Condition assessment of reinforced and prestressed concrete bridges using visual inspection and 3D modeling

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Abstract

This study explores UAV-based 3D modeling for bridge damage assessment. UAVs with high-resolution cameras captured images of two bridges at different life cycle stages and locations. These images were processed into detailed 3D models, offering more accurate evaluations than traditional visual inspections (VI). The models provided precise damage localization, geometric data information, and identified areas requiring urgent maintenance, reducing repair costs and time. Despite the advantages, challenges such as model accuracy and flight planning precision were noted. The results showed that larger and more complex bridges require significantly greater resources for 3D modeling, including longer flight and processing times, higher data volumes, and increased detail in the models, as reflected in the differences between the two case studies. Future research should focus on optimizing data acquisition, enhancing algorithms, and integrating augmented reality (AR) to improve collaboration and decision-making in bridge inspections.

Keywords: damage assessment; drone; photogrammetry; UAV visual inspections; 3D modeling; 3D reconstruction.

1 Introduction

Bridges are a fundamental component of a nation's highway network, playing a critical role in economic growth, social integration, and urban development. However, these structures are susceptible to significant deterioration due to aging, environmental factors, extended use, and other contributing elements, which can compromise structural safety, increase maintenance, and repair costs, and, in extreme cases, lead to collapse [1], [2].

As the number of deteriorating bridges continues to increase, the impacts on resource consumption, environmental sustainability, and public safety become more pronounced [3]. For instance, the latest infrastructure report card by the American Society of Civil Engineers (ASCE) reveals that a significant portion of bridges in the United States is over 50 years old. Furthermore, approximately 7.5% of the nation's bridges are classified as structurally deficient and in "poor" condition, and addressing these deficiencies would require an estimated $5.9 billion to repair and upgrade the country's infrastructure system [4]. In contrast, in countries like Ecuador, more than 50% of the nation's bridges are in "poor" or “fair” condition [5].

Given these challenges, many countries have adopted various methods to monitor the extent and severity of existing defects or deterioration, ensuring that structures remain within acceptable condition limits [6]. The primary objective of assessing an existing bridge is to evaluate its current and future structural safety [7], with the ultimate goal of structural condition assessments preventing bridge collapses [8]. In recent years, field testing techniques for assessing the condition of bridges have significantly advanced [5], [8]. These condition assessment methods are generally classified into visual inspections, non-destructive testing (NDT), and bridge load testing [9], [10], [11], with visual inspections (VIs) being the most widely used method. Advances in inspection technologies, such as UAV-based inspections and 3D photogrammetry, have significantly improved the precision and efficiency of VIs [12], [13].

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This paper evaluates the use of UAV-based 3D modeling for bridge condition assessment, comparing its implementation in two case studies bridges. The research highlights how UAV technology, combined with 3D photogrammetry, improves the accuracy and efficiency of traditional VIs. The case studies demonstrate the practical benefits and challenges of this approach, aiming to enhance cost-effectiveness and support better-informed decision-making in bridge infrastructure management.

2 Visual inspections

2.1 UAVs for Visual Inspections

Visual inspection (VI) is one of the most widely used NDT methods for assessing structural integrity, playing a critical role in detecting damage and pinpointing its location within the structure [14]. This method is efficient and cost-effective for identifying superficial defects; however, it does not provide detailed or quantitative information about internal issues. Typically, VI is used to detect problems such as cracking, spalling, exposed reinforcement, beam delamination, concrete deterioration, and reinforcement corrosion [14].

The effectiveness of VIs largely depends on the inspector's experience and expertise, particularly in understanding structural behavior, materials, and construction methods [15]. A study by the Federal Highway Administration (FHWA) to assess the reliability of visual inspections of highway bridges found significant variability in the condition ratings assigned during routine inspections. Specifically, approximately 68% of condition ratings fell within one rating point of the average [16]. Therefore, to achieve a more accurate assessment of the structure’s condition, combining visual inspections (VIs) with other NDT methods is recommended. Furthermore, evaluating UAV recordings by multiple inspectors can help reduce variability and enhance the reliability of the overall assessment.

Figure 1. Example of a UAV used for VIs [17]

VIs can be challenging when assessing hard-to-reach structural elements, often requiring specialized personnel or equipment. To overcome this challenge, remotely controlled unmanned aerial vehicles (UAVs, see Figure 1) offer a solution for performing these complex inspections. Despite their advantages, UAVs have limitations, such as their limited payload capacity, which restricts them to using only compact, lightweight digital cameras for photo or video documentation. Additionally, UAV flight time is relatively short due to battery constraints, and their low weight makes them highly sensitive to adverse weather conditions, particularly strong winds. It is important to note that in many regions, security regulations mandate special flight permits, and fully autonomous flights may be restricted or prohibited in certain areas [18].

The choice between traditional inspections and UAV-based inspections depends on the specific circumstances and requirements of the project. For example, traditional inspections are more suitable for easily accessible areas where detailed analysis is needed, while UAV-based inspections are ideal for hard-to-reach or dangerous locations, offering quick and cost-effective assessments. Image-based 3D modeling

UAV photogrammetry is a technique that uses UAVs equipped with high-resolution cameras to capture images of a structure from various angles [19]. These images are then processed using photogrammetric software to create detailed 3D models that provide a comprehensive visualization of the entire bridge structure [12]. These models offer significant advantages in defect localization and three-dimensional measurement, making assessing the extent of damage and planning repairs easier. Using high-fidelity 3D models offers a safer, more efficient, and more accurate approach to bridge evaluation [19]. Furthermore, 3D point clouds generated using UAV photogrammetry or UAV LiDAR can be transformed into Building Information Models (BIM) or structural analysis models, such as Finite Element Models (FEM) [20]. However, challenges such as high noise levels, low geometry accuracy, and image quality can affect the overall precision of the model, limiting its effectiveness in damage detection and quantification [13].

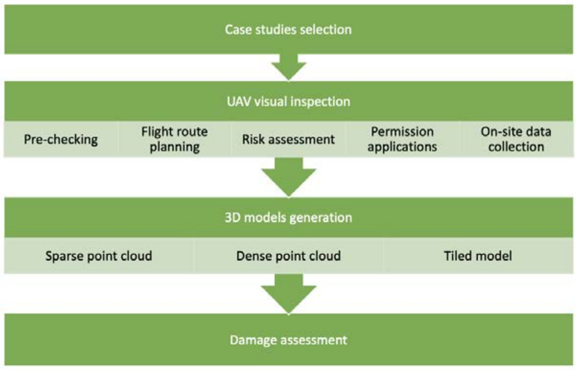


Figure 2. Methodology

3 Case study

3.1 Bridges' selection

The methodology used in this research is illustrated in Figure 2. First, two bridges were selected for this study. They represent different stages of their life cycle, are located in distinct geographical areas, and vary in their geometric characteristics. The first bridge, a reinforced concrete girder bridge, built in 1980, is located over the Tambura ravine on the old Ilumán-San Antonio highway in the Imbabura Province, Ecuador, with a length of 34.3 meters in three spans (Figure 3).

Figure 3. Bridge from Case Study 1

The second bridge, a post-tensioned box girder bridge built in 2014 using the balanced cantilever method, is located in the Ruta Viva highway, which provides access to Mariscal Sucre Airport in the capital city of Quito, Ecuador, and has a length of 315 meters (Figure 4).

Figure 4. Bridge from Case Study 2

The selection aims to develop 3D models of bridges in different phases of their life cycle, providing valuable insights into the effectiveness of 3D models in detecting the effects of aging on bridges. Additionally, as the bridges are in different geographical regions, the 3D models will allow for the evaluation of how factors such as variations in environmental conditions may influence visible defects in the structures. Furthermore, due to the differences in the span and overall size of the bridges, the study will identify the variations in the resources needed to construct the 3D models. This diversity of bridges will contribute to a deeper understanding of the capabilities and limitations of 3D modeling for damage detection in infrastructures across various contexts.

3.2 UAV Visual inspection

Figure 5. UAV used for the inspection

To conduct an effective and thorough bridge inspection, several key aspects were considered. The DJI Mini 3 [21] was selected as the drone to be used in the inspection (see Figure 5). A flight time of a minimum 25 minutes was essential to ensure uninterrupted inspection sessions, and two additional batteries were required. The drone's high-resolution camera allowed for the capture of detailed images in low-light conditions, which are commonly found under bridge decks [22]. Moreover, the drone was capable of recording high-quality video for video-based inspections when needed. The locations of the bridges required the use of a drone equipped with a long-range remote-control system to access areas that were otherwise inaccessible.

The UAV inspection process involves several tasks, including site pre-checking, flight route planning, risk assessment, permission applications, and on-site data collection (see Figure 2). [13]. Among these, flight route planning plays a crucial role in data quality, as it influences factors such as lighting conditions, camera angles, offset distances, flight patterns, and image overlap [13]. A well-designed flight plan is essential to meet photogrammetry constraints, ensuring sufficient baselines between camera viewpoints, adequate overlap between adjacent images, and minimizing optical occlusions caused by surrounding obstacles [12]. To satisfy the accuracy demands, thorough flight path planning was done prior to each flight. The flight plan used in both case studies was executed manually due to the large number of electric cables, vegetation, and existing infrastructure in the area, which could have caused difficulties for automated flight plans.

Figure 6. Sample images captured using the UAV on case study bridge 1 (left) and 2 (right)

Regarding image overlap, a larger overlap generally increases the likelihood of successful 3D reconstruction but also requires capturing more images, which results in longer processing times [12]. Overlap rates are rarely reported and typically rely on empirical observations. However, some studies recommend an endlap of 60% ± 5% and a sidelap of 30% ± 15%, or a minimum of 50% overlap [23]. In the UAV inspections conducted, a 70% overlap was used in all directions. Finally, the distance between the UAV and the bridges was influenced by factors including the camera field of view, sensor resolution, and the safety of the equipment [13]. Figure 6 shows a sample of the images obtained from the inspection.

3.3 3d models

By converting images obtained from the UAV inspections into a photorealistic 3D model of the bridges, inspectors can conduct structural condition assessments in a virtual environment. This method provides a comprehensive evaluation while eliminating the safety risks and time constraints of field inspections [19]. It is important to mention that the accuracy of the 3D models can be directly affected by the image acquisition setup, including factors such as camera positioning, the number of captured images, image overlap, and image quality [19].

There are many software options available for photogrammetric 3D reconstruction of objects, both open-source (e.g., openMVG, openMVS, Meshroom) and commercial (e.g., Agisoft Metashape, ContextCapture, Pix4D Mapper) [12]. In this study, Agisoft Metashape was selected for 3D bridge modeling. The hardware and software used for processing the data are shown in Table 1.

Table 1. Hardware and software used for processing data.

Type	Item	Description
Hardware	Operating system	Windows 11 Home, 64-bit
	CPU	Intel (R) Core (TM) i9-14900HX
	RAM	32 GB
	GPU	NVIDIA RTX4070 (Driver: 32.0.15.6094) Intel (R) UHD Graphics (Driver: 31.0.101.5187)
Software	Agisoft Metashape	To process the images for a 3D model

The results of the two case studies are presented in Table 2. The comparison between the two case studies reveals significant differences in terms of bridge characteristics, data collection, and model processing. Case Study 1 involves a smaller, older bridge (34.3 meters, built in 1980), while Case Study 2 features a larger, modern bridge (315 meters, built in 2014). These differences are reflected in the data collection and processing times.

In Case Study 1, the flight time was 30 minutes, reflecting the smaller size of the bridge. In contrast, Case Study 2, with its much larger total length, required 60 minutes of flight time. This increase in flight time for Case Study 2 is consistent with the larger area that needed to be covered during the inspection, as well as the greater amount of data required for a detailed 3D model. The longer flight time in Case Study 2 also indicates the higher resource demands of inspecting larger structures, which could affect the logistics and cost of UAV-based inspections for more extensive infrastructure projects.

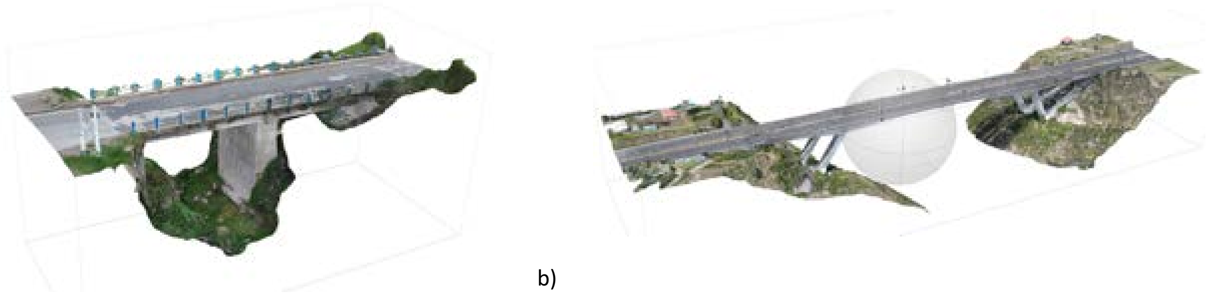
Case Study 1 required only 41 minutes for data collection, compared to 639 minutes for Case Study 2, highlighting the complexity of the larger bridge.

The processing times for 3D model creation further emphasize this disparity, with Case Study 1 taking 68 minutes and 7 seconds and Case Study 2 requiring 9 hours and 33 minutes. Additionally, the number of points generated for Case Study 2 (185.8 million) is vastly greater than that of Case Study 1 (10.29 million), reflecting the increased level of detail needed for the larger structure.

Finally, the Ground Sampling Distance (GSD) for Case Study 1, at 3.83 mm/pixel, offers higher resolution data compared to Case Study 2 (1.37 cm/pixel), suggesting better accuracy and detail in the model. Overall, the findings illustrate how the size and complexity of the bridge directly influence both the time and resources required for UAV-based 3D modeling, as well as the resulting data quality.

3.4 Damage assessment

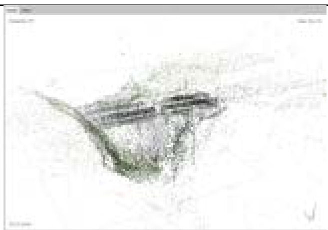
In this study, 3D models generated from UAV-captured images (see Figure 7) were used to identify and assess damages in the case study bridges.



a) b)

Figure 7. 3D models of a) Case Study 1 and b) Case Study 2

Table 2. Comparison of the two case studies in terms of data collection and 3d modeling

		Case Study 1	**Case Study 2**
Data collection	Number of photos	276	799
	Flight time	30 min	60 min
Sparse point cloud			
	Points generated	50.2 k	178 k
	Processing time	2 min 17 sec	9 min
Dense point cloud			
	Points generated	10.29 mill	185 mill
	Processing time	13 min	1 h 41 min
Tiled model			
	Processing time	22 min 50 sec	6 h 43 min
Average GSD		3.83 mm/pixel	1.37 cm/pixel

Through these models, several structural defects were identified and measured, including concrete spalling (see Figure 8), as well as the size of holes and exposed reinforcement on the piers of Case Study 1 (see Figure 9). This approach enabled precise measurements, allowing for a more detailed evaluation compared to traditional visual inspections (VI). However, while the lengths of cracks could be measured and crack maps could potentially be developed, crack widths could not be determined, representing a limitation. It is recommended to use complementary non-destructive testing (NDT) methods to address this issue or incorporate modern segmentation models for crack image analysis [24].

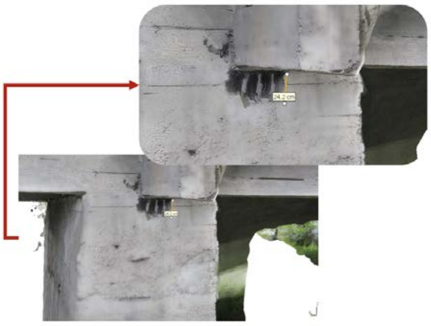


Figure 8. Damage measurements of Case Study 1

Figure 9. Damage measurements of Case Study 2

Additionally, 3D models allow for a detailed analysis and precise location of damages (see Figure 10). This is especially beneficial for bridges where physical inspections may be limited or hazardous due to hard-to-reach areas or complex structural features.

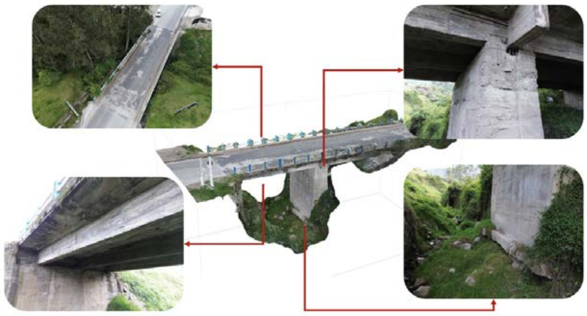


Figure 10. Location of damages

Furthermore, 3D models provide accurate geometric information about the structure, as shown in Figure 11. This is especially valuable when technical drawings are unavailable, a common issue in countries lacking a Bridge Management System (BMS) [5].

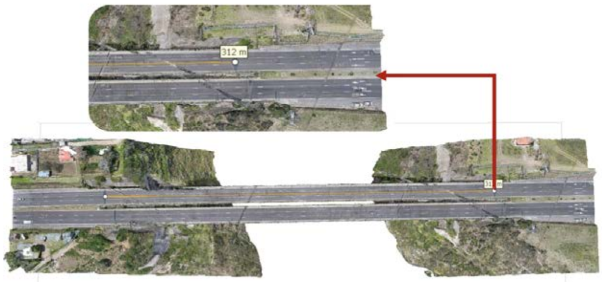


Figure 11. Geometric information of Case Study 2

In addition to improving damage detection, the 3D models generated in this study provided valuable inputs for maintenance and repair planning. By accurately mapping the location and extent of visible defects, the models enabled infrastructure managers to prioritize interventions based on objective data. This targeted approach facilitates better resource allocation, allowing maintenance teams to focus on the most critical areas, and contributes to extending the structure's service life while minimizing operational disruptions.

Furthermore, the clear and detailed visualization of damage allows for a better understanding of the bridge's structural condition among key stakeholders, including engineers, inspectors, and maintenance authorities. By offering a 3D digital representation of the bridge's condition, the models help align technical assessments with management decisions. This integration enhances coordination, streamlines repair planning, and ultimately strengthens the overall effectiveness of infrastructure management strategies.

4 Discussion

This study demonstrates the effectiveness of UAV-based 3D modeling for bridge damage assessment. It is worth mentioning that choosing an affordable drone offers a practical and economical solution for enhancing and modernizing current inspection practices in Ecuador [17]. Furthermore, the 3D models provided accurate measurements and detailed damage localization, offering significant advantages over traditional VI. These models also provided accurate geometric data, which proved especially valuable when technical drawings were unavailable, a challenge recognized in other studies [5].

Despite the advantages of UAV-based 3D modeling, several challenges remain, particularly concerning the accuracy and level of detail in the generated models, as well as the necessity for precise flight planning. These challenges are consistent with the findings from [12], [13], which also highlighted the significant reliance on the inspector's expertise. Furthermore, the complex geometry of the bridge can lead to incomplete coverage of the structure or insufficient image overlap, affecting the quality and accuracy of the final 3D model.

Future research could focus on optimizing the image acquisition process and developing more efficient algorithms to reduce processing times while improving model accuracy. Furthermore, the integration of augmented reality (AR) could greatly improve bridge inspections. By enabling multiple engineers to assess the same bridge, AR could help reduce results variability, increasing the consistency and reliability of inspections. This collaborative approach would not only improve decision-making but also ensure more accurate inspections.

5 Conclusions

The findings of this research highlight the significant potential of UAV-based 3D modeling for bridge damage assessment, demonstrating its effectiveness in improving the evaluation process, optimizing maintenance resources, and enhancing communication. The following key conclusions were identified:

- UAV-based 3D modeling provided accurate measurements and detailed damage localization, which allowed for a more thorough evaluation than traditional VI.
- The 3D models provided geometric data, especially valuable in cases where technical drawings were unavailable.
- The 3D models were essential for precisely identifying areas of the bridge requiring urgent attention, thus contributing to reduced repair costs and maintenance time.
- The use of 3D models can enhance communication among stakeholders, such as engineers and maintenance authorities, by providing a clear and detailed visualization of the damage.
- The 3D models allowed for a better understanding of the structural condition of the bridges, facilitating more informed decisions about repairs and efficient resource allocation. This was especially evident in Case Study 2, where complex geometries were easier to assess using the 3D models.
- Despite its strengths, challenges remain, including the accuracy and level of detail in the 3D models, as well as the need for precise flight planning.
- The complex geometry of bridges in both case studies led to some areas being harder to capture with sufficient detail, affecting image overlap and final model accuracy.

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