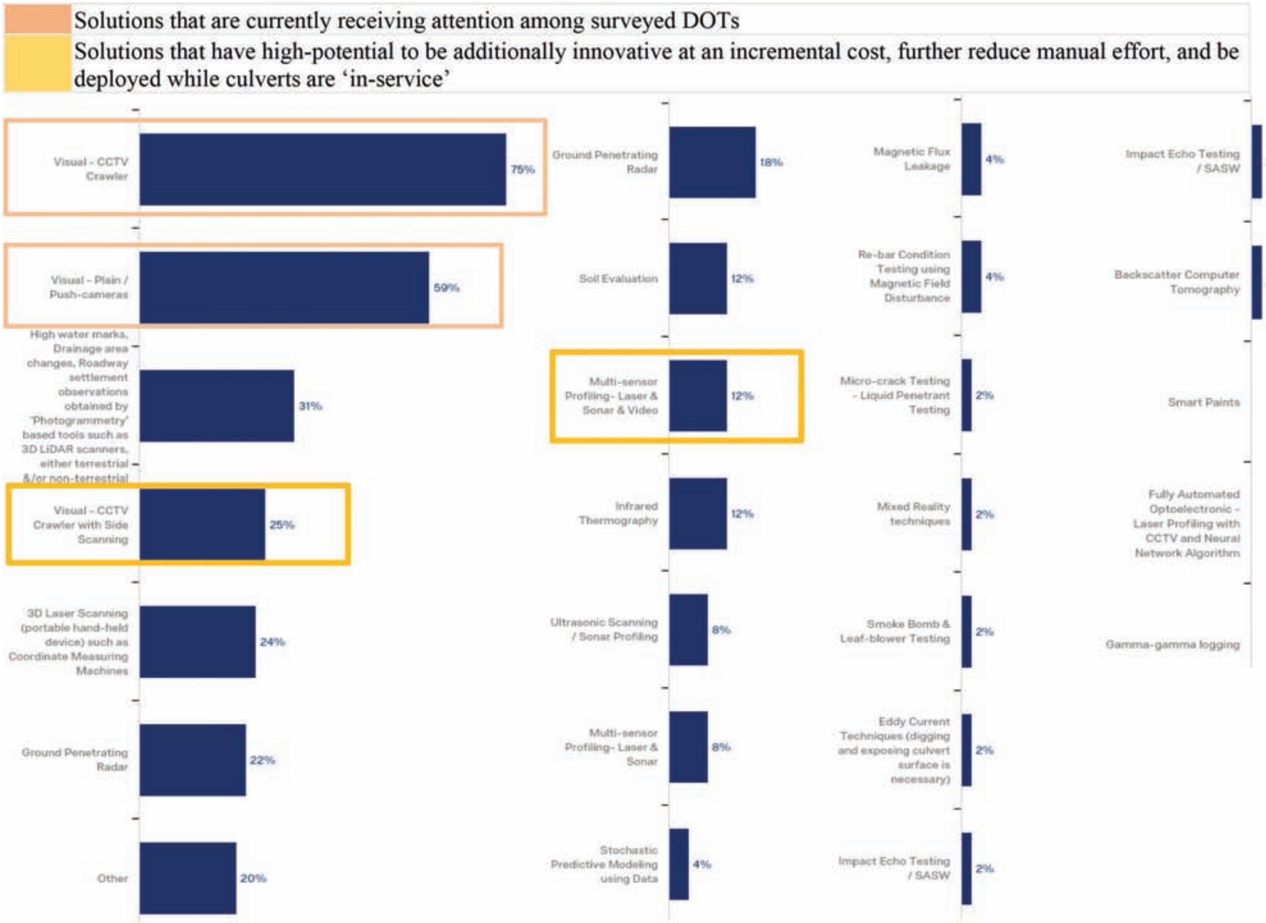


Figure 6.5 Percentage of respondents and their cognizance of the synthesized technologies.

project (Youngblood, 2017) shown in Figure 6.6. In addition, being low weight was given medium to high importance. Deployability from a far distance was rated less important. Overall, it can be said that the respondents' knowledge of the state-of-the-art in culvert inspection was primarily centered on manual

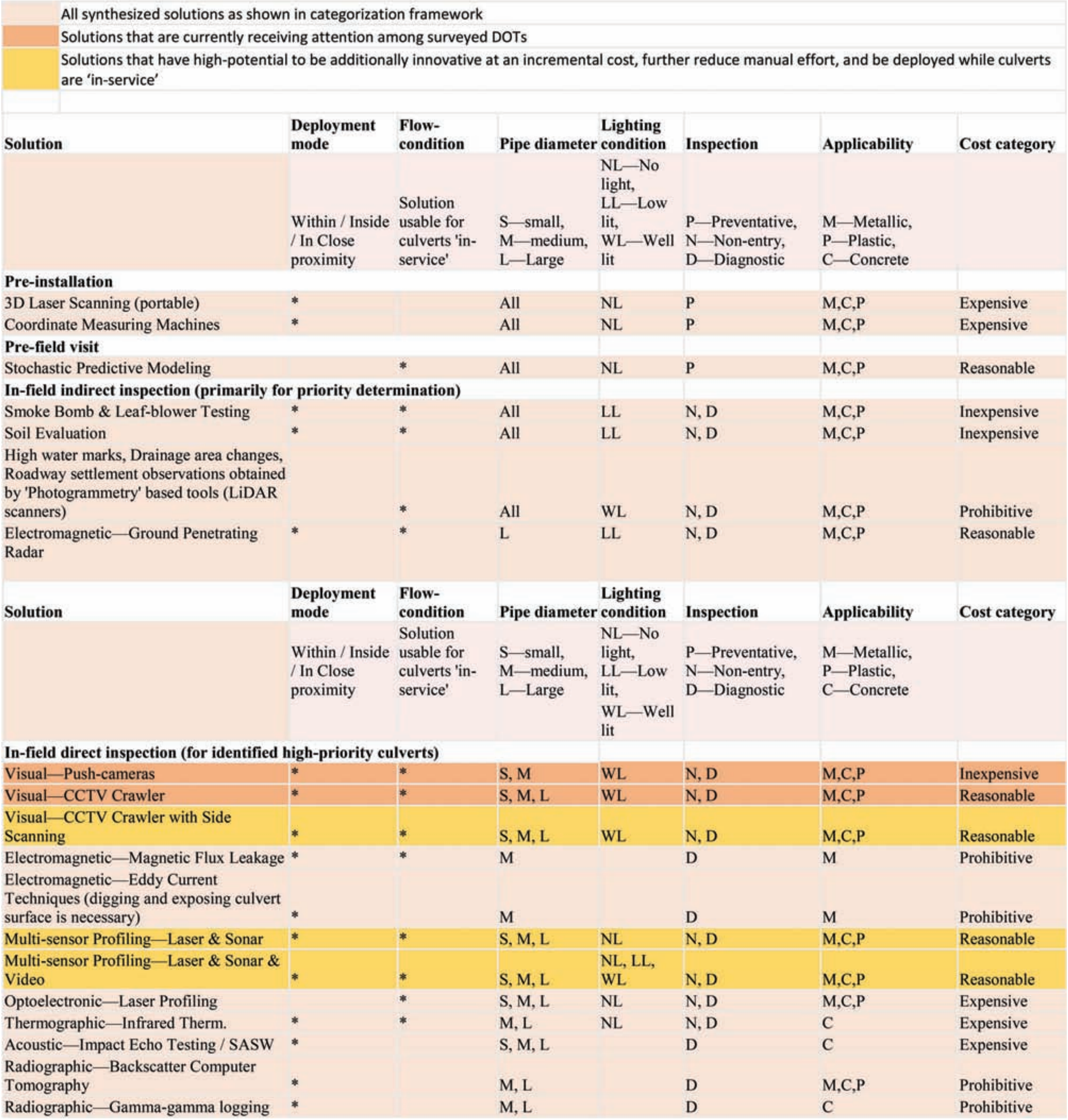
Figure 6.6 The HIVE camera unit and image taken by it. (Source: http://dot.state.mn.us/research/reports/2017/201716.pdf.)

entry reducing visual inspection tools, mainly using video, and respondents were less aware of incremental innovations to robotic crawlers such as side-scanning cameras that can dramatically increase productivity and while raising costs only incrementally. This is because as described in section 5.1.2.3, having a visual method based technical solution with side scanning camera greatly increases the effectiveness and efficiency of the method by eliminating the need for stopping, panning, tilting and zooming, thereby reducing the in-field time and effort for the system operator.

7. RECOMMENDATIONS AND CONCLUSION

This study revealed that no standard inspection guidelines exist for small culverts, and that inspection practices vary significantly across states. DOT survey results confirmed that most DOTs do not have a specific technical solution for small to medium culvert inspections, and instead, primarily rely on visual examination conducted by field personnel, often from the open ends of the culvert, limiting the range of flaws and failure modes that can be identified, and the desired early warning benefits of inspection. The synthesis of available technical solutions demonstrates that a broad range of technologies are available to facilitate culvert inspection. However, many methods can be employed only for a limited set of culvert materials and operating conditions. As a result, more broadly applicable inspection methods such as visual camera based and multi-sensing techniques stand out for their high potential to provide significant insight into the condition of a variety of culvert types at low to moderate cost (see Figure 7.1).

Specifically, as shown in Figure 7.2, five solutions—three from the visual solution space and two from the multi-sensor approach as described in sections 5.1.2 and 5.1.6, respectively stand out. Keeping in mind the critical and highly important design parameters of the ability to carry out the inspection of the culvert while keeping the culvert in-service and reduction in manual effort, the focus for DOT's such as INDOT should thus be to develop and deploy a low-cost multi-sensing solution founded on visual techniques, with the added ability to navigate within a culvert via deployment on a remote controlled mobile platform (e.g., a radio controlled (RC) vehicle)—a method broadly termed a visual-camera-on-crawler solution. Inspiration for this type of system can be derived by combining devices such as the Ultrasonic Culvert Inspection System developed by the Southwest Research Institute (SwRI) and FHWA with additional capability to be mounted on a crawler for use in dry culvert conditions as is done with MnDOT's HIVE. Additionally, for visual-camera-on-crawler techniques, improvements such as use of a side scanning camera could greatly enhance the efficiency and effectiveness of the method by eliminating the need for stopping, panning, tilting and zooming, thereby reducing the in-field time and effort for the system operator. Finally, over the longer term, beyond adoption of technology to facilitate inspection, a systematized phase-wise approach for issue-detection and maintenance should likely be developed for culverts. Such a system would be particularly valuable when used in combination with the Esri Collector Application database that INDOT has commissioned for infrastructure maintenance. Furthermore, as data is collected via these systems, stochastic predictive models could be developed to provide INDOT asset managers with an informed basis to schedule inspections and enhance overall resource utilization and efficiency in the inspection and maintenance of culvert. Furthermore, it was found that INDOT has commissioned the utilization of the Esri Collector Application for asset management. In regard to this development, we developed a comprehensive inspection process tree for issue detection as described in section 5.4. Such a system would be particularly useful alongside the Esri Collector Application cum database for infrastructure

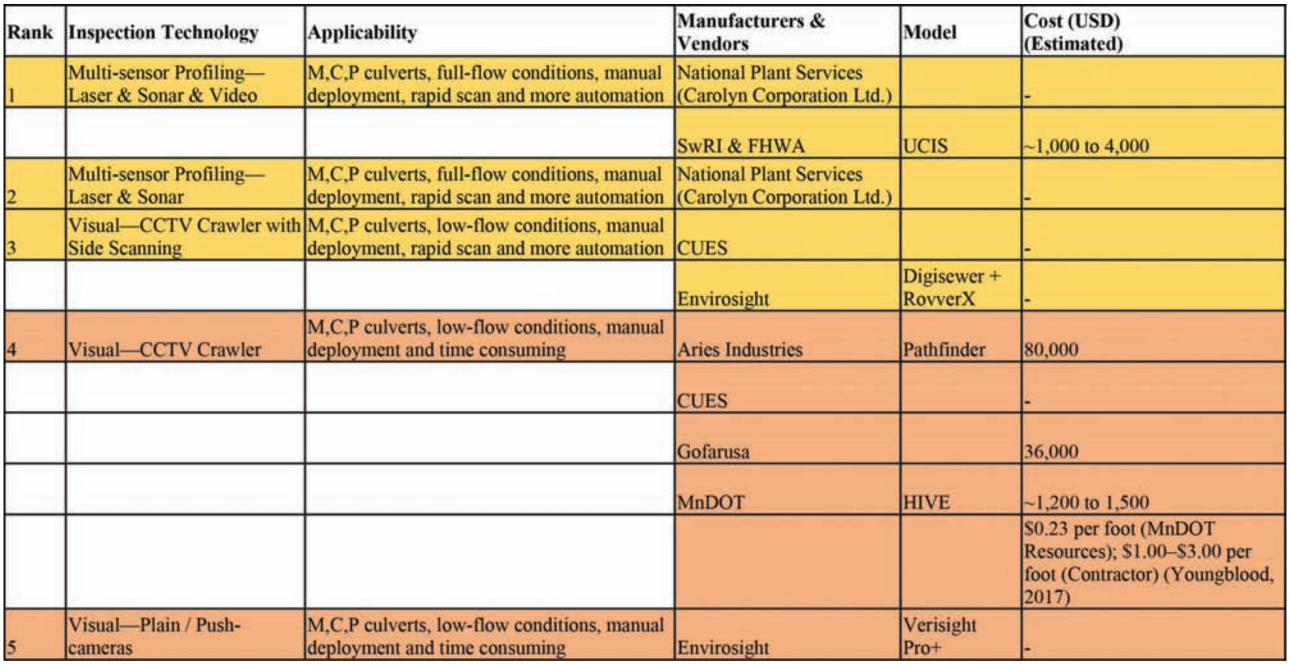


⬜	All synthesized solutions as shown in categorization framework
🟧	Solutions that are currently receiving attention among surveyed DOTs
🟨	Solutions that have high-potential to be additionally innovative at an incremental cost, further reduce manual effort, and be deployed while culverts are 'in-service'

Solution	Deployment mode	Flow-condition	Pipe diameter	Lighting condition	Inspection	Applicability	Cost category
	Within / Inside / In Close proximity	Solution usable for culverts 'in-service'	S—small, M—medium, L—Large	NL—No light, LL—Low lit, WL—Well lit	P—Preventative, N—Non-entry, D—Diagnostic	M—Metallic, P—Plastic, C—Concrete	
Pre-installation							
3D Laser Scanning (portable)	*		All	NL	P	M,C,P	Expensive
Coordinate Measuring Machines	*		All	NL	P	M,C,P	Expensive
Pre-field visit							
Stochastic Predictive Modeling		*	All	NL	P	M,C,P	Reasonable
In-field indirect inspection (primarily for priority determination)							
Smoke Bomb & Leaf-blower Testing	*	*	All	LL	N, D	M,C,P	Inexpensive
Soil Evaluation	*	*	All	LL	N, D	M,C,P	Inexpensive
High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools (LiDAR scanners)		*	All	WL	N, D	M,C,P	Prohibitive
Electromagnetic—Ground Penetrating Radar	*	*	L	LL	N, D	M,C,P	Reasonable
Solution	**Deployment mode**	**Flow-condition**	**Pipe diameter**	**Lighting condition**	**Inspection**	**Applicability**	**Cost category**
	Within / Inside / In Close proximity	Solution usable for culverts 'in-service'	S—small, M—medium, L—Large	NL—No light, LL—Low lit, WL—Well lit	P—Preventative, N—Non-entry, D—Diagnostic	M—Metallic, P—Plastic, C—Concrete	
In-field direct inspection (for identified high-priority culverts)							
Visual—Push-cameras	*	*	S, M	WL	N, D	M,C,P	Inexpensive
Visual—CCTV Crawler	*	*	S, M, L	WL	N, D	M,C,P	Reasonable
Visual—CCTV Crawler with Side Scanning	*	*	S, M, L	WL	N, D	M,C,P	Reasonable
Electromagnetic—Magnetic Flux Leakage	*	*	M		D	M	Prohibitive
Electromagnetic—Eddy Current Techniques (digging and exposing culvert surface is necessary)	*		M		D	M	Prohibitive
Multi-sensor Profiling—Laser & Sonar	*	*	S, M, L	NL	N, D	M,C,P	Reasonable
Multi-sensor Profiling—Laser & Sonar & Video	*	*	S, M, L	NL, LL, WL	N, D	M,C,P	Reasonable
Optoelectronic—Laser Profiling		*	S, M, L	NL	N, D	M,C,P	Expensive
Thermographic—Infrared Therm.	*	*	M, L	NL	N, D	C	Expensive
Acoustic—Impact Echo Testing / SASW	*		S, M, L		D	C	Expensive
Radiographic—Backscatter Computer Tomography	*		M, L		D	M,C,P	Prohibitive
Radiographic—Gamma-gamma logging	*		M, L		D	C	Prohibitive

Figure 7.1 Technology choice prescription.

maintenance. Furthermore, as data is collected via these systems, stochastic predictive models should be developed using the probabilistic approach described in section 5.1.1.1, which will provide INDOT asset managers with a potentially reliable basis to make resource allocation decisions thereby enhancing the overall resource utilization for the inspection and maintenance of state infrastructure.



Rank	Inspection Technology	Applicability	Manufacturers & Vendors	Model	Cost (USD) (Estimated)
1	Multi-sensor Profiling—Laser & Sonar & Video	M,C,P culverts, full-flow conditions, manual deployment, rapid scan and more automation	National Plant Services (Carolyn Corporation Ltd.)		-
			SwRI & FHWA	UCIS	~1,000 to 4,000
2	Multi-sensor Profiling—Laser & Sonar	M,C,P culverts, full-flow conditions, manual deployment, rapid scan and more automation	National Plant Services (Carolyn Corporation Ltd.)		-
3	Visual—CCTV Crawler with Side Scanning	M,C,P culverts, low-flow conditions, manual deployment, rapid scan and more automation	CUES		-
			Envirosight	Digisewer + RovverX	-
4	Visual—CCTV Crawler	M,C,P culverts, low-flow conditions, manual deployment and time consuming	Aries Industries	Pathfinder	80,000
			CUES		-
			Gofarusa		36,000
			MnDOT	HIVE	~1,200 to 1,500
					$0.23 per foot (MnDOT Resources); $1.00–$3.00 per foot (Contractor) (Youngblood, 2017)
5	Visual—Plain / Push-cameras	M,C,P culverts, low-flow conditions, manual deployment and time consuming	Envirosight	Verisight Pro+	-

Figure 7.2 Ranked recommendation of synthesized technologies based on survey, findings, and analysis.

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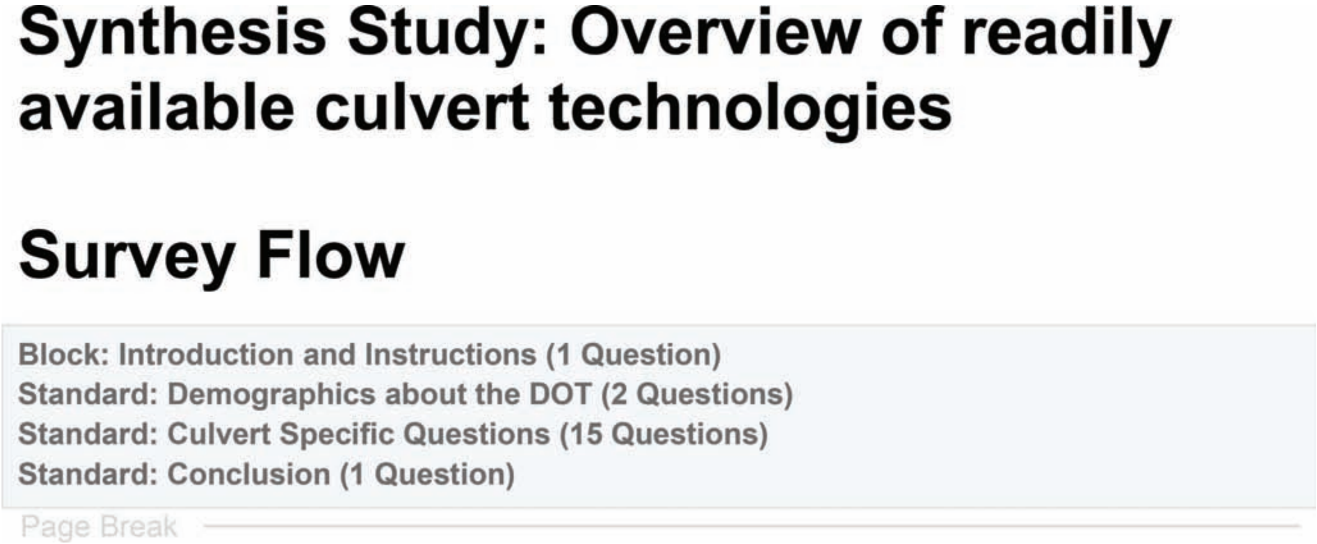
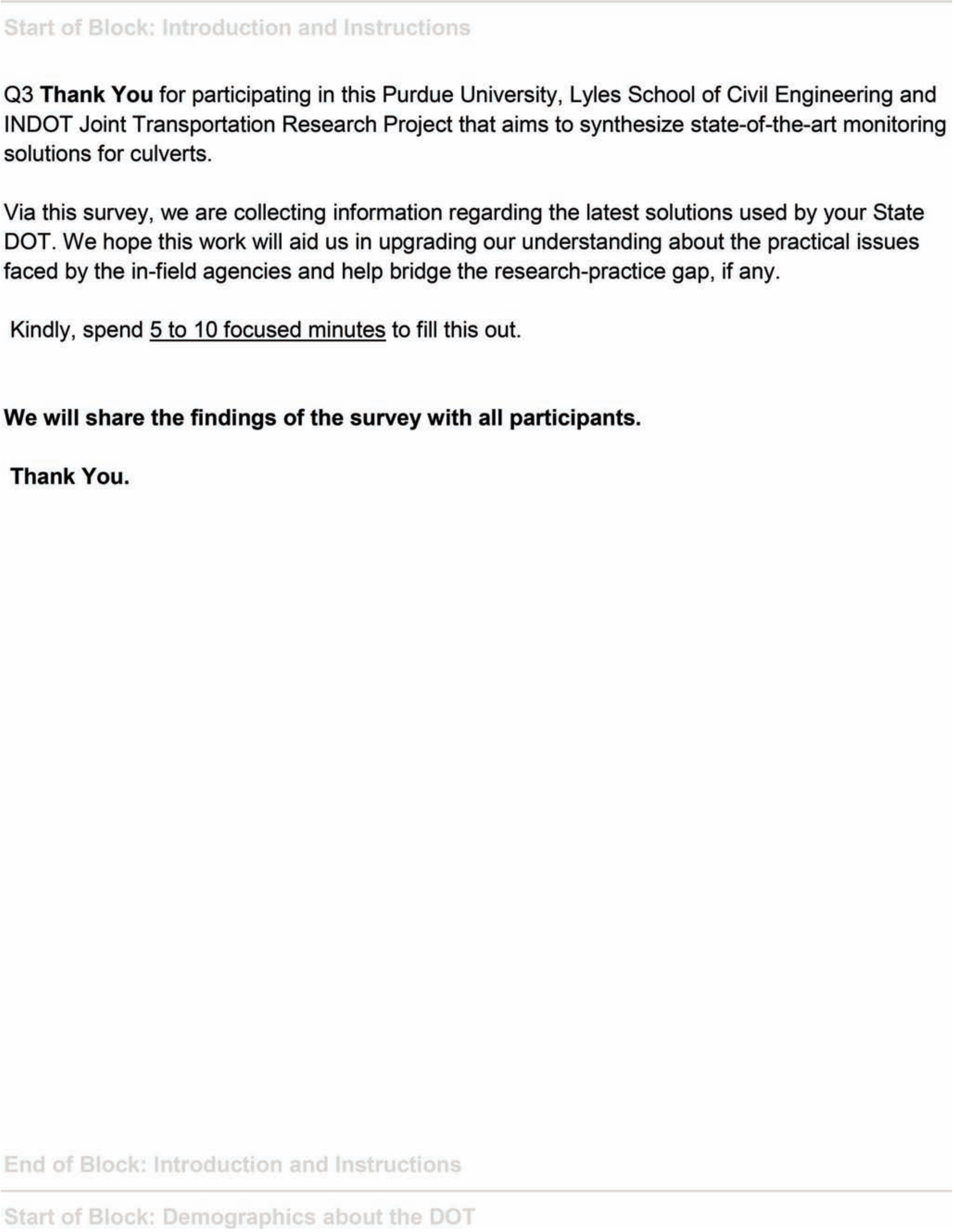
APPENDIX A: SURVEY QUESTIONNAIRE SENT TO DOTS IN THE USA



Synthesis Study: Overview of readily available culvert technologies

Survey Flow

Block: Introduction and Instructions (1 Question)
Standard: Demographics about the DOT (2 Questions)
Standard: Culvert Specific Questions (15 Questions)
Standard: Conclusion (1 Question)



Start of Block: Introduction and Instructions

Q3 **Thank You** for participating in this Purdue University, Lyles School of Civil Engineering and INDOT Joint Transportation Research Project that aims to synthesize state-of-the-art monitoring solutions for culverts.

Via this survey, we are collecting information regarding the latest solutions used by your State DOT. We hope this work will aid us in upgrading our understanding about the practical issues faced by the in-field agencies and help bridge the research-practice gap, if any.

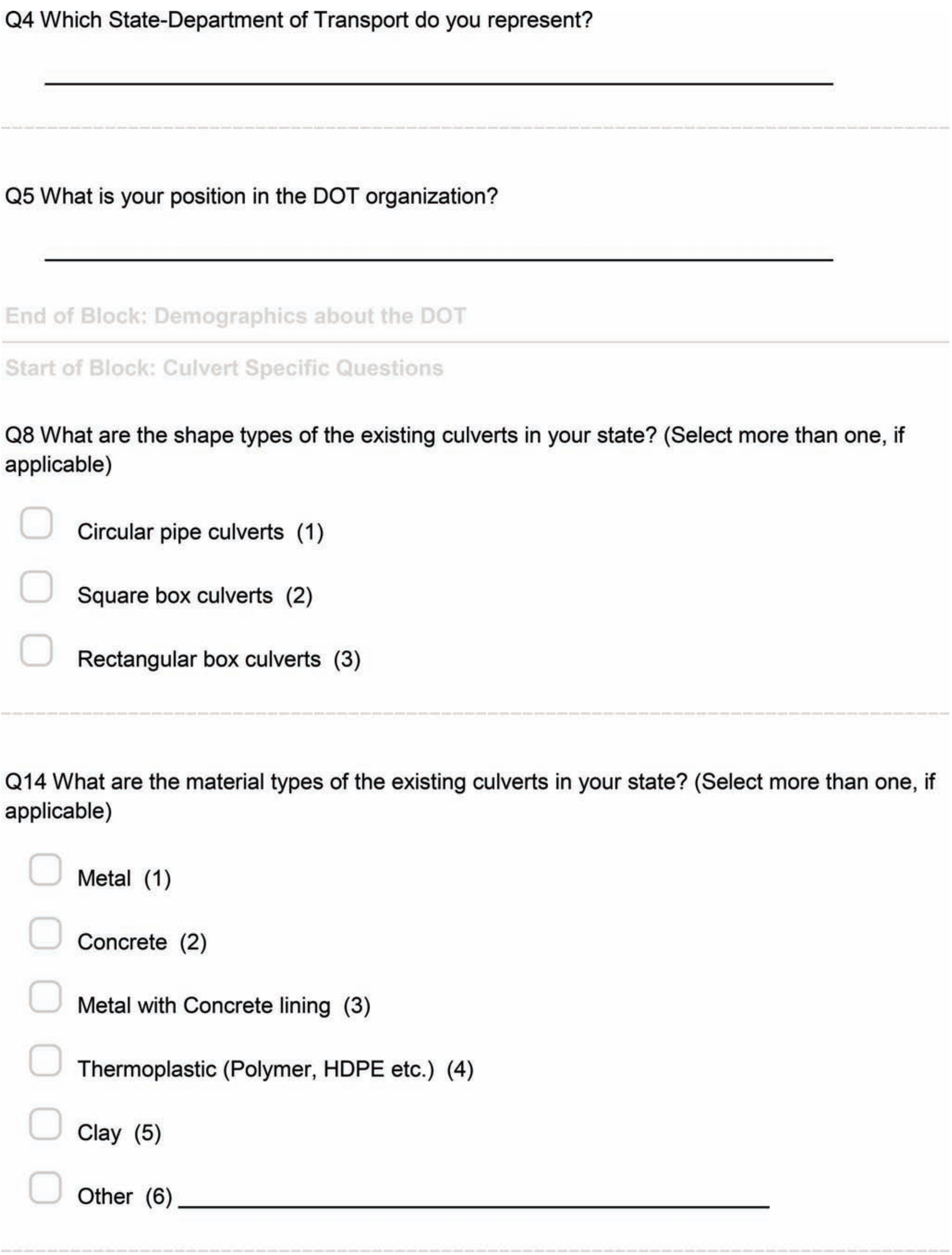
Kindly, spend <u>5 to 10 focused minutes</u> to fill this out.

We will share the findings of the survey with all participants.

Thank You.

End of Block: Introduction and Instructions

Start of Block: Demographics about the DOT



Q4 Which State-Department of Transport do you represent?

____

Q5 What is your position in the DOT organization?

____

End of Block: Demographics about the DOT

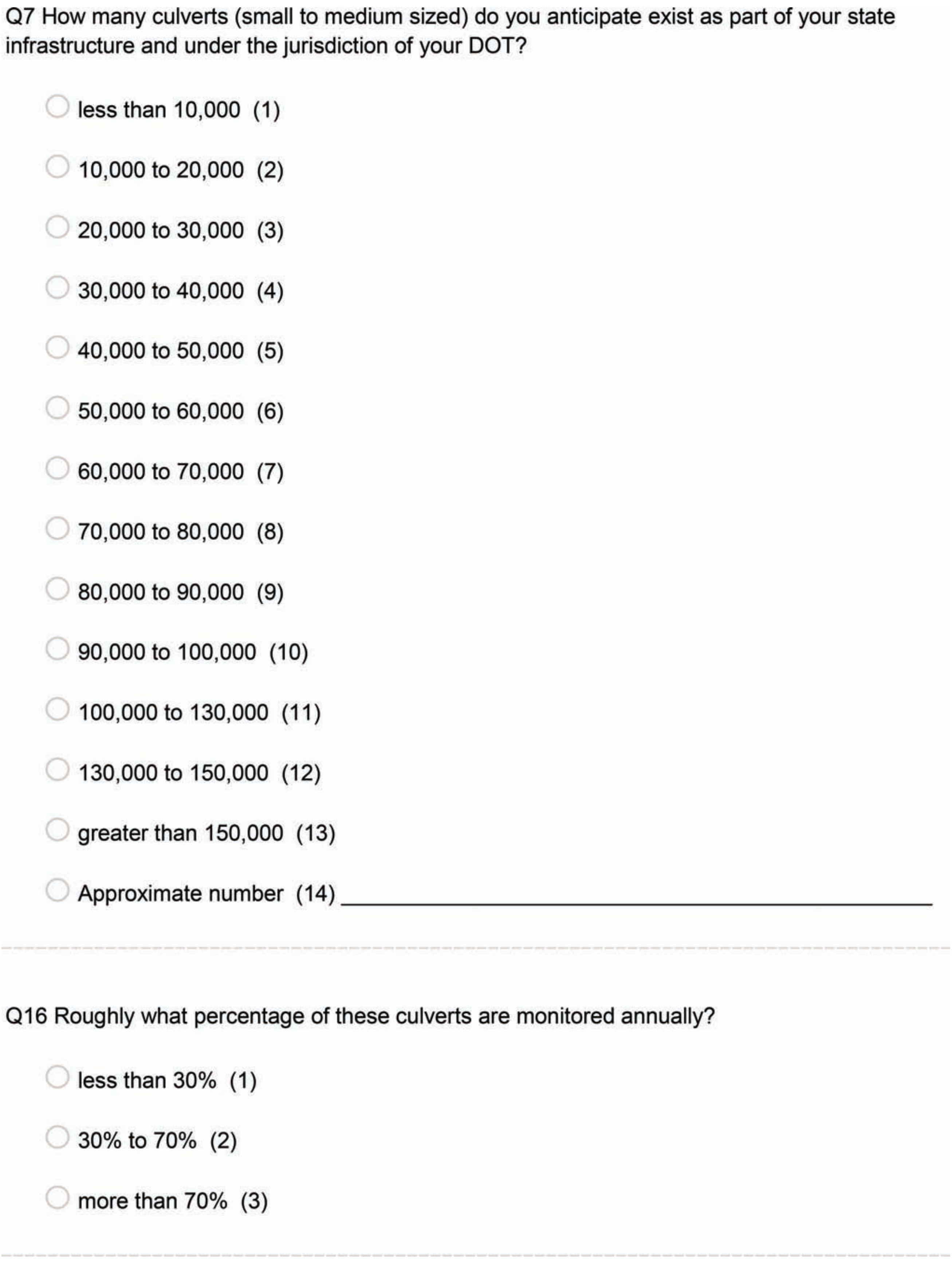
Start of Block: Culvert Specific Questions

Q8 What are the shape types of the existing culverts in your state? (Select more than one, if applicable)

- ☐ Circular pipe culverts (1)
- ☐ Square box culverts (2)
- ☐ Rectangular box culverts (3)

Q14 What are the material types of the existing culverts in your state? (Select more than one, if applicable)

- ☐ Metal (1)
- ☐ Concrete (2)
- ☐ Metal with Concrete lining (3)
- ☐ Thermoplastic (Polymer, HDPE etc.) (4)
- ☐ Clay (5)
- ☐ Other (6) ____



Q7 How many culverts (small to medium sized) do you anticipate exist as part of your state infrastructure and under the jurisdiction of your DOT?

○ less than 10,000 (1)

○ 10,000 to 20,000 (2)

○ 20,000 to 30,000 (3)

○ 30,000 to 40,000 (4)

○ 40,000 to 50,000 (5)

○ 50,000 to 60,000 (6)

○ 60,000 to 70,000 (7)

○ 70,000 to 80,000 (8)

○ 80,000 to 90,000 (9)

○ 90,000 to 100,000 (10)

○ 100,000 to 130,000 (11)

○ 130,000 to 150,000 (12)

○ greater than 150,000 (13)

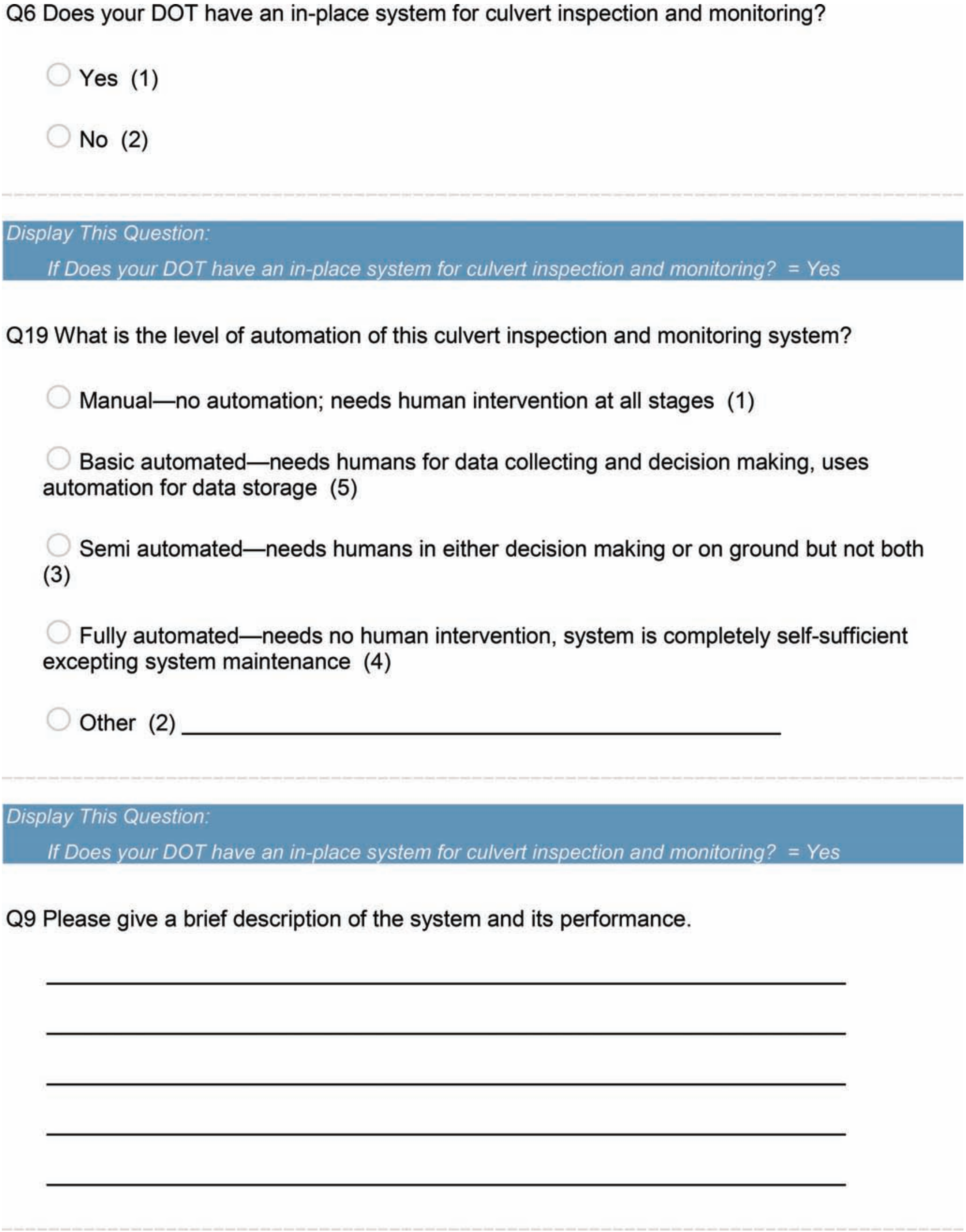
○ Approximate number (14) ____

Q16 Roughly what percentage of these culverts are monitored annually?

○ less than 30% (1)

○ 30% to 70% (2)

○ more than 70% (3)



Q6 Does your DOT have an in-place system for culvert inspection and monitoring?

○ Yes (1)

○ No (2)

Display This Question:

If Does your DOT have an in-place system for culvert inspection and monitoring? = Yes

Q19 What is the level of automation of this culvert inspection and monitoring system?

○ Manual—no automation; needs human intervention at all stages (1)

○ Basic automated—needs humans for data collecting and decision making, uses automation for data storage (5)

○ Semi automated—needs humans in either decision making or on ground but not both (3)

○ Fully automated—needs no human intervention, system is completely self-sufficient excepting system maintenance (4)

○ Other (2) ____

Display This Question:

If Does your DOT have an in-place system for culvert inspection and monitoring? = Yes

Q9 Please give a brief description of the system and its performance.

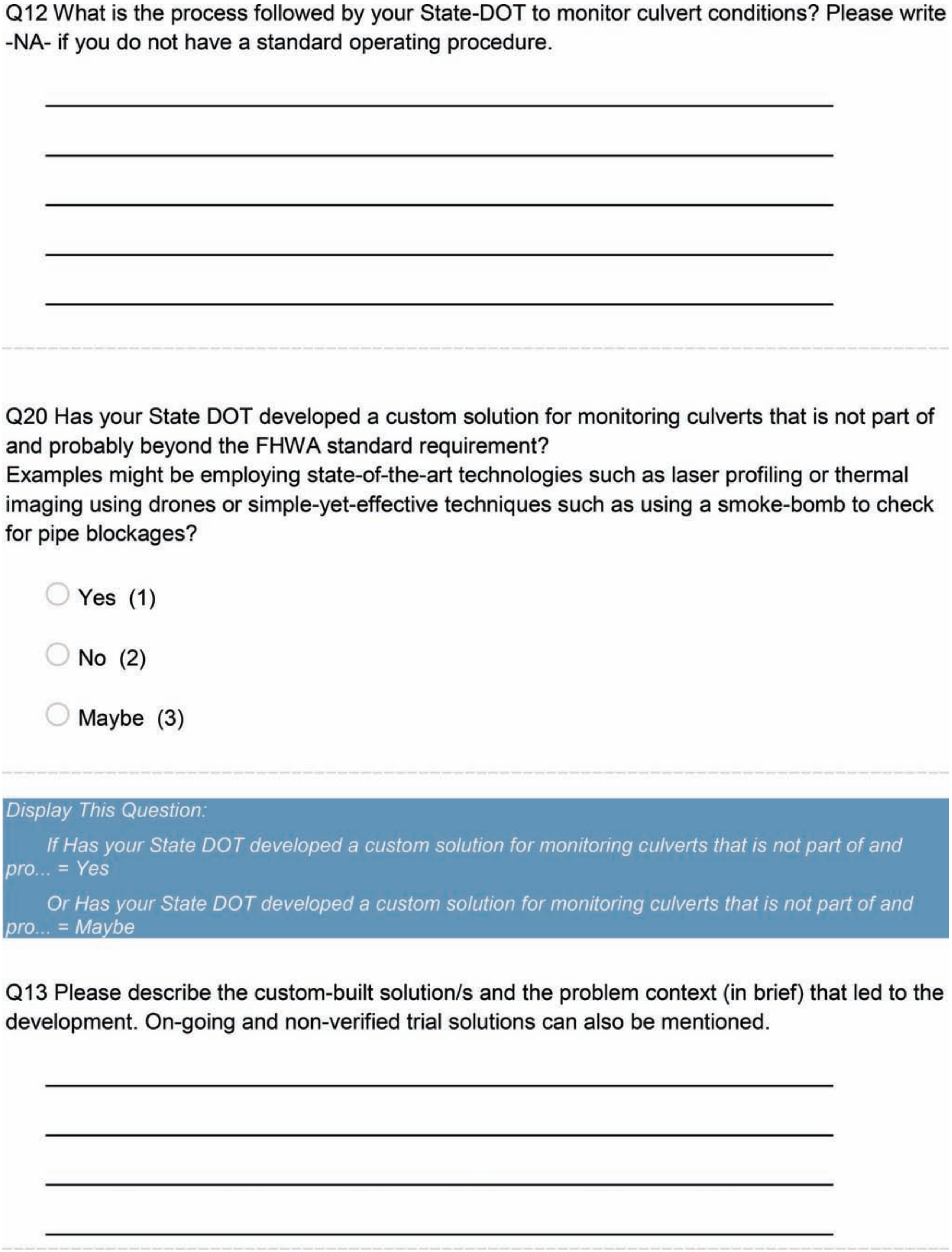
____

____

____

____

____



Q12 What is the process followed by your State-DOT to monitor culvert conditions? Please write -NA- if you do not have a standard operating procedure.

____

____

____

____

____

Q20 Has your State DOT developed a custom solution for monitoring culverts that is not part of and probably beyond the FHWA standard requirement?
Examples might be employing state-of-the-art technologies such as laser profiling or thermal imaging using drones or simple-yet-effective techniques such as using a smoke-bomb to check for pipe blockages?

○ Yes (1)

○ No (2)

○ Maybe (3)

Display This Question:

If Has your State DOT developed a custom solution for monitoring culverts that is not part of and pro... = Yes

Or Has your State DOT developed a custom solution for monitoring culverts that is not part of and pro... = Maybe

Q13 Please describe the custom-built solution/s and the problem context (in brief) that led to the development. On-going and non-verified trial solutions can also be mentioned.

____

____

____

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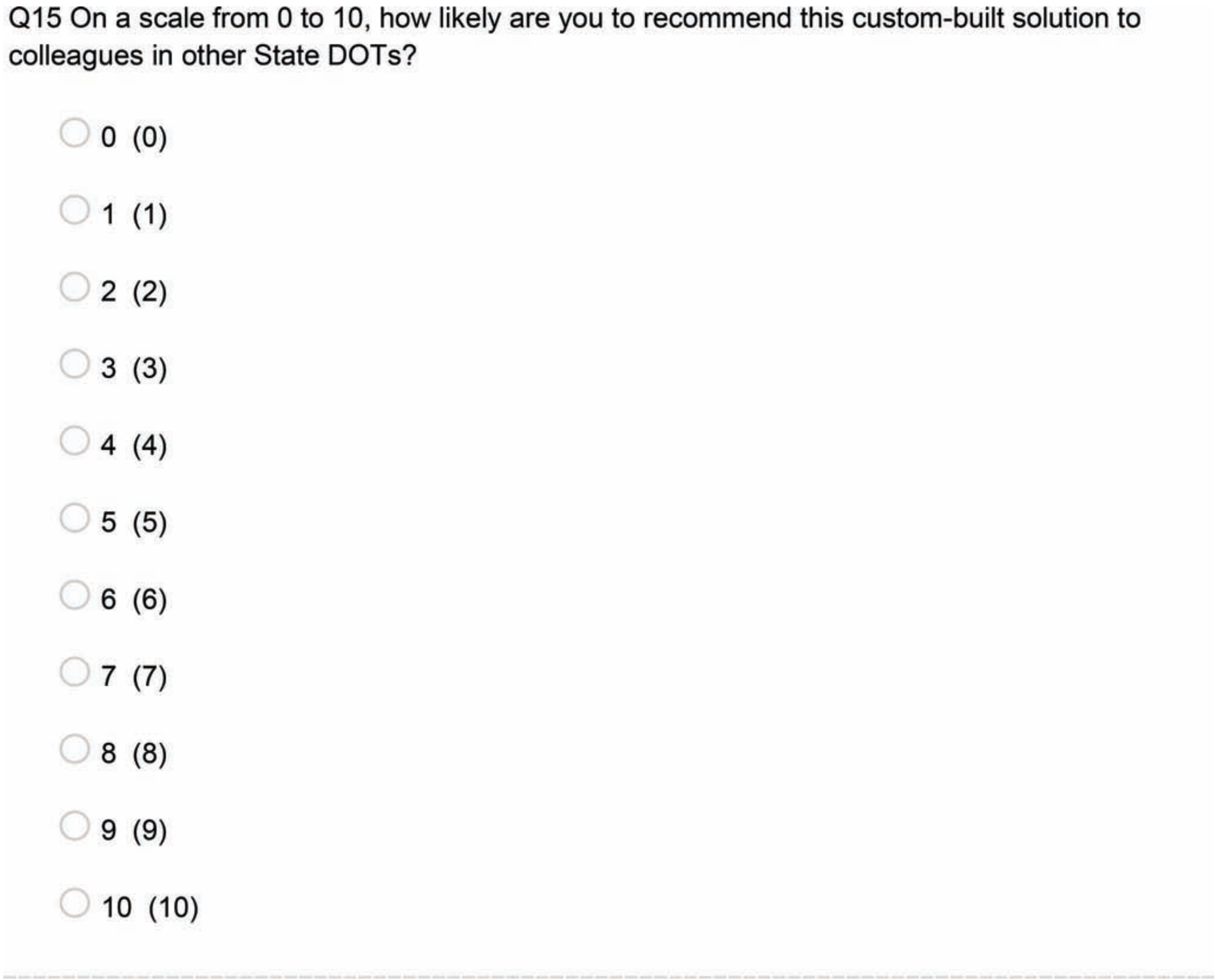


Q15 On a scale from 0 to 10, how likely are you to recommend this custom-built solution to colleagues in other State DOTs?

○ 0 (0)

○ 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

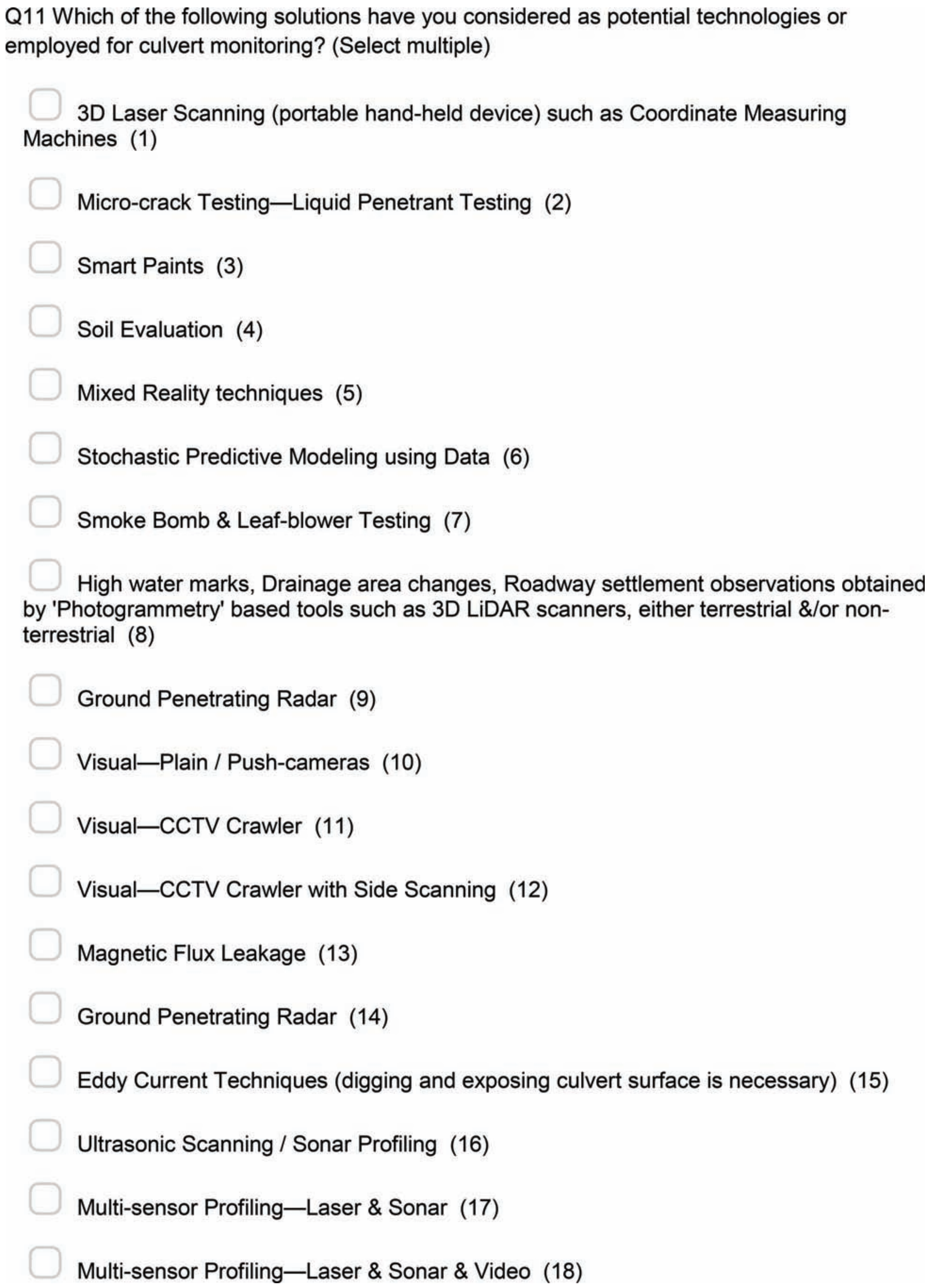
○ 6 (6)

○ 7 (7)

○ 8 (8)

○ 9 (9)

○ 10 (10)



Q11 Which of the following solutions have you considered as potential technologies or employed for culvert monitoring? (Select multiple)

☐ 3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines (1)

☐ Micro-crack Testing—Liquid Penetrant Testing (2)

☐ Smart Paints (3)

☐ Soil Evaluation (4)

☐ Mixed Reality techniques (5)

☐ Stochastic Predictive Modeling using Data (6)

☐ Smoke Bomb & Leaf-blower Testing (7)

☐ High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial (8)

☐ Ground Penetrating Radar (9)

☐ Visual—Plain / Push-cameras (10)

☐ Visual—CCTV Crawler (11)

☐ Visual—CCTV Crawler with Side Scanning (12)

☐ Magnetic Flux Leakage (13)

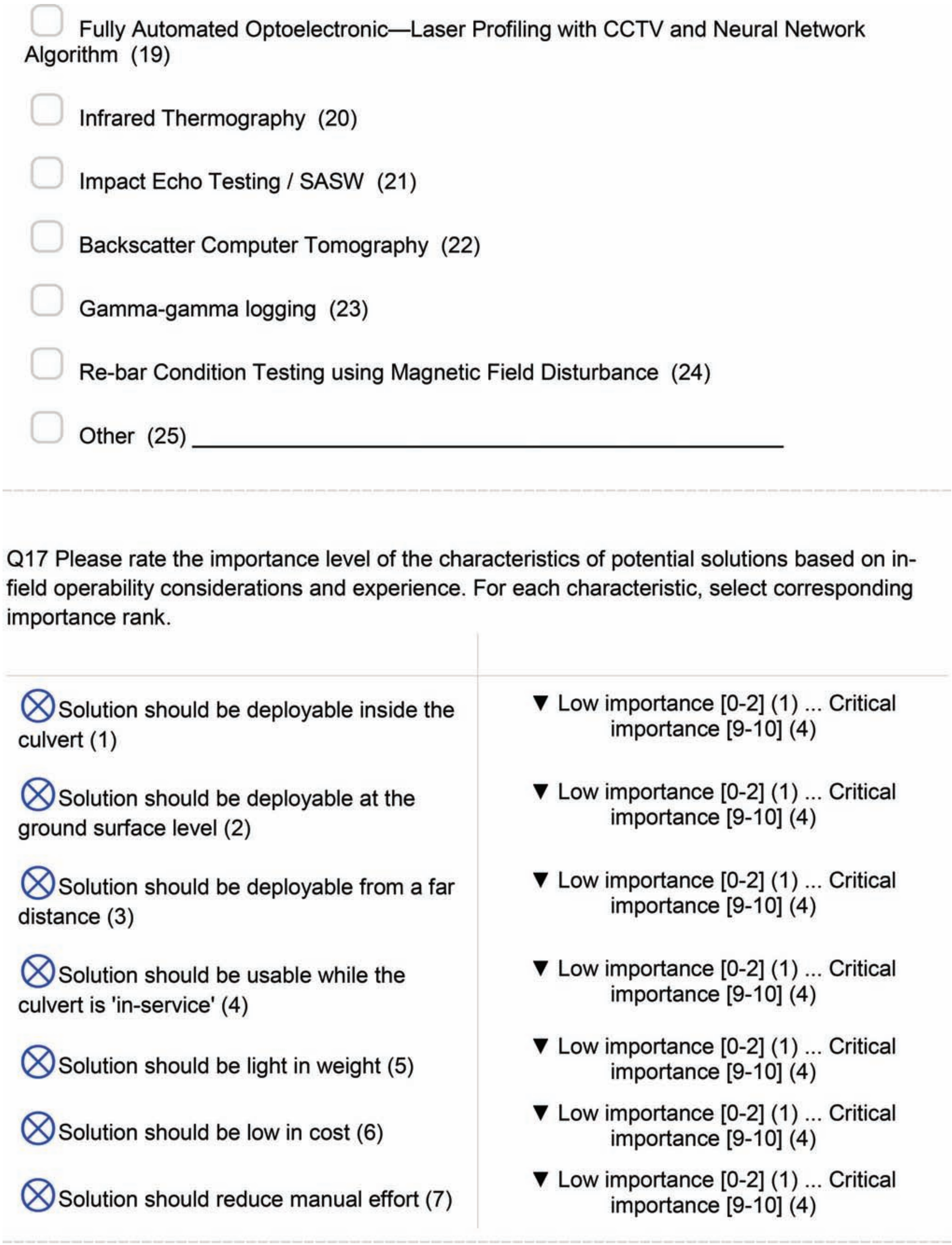
☐ Ground Penetrating Radar (14)

☐ Eddy Current Techniques (digging and exposing culvert surface is necessary) (15)

☐ Ultrasonic Scanning / Sonar Profiling (16)

☐ Multi-sensor Profiling—Laser & Sonar (17)

☐ Multi-sensor Profiling—Laser & Sonar & Video (18)



☐ Fully Automated Optoelectronic—Laser Profiling with CCTV and Neural Network Algorithm (19)

☐ Infrared Thermography (20)

☐ Impact Echo Testing / SASW (21)

☐ Backscatter Computer Tomography (22)

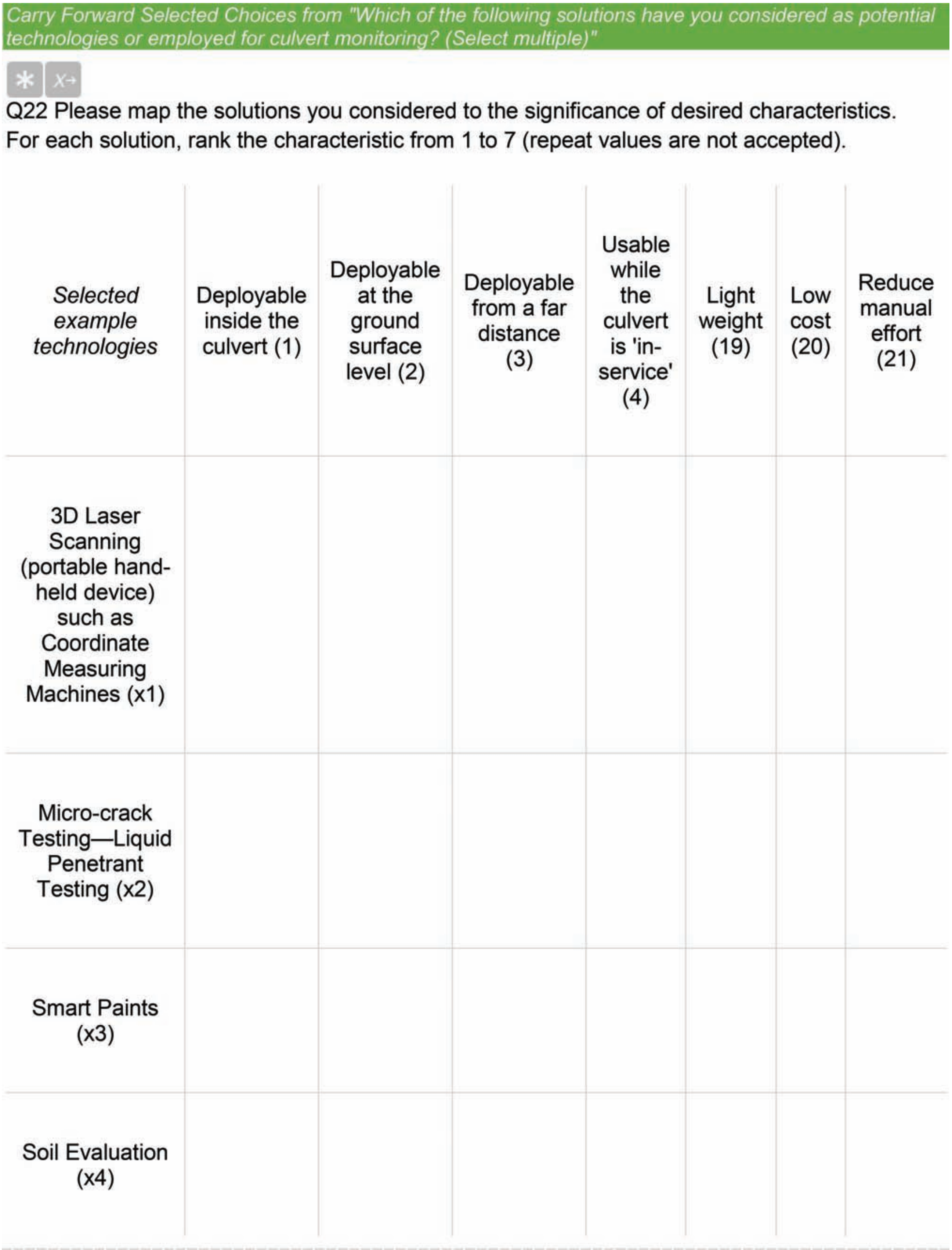
☐ Gamma-gamma logging (23)

☐ Re-bar Condition Testing using Magnetic Field Disturbance (24)

☐ Other (25) ____

Q17 Please rate the importance level of the characteristics of potential solutions based on in-field operability considerations and experience. For each characteristic, select corresponding importance rank.

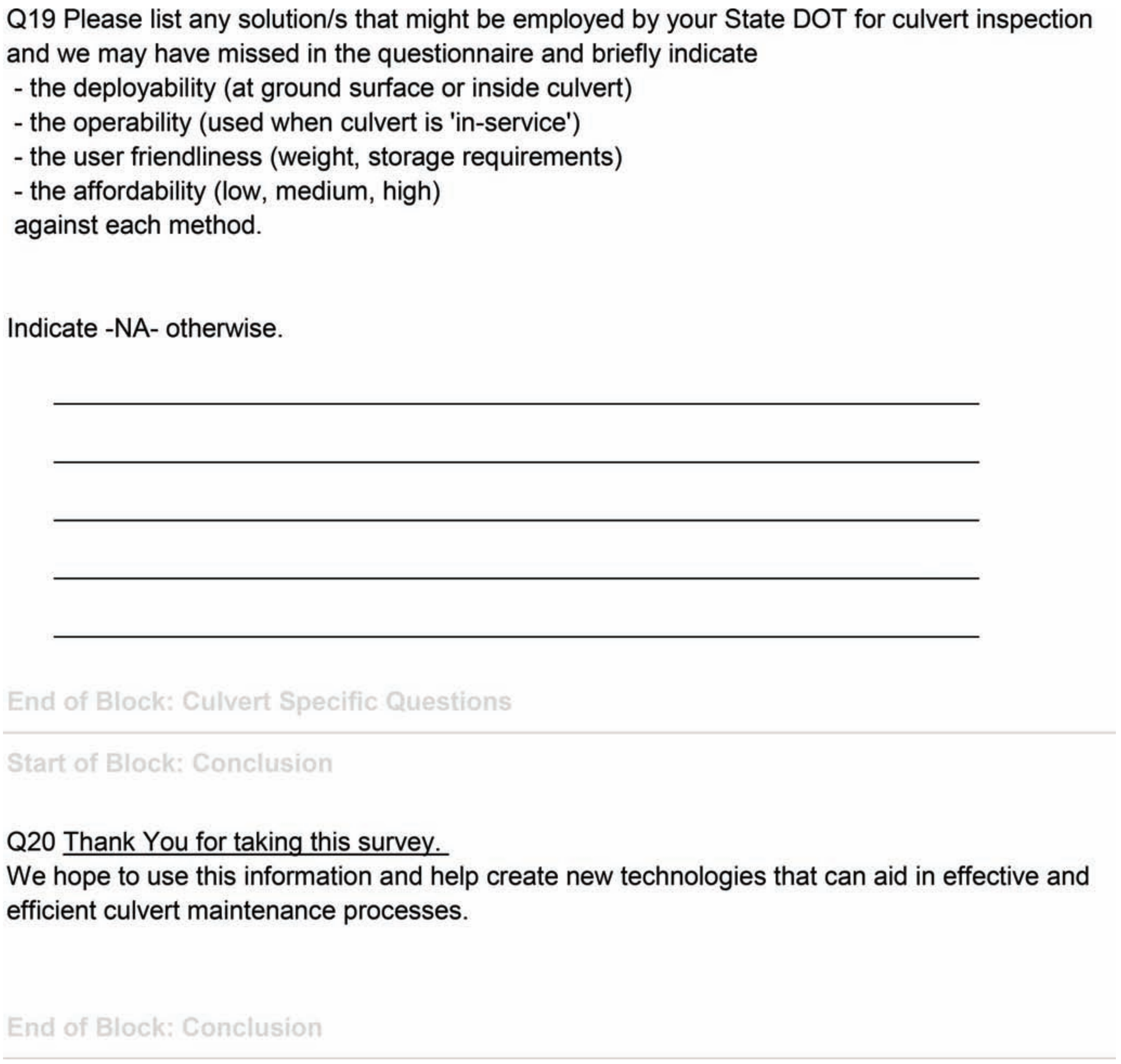
⊗ Solution should be deployable inside the culvert (1)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)
⊗ Solution should be deployable at the ground surface level (2)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)
⊗ Solution should be deployable from a far distance (3)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)
⊗ Solution should be usable while the culvert is 'in-service' (4)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)
⊗ Solution should be light in weight (5)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)
⊗ Solution should be low in cost (6)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)
⊗ Solution should reduce manual effort (7)	▼ Low importance [0-2] (1) ... Critical importance [9-10] (4)



Carry Forward Selected Choices from "Which of the following solutions have you considered as potential technologies or employed for culvert monitoring? (Select multiple)"

Q22 Please map the solutions you considered to the significance of desired characteristics. For each solution, rank the characteristic from 1 to 7 (repeat values are not accepted).

Selected example technologies	Deployable inside the culvert (1)	Deployable at the ground surface level (2)	Deployable from a far distance (3)	Usable while the culvert is 'in-service' (4)	Light weight (19)	Low cost (20)	Reduce manual effort (21)
3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines (x1)							
Micro-crack Testing—Liquid Penetrant Testing (x2)							
Smart Paints (x3)							
Soil Evaluation (x4)							



Q19 Please list any solution/s that might be employed by your State DOT for culvert inspection and we may have missed in the questionnaire and briefly indicate

- the deployability (at ground surface or inside culvert)
- the operability (used when culvert is 'in-service')
- the user friendliness (weight, storage requirements)
- the affordability (low, medium, high)

against each method.

Indicate -NA- otherwise.

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End of Block: Culvert Specific Questions

Start of Block: Conclusion

Q20 Thank You for taking this survey.
We hope to use this information and help create new technologies that can aid in effective and efficient culvert maintenance processes.

End of Block: Conclusion

APPENDIX B: THE LARGE CULVERT (>6.1M 20 FEET] IN LENGTH) CONDITION RATING SCALE RECOMMENDED BY THE NBIS*

Code	Description
9	No deficiencies.
8	No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift.
7	Shrinkage cracks, light scaling, and insignificant spalling which does not expose reinforcing steel. Insignificant damage caused by drift with no misalignment and not requiring corrective action. Some minor scouring has occurred near curtain walls, wingwalls, or pipes. Metal culverts have a smooth symmetrical curvature with superficial corrosion and no pitting.
6	Deterioration or initial disintegration, minor chloride contamination, cracking with some leaching, or spalls on concrete or masonry walls and slabs. Local minor scouring at curtain walls, wingwalls, or pipes. Metal culverts have a smooth curvature, non-symmetrical shape, significant corrosion, or moderate pitting.
5	Moderate to major deterioration or disintegration, extensive cracking and leaching, or spalls on concrete or masonry walls and slabs. Minor settlement or misalignment. Noticeable scouring or erosion at curtain walls, wingwalls, or pipes. Metal culverts have significant distortion and deflection in one section, significant corrosion or deep pitting
4	Large spalls, heavy scaling, wide cracks, considerable efflorescence, or opened construction joint permitting loss of backfill. Considerable settlement or misalignment. Considerable scouring or erosion at curtain walls, wingwalls, or pipes. Metal culverts have significant distortion and deflection throughout, extensive corrosion or deep pitting.
3	Any condition described in Code 4 but which is excessive in scope. Severe movement or differential settlement of the segments, or loss of fill. Holes may exist in walls or slabs. Integral wingwalls nearly severed from culvert. Severe scour or erosion at curtain walls, wingwalls, or pipes. Metal culverts have extreme distortion and deflection in one section, extensive corrosion, or deep pitting with scattered perforations.
2	Integral wingwalls collapsed, severe settlement of roadway due to loss of fill. Section of culvert may have failed and can no longer support embankment. Complete undermining at curtain walls and pipes. Corrective action required to maintain traffic. Metal culverts have extreme distortion and deflection throughout with extensive perforations due to corrosion.
1	Bridge closed. Corrective action may put bridge back in light service.
0	Bridge closed. Replacement necessary.

*Taken from the FHWA NHI 12-049 - December 2012: NBIS - Bridge Inspector's Reference Manual (BIRM) Chapter 14.

APPENDIX C: SELECTED SURVEY RESPONSES TO QUESTION REGARDING CULVERT INSPECTION PROCESS AND KNOWLEDGE OF SOLUTIONS

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
AL	Deputy Maintenance Engineer	No in-place system	NA	Visual—Plain / Push-cameras, Visual—CCTV Crawler
AZ	Maintenance Engineer Administrator	No in-place system	NA	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Other—Can often visually scan from one side of culvert
Did not specify	State Bridge Inspection Engineer	An in-house data management system and flood monitoring software is used.	Biannual Inspection of every culvert which is designated by NHI as a bridge structure. Around the clock monitoring of flood prone structures.	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Magnetic Flux Leakage, Ground Penetrating Radar, Ultrasonic Scanning / Sonar Profiling, Infrared Thermography
CA	Senior Engineer	Each culvert is inspected by inspectors using GPS data collectors.	Only culverts with problems are flagged for closer monitoring. Culverts are also monitored for storm water and regular maintenance.	Visual—CCTV Crawler
CT	Supervising Engineer	No in-place system	Currently inventorying and rating small culvert condition as part of MS4 permit requirements. Routinely (biennially) inspect culverts 6 feet (span) or larger following FHWA National Bridge Inventory rating requirements.	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, Soil Evaluation, Stochastic Predictive Modeling using Data, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning
CT	Principal Engineer	No in-place system	NA	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—CCTV Crawler, Other - Mandrel Testing
DE	State Bridge Engineer	Culverts with an opening of greater than 20 sf and a minimum height of 4′ are treated as bridges and follow the NBI inspection standards, including having inspection data stored in a AASHTO BrM database. Culverts with an opening smaller than or equal to 20 sf are inventoried into a drainage system database, but there is currently no required frequency for follow up inspection. All culverts are post-installation inspected prior to acceptance.	Similar to system description provided here	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning

APPENDIX C
(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
FL	State Drainage Engineer	No in-place system	Florida only routinely inspects culverts and box culverts that qualify as designated bridges, i.e., any crossing that is 20 feet or greater. Therefore, multiple pipe openings that result in a measured distance of 20 feet, out-to-out, are inspected every two (2) years. All other culverts are video inspected for either roadway improvement projects or due to noted problems occurring at the surface. This may include settlement of the roadway or embankment above a given crossing, or some other type of flooding issue associated with a given culvert.	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler with Side Scanning, Multi-sensor Profiling—Laser & Sonar & Video
IA	Bride Preservation Engineer	No in-place system	The culvert inspection procedure is outlined in the state Bridge Inspection Manual	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial
IA	Assistant State Maintenance Engineer	An in house application is used called "Collector." Inspectors use IPads to enter the data and then upload it over a cellular network. Data is entered one time in the field and stored in a historical database that allows for comparison and decision making.	Data is collected on every culvert across the state every two years (1/2 the state every year). Data collection is done using a collector application and is geo-located; pictures can be taken and all data can be compared historically.	Visual—CCTV Crawler
ID	Maintenance Services Manager	No in-place system	NA at this time, working to create a comprehensive inventory of existing culverts in an effort to develop a program.	Other—Nothing under consideration at this time.
KS	Bridge Management Engineer	State inspects all structures with 10′ spans or greater that are on the State Highway System. All structures with spans between 10′ and 20′ are inspected on a 4-year cycle. They all receive element level inspections, just like the bridges on the state system.	All structures on the State Highway System with spans between 10′ and 20′ receive element level inspections.	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—Plain / Push-cameras, Ultrasonic Scanning / Sonar Profiling, Infrared Thermography
KS	Bridge Inspection Engineer	Collect data on all structures 10 feet or greater and inspect by NBI & Element levels.	Inspect 10′ to 20′ structures on a 4 year cycle that is reduced by condition to either a 2 or 1 year cycle.	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Other—have considered drones
KY	Transportation Engineering Branch Manager	No in-place system	NA	Visual—CCTV Crawler

APPENDIX C
(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
LA	Bridge Inspection Engineer	Inspected manually per NBIS regulations and data is stored in a cloud based software.	Inspected per the NBIS regulations.	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, Micro-crack Testing—Liquid Penetrant Testing, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Ground Penetrating Radar, Multi-sensor Profiling—Laser & Sonar, Multi-sensor Profiling—Laser & Sonar & Video, Infrared Thermography, Re-bar Condition Testing using Magnetic Field Disturbance
ME	Superintendent of Highway Operations	This is a system developed using a vendor to write the code which we the state owns. This is more than an asset management system with which we have incorporated time and attendance. All of the work that the maintenance crews do is recorded in this system and reported against the asset(s) they work on and asset conditions are updated when worked on. Assets are located with GPS and spatially represented in the departments homegrown GIS layers.	Based on the current condition ratings	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Magnetic Flux Leakage
MI	Grading and Drainage Engineer	No in-place system	Box culverts greater than 10 foot span are part of the bridge inventory and undergo more routine inspections. Smaller culverts are occasionally (not routinely) inspected but typically not until there is some awareness of problems.	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Ground Penetrating Radar
MI	Flexible Pipe Specialist	No in-place system	Working on systematic inspection schedule after development of a data base.	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, Soil Evaluation, Smoke Bomb & Leaf-blower Testing, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Ground Penetrating Radar, Multi-sensor Profiling—Laser & Sonar, Multi-sensor Profiling—Laser & Sonar & Video
MI	Construction Engineer	Bi-annual inspections for large culverts (10 feet or larger measured along the centerline of the road); videotaping culverts on an as-needed basis.	Bi-annual inspections for large culverts (10 feet or larger measured along the centerline of the road); Ratings are tracked and projects are scoped based on condition ratings; videotaping culverts on an as-needed basis and prior to reconstruction projects.	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, Soil Evaluation, Ground Penetrating Radar, Ground Penetrating Radar

(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
MI	Grading and Drainage Engineer	No in-place system	NA	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—Plain / Push-cameras, Visual—CCTV Crawler
MN	Project Engineer	HydInfra (Hydraulics Infrastructure) being replaced with TAMS 2 for asset management of several different assets including culverts. The system tracks locations and overall condition including deficiencies and provides recommended repairs based on deficiencies.	Inspect all culverts rated a 4 (worst condition) or 0 (not able to inspect) annually, condition 3 bi-annually, 2 or 1 (like new pipe) every 5 years.	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Other—Participated in a study to evaluate the cost-benefit and different technologies of enhanced inspection, meaning anything beyond a simple visual inspection.
MN	Hydrologist	Transitioning to more of an automated system. Current system is basic to semi-automated.	Monitored at State level.	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Multi-sensor Profiling—Laser & Sonar, Multi-sensor Profiling—Laser & Sonar & Video
MN	HydInfra Coordinator	In 1996, MnDOT developed "HydInfra" to inventory and inspect culverts less than 10-foot span and storm drainage assets. HydInfra has been improved over the years to help make decisions based on the inspection data. 20 years of data has revealed strengths and weaknesses in a variety of pipe materials that we can apply in design decisions. HydInfra included GPS field inspection, GIS data tools and automated data reports from the start. HydInfra will evolve into Transportation Asset Management System (TAMS) software. TAMS will enable tracking of repairs, with costs, and ultimately lifecycle cost analysis.	District personnel inspect culverts. The inspection criteria is in the HydInfra Culvert and Storm Drainage System Inspection Manual (PDF) http://www.dot.state.mn.us/bridge/pdf/hydraulics/hydinfra-culvert-and-storm-drainage-system-inspection-manual.pdf	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—CCTV Crawler, Multi-sensor Profiling—Laser & Sonar & Video, Other—http://dot.state.mn.us/research/reports/2017/201716.pdf
MN	HydInfra Coordinator	HydInfra pertains to culverts with less than 10-foot span and other storm drainage assets. Converted to Asset Management software 2018. Inspections by people in field. Performance Measure established inspection cycle for culverts under highway lanes.	HydInfra Culvert and Storm Drainage System Inspection Manual	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—CCTV Crawler

(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
MS	State Maintenance Engineer	System performance is addressed primarily on a reactive basis. Culvert blockage is assessed annually through condition surveys	Condition surveys are conducted on 2800 1/10 mile, randomly selected segments each year. All culverts are assessed for blockage/function and that data is extrapolated to the rest of the system to analyze Level of Service.	Visual—Plain / Push-cameras, Visual—CCTV Crawler
MT	Maintenance Operations Manager	Implemented Agile Assets Maintenance management system. This stores the results of the inspections facilitating report development	Inspect most culverts at least annually.	Soil Evaluation, Visual—Plain / Push-cameras, Visual—CCTV Crawler
NC	Operations Program Management	Humans collect and analyze the data but the data is stored in a database	Bridge Size Pipes are reported on among internal performance measures	Visual—CCTV Crawler
ND	Engineer III, Bridge Mgmt.	No in-place system	NA	Soil Evaluation, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Ground Penetrating Radar, Infrared Thermography
ND	State Bridge Engineer	No in-place system	The only culverts that get inspected are the ones on upcoming corridor projects.	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning
NE	NBIS Program Manager	No in-place system	Follow NBIS regulations and standards to inspect all culverts 20 feet and longer. No standard operating procedures for culverts less than 20 feet	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Other—Our bridge research department is considering GPR for some of bridge inspections.
NY	Drainage Program Manager	Large culvert inventory is complete and they are inspected every two years. Small culverts are about 50% inventoried with inspections completed based on personnel availability. This system is java based and sufficient to keep track of culvert assets. Currently developing an enterprise asset management system that will include all assets statewide. It will be tied to a maintenance management system that will incorporate work orders and keep track of man hours for billing	Large culverts are assessed by professional engineers through structures department as well as consultants. They are inspected every two years along with bridges. The inspections are thorough with scores applied to quantifiable items, usually based on units of number or square feet.Small culverts are inspected based on methods developed within one of the 10 regions. Currently less than 50% of the regions inspect small culverts regularly with inspection methods varying from manual inspections with a piece of paper and pencil, to the use of a hand held device or tablet. Some of this data is inputted into the Oracle based inventory platform and some is kept in standalone systems developed by each region. A new enterprise system will tie this all together but personnel availability for data collection will remain a challenge	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, Soil Evaluation, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Ground Penetrating Radar

APPENDIX C
(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
OH	Hydraulic Engineer	Culverts are inspected by a human who judges the condition of several aspects of the culvert including shape, alignment, joints, material condition and others. The information is input directly into a tablet and sent to a data base. Information is easily accessible through a GIS map web based system for anyone to see	System is set up and process is outlined in online manual	3D Laser Scanning (portable hand-held device) such as Coordinate Measuring Machines, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Ground Penetrating Radar, Ultrasonic Scanning / Sonar Profiling, Multi-sensor Profiling—Laser & Sonar, Multi-sensor Profiling—Laser & Sonar & Video, Infrared Thermography, Impact Echo Testing / SASW
OH	Hydraulic Engineer	ESRI Collector. Central Office created the Culvert App for Inventory and Inspection. Use IPad mini mobile devices.	Size and condition: Greater than 12″ to less than 48″—10-year inspection frequency. Greater than 48″ to less than 120″—5-year inspection frequency. If in the General Appraisal, the lowest critical inspection item of the culvert or storm sewer is 4 or less then the inspection frequency is 1 year.	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler
OH	Roadway Services Engineer	Manual inspection of 90% and 10% inspected by remote camera. Majority of Culverts are inspected from ends only. Culverts are defined as any drainage structure having a span/diameter less than 10ft. Culverts are rated from 0 to 9, 9 being new without defects	Culvert's rated >4″ and <48″ diameter are on a 10-yr inspection schedule. Culvert's rated >4″ and >48″ are on a 5-yr inspection schedule. All culverts rated <4 are on an annual inspection schedule. Those culverts in very poor condition (2–3) are monitored as needed until replaced. Culverts rated 0–1 have the road closed until culvert can be scheduled (not common)	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Ground Penetrating Radar, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Ground Penetrating Radar, Infrared Thermography
OH	Culvert Engineer	Culvert inspection and inventory system based on culvert manual developed roughly 10 years ago. Culvert data base where inspection and inventory data entered in database	Rating scale for culverts similar to bridge inspections: 9 being the best, and 0 being the worst. Deficient culverts, 4 or less, are inspected on annual basis. Non-deficient 48″ or less culverts once every 10 years. Culverts greater than 48″ non-deficient, inspected once every 5 years	Visual—Plain / Push-cameras, Visual—CCTV Crawler
SC	State Maintenance Engineer	Each county office reviews one sixth of their roadway miles each year for proper drainage. This includes inspecting all culverts and driveway pipes. Some larger culverts are inspected annually by bridge inspection teams	Maintain records of annually inspected culverts and document any deficiencies and record any repairs or upgrades to clear the deficiencies	Visual—Plain / Push-cameras, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Ultrasonic Scanning / Sonar Profiling, Backscatter Computer Tomography

APPENDIX C
(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
TX	Director of Operations-BWD	Current system serves the purpose however it is labor intensive	Review larger, bridge class culverts every 2 years with local maintenance forces. They enter the data into a software app called MBITS. The local section performs maintenance work that they are capable of doing. More extensive repairs are sent to the District office for contract preparations	Visual—Plain / Push-cameras
TX	District Director of Operations	No in-place system	Maintenance employees ride roads daily monitoring conditions and address issues as they arise. Typically issues are noticed after rain events and reported up the chain to the supervisor and prioritized for repairs if needed	High water marks, Drainage area changes, Roadway settlement observations obtained by 'Photogrammetry' based tools such as 3D LiDAR scanners, either terrestrial &/or non-terrestrial, Visual—Plain / Push-cameras, Visual—CCTV Crawler, Other—We've used camera's when we can't get to the source of the issue. This is usually done after identifying an issue
UT	Director of Maintenance	Currently changing to a new culvert inspection program with new MQA program. Both are currently in development. In previous MQA program, culverts were inspected twice a year by individual inspection. Grades were used to identify funding spent and future funding needs	UDOT uses tracked culvert devices and pole cameras	Mixed Reality techniques, Visual—CCTV Crawler
UT	Hydraulic Engineer	No in-place system	NA	Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning, Other—Pole cameras
VA	Assistant State Bridge Engineer	No in-place system	Non-NBI culverts with a hydraulic opening of 36 square feet or more are inspected at the same level as NBI structures with the exception that the frequency of inspection can be up to 48 months—depending on condition. Culverts smaller than this requirement are only periodically inspected as conditions warrant.	Stochastic Predictive Modeling using Data, Visual—CCTV Crawler, Visual—CCTV Crawler with Side Scanning
VA	District Maintenance Engineer	No in-place system	For small to medium none	Visual—Plain / Push-cameras, Visual—CCTV Crawler
WA	Bridge Preservation Engineer	Follow parallel criteria to NBIS. Frequency is established by agency as a non-reportable structure. See Washington State Bridge Inspection Manual, M 36-64.08, for details	Repairs are communicated to bridge maintenance as a bridge repair item	Visual—CCTV Crawler

APPENDIX C
(Continued)

DOT	Position	Description of the DOT's in-place system for culvert inspection and monitoring	Process followed by the DOT to monitor culvert conditions*	Proposed solutions with which DOT is familiar (among those outlined or described in the survey)
WA	Stormwater Compliance	Maintenance personnel conduct inspections, in the field, in HATS program. HATS program was developed for use on the iPad. Data is synced and stored in database. Once synced data is available to all	Conduct routine and level 1 inspections. Routine inspections are many times just a drive by of problem culverts or a quick look in those areas that see significant rainfall. Level 1 is evaluating the condition of the culvert. Those inspections are to occur every 5 years and generally are divided out to 20% every year	Visual—CCTV Crawler
WA	Bridge Engineer	Performed for drainage and fish passages under highways	Performed every 2 years	Eddy Current Techniques (digging and exposing culvert surface is necessary), Re-bar Condition Testing using Magnetic Field Disturbance
WI	Maintenance Engineer	Use Collector for ArcGIS Online to collect inventory and inspection information for culverts. Just starting this and don't have much to report on performance other than it is much quicker to collect the data through Collector than to record the information with pencil and paper	NA	Visual—CCTV Crawler
WV	Hydraulic & Drainage Unit Leader, Design	No in-place system	NA	Visual—Plain / Push-cameras, Visual—CCTV Crawler
WV	Director, Maintenance Division	No in-place system	NA	Visual—Plain / Push-cameras

*NA = no standard operating procedure exists.

APPENDIX D: CONTACT INFORMATION FOR SURVEY PARTICIPANTS*

State	Position	Name	Email	Phone
AR	District Maintenance Engineer	Johnathon Mormon	Johnoathon.Mormon@ardot.gov	(501) 569-2270
CA	Culvert Inspection Statewide Coordinator	Manuel Morales	Manuel.morales@dot.ca.gov	(916) 653-2143
CT	Transportation Principal Engineer	Leo Fontaine	Leo.fontaine@ct.gov	(860) 594-3180
CT	Maintenance Division	Eoin McClure	Eoine.mcclure@ct.gov	(203) 264-5383
FL	District Maintenance Systems Admin.	Jeffrey Mednick	Jeffrey.mednick@dot.st.fl.us	(863) 519-2320
FL	Roadway Operations Engineer	Kristin McCrary	Kristin.mccrary@dot.state.fl.us	(850) 410-5517
GA	State Bridge Maintenance Engineer	Andy Doyale	adoyle@dot.ga.gov	(404) 635-2893
IA	Bridge Maintenance Engineer	Scott Neubauer	Scott.Neubauer@iowadot.us	(515) 239-1165
ID	Engineer Manager	Mike Ebright	Mike.Ebright@itd.idaho.gov	(208) 334-8413
IL	Bridge Inspection Program Manager	Steve Beran	Steve.Beran@illinois.gov	(217) 785-2927
KY	Maintenance Division	Wheeler Nevels	Wheeler.nevels@ky.gov	(502) 564-4556
LA	Asst. Bridge Maintenance Engineer	Jasmine Galjour	Jasmine.galjour@la.gov	(225) 379-1795
LA	Maintenance Division	Jeff Brown	Jeffrey.brown@la.gov	(225) 379-1305
MD	Highway Hydraulics	Kiona Leah	kleah@sha.state.md.us	(410) 545-8044
ME	Transportation Resource Manager	Randy Geaumont	Randy.geaumont@main.gov	
MI	Operations Field Services	Todd Rowley	Rowleyt@michigan.gov	(517) 322-3311
MI	Bridge Inspection Program Manager	Richard Kathrens	kathrensr@michigan.gov	(517) 322-5715
MN	Systems Coordinator	Moe Clark	Clark.moe@state.mn.us	(651) 366-3545
MS	Maintenance Deputy Director	Bradley Williams	bgwilliams@mdot.ms.gov	(601) 359-7111
MS	Bridge Inspection Program Manager	Richard Withers	rwithers@mdot.ms.gov	(601) 359-7200
NE	Division Manager	Mark Traynowicz	Mark.Traynowicz@nebraska.gov	(402) 479-4701
NC	State Maintenance Field Coordinator	Terry Mclaurin	tmclaurin@ncdot.gov	(919) 835-8431
ND	Maintenance Division	Jon Ketterling	jketterl@nd.gov	(701) 516-4391
NH	Chief Bridge Inspector	Kenneth Morrison	Kenneth.morrison@dot.nh.gov	(603) 271-2732
NM	State Bridge Management Engineer	Jeff Vigil	Jeff.vigil@state.nm.us	(505) 827-5457
NV	Chief Maintenance & Asset Manager	Anita Bush	abush@dot.state.nv.us	(775) 888-7540
NY	Bridge Maintenance Program Manager	Jennifer Hawkins	Jennifer.Hawkins@dot.ny.gov	(518) 457-8485
OH	District Roadway Services Manager	Dan Wise	Dan.Wise@dot.ohio.gov	(740) 833-8023
OH	Structures Planning Engineer	Brandon Collett	Brandon.collet@dot.ohio.gov	(513) 933-6643
OH	Hydraulic Engineer	Mike McColeman	Matt.Cozzoli@dot.ohio.gov	(614) 644-9146
OK	Field Services	Tony Sutton	tsutton@odot.org	(405) 521-6493
SC	Assistant Construction Engineer	Jeff Terry	TerryJS@scdot.org	(803) 641-7660
SD	Bridge Inspection Engineer	Cody Axlund	Cody.Axlund@state.sd.us	(605) 773-3390
TX	Director of Maint. Field Support	Dennis Markwardt	Dennis.Markwardt@txdot.gov	(512) 416-3093
VA	Maintenance Division	Steve McNeely	Steven.McNeely@vdot.virginia.gov	(804) 524-6096
WA	Maintenance Operations Assistant	Jay Wells	wellsj@wsdot.wa.gov	(360) 705-7863
WI	Chief Structure Maintenance Engineer	Richard Marz	Richard.marz@dot.wi.gov	(608) 266-8195
WI	Civil Engineer	Ned Grady	Ned.Grady@dot.wi.gov	(608) 266-3813

*Note that in many of the cases, the survey was internally distributed by a DOT representative to appropriate officers; hence, responses in Appendix C and DOT personnel listed in Appendix D cannot be directly correlated.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at:
http://www.purdue.edu/jtrp

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An open access version of this publication is available online. This can be most easily located using the Digital Object Identifier (doi) listed below. Pre-2011 publications that include color illustrations are available online in color but are printed only in grayscale.

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