

## Article

# Remote Bridge Inspection and Actual Bridge Verification Based on 4G/5G Communication Environments

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**Abstract:** The close-up visual inspection of bridges faces several problems, including a lack of financial resources and human personnel. Hence, there has been increasing use of artificial intelligence (AI) and information and communications technology (ICT) to solve them. We previously investigated remote inspection—in which skilled engineers provided on-site support from a remote location—with the aim of reducing the labor required for on-site work and addressing the lack of personnel through the use of AI and ICT. Sharing images of bridges from inspection sites to remote locations via the Internet enables remote assessment of the sites and the ability to consider and diagnose damage. Mobile communications can be used to upload images, although the volume of image data required for inspection can be enormous and take considerable time to upload. Consequently, in this study, we investigated image uploads using 5G communication—that is, the fifth-generation technology standard for broadband cellular networks. Moreover, we measured the upload times when using 4G and 5G services and examined their operation based on differences in the communication environments. We concluded that the simulated remote inspection can be efficiently performed by adjusting the inspection method to the communication environment.

**Keywords:** 4G; 5G; remote inspection; bridge; images



**Citation:** Yoshikura, M.; Minami, T.; Fukuoka, T.; Fujii, M.; Takayama, J. Remote Bridge Inspection and Actual Bridge Verification Based on 4G/5G Communication Environments.

*Electronics* **2023**, *12*, 3203. <https://doi.org/10.3390/electronics12143203>

Academic Editor: Chiman Kwan

Received: 17 April 2023

Revised: 14 July 2023

Accepted: 19 July 2023

Published: 24 July 2023



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## 1. Introduction

Many of the approximately 720,000 bridges in Japan were built during periods of high economic growth (1954–1972), and by 2030 over 50% of them will be over 50 years old [1]. Since 2014, the Ministry of Land, Infrastructure, Transport, and Tourism has required road administrators to conduct close visual inspections once every five years to properly maintain bridges with the aim of extending their service life and reducing inspection costs. However, in municipalities that lack financial resources and personnel, it can be difficult to continuously conduct such inspections. Moreover, evidently, inspection/diagnosis results vary depending on the inspector, even though the diagnoses are made by inspection engineers [2].

To address these problems, there are increasing expectations that the introduction of the latest technologies can alleviate labor constraints regarding bridge inspections. The latest technologies—including drones and AI for visual inspection, photography, and damage diagnosis conducted by humans in conventional inspections—are being used with the aim of improving the efficiency of operations [3]. Damage detection using image recognition techniques can eliminate the variations in diagnoses by inspectors and simultaneously enable the analysis of changes over time.

Many studies have been conducted in recent years to detect crack damage [4–6]. In such cases, high-resolution images are required to detect cracks with a width of 0.1–0.2 mm on concrete surfaces—that is, a general digital camera can be used to obtain a large number of images taken at distances of 0.5–3.0 m [7]. There have also been several studies on imaging using drones [8–10], but a problem associated with all of them has been the low accuracy of damage detection using drone-sourced images. This is because damage detection using AI requires shooting under specific conditions, including high resolution, brightness, and saturation of the images.

We had previously developed a bridge inspection support system to achieve remote inspection using AI [11,12]. In conventional close visual inspection, multiple inspection engineers work at a single bridge site [13]. If remote inspection support can be achieved, then a reduction in inspection engineers can be achieved, such as having a single skilled engineer supporting multiple sites, as shown in Figure 1. Additionally, there would be no physical distance restrictions, so engineers in urban areas could provide support to those in remote rural areas, which could lead to reduced travel time for them.

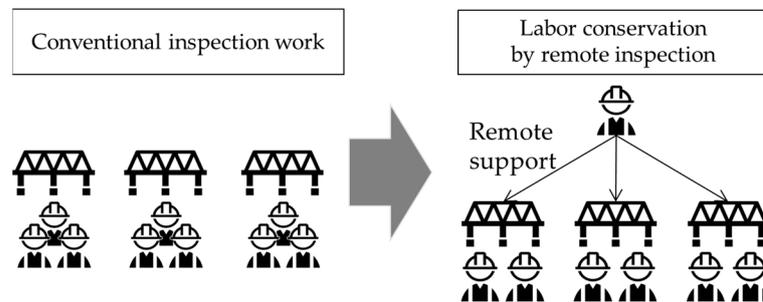


Figure 1. Labor conservation using remote inspection.

Figure 2 shows the remote inspection ideal. First, images taken by novice engineers at a bridge site are uploaded to the remote bridge inspection support system, the damage then being automatically detected using AI. A skilled engineer in a remote location considers and diagnoses the damage from the detection results. Moreover, bridge photographic work can be conducted by even inexperienced engineers, the automatic damage detection enabling reduced labor requirements for inspection work by skilled engineers in remote locations. Moreover, sharing images in real time could enable the use of this system for the instruction and training of novice engineers in the field by skilled engineers in remote locations.

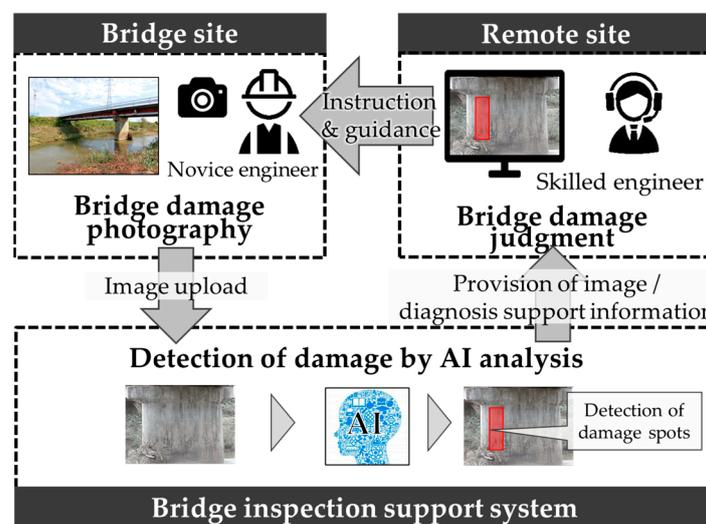
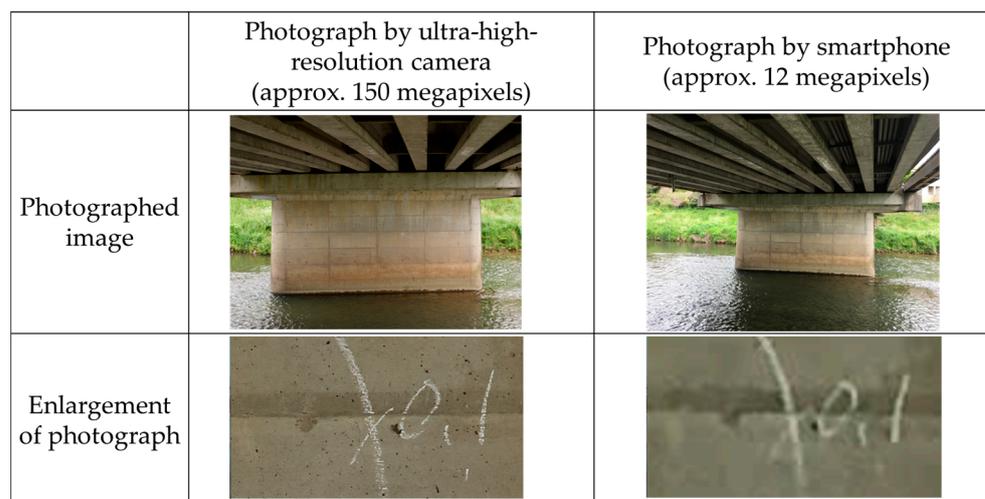


Figure 2. Diagram of remote inspection using bridge inspection support system.

Using this remote inspection support system requires high-resolution images to be obtained so that a skilled inspection engineer in a remote area can diagnose damage from them. Figure 3 shows a comparison of a high-resolution image taken using an ultra-high-definition camera (approximately 150 megapixels) and an image taken using a smartphone. Because of the difference in camera lenses, the field of view is narrower in ultra-high-definition cameras and wider in smartphones. Upon enlarging the image, chalking and black spots on the concrete surface are visible in the high-resolution image, but the smartphone image is blurry. However, although the high-resolution images enable better assessment of damage—with a level of detail and information similar to that obtained from visual observations—the volume of data required becomes enormous.



**Figure 3.** Camera resolution and image enlargement results.

Using the remote inspection approach is the aim of this study, and images are uploaded via the Internet using mobile communication from the site. The maximum image size for a high-resolution image taken using a 150-megapixel ultra-high-definition camera can be as much as 600 Mb. Thus, if all bridge members are photographed, the volume of image data will be enormous, making efficient uploading of high-resolution images essential if the benefits of labor conservation in inspection work are to be achieved.

Consequently, in this study, we verified the time reduction achieved in using high-speed, large-capacity 5G services, with the aim of improving image uploading efficiency and measuring and comparing the upload times of high-resolution images in 4G and 5G communication environments. We also conducted a simulated experiment in which a bridge engineer from a remote location confirmed damage using high-resolution images via a 5G-based remote inspection support system, where we demonstrated the usefulness of remote inspection and its challenges.

Not all bridges are located in 5G coverage areas, making the use of ultra-high-definition (150 megapixels) cameras difficult. Therefore, we considered the case of uploading images from a general digital camera via 4G. To clearly confirm concrete surfaces even with enlarged images, there are differences in the shooting method and number of images depending on the camera resolution (Table 1).

**Table 1.** Comparison of different camera resolutions when photographing bridges.

	Resolution	Shooting Distance	Number of Shots
High-definition camera	High	Far	Low
General digital camera	Low	Close	Many

A high-resolution camera can take high-resolution images at some distance from the bridge, and the number of shots required is much reduced. However, in the case of a general digital camera, images need to be taken at a distance much closer to the bridge. Additionally, the number of adjacent images required increases as they need to overlap to prevent omissions. Consequently, we measured the difference in the amount of data generated using the different camera resolutions and estimated the time required to upload the image data via 4G and 5G networks.

Finally, we proposed an efficient remote inspection method that considered the upload time due to differences in the communication environment based on the implementation of a system to facilitate bridge inspection.

## 2. Theory: Overview of Bridge Inspection Support System

In this study, we used a bridge inspection support system previously developed by the authors to detect crack damage from bridge photographs using image recognition technology [11,14–16]. Images taken using an ultra-high-definition camera could be uploaded to the system, the bridge image storage and crack damage detection results being confirmed via the Internet. This study was published in the June 2020 edition of the “Inspection Support Technology Performance Catalog (Draft)” [17]. The detailed explanation is as follows.

Figure 4 shows an overview of the bridge inspection support system. First, the bridge to be inspected is photographed using a 150-megapixel ultra-high-definition camera, the iXU-RS 1000 aerial camera, capable of capturing 100-megapixel (11,608 × 8708 pixels) images. The camera dimensions are 97.4 × 93 × 170.5 mm, and it weighs 930 g, making it portable. The ultra-high-resolution images enable the visual recognition of cracks with the same dexterity as close visual inspection, even with images taken at some distance from the bridge. In our previous work, a crack of approximately 0.2 mm could be confirmed from an image of a pier taken at a distance of 17 m [8].

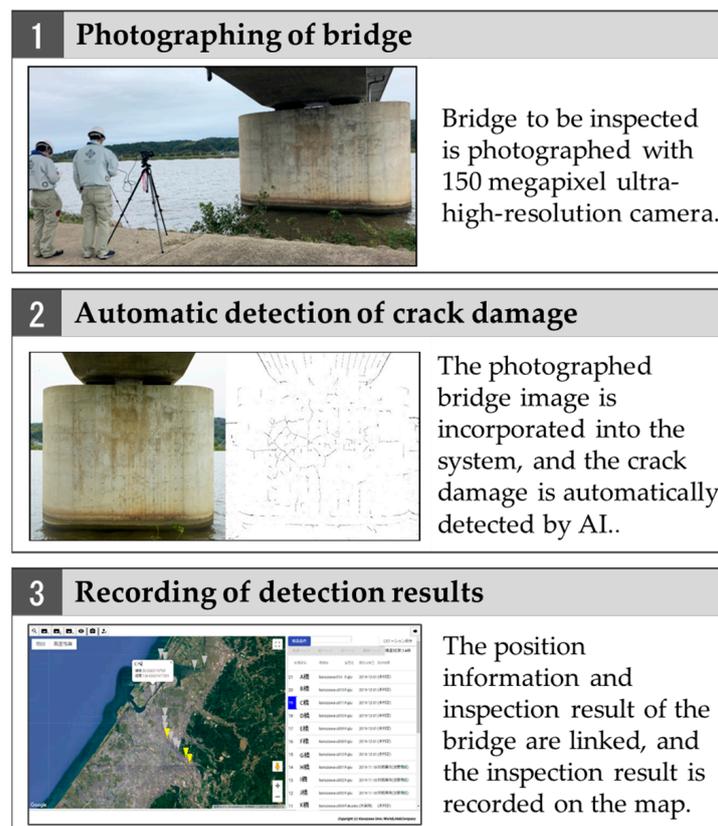
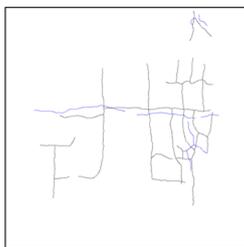
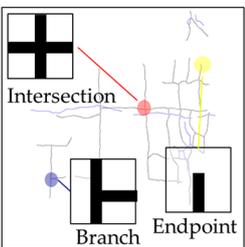
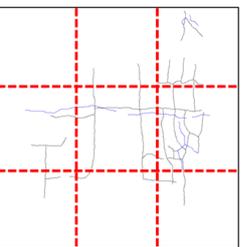


Figure 4. Flow chart of the bridge inspection support system.

Next, the bridge image is uploaded to the system, and cracks are automatically detected by image recognition technology using deep learning techniques. As deep learning, semantic segmentation, which is an image processing technique, was used to automatically extract the cracked areas of the image. Semantic segmentation is a technique that estimates the image area of the object to be detected on a pixel-by-pixel basis. In this technique, images were first divided into arbitrary regions and annotated on the objects to be detected. The annotated images were used as training data to learn features and create models. This model estimated the area of the object to be detected in the unknown image using convolutional learning. Using this technique, “Crack areas” and “non-crack areas” can be estimated pixel-by-pixel using a model trained in advance from bridge images. Moreover, the length and width of the detected cracks can be calculated, and a crack map created. As shown in Figure 5, the features of the cracks can be extracted from the crack map created. Extraction of features—such as the size, shape, and location of the cracks—can provide support information for inspection engineers to consider and diagnose damaged areas.

Crack scale	Crack shape	Crack occurrence locations
		
Count the total number of pixels that are cracks (divide by crack width).	Calculate the intersections, branches, and endpoints of each crack.	Calculate which position in the overall inspection location has more cracks.

**Figure 5.** Example of crack feature extraction.

Finally, the location of the bridge and the inspection results are linked, the inspection results being displayed on the map. By grouping bridge groups by manager, diagnosis results, or inspection data, this information can be useful as reference material for determining the priorities of detailed inspection and repair programs.

### 3. Methods: Measurement Experiment of Image Upload Time

#### 3.1. Purpose of Experiment

The volume of data from ultra-high-resolution images of bridges taken using a 150-megapixel camera is enormous, with the upload time varying greatly depending on the communication speed. Consequently, we determined the upload time due to the differences between 4G and 5G communication environments.

An actual bridge was photographed in advance using a 150-megapixel camera, and the bridge images were uploaded to the bridge inspection support system from the 4G and 5G area points. The time taken for this process was measured.

#### 3.2. Target Bridge

The target bridge was a two-span girder bridge of length 41.3 m and width 4 m, constructed in 1967 (Figure 6), with a river running beneath it. The bridge type was steel plate girder, and the main material of the floor slab and bridge pier was concrete, and it was a general road with one lane. In the close visual inspection conducted every five years, the soundness of the bridge is determined on four levels (Table 2). In 2016, a close visual inspection of the target bridge detected corrosion, cracks, leaks, and stagnant water damage. Therefore, it was diagnosed as Soundness II.



Figure 6. Appearance of target bridge R.

Table 2. Bridge soundness category [18].

Classification		Condition
Soundness I	No damage	The bridge has not been disturbed.
Soundness II	preventive maintenance phase	The bridge is not disturbed, but it is desirable to take preventive maintenance measures.
Soundness III	early action phase	The bridge might be affected, and action should be taken early.
Soundness IV	emergency action phase	The bridge is impaired or likely to be impaired and in urgent need of repair.

Bridge R is located in an open field approximately 1.3 km away from a neighboring station, and the communication environment was that of a 4G-serviced area for all three major communication carriers (Figure 7).

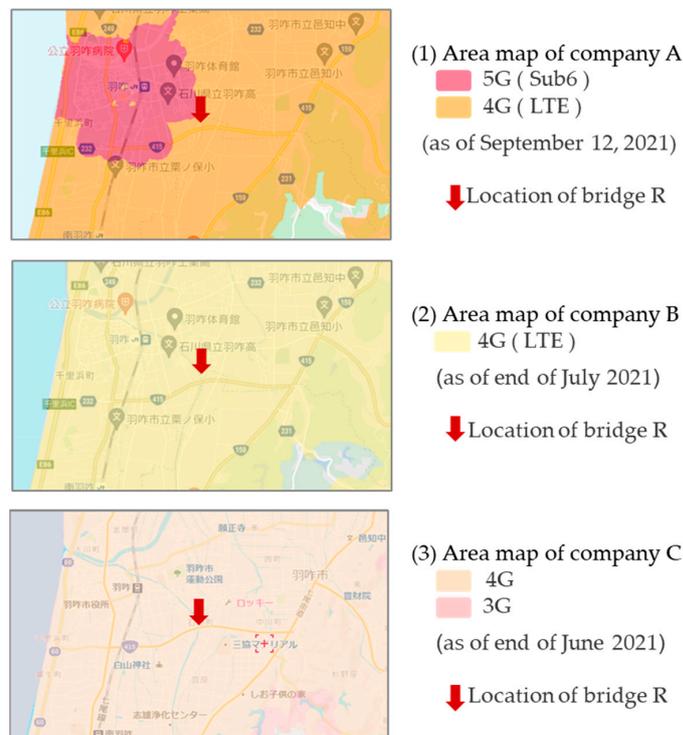


Figure 7. Diagram of the communication area of each communication carrier at bridge [19–21].

Panoramas of bridge R, its piers, and its baseplates were obtained in advance to be used as target images in the experiment. The time required for photographing the bridge was approximately 90 min. The images comprised three panorama images (with an average

data size of approximately 5 Mb each), two bridge pier images (approximately 120 Mb each), and 16 baseplate images (approximately 120 Mb each), for a total of 21 images. The total data capacity of the images was approximately 2.2 Gb.

### 3.3. Experimental Location

The three locations of target bridges were used for the 4G experimental area; two locations in *K* city were used for the 5G area. The devices used to upload the images included the Galaxy S20 5G smartphone and a Let's Note PC (model number CF-SV7LD3VU). The specifications of the PC were as follows: OS, Win10 Pro64bit; CPU, core i5-8250U (1.6 GHz); RAM, 8 Gb; and storage, SDD 256 Gb. Wired tethering connecting the 5G smartphone and PC via a local area network (LAN) was used to upload images from the PC to the bridge inspection support system. The 5G smartphone used was capable of 4G communication in the 4G area, so the same device configuration could be used in the 4G experimental area.

### 3.4. Upload Procedure

We measured the total work time ( $Tt$ ) from uploading each individual image from the PC to the bridge inspection support system until all 21 images had been uploaded. The total work time ( $Tt$ ) can be expressed as follows:

$$Tt = Ta + Tb \quad (1)$$

where  $Tt$  denotes the total work time,  $Ta$  denotes the upload time, and  $Tb$  denotes the PC operation time.

Additionally, a 4G connection can occur even in a 5G area, so the upload speed (throughput) was measured before the start of the experiment to confirm a 5G connection. The communication speed varies by minute amounts due to the influence of the usage environment and is not always constant, so it is not a given that the 21 images are uploaded at the measured throughput.

### 3.5. Image Upload Work Time Measurement Results

Table 3 shows the image upload results. The total work times are 35 min and 16 s on average for the 4G network and 14 min and 38 s on average for the 5G network, the upload work being completed using the 5G connection in less than half the time than that of the 4G connection. When comparing the image upload time, the 4G connection takes 26 min and 19 s, whereas the 5G connection takes an average of 5 min and 21 s, the 5G connection having an upload speed five times that of the 4G connection. In the case of *Bridge R*, it is evident that using 5G-based communication could reduce the upload time by 20 min compared to using 4G-based communication, with the total work time being shortened by more than half.

**Table 3.** Image upload work time.

Communication Environment	Location	Throughput (Mbps)	UPLOAD TIME	PC Operation Time	Total Work Time	
4G	Bridge R	14	24 min 24 s	9 min 35 s	33 min 59 s	
	Bridge H	8	30 min 15 s	8 min 2 s	38 min 17 s	
	Bridge I	11	24 min 18 s	9 min 15 s	33 min 33 s	
	Average	11	26 min 19 s	8 min 57 s	35 min 16 s	
5G	Location (1)	First	90	6 min 0 s	8 min 13 s	14 min 13 s
		Second	80	5 min 59 s	10 min 3 s	16 min 2 s
		Third	97	5 min 20 s	9 min 40 s	15 min 0 s
	Location (2)	First	120	5 min 10 s	9 min 59 s	15 min 9 s
		Second	100	4 min 52 s	9 min 3 s	13 min 55 s
		Third	99	4 min 46 s	8 min 42 s	13 min 28 s
	Average	98	5 min 21 s	9 min 17 s	14 min 38 s	

#### 4. Results: Simulated Remote Inspection by Bridge Engineers

##### 4.1. Purpose of Simulated Remote Inspection

If the image upload time can be shortened by using 5G networks, then the images can be shared from the bridge site to remote locations, and damage confirmation can be conducted simultaneously with on-site work, even from remote locations. Consequently, we conducted a simulated remote inspection where inspection engineers used a bridge inspection support system to investigate its usefulness and problems in terms of the operation of remote inspection using 5G networks.

##### 4.2. Overview of Simulated Remote Inspection

In the simulation experiment, a novice engineer at the simulated bridge site shares images of the bridge with a skilled engineer in the office via the inspection support system and receives inspection instructions, as shown in Figure 8. The simulated bridge site is located in K city Point (1), which is the 5G area in which the experiments discussed in Section 3 were conducted. A civil engineering student with no bridge inspection experience was set as the novice engineer. Additionally, the university campus of this research group was used as the simulated office, and Mr. A—a professional engineer with a Ph.D. in engineering and experience in construction division/steel structures and concrete, with concrete diagnosis certification—was set as the skilled engineer.

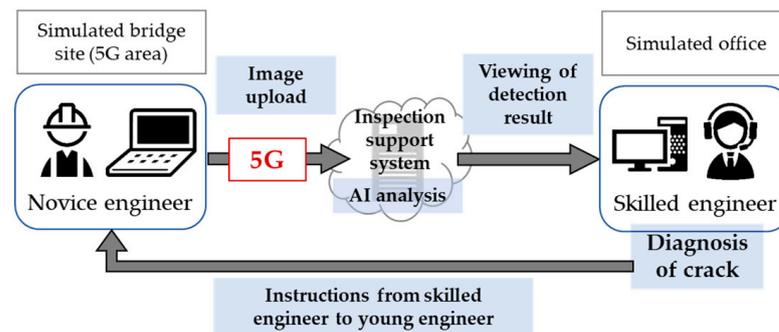


Figure 8. Configuration of the simulated remote inspection.

We used the same equipment configuration and 21 bridge images as detailed in Section 3 for the image uploads. The Webex (Cisco) online conferencing system was used as the communication system between the simulated bridge site and the simulated office.

##### 4.3. Experimental Scenario

In the simulation experiment, we conducted a series of tasks—from the uploading of the images to remote inspection and damage judgment—as shown in Figure 9. First, we uploaded the image from the simulated bridge site. The AI analysis for detecting cracks from images takes approximately 30 min, so we conducted the analysis in advance, saving the results on the inspection support system. A skilled engineer at the remote location visually confirmed the uploaded images and the AI detection results to confirm the crack damage, as shown in Figure 10.

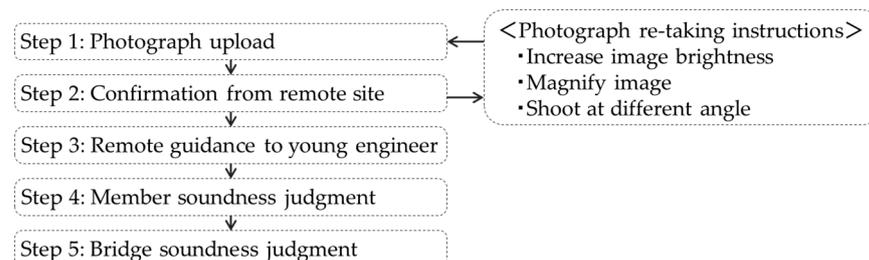
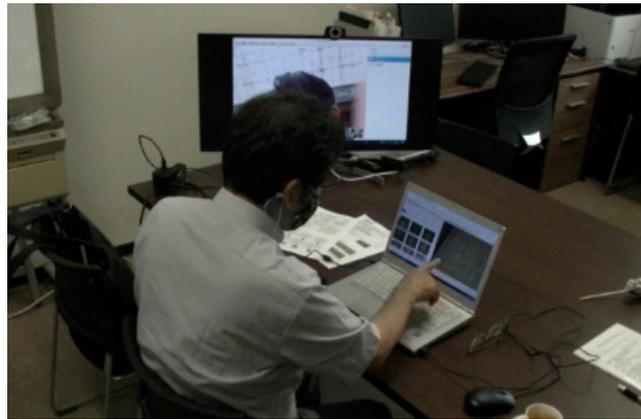


Figure 9. Experimental scenario.



**Figure 10.** Subject (engineer) giving remote instruction in a simulated office.

As previously shown in Figure 3, high-resolution images can provide detailed information even when enlarged, details of which are evident even when seen on a notebook PC. After image confirmation, the skilled engineer instructs the novice engineer at the bridge site to provide additional images as needed, providing instructions from the remote location. In this experiment, a remote skilled engineer instructs a novice on-site engineer to re-take and upload enlarged photographs of bridge members and photographs taken from different angles, verifying whether on-site and remote engineers can coordinate in an organic manner. Additionally, the following three instructions were each provided once—that is, “increase the image brightness”, “magnify the image”, and “shoot from a different angle”.

The skilled engineer then diagnoses the countermeasure categories for crack damage, considering their soundness. In this experiment, diagnosis is made on the assumption that there is no damage other than cracks.

#### 4.4. Experimental Results

Based on the experimental scenario shown in Figure 9—which assumes remote inspection—we demonstrated that a skilled engineer in a remote location could conduct operations for judging crack damage in a bridge from images. Even in a remote location, it is possible to visually recognize cracks from an ultra-high-resolution image of the bridge and determine the classification of countermeasures. In *Step 2* of the experimental scenario, the instruction to “enlarge the image” was included as an additional instruction, but it was found that if the image was a 150-megapixel image, the original image could be viewed without having to re-capture the image. Additionally, the brightness of the image tended to be lower at the top of the pier, but this could be manipulated by editing the image to enhance it. It was also found that communication between the on-site and remote engineers was particularly important in advancing the experimental scenario. In this experiment, the subjects used an online conferencing system and were able to communicate while observing each other, but when the remote engineer was giving detailed feedback and instructions, it was difficult to clearly convey what they were pointing to in an image.

*Mr. A*, who participated in this experiment as a skilled engineer, worked for a general construction consulting company and was also responsible for educating novice engineers. Consequently, after the simulated remote inspection experiment, we conducted an interview regarding the inspection process using our remote inspection support system, the results of which are shown in Table 4. The interviewee evaluated the system as being capable of enabling sufficiently good assessments from images (even if remote) if the images showed typical cracks. He was also of the opinion that the fact that an image could be re-taken immediately on site, since there was an on-site engineer, was a favorable aspect of the system. Moreover, he advised that, although it takes time to upload images in 4G-based areas, it would be better to consider efficient remote inspection by changing inspection

methods to accommodate slower 4G networks—that is, the methods should differ from those used in 5G-based areas.

**Table 4.** Interviews about simulated remote inspection.

Item	Interview Result
System operability	Operation possible with manual
Image upload waiting time	No need to wait on-site as a remote engineer can be contacted when upload is complete
AI analysis	Objective records can be kept
Visual inspection of images from remote area	Can visually recognize typical cracks in images Can handle the re-taking of photographs Brightness and enlargement of photographs can be changed using software, making the re-taking of photographs unnecessary The re-taking of photographs may be necessary when a bridge member needs to be seen from a different angle Novice engineers can be instructed from remote locations
Diagnosis/assessment	Judgment of crack countermeasure category is possible
Operation	Changing the operation method of the tool needs to be considered depending on 5G and 4G communication area
Future use	Can be used as an educational tool

## 5. Discussion: Image Data Volume and Upload Time

In Sections 3 and 4, we used a 150-megapixel ultra-high-definition camera to capture high-resolution images. Such a camera can be used to visualize cracks by enlarging the image [6]. However, ultra-high-definition cameras are expensive and can be difficult to use for all bridges. Consequently, we used a 20-megapixel digital camera (Nikon Z 50)—which is generally available—together with a 250-mm telephoto lens in an attempt to take high-resolution images. Using a 20-megapixel camera, the total volume of data increased because multiple images had to be taken of a single pier. Here, we discuss the differences in the volume of data due to the camera resolution and the subsequent differences in upload times due to the communication environment.

### 5.1. Camera Resolution and Bridge Image Data Volume

When taking images of bridge pier members and multiple images are required (instead of a single image), adjacent images need to be overlapped to ensure that there are no omissions in the image captures, after which the images have to be properly composited. Consequently, the number of shots increases, as does the volume of data.

Table 5 shows the results of calculating the volume of actual image data. For the images of one pier of *Bridge U* in Prefecture I using a 20-megapixel Nikon camera, the photographing distance from the target pier was approximately 17 m, and the extent of the overlap needed was set to 60–70%, requiring 62 shots. The volume of data per image was approximately 10 Mb, with the total volume of data for the 62 images being 568 Mb.

**Table 5.** Volume of data for the pier images.

	Approx. 20 Megapixels	Approx. 150 Megapixels
Photographed image		
Number of images	62 images	1 image
Total data volume	Approx. 568 Mb	Approx. 120 Mb

Moreover, for *Bridge R*—which was the target bridge detailed in Section 3—the images were taken from a position approximately 12 m from the pier, a 150-megapixel camera being able to capture the image with a single 120-Mb shot.

5.2. Upload Time with Respect to Image Data Volume

It is evident that the image upload time increases as the bridge image data volume increases. Consequently, we investigated the change in upload times due to changes in the image data volume. We used the 5G and 4G connections at the 5G verification facility in the prefecture, where we prepared image data with data volumes of 100, 300, 500, 1000, 1500, and 2000 Mb and measured the upload times.

The upload time was defined to be the time from the start of the uploading process to its conclusion—that is, from the notebook PC to the cloud server (Google Drive). The upload of each data volume was conducted three times, and their averaged results are shown in Figure 11. The upload time is zero when the volume of data is zero, so linear approximation using an intercept of zero can be used. Calculating the ratio of the slopes of the approximation formulae for the 4G and 5G connections, the upload time for the 5G connection is approximately 42% of that for the 4G connection.

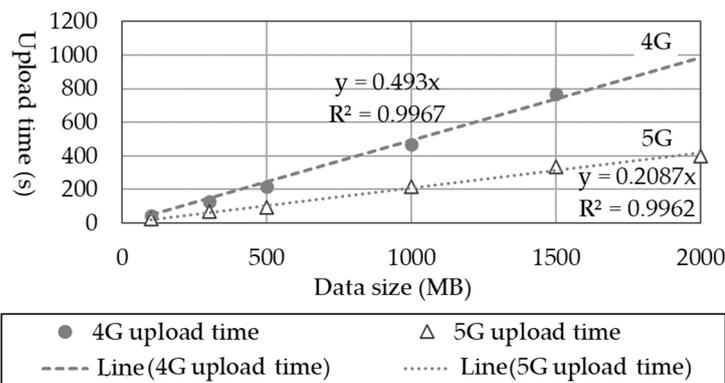


Figure 11. Data volume and upload time.

The communication environment and the type of uploaded data differ from the experiment detailed in Section 3.5, so although the reduction ratio of the upload time using the 5G connection is different, it is evident that increases in the data volume proportionally increase the upload time. Moreover, the upload time could be considerably reduced using the 5G connection in comparison to the 4G connection.

5.3. Discussion of Camera Resolution and Data Upload Time

We calculated the estimated time required to upload an image of one pier due to differences in camera resolution and communication environment based on the results discussed in Sections 5.1 and 5.2, as shown in Table 6.

Table 6. Estimated image upload time for one bridge pier.

		Camera Resolution	
		20 Megapixels	150 Megapixels
Communication environment	4G	4 min 40 s	59 s
	5G	1 min 58 s	25 s

When calculating the time for the 568-Mb data volume (via the 20-megapixel camera) using a linear approximation of the graph shown in Figure 11, the upload time is 4 min 40 s for the 4G connection and 25 s for the 5G connection. When shooting using the 150-megapixel camera, it takes 59 s for the 4G connection and 25 s for the 5G connection. Compared to uploading via a 4G connection using a 20-megapixel camera, uploading via a 5G connection using a 150-megapixel camera reduces the upload time to 1/10 (by 90%).

## 6. Operation of Remote Inspection for Each Communication Environment on *Bridge R*

We considered efficient remote inspection operation methods for each communication environment (4G and 5G) based on the advice of *Mr. A*, the inspection engineer mentioned in Section 4.

### 6.1. Comparison of 4G and 5G Upload Speeds

The communication speeds for the 4G and 5G networks were not uniform or consistent within all areas, the speeds varying depending on the communication environment. The reduction in image-upload time when comparing the 4G and 5G connections also changed due to speed variations. As such, we compared the speed variations for the 4G and 5G connections.

Table 7 shows the 4G and 5G upload communication speeds obtained from each communication carrier as of July 2022. The communication speed has a theoretical value that can be demonstrated in an environment under optimal conditions and an execution speed experienced under real-world conditions. However, none of the three companies disclosed their execution speed for 5G connections, with only *Company A* providing an estimated communication speed. Consequently, in this section, we discuss the execution speed of the 4G connection of *Company A* and the estimated communication speed of the 5G connection.

**Table 7.** Upload speed of each communication carrier [22–27] (Unit: Mbps).

	4G		5G	
	Theoretical Value	Execution Speed	Theoretical Value	Estimated Communication Speed
Company A	131	17–39	480	82–168
Company B	112	11–26	481	Not disclosed
Company C	46	13–25	159	Not disclosed

The 4G execution speed is 17–39 Mbps, and the estimated 5G communication speed is 82–168 Mbps. In a communication environment where the 4G connection has a maximum speed of 39 Mbps and the 5G connection has a minimum speed of 82 Mbps, the speed of the 5G connection is approximately twice that of the 4G connection. Additionally, in a communication environment where the 4G connection has a minimum speed of 17 Mbps and the 5G connection has a maximum speed of 168 Mbps, the speed of the 5G connection is approximately 10 times that of the 4G connection. Consequently, the upload speed of the 5G connection compared to that of the 4G connection can be expected to fluctuate by a factor of 2–10 times, depending on the communication environment. Results fluctuated by a factor of approximately 5 in the upload experiment detailed in Section 3 and by a factor of approximately 2.5 in the upload time measurement detailed in Section 5, both of which are within the expected range.

### 6.2. Operation of Remote Inspection for Each Communication Environment

Due to variations in communication speeds, the 5G connection exhibited a fluctuation range of approximately 2 at the minimum level when compared to the 4G connection and approximately 10 at the maximum level; the use of 5G connections improves the efficiency of uploading work. However, as the 5G connection could not be used at all bridge sites, we investigated whether 4G could be efficiently operated by devising different inspection work procedures.

As discussed in Section 4, the operational flow of remote inspection using the bridge inspection support system for *Bridge R* consisted of photographing the bridge at the inspection site, uploading the image to the bridge inspection support system, confirmation of the image by a skilled inspection engineer at a remote area, consideration of the damage, and instructing and guiding the on-site engineers. In the case of *Bridge R*—which was in a 4G area—it took 90 min to take the panoramas and images of the bridge pier and baseplate.

Moreover, the uploading of the images took approximately 34 min (to upload 21 images), as shown in Figure 13 (1).

In a previous study, it took 10–15 min for an inspection engineer to detect cracks from a single image of the entire pier surface taken using an ultra-high-definition camera [16]. While AI-based damage detection work using the remote inspection support system could be expected to reduce engineering labor resources, it could take approximately 30 min to confirm 21 images. If it takes a certain amount of time to shoot, transmit, and confirm images, then the time could be shortened by proceeding with some of the work in parallel. Consequently, we proposed a method of shooting and uploading for each span.

Bridge R has two spans, so the baseplate and Pier P1 of Span 1 (on the side of Abutment A1) can be set as *photography* (1), and the baseplate and Pier P1 of Span 2 (on the side of Abutment A2) can be set as *photography* (2); this procedure is conducted as a two-section photographic and uploading process, as shown in Figure 12. *Photography* (1) comprises three panoramic images, eight baseplate images, and one bridge pier image, and *Photography* (2) comprises eight baseplate images and one bridge pier image. The volume of data for the panoramic images is not large, measuring just 5 Mbps/image; therefore, we could assume that the time taken for *Photography* (1) and *Photography* (2) be equally divided.

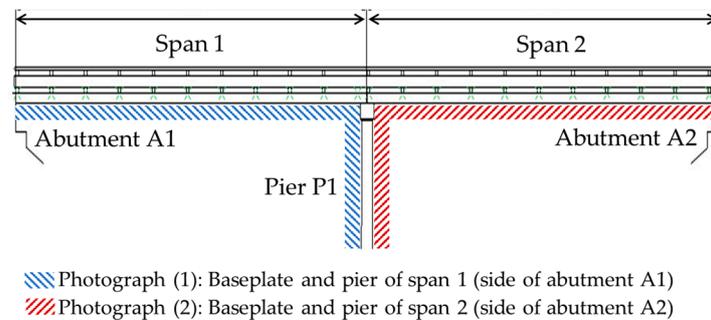


Figure 12. Target area for the two-section photography of the side view of Bridge R.

Figure 13 (2) shows the case where the work is conducted in two parts. The total time for shooting and uploading is the same as that shown in Figure 13 (1), but after the first upload, a skilled engineer at a remote location can check the image in parallel with the second shoot, cutting the confirmation time in half. However, as previously mentioned, the present study did not measure the confirmation time—that is, of the skilled engineers—making continued research into the specific reduction in time essential.

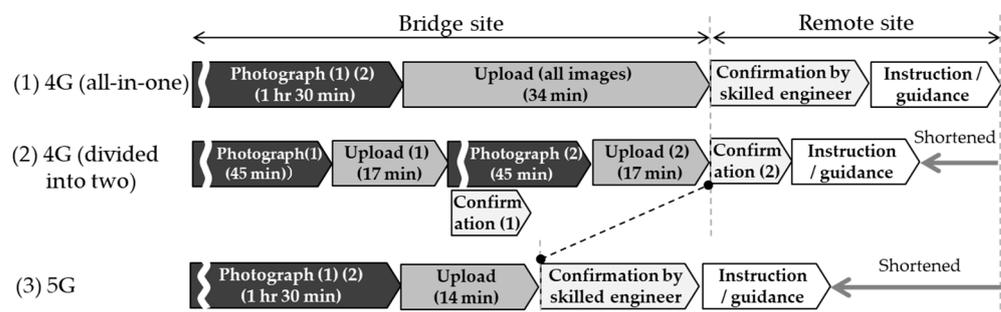


Figure 13. Operation of remote inspection for the 4G and 5G communication environments.

Moreover, when Bridge R is in a 5G area, the upload time is 14 min, which is 20 min shorter than in the 4G area, so even if shooting and uploading are conducted simultaneously, the overall work time can be shortened compared to that of the 4G area, and remote inspection can be conducted more efficiently, as shown in Figure 13 (3). In the case of a bridge with many spans, even in a 5G communication environment, it is evident that increased efficiency can be achieved by dividing the images into one or more spans and uploading them accordingly.

## 7. Conclusions

In this study, we verified the bridge-inspection labor reduction via a remote inspection support system that uses ultra-high-definition images and ultra-high-speed 5G communication. First, to determine the reduction in image upload time using 5G communication, we measured the upload time of bridge images using 4G and 5G networks, respectively. The upload time for the 21 images of *Bridge R* (total data capacity: approximately 2.2 Gb) was five times faster using a 5G network than using a 4G network. Moreover, the overall upload time—including the notebook PC upload time—could be shortened by approximately 20 min using the 5G network compared to using the 4G network, enabling a reduction in labor accordingly.

To verify the feasibility of remote inspection using 5G communication, we then conducted a remote bridge inspection simulation experiment. A remote skilled engineer could confirm cracks from uploaded images, giving instructions and offering guidance to the personnel at the bridge site from a remote location. Using 5G communication to rapidly share images enabled the realization of collaborative inspection work between the skilled engineer at a remote location and the engineer at the bridge site while maintaining two-way communication between them. If in an environment where appropriate instructions could be received from a remote skilled engineer, then bridge photography at the bridge site could be performed by inexperienced engineers. Evidently, using 5G communication with this system could enable skilled engineers to inspect bridges at multiple locations from the office, improving inspection efficiency even with limited personnel.

Currently, 5G areas are to some extent limited and ultra-high-definition cameras can be expensive, making it unrealistic to use them for actual bridge inspections. Consequently, we estimated the time required to upload images taken using a generally available 20-megapixel camera over a 4G connection. The upload could take up to 10 times longer than when using an ultra-high-definition camera and a 5G connection. Even if it currently takes some time to upload images from a bridge site using a mobile connection, we consider that this time could be reduced by a factor of 10 by using ultra-high-definition cameras and a 5G connection in the future. Moreover, the speed of 5G connections is still in development and will continue to improve. Even though 5G technology is not yet commonplace today, if the use of ultra-high-definition cameras and ultra-high-speed communication becomes the norm due to future technological developments, then the use of these technologies could lead to a considerable reduction in personnel requirements.

Finally, we proposed an operational method for shooting and uploading images of each span, with the aim of improving efficiency, by using an inspection operation method under 4G conditions. Time reductions could be achieved by simultaneously implementing the shooting and uploading of images for each span and having the remote engineer conduct image confirmation. Consequently, efficient inspection work could be achieved by changing the operation of remote inspection based on the communication environment at the bridge site.

Future research should verify the efficiency and efficacy of work conducted under specific conditions for *Bridge R*, as well as various other bridges. Clearly, the number of images and the volume of data could change depending on the size and scale of a bridge. Consequently, even when using 5G communication, if the volume of data becomes too large, it could be more efficient to divide shooting and uploading into multiple tasks. In addition, because the shooting time varies depending on the resolution of the camera, it is necessary to measure the shooting time by using different cameras to shorten the shooting time. It could also be necessary to verify the time required for a skilled engineer to confirm images, as the appropriate number of divisions for shooting and uploading could change depending on the time taken for a skilled engineer to confirm images remotely.

**Author Contributions:** Conceptualization, M.Y., M.F., T.F. and T.M.; methodology, M.Y., M.F., T.F. and T.M.; software, T.F.; validation, M.Y., T.M. and T.F.; formal analysis, M.Y. and T.F.; investigation, M.Y. and T.F.; resources, M.Y., T.M. and T.F.; data curation, M.Y., T.M. and T.F.; writing—original draft preparation, M.Y.; writing—review and editing, M.Y. and M.F.; visualization, M.Y.; supervision, M.F. and J.T.; project administration, M.F.; funding acquisition, M.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Road Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Road Maintenance Annual Report. Calculated from Appendix (8) Number of Bridges and Tunnels by Year of Construction. Bridges. p. 230. Available online: [https://www.mlit.go.jp/road/sisaku/yobohozen/pdf/r02/r02\\_08maint.pdf](https://www.mlit.go.jp/road/sisaku/yobohozen/pdf/r02/r02_08maint.pdf) (accessed on 3 February 2022).
2. Japan Society of Next Generation Sensor Technology. Report on Questionnaire of Bridge Inspection Work in Municipal Bridges. Conclusion, (1) Inspection Work, Q14 Results. p. 57, 3.2. Available online: [https://www.socialinfra.org/p\\_activity/questionnaire/Bridge\\_tenken\\_Digest.pdf](https://www.socialinfra.org/p_activity/questionnaire/Bridge_tenken_Digest.pdf) (accessed on 3 February 2022).
3. Ministry of Land, Infrastructure, Transport and Tourism, Efforts Toward On-Site Implementation of Innovative Technologies and Support for Local Governments Lacking Technical Staff, Future Investment Council, Industry-Government Council “Next Generation Infrastructure” Meeting (2nd), Material 2. p. 5. Available online: <https://www.kantei.go.jp/jp/singi/keizaisaisei/miraitoshikaigi/sankankyougikai/infrastructure/dai2/siryou2.pdf> (accessed on 20 June 2022).
4. Chun, P.-J.; Shimamoto, Y.; Okubo, K.; Miwa, C.; Ohga, M. Deep learning and Random Forest based crack detection from an image of concrete surface. *J. Jpn. Soc. Civ. Eng.* **2017**, *73*, I\_297–I\_307. [CrossRef] [PubMed]
5. Fujita, Y.; Taguchi, T.; Hamamoto, Y. Image mosaicking and semi-automatic crack evaluation for visual inspection of concrete structures. *J. Jpn. Soc. Civ. Eng.* **2018**, *74*, 18–32. [CrossRef]
6. Minami, T.; Fukuoka, T.; Fujiu, M.; Sagae, M. Analysis on improvement of resolution and accuracy of automatic crack detection using average shift mesh. *Artif. Intell. Data Sci.* **2020**, *1*, 473–480.
7. Machiguchi, A.; Mizuno, H.; Akasaka, T.; Sugimoto, A.; Ando, M.; Urata, K.; Kita, T. Introduction example of simple inspection using AI bridge diagnosis support system in Nanao City. *Infrastruct. Maint. Pract.* **2022**, *1*, 337–344.
8. Saito, S.; Fujiu, M.; Fukuoka, T. Proposal of remote inspection method for labor saving of bridge inspection through adaptation of AI and VR technology to real bridges. *Infrastruct. Maint. Pract.* **2022**, *1*, 372–377.
9. Hayashi, D.; Zhen, W.; Hu, Y.; Li, Y.-J.; Yamakawa, S.; Scherer, S.; Kitani, K.; Shimada, K. 3D model generation and automatic conversion to FEM model for inspection and evaluation of concrete structures. *Infrastruct. Maint. Pract.* **2022**, *1*, 189–195.
10. Nitta, Y.; Yuta, S.; Takewaka, S.; Ohtsuki, T.; Kondou, K.; Watanabe, K.; Yamauchi, G. Considerations on the superiority of robots for bridge inspection and its performance evaluation method for social implementation. *J. Robot. Soc. Jpn.* **2022**, *40*, 35–53. [CrossRef]
11. Minami, T.; Fujiu, M.; Takayama, J.; Suda, S.; Okumura, S.; Watanabe, K. A basic study on diagnostic imaging technology for bridge inspection using super high-resolution camera. *Sociotechnica* **2018**, *15*, 54–64.
12. Yoshikura, M.; Minami, T.; Fukuoka, T.; Fujiu, M.; Takayama, J. A study on communication between bridge inspection site and remote site using 5G and bridge damage inspection support system. *Artif. Intell. Data Sci.* **2020**, *1*, 545–553.
13. Japan Civil Engineering Consultants Association, Kinki Branch, Bridge Inspection (Guidance on Appropriate Periodic Inspection Methods for Bridges), Report by Research Committee on Maintenance and Management of Public Civil Engineering Facilities. p. 2-1-14. Available online: <https://www.kk.jcca.or.jp/upload/oteire/02/file01.pdf> (accessed on 20 June 2022).
14. Minami, T.; Fujiu, M.; Takayama, J.; Suda, J.; Okumura, S. A Study on Image Diagnostic Technology for Bridge Inspection Using Ultra High Resolution Camera. In Proceedings of the 5th International Conference on Road and Rail Infrastructure, Zadar, Croatia, 17–19 May 2018; pp. 79–85.
15. Minami, T.; Urata, W.; Fujiu, M.; Fukuoka, T.; Takayama, J. Analysis of the effect of image attributes and inspection skills on image diagnosis of bridges—Using super high resolution camera. *J. Jpn. Soc. Civ. Eng.* **2019**, *75*, I\_50–I\_57. [CrossRef] [PubMed]
16. Urata, W.; Minami, T.; Ishimura, N.; Fujiu, M.; Fukuoka, T.; Takayama, J. Analysis of the influence of inspection skills of bridge inspection on crack detection results and required time in diagnostic imaging of bridges—Study using super high resolution camera. *J. Jpn. Soc. Civ. Eng.* **2020**, *75*, I\_591–I\_598. [CrossRef] [PubMed]
17. Ministry of Land, Infrastructure, Transport and Tourism, Inspection Support Technology Performance Catalog (Draft), June 2020, Technical Number BR010005-V0020. Available online: <https://www.mlit.go.jp/road/sisaku/inspection-support/pdf/11.pdf> (accessed on 3 March 2023).
18. Ministry of Land, Infrastructure, Transport and Tourism Road Bureau, Road and Bridge Inspection Guidelines (February 2019). Available online: [https://www.mlit.go.jp/road/sisaku/yobohozen/tenken/yobo4\\_1.pdf](https://www.mlit.go.jp/road/sisaku/yobohozen/tenken/yobo4_1.pdf) (accessed on 9 July 2023).

19. NTT Docomo Inc.; Service Area Map. Available online: <https://www.nttdocomo.co.jp/area/servicearea/?rgcd=05&cmcd=5G&scale=250000&lat=36.88708&lot=136.79935> (accessed on 25 September 2021).
20. KDDI Corporation, Service Area Map. Available online: <https://www.au.com/mobile/area/map/> (accessed on 25 September 2021).
21. SoftBank Corporation, Service Area Map. Available online: <https://www.softbank.jp/mobile/network/area/map/> (accessed on 25 September 2021).
22. NTT Docomo Inc.; Premium 4G. Available online: [https://www.docomo.ne.jp/area/premium\\_4g/](https://www.docomo.ne.jp/area/premium_4g/) (accessed on 16 July 2022).
23. NTT Docomo Inc.; 5G. Available online: [https://www.docomo.ne.jp/area/5g/?icid=CRP\\_menu\\_to\\_CRP\\_AREA\\_5g](https://www.docomo.ne.jp/area/5g/?icid=CRP_menu_to_CRP_AREA_5g) (accessed on 16 July 2022).
24. KDDI Corporation, Execution Speed. Available online: <https://www.au.com/mobile/area/effective-speed/i/#ios> (accessed on 16 July 2022).
25. KDDI Corporation, Ultra-High-Speed Communication Area. Available online: [https://www.au.com/mobile/area/other\\_speed/](https://www.au.com/mobile/area/other_speed/) (accessed on 16 July 2022).
26. SoftBank Corporation, Frequently Asked Questions. Available online: <https://www.softbank.jp/support/faq/view/10870> (accessed on 16 July 2022).
27. SoftBank Corporation. Ministry of Internal Affairs and Communications Execution Speed Survey. Measurement Method/Measurement Results. Available online: <https://www.softbank.jp/mobile/network/service/speed-survey/> (accessed on 16 July 2022).

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