Results and Discussions of Robot-supported Periodic Inspection of Long-span Prestressed Concrete Bridge

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ABSTRACT

The revision of the Road Act in 2013 mandated inspection of bridges by the road administrator concerned in Japan. A bridge regular inspection is conducted once in five years from 2014. In local municipalities, increasing the efficiency of periodic inspections and reducing inspection costs have become major issues. At the end of February 2019, the Guideline for Periodic Road Bridges Inspection was revised so that new inspection technology could be used. It is strongly desired to increase the number of cases of periodic inspection of bridges incorporating robotic technology (RT) such as drones. Gifu University research team adopted RT into the legal periodical inspection of Kakamigahara Bridge in Gifu, Japan in 2018 before the revision of the Guideline. Based on the guidelines (draft) proposed by a committee of our team, two step inspections were adopted. In the first step, "preliminary survey" was carried out by using RT. In the second step, "close visual inspection" was conducted on the whole bridge by human inspectors with the results of the preliminary survey. This paper reports results of the survey and the visual inspection, and discusses effects of adopting the preliminary survey into the legal periodical inspection. The preliminary survey enabled the engineers to ascertain and inventory the types and positions of defects beforehand, allowing a significant reduction in the number of days of one side closure of the bridge from 10 to 4. The inspection results were arranged by two types of techniques for comparison, demonstrating that “connecting defect maps of 3D structural models with images” is effective. Findings from the implementation activities were summarized regarding the form of using inspection RT, presenting the performance requirements, performance verification, enhancing the work environment, safety measures, etc.

Keywords: Periodic inspection, Prestressed concrete bridge, Robotic technology, Visual inspection

1. INTRODUCTION

The revision of the Road Act in 2013 mandated inspection of bridges by the road administrator in Japan. The bridge regular inspection is conducted once in five years from 2014. So far, the regular bridge inspections were mandated to conduct by human inspectors and based on the close visual inspection. However, inefficiency of the regular inspections and increase of inspection costs have become major issues in local municipalities. In order to solve those issues, introduction of robotic technology (RT) has been desired. Under these circumstances, the Guideline for Periodic Road Bridges Inspection [1] was revised in February 2019. One of the important points of this revise is it allows not only visual inspection, but also using any methods, such as RT, which are recognized to obtain the same quality information as visual inspection. From this background, it is strongly desired to increase the number of cases of periodic inspection of bridges incorporating RT such as drones so as to accelerate introduction of RT to improve inspection efficiency.

Gifu University conducted research titled “Implementation of effective SIP maintenance technology by maintenance expert (ME) network” (hereafter referred to as “Gifu University SIP [2]”) from September 2016 to March 2019 as part of the technology for maintenance renewal, and management of infrastructure, a project under the Cabinet Office’s Cross-ministerial Strategic Innovation Promotion Program (SIP).

Prior to the revision of the Guideline [1], robot-supported periodic inspection of a 594m long-span prestressed concrete bridge, Kakamigahara Bridge which is managed by Kakamigahara city in Gifu prefecture (Fig.1), was conducted by Gifu University SIP team in 2018. When adopting RT, the team faced various problems including conformity to current technical standards, such as the Guideline before the revision and Gifu Prefecture's Bridge Inspection Manual [3], ascertaining the characteristics, evaluating the performance, and devising combinations of various RTs, and processes of cost determination and order placing. To provide solutions of these problems, an inspection guidelines (draft) [4] and other proposals were formulated by authors. The wide pedestrian sections of the bridge made it difficult to use a general large-scale bridge inspection vehicle with a 4m boom (Fig. 2) to inspect the undersurface of the bridge. The bridge therefore required special inspection methods including the use of an ultralarge inspection vehicle with a 5m boom, ropework, and inspection scaffolding.

This paper reports on the results of the robot-supported periodic bridge inspection on Kakamigahara Bridge, as well as subjects and advantages newly recognized through actual RT inspection. Points of attention and ideas for using RT inspection are also reported.

2. PRELIMINARY SURVEY AT KAKAMIGAHARA BRIDGE

2.1 Principles and process flow

The inspection guidelines (draft) [4] were formulated for robot-supported inspections, and although the functions of some RT has been verified by field testing, there was hardly any field experience in actual periodic inspection. For this reason, it is considered that to appropriately select the RT and judge the application method for inspection by bridge managing parties and inspecting parties is currently difficult. In order to overcome those issues, the Gifu University SIP, which had conducted field testing twice before, proposed to carry out two step inspections. In the first step, "preliminary survey" was carried out by RT prior to the close visual inspection of the periodic inspection of Kakamigahara Bridge as supporting close visual inspection. In the second step, "close visual inspection" was conducted on the whole bridge with the results of the preliminary survey by a construction consultant with expertise knowledge about periodic inspection of bridges.

The goal of the preliminary survey was to acquire information regarding defective events on intended members (undersurfaces of slabs, main girders, and substructure) through the eyes of a robot, etc., to support the subsequent close visual inspection. As to the visual inspection, the efficiency of the work is enhanced by allowing the inspectors to ascertain the members and ranges to be subjected to intensive observation based on the defect information detected by the preliminary survey.

Regarding the specific process flow, extra time was planned between the preliminary survey and close visual inspection to allow for research/investigation of questions arising from respective defects recognized during the preliminary survey and preparation for appropriate operation during close visual inspection.

2.2 RTs and their combinations

In view of the results of field testing by Gifu University SIP, it was judged difficult to cover the preliminary survey of all members of the bridge by a single RT in consideration of the functions and performance of the current level of RT. Therefore, the method which combines the six types of RTs listed in Fig.3 was proposed for the present preliminary survey. Fig. 4 shows the role allotment of each RT for members under preliminary survey.

Fig.1 Kakamigahara Bridge

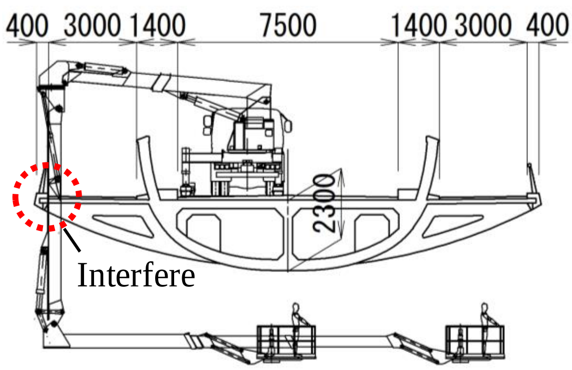


Fig.2 Inspection with a general large-scale inspection vehicle

2.3 Contents of preliminary survey

The following three types of survey were proposed and conducted so that RT could be well utilized:

2.3.1 Narrow area survey

The narrow area survey was conducted for detecting various defects including cracks 0.2 mm or more in width. Detailed images of members were shoot at a short distance with a relatively narrow camera field of view. It was confirmed in the field testing by Gifu University SIP that the RTs used in the narrow area meet the performance requirements shown in Table 1 [5].

2.3.2 Wide area survey

The wide area survey was conducted for ascertaining the state of the entire bridge, capturing various defects excluding small defects, and their positional relations, and creating orthophotographs and 3D models of the bridge.

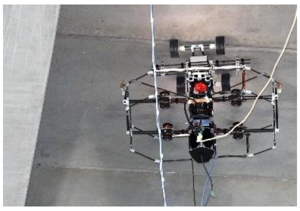
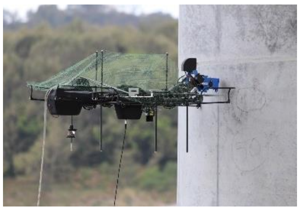
Type	Name of RT	Developing Company	Working	Name of RT	Developing Company	Working
Drone	(1) Two-wheeled drone with camera for bridge inspection	Fujitsu Limited and Nagoya Institute of Technology		(2) Drone with controllable pitch propellers	DENSO corporation	
Robotic Camera	(3) Robotic camera indicating crack scale for bridge inspection	Sumitomo Mitsui Construction Company, Limited and Hitachi Industry & Control Solutions, Limited		(4) Camera system for bridge inspection	Zivil survey design corporation	
RT with Hammer	(5) Drone with wheels for visual observation and hammering tests	SHIN-NIPPON Nondestructive Inspection Company, Limited		(6) Drone with hammering test equipment for bridge inspection	NEC Corporation	

Fig. 3 RTs for preliminary survey of Kakamigahara Bridge

		A2–P9	P9	P9–P8	P8	P8–P7	P7	P7–P6	P6	P6–P5	P5	P5–P4	P4	P4–P3	P3	P3–P2	P2	P2–P1	P1	P1–A1
Preliminary Survey	Wide view	(2)																		
Preliminary Survey	Narrow view: Superstructure	(3)		(3)		(4)		(2)		(2)		(4)		(4)		(4)		(3)		(3)
Preliminary Survey	Narrow view: Bearing		(1)		(1)		(1)		(1)		(1)		(1)		(1)		(1)		(1)	
Preliminary Survey	Narrow view: Substructure		(1)		(1)		(2)		(2)		(2)		(1)		(1)		(1)		(1)	
Preliminary Survey	Hummering test	Superstructer (5) , Substructure (6)																		
Human Visual Inspection		Inspection vehicle					Wide Zone / Rope work	Inspection vehicle			Wide Zone / Rope work	Inspection vehicle								

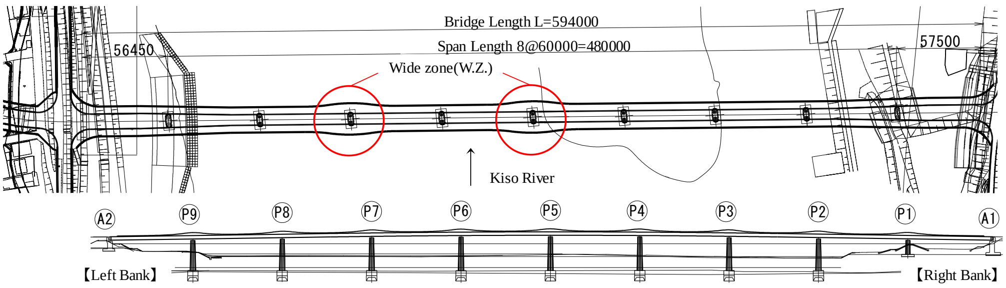


Fig. 4 Combination of RTs

Table 1 Requirements for information obtained through RT

Requirements			Verification
Detection of defect	Presence and type	defect can be detected and classified.	Pictures and sketches of defect are provided to confirm the requirements in the left column. The locations, ranges and directions of defect shown in the provided pictures and sketches are roughly in agreement with those in the defect chart prepared by visual inspection from a short distance.
	Location	defect can be detected in a manner to allow sketching of defectd portions in relation to other members.	
	Size	The overall image can be obtained to judge whether the defect is localized or extensive.	
	Direction and pattern	The direction (horizontal, vertical, diagonal, longitudinal or transverse to reinforcement, etc.) and pattern (map cracking, etc.) of defect can be detected.	
	Water penetration paths	The source and path of water ingress can be detected regarding defect involving water, such as water leakage and free lime.	
Measurement of defect	Size	Crack width: The crack width of 0.2 mm or more can be measured with an error margin of 0.0 to + 0.1 mm.	The measurement results of defect described in the defect chart prepared by visual inspection from a short distance or artificially created accuracy verification marks are roughly within the tolerances shown in the left column.
		Crack length, peeling, rebar exposure, leakage, etc.: The size can be measured with an error margin of 5 cm. (Length: L = XX cm, Area: A = XX cm × XX cm)	
	Displacement	The displacements of expansion gaps and bearings can be measured with an error margin of 10 mm.	

※ The following performance is required so that there can be no omission of cracks with a width of 0.3 mm or more.
For a crack width of 0.2 mm, it is acceptable to output a measurement result of 0.3 mm (0.2 mm + error 0.1 mm) to be on the safe side.
For a crack width of 0.3 mm, it is not acceptable to output a measurement result of 0.2 mm (0.3 mm - error 0.1 mm) on the dangerous side.

The entire bridge was serially shoot using a camera with a relatively wide field of view. The shooting range was around 5m by 3.4m. The resolution was around 0.84mm/pixel to be capable of detecting cracks with a width of around 0.3mm. It was confirmed in the field testing by Gifu University SIP that the RT used in the wide area research satisfies this performance requirement. The wide area survey gives full play to the high speed of drone-type robots, curtailing the time of work on site.

2.3.3 Hammering test

The hammering tests by RT were conducted on segments with discoloration, etc., which suggest delamination or blistering of concrete, found during wide and narrow area research. Note that segments where delamination or blistering was suspected were extracted from all sections of the bridge, but the RT hammering tests were conducted only on Pier P9 in the substructure and Span P7-P8 in the superstructure, due to the work efficiency and available time limitations of the robot. It was decided that other segments would be subjected to confirmation by close visual inspection.

2.4 Results of preliminary survey

The results of the narrow area survey were inventoried into defect maps and photo files for reference when organizing close visual inspection. The defect maps were laid out on the background of the orthophotographs created based on the wide area research to facilitate understanding of the positional relations between defects and the structure. Furthermore, by the RT which is shown at Fig.3 (1), 3D structural models were displayed on a tablet as shown in Fig. 5 to show the position of each defect detected. This was also connected with its photograph, along with the soundness judgment, to be available at the site of close visual inspection for enhancing the work efficiency.

As to the results of wide area survey, the orthophotograph of each structural unit (a span in the superstructure and a pier in the substructure) was divided into 5m × 5m mesh as shown in Fig. 6 by the RT which is shown at Fig.3 (2), with each mesh unit being connected to original photographic images. Defect marking, note entering, and image expansion can be done on the original photographic images. This significantly facilitated confirmation of defects on the desk and preparation of materials for planning subsequent close visual inspection.

Comparison between the images acquired by the wide and narrow area survey revealed that cracks with a width of approximately 0.3mm can be comfortably detected by either of the methods as shown in Fig. 7. It was therefore judged that

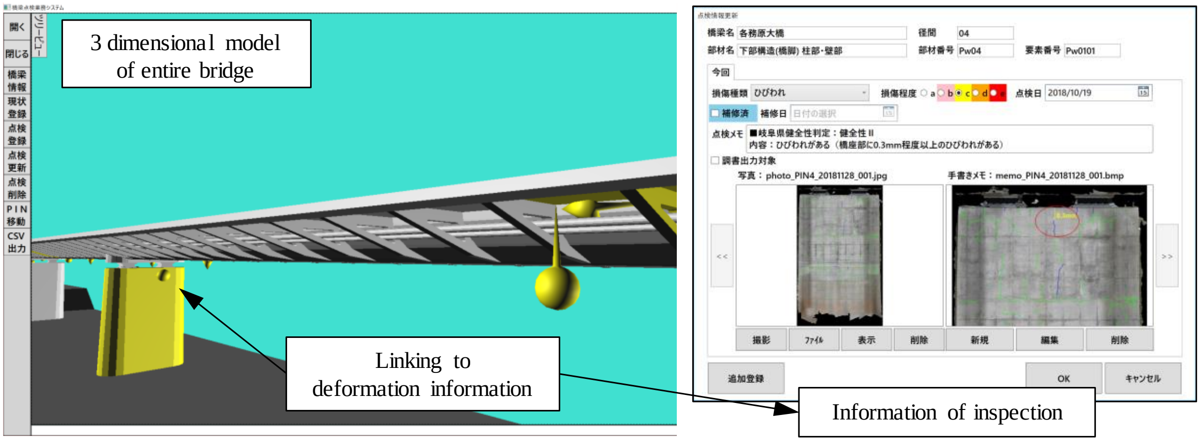
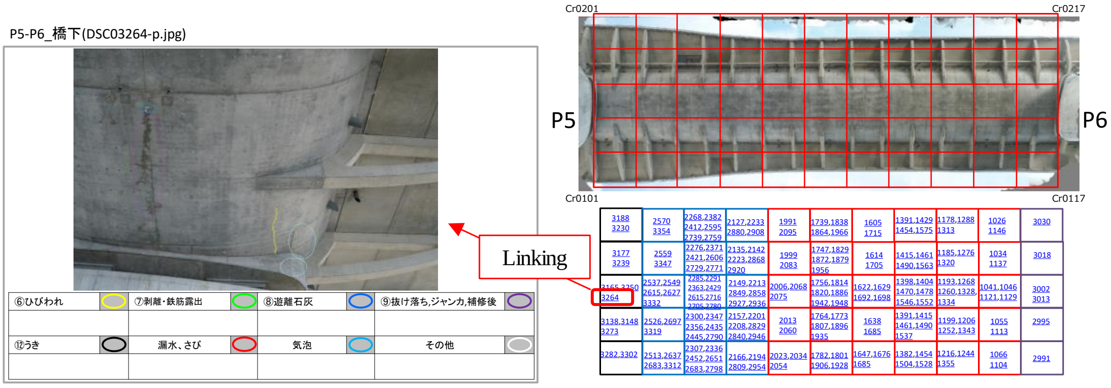


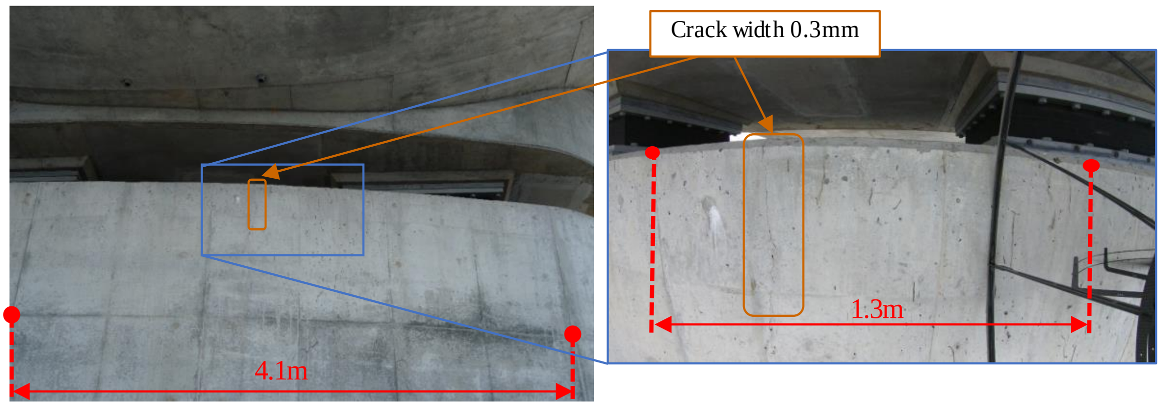
Fig. 5 Connect defect maps of 3D structural models with images



(a) Deformation information for each wide area

(b) Photo ledger information of wide area survey

Fig. 6 Results of wide area survey



(2) Drone with controllable pitch propellers
(6000×4000pixcel, Resolution 350×350dpi)
(a) Acquisition image of wide area survey

(1) Two-wheeled drone with camera for bridge inspection
(3840×2160pixcel, Resolution 96×96dpi)
(b) Acquisition image of narrow area survey

Fig. 7 Comparison between the images acquired by the wide and narrow area survey the RT system employed in the wide area survey was more effective for preliminary survey. With possible enhancement of camera performance, the photographing accuracy is expected to approach that of narrow area research, further increasing the efficiency of preliminary survey.

Preliminary survey utilizing RT as stated above enabled us to ascertain and inventory the types and positions of defects, thereby allowing us to narrow down the areas and segments where intensive close visual inspection is required. As a result, the number of days required for close visual inspection using the ultralarge inspection vehicle on Kakamigahara Bridge was significantly reduced to 4 days, which would otherwise have been 10 days by conventional techniques.

3. DISCUSSIONS FOR PROMOTING THE USE OF RT

Based on the above-mentioned implementation of RT for preliminary survey and research activities of Gifu University SIP over two years, the authors present newly recognized problems, advantages of using RT, and points of note and ideas regarding the use of RT as follows:

3.1 Forms of use

The forms of use of RT include the following three types:

(1) Use for inspection of segments where close visual inspection is difficult
Use RT exclusively for segments that have not been covered by conventional inspection.

(2) Use for preliminary survey
Carry out inspection beforehand through the eyes of a robot, followed by overall close visual inspection. The efficiency of visual inspection can be increased by making use of the results of the preliminary survey.

(3) Use for screening survey
Carry out research beforehand through the eyes of a robot to narrow the areas requiring confirmation, followed by close visual inspection. There may be sound bridges requiring no close visual inspection.

The authors consider that, from now on, the following procedure is effective in appropriately ascertaining and recording the condition of a bridge: For the first inspection, carry out preliminary survey using RT, followed by overall close visual inspection. For subsequent inspections, limit the ranges of close visual inspection based on screening survey by RT.

3.2 Presentation of performance requirements for RT

The administrator of a bridge should present reasonable performance requirements in specific terms for RT to be used (Table 1, for instance). The performance requirements to be presented should specify the defect-detecting accuracy just enough for judging the soundness class. Excessively demanding performance requirements should not be presented.

If excessive performance to measure extremely fine crack width is required, for instance, then a significantly large number of photographs becomes necessary to ensure the image resolution. This will complicate the subsequent image processing and data management, possibly reducing the work efficiency of judging the soundness class based on the images. Care should be exercised to present performance requirements in consideration of efficient data processing, while ensuring the minimum quality required of information acquired by RT. Judging from the results of the close visual inspection conducted following the preliminary survey, the performance requirements for RT given in Table 1 were appropriate.

3.3 Performance verification of RT

Whether or not the RT to be employed meets the performance requirements specified by the administrator of a bridge is verified by the following three methods:

(1) Performance verification by field testing
Carry out performance verification by preparing field-testing bridges with marks to verify the image accuracy. Bridges for field testing may be prepared by the bridge administrator or possibly by a third-party institution for shared use in the region.

(2) Verification by actual use experience under control of other bridge administrators

(3) Verification by catalogues, etc., issued by public organizations such as the Ministry of Land, Infrastructure, Transport and Tourism [1]

Since there have only been limited examples of performance verification by field testing so far, it is considered advisable to select (1) as a standard for the time being. Note that it is desirable to standardize the marks for verification to ensure generality of field testing. In performance verification, it is also advisable to confirm the operability of the function for measuring the length of defects and crack width, in consideration of the research results being used later.

3.4 Preparation of work environment for utilizing drone-type inspection RT

When utilizing drone-type inspection RT, care should be exercised for the following work environments:

(1) Ensuring a good visibility
The visibility of the entire research area from the operation point should be ensured, as radio waves used for controlling a drone are mostly line of sight. Ensuring the visibility is also necessary when using an auto-tracking total station for the positioning control of the drone. When the site is wooded, felling of trees may be necessary beforehand.

(2) Work plan in consideration of wind characteristics
The flight stability of general drones is reduced by strong wind with a wind speed of around 5m/sec or more. The wind conditions may change from morning to afternoon in certain areas, or the wind may tend to keep shifting near a bridge. Such wind characteristics should be ascertained beforehand to formulate an efficient work plan.

(3) Dealing with radio wave disturbance
A general drone is normally controlled by radio waves in frequency bands of 2.5GHz or 5GHz, which are prone to interference from other devices such as Wi-Fi systems and radar. The radio wave conditions of the neighbouring areas should be confirmed beforehand for safe and efficient drone work, with countermeasures for radio wave disturbance being investigated.

(4) Work on the water
The Civil Aeronautics Act limits the flight of a drone to visual flying. Operation of a drone on a boat may therefore be necessary when inspecting a bridge crossing a wide river. Postural stability of the robot operator should be ensured when the river flows fast or when the water is shallow with a risk of the bottom of the boat coming in contact with the riverbed.

3.5 Safety measures for utilizing drone-type inspection RT

When using drone-type inspection RT, safety measures different from those for conventional inspection are required.

(1) Ensuring safety in the event of radio wave disturbance
When the drone control signals are disrupted by obstacles or radio wave disturbance occurs due to interference, measures should be taken to prevent runaway of the drone.

(2) Ensuring safety of road users
Safety measures should be taken to protect the road users (vehicles and pedestrians) on the bridge from being injured by an out-of-control drone, even when the operation is carried out under the bridge. Permission for road occupancy or road use should be obtained depending on the methods of work.

(3) Supply and backup of a substitute drone
Since an inspection robot is a precision machine, a supply system for a substitute drone should be established in case of trouble, such as malfunction.

3.6 Arrangement and storage of research results

The results of inspection using RT can be systematized in the following forms:

(1) Defect maps of 2D drawings and photograph files (conventional technique)
(2) Connect defect maps of 2D images with images
(3) Connect defect maps of 3D structural models with images
(4) Connect defect maps of 3D images with images

Though (4) is the targeted form, the present results were summarized in the forms of (2) and (3) due to the processing capacity of computers. It was then judged that the form of (3) is desirable for close visual inspection in view of the ease of reference to the results of preliminary survey and modifiability.

The following three storage systems are conceivable for inspection results:

(1) Storage by each bridge administrator
(2) Storage at data center, etc., of each municipality including prefecture
(3) Storage at the national data center

In consideration of the risks including earthquakes, storage system (3) is desirable with the advantage of standardizing the format of the research results.

4. CONCLUSIONS

This paper reported the results of preliminary survey prior to close visual inspection of a periodic inspection of a long-span prestressed concrete bridge using RT based on the inspection guidelines (draft) formulated by Gifu University SIP [2]. Problems newly recognized by actually using robotic inspection techniques were also reported, as well as the advantages of applying RT, points of attention, and ideas. These are summarized as follows:

(1) Preliminary survey was carried out on Kakamigahara Bridge, a long-span prestressed concrete bridge with a large cross-section, utilizing RT. This enabled the engineers to ascertain and inventory the types and positions of defects beforehand, allowing a significant reduction in the number of days of one side closure of the bridge from 10 days to 4 days.

(2) Wide- and narrow-area surveys using RT were attempted in this research. By comparison of those results, it was demonstrated that efficient work on site can be achieved by enhancing the performance of the camera mounted on the drone.

(3) The inspection results were arranged by two types of techniques for comparison, demonstrating that “connecting defect maps of 3D structural models with images” is effective for close visual inspection.

(4) Findings from the implementation activities were summarized regarding the form of using inspection RT, presenting the performance requirements, performance verification, enhancing the work environment, safety measures, etc.

It is hoped that this report will serve as a reference for bridge administrators and inspection engineers who look to bridge inspection utilizing inspection RT.

ACKNOWLEDGEMENTS

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