# TECHNOLOGY SOLUTIONS TO ENHANCE VISUAL BRIDGE INSPECTIONS IN SOUTH AFRICA

LANA KEMP

# TECHNOLOGY SOLUTIONS TO ENHANCE VISUAL BRIDGE INSPECTIONS IN SOUTH AFRICA

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# DISSERTATION SUMMARY

# TECHNOLOGY SOLUTIONS TO ENHANCE VISUAL BRIDGE INSPECTIONS IN SOUTH AFRICA

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In South Africa it is a requirement for all road owners to conduct principle visual bridge inspections of all structures every five years, as per TMH 19. A principal inspection is a comprehensive visual inspection of the entire structure and is conducted by qualified bridge inspectors. This dissertation introduces the application of new Fourth Industrial Revolution (4IR) technology solutions into the realm of bridge inspection methodologies in South Africa, aimed to enhance the current bridge inspection methodology, while considering the cost and time components. For this study image data for eight bridge and culvert structures were captured using Unmanned Aerial Vehicles (UAVs). Point cloud models were created from the captured images by using photogrammetry software. Accredited bridge inspectors were approached to complete new inspection sheets of the bridge structures using only the point cloud models and captured images, as a proposed new inspection methodology. The cost and time components of the new inspection methodology were recorded and the cost and time components of traditional TMH 19 inspections were analysed. Existing inventory and

inspection images of bridge roadway joints were compiled to develop different Convolutional Neural Network (CNN) models and the possibility of classifying bridge defects autonomously were considered. This dissertation compares historic inspection ratings to the new inspection ratings to investigate the effectiveness and practicality of the new proposed inspection methodology. The cost and time components of the new inspection methodology and traditional TMH 19 inspections were compared to determine if the new proposed inspection methodology prove to have any cost- and time benefits. The prediction results of the different CNN models were compared and analysed to determine if it is possible to detect and classify bridge defects autonomously, using existing image data and applying deep learning and computer vision techniques. The study concluded that bridge inspectors can use point cloud models and captured images to complete inspection sheets, as a proposed new inspection methodology. Bridge inspectors are able to identify and rate critical defects, but there are limitations to the application of the new methodology and specific use cases need to be identified. The time- and cost-saving aspects of the new inspection methodology did not prove to have any benefits and depend on limiting the human aspect of inspections, possible through computer vision and deep learning applications to identify defects autonomously. The best performing CNN model utilises transfer learning and data augmentation to predict with 95% accuracy from images if a bridge roadway joint has a defect and with 65% accuracy if the bridge roadway joint has no defect.

# DECLARATION

I, the undersigned hereby declare that:

I understand what plagiarism is and I am aware of the University's policy in this regard;

The work contained in this thesis is my own original work;

I did not refer to work of current or previous students, lecture notes, handbooks or any other study material without proper referencing;

Where other people's work has been used this has been properly acknowledged and referenced;

I have not allowed anyone to copy any part of my dissertation;

I have not previously in its entirety or in part submitted this thesis at any university for a degree.

**Lana Kemp**

**12026574**

**1 February 2022**

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# 1 INTRODUCTION

## 1.1 BACKGROUND

Bridge structures are key components to the success of a country's transportation system. South Africa has thousands of bridge structures forming part of the road network. These structures are owned by national authorities, provincial authorities and district metros, responsible for the maintenance and safety of these structures. Routine inspections and maintenance are important to preserve the structural integrity of bridge structures for a maximum design life and to ensure the safety of all users.

In South Africa, principle visual inspections for all bridge structures are required every five years. A principal inspection is a comprehensive visual inspection of the whole structure and forms the basis of the road structure management system. It should be conducted by suitable qualified personnel experienced in structural design and maintenance (COTO, 2020b). Bridge and senior bridge inspectors are thus scarce, highly qualified and experienced persons. For such individuals to inspect all bridges and major culverts in a defined region, is a time consuming and costly exercise. Smaller authorities and metros do not always have the necessary funds available to perform routine bridge inspections as required. Budget and capacity constraints often lead to inspections not being executed or the use of unqualified inspectors, which results in poor quality inspection data. High quality inspection data as input to a Bridge Management System (BMS) is essential to determine accurate maintenance budgets and schedules to protect the structural life and integrity of bridge structures and to ensure safety of all users.

The ability to collect, store and utilise large datasets is transforming the world. Technology is rapidly evolving and what was previously considered a limitation is now possible. Technology should be utilised to collect valuable data and improve the reliability of information from which important decisions are made. International studies have shown success in utilising technology for visual bridge inspections and the need to adopt these methods in a South African context has been identified (Wells & Lovelace, 2018; Ciampa et al., 2019; Jahanshahi et al., 2009; Perry et al., 2020).

This dissertation focusses on incorporating Fourth Industrial Revolution (4IR) technologies in the current South African TMH 19 visual bridge inspection methodology. The proposed new inspection methodology utilises Unmanned Aerial

Vehicles (UAVs), photogrammetry, computer vision and deep learning techniques, aiming to improve the overall quality and consistency of bridge inspections, while considering the cost and time components.

UAVs have the ability to capture image data of bridge structures where human accessibility is limited. By processing the captured images using photogrammetry software, a point cloud model can be developed. These models and images could then be used as a reference for inspections and reduce physical site visits where possible. It is important to consider all the cost and time components of the new proposed inspection methodology to determine if the enhancements and utilisation of 4IR technologies are beneficial to all users. The time- and cost-saving aspects of the new inspection methodology depends on limiting the human involvement in inspections. This would be possible if historic inspection and inventory image data could be used to develop deep learning Convolutional Neural Network (CNN) models to identify defects autonomously.

## 1.2 OBJECTIVES OF THE STUDY

The objectives for this study are to:

1. Determine if visual bridge inspections could be performed using only point cloud models and images;

2. Determine if the new proposed inspection methodology prove to have cost- and time benefits, and

3. Determine if it is possible to detect and classify bridge defects autonomously, using existing image data and applying deep learning and computer vision techniques.

## 1.3 SCOPE OF THE STUDY

The study consisted of the following components and activities:

1. Capture image data for bridge and major culvert structures using UAVs;

2. Process captured images to create point cloud models using photogrammetry software;

3. Approach accredited bridge inspectors to identify defects, rate defects and complete new inspection sheets, using only point cloud models and captured images, for bridge structures;

4. Compare the new inspection sheets and ratings captured using the new inspection methodology and historic inspection sheets from traditional TMH 19 inspections;

5. Compare cost and time components of traditional TMH 19 inspections and the new inspection methodology, and

6. Develop different CNN models to investigate the possibility of using existing inspection and inventory image data to predict and classify defects of a bridge element autonomously.

This research forms part of an ongoing project initiated by the Council of Scientific and Industrial Research (CSIR) in 2019, focussing on the enhancement of the current visual inspection methodology for bridge and major culvert structures (Kemp et al., 2021).

Eight structures were identified for the study and form part of the Gauteng provincial road network and Landowner permission was granted by the Gauteng Department of Roads and Transport to conduct the study.

Premier Mapping Africa was appointed by the CSIR to capture image data for the eight structures using UAVs. Premier Mapping Africa manage aerial survey projects and is licensed to offer aerial survey services using full sized aircrafts as well as remote piloted aerial systems (RPAS). Premier Aviation holds an Air Operator Certificate (AOC) for manned aerial surveys and a Remote Operator Certificate (ROC) for RPAS aerial photography. Photogrammetry software, Pix4D, were used to process the captured images and to create point cloud models. Pix4D software was used in this study as this is the preferred software commercially used by Premier Mapping Africa. Premier Mapping Africa provided technical assistance regarding the hardware and software used for capturing and processing images.

Two independent COTO-accredited bridge inspectors were approached to identify defects, rate defects, and complete new inspection forms of two bridge structures. Historical inspections sheets, completed during the 2016 traditional TMH 19 routine visual bridge inspection as captured in the CSIR STRUMAN Bridge Management System (BMS), were used as reference and comparison. The results of the inspections were subjective to the bridge inspectors' expertise and experience.

The STRUMAN BMS system is currently the only road structures management system in South Africa based on the DER-rating system as prescribed in the COTO manual, TMH19 Manual for the Visual Assessment of Road Structures (COTO, 2020a). All nine provinces in South Africa are currently using the STRUMAN BMS system. Data from the CSIR STRUMAN BMS was utilized for comparing inspection ratings. Inspection and inventory images were used to develop CNN models to identify and classify bridge roadway joint defects.

Data were collected from a consulting company who conducted routine visual inspections for bridge and culvert structures on the Western Cape provincial road network in 2019. The data included the duration of each inspection and the associated professional fees charged for bridge inspectors and technical assistants. The cost and time components of large culvert and medium and large bridge asset classes were considered.

## 1.4 METHODOLOGY

Image data of four bridge and four major culvert structures were captured from two different sites in 2020, using UAVs and cameras. These structures form part of the Gauteng provincial road network and are in close proximity of Pretoria.

The captured image data were processed using photogrammetry software to create point cloud models. Two independent, COTO-accredited senior bridge inspectors were approached to conduct visual inspections and complete inspection sheets using only the point cloud models and captured images of two bridge structures. The inspectors attempted to identify and rate defects in accordance with the TMH 19 Degree, Extent and Relevancy (DER)-rating method. The ratings of the identified defects were compared to the historic inspection sheets of the structures, as captured in the CSIR STRUMAN BMS system. The structure defect ratings were evaluated individually and where significant differences were noted in the ratings, further investigations were conducted.

The cost and duration of conducting physical on-site visual bridge inspections for different bridge asset classes were compiled from data supplied by a consulting engineering company. The data are based on visual inspections conducted in 2019, over a period of 11 days and included the visual inspections of 121 bridges and culverts. The cost and time components were compared to the estimated cost and duration of the new proposed inspection methodology. This included capturing images, processing the image data and inspections.

The CSIR STRUMAN BMS contains inspection and inventory images captured during routine visual bridge inspections. 600 images of bridge roadway joints captured in the system were classified according to Defect and No Defect datasets. Different CNN classification models were developed to predict whether an image of a bridge roadway joint contained a defect or not. The image datasets were used to train, validate, and test the performance of the CNN model. The performance of the CNN models was evaluated using a Confusion Matrix and Classification report and the best performing model was selected. In conclusion the selected model's performance was evaluated when introduced to new unseen images.

## 1.5 ORGANISATION OF THE DISSERTATION

The dissertation consists of the following chapters and appendices:

- Chapter 1 is an introduction stating the objectives of this study. The chapter provides background of visual bridge inspections in South Africa and how technology could be utilised to enhance the current inspection methodology.
- Chapter 2 is a technical introduction based on a literature review of bridge inspections and current practices, both locally and internationally.
- Chapter 3 describes the experimental setup and the field work conducted to capture image data, create point cloud models and complete new inspections sheets using the new proposed inspection methodology.
- Chapter 4 is the comparison between the new inspection methodology and traditional TMH 19 inspections in terms of defect ratings and cost and time

components. The chapter also presents the performance of the different CNN models.

- Chapter 5 is a discussion of the results.
- Chapter 6 gives the conclusions and recommendations based on the results of the study.
- Chapter 7 lists the references used in this study.
- Attached in Appendix A and B are the historic inspections sheets of the structures and the new inspection sheets completed during the study.

# 2 BACKGROUND AND LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter provides a review of applicable literature and background to the research area. This includes the current visual bridge inspection methodology in South Africa, both international and local application of new technology for bridge inspections and the current legal requirements for UAV operations in South Africa.

## 2.2 TMH 19 VISUAL INSPECTION METHODOLOGY

In South Africa, bridge and culvert structures are inspected using a defects-based system as prescribed in TMH 19. Visual inspections require the inspector to conduct physical on-site inspections of all bridge structures on a road network.

According to TMH 19, inspection data should be collected during visual inspection of structures and each structure must be appraised for condition of serviceability and safety at network level. The inspection data are captured by completing standard inspections forms (COTO, 2020b).

### 2.2.1 Structure class and size categories

Structures can be categorised according to class and size as specified in TMH 19. These classes are shown in Table 2-1.

**Table 2-1: Structure class and size categories (COTO, 2020b)**

| Structure class and size category (sub-class) | Overall Structure Length |
|---|---|
| Small Culvert | Shorter than 5 m |
| Medium Culvert | From 5 m but shorter than 10 m |
| Large Culvert | Longer than 10 m |
| Small Bridge | Shorter than 20 m |
| Medium Bridge | From 20 m but shorter than 50 m |
| Large Bridge | From 50 m but shorter than 100 m |
| Very Large Bridge | Longer than 100 m |

### 2.2.2 DER rating system

During visual inspections, defects are identified on the various structural elements and rated in terms of the DER rating system. The possible DER rating values are shown in Table 2-2.

DER refers to (COTO, 2020b):

- Degree (D): How bad or severe is the defect;
- Extent (E): How widespread is the defect on the inspection item inspected, and
- Relevancy (R): The consequence of the defect with regards to the structural or functional integrity of the inspection item or the safety of the user of the structure.

**Table 2-2: Allowable DER ratings (COTO, 2020b)**

| Rating | D (Degree) | E (Extent) | R (Relevancy) | |
|---|---|---|---|---|
| X | Not applicable | | | |
| U | Unable to inspect | | | |
| 0 | No Visible defects | | | |
| 1 | Minor | Local | Minimum | No structural integrity or safety issues |
| 2 | Moderate | More than local | Moderate | Some possible structural integrity or safety issues |
| 3 | Warning | Less than general | Major | Structural integrity or safety compromised |
| 4 | Severe | General | Critical | Potentially a serious impact on structural integrity and/or user safety |

The CSIR has been involved in the development of various road-related management systems. One of these management systems is STRUMAN, which started out as a Bridge Management System (BMS), but since evolved into a structure management system for road related structures, including bridges, major culverts, lesser culverts, retaining walls, road tunnels, gantries, and light masts. STRUMAN has also been adapted to be used for the management of civil engineering port structures (Nordengen & Nell, 2005; Roux et al., 2010).

All nine provinces in South Africa are currently using the STRUMAN BMS system. The system is currently the only road structures management system in South Africa based on the DER-rating system as prescribed in TMH 19. The enhancement of the software and inspection methodology to accommodate new technologies are essential to the future and adoption of the system.

Identifying defects form the basis of this bridge management system. It is important for relevant defects with potential consequences to be identified and rated, to ensure the safety of all users and/or the structural or functional integrity of the structure (COTO, 2020a).

The main types of defects are (COTO, 2020a):

- Deficiencies;
    - Design deficiencies;
    - Construction deficiencies, and
    - Material performance related deficiencies.
- Damage, and
- Deterioration.

DER ratings, combined with the weights allocated to the different structural elements, are used to calculate a condition index for the structure. The condition index is the Priority Condition Index (PCI), used to categorise the structure as very good, good, fair, poor or critical. The PCI is used to create a maintenance schedule by ranking bridges according to condition and indicates which structures need to be prioritised. Descriptions and the PCI ranges for each of these condition categories are presented in Table 2-3 (COTO, 2013).

**Table 2-3: Condition categories and descriptions (COTO, 2013)**

| Condition Category | PCI Range | Condition Category Description |
|---|---|---|
| Very Good | 85 to 100 | Asset is still like new and no problems are expected. |
| Good | 70 to 85 | Asset is still in a condition that only requires routine maintenance to retain its condition. |
| Fair | 50 to 70 | Some clearly evident deterioration and would benefit from preventative maintenance or requires renewal of isolated areas. |
| Poor | 30 to 50 | Asset needs significant renewal or rehabilitation to improve its structural integrity |
| Critical | 0 to 30 | Asset is in imminent danger of structural failure and requires substantial renewal or upgrading with less than 10% of Expected Useful Life (EUL) remaining. |

The TMH 19 Part B document serves as a reference document for structure inspectors. The document includes sections with example photos of defects and corresponding defect ratings on structural elements for various structure types. The document aims to reduce the amount of subjectivity involved in the inspection process (COTO, 2020b).

Improving the quality and constancy of visual bridge inspections should be prioritised. Condition ratings assigned to defects would be more consistent if not reliant on human subjectivity and experience.

### 2.2.3 Inspection photographs

As part of a visual bridge inspection, inspectors are required to capture photographs indicating the location and details of defects. There is no standard form to capture these photographs and it is left to the discretion of the inspector. The following are required in most cases (COTO, 2020b):

- To capture at least one photo of each type of defect on an inspection item;
- To capture a close-up view of the defect and a view of the defect in relation to the overall structure or inspection item, and
- To have a description attached to the image in which the defect and the position of the defect are described.

It is important to record all adequate information for each inspection photo during the inspection. This enables the inspector to link the correct photograph(s) to the corresponding defect and structure. Some cameras have Global Positioning System (GPS) tagging functionality and can assist with linking photos to the correct structure but cannot assist in linking the photo to the correct defect. When capturing photographs of cracks, it is advised to outline the cracks with chalk or to include an object in the photo to provide scale, such as a ruler or crack width gauge (COTO, 2020b):

### 2.2.4 Bridge inspector qualifications

The requirements for a person to be accredited as an inspector of road structures are stipulated by the COTO Structures Sub-Committee and are included in TMH19. COTO has three grades of inspectors, namely a Senior Bridge Inspector, Bridge Inspector and Culvert Inspector (COTO, 2020b).

The requirement for accreditation as a Bridge Inspector are as follows (COTO, 2020a):

*"Professional Engineers who have an absolute minimum of 5 years bridge and culvert design experience obtained during the last 25 years or Professional Technologists who have a minimum of 10 years bridge and culvert design experience obtained during the last 25 years. Experience put forward must be personal design experience and does not include signing off designs done by others. Managers in charge of structural design, who do not have the required years of personal design experience themselves, do not qualify. Time spent on site does not qualify as design experience towards accreditation."*

The requirement for accreditation as a Senior Bridge Inspector are as follows (COTO, 2020a):

*"Professional Engineers with a minimum of 15 years full time personal bridge design experience accumulated over their career. Professional Technologists with 20 years' experience of a similar senior/team leading nature in bridge design will also be considered. Applicants, at the COTO Structures Subcommittee Accreditation Panel's discretion, may be required to attend an interview to confirm their eligibility. It is of utmost importance that the applicant also has personal design experience in continuous prestressed bridges as well extensive other experience. Ideally such a candidate will also be in a senior position involving the overseeing and advising of more junior bridge designers. As such, the candidate will have made bridges and the management of*

*bridges their full time career and will be conversant with all aspects of the management of road structures from design through to construction, maintenance and repair. The design experience put forward must be personal experience and does not include merely signing off designs done by others. Managers in charge of design sections, who do not have the required years of personal design experience themselves, do not qualify."*

The requirements for accreditation as a Culvert Inspector are as follows (COTO, 2020a):

*"A qualified technician, technologist or engineer with an absolute minimum of 5 years bridge and culvert design experience obtained during the last 20 years. Structural design experience will also be considered. Time spent on site does not qualify as design experience towards accreditation."*

## 2.3 INTERNATIONAL APPLICATION OF TECHNOLOGY FOR BRIDGE INSPECTIONS

International studies have shown success in the application of UAVs, image processing, deep learning and computer vision for bridge inspection and the need to adopt these methods in the South African context has been identified.

### 2.3.1 UAV applications for bridge inspections

A literature review of the current state of practice for the United States bridge inspection programs has been conducted by the Utah State University. The study concluded that the current technology limits UAS use to an assistive tool for the inspector to perform a bridge inspection faster, safer, and without traffic closure. The study concluded that major challenges for UAVs are satisfying restrictive Federal Aviation Administration regulations, control issues in a GPS-denied environment, pilot expenses and availability, time and cost allocated to tuning, maintenance, post-processing time, and acceptance of the collected data by bridge owners. The research indicates that using UASs with self-navigation abilities and improving image-processing algorithms to provide results near real-time could revolutionize the bridge inspection industry by providing accurate, multi-use, autonomous three-dimensional models and damage identification (Dorafshan & Maguire, 2018).

A more recent study conducted by the Sustainable Civil Infrastructure Research Group, Department of Civil and Environmental Engineering, Research Institute of Sciences and Engineering and the University of Sharjah compiled research from sixty-five journal and conference papers published in the last two decades on non-destructive testing (NDT) methods and the use of UAVs for bridge condition assessments. The study highlighted that Transportation Agencies and government stakeholder need technologies to overcome the challenges posed by traditional methods while simultaneously delivering reliable data. The study concluded that mitigating risk of accidents during bridge inspection process and accessibility advantages have driven research towards the implementation of UAVs. UAVs have proven improved accessibility and cost efficiency, avoidance of traffic closure, as well as reduced safety hazards during the inspection process. Although UAVs offer several advantages over traditional inspection techniques, they are also incumbered with inherent limitations and several challenges for researchers to further consider and investigate which include the following (Feroz & Abu Dabous, 2021):

1. Additional studies are required to comprehensively characterize surface and subsurface defects simultaneously which may be achieved by equipping UAVs with multiple sensors such as LiDAR, thermal and optical cameras. Additionally, assimilation of inertial and spatial sensors can generate georeferenced 3D data.

2. Rigorous research is required to enhance drone performance under varying weather and illumination conditions. It is critical to identify the relation between drone altitude and damage detection accuracy.

3. GPS-free stabilization of UAVs and the utilization of advanced onboard visual and obstacle avoidance sensors such as multidirectional vision stability sensors as well as collision-tolerant design need to be explored further in the context of bridge monitoring.

4. Detailed cost–benefit analysis to clearly quantify and outline the expenses associated with UAV operation is needed.

5. More studies are needed to quantify savings associated with time and assess reduction in safety risks related to UAV implementation compared to traditional visual inspection.

6. Investigation of potential incorporation of UAV within inspection guidelines in bridge inspection manuals with specific standard procedures for data collection and analysis.

7. Studying the applicability of drone-based inspection for various bridge types, materials and geometries.

8. Future studies need to further explore potential of emerging technologies such as Artificial Intelligent and Internet of Things techniques for autonomous data collection and processing. Examining real time data processing and a feasibility assessment of remote inspections using 5G connectivity should be explored.

A three-phased study conducted by the Minnesota Department of Transport together with industry stakeholders, investigated the use of UAVs for bridge inspections. The study focussed on rules and regulations, UAV hardware and the ability of UAVs to collect quality inspection data. The ability of UAV technology to conduct bridge inspections was confirmed by the Minnesota study, but the practicality to conduct network inspections of thousands of structures is yet to be determined (Wells & Lovelace, 2018).

The Minnesota study used a senseFly albris UAV, designed for commercial inspection and mapping. The albris imaging payload consisted of a TripleView head containing a high-definition video camera, a 38 Mega-Pixel (MP) still camera, and an infrared camera Benefits recorded in the study for using an inspection-specific mapping and photogrammetry UAV, include (Wells & Lovelace, 2018):

- Ability to view vertically up and down;
- Option of pre-programmed flight or interactive flight;
- High-Resolution Photogrammetry;
- Ability to fly without GPS signal;
- Relatively long battery life;
- Distance Lock and Cruise Control, and

- On-board LED lighting and camera flash.

Limitations recorded in the study for using an inspection-specific mapping and photogrammetry UAV, include (Wells & Lovelace, 2018):

- Confined spaces, and
- Set-up, which requires more involvement.

The University of Sannio, Department of Engineering, has addressed some of the practical issues on the use of UAVs for construction inspections and these include (Ciampa et al., 2019):

- The need for a qualified pilot to operate the UAV;
- Permission needed from landowners and the Italian Civil Aviation Authority;
- Mechanical malfunction or loss of power can cause a UAV to fall;
- Limited flight time due to battery life;
- Influence of weather conditions, and
- Large amount of data collected.

Similar to South Africa, in the UK, condition assessment of structures through conventional inspection practices mainly still relies on human-based visual inspection and the main approaches for conducting inspections include scaffolding, rope, elevating platforms or a special vehicle. This often requires special training for data acquisition. Noted in the study, from the top industries using UAVs in the US, only 9% of these industries use UAVs in construction (structure) application, as shown in Figure 2-1. The need to increase the use of UAVs in condition assessments of structures was identified (Ciampa et al., 2019).

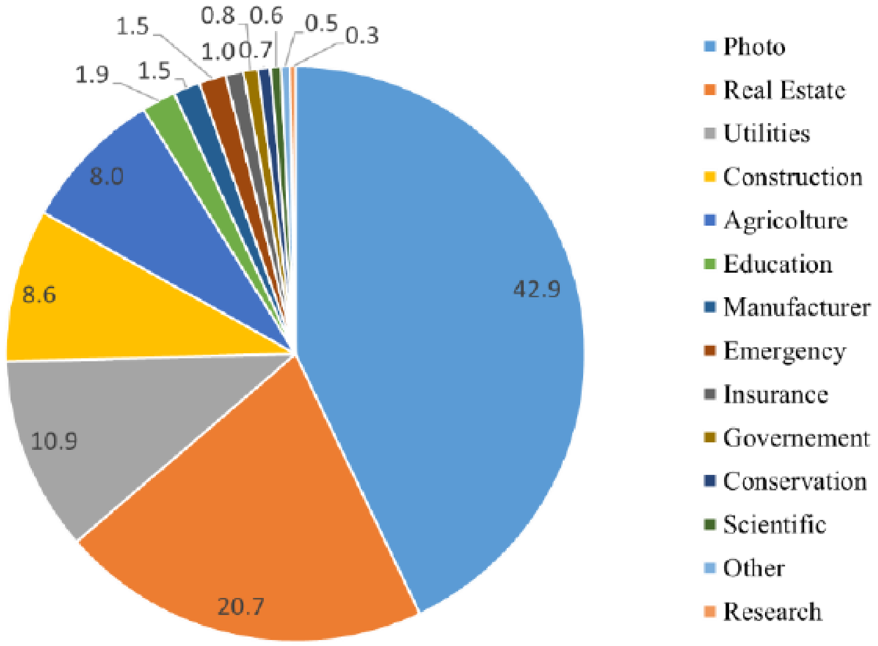



**Figure 2-1: Top industries using UAVs in the US (Ciampa et al., 2019)**

A report on “The use of unmanned aerial systems to remotely collect data for road infrastructure” as part of a special project of the World Road Association, confirms the application of UAVs by transportation agencies from Canada to Tanzania. UAVs are used to collect data, design and construct road infrastructure, inspect bridges, monitor roads, identify flood damage risks, reconstruct crash scenes and monitor traffic and road conditions. Public agencies under pressure to reduce costs and adapt new technologies, are turning to UAVs as one means of improving operations and cutting costs (PIARC, 2018).

The report included advantages and disadvantages of using UAVs compared to traditional methods for bridge inspection, such as the use of an Aerial Work Platform (AWP) and rope access. These comparisons are summarised in Table 2-4 and Table 2-5.

**Table 2-4: Advantages and disadvantages of Unmanned Aerial System (UAS) compared to traditional methods (AWP) (PIARC, 2018)**

| Bridge Inspection | |
|---|---|
| **UAS Advantages** | **AWP Disadvantages** |
| • Low capital and maintenance costs<br>• Increased safety of inspector and public<br>• No bridge weight restrictions<br>• No lane closures required<br>• Less mobilization (time and cost) | • High capital and maintenance costs<br>• Safety of inspector and public<br>• Bridge weight restrictions<br>• Lane closures required<br>• Huge mobilization (time and cost) |
| **AWP Advantages** | **UAS Disadvantages** |
| • Ability for inspector to be within arm's reach of bridge components<br>• More reliable as inspector can touch and feel bridge components<br>• Ability to perform non-destructive tests<br>• Continuous uninterrupted inspection for long hours | • Inspector within arm's reach not possible<br>• Less reliable as inspections can only be done from a distance<br>• Non-destructive tests cannot be performed<br>• Limited flight time due to battery life |

**Table 2-5: Advantages and disadvantages of UAS compared to traditional methods (Rope Access) (PIARC, 2018)**

| Bridge Inspection | |
|---|---|
| **UAS Advantages** | **Rope Access Disadvantages** |
| • Easy and fast<br>• More efficient<br>• Safe to operate | • Cumbersome process<br>• Less efficient<br>• Less safe for inspector |
| **Rope Access Advantages** | **UAS Disadvantages** |
| • Ability for inspector to be within arm's reach of bridge components<br>• More reliable as inspector can touch and feel bridge components<br>• Ability to perform non-destructive tests<br>• Low equipment cost | • Inspector within arm's reach not possible<br>• Less reliable as inspections can only be done from a distance<br>• Non-destructive tests cannot be performed<br>• Equipment cost is high compared to rope access |

The World Road Association report encourages Low-Medium Income Countries (LMIC) to adopt and evaluate technologies such as the use of UAVs for bridge inspection. Their recommendation for UAV application in concrete and steel bridge inspection is summarised in Table 2-6.

**Table 2-6: Recommendation for UAV application in concrete and steel bridge inspections (PIARC, 2018)**

| | |
|---|---|
| 1. | UASs can be successfully used for concrete bridge inspection for identifying the concrete delamination. Use of better thermal sensor may produce better results. |
| 2. | Infrared images of bridge decks and elements are already a common and accepted way to obtain information on concrete delamination. UAVs can provide a very efficient way to collect infrared images of bridge decks and elements as they can be equipped with an infrared camera. |
| 3. | UASs can be used in the field during bridge inspections safely. Based on the UASs size, weight, controllability and built-in fail safes, the risk to inspection personnel and public is very low. |
| 4. | UASs are more suitable as a tool for inspections of larger bridges, but there can also be some advantages for smaller bridge inspections. (i.e., short span bridges and culverts). |
| 5. | UASs themselves cannot perform inspections independently but can be used as a tool for bridge inspectors to view and assess bridge element conditions. |
| 6. | Defects can be identified and viewed with a level of detail equivalent to a close-up photo for the areas that are not easy accessible. |
| 7. | UASs with the ability to direct cameras upward and the ability to fly without a GPS signal are important features when using this technology as an inspection tool. |
| 8. | UAS Technology is evolving rapidly and inspection-specific UAS features are just coming into the marketplace that will increase their effectiveness as it related to bridge safety inspection |
| 9. | In some type of inspections, a UAS has the capabilities to be used in lieu of an under bridge inspection vehicle and would provide significant savings. These savings would come in the form of reduced or eliminated traffic control and reduced use of under bridge inspection vehicles and lifts. |
| 10. | Safety risks associated with traffic control, working at height and in traffic could be minimised with the use of UASs. Additionally, UASs can be utilized as an effective method to determine stream or river bank conditions upstream or downstream of the bridge as well as capture large overall aerial maps of dynamic bank erosion and lateral scour conditions. |
| 11. | UASs can provide important pre-inspection information for planning large-scale inspections. Information such as clearances, rope access anchor points and general conditions can easily be obtained with a UAV and would aid in the planning of an inspection. |
| 12. | The use of UAVs to aid bridge inspection should be considered as a tool to a qualified team leader when a hands-on inspection is not required. |

| |
|---|
| 13. The use of UAVs to aid bridge inspections should be considered for routine inspections to improve the quality of the inspection by obtaining information and detail that may not be readily obtained without expensive access methods. They should also be considered where they can increase safety for inspection personnel and the traveling public. |
| 14. Topics for investigations in a future phase:<br>a. Cost comparison with Aerial Work Platform and traffic control;<br>b. Explore inspection-specific UAS technology;<br>c. Compile a best practices document, and<br>d. Incorporate UAS technology into an actual inspection |
| 15. Measurements can be estimated from images, but tactile functions (e.g., cleaning, sounding, measuring and testing) equivalent to a hands-on inspection cannot be replicated using UASs. |
| 16. Other non-destructive tests performed by an experienced inspector cannot be done by using UAS. |

A study conducted by the Bauhaus University in Germany, investigated a Building Information Modelling (BIM) related workflow for image-based deformation monitoring of bridges. The study concluded using UAVs for aerial image-based deformation monitoring of bridges or bridge elements to create dense 3D reconstructions from digital imagery, proved to be a promising approach. The study indicated that future research should be focused on automatic damage detection and quantification of damage (Hallermann et al., 2018).

### 2.3.2 Photogrammetry, computer vision and deep learning

An international survey and evaluation of promising approaches for automatic image – based defect detection of bridge structures has been conducted in 2009 in the USA. The study noted that among the possible techniques for inspecting civil infrastructure, the use of optical instrumentation relying on image processing is less time consuming and an inexpensive alternative to current (traditional) monitoring methods (Jahanshahi et al., 2009).

Several image processing techniques, including enhancement, noise removal, registration, edge detection, line detection, morphological functions, colour analysis, texture detection, wavelet transform, segmentation, clustering and pattern recognition, are key pieces that should be merged to solve this problem (Jahanshahi et al., 2009).

The utility, limitations and leading approaches for the three main techniques, are summarised in Table 2-7.

**Table 2-7: Summary of technique, identified defect and limitation (Jahanshahi et al., 2009)**

| Technique | Defect(s) | Limitation |
| --- | --- | --- |
| Image registration | Deformed and missing members | Needs improvement in order to reconstruct a 3D model for localisation purposes |
| Morphological image processing | Cack patterns | Irregular back-ground from images is problematic |
| Discrete wavelet | Cracks and corrosion detection | Corrosion detection requires more research to correctly segment and classify the defected regions |

The rapid evolvement of technology creates the possibility to achieve what was previously considered a limitation. A more recent study conducted in 2020 in the US, focused on streamlined bridge inspection system, utilising UAVs and machine learning applications (Perry et al., 2020).

The study proposed advance data analytics tools to automatically (Perry et al., 2020):

1. Identify type, extent, growth, and 3D location of defects using computer vision techniques;
2. Generate a 3D point-cloud model and segment structural elements using human-in-the-loop machine learning, and
3. Establish a geo-referenced element-wise as-built bridge information model to document and visualize damage information.

As shown in the USA study, most image processing approaches are limited to detect only one type of defect at a time. The US study presented and evaluated the steps and algorithms that are necessary for detecting various changes simultaneously by digital image processing and the introduction of machine learning (Perry et al., 2020).

A schematic illustration of the proposed automated bridge inspection system is shown in Figure 2-2.

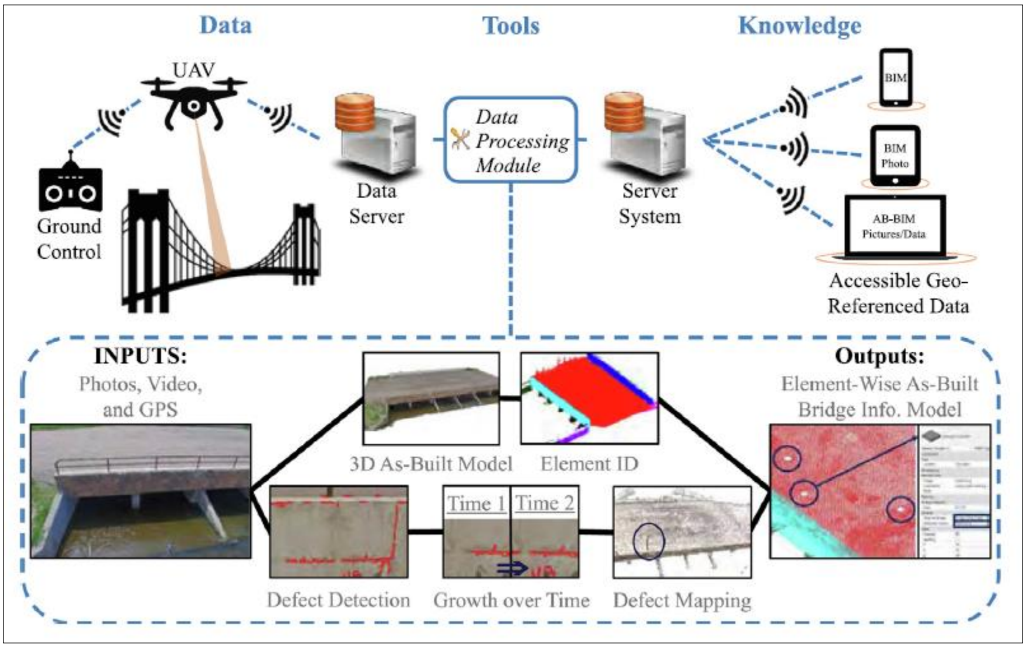



**Figure 2-2: Proposed Automated Bridge Inspection System (Perry et al., 2020)**

The advancement of deep learning, as a branch of machine learning, and a CNN developed with more hidden layers and a more complex network structure, has more powerful feature learning and feature expression abilities than traditional machine learning methods (Al-Saffar et al., 2017).

CNN is a multi-layer artificial neural network specially designed to handle two-dimensional (image) input data. The use of CNN allows for learning and extracting relevant features, while eliminating the need for a complex modelling process. The use of CNN models for image classification, object detection, attitude estimation and image segmentation, has delivered good results and progress in this field (Al-Saffar et al., 2017).

The accuracy of the CNN architecture highly depends upon three factors namely, large scale database, high end computational unit and the network depth. The requirement of training large databases is solved due to availability of public databases. Transfer learning can be used to fine-tune the pre-trained network parameters, obtained from training large databases, for an image classification task. To improve the recognition accuracy further towards a human vision system, researchers proposed deeper CNN architectures and developed the VGG16 architecture for object recognition tasks (Shaha & Pawar, 2018).

For image classification tasks, it is necessary to expand the insufficient training image samples through various data augmentation methods. To avoid overfitting requires a large amount of labelled data to train CNN models. In the case of insufficient training data, regularization technologies are commonly used to prevent overfitting, such as Dropout, Batch Normalization and data augmentation. Data augmentation refers to the process of creating new similar samples of the training set through employing random crop, horizontal flip, rotation, shifting, colour jittering, addition of noise and Principal Component Analysis (PCA) jittering (Shijie et al., 2017).

A study conducted by Utah State University investigated the feasibility and application of deep learning CNN for UAV-assisted structural inspections of concrete decks. The training dataset consisted of lab-made bridge deck images with cracks. The study concluded that it is feasible to apply deep learning CNNs in autonomous civil structural inspections with comparable results to human inspectors. The results indicated that the fully trained dataset had a validation accuracy of 94.7% and a validation accuracy of 97.7% when using transfer learning (Dorafshan et al., 2018).

## 2.4 LOCAL APPLICATION OF NEW TECHNOLOGY FOR BRIDGE INSPECTIONS

The practical use of technologies such as UAVs and photogrammetry to enhance bridge inspections are currently being investigated by the CSIR. This ongoing project conducted a proof of concept study, which delivered potential to enhance the visual bridge inspection methodology in South Africa (Kemp et al., 2021).

The proof of concept included the capturing of image data using an UAV for two bridges on the Gauteng provincial bridge network. TMH 19 visual assessments of these two bridges were conducted in 2016 and the inspection data for both bridges, including all the identified defects, the DER ratings for these defects, the condition indices (PCI) and inspection and inventory photos, were made available from the STRUMAN database (Kemp et al., 2021).

The same defects identified during the 2016 visual bridge inspections were investigated using point cloud models. The defects were clearly visible from the photos where sufficient natural light were present (Kemp et al., 2021).

The study concluded that bridge inspections are possible using UAVs and photogrammetry. A point cloud model adds context to the defects as a fourth dimension to the DER-rating methodology. Investigating the defects on the point cloud model gives perspective on where the defect is located and provides more information regarding the relevancy of the defect (Kemp et al., 2021).

The South African National Roads Agency (SANRAL) indicated as part of their bridge management, the use of UAVs has been investigated. Videos were captured of bridge bearings and viewed by qualified inspectors. This method proved to be time consuming and had limitations. The UAV had to be licenced with the civil aviation authorities and regulations did not permit for UAVs to be operated over roads. Inspectors were unable to inspect confined spaces. Although SANRAL does not make use of UAVs for bridge inspections, the organisation acknowledged the advantages of using UAVs for specific applications (Kruger & Nyokana, 2018).

## 2.5 LEGAL REQUIREMENTS FOR UAV OPERATIONS IN SOUTH AFRICA

When considering UAV application for bridge inspections, it is important to consider the legal and regulatory requirements pertaining to UAV operations in South Africa. Aviation regulations in South Africa for UAV operations remain relatively strict compared to other countries.

UAV operation in South Africa is subjected to the following rules. Applications outside the scope of these requirements need additional approval from the South African Civil Aviation Authority (SACAA) (SACAA, 2017):

1. UAVs may not be flown within a 10 km radius of an airport without special permission from SACAA;
2. UAVs with a mass exceeding 7 kg may not be flown;

3. UAVs may not be flown within 50 m of people or private property (without permission from the property owner);

4. UAV pilots must maintain a visual line of sight with their UAVs at all times while in flight;

5. UAVs may only be flown during daylight hours, and

6. According to the SANPARKS website "The use of UAVs inside (or over) national parks is strictly prohibited." (https://www.sanparks.org/assets/docs/tourism_reservations/park-regulations).

The main limitation for the use of UAVs for bridge inspections in South Africa is flying within 50 m of a public road. Permission to operate outside the scope of requirements can be granted by the SACAA and should be included in the Remotely Piloted Aircraft Systems (RPAS) Operators Certificate (ROC).

Each UAV operation requires different licences for approval depending on the type of operation. The different licenses required for the different types of operations are summarised in Table 2-8 (Kock, 2015).

**Table 2-8: RPAS operations versus required approval**

| | **Type of Operation** | | | | |
|---|---|---|---|---|---|
| | | Commercial | Corporate | Non-profit | Private |
| **Required Approval** | Air Service Licence (ASL) | YES | N/A | N/A | N/A |
| | RPAS Operators Certificate (ROC) | YES | YES | YES | N/A |
| | RPAS Letter of Approval (RLA) | YES | YES | YES | N/A |
| | Remote Pilot Licence (RPL) | YES | YES | YES | N/A |
| | Certificate of Registration (C of R) | YES | YES | YES | N/A |

Using UAVs for bridge inspections requires a commercial licence and includes the following (SACAA, 2017):

- Air service licence;
- RPAS operators certificate;
- RPAS letter of approval;
- Remote pilot licence;
- Certificate of registration, and
- RPAS maintenance technician.

The process to obtain approval for a specific operation requires the following six steps (SACAA, 2017):

1. Registration of the UAV;
2. Letter of approval from the Director of the South African Civil Aviation Authority;
3. Pilot licence;
4. Operators' certificate;
5. Submit flight plan detailing the mission, and
6. Permission from landowner.

## 2.6 DISCUSSION

This dissertation aimed to address the following aspects of the existing bridge inspection methodology in South Africa, as identified from the literature, through the application of technology such as UAVs, photogrammetry, computer vision and deep learning:

- Context of where defects are located on a bridge structure is often limited when capturing individual inspection photographs. The quality of photographs is often not captured to standard and add inadequate value to the inspection. If no dimensions or context are added to the photographs, explaining and motivating the inspection and the structure defects to individuals who have not attended the site-visit, could be challenging.

- Bridge and senior bridge inspectors are scarce, highly qualified and experienced persons. For such individuals to inspect all bridges and major culverts in a defined region, is a time consuming and costly exercise. Smaller municipalities do not always have the necessary funds available for routine bridge inspections as required. These budget and capacity constraints often lead to inspections not being executed or the use of unqualified inspectors, resulting in poor quality inspection data. Good quality inspection data as input to a bridge management system is essential to determine maintenance budgets and schedules to protect the structural life and integrity of a bridge and ensure safety for all users.

- International studies have shown success in this field and the need to adopt these methods in a South African context has been identified. The World Road Association report encourages LMIC to adopt and evaluate technologies such as the use of UAVs for bridge inspection. The rapid evolvement of technology creates the possibility to achieve what was previously considered a limitation.

- Enhancing the inspection methodology to capture image data and perform visual bridge inspections by utilising new technologies, such as UAVs and point cloud models have the potential to improve the quality and consistency of inspections. Inspectors could reduce the number of structures requiring on-site inspections. The cost and time constraints could be addressed by developing deep learning models for autonomous defect detection.

This dissertation built on the CSIR’s foundation research and adopting international practises in a South African context, aiming to achieve the following objectives:

- Determine if visual bridge inspections could be conducted using only point cloud models and images;

- Determine if using image data for visual bridge inspections prove to have cost and time saving benefits compared to traditional TMH 19 inspections, and
- Determine if existing image data could be utilised to develop deep CNN models to identify and classify defects autonomously.

# 3 METHODOLOGY

This chapter contains the data acquisition methodologies and the different data types collected for this research. Multiple data sources and data sets, both new and existing, have been utilised. This includes previous bridge inspection data, CSIR STRUMAN BMS data, bridge consulting engineers' professional rates, image data captured and data recorded during the inspections.

## 3.1 CAPTURING IMAGE DATA

For this study, image data of eight structures (four bridges and four major culverts) were captured during two site visits in 2020, referred to as Site 1 and Site 2. These structures are located on the Gauteng provincial road network. The structures were chosen based on their proximity to Pretoria and their location on a road with relatively low traffic volumes.

Premier Mapping Africa was appointed by the CSIR to capture the image data for the identified structures using an UAV. Premier Mapping Africa manage aerial survey projects and is licensed to offer aerial survey services using full sized aircraft as well as remote piloted aerial systems (RPASs). Premier Aviation holds an Air Operator Certificate (AOC) for manned aerial surveys and an ROC for RPAS aerial photography. Premier Mapping Africa specialise in surveys and industrial inspections. Premier Mapping submitted an application for the flight missions and permission was granted by the SACAA. The CSIR requested permission from the landowner, the Gauteng Department of Roads and Transport (GDRT), to capture images of the structures using an UAV.

TMH 19 visual inspections of these structures were conducted in 2016. The inspection data for these structures, including all the identified defects, the assigned DER ratings of defects, the condition indices (PCI) and inspection and inventory photos, were available in the CSIR STRUMAN BMS database. Details on these structures are presented in Table 3-1 and the structure locations in Figure 3-1.

**Table 3-1: Details of the inspected structures**

| SITE 1 | | | | |
|---|---|---|---|---|
| Date: 17 February 2020 | | | | |
| | **Class** | **Structure No.** | **PCI** | **Condition Category** |
| Bridge 1 | Large Bridge | D631_01N_B4435 | 64.30 | Fair |
| Bridge 2 | Medium Bridge | D631_01N_B4095 | 93.80 | Very Good |
| **SITE 2** | | | | |
| Date: 19 November 2020 | | | | |
| | **Class** | **Structure No.** | **PCI** | **Condition Category** |
| Bridge 3 | Medium Bridge | D2377_01N_B1106 | 95.25 | Very Good |
| Bridge 4 | Medium Bridge | K175_01N_B5102A | 74.44 | Good |
| Culvert 1 | Large Culvert | K175_01N_IDC0423 | 100.00 | Very Good |
| Culvert 2 | Large Culvert | K175_01N_IDC0424 | 97.97 | Very Good |
| Culvert 3 | Large Culvert | K175_01N_IDC0460 | 73.94 | Good |
| Culvert 4 | Large Culvert | P6_01N_IDC0459 | 98.30 | Very Good |

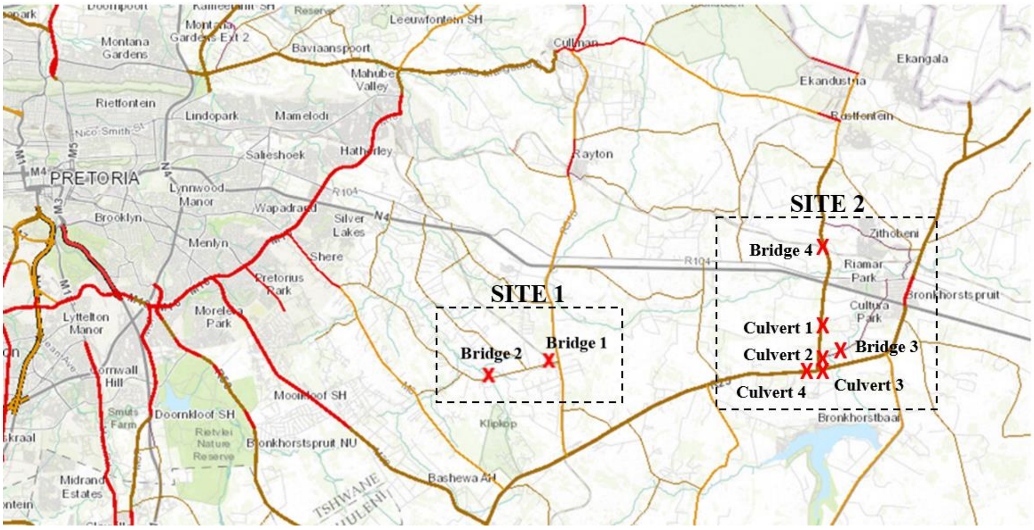



**Figure 3-1: Location of the inspected structures (Gauteng RAMS Geo-spatial Decision Support System)**

### 3.1.1 Site 1 structures

The two structures captured from Site 1, were used in the CSIR proof of concept study. The two structures are both bridges. Bridge 1 is a rail-over-road bridge and Bridge 2 a road-over-river bridge. The capturing of image data were conducted on

17 February 2020 and started in the morning from 08:00. The weather conditions were clear with no clouds. Bridge diagrams with key dimensions, as captured in the CSIR STRUMAN BMS inventory data, are shown in Figure 3-2. These diagrams are not drawn to scale and are only for conceptual purposes.

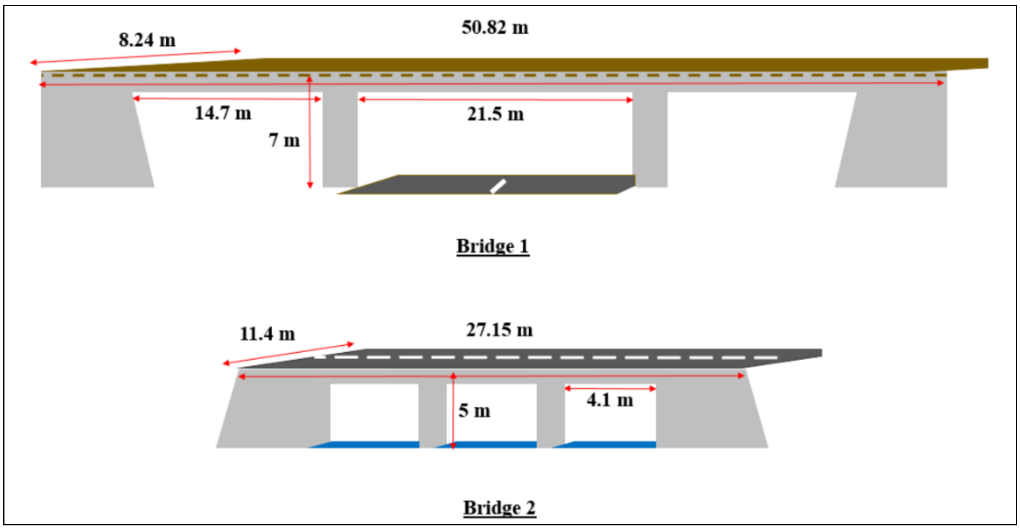



**Figure 3-2: Diagrams of key dimensions of bridges from Site 1**

Bridge 1 is a three-span railway bridge with an overall length of 50.8 m, overall width of 8.2 m and maximum height of 7.0 m. Images were captured using a manually operated UAV. Images underneath the bridge were captured by walking on the ground using the UAV as a hand gimbal. The total duration of capturing image data of the bridge was approximately 45 minutes and the battery was changed after 30 minutes. A total of 462 images were captured and the time recorded from capturing the first image to the last image was 32 minutes.

Bridge 2 is a three-span river bridge with an overall length of 27.2 m, overall width of 11.4 m and maximum height of 5.0 m. The same approach was followed as with the Bridge 1 to capture the images, but vegetation in the river prevented the UAV pilot to capture images underneath the bridge with the UAV. Images underneath the bridge were captured by walking on the ground using the UAV as a hand gimbal. The total duration of the bridge inspection was approximately 30 minutes and only one battery was used. A combination of 359 images were captured and the time recorded from capturing the first image to the last image was 24 minutes.

For this study, the full duration of capturing image data were considered, this included preparation time and the change of battery if needed.

### 3.1.2 Site 2 structures

Image data of six structures were captured on 19 November 2020 for two bridges and four culverts. Both bridges, Bridge 3 and Bridge 4 are river bridges and the four culverts, Culvert 1 to Culvert 4, are major culverts. The capturing of image data started in the morning from 07:00 and the weather conditions were partly cloudy. Bridge and culvert diagrams with key dimensions, as capture in the CSIR STRUMAN BMS inventory data, are shown in Figure 3-3 and Figure 3-4. These diagrams are not drawn to scale and are only for conceptual purposes.

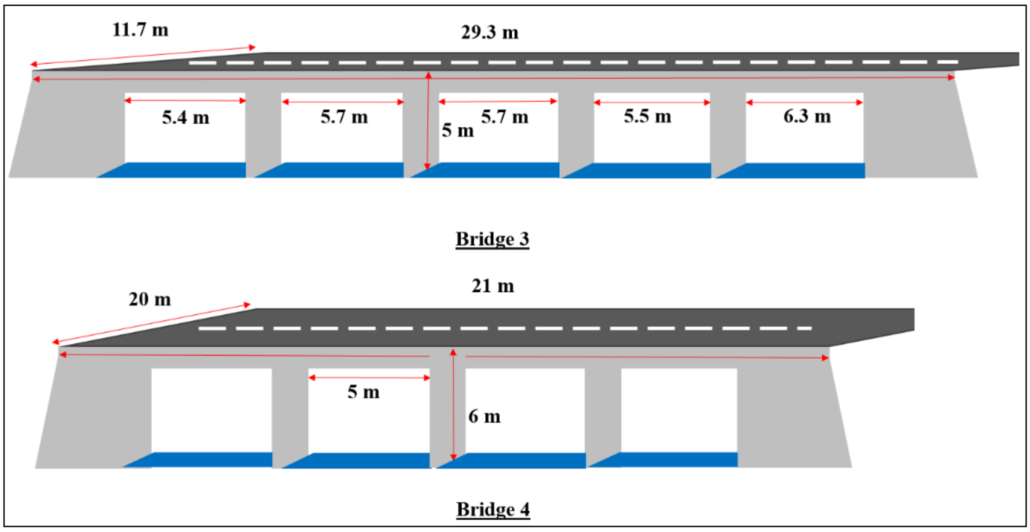



**Figure 3-3: Diagrams of key dimensions of bridges from Site 2**

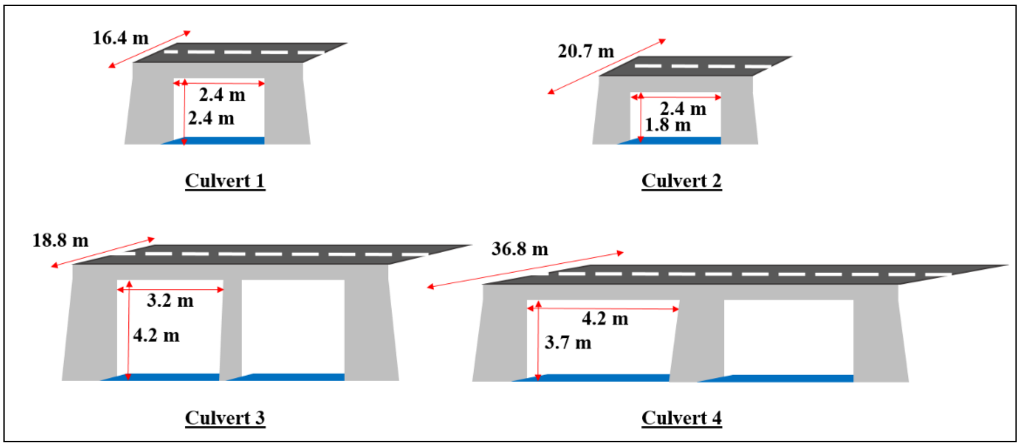



**Figure 3-4: Diagrams of key dimensions of culverts from Site 2**

The same approach used to capture the bridge structures from Site 1, was used to capture images for structures from Site 2.

Bridge 3 is a five-span river bridge with an overall length of 29.3 m, overall width of 11.7 m and maximum height of 5 m. Images were captured using a manually operated UAV. The total duration of capturing images was approximately 35 minutes. The battery was changed during the inspection. A total of 429 images were captured and the time recorded from capturing the first image to the last image was 23 minutes.

Bridge 4 is a four span river bridge with an overall length of 21 m, overall width of 20 m and maximum height of 6 m. Images were captured using a manually operated UAV. The total duration of the bridge inspection was approximately 40 minutes. The battery was changed during the inspection. A total of 340 images were captured and the time recorded from capturing the first image to the last image was 25 minutes.

Culvert 1 is a one cell major culvert with an internal cell width of 2.4 m, internal cell height of 2.4 m and an overall cell length of 16.4 m. Aerial images were captured using a manually operated UAV and images inside the culvert were captured by walking through the culvert using the UAV as a hand gimbal. The total duration of capturing images of the culvert was approximately 30 minutes. The battery was not changed during the inspection. A total of 378 images were captured and the time recorded from capturing the first image to the last image was 23 minutes. It should be noted that this was the first structure captured on the day, thus the longer duration compared to the other culvert inspections.

Culvert 2 is a one-cell major culvert with an internal cell width of 2.4 m, internal cell height of 1.8 m and an overall cell length of 20.7 m. Aerial images were captured using a manually operated UAV and images inside the culvert were captured by walking through the culvert using the UAV as a hand gimbal. The total duration of capturing images of the culvert was approximately 20 minutes. The battery was not changed during the inspection. A total of 148 images were captured and the time recorded from capturing the first image to the last image was 11 minutes.

Culvert 3 is a two-cell major culvert with an internal cell width of 3.2 m, internal cell height of 4.2 m and an overall cell length of 18.8 m. Aerial images were captured using a manually operated UAV and images inside the culvert were captured by walking through the culvert using the UAV as a hand gimbal. The total duration of capturing image data of the culvert was approximately 25 minutes. The battery was not changed during the inspection. A total of 230 images were captured and the time recorded from capturing the first image to the last image was 17 minutes.

Culvert 4 is a two-cell major culvert with an internal cell width of 4.2 m, internal cell height of 3.7 m and an overall cell length of 36.8 m. There were higher traffic volumes on the road over the structure than anticipated and it was decided to not use the UAV to capture aerial images. Images of the culvert were captured by walking through the culvert using a normal camera. The total duration of capturing images of the culvert was approximately 30 minutes. A total of 351 images were captured and the time recorded from capturing the first image to the last image was 25 minutes.

Summarised in Table 3-2 are the important data recorded during the image capturing of structures from Site 1 and Site 2 and the equipment used to capture the images.

**Table 3-2: Summary data of the captured structures**

| | Duration [min] | Technical Equipment Used | Battery Change | Total Images Captured |
|---|---|---|---|---|
| **SITE 1** | | | | |
| **Bridge 1** | 45 | UAV: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | Yes | 462 |
| **Bridge 2** | 30 | UAV: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | No | 359 |
| **SITE 2** | | | | |
| **Bridge 3** | 35 | UAV: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | Yes | 429 |
| **Bridge 4** | 40 | UAVe: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | Yes | 340 |
| **Culvert 1** | 30 | UAV: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | No | 378 |
| **Culvert 2** | 20 | UAV: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | No | 148 |
| **Culvert 3** | 25 | UAV: DJI Inspire 2<br>Camera: Zenmuse x4S (20 MP) | No | 230 |
| **Culvert 4** | 30 | Hand camera: Sony A7RIV (61 MP) | No | 351 |

The UAV flight paths and the position of the UAV when each image was captured for the bridges and culverts are shown in Figure 3-5.

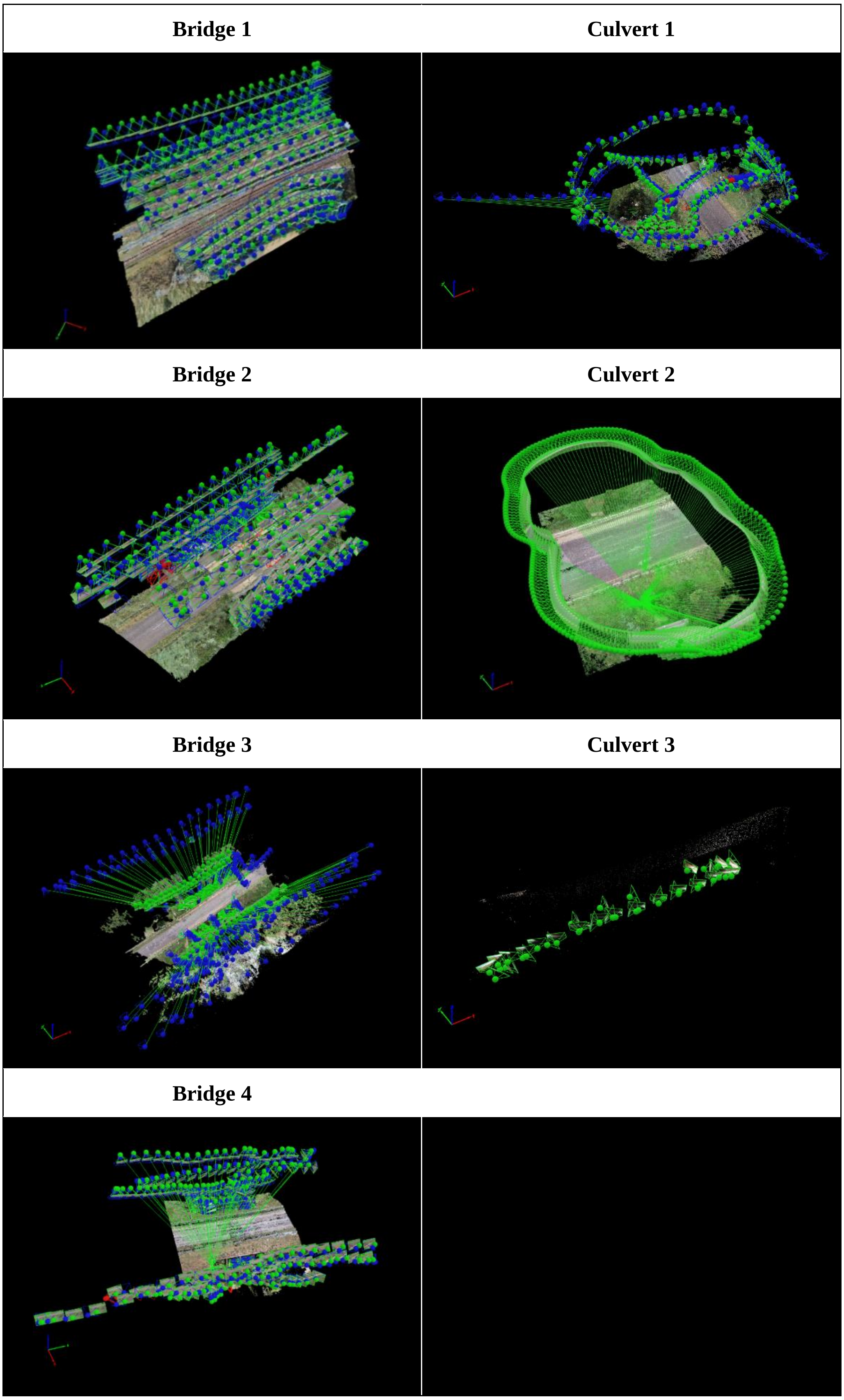



**Figure 3-5: UAV flight paths and position of captured images**

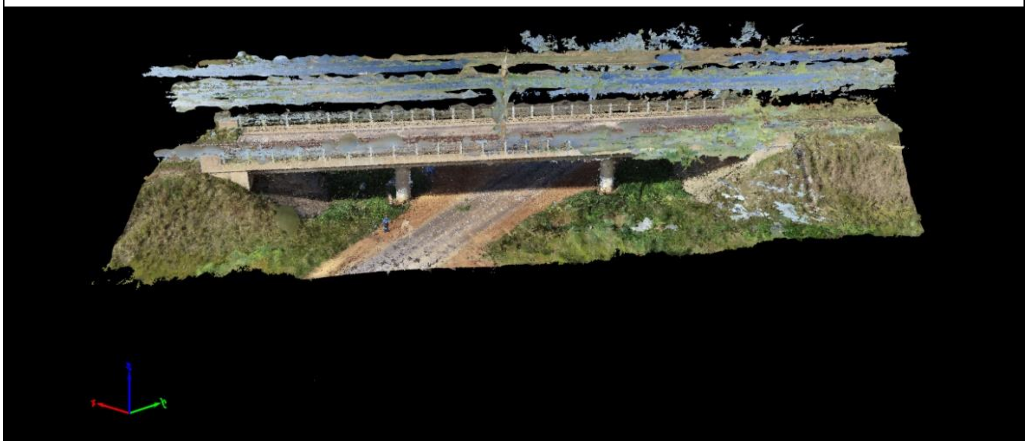
## 3.2 POINT CLOUD MODELS

The images captured during the inspections were processed using Pix4D photogrammetry software to create point cloud models. A desktop i-core 7 with a 64 GB SSD and 128 GB RAM computer was required to process the images. The total processing time to create a point cloud model from the captured images was approximately five to six hours per structure. An accuracy of 20 to 40 mm was attained in generating the point cloud models, with an average georeferencing GPS error of 1 m.

After the images have been processed, a free software package, Pix4D Mapper, was used to view the point cloud models. The point cloud models created from the captured structure images are shown in Figure 3-6.

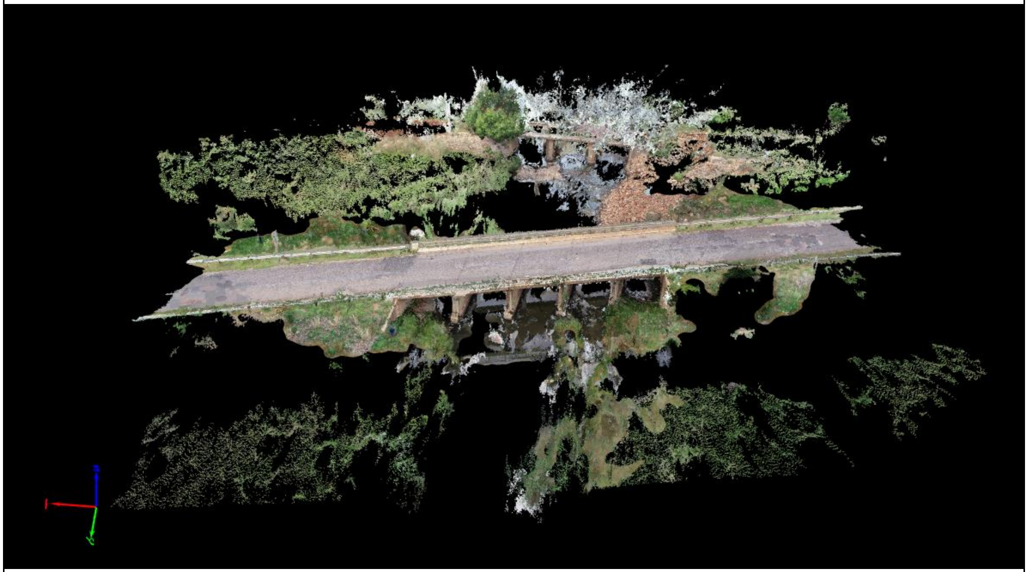
It should be noted that the normal hand camera georeferencing was not compatible with Pix4D and it was not possible to generate point cloud models from the captured images for Culvert 3 and 4.

**Bridge 1**



**Bridge 2**

**Bridge 3**



**Bridge 4**

**Culvert 1**

**Culvert 2**

**Figure 3-6: Generated point cloud models from captured images**

Pix4D Mapper opens a project in "Map View" and shows the structure location on a Google Earth base map. This location is based on the georeferenced images captured by the UAV and indicates the spatial orientation of the structure as shown in Figure 3-7.


**Figure 3-7: Spatial orientation of the structure**

The point cloud model of the structure can be viewed in the "rayCloud" tab, by selecting the "Point Clouds" and "Triangle Meshes" layers.

When selecting any point on the point cloud model, Pix4D Mapper generates a list of captured images in which the selected point is visible. This enables the viewer to select a suitable image, with the required detail, lighting and preferred captured angle for further inspection, as demonstrated in Figure 3-8.

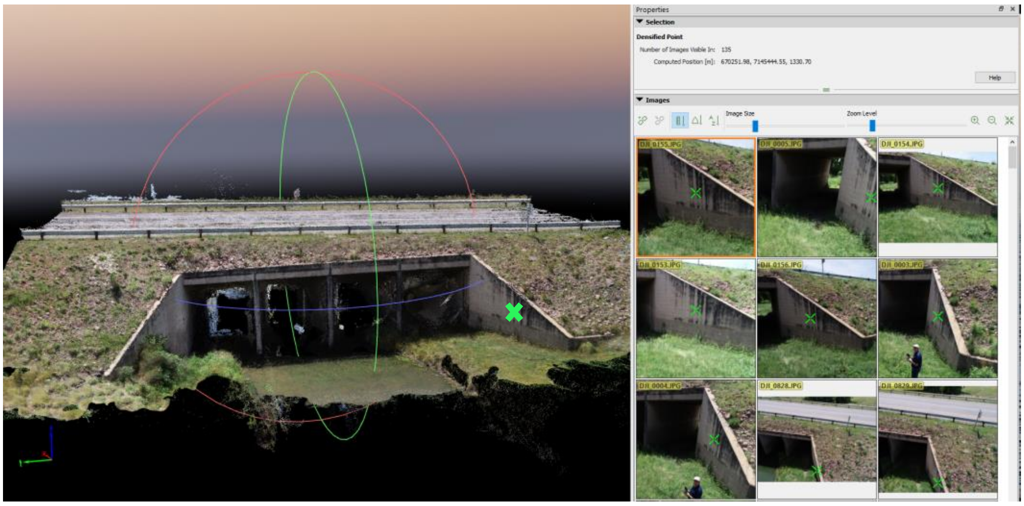



**Figure 3-8: Selecting a point on the point cloud model**

The properties of the selected point indicate the number of images the specific point is visible in. As shown in Figure 3-8, the selected point on the wing wall is visible in 135 different images. The list of images are sorted by capturing distance, placing the image captured at closest range first. The images captured at closest range will have the best quality and least pixilation when the image is enlarged for more detail. The list of images can also be altered to size and zoom level for the viewer to see more detail or to show more images on the screen. Once the most suited image has been identified, the image can be enlarged by hovering over the image with the cursor and pressing the space bar key on the keyboard. The image will open in full screen mode and enables the viewer to enlarge and navigate through the image as shown in Figure 3-9 and Figure 3-10.

**Figure 3-9: Full screen mode of the selected image**

**Figure 3-10: Enlarged image of the selected bridge element**

This functionality in Pix4D Mapper software formed part of the new proposed inspection methodology. The software was used by the inspectors to view, identify and rate the structure defects, by navigating through the point cloud models and captured images.

## 3.3 INSPECTION DATA

One of the objectives for this study was to determine if an accredited bridge inspector would be able to inspect structures, identify and rate defects confidently using only the point cloud models and captured images.

To determine the practicality of the new proposed inspection methodology, two independent COTO accredited senior bridge inspectors were approached to inspect and complete inspection sheets for two of the captured structures. The inspectors completed an inspection sheet and assigned DER-ratings, using only the point cloud models and images. The new ratings were then compared to historic data in the CSIR STRUMAN BMS captured during traditional TMH 19 visual inspections.

### 3.3.1 Defect ratings using new inspection methodology

The two accredited bridge inspectors each inspected two bridge structures, using only the point cloud models and captured images. Comments on the practicality and limitations of the inspections were noted and the duration of each inspection was recorded.

The structures selected for inspection are different in class and size and have defects recorded on historic inspection sheets. The following two structures were selected for inspection:

- Bridge 1, a large bridge, and
- Bridge 2, a medium bridge.

The inspectors participating in this study are active accredited bridge inspectors with bridge design experience. The two inspectors participating in the study were:

- Inspector 1: Chris Lötter from JG Afrika , and
- Inspector 2: Gerrit Visser from Royal Haskoning DHV.

The inspections were conducted at JG Afrika’s offices in Pietermaritzburg, using the new proposed methodology. The following hardware and software setup, as shown in Figure 3-11, was used for the inspections:

- Laptop;
- Additional computer monitor;
- Wireless mouse and keyboard;
- Installed Pix4D Mapper software;
- Softcopy of the TMH 19 inspection sheet, and
- Hardcopy of the STRUMAN remedial activity list.

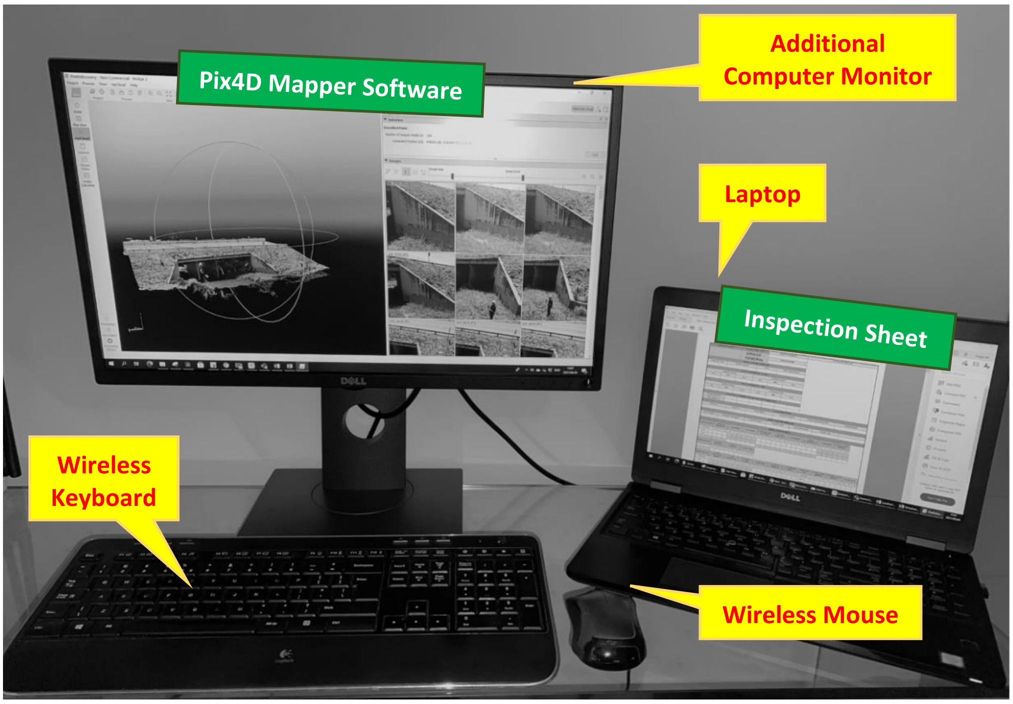



**Figure 3-11: Hardware and software setup**

The larger monitor enabled the inspectors to enlarge the images and see more detail. The additional computer monitor also enabled the inspector to have both the inspection sheet and Pix4D Mapper open simultaneously. The inspectors could complete the inspection sheet while navigating through the point cloud model and images. The corresponding remedial activities were captured from a hardcopy and re-used for all the inspections. Having a hardcopy of the remedial activities eliminated the need for the inspector to navigate between two different files on the laptop screen.

The following methodology was proposed to identify defects, rate defects and complete the inspection sheets for each structure:

1. Open Pix4D Mapper on the additional computer monitor and select the structure for inspection;
2. Open the appropriate inspection sheet on the laptop screen;
3. Use the “Map View” in Pix4D Mapper to comprehend the spatial orientation of the structure and number the structure elements according to convention;
4. Open the “RayCloud” tab and select the “Point Clouds” and “Triangular Meshes” layers to view the point cloud model of the structure;
5. Investigate the structure and structure elements by rotating the point cloud model, using different zoom levels and viewing the structure from different angles;
6. Start inspecting the structure systematically. Inspect each structure element by selecting a point of interest on the point cloud model and view the list of generated images;
7. Select the image with the preferred detail, lighting, and angle;
8. Inspect the image in full screen mode at different zoom levels and navigate through the image;
9. Rate defects identified on the element, using the DER-rating system as prescribed in TRH 19 and capture the ratings and corresponding remedial activities on the inspection sheet;
10. Repeat steps 7 to 9 to inspect the same element, but selecting different images captured at different angles, and
11. Once satisfied with the inspection and defect ratings of an element, repeat steps 6 to 10 for all structure elements.

The inspectors had a brief demonstration and overview of the software and the proposed methodology before starting the inspections. The inspectors completed the inspection sheets independently and did not have access to the structure's historic inspection ratings. During the inspections all comments regarding the practicality and limitations were noted and the duration of each inspection was recorded. Although it was proposed to complete inspection sheets electronically, the inspectors preferred completing hard copy forms.

### 3.3.2 Historic TMH 19 defect ratings

To determine the effectiveness of the new inspection methodology and if the same defects could be identified and rated using only point cloud models and captured images, the inspection ratings of the new inspections were compared to historic TMH 19 visual inspection data.

The structures selected for this study were previously inspected in 2016 as part of the Gauteng provincial road network routine visual bridge inspections. At the time of conducting the study, the Province was preparing for the next round of TMH 19 visual bridge inspections. Unfortunately, the inspections were not executed when this study was concluded and thus the 2016 inspection data were used for comparison.

Although 2016 inspection data were used for comparison, the same defects should still be visible and ratings should not vary significantly, unless maintenance have been done or a structure deteriorated considerably since 2016. The structure defect ratings were evaluated individually and where significant differences were noted in the ratings, further investigations were conducted. The completed 2016 inspection sheets for the selected structures can be viewed in Appendix A.

## 3.4 COST AND TIME COMPONENTS

To determine if the new inspection methodology has cost and time saving benefits, the cost and time components of traditional TMH 19 bridge inspections and inspections using only point cloud models and images, were compared.

Data were collected from a consulting engineering company conducting routine visual inspections of structures on the Western Cape provincial road network. The inspections took place in 2019 over a period of 11 days and included the visual inspections of 121 bridges and culverts. The data collected included the actual time spent on inspections, the total duration of inspections and the cost associated with each inspection. Each of the structures were inspected by an accredited senior bridge inspector or culvert inspector and was accompanied by a technical assistant. The team consisted of three inspectors and three technical assistants who conducted inspections simultaneously. The analysis of the inspection data is presented in Chapter 4.

The cost and time components of the new inspection methodology were estimated based on the data recorded during capturing the image data, processing the images and the inspections of the selected structures. The cost of capturing and processing the images were based on the actual quotation supplied by Premier Mapping Africa. The cost of new inspections was based on the professional fees supplied by the consulting engineering company.

The cost and time components for transportation to site and between the structures would be the same using either the traditional TMH 19 inspection methodology or the new inspection methodology. For this study the travel components were thus omitted.

## 3.5 DEFECT CLASSIFICATION MODELS

The cost and time saving aspects of the new inspection methodology will depend on limiting the human involvement of inspections. To determine if existing inspection and inventory image data could be used to identify defects autonomously, deep learning models were developed to categorise images and predict if a bridge element had a defect or not. The bridge element selected for this study was bridge roadway joints. Different CNN models were developed and evaluated to optimise the performance and ultimately select the best suited model.

CNN is a class of deep neural networks to analyse visual imagery. CNN allows for extraction of higher representation content of images. Unlike conventional image recognition where image features are defined manually, CNN uses raw pixel data of images, trains the model and extracts the features automatically for more accurate classification.

The CSIR BMS inspection and inventory image data were used to compile images of roadway joints of different type and size bridges in South Africa. The images were categorised according to Defect and No Defect classes. A total of 600 images were used, 400 images belonging to the Defect class and 200 images to the No Defect class. Examples of images from the two classes are shown in Figure 3-12 and Figure 3-13.

**Figure 3-12: Examples of images in the Defect class**

**Figure 3-13: Examples of images in the No Defect class**

The CNN classification models were developed using the Spider programming environment written in Python and built-in libraries such as Keras and Sklearn were utilised. These libraries contain efficient tools used in machine learning and statistical modelling, including classification.

The data were spilt in three subsets used for training, validation and testing. 80% of the data were used for training and 20% used for testing. The training set, containing representative data of Defect and No Defect roadway joint images, was further split in 80% training and 20% validation datasets. The test dataset was not included in any training or validation stages and only introduced in the final testing stage to determine the performance of the model when introduced to new unseen data.

It is important for the Defect and No Defect classes to be balanced and have the same number of images during training, to avoid any bias when predicting a class. Data augmentation, a computer vision technique, was used to extend and balance the No Defect dataset. Images from the No Defect class were flipped, shifted and rotated at different angles to create more images, equal to the number of images in the Defect class.

The first model developed, referred to as the baseline model, was a simple CNN model. The model consisted of two convulsion layers, two pooling layers and a dense output layer. Since this is ‘n binary classification problem with only two classes, activation functions ReLU was defined for the intermediate layers, Sigmoid for the output layer and Binary Cross-entropy as the Loss function. The Loss function evaluates how well the specific algorithm models the given data. The model was trained and validated with the respective datasets for 50 epochs and the performance of the model was evaluated with a Confusion Matrix and Classification report to summarise the prediction results. The baseline model developed is shown in Figure 3-14.

```
#Define Baseline Model

Baseline_model = keras.Sequential([
            keras.layers.Conv2D(16, kernel_size=(3,3), activation='relu',input_shape=(224,224,3)),
            keras.layers.MaxPool2D(),
            keras.layers.Conv2D(32, kernel_size=(3,3), activation='relu'),
            keras.layers.MaxPool2D(),
            keras.layers.Flatten(),
            keras.layers.Dense(1,activation='sigmoid')])

Baseline_model.compile(optimizer=keras.optimizers.Adam(),
              loss='binary_crossentropy',
              metrics= ['accuracy'])

history = Baseline_model.fit(train_data, epochs=50,validation_data=val_data, shuffle=True)

#Evaluate Results

predictions = []
labels =  []

for x, y in val_data:
  Y_pred = (Baseline_model.predict(x) > 0.5).astype("int32")
  actual = y.numpy()
  predictions = np.concatenate([predictions,Y_pred[:,-1]], axis= 0)
  labels = np.concatenate([labels,actual], axis= 0)


print(confusion_matrix(labels, predictions))
print(classification_report(labels, predictions, target_names = ['Defect (Class 0)','No Defect (Class 1)']))
```

**Figure 3-14: CNN Baseline model**

The second model developed was a more complex CNN model with deeper layers. The model consisted of three convulsion layers, three pooling layers and a dense output layer. ‘Dropout’ and ‘Early Stopping’ were introduced to avoid the model from overfitting on the training data, saving the weights of the model when validation loss was at a minimum. The same activation and Loss function were defined as specified in the baseline model. The model trained for 12 epochs before early stopping was called, as the validation accuracy did not improve for 5 consecutive epochs. The performance of the model was evaluated with a Confusion Matrix and Classification report. The more complex CNN model developed is shown in Figure 3-15.

```
#Define more complex CNN Model

CNN_model = keras.Sequential([
            keras.layers.Conv2D(32, kernel_size=(3,3), activation='relu',input_shape=(224,224,3)),
            keras.layers.MaxPool2D(),
            keras.layers.Conv2D(64, kernel_size=(3,3), activation='relu'),
            keras.layers.MaxPool2D(),
            keras.layers.Conv2D(125, kernel_size=(3,3), activation='relu'),
            keras.layers.MaxPool2D(),
            keras.layers.Flatten(),
            keras.layers.Dropout(0.5),
            keras.layers.Dense(1,activation='sigmoid')])

CNN_model.compile(optimizer=keras.optimizers.Adam(),
              loss='binary_crossentropy',
              metrics= ['accuracy'])

es = EarlyStopping(monitor='val_loss', mode='min', verbose=1, patience=5)
mc = ModelCheckpoint('best_model.h5', monitor='val_accuracy', mode='max', verbose=1, save_best_only=True)

history = CNN_model.fit(train_data, epochs=50,validation_data=val_data, shuffle=True, callbacks=[es,mc])
saved_model = keras.models.load_model('best_model.h5')

#Evaluate Results

predictions = []
labels =  []

for x, y in val_data:
  Y_pred = (saved_model.predict(x) > 0.5).astype("int32")
  actual = y.numpy()
  predictions = np.concatenate([predictions,Y_pred[:,-1]], axis= 0)
  labels = np.concatenate([labels,actual], axis= 0)


print(confusion_matrix(labels, predictions))
print(classification_report(labels, predictions, target_names = ['Defect (Class 0)','No Defect (Class 1)']))
```

**Figure 3-15: More complex CNN model**

For the third model, transfer learning was introduced. Transfer learning utilises pre-trained weights of a previous model developed with large datasets and more classes. Transfer learning can be used by freezing the early convolutional layers of the network and only specify and train the last few layers and output layer, to reduce the computation time and to make predictions based on the requirements of the current dataset. The transfer learning model used was the VGG16 model developed with the ImageNet dataset. ‘Dropout’ and ‘Early Stopping’ were included, and the same activation and Loss function were defined as specified in the baseline model. The model trained for 10 epochs before early stopping was called. The performance of the model was evaluated with a Confusion Matrix and Classification report. The transfer learning VGG16 model developed is shown in Figure 3-16.

```
VGG16_model = tf.keras.applications.VGG16(input_shape = (224, 224, 3), include_top = False, weights = "imagenet")
VGG16_model.trainable = False

TL_model = tf.keras.Sequential([VGG16_model,
                                 keras.layers.Flatten(),
                                 keras.layers.Dense(100,activation='relu'),
                                 keras.layers.Dropout(0.5),
                                 keras.layers.BatchNormalization(),
                                 keras.layers.Dense(1,activation='sigmoid')])


TL_model.compile(optimizer=keras.optimizers.Adam(),
              loss='binary_crossentropy',
              metrics= ['accuracy'])

es = EarlyStopping(monitor='val_loss', mode='min', verbose=1, patience=5)
mc = ModelCheckpoint('best_model.h5', monitor='val_accuracy', mode='max', verbose=1, save_best_only=True)

history = TL_model.fit(train_data, epochs=50,validation_data=val_data, shuffle=True, callbacks=[es,mc])
saved_model = keras.models.load_model('best_model.h5')

#Evaluate Results

predictions = []
labels =  []

for x, y in val_data:
  Y_pred = (saved_model.predict(x) > 0.5).astype("int32")
  actual = y.numpy()
  predictions = np.concatenate([predictions,Y_pred[:,-1]], axis= 0)
  labels = np.concatenate([labels,actual], axis= 0)


print(confusion_matrix(labels, predictions))
print(classification_report(labels, predictions, target_names = ['Defect (Class 0)','No Defect (Class 1)']))
```

**Figure 3-16: Transfer Learning VGG16 model**

For the final model, an even larger dataset was created using more data augmentations to increase the number of images for each class to 3 600 images. Each image in the Defect class was augmented eight times and the images in the No Defect class 17 times to ensure the datasets were balanced. The VGG16 transfer learning model developed was used and retrained with the larger dataset. The model trained for nine epochs before early stopping was called. The performance of the model was evaluated with a Confusion Matrix and Classification report.

Finally, the test dataset was fit to the VGG16 transfer learning model, trained with the larger dataset, to predict the classes of the unseen images. The predicted class of each image was compared to the actual class to evaluate the final performance of the model.

## 3.6 SUMMARY

This chapter described the experimental setup and the field work conducted for this study. Image data of eight different structures were captured from two sites using UAVs. The images were processed to create point cloud models. The new inspection methodology was introduced and presented to accredited bridge inspectors. The bridge inspectors completed new inspection sheets and the historic inspection sheets were obtained from the STRUMAN BMS database for comparison.

The different cost and time components of the new inspection methodology were recorded. Data were collected from a consulting engineering company conducting routine visual inspections of structures on the Western Cape provincial road network.

Historic inspection and inventory photos of bridge roadway joints were categorised in Defect and No Defect classes. Different deep learning CNN models were developed to categorise images and predict if a bridge element had a defect or not.

# 4 RESULTS

## 4.1 INTRODUCTION

This chapter presents the results for the comparison between traditional TMH 19 visual inspections and the new inspection methodology, in terms of defect ratings and the cost and time components. The bridge inspectors' comments and remarks recorded during the inspections provided valuable insights to the practicality and feasibility of the new inspection methodology. The performance of the different CNN models was compared to select the best suited model to predict and classify bridge roadway joint defects.

## 4.2 INSPECTION RATINGS

The practicality of the new inspection methodology depends on the ability of bridge inspectors to identify and rate defects using only point cloud models and captured images. The new inspection ratings were compared to historic inspection data for two bridge structures. The two structures selected for inspection were different in class and size and had defects recorded on the historic inspection sheets. The following structures were selected for inspection and comparison:

- Bridge 1 (large bridge), and
- Bridge 2 (medium bridge).

### 4.2.1 Defect ratings captured during traditional TMH 19 inspections

The structures selected for this study were previously inspected in 2016 as part of the Gauteng Provincial Road network visual bridge inspections. A summary of the identified defect types and DER-ratings based on the 2016 visual inspections for Bridge 1 and Bridge 2, as captured in the CSIR STRUMAN BMS, are shown in Table 4-1.

### 4.2.2 Defect ratings captured using new inspection methodology

The two bridge inspectors each completed new inspection sheets using the new proposed inspection methodology. They identified defects and assigned DER-ratings to the defects. A summary of the identified defect types and corresponding DER-ratings for Bridge 1 and Bridge 2, captured during the inspections are shown in Table 4-1. The completed inspection sheets can be viewed in Appendix B.

The bridge inspectors were unable to inspect all the bridge elements using the new inspection methodology. The elements captured as "unable to inspect" on the inspection sheets for Bridge 1, included abutment foundation, pier foundations and bearings. The inspectors were able to inspect all the Bridge 2 elements.

Different colours were used to illustrate the variance in the new inspection ratings compared to the historic inspection ratings for each defect in Table 4-1.

**Table 4-1: Identified defects and DER-ratings**

| **Legend** | **Difference in DER-ratings** | **0** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|---|

<table>
<tr><th rowspan="2">Defect</th><th colspan="3">Element and DER-rating</th></tr>
<tr><th>Historic Inspection</th><th>Inspector 1</th><th>Inspector 2</th></tr>
<tr><th colspan="4">Bridge 1</th></tr>
<tr><td>1. Interlocking blocks missing</td><td>04. Approach embankment protection works<br><table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A2</td><td>1</td><td>1</td><td>1</td></tr></table></td><td>04. Approach embankment protection works<br><table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A2</td><td>1</td><td>2</td><td>1</td></tr></table></td><td>01. Approach embankment<br><table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A2</td><td>1</td><td>2</td><td>1</td></tr></table></td></tr>
<tr><td>2. Vegetation growing through interlocking paving on abutment</td><td>04. Approach embankment protection works<br><table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A2</td><td>1</td><td>1</td><td>1</td></tr></table></td><td>04. Approach embankment protection works<br><table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>2</td><td>2</td><td>2</td></tr></table></td><td>04. Approach embankment<br><table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>2</td><td>1</td><td>1</td></tr></table></td></tr>
</table>

3. Abutment seating cracks

06. Abutments

| | D | E | R |
|---|---|---|---|
| A1 | 3 | 1 | 3 |
| A2 | 3 | 1 | 3 |

06. Abutments

| | D | E | R |
|---|---|---|---|
| A1 | 1 | 2 | 1 |
| A2 | 1 | 2 | 1 |

06. Abutments

| | D | E | R |
|---|---|---|---|
| A1 | 1 | 1 | 1 |
| A2 | 1 | 1 | 1 |

4. Spall on wing wall

07. Wingwall/ Retaining walls

| | D | E | R |
|---|---|---|---|
| A2 | 0 | - | - |

07. Wingwall/ Retaining walls

| | D | E | R |
|---|---|---|---|
| A2 | 1 | 1 | 1 |

07. Wingwall/ Retaining walls

| | D | E | R |
|---|---|---|---|
| A2 | 1 | 1 | 1 |

5. Debris on deck surface

10. Kerbs/ Sidewalk

| | D | E | R |
|---|---|---|---|
| AS | 0 | - | - |

10. Kerbs/ Sidewalk

| | D | E | R |
|---|---|---|---|
| AS | 1 | 2 | 1 |

10. Kerbs/ Sidewalk

| | D | E | R |
|---|---|---|---|
| A1 | 1 | 1 | 1 |

6. Guardrails missing

12. Pier protection works

| | D | E | R |
|---|---|---|---|
| P1 | 0 | - | - |
| P2 | 0 | - | - |

12. Pier protection works

| | D | E | R |
|---|---|---|---|
| P1 | 3 | 4 | 3 |
| P2 | 3 | 4 | 3 |

12. Pier protection works

| | D | E | R |
|---|---|---|---|
| P1 | 2 | 4 | 3 |
| P2 | 2 | 4 | 3 |

7. Missing abutment drainage/ blocked drainage

16. Support drainage

| | D | E | R |
|---|---|---|---|
| A1 | 0 | - | - |
| A2 | 0 | - | - |

16. Support drainage

| | D | E | R |
|---|---|---|---|
| A1 | 2 | 3 | 2 |
| A2 | 2 | 3 | 2 |

16. Support drainage

| | D | E | R |
|---|---|---|---|
| A1 | 3 | 4 | 2 |
| A2 | 3 | 4 | 2 |

<table>
<tr><td>8. Blocked joint/ damaged gland of claw joint</td>
<td>17. Expansion joints<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>0</td><td>-</td><td>-</td></tr><tr><td>A2</td><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>17. Expansion joints<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>3</td><td>3</td><td>2</td></tr><tr><td>A2</td><td>3</td><td>3</td><td>2</td></tr></table></td>
<td>17. Expansion joints<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>3</td><td>4</td><td>2</td></tr><tr><td>A2</td><td>3</td><td>4</td><td>2</td></tr></table></td></tr>
<tr><td>9. Impact damage</td>
<td>20. Deck slab<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>S2</td><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>20. Deck slab<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>S2</td><td>2</td><td>1</td><td>1</td></tr></table></td>
<td>20. Deck slab<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>S2</td><td>1</td><td>1</td><td>1</td></tr></table></td></tr>
<tr><td colspan="4">Bridge 2</td></tr>
<tr><td>1. Settlement of approach embankments</td>
<td>01. Approach embankment<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>0</td><td>-</td><td>-</td></tr><tr><td>A2</td><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>01. Approach embankment<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>2</td><td>3</td><td>2</td></tr><tr><td>A2</td><td>2</td><td>3</td><td>2</td></tr></table></td>
<td>01. Approach embankment<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>1</td><td>1</td><td>1</td></tr><tr><td>A2</td><td>1</td><td>1</td><td>1</td></tr></table></td></tr>
<tr><td>2. Guardrails not attached to end blocks</td>
<td>02. Guardrails<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>02. Guardrails<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>3</td><td>4</td><td>3</td></tr></table></td>
<td>02. Guardrails<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>3</td><td>4</td><td>3</td></tr></table></td></tr>
<tr><td>3. Waterway debris and vegetation</td>
<td>03. Waterway<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>2</td><td>2</td><td>2</td></tr></table></td>
<td>03. Waterway<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>03. Waterway<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td></tr>
<tr><td>4. Abutment crack</td>
<td>06. Abutments<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>1</td><td>1</td><td>1</td></tr></table></td>
<td>06. Abutments<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>06. Abutments<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>0</td><td>-</td><td>-</td></tr></table></td></tr>
</table>

<table>
<tr>
<td>5. Vegetation on road surface/ hidden guardrail</td>
<td>08. Surfacing<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>3</td><td>3</td><td>2</td></tr></table></td>
<td>08. Surfacing<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>1</td><td>2</td><td>1</td></tr></table></td>
<td>10. Kerbs/ sidewalks<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>1</td><td>1</td><td>1</td></tr></table></td>
</tr>
<tr>
<td>6. Scuppers too short and blocked</td>
<td>09. Superstructure drainage<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>2</td><td>4</td><td>1</td></tr></table></td>
<td>09. Superstructure drainage<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>2</td><td>4</td><td>2</td></tr></table></td>
<td>09. Superstructure drainage<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>1</td><td>4</td><td>1</td></tr></table></td>
</tr>
<tr>
<td>7. Corroded handrails</td>
<td>12. Parapet<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>2</td><td>4</td><td>1</td></tr></table></td>
<td>12. Parapet<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>12. Parapet<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td>
</tr>
<tr>
<td>8. Spall on pier</td>
<td>14. Piers and columns<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>P1</td><td>1</td><td>2</td><td>1</td></tr><tr><td>P2</td><td>1</td><td>2</td><td>1</td></tr></table></td>
<td>14. Piers and columns<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>P1</td><td>0</td><td>-</td><td>-</td></tr><tr><td>P2</td><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>14. Piers and columns<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>P1</td><td>0</td><td>-</td><td>-</td></tr><tr><td>P2</td><td>0</td><td>-</td><td>-</td></tr></table></td>
</tr>
<tr>
<td>9. Joint needs new asphalt plug</td>
<td>17. Expansion joints<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>0</td><td>-</td><td>-</td></tr><tr><td>A2</td><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>17. Expansion joints<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>2</td><td>4</td><td>1</td></tr><tr><td>A2</td><td>2</td><td>4</td><td>1</td></tr></table></td>
<td>17. Expansion joints<table><tr><th></th><th>D</th><th>E</th><th>R</th></tr><tr><td>A1</td><td>2</td><td>4</td><td>2</td></tr><tr><td>A2</td><td>2</td><td>4</td><td>2</td></tr></table></td>
</tr>
<tr>
<td>10. Faded clearance signs and missing structure number</td>
<td>21. Miscellaneous<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>21. Miscellaneous<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>0</td><td>-</td><td>-</td></tr></table></td>
<td>21. Miscellaneous<table><tr><th>D</th><th>E</th><th>R</th></tr><tr><td>1</td><td>1</td><td>1</td></tr></table></td>
</tr>
</table>

The PCI values for the two bridge structures were calculated in the STRUMAN BMS based on the new inspection ratings to determine the condition categories of the structures. Table 4-2 show the new PCI values and condition categories compared to the historic values as captured in the STRUMAN BMS.

**Table 4-2: PCI and condition category of new inspections**

| Class | Structure No. | Inspections | PCI | Condition Category |
|---|---|---|---|---|
| **Bridge 1** | | | | |
| Large Bridge | D631_01N_B4435 | Historic | 64.30 | Fair |
| | | Inspector 1 | 82.99 | Good |
| | | Inspector 2 | 82.97 | Good |
| **Bridge 2** | | | | |
| Medium Bridge | D631_01N_B4095 | Historic | 93.80 | Very Good |
| | | Inspector 1 | 90.99 | Very Good |
| | | Inspector 2 | 90.96 | Very Good |

### 4.2.3 Bridge inspectors' comments

The bridge inspectors' comments and remarks were recorded during the new inspection. This included limitations of the software and confidence of inspection ratings. The following remarks and comments were noted:

- The inspectors required dimensions of the bridges, including an indication of the scale and slope. The inspectors were unable to determine the flow direction of the river for Bridge 2;
- The software should indicate the orientation or angle from which images were taken. An image in the longitudinal direction of the bridges was required to determine the abutment and approach embankment settlement for Bridge 1 and Bridge 2;
- To improve the navigation of the point cloud model, a reset function is needed to return the model to the bridge's original orientation;

- Images captured in the shadow of the bridge were difficult to inspect and the details on the images were unclear. The inspectors were unable to inspect the bearings of Bridge 1;

- The UAV pilot needs experience and training to ensure all bridge elements are captured and to focus on important elements. Images should be captured from a closer distance to the bridge;

- Inspections would be easier if the flight path were the same as the inspection sequence. The flight path could be specified by inspectors;

- The software requires a tool to label defects on the point cloud model for a more interactive inspection;

- Images could be grouped to create individual point cloud models of each bridge element for more detailed inspections;

- To use the software and navigating through the point cloud models require training. After the inspectors completed the first bridge, they were more comfortable and accustomed to the process. They were able to inspect the second bridge easier and faster;

- The inspectors were able to determine with confidence whether a bridge requires further inspection or not. Bridge 1 had an abutment seating crack and the inspectors indicated the bridge requires a physical on-site inspection. They were confident inspecting and rating defects of Bridge 2 and did not see a need for further inspection;

- The inspectors indicated they had a lower confidence in rating defects using only images and this resulted in more conservative (higher) defect ratings, and

- Capturing inspection data electronically will be easier and safer using the new inspection methodology.

## 4.3 COST AND TIME COMPONENTS

The cost and time components of traditional TMH 19 bridge inspections and the new inspection methodology were compared to determine if the new inspection methodology have cost and time saving benefits.

### 4.3.1 Cost and time components of traditional TMH 19 inspections

The data collected from the consulting engineering company were analysed and the average time and cost of the inspections for the different structure asset classes were calculated.

The inspection took place in 2019 over a period of 11 days and included the visual inspections of 121 bridges and culverts. The number of structures inspected per day by each inspector are shown in Figure 4-1.

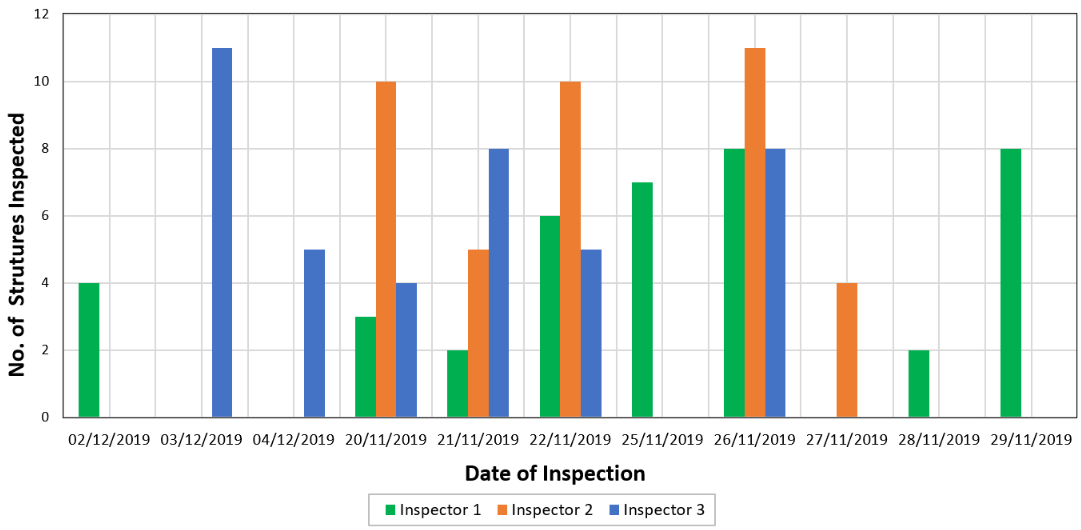



**Figure 4-1: Number of structures inspected per day**

The cost of each inspected structure was calculated based on the actual time spent on the inspection and the inspector's and technical assistant's professional fees. The inspections were in close proximity of the consulting engineering company's offices and travel was charged as a lump sum and not included in the cost calculation.

Although the cost for each structure was calculated based on the actual time spent on each inspection, the total duration of the inspection was of interest to this study as it includes the preparation time on site. The cost and time calculations included the completion of inspection sheets on site. The inspection sheets were manually captured into the BMS on return to the office.

The associated cost and total duration of each bridge and culvert inspection are shown in Figure 4-2 and Figure 4-3. The calculated average cost and duration per structure class are summarised in Table 4-3.

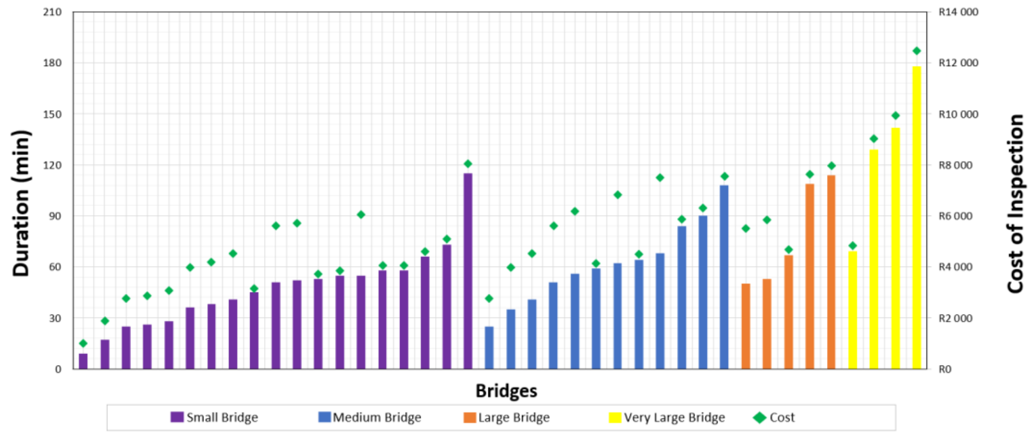



**Figure 4-2: Cost and duration of inspected bridge structures**

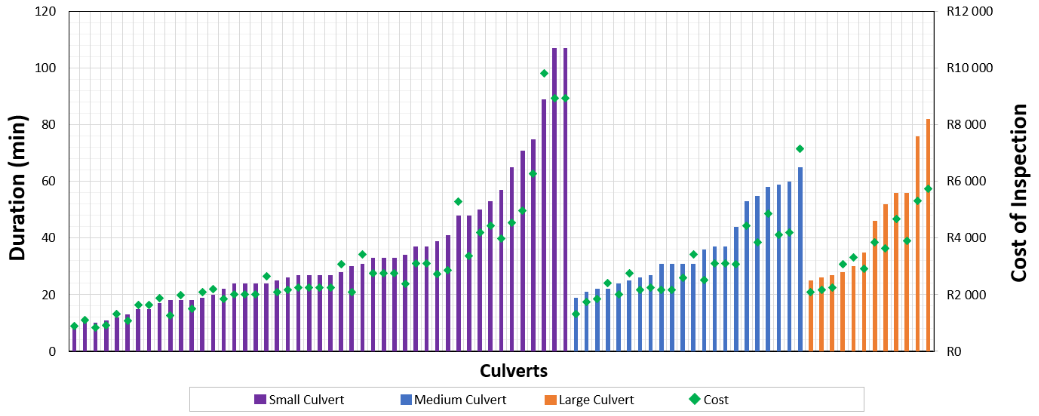



**Figure 4-3: Cost and duration of inspected culvert structures**

**Table 4-3: Average cost and duration per structure class**

| Class | No of structures | Average inspection cost per structure | Average duration of inspection |
|---|---|---|---|
| Small Culvert | 47 | R2 978.07 | 0:34 |
| Medium Culvert | 22 | R3 058.53 | 0:37 |
| Large Culvert | 12 | R3 625.49 | 0:46 |
| Small Bridge | 19 | R4 117.79 | 0:47 |
| Medium Bridge | 12 | R5 475.57 | 1:02 |
| Large Bridge | 5 | R5 786.34 | 1:10 |
| Very Large Bridge | 4 | R9 063.83 | 2:09 |

### 4.3.2 Cost and time components of new inspection methodology

The new inspection methodology included additional components compared to traditional TMH 19 inspections. The new inspection methodology consists of three main tasks: capturing of images, processing of images and the inspection of structures.

For this study the duration of processing the images only considers the manual input required to create point cloud models and excludes the computation time. The duration of processing the captured images to create point cloud models included the following:

- Initial setup - 30 minutes of manual processing and two and a half hours computation time, and
- Addition of control - one hour of manual processing and four to five hours computation time.

The manual processing required to create the point cloud models was estimated to be one and a half hours per structure.

The time spent on the new inspections was recorded for each structure and summarised in Table 4-4. The time recording started when the inspectors began with the first step of the new proposed methodology. This included the preparation time of the inspection and the completion of the inspection sheets but excludes the duration of the demonstration and overview of the new inspection methodology.

**Table 4-4: Duration of inspections using the new inspection methodology**

| | Class | Inspector 1 | Inspector 2 |
|---|---|---|---|
| Bridge 1 | Large Bridge | 1:14 | 1:15 |
| Bridge 2 | Medium Bridge | 0:35 | 0:34 |

Culverts were not inspected as part of this study but a conservative estimate of 30 minutes for a large culvert inspection was used based on the duration of the bridge inspections.

The cost of capturing and processing the images was calculated based on the actual amount quoted by Premier Africa. The cost was not calculated per hour but as a unit cost per structure. The cost included capturing the images, processing the images and the use of equipment. The cost per structure was R 12 000.

The cost of each new inspection and completing inspection sheets were calculated using the same professional hourly fees provided by the consulting engineering company. The calculated inspection cost of each structure class is shown in Table 4-5.

**Table 4-5: Cost of new inspections**

| | Class | Average inspection cost per structure |
|---|---|---|
| Bridge 1 | Large Bridge | R1 925.48 |
| Bridge 2 | Medium Bridge | R891.67 |
| Culvert | Large Culvert | R406.36 |

### 4.3.3 Cost and time comparison

The duration and cost involving the new inspection methodology and traditional TMH 19 inspections were compiled for comparison. Image data were captured for only large and medium bridges and large culverts. The cost and time components for the three structure asset classes are summarised in Table 4-6 and Table 4-7.

**Table 4-6: Summary of inspection time components**

| Time components | Culverts | Bridges | |
|---|---|---|---|
| | Large | Medium | Large |
| **New Inspection Methodology** | | | |
| Preparation for capturing images<br>Duration of capturing images | 0.30 | 0:35 | 0.45 |
| Image processing | 1:30 | 1:30 | 1:30 |
| Preparation of inspection<br>Duration of inspection<br>Completion of inspection sheet | 0:30 | 0:35 | 1:15 |
| **Total Duration** | **2:30** | **2:40** | **3:30** |
| **Traditional TMH 19 Inspections** | | | |
| Preparation of inspection<br>Duration of inspection<br>Completion of inspection sheet | 0:45 | 1:00 | 1:10 |
| **Total Duration** | **0:46** | **1:02** | **1:10** |

**Table 4-7: Summary of inspection cost components**

| Cost components | Culverts | Bridges | |
|---|---|---|---|
| | Large | Medium | Large |
| **New Inspection Methodology** | | | |
| Preparation for capturing images<br>Cost of capturing images<br>Image processing | R 12 000 | R 12 000 | R 12 000 |
| Preparation of inspection<br>Cost of inspection<br>Completion of inspection sheet | R 406 | R 892 | R 1 925 |
| **Total Cost** | **R 12 406** | **R 12 892** | **R 13 925** |
| **Traditional TMH 19 Inspections** | | | |
| Preparation of inspection<br>Cost of inspection<br>Completion of inspection sheet | R 3 625 | R 5 476 | R 5 786 |
| **Total Cost** | **R 3 625** | **R 5 476** | **R 5 786** |

## 4.4 COMPARISON OF CNN MODEL PERFORMANCE

The performance of each CNN model was evaluated through a Confusion Matrix, Classification report and considering the training and validation accuracy and loss. The evaluation metrics of the different models were compared to select the best suited model. The best model was then used to predict the classes of the test dataset.

### 4.4.1 Training and validation accuracy

The accuracy of the training and validation datasets were recorded for each epoch in the training and validation stage. The accuracy of the models was calculated based on the model's ability to predict the correct class of an image. The training and validation accuracies for the different models for each epoch are shown in Figure 4-4.

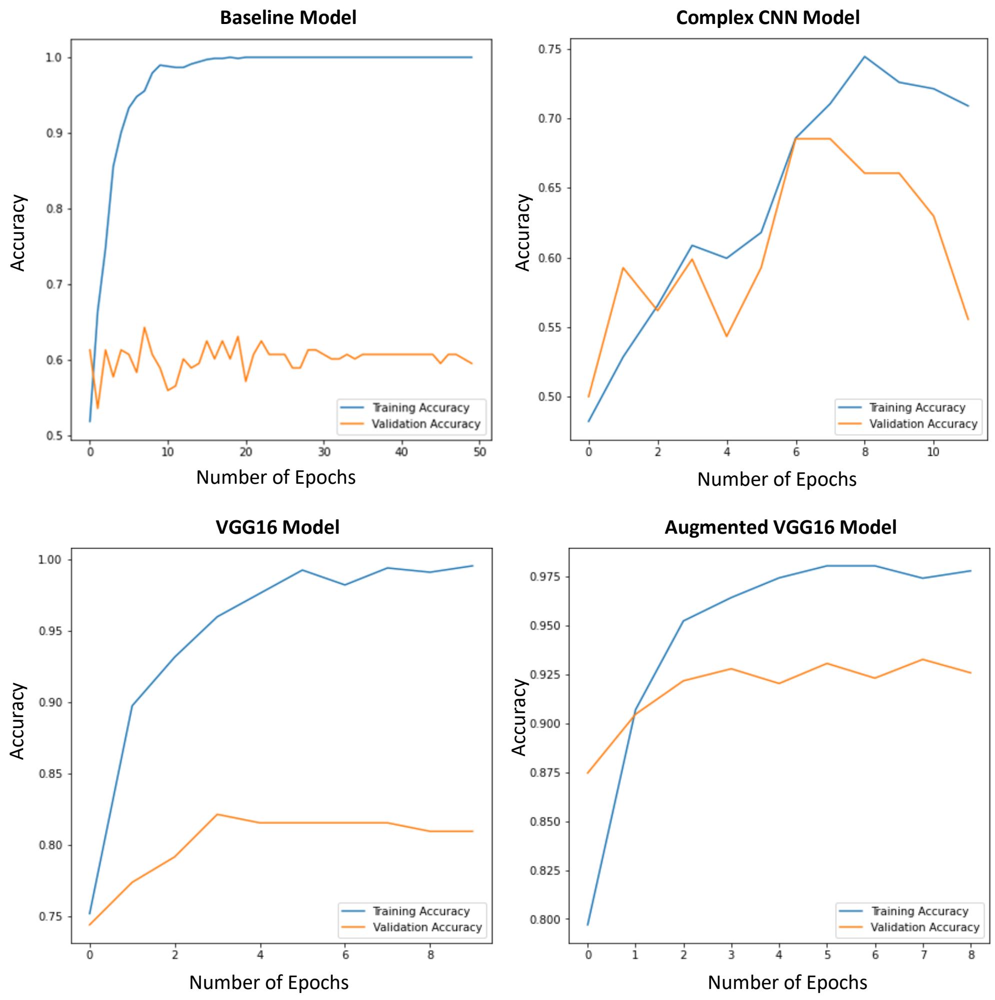



**Figure 4-4: CNN model training and validation accuracy**

### 4.4.2 Training and validation loss

The Loss function compares each of the predicted probabilities of a class, to the actual class output, which is 0 or 1 for Binary Cross-entropy, during the training and validation stage. It then calculates the score that penalises the probabilities based on the distance from the expected value. The loss is thus a measure of how close or far the actual value is from the predicted value.

The loss was recorded for each epoch in the training and validation stage. The training and validation loss for the different models for each epoch are shown in Figure 4-5.

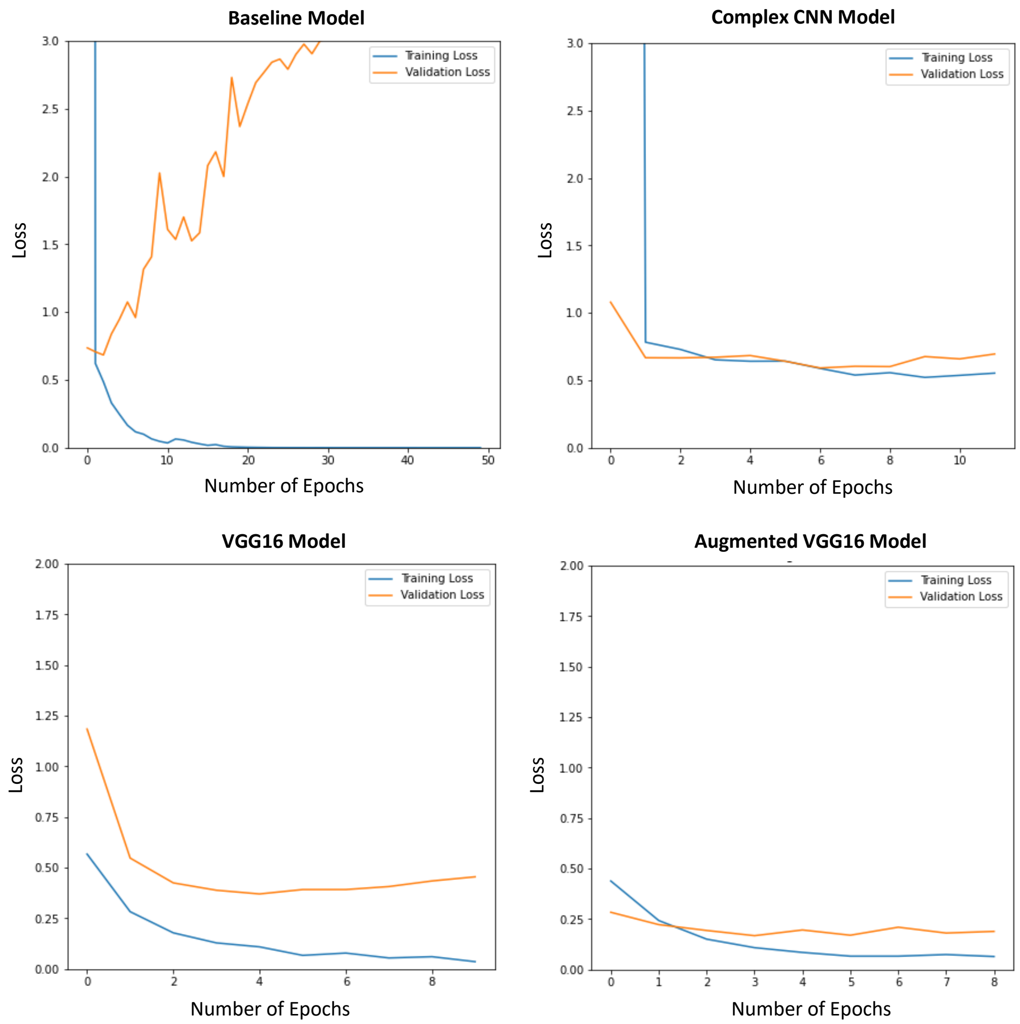



**Figure 4-5: CNN model training and validation loss**

### 4.4.3 Confusion Matrix

A Confusion Matrix is a summary of the model predictions and provides insight to the accuracy and precision of predicted classes versus the actual class. After the model had been trained, the validation dataset was fitted to the model and the predicted and actual classes were recorded for each image. A Confusion Matrix for each of the validation predictions and actual classes were constructed for each model. The Confusion Matrix for each model is shown in Table 4-8.

**Table 4-8: Confusion Matrix of CNN models**

| **Baseline Model** | | | **Complex CNN Model** | | |
|---|---|---|---|---|---|
| | Predicted Defect | Predicted No Defect | | Predicted Defect | Predicted No Defect |
| Actual Class Defect | **55** | **28** | Actual Class Defect | **27** | **56** |
| Actual Class No Defect | **40** | **45** | Actual Class No Defect | **5** | **80** |

| **VGG16 Model** | | | **Augmented VGG16 Model** | | |
|---|---|---|---|---|---|
| | Predicted Defect | Predicted No Defect | | Predicted Defect | Predicted No Defect |
| Actual Class Defect | **65** | **18** | Actual Class Defect | **670** | **63** |
| Actual Class No Defect | **12** | **73** | Actual Class No Defect | **36** | **697** |

### 4.4.4 Classification report

A Classification report is used to measure the quality of the predictions from a classification algorithm. The report summarises the predictions in terms of precision, recall and F1-score. The metrics of a classification report uses the predictions made for each class. Precision is the percentage of the predictions that were correct, recall is the fraction of the correctly identified classes and the F1-score is the weighted harmonic mean of precision and recall.

A Classification report was generated for each of the models, based on the predictions made on the validation dataset. A summary of the results for each model and class is shown in Figure 4-6.

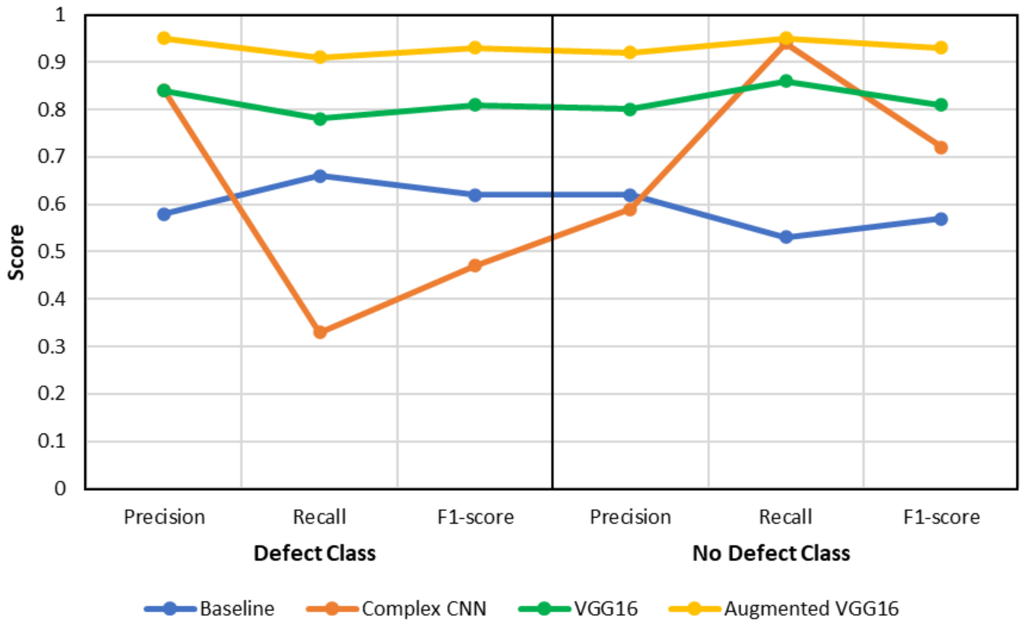



**Figure 4-6: Classification report results**

### 4.4.5 Test dataset

As a final measure of the model's performance, the test dataset was fitted to the VGG16 model, trained with the larger augmented dataset. This evaluated the model's ability to predict the correct class of unseen images.

The test dataset had 80 Defect images and 40 No Defect images. A Confusion Matrix and Classification report was generated to evaluate the results as shown in Table 4-9 and Table 4-10.

**Table 4-9: Confusion Matrix for the test dataset**

| | Predicted Defect | Predicted No Defect |
|---|---|---|
| Actual Class Defect | **76** | **4** |
| Actual Class No Defect | **14** | **26** |

**Table 4-10: Classification Report for the test dataset**

| Model | Precision | | Recall | | F1-score | |
|---|---|---|---|---|---|---|
| | Defect | No Defect | Defect | No Defect | Defect | No Defect |
| VGG16 Augmented | 0.95 | 0.65 | 0.84 | 0.87 | 0.89 | 0.74 |

## 4.5 SUMMARY

This chapter presented the results of the study. The defect ratings captured during the new inspections of two bridge structures were compiled to determine if critical defects recorded on the historic inspection sheets were identified and rated accordingly. The bridge inspectors' comments and remarks recorded during the inspections provided valuable insights to the practicality and feasibility of the new inspection methodology.

The data on visual bridge inspections from the consulting engineering company were analysed. The cost and time components for large culverts, medium and large bridge asset classes recorded during the new inspections and the analysed data for traditional TMH 19 inspections were compiled for comparison.

The performance of the different CNN models was evaluated and the VGG16 Augmented model was selected as the best suited model to predict and classify bridge roadway joint defects.

# 5 DISCUSSION OF RESULTS

## 5.1 INTRODUCTION

In this chapter the comparison between the new inspection methodology and traditional TMH 19 inspections are discussed, based on the results and findings presented in Chapter 4. The performance of the CNN models is discussed as application for autonomous defect prediction and classification.

## 5.2 COMPARISON OF INSPECTION RATINGS

The two bridge inspectors were able to inspect and complete inspection sheets for two bridge structures using the new proposed inspection methodology. The inspectors only used the point cloud models and captured images during inspections.

The first bridge inspected was Bridge 1. Considering the new completed inspection sheets, the inspectors identified and rated nine different defects. All the defects recorded on the historic inspection sheet were identified and an additional five defects were captured. The additional defects captured include a spall on the wing wall, debris on the deck surface, guardrails missing for pier protection, missing abutment drainage, blocked drainage, a blocked joint, damaged gland of the claw joint and impact damage on the deck slab. The new defect ratings were similar compared to the historic ratings. The slight variance in the ratings was subjective to the different inspectors' interpretation of the defects. The inspectors were unable to inspect the abutment foundations, pier foundations and the bearings of the bridge. An image in the longitudinal direction of the bridge was required to confirm foundation settlement. Although full details of the abutment seating crack were unclear from the images, the inspectors were still able to identify the defect. The inspectors recommended an on-site inspection for further investigation as this defect was located on a critical element.

For the second structure the inspectors were more comfortable and accustomed to the new inspection methodology. Considering the new completed inspection sheets for Bridge 2, the inspectors were able to identify and rate six different defects. The inspectors were able to identify two of the six defects recorded on the historic inspection sheet and an additional four defects were captured. The additional defects captured include settlement of approach embankments, guardrails not attached to the end blocks, a joint in need of a new asphalt plug, faded clearance signs and the missing structure number. The defects not captured during the inspection were debris and vegetation in the waterway, a crack in the abutment wall, corroded handrails and a spall on a pier. The inspectors were able to inspect the waterway and handrails but did not record any defects. The inspectors were unable to determine the flow direction of the river. The inspectors were unable to identify the 0.2 mm vertical crack in the abutment wall and the spall on one of the piers, from the images. The new defect ratings for the scupper defect were similar compared to the historic ratings. There was a difference in the rating of the vegetation on road surface hiding the guardrail defect. The historic inspection sheet indicated a higher degree rating compared to the new inspections. The inspector on-site could have perceived the defect to be more hazardous than the inspectors' interpretations from the images. The inspectors were confident in the inspection and defect ratings and indicated an on-site inspection is not required.

Considering the new PCI values calculated for the two bridge structures, the structure conditions based on the new inspection ratings for Bridge 1 was categorised as "good" and "very good" for Bridge 2. The condition of Bridge 1 was historically categorised as "fair". The difference in the categories is due to the abutment seating crack which was rated higher during the traditional TMH 19 inspection. The defect is located on a critical structure element and had a higher priority weighting, contributing to the lower PCI value and condition category. Bridge 2 condition was historically categorised as "very good" and corresponded to the new inspection ratings condition categories.

## 5.3 COMPARISON OF COST AND TIME COMPONENTS

The cost and time components of the new inspection methodology and the traditional TMH 19 inspections were compared to determine if the new inspection methodology have cost or time saving benefits. The three structure asset classes used for comparison were large culverts, medium and large bridges. The total cost and duration of inspections for each asset class are summarised in Table 5-1.

**Table 5-1: Summary of the total cost and duration of inspections**

| | Culvert | Bridges | |
|---|---|---|---|
| | Large | Medium | Large |
| **New Inspection Methodology** | | | |
| Cost | R 12 406 | R 12 892 | R 13 925 |
| Duration | 2:30 | 2:40 | 3:30 |
| **Traditional TMH 19 Inspections** | | | |
| Cost | R 3 625 | R 5 476 | R 5 786 |
| Duration | 0:46 | 1:02 | 1:10 |

The analysis of the bridge inspection data for Western Cape calculated an average inspection cost of R 3 625 per large culvert, R 5 475 per medium bridge and R5 786 per large bridge. The duration of these inspections were 46 minutes, 62 minutes and 70 minutes, respectively.

The new inspection methodology had additional cost and time components compared to traditional TMH 19 inspections, including capturing of images and image processing. The cost and time components recorded during the study for the new inspection methodology estimated a cost of R12 406 for large culverts, R12 892 for medium bridges and R13 925 for large bridges. The total duration of the process for a medium bridge was two hours 40 minutes and for a large bridge three hours 30 minutes. Culverts were not included for new inspections and a conservative 30 minutes was use for inspections. The total duration for a large culvert inspection was estimated to be 2 hours 40 minutes.

The total duration of the new inspection methodology was longer than the duration of traditional TMH 19 inspections for all asset classes. Considering only the inspection components of the new inspection methodology, the duration of inspections using point cloud models and images were shorter for large culverts and medium bridges. The inspection duration of the large bridge was 5 minutes longer. This was the first bridge the inspectors inspected and they were still adjusting to the new methodology and software.

The overall cost calculated for the new inspection methodology is considerably higher compared to the traditional TMH 19 inspections for all asset classes. Capturing and processing the images were the largest cost component. The cost of the inspection components for the new methodology was significantly lower for all asset classes compared to the traditional TMH 19 inspections. The inspectors did not require a technical assistant for the new inspections and the duration of inspections were shorter for the large culvert and medium bridge.

Bridge inspection is still a relatively new application for UAVs in South Africa and as the demand increases to capture images of bridge structures for an entire road network, the cost could be reduced. Consulting engineering companies conducting bridge inspections could build internal capacity to capture and process images. Images could be preselected for processing to create point cloud models with less images and reduce the computation time.

## 5.4 AUTONOMOUS DEFECT DETECTION

The cost and time saving aspects of the new inspection methodology will depend on limiting the human involvement of inspections. Autonomous defect detection for bridge inspections will reduce the time spent on inspections and improve the quality and constancy of bridge inspections. This study focussed on using existing inspection and inventory image data to predict and classify bridge roadway joint defects autonomously. To compare the different CNN models the performance of each model was evaluated.

The first model developed was the Baseline model and had a maximum validation accuracy of 64%. Evaluating the validation loss, the baseline model was overfitting on the training data as the validation loss continued to increase for each epoch. These results were confirmed in the Confusion Matrix and Classification report.

For the second model an additional convolution layer was added to increase the complexity. The Complex CNN model had a maximum validation accuracy of 68%. The addition of a Drop Out layer and Early Stopping prevented the model from overfitting as indicated in the validation loss. Considering the Confusion Matrix and Classification report, the model performed better than the Baseline model in predicting the No Defect class but performed worse predicting the Defect class.

The third model utilised pretrained weights of the VGG16 transfer learning model. The model had a validation accuracy of 82%. The Drop Out layer and Early Stopping prevented the model from overfitting, confirmed in the validation loss results. The Confusion Matrix and Classification report indicated the performance of the model is balanced in predicting either the No Defect or Defect class.

For the final model, the validation and training datasets were augmented to increase the number of images. The VGG16 model was retrained with the larger dataset and had the best validation accuracy of 93% and lowest validation loss compared to the other models. The Confusion Matrix and Classification report indicated the model predicting the classes of the validation dataset with 95% precision for the Defect class and 92% for the No Defect class. The Augmented VGG16 model was selected as the best performing model for predicting whether a bridge roadway joint image had a defect or not.

To evaluate the model performance when introduced to unseen images, the test dataset containing 80 images of bridge roadway joints with defects and 40 images of non-defected bridge roadway joints, were fitted to the Augmented VGG16 model. The model classified 95% of the Defect images correctly and 65% of the No Defect images correctly.

Evaluating the different model performances indicates the positive effect techniques such as Drop Out, Early Stopping and data augmentation have on the performance of the model. The model validation accuracy increased from 64% to 93%. The need for larger datasets with more representative images is evident in the performance of the model when introduced to new unseen images.

## 5.5 SUMMARY

In this chapter the results of the study were discussed. The defect ratings of the new inspections were compared to the historic inspections and differences in the ratings were discussed. The bridge inspectors were able to identify and rate majority of the defects for the two bridges and could indicate if further on-site inspections were needed.

The cost and time components of the new inspection methodology and traditional TMH 19 inspections were compared. The new inspection methodology was more expensive and time consuming compared to traditional TMH 19 inspections for all the asset classes analysed.

The performance of the different CNN models was discussed. The results indicated the positive effect techniques such as Drop Out, Early Stopping and data augmentation had on the performance of the models. The need for larger datasets with more representative images to improve the performance of the models were identified. The Augmented VGG16 model were able to classify 95% of the Defect roadway joint images correctly and 65% of the No Defect images correctly.

# 6 CONCLUSIONS AND RECOMMENDATIONS

## 6.1 CONCLUSIONS

Based on the results the following could be concluded from the study and is discussed in more detail in the subsequent sections:

- Visual bridge inspections can be performed using only point cloud models and images as a proposed new inspection methodology;
- The proposed new inspection methodology did not prove to have cost- or time-saving benefits, and
- It is possible to detect and classify bridge defects autonomously, using existing image data and applying deep learning and computer vision techniques, if large datasets are available.

### 6.1.1 New inspection methodology

The new inspection methodology has the potential to be a practical alternative or form part of traditional TMH 19 inspections in the future. Visual bridge inspections can be performed using only point cloud models and images. The inspectors were able to inspect structures and identify critical defects using the new inspection methodology. The point cloud models and captured images provided sufficient detail for inspectors to confidently inspect the majority of the bridge structure elements and rate defects accordingly.

The inspectors were able to identify the majority of the defects recorded on the historic inspection sheets of the bridge structures and capture additional defects. Defects such as a small crack and spall, were omitted in the inspections. The inspectors were unable to inspect the pier foundations, abutment foundations and bearings. These limitations of the new inspection methodology could be improved by additional training of the UAV pilot to capture images of the bridge from a closer distance and to focus on critical bridge elements. In conclusion the inspectors were able to recommend whether the structure required further on-site inspection or not.

The new inspection methodology could be used as a screening process for principal visual bridge inspections. Structures could be inspected using point cloud models and images and identify critical structures requiring further on-site inspection. This could reduce the number of structures inspectors have to physically inspect and only focus on the critical bridge elements on-site. The screening process could be performed by less experienced accredited bridge inspectors and accredited senior bridge inspectors could perform quality control of the inspections.

The new inspection methodology enables bridge inspectors to reassess a bridge, without having to schedule an on-site inspection. The bridge defects could be discussed with peers for different perspectives and provide addition input if required.

Bridge inspectors often prefer capturing inspections on paper-based inspection sheets due to security risks on-site and inspection data needs to be recaptured manually in the BMS. Using the new inspection methodology, inspection data can be captured electronically and automatically linked to the BMS.

Point cloud models could be incorporated into a BMS. Basic inventory information could be generated from the models such as number of spans, location and measurements. Data captured in the BMS could be verified using the point cloud models for quality control. The point cloud models provide additional information such as context of where defects are located on the structure. Information could be presented more graphically compared to traditional databases and improve data management.

### 6.1.2 Cost- and time-saving benefits

The new inspection methodology did not have cost or time saving benefits considering the total cost and duration, compared to traditional TMH 19 inspections. However, the inspection component of the new inspection methodology has potential cost and time saving benefits. Inspections from point cloud models and images could be performed faster compared to the traditional TMH 19 inspections if the inspector is comfortable and accustomed to the new inspection methodology. The new inspection methodology does not require a technical assistant and inspections could be performed off-site. Bridge inspectors do not have to travel between structures and could inspect more structures per day.

Bridge inspection is still a relatively new application for UAVs in South Africa and as the demand increases to capture images of bridge structures for an entire road network, the cost could be reduced. Consulting engineering companies conducting bridge inspections could build internal capacity to capture and process images. Images could be preselected for processing to create point cloud models with less images and reduce the computation time.

Bridge inspections for strategic bridges require an Under Bridge Inspection Unit (UBIU). Strategic bridges have restricted access due to the height and size of the structure or if located over a river. The new methodology could replace the use of an UBIU and capture images with an UAV, reducing the cost of strategic inspections and ensure the safety of bridge inspectors.

### 6.1.3 Autonomous defect detection

The new inspection methodology will have cost and time saving benefits if human involvement could be limited. It is possible to detect and classify bridge defects autonomously, using existing image data and applying deep learning and computer vision techniques, if large datasets are available.

Different CNN models were developed to predict whether an image of a bridge roadway joint had a defect or not. The best performing model, VGG16 Augmented model, could predict with 95% accuracy if an image had a defect and with 65% accuracy if an image had no defect.

The model can only predict the class of an images based on the data used during training. The original dataset was relatively small to develop an accurate CNN model. Transfer learning and data augmentation improved the performance, but more representative images are required to increase the accuracy of the model when predicting classes of unseen data, especially for the No Defect class.

## 6.2 RECOMMENDATIONS

The new inspection methodology proved to be valuable in concept but has limitations in practice. With the rapid evolvement of technology, these limitations promise to be a possibility in the near future.

The inspectors' comments and remarks captured during this study should be considered to improve the methodology. Images should be captured at a closer distance to the bridge structure. The UAV pilot should receive additional training to focus on critical bridge elements and to ensure sufficient images are captured during the UAV flight path. The addition of light to the UAV should be investigated to improve the quality of images captured in the shadow part of the bridge. Additional tools and features could be developed for software to improve the navigation of point cloud models. Functions such as labelling of defects and measuring dimensions could enhance the inspector's interactive experience during the inspections.

Although the new proposed inspection methodology is more reliant on the quality of the images than the point cloud models, improving the quality of the point cloud models could be considered. This include investigating different image processing techniques and the use of different photogrammetry software.  A suitable ground sampling distance (GSD) and the overlapping rate of images influencing the flight time could also be considered.

The storage of data and images also needs consideration. Currently, the STRUMAN BMS makes provision for 17 typical inventory images and the number of defect images captured during an inspection, as prescribed in TMH 19. The point cloud models that were created comprised approximately 450 images for the large bridge structures and 350 images for the medium bridge structures. If image data to create point cloud models are captured for an entire network of structures, the images will need to be stored on cloud-based platforms. Preselecting images to create point cloud models with fewer images could potentially reduce the required storage space and computation time to process the images.

The new inspection methodology proved to be more expensive compared to traditional TMH 19 inspections. Specific use cases for the new inspection methodology should be identified, such as inspections for strategic bridges requiring an UBIU.

The VGG16 Augmented CNN model developed could be improved by increasing the dataset with more representative images. Different transfer learning models could be explored to better fit the requirements of the dataset. The individual layers in the CNN of the VGG16 Augmented model could be investigated to ensure the correct features are extracted from the image and could be adjusted accordingly.

The model could be further developed by introducing more classes for different rated defects. Experienced bridge inspectors could assist in defining these classes, ensuring consistent defect ratings. The model could then be used to predict the ratings of defects and not be depended on human subjectivity.

Different CNN models could be developed for each bridge element and incorporated in the new inspection methodology to identify and predict defect ratings based on the images captured using a UAV, advancing into complete autonomous defect detection and rating.

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# APPENDIX A

Print Date: 2021/07/07 10:47:11

## STRUMAN Bridge and Structure Management System

**Inspection Sheet - Structure: D631_01N_B4435 - RAILWAY BRIDGE**

### Inspection Sheet_TMH19

| Authority | Structure Type | Structure Number |
|---|---|---|
| **Gauteng** | **Bridge** | D631_01N_B4435 |
| | | **Structure Name** |
| | | RAILWAY BRIDGE |

**Inspection Information**

| Inspection Type | Inspector Name | Firm | Date |
|---|---|---|---|
| Principal | K Dahlgren | J&G | 2016/03/07 |

**GPS Coordinates**

| Latitude (South) | | | Longitude (East) | | |
|---|---|---|---|---|---|
| DD | MM | SS.s | DD | MM | SS.s |
| -25.854 | -25 | | 28.5192 | 28 | |

**Vertical Clearances**

| | | | | |
|---|---|---|---|---|
| Position/Span No | South Bound Carriage Way | | | |
| Minimum Height (m) | 5.37 | | | |

**Location Details**

| Road No. | Section No. | Route km | Other Structure No. | N Route Over/Under |
|---|---|---|---|---|
| D631 | 01N | 17.00 | D631_01N_IDB1641 | Under |

**Structure Information**

| No of spans | Bridge orientation | Overall length | Angle of skew | Year constructed | Bridge Type |
|---|---|---|---|---|---|
| 3 | East/West | 50.82 | | 1983 | Continuous |

**Inspection Ratings**

**General Items**

| | | D | E | R |
|---|---|---|---|---|
| 01. Approach Embankment | A1 | 0 | - | - |
| 01. Approach Embankment | A2 | 0 | - | - |
| 02. Guardrail | | X | - | - |
| 03. Waterway | | X | - | - |
| 04. Approach Embankment Protection Works | A1 | 0 | - | - |
| 04. Approach Embankment Protection Works | A2 | 1 | 1 | 1 |
| 05. Abutment Foundations | A1 | 0 | - | - |
| 05. Abutment Foundations | A2 | 0 | - | - |
| 06. Abutments | A1 | 3 | 1 | 3 |
| 06. Abutments | A2 | 3 | 1 | 3 |
| 07. Wing/ Retaining Walls | A1 | 0 | - | - |
| 07. Wing/ Retaining Walls | A2 | 0 | - | - |
| 08. Surfacing | | 0 | - | - |
| 09. Superstructure Drainage | | X | - | - |
| 10. Kerbs / Sidewalks | | X | - | - |
| 11. Parapet | | 0 | - | - |
| 21. Miscellaneous Items | | X | - | - |

**Pier Items**

| | | D | E | R |
|---|---|---|---|---|
| 12. Pier Protection Works | P1 | X | - | - |
| 12. Pier Protection Works | P2 | X | - | - |
| 13. Pier Foundations | P1 | 0 | - | - |
| 13. Pier Foundations | P2 | 0 | - | - |
| 14. Piers & Columns | P1 | 0 | - | - |
| 14. Piers & Columns | P2 | 0 | - | - |

**Other Support Items**

| | | D | E | R |
|---|---|---|---|---|
| 15. Bearings | A1 | 0 | - | - |
| 15. Bearings | A2 | 0 | - | - |
| 15. Bearings | P1 | 0 | - | - |
| 15. Bearings | P2 | 0 | - | - |
| 16. Support Drainage | A1 | X | - | - |
| 16. Support Drainage | A2 | X | - | - |
| 16. Support Drainage | P1 | X | - | - |
| 16. Support Drainage | P2 | X | - | - |
| 17. Expansion Joints | A1 | 0 | - | - |
| 17. Expansion Joints | A2 | 0 | - | - |
| 17. Expansion Joints | P1 | X | - | - |
| 17. Expansion Joints | P2 | X | - | - |

**Span Items**

| | | D | E | R |
|---|---|---|---|---|
| 18. Longitudinal Members | S1 | X | - | - |
| 18. Longitudinal Members | S2 | X | - | - |
| 18. Longitudinal Members | S3 | X | - | - |
| 19. Transverse Members | S1 | X | - | - |
| 19. Transverse Members | S2 | X | - | - |
| 19. Transverse Members | S3 | X | - | - |
| 20. Decks and Slabs | S1 | 0 | - | - |
| 20. Decks and Slabs | S2 | 0 | - | - |
| 20. Decks and Slabs | S3 | 0 | - | - |

**Remedial Work**

| | Inspection Item | Position | Activity | Qty | Unit | Urg | MS | Remarks | MF | Photos |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 06. Abutments | BU | 120. Seal cracks | 3 | m | 3 | N | Bearing close to edge | | S03 |
| 2 | 04. Approach Embankment Protection Works | U2 | 401. Apply weed killer/ant poison and remove growth | 20 | m2 | 1 | N | Vegetation protection works | | S02 |
| 3 | 04. Approach Embankment Protection Works | U2 | 160. Interlocking blocks | 5 | m2 | 1 | N | Missing / stolen interlocking blocks | | S01 |

**Inspector's assessment of structure condition and further comments**

| | | |
|---|---|---|
| Inspector's Comments | Good condition | |
| Further inspection needed ? | N | If further inspection required, indicate special requirements: |
| UBIU used ? | N | |
| UBIU needed ? | N | |

| D -DEGREE | | | | | | | E - EXTENT | | | | R - RELEVANCY | | | | U - URGENCY | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NA | UA Insp | None | Minor | Fair | Poor | Severe | Local | >Local | <Gnl | General | Min | Moderate | Major | Critical | Record | Monitor | Routine | <10 yrs | <5 yrs | ASAP |
| X | U | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | R | 0 | 1 | 2 | 3 | 4 |

( 501310240645151644151810 ) : D631_01N_B4435 - RAILWAY BRIDGE

Page 1 of 1

Print Date: 2021/07/07 11:53:31

## STRUMAN Bridge and Structure Management System

**Inspection Sheet - Structure: D631_01N_B4095 - BOSCHKOP RIVER BRIDGE**

**Inspection Sheet_TMH19**

| Authority | Structure Type | Structure Number |
|---|---|---|
| Gauteng | Bridge | D631_01N_B4095 |
| | | **Structure Name** |
| | | BOSCHKOP RIVER BRIDGE |

**Inspection Information**

| Inspection Type | Inspector Name | Firm | Date |
|---|---|---|---|
| Principal | K Dahlgren | J&G | 2016/03/07 |

**GPS Coordinates**

| Latitude (South) | | | Longitude (East) | | |
|---|---|---|---|---|---|
| DD | MM | SS.s | DD | MM | SS.s |
| -25.8634 | -25 | | 28.4768 | 28 | |

**Vertical Clearances**

| | | | | |
|---|---|---|---|---|
| Position/Span No | | | | |
| Minimum Height (m) | | | | |

**Location Details**

| Road No. | Section No. | Route km | Other Structure No. | N Route Over/Under |
|---|---|---|---|---|
| D631 | 01N | 12.50 | D631_01N_IDB1642 | Over |

**Structure Information**

| No of spans | Bridge orientation | Overall length | Angle of skew | Year constructed | Bridge Type |
|---|---|---|---|---|---|
| 3 | North/South | 27.15 | 0 | 1979 | Simply supported |

**Inspection Ratings**

**General Items**

| Item | Pos | D | E | R |
|---|---|---|---|---|
| 01. Approach Embankment | A1 | 0 | - | - |
| | A2 | 0 | - | - |
| 02. Guardrail | | 0 | - | - |
| 03. Waterway | | 2 | 2 | 2 |
| 04. Approach Embankment Protection Works | A1 | X | - | - |
| | A2 | X | - | - |
| 05. Abutment Foundations | A1 | 0 | - | - |
| | A2 | 0 | - | - |
| 06. Abutments | A1 | 1 | 1 | 1 |
| | A2 | 0 | - | - |
| 07. Wing/ Retaining Walls | A1 | 0 | - | - |
| | A2 | 0 | - | - |
| 08. Surfacing | | 3 | 3 | 2 |
| 09. Superstructure Drainage | | 2 | 4 | 1 |
| 10. Kerbs / Sidewalks | | 0 | - | - |
| 11. Parapet | | 2 | 4 | 1 |
| 21. Miscellaneous Items | | X | - | - |

**Pier Items**

| | 12. Pier Protection Works | | | 13. Pier Foundations | | | 14. Piers & Columns | | |
|---|---|---|---|---|---|---|---|---|---|
| | D | E | R | D | E | R | D | E | R |
| P1 | X | - | - | 0 | - | - | 1 | 2 | 1 |
| P2 | X | - | - | 0 | - | - | 1 | 2 | 1 |

**Other Support Items**

| | 15. Bearings | | | 16. Support Drainage | | | 17. Expansion Joints | | |
|---|---|---|---|---|---|---|---|---|---|
| | D | E | R | D | E | R | D | E | R |
| A1 | X | - | - | X | - | - | 0 | - | - |
| A2 | X | - | - | X | - | - | 0 | - | - |
| P1 | X | - | - | X | - | - | 0 | - | - |
| P2 | X | - | - | X | - | - | 0 | - | - |

**Span Items**

| | 18. Longitudinal Members | | | 19. Transverse Members | | | 20. Decks and Slabs | | |
|---|---|---|---|---|---|---|---|---|---|
| | D | E | R | D | E | R | D | E | R |
| S1 | X | - | - | X | - | - | 0 | - | - |
| S2 | X | - | - | X | - | - | 0 | - | - |
| S3 | X | - | - | X | - | - | 0 | - | - |

**Remedial Work**

| | Inspection Item | Position | Activity | Qty | Unit | Urg | MS | Remarks | MF | Photos |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14. Piers & Columns | AP | 118. Repair spall (including honeycombing) | 10 | L | 2 | N | Minor spall | | |
| 2 | 11. Parapet | AS | 459. Paint steel rails | 20 | m2 | 1 | N | Flaking paint | | |
| 3 | 09. Superstructure Drainage | AS | 353. Extend scupper below deck soffit | 6 | No | 1 | N | Staining surface | | |
| 4 | 08. Surfacing | BU | 207. Clear debris | 6 | m3 | 2 | N | Vegetation along guardrail | | |
| 5 | 03. Waterway | S1 | 207. Clear debris | 4 | m3 | 1 | N | Minor debris | | |
| 6 | 06. Abutments | U1 | 120. Seal cracks | 3 | m | 1 | N | Vertical 0.2mm crack | | |

**Inspector's assessment of structure condition and further comments**

| | | |
|---|---|---|
| Inspector's Comments | Good condition | |
| Further inspection needed ? | N | If further inspection required, indicate special requirements: |
| UBIU used ? | N | |
| UBIU needed ? | N | |

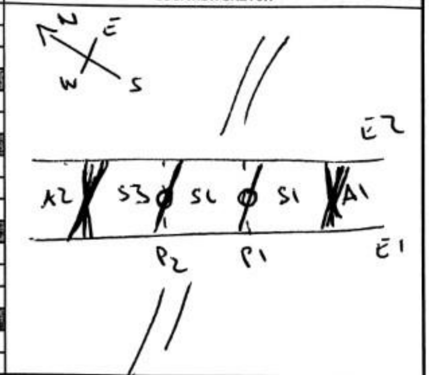
| D -DEGREE | | | | | | | E - EXTENT | | | | R - RELEVANCY | | | | U - URGENCY | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NA | UA Insp | None | Minor | Fair | Poor | Severe | Local | >Local | <Gnl | General | Min | Moderate | Major | Critical | Record | Monitor | Routine | <10 yrs | <5 yrs | ASAP |
| X | U | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | R | 0 | 1 | 2 | 3 | 4 |

# APPENDIX B

Start = 9:36 Say 1415 hrs
END = 11:12

4435

| ROAD AUTHORITY | STRUCTURE TYPE | BRIDGE NUMBER | LOCATION SKETCH |
|---|---|---|---|
| | BRIDGE - GENERAL | Bridge 1 | |
| | | BRIDGE NAME | |




**INSPECTION INFORMATION**

| Inspection Type | Inspector Name | Firm | Date (dd/mm/yyyy) |
|---|---|---|---|
| | Cotter | | |

**GPS COORDINATES - START**

| Latitude (South) DD | MM | SS.s | Longitude (East) DD | MM | SS.s |
|---|---|---|---|---|---|
| | | | | | |

**GPS COORDINATES - END**

| Latitude (South) DD | MM | SS.s | Longitude (East) DD | MM | SS.s |
|---|---|---|---|---|---|
| | | | | | |

**VERTICAL CLEARANCES (road over road bridges only)**

| Position/Span No | | | | | | |
|---|---|---|---|---|---|---|
| Min height (m) | | | | | | |

**LOCATION DETAIL**

| Road No. | Road km | Road Name | Feature Crossed | Feature Name/Road No. | Region/Depot |
|---|---|---|---|---|---|
| | | | | | |

**STRUCTURE INFORMATION**

| No. of Spans | Structure Orientation | Overall Length | Overall Width | Year Constructed | Bridge Type |
|---|---|---|---|---|---|
| 3 | NW | — | — | | |

**INSPECTION RATINGS**

| INSPECTION ITEM | | 1. Approach Embankment D | E | R | 2. Guardrail D | E | R | 3. Waterway D | E | R | 4. Approach Emb. Prot Works D | E | R | 5. Abutment Foundations D | E | R | 6. Abutments D | E | R | 7. Wing / Retaining Walls D | E | R | 8. Surfacing D | E | R | 9. Super-Struct. Drainage D | E | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abut | 1 | ~~2~~ | ~~2~~ | 2 | | | | | | | 2 | 2 | 2 | u | | | 1 | 2 | 1 | 0 | | | | | | | | |
| Abut | 2 | ~~1~~ | ~~2~~ | 1 | | | | | | | 1 | 2 | 1 | u | | | 1 | 2 | 1 | 1 | 1 | 1 | | | | | | |
| | | 0 | | | X | | | X | | | | | | | | | | | | | | | X | | | 0 | | |

| INSPECTION ITEM | 10. Kerbs / Sidewalks D | E | R | 11. Parapet / Handrail D | E | R | 21. Misc. Items D | E | R |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 0 | | | 0 | | |

| INSPECTION ITEM | | 12. Pier Protection Works D | E | R | 13. Pier Foundations D | E | R | 14. Piers & Columns D | E | R | 15. Bearings D | E | R | 16. Support Drainage D | E | R | 17. Expansion Joints D | E | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abut | 1 | | | | | | | | | | u | | | 2 | 3 | 2 | 3 | 3 | 2 |
| Abut | 2 | | | | | | | | | | u | | | 2 | 3 | 2 | 3 | 3 | 2 |
| Pier | 1 | 3 | 4 | 3 | u | | | 0 | | | u | | | X | | | | | |
| Pier | 2 | X3 | 4 | 3 | u | | | 0 | | | u | | | X | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |

| INSPECTION ITEM (Position) | | 18. Longitudinal Member D | E | R | 19. Transversal Members D | E | R | 20. Deck Slab D | E | R |
|---|---|---|---|---|---|---|---|---|---|---|
| Span | 1 | X | | | X | | | 0 | | |
| Span | 2 | X | | | X | | | 2 | 1 | 1 |
| Span | 3 | X | | | X | | | 0 | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |

| ITEM | POSITION | ACTIVITY CODE or DESCRIPTION | QTY | Unit | U | Make safe | REMARKS | Rpt Photo | Mon freq |
|---|---|---|---|---|---|---|---|---|---|
| 4 | A1 | ~~407~~ 401 | | | 1 | | Clear vegetation weed killer | | |
| 4 | A2 | 160 | | | 1 | | Repair protection works | | |
| 4 | A2 | 155 | | | 1 | | Backfill erosion | | |
| 6 | A1 | 120 | | | 0 | | Possible splitting crack on abut. beam. | | |
| 7 | A2 | ~~120~~ 118 | | | 3 | | Deck compression due to lack of exp. joint size | | |
| 16 | A1 | 205 | | | 3 | | Missing abut. drainage | | |
| 16 | A2 | 205 | | | 3 | | Blocked drainage | | |

Inspector's assessment and further comments: General condition good.

| FURTHER INSPECTION REQUIRED ? Y/N | Y | IF FURTHER INSPECTION REQUIRED IS "Y" Then please indicate any special requirements ie. 6m Ladder, Bush cutting, UBIU, better weather etc. If nothing please state "none" | Abut bearing seat to be inspected closer |
|---|---|---|---|
| Was UBIU used ? Y/N | | | |
| Is the UBIU needed for future inspections? Y/N | | | |

| D - DEGREE | | | | | | | E - EXTENT | | | | R - RELEVANCY | | | | R | | U - URGENCY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not Applicable | Unable to inspect | None | Minor | Moderate | Warning | Severe | Local | More than local | Less than general | General | Min | Moderate | Major | Critical | Record only | Monitor only | Routine | < 10 yrs | < 5 yrs | ASAP |
| X | U | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | R | 0 | 1 | 2 | 3 | 4 |

| | | | | |
|---|---|---|---|---|
| 17 | BA | 315 | 3 | Damaged armd element to be replaced. |
| 20 | S2 | 118 | R | Deck impact damaged. |
| 10 | A3 | 207 | 1 | Clean deck surface. |

09:35 — 11:12 | 1hr 15min

| ROAD AUTHORITY | STRUCTURE TYPE | BRIDGE NUMBER |
|---|---|---|
| | **BRIDGE - GENERAL** | B1 |
| | | BRIDGE NAME |
| | | 4435 |

**INSPECTION INFORMATION**

| Inspection Type | Inspector Name | Firm | Date (dd/mm/yyyy) |
|---|---|---|---|
| PI | G. Visser | CHDHN | 10/09/2021 |

**GPS COORDINATES - START**

| Latitude (South) DD | MM | SS.s | Longitude (East) DD | MM | SS.s |
|---|---|---|---|---|---|
| | | | | | |

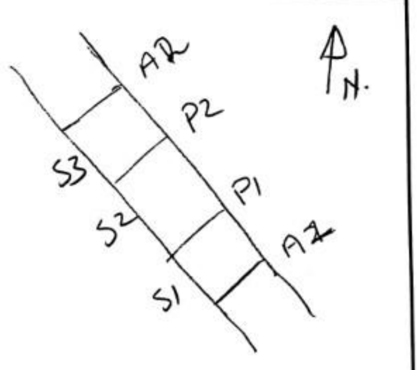
**GPS COORDINATES - END**

| Latitude (South) DD | MM | SS.s | Longitude (East) DD | MM | SS.s |
|---|---|---|---|---|---|
| | | | | | |

**VERTICAL CLEARANCES (road-over-road bridges only)**

| Position/Span No | | | | | | |
|---|---|---|---|---|---|---|
| Min height (m) | | | | | | |

**LOCATION SKETCH**




**LOCATION DETAIL**

| Road No. | Road km | Road Name | Feature Crossed | Feature Name/Road No. | Region/Depot |
|---|---|---|---|---|---|
| | | | | | |

**STRUCTURE INFORMATION**

| No. of Spans | Structure Orientation | Overall Length | Overall Width | Year Constructed | Bridge Type |
|---|---|---|---|---|---|
| 3 | NW | | | | |

**INSPECTION RATINGS**

| INSPECTION ITEM | | 1. APPROACH EMBANKMENT | | | 2. GUARDRAIL | | | 3. WATERWAY | | | 4. APPROACH EMB. PROT WORKS | | | 5. ABUTMENT FOUNDATIONS | | | 6. ABUTMENTS | | | 7. WING / RETAINING WALLS | | | 8. SURFACING | | | 9. SUPER-STRUCT. DRAINAGE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| POSITION | | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R |
| Abut | A1 | 2 | 1 | 1 | | | | | | | 0 | | | 4 | | | 1 | 1 | 1 | 0 | | | | | | | | |
| Abut | A2 | 1 | 2 | 1 | | | | | | | 0 | | | 4 | | | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | | X | | | X | | | | | | | | | | | | | | | X | | | 0 | | |

| INSPECTION ITEM | 10. KERBS / SIDEWALKS | | | 11. PARAPET / HANDRAIL | | | 21. MISC. ITEMS | | |
|---|---|---|---|---|---|---|---|---|---|
| | D | E | R | D | E | R | D | E | R |
| | 1 | 1 | 1 | 0 | | | X | | |

| INSPECTION ITEM | | 12. PIER PROTECTION WORKS | | | 13. PIER FOUNDATIONS | | | 14. PIERS & COLUMNS | | | 15. BEARINGS | | | 16. SUPPORT DRAINAGE | | | 17. EXPANSION JOINTS | | | INSPECTION ITEM | | 18. LONGITUDINAL MEMBER | | | 19. TRANSVERSAL MEMBERS | | | 20. DECK SLAB | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| POSITION | | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | POSITION | | D | E | R | D | E | R | D | E | R |
| Abut | 1 | | | | | | | | | | 4 | | | 3 | 4 | 2 | 3 | 4 | 2 | Span | 1 | X | | | X | | | 0 | | |
| Abut | 2 | | | | | | | | | | 4 | | | 3 | 4 | 2 | 3 | 4 | 2 | Span | 2 | X | | | X | | | 1 | 1 | 1 |
| Pier | 1 | 2 | 4 | 3 | 4 | | | 0 | | | 4 | | | 0 | | | X | | | Span | 3 | X | | | X | | | 0 | | |
| Pier | 2 | 2 | 4 | 3 | 4 | | | 0 | | | 4 | | | 0 | | | X | | | Span | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | | Span | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | | Span | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | | Span | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | | Span | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | | Span | | | | | | | | | | |

| ITEM | POSITION | ACTIVITY CODE or DESCRIPTION | QTY | Unit | U | Make safe | REMARKS | Rpt. Photo | Mon freq |
|---|---|---|---|---|---|---|---|---|---|
| 1. | A1 | 401: Prey weed killer | | m² | 0 | | | | |
| 1. | A2 | 160: Repair stone pitching | | m² | 1 | | | | |
| 1. | A2. | 155: Backfill erosion | | | 1 | | | | |
| 6 | A1. | 120: Seal cracks | | | 1 | | | | |
| 6. | A1 | 103: Clean concrete surface | | | | | | | |
| 6 | A2 | 103: Clean concrete surface | | | | | | | |
| 7. | A2 | 118: Repair spall | | | | | Re-instate gap (EJ) | | |
| 12. | AP | 460: Provide guardrails | | | | | | | |
| 16 | BA | 205: Clear blocked drainage | | | | | | | |
| 17 | BA. | 208: Clean joint | | | | | | | |
| 17. | BA. | 315: Replace glands of clampout | | | | | | | |
| 20. | S1 | 118: Repair spall | | | R | | Impact damage. | | |

Inspector's assessment and further comments: The cracks in the Abutment capping beam to be investigated further.

The structure is generally in a good condition

| FURTHER INSPECTION REQUIRED ? Y/N | Y | IF FURTHER INSPECTION REQUIRED IS "Y" Then please indicate any special requirements ie. 6m Ladder, Bush cutting, UBIU, better weather etc. If nothing please state "none" | |
|---|---|---|---|
| Was UBIU used ? Y/N | | | |
| Is the UBIU needed for future inspections? Y/N | | | |

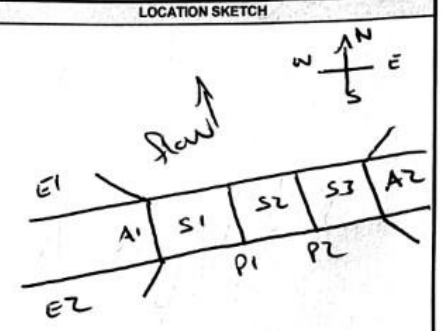
| D - DEGREE | | | | | | | E - EXTENT | | | | R - RELEVANCY | | | | U - URGENCY | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not Applicable | Unable to Inspect | None | Minor | Moderate | Warning | Severe | Local | More than local | Less than general | General | Min | Moderate | Major | Critical | Record only | Monitor only | Routine | < 10 yrs | < 5 yrs | ASAP |
| X | U | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | R | 0 | 1 | 2 | 3 | 4 |

10 AS 207. Clear debris R.

START 11:44
END 12:20 35 min.

| ROAD AUTHORITY | STRUCTURE TYPE | BRIDGE NUMBER |
|---|---|---|
| | BRIDGE - GENERAL | Bridge 2 |
| | | BRIDGE NAME |

LOCATION SKETCH




**INSPECTION INFORMATION**

| Inspection Type | Inspector Name | Firm | Date (dd/mm/yyyy) |
|---|---|---|---|
| | Cotter | | 10/9/2021 |

**GPS COORDINATES - START**

| Latitude (South) | | | Longitude (East) | | |
|---|---|---|---|---|---|
| DD | MM | SS.s | DD | MM | SS.s |
| | | | | | |

**GPS COORDINATES - END**

| Latitude (South) | | | Longitude (East) | | |
|---|---|---|---|---|---|
| DD | MM | SS.s | DD | MM | SS.s |
| | | | | | |

**VERTICAL CLEARANCES (road-over-road bridges only)**

| | | | | | | |
|---|---|---|---|---|---|---|
| Position/Span No | | | | | | |
| Min height (m) | | | | | | |

**LOCATION DETAILS**

| Road No. | Road km | Road Name | Feature Crossed | Feature Name/Road No. | Region/Depot |
|---|---|---|---|---|---|
| | | | | | |

**STRUCTURE INFORMATION**

| No. of Spans | Structure Orientation | Overall Length | Overall Width | Year Constructed | Bridge Type |
|---|---|---|---|---|---|
| 3 | WE | | | | |

**INSPECTION RATINGS**

| INSPECTION ITEM | | 1. APPROACH EMBANKMENT | | | 2. GUARDRAIL | | | 3. WATERWAY | | | 4. APPROACH EMB. PROT WORKS | | | 5. ABUTMENT FOUNDATIONS | | | 6. ABUTMENTS | | | 7. WING / RETAINING WALLS | | | 8. SURFACING | | | 9. SUPER-STRUCT. DRAINAGE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| POSITION | | 2 D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R |
| Abut | 1 | 0 | 3 | 2 | | | | | | | X | | | 0 | | | 0 | | | 0 | | | | | | | | |
| Abut | 2 | 0 | 3 | 2 | | | | | | | X | | | 0 | | | 0 | | | 0 | | | | | | | | |
| | | 2 | | | 3 | 4 | 3 | 0 | | | | | | | | | | | | | | | 0 | | | 2 | 4 | 2 |

1 2 1

| INSPECTION ITEM | 10. KERBS / SIDEWALKS | | | 11. PARAPET / HANDRAIL | | | 21. MISC. ITEMS | | |
|---|---|---|---|---|---|---|---|---|---|
| | D | E | R | D | E | R | D | E | R |
| | 0 | | | 0 | | | | | |

| INSPECTION ITEM | | 12. PIER PROTECTION WORKS | | | 13. PIER FOUNDATIONS | | | 14. PIERS & COLUMNS | | | 15. BEARINGS | | | 16. SUPPORT DRAINAGE | | | 17. EXPANSION JOINTS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| POSITION | | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R | D | E | R |
| Abut | 1 | | | | | | | | | | 0 | | | X | | | 2 | 4 | 1 |
| Abut | 2 | | | | | | | | | | 0 | | | X | | | 2 | 4 | 1 |
| Pier | 1 | X | | | 0 | | | 0 | | | 0 | | | X | | | 0 | | |
| Pier | 2 | X | | | 0 | | | 0 | | | 0 | | | X | | | 0 | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |

| INSPECTION ITEM | | 18. LONGITUDINAL MEMBER | | | 19. TRANSVERSAL MEMBERS | | | 20. DECK SLAB | | |
|---|---|---|---|---|---|---|---|---|---|---|
| POSITION | | D | E | R | D | E | R | D | E | R |
| Span | 1 | X | | | X | | | 0 | | |
| Span | 2 | X | | | X | | | 0 | | |
| Span | 3 | X | | | X | | | 0 | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |

| ITEM | POSITION | ACTIVITY CODE or DESCRIPTION | QTY | Unit | U | Make safe | REMARKS | Rpt. Photo | Mon freq |
|---|---|---|---|---|---|---|---|---|---|
| 2 | BA | 451 | | | 3 | | Attach guardrail to end blocks. | | |
| 1 | BA | 504 | | | 3 | | Possible approach settlement. | | |
| 9 | AS | 208 | | | 3 | | Clear scuppers | | |
| 9 | AS | 353 | | | 3 | | Extend scuppers. | | |
| 8 | AS | 207 | | | 1 | | Clear sand on deck | | |
| 17 | BA | 306 | | | 3 | | Install thorma joint with approach slab. | | |
| 21 | BA | 604 | 4 | NO | 1 | | Replace faded clearance signs. | | |

Inspector's assessment and further comments:

General condition good.

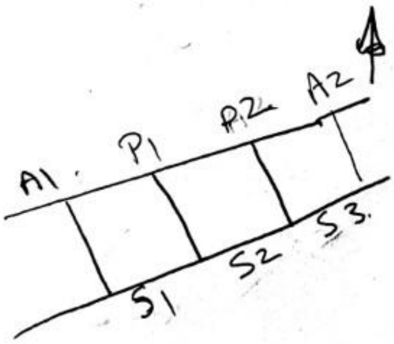
| | | IF FURTHER INSPECTION REQUIRED IS "Y" |
|---|---|---|
| FURTHER INSPECTION REQUIRED ? Y/N | N | Then please indicate any special requirements |
| Was UBIU used ? Y/N | N | ie. 6m Ladder, Bush cutting, UBIU, better weather etc. |
| Is the UBIU needed for future inspections? Y/N | N | If nothing please state "none" |

| D - DEGREE | | | | | | | E - EXTENT | | | | R - RELEVANCY | | | | U - URGENCY | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not Applicable | Unable to Inspect | None | Minor | Moderate | Warning | Severe | Local | More than local | Less than general | General | Min | Moderate | Major | Critical | Record only | Monitor only | Routine | < 10 yrs | < 5 yrs | ASAP |
| X | U | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | R | 0 | 1 | 2 | 3 | 4 |

11:45 – 12:20.

| ROAD AUTHORITY | STRUCTURE TYPE | BRIDGE NUMBER |
|---|---|---|
| | BRIDGE - GENERAL | |
| | | BRIDGE NAME |
| | | |

LOCATION SKETCH




**INSPECTION INFORMATION**

| Inspection Type | Inspector Name | Firm | Date (dd/mm/yyyy) |
|---|---|---|---|
| PI | G.Visser | RHDHV | 10/09/2021 |

**GPS COORDINATES - START**

| Latitude (South) DD | MM | SS.s | Longitude (East) DD | MM | SS.s |
|---|---|---|---|---|---|
| | | | | | |

**GPS COORDINATES - END**

| Latitude (South) DD | MM | SS.s | Longitude (East) DD | MM | SS.s |
|---|---|---|---|---|---|
| | | | | | |

**VERTICAL CLEARANCES**

| Position/Span No | | | | | | |
|---|---|---|---|---|---|---|
| Min height (m) | | | | | | |

**LOCATION DETAIL**

| Road No. | Road km | Road Name | Feature Crossed | Feature Name/Road No. | Region/Depot |
|---|---|---|---|---|---|
| | | | | | |

**STRUCTURE INFORMATION**

| No. of Spans | Structure Orientation | Overall Length | Overall Width | Year Constructed | Bridge Type | |
|---|---|---|---|---|---|---|
| 3 | W/E | | | | | |

**INSPECTION RATINGS**

| INSPECTION ITEM | | 1. APPROACH EMBANKMENT D | E | R | 2. GUARDRAIL D | E | R | 3. WATERWAY D | E | R | 4. APPROACH EMB. PROT WORKS D | E | R | 5. ABUTMENT FOUNDATIONS D | E | R | 6. ABUTMENTS D | E | R | 7. WING / RETAINING WALLS D | E | R | 8. SURFACING D | E | R | 9. SUPERSTRUCT DRAINAGE D | E | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abut | 1 | 1 | 1 | 1 | | | | | | | X | | | 0 | | | 0 | | | 0 | | | | | | | | |
| Abut | 2 | 1 | 1 | 1 | | | | | | | X | | | 0 | | | 0 | | | 0 | | | | | | | | |
| | | | | | 3 | 4 | 3 | 0 | | | | | | | | | | | | | | | 0 | | | 1 | 4 | 1 |

| INSPECTION ITEM | 10. KERBS / SIDEWALKS D | E | R | 11. PARAPET / HANDRAIL D | E | R | 21. MISC. ITEMS D | E | R |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 1 | 0 | | | 1 | 1 | 1 |

| INSPECTION ITEM | | 12. PIER PROTECTION WORKS D | E | R | 13. PIER FOUNDATIONS D | E | R | 14. PIERS & COLUMNS D | E | R | 15. BEARINGS D | E | R | 16. SUPPORT DRAINAGE D | E | R | 17. EXPANSION JOINTS D | E | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abut | 1 | | | | | | | | | | 0 | | | X | | | 2 | 4 | 2 |
| Abut | 2 | | | | | | | | | | 0 | | | X | | | 2 | 4 | 2 |
| Pier | 1 | X | | | 0 | | | 0 | | | 0 | | | X | | | 0 | | |
| Pier | 2 | X | | | 0 | | | 0 | | | 0 | | | X | | | 0 | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |
| Pier | | | | | | | | | | | | | | | | | | | |

| INSPECTION ITEM | | 18. LONGITUDINAL MEMBER D | E | R | 19. TRANSVERSAL MEMBERS D | E | R | 20. DECK SLAB D | E | R |
|---|---|---|---|---|---|---|---|---|---|---|
| Span | 1 | X | | | X | | | 0 | | |
| Span | 2 | X | | | X | | | 0 | | |
| Span | 3 | X | | | X | | | 0 | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |
| Span | | | | | | | | | | |

| ITEM | POSITION | ACTIVITY CODE or DESCRIPTION | QTY | Unit | U | Make safe | REMARKS | Rpt. Photo | Mon freq |
|---|---|---|---|---|---|---|---|---|---|
| 2. | BA | 451 Attach to endblock | | | 3 | | | | |
| 1. | BA | 504. Repair settlement | | | 2 | | | | |
| 9. | AS | 353 Extend scuppers | | | 3 | | | | |
| 9. | AS | 208. Clean scuppers | | | 3. | | | | |
| 10. | AS. | 207. Clear debris | | | 3. | | | | |
| 17 | BA | 306 New asphaltic plug | | | 3 | | | | |
| 21 | | 601. Install chainage | | | 3. | | | | |
| 21 | | 620. Install structure # | | | 3. | | | | |

Inspector's assessment and further comments:

The structure is generally in a good condition

| FURTHER INSPECTION REQUIRED ? Y/N | | IF FURTHER INSPECTION REQUIRED IS "Y" Then please indicate any special requirements ie. 6m Ladder, Bush cutting, UBIU, better weather etc. If nothing please state "none" | No. |
|---|---|---|---|
| WATER INSPECTION ? Y/N | | | |
| UBIU Needed for future inspections? Y/N | | | |

| D-DEGREE | | | | | E-EXTENT | | | | R-RELEVANCY | | | | | | U-URGENCY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Minor | Moderate | Warning | Severe | Local | More than local | Less than general | General | Min | Moderate | Major | Critical | Record only | Monitor only | Routine | < 10 yrs | < 5 yrs | ASAP |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | R | 0 | 1 | 2 | 3 | 4 |