Bridge Inspection Field Support and Inspection Method by Heat Map Using 3D Point Cloud Data in Japan

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Abstract –

It is inevitable that the decrease in Japan's working population due to the declining general population, low birth rate, and ageing population will lead to a shortage of skilled infrastructure inspectors. Therefore, it is important to improve and equalize the quality of inspection data, which are the basis for understanding the condition of bridges, to allocate appropriate and optimal budgets, and to formulate life-extension repair plans. It is also important to improve the quality of inspection data, which are the basis for assessing the condition of bridges, and to equalize the data so that the progression of damage can be properly assessed, an accurate diagnosis can be made, and appropriate measures can be planned. In this study, we propose a method for supporting the field inspection of bridges by visualizing abnormalities using a heat map based on 3D point cloud data representing the bridge to be inspected. The proposed method is evaluated by infrastructure inspectors, and the requirements and issues for the field support technology are summarized.

Keywords –

Bridge Inspection; Three-dimensional Point-cloud Data; Heat Map; Digital Transformation

1 Introduction

1.1 Background

1.1.1 Status of bridge inspection

Japan has about 730,000 road bridges with a length of 2 m or more. Most of them were built during the period of high economic growth and are rapidly ageing. By 2029, 52% of these bridges will be at least 50 years old. The number of bridges managed by local authorities that are subject to traffic restrictions due to ageing has tripled in the 10 years between 2008 and 2018 [1]. Moreover, there are many bridges that are still in use 80 years after their construction without major damage due to appropriate repair and reinforcement.

In 2014, a 5-year periodic inspection was stipulated to obtain the information necessary for proper maintenance of bridges in order to avoid damage to road users and third parties, avoid long-term malfunctions and failures, and enact timely measures to extend their service life [2]. During periodic inspections, the condition of the bridge is assessed visually, a diagnosis of soundness is made for reference, and countermeasures to be taken before the next periodic inspection are established. In addition, data on the external condition and the degree of damage are obtained for comparison with the results of previous inspections and to study the maintenance plan. It is also important to transfer the information from the inspection results and repairs. However, because of the large number of bridges and parts to be inspected, it is time-consuming for inspectors.

1.1.2 Use of digital transformation in the infrastructure sector

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) set up the "Digital Transformation (DX) Promotion Headquarters for the Infrastructure Sector of MLIT" on 29 July 2020 [3]. As a result, MLIT uses data and digital technology in the infrastructure sector to transform social infrastructure and public services in response to the needs of the public, by transforming the work itself, the organization, the processes, and the culture and working style of the construction industry and MLIT, and by promoting public understanding of infrastructure. MLIT has established a policy of promoting public understanding of infrastructure and realizing safe, secure, and prosperous lives. The introduction of advanced and new technologies is indispensable for the introduction of new technologies and the measures to achieve them, such as Society 5.0 and DX. In addition, MLIT is promoting "i-Construction," which aims to increase the productivity of construction sites by 20% by 2025 through the use of information and communications technology and 3D data in all construction processes. With these initiatives, sharing information on bridge inspections with 3D data will improve the efficiency of inspection efforts and enable rapid response in an emergency. In addition, the use of 3D data for bridge maintenance and management will make it possible to easily grasp the location and extent of damage, as well as the overall bridge condition, which will be useful for determining the cause and diagnosis of bridge deterioration [4]–[8].

1.2 Objectives of this study

To improve the efficiency of bridge inspection work, this study proposes a bridge inspection field support technology as a method to determine the damage of surface irregularities from the 3D data of bridges, to efficiently evaluate overall bridge damage, and to visually grasp the change and position of damage over time. In this paper, we propose a new method for visualizing the damage of a bridge using 3D point cloud data. The 3D data are acquired by photogrammetry using a camera or a ground-based terrestrial laser scanner (TLS).

To improve the efficiency of the periodic inspection of bridges, we propose a bridge inspection method that uses a heat map to generally check the appearance of bridges before visual inspection and to screen the bridges or bridge components to be inspected.

The contribution of this research is that we have clarified a method to analytically visualize the ageing process using point cloud data sets. The method was applied to support bridge inspections, and actual practitioners (inspectors) evaluated the method.

1.3 Research flow

The research flow of this study is as follows.

In Section 2, we summarize the status and issues of bridge maintenance management since the Sasago Tunnel ceiling plate failure accident, and how to use 3D data to prevent such failures.

In Section 3, we set up field situations and summarize how to make a heat map. In this section, we present the results of experiments based on the contents of

In Section 4, we conduct a demonstration experiment based on the procedures in Section 3. The contents of the experiment, the results obtained, and the issues to be addressed are summarized.

Finally, in Section 5, we interviewed inspection practitioners about the application of heat maps to the 3D damage drawing support system [9] previously developed by the authors. This paper reports the requirements for the field support technology and system, and the issues in applying the system to practice.

2 Status and challenges of bridge maintenance and management

2.1 Status of bridge maintenance

In December 2012, the Sasago Tunnel was closed for a long time as a result of a fallen ceiling plate which claimed the lives of nine people. This incident reaffirmed the importance of maintaining and renewing social infrastructure, and in March 2014, regular inspections by close observation every 5 years became a legal requirement. From 2014 to 2018, mandated inspections were carried out based on the 2014 edition of the *Periodic Inspection Guidelines for Bridges*. Bridges under the direct control of the national government were inspected according to the periodic bridge inspection guidelines, while bridges under the control of local authorities were inspected according to the periodic road bridge inspection guidelines. However, in 2019, the periodic bridge inspection guidelines were revised to streamline the inspection process while ensuring the quality of periodic inspections, in response to the occurrence and oversight of deformations that may affect the safety of third parties after periodic inspections and the development of inspection support technologies, such as photography and non-destructive testing [10], [11]. In the revised guidelines, the focus of periodic inspections is on the damage and structural characteristics, and the inspection targets are narrowed down to streamline the inspection process. In addition, guidelines for the use of new technologies and a performance catalogue [12] have been developed to supplement, replace, and enhance close visual inspection.

2.2 Challenges in bridge maintenance

Bridge maintenance has three main challenges.

2.2.1 Limited budget

The budget for the maintenance and repair of national highways under national government control should be increased to cope with the ageing of facilities, but it has decreased by about 20% from 320.2 billion yen in 2004 to 251.5 billion yen in 2013, in line with the decrease in the national public works budget [13]. In 2012, a disaster prevention and safety subsidy were established, and financial support and budget increases were implemented, such as priority allocation for inspection and repair projects for bridges and other structures. In 2012, the government established the Disaster Prevention and Safety Grant, which provides financial support and increases the budget for bridge inspection and repair projects.

2.2.2 Underutilization of technology that could improve efficiency

The revision of the inspection guidelines has led to the development of guidelines and performance catalogues for the use of new technologies that complement, replace, or enhance close visual inspection, but their use is still limited.

2.2.3 Lack of human resources and skills

As of June 2019, there were no civil engineers involved in bridge maintenance work in about 30% of towns and 60% of villages, and 54% of direct inspections and 42% of inspectors commissioned by local governments had not taken the road management practitioner training course or the road bridge maintenance skills course conducted by MILT. In addition, many bridges have been reported to require repair or reinforcement after the first round of mandated inspections, so human resources have been allocated to repair planning, design, and implementation.

2.3 Using 3D data to solve problems

In this study, we propose an inspection support technology that obtains 3D data of a bridge, creates a heat map from the data, and visualizes damage points as a 3D model to improve the efficiency of on-site work for bridge inspectors. We believe that this technology can improve the efficiency of inspection work by detecting damage from abnormalities identified by the heat map and extracting locations should be focused on during inspections.

To solve the problems of insufficient budget, technical skills, and manpower, local surveyors who do not specialize in bridge design have been commissioned to carry out bridge inspections, and inspections have been simplified and carried out by local government employees (in-house inspections) [14]. However, potential problems include inspectors lacking sufficient knowledge about bridges and bridge damage, reduction in accuracy of the inspection due to simplification, differences in results between first and second inspections, and damage that had been previously identified being missed. The 3D data can be deployed in a 3D maintenance management system. By recording damage data as a heat map or 3D data and bringing it to the site, the risk of missing previously identified damage will be reduced. In addition, quantitative evaluation of the degree of damage from the heat map will reduce the variability of evaluation among inspectors.

3 Heat mapping and visualization of anomalies

3.1 Visualization of anomalies with heat maps

The process flow for creating a heat map from point cloud data is shown in Figure 1. A camera and TLS are used to measure the bridge. Images or movies taken by the camera are cut out at regular intervals to generate 3D point cloud data with structure from motion (SfM) processing to recover the shape from the images. The difference between the point cloud data generated by the SfM process or the TLS process and the reference data, which simulate the undamaged surface, is visualized by the colour change. The heat map is created using the point cloud processing software CloudCompare. In the comparison, first, by using the align function of CloudCompare, feature points in the acquired point cloud data of two periods are manually selected, aligned, and superimposed. Next, the compute cloud/cloud distance and compute cloud/mesh distance functions are used to

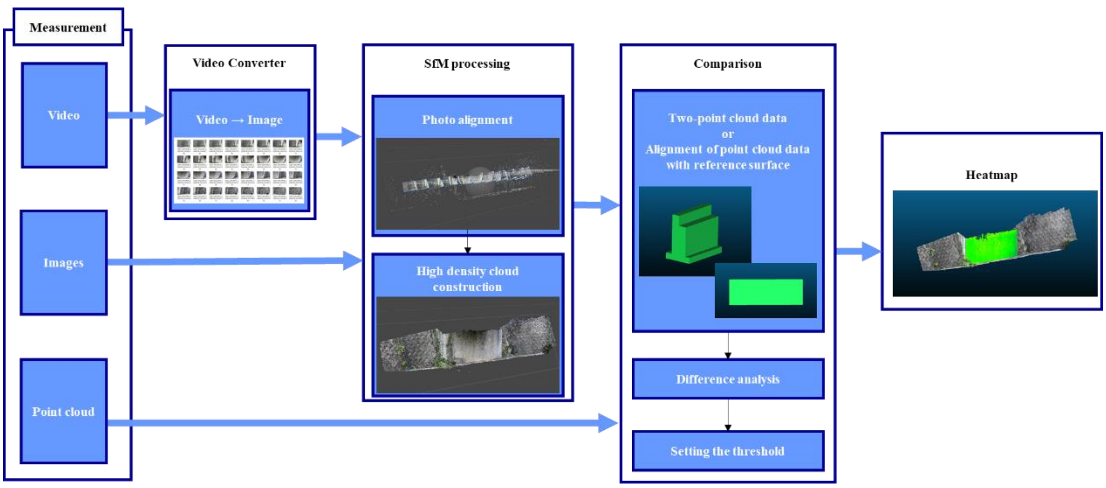


Figure 1. Flow of heatmap creation

perform a difference analysis of the two superimposed data sets and create a heat map. The difference between the two data sets is represented by a change in colour, for example, a change to blue if the bridge is concave or to red if it is swollen.

3.2 Damage to the detection object

Damage that can be detected using a heat map includes dampness, delamination, exposure of steel bars, and cracking of concrete members, as required by the periodic bridge inspection guidelines.

3.3 Equipment used

In this study, to obtain 3D point cloud data for bridges, we use FARO Focus 3D X330 as the TLS and SfM technology to generate high-density point cloud data from images taken by a camera (GoPro Hero9 Black).

3.4 Heat map creation

To create a heat map from the 3D point cloud data of a bridge, two field situations were set up. The first is a case where previous cloud data for the target bridge are available, and the second is a case where no previous point cloud data are available. When previous point cloud data are available, the past and present point cloud data are compared. The flow of the comparison with previous data is shown in Figure 2. The point cloud data of two periods are aligned so that the same positions overlap, the difference analysis is performed using the previous data, and a heat map is generated by setting the threshold. In addition to analysis of differences in the point cloud data by TLS (method (1)) and analysis of differences in the point cloud data by SfM (method (2)), comparison of the TLS point cloud data and SfM point cloud data is carried out on the assumption that the measurement method is different between the present and the past (method (3)). The heat map patterns are shown in Tables 1 and 2. When previous point cloud data are not available, a reference plane that simulates the undamaged surface is created and compared with the point cloud data. The reference plane should be the same as that of the bridge when it was built, but if as-built data or drawings are not available, the reference plane is made from the current measurement data. The reference plane in this study is created by using the Primitive Factory function of CloudCompare (method (A)), the 3D parametric model [15], [16] constructed for the bridge of interest (method (B)), and the RANSAC function [17] (method (C)) to generate the plane from the point cloud. See Figure 3 for details.

4 Demonstrations

4.1 Content and results of the experiment

The proposed method was tested on two bridges, the Warazuhata Bridge in Sennan City, Osaka Prefecture (22.1 m long by 4.0 m wide), and an unnamed bridge in Saitama Prefecture (2.0 m long by 4.5 m wide), as well as on laboratory buildings on the campus of Kansai University ‘Figure 4’. Previous point cloud data were available for Warazuhata Bridge. At the Warazuhata Bridge and the laboratory buildings, paper clay and wall stickers with a thickness of about 1 to 2 cm were attached to the abutments to simulate damage ‘Figure 5’. The data obtained before sticker application were as previous data and the data after application of the stickers were used as current data. The camera was pointed at the front of the abutment and moved to the side. In the TLS measurement,

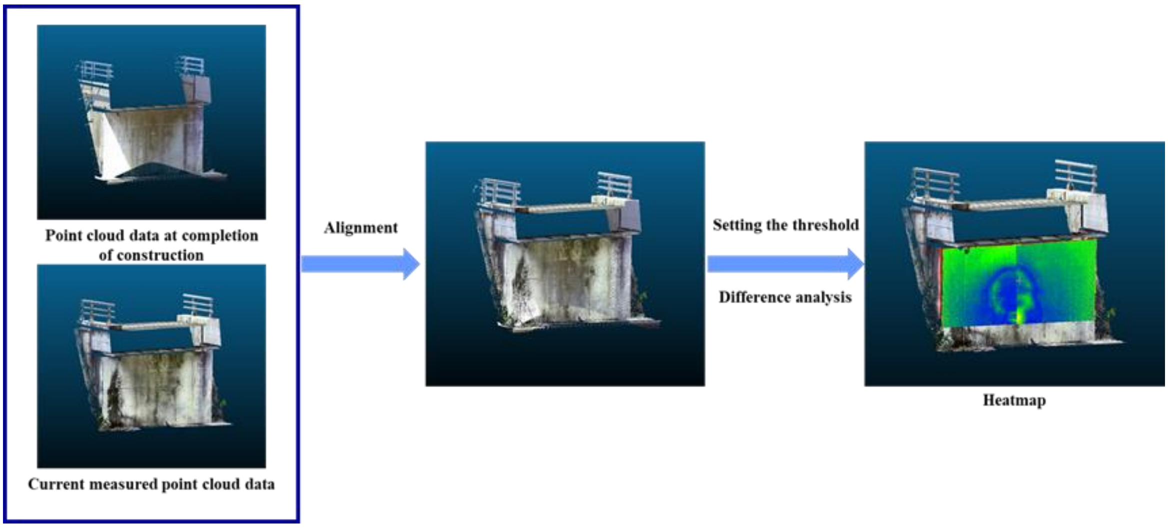


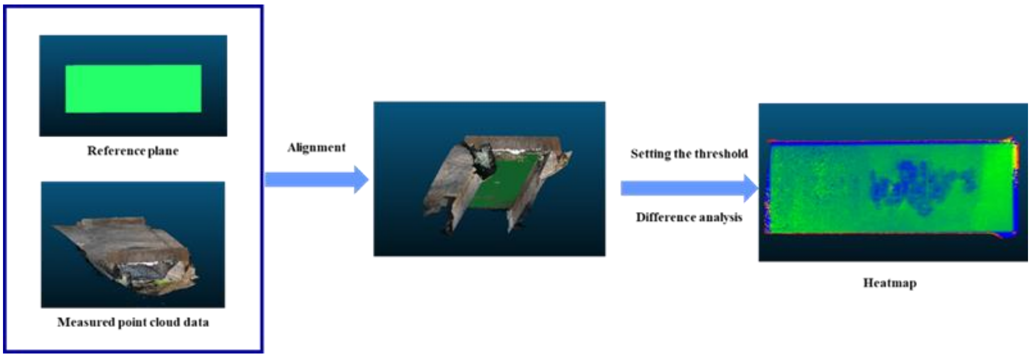
Figure 2. Flow of comparison between past and present data when historical point cloud data are available

Table 1. Patterns of heat map creation when historical point cloud data are available

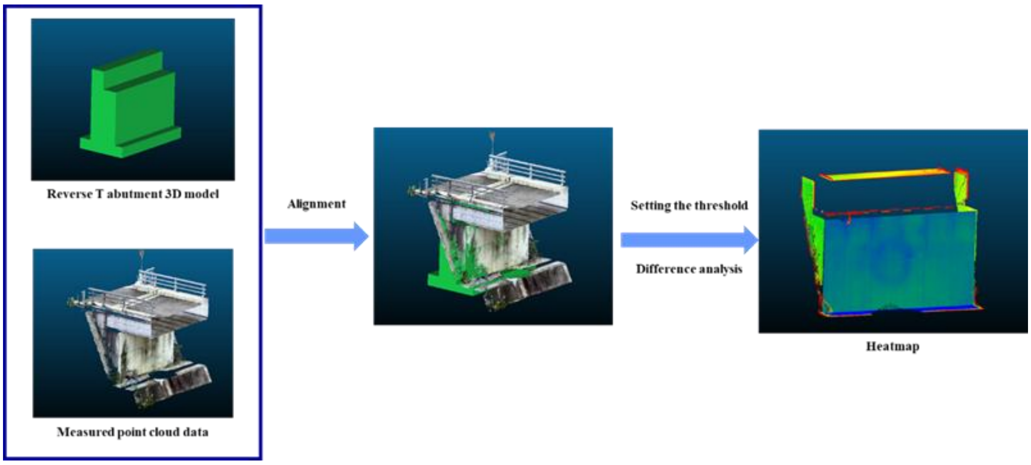
Creation pattern	Measurement type	
	The past	Current
(1)	TLS	TLS
(2)	Camera (SfM)	Camera (SfM)
(3)	TLS	Camera (SfM)

Table 2. Patterns of heat map creation when historical point cloud data are not available

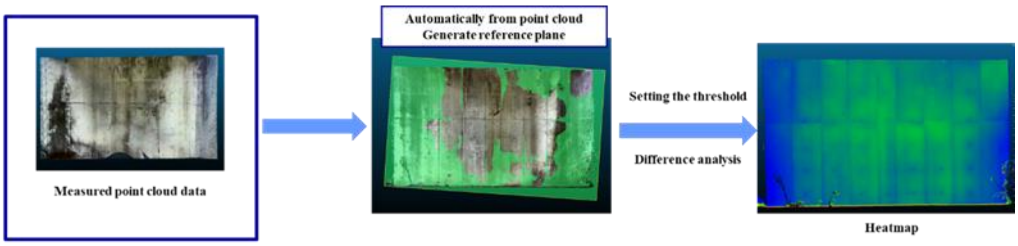
Creation pattern	How to create a reference plane
(A)	Reference plane created using Cloud Compare's Primitive factory function
(B)	The plane of the 3D parametric model is the reference plane
(C)	Reference planes created from point cloud data using the RANSAC function



(A) Flow of comparison with reference plane



(B) Flow of comparison with 3D model



(C) Flow of comparison with automatically generated criteria

Figure 3. Flow of comparison between reference plane and current point cloud data when no historical point cloud data are available

(L) Warazuhata Bridge, Osaka Prefecture
(R) Unnamed bridge, Saitama Prefecture

Kansai University laboratory buildings
(L) 5th laboratory building
(R) 4th laboratory building

Figure 4. Settings of the experiment

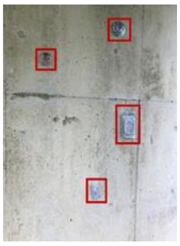


Figure 5. Paper clay and wall stickers pasted on the vertical wall of the abutment of Warazuhata Bridge

the camera was placed in front of the damage and the 3D data were constructed using FARO SCENE data processing software. The heat map of the Warazuhata Bridge is shown in Figure 6.

The colour of the heat map was set so that the amount of difference increases from green to red. The area where the pseudo-damage was pasted is drawn in bright green, unlike the surrounding area. From the figure, the damage can be visualized by the colour change. Figure 7 shows the results for method (2), comparison of SfM point cloud data. Like method (1), a colour change was observed at the point where the pseudo-damage was pasted, but relative to the comparison with method (2), the colour change was also observed at points other than where the pseudo-damage was pasted. This may be due to the inferior accuracy of the SfM point cloud data compared with the TLS point cloud data. Similarly, in method (3), where TLS and SfM point cloud data are used ‘Figure 8’, damage can be confirmed from the heat map. As with methods (1) and (2), a colour change was observed at the point where the pseudo-damage was pasted, and the damage could be visualized by the heat map. However, because the SfM point cloud data did not measure the upper part of the abutment, it was not possible to compare the damage of the entire abutment.

On the unnamed bridge, concrete spalls were widely observed on the underside of the deck in the field, as shown by the orthographic image in Figure 9. Extensive delamination and exposure of steel bars were also observed. In this study, the current SfM point cloud data were used to verify the results in the absence of previous

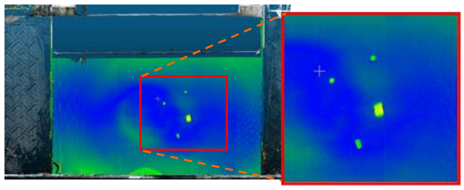


Figure 6. Heatmap of Warazuhata Bridge Method (1) (TLS/TLS)
(L) General view (R) Enlarged view

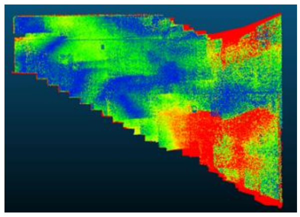


Figure 7. Experimental building Heat map of method (2) (SfM/SfM)

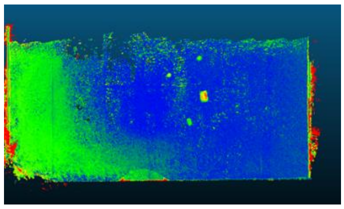


Figure 8. Heat map of Warazuhata Bridge Method (3) (TLS/SfM)

Figure 9. Orthoimage of the underside of the main deck of the unnamed bridge

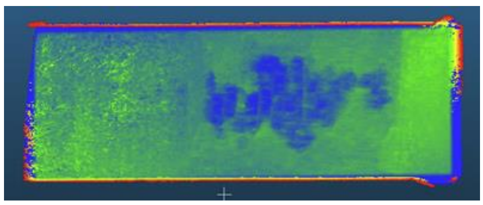


Figure 10. Heat map of the unnamed bridge using method (A)

data. Figure 10 shows the results of visualization of the damage by aligning the reference plane created by method (A) using the Primitive Factory function of CloudCompare on the SfM point cloud data.

4.2 Considerations

In this study, the heat map was made according to the flow diagram shown in Figure 1. The experimental results showed that the position of the pseudo-damage and the position of the delamination coincided with the position of the colour change in the heat map, suggesting that the waviness and delamination of concrete can be visualized. This suggests that the proposed method is reasonable. However, cracks in the concrete were not visualized by a colour change in the heat map. It was found that the heat map could visualize damage that created unevenness, such as waviness and delamination, but could not visualize damage without unevenness or small damage such as cracks. By creating heat maps from the point cloud data from two different periods, it is possible to see the change over time and to identify the time when the damage occurred. In the absence of point cloud data from two different periods, it is difficult to determine the most appropriate among the three methods because it takes time to align the planes to visualize the damage. and a suitable for creating the reference plane differs depending on the measured data. As shown in Figure 8, the heat map shows a colour change in areas where the pseudo-damage is not pasted, which is more extensive in the SfM point cloud data than in the TLS point cloud data. This may be due to the difference in accuracy between the TLS and SfM point cloud data. Because TLS point cloud data are more accurate than are SfM point cloud data, it is possible to use TLS as the basic measurement method, and to use a camera when TLS cannot be installed or when measurement is dangerous. The threshold value of the heat map was changed for each bridge or building to make damage detection easier. However, to evaluate bridges with the same standard, the threshold value should be kept constant. Because the SfM point cloud data are different from the actual size of the bridge, it may not be possible to visualize the damage if the threshold is kept constant. As a solution to this problem, we propose a method for visualizing the damage with the same threshold value for all bridges by adding location information to the SfM point cloud data. In addition, it is thought that damage can be quantitatively evaluated by this method.

5 Application as a bridge inspection support technology and as a bridge inspection method

The authors have developed a support system for creating 3D damage diagrams to enable maintenance workers to grasp and share the location and status of damage intuitively and accurately. Since the heat map information proposed in this study is also based on 3D point cloud data, it can be superposed on this system. Therefore, we conducted an evaluation meeting by practitioners to evaluate the effectiveness of using heat map information on mobile devices for inspection work in the field. The main opinions raised at the evaluation meeting are as follows.

- A heat map showing the areas to be focused on during the field survey will improve the efficiency of the field work and save time.
- By looking at the changes over time, 10 years ago, 5 years ago and now, it is possible to understand the trend of damage and make use of this information in the inspection. However, care should be taken to avoid focusing too much on old damage.
- In the case of inexperienced practitioners, the support is likely to be more effective, while in the case of experienced practitioners, quantitative evaluation is needed, not just finding support.
- Differences must also be able to be correctly evaluated for point cloud data generated by different la-ser scanners and cameras used.
- It is difficult to use this method in general because of the limitation that the results are different de-pending on the location of the machine and the weather conditions. However, it is thought that the restriction can be solved by organizing the method of measurement, the method of setting up the machine and the method of analysis and formulating the guideline.

For the heat map to be used as a "bridge inspection method" in periodic inspections, it is essential to increase the number of demonstration tests, improve the accuracy verification, and be able to quantitatively evaluate the size and depth of damage. However, it is suggested that the method can be used in some bridge conditions, such as where there is no third-party damage, or where there is little road traffic, or where the bridge is not on an important route.

6 Conclusion

In this study, to help infrastructure engineers carry out bridge inspection in the field more efficiently, we have proposed a method for detecting damage before the field survey by constructing a heat map based on 3D point cloud data measured by TLS and photography during a field survey before the regular inspection. In this study, we measured a bridge using TLS and a camera and constructed a heat map with 3D data. The method of using the results with the 3D data was evaluated by inspection practitioners, and the issues and points to be noted were summarized. In the future, we will study how to use heat maps to visualize and detect damage with generally smooth features, such as narrow cracks, and how to evaluate damage quantitatively by adding location information to point cloud data. In addition, we plan to conduct more experiments to verify the accuracy of the method and clarify the range of application.

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