PERIODIC INSPECTION OF PC BRIDGE WITH BOTH ROBOT TECHNOLOGIES AND CLOSE VISUAL OBSERVATION

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ABSTRACT

The Guideline for Periodic Road Bridge Inspection was revised in February 2019 so that new inspection technology could be used in Japan. Gifu University SIP research team adopted robot technology (RT) for the mandated periodic inspection of Kakamigahara Bridge in Gifu, Japan, 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 entire bridge by inspectors using the results of the preliminary survey. The preliminary survey utilizing RT enabled the inspectors to ascertain and inventory the types and locations of defects, thereby allowing them to narrow down the locations and segments where intensive close visual observation is required. As a result, the number of days required for close visual inspection using an ultra-large inspection vehicle on Kakamigahara Bridge was significantly reduced to 4, which would otherwise have been 10 by conventional techniques. The RT used had a sufficient defect detection accuracy to be able to substitute for close visual observation if utilized while paying attention to the blind spots of the camera.

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

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1. INTRODUCTION

In Japan, the revision of the Road Act in June 2013 mandated inspection of bridges, tunnels etc. by road administrators. Periodic inspection once every 5 years began in July 2014, with the first round being completed in March 2018. Approximately 720,000 bridges all over Japan require periodic inspection, 70% of which are under the administration of municipalities. Streamlining and cost reduction by introducing new inspection technologies are therefore pressing issues for bridge maintenance by municipalities. The application of robot technology (RT) including drones with built-in cameras to periodic inspection is expected to bring about various advantages, such as mitigating traffic congestion during inspection, improving safety of inspection work, accumulating detailed data, as well as reduction in inspection cost. The Guideline for Periodic Road Bridge Inspection [1] was revised in February 2019, so that new inspection technology could be used. Now, it is strongly desired to increase the number of cases of periodic inspection of bridges incorporating RT such as drones with built-in cameras.

Our Gifu University SIP research team (hereafter referred to as "Gifu University SIP" or "our team") [2] is one of the project teams for supporting regional implementation of new technologies for municipalities in the category of "Infrastructure Maintenance, Renovation, and Management" under the SIP (Cross-ministerial Strategic Innovation Promotion Program), supervised by the Cabinet Office. Gifu University SIP was adopted in September 2016 and its activities completed in March 2019. Prior to the revision of the Guideline, robot-supported periodic inspection of a bridge was conducted by Gifu University SIP. When adopting RT, the team faced various challenges including conformity to current technical standards, such as the Guideline for Periodic Inspection of Road Bridges and Gifu Prefecture's Bridge Inspection Manual [3], ascertainment of the characteristics, evaluation of the performance, and selection of the combinations of various RTs, and determination of the processes of cost estimation and order placing .

Gifu University SIP formulated inspection guidelines (draft) and other proposals to provide solutions to these challenges in 2017 [2]. In FY2018, our team provided support using RT in the periodic inspection of Kakamigahara Bridge (Figure 1) conducted by Kakamigahara City. First, a preliminary survey was conducted using TR, and then the results were used to perform a close visual inspection (Figure 2). As a result, the period of traffic restriction on one side of the bridge surface was shortened from 10 days to 4 days.

In this contribution, we introduce the use cases of RT for the periodic inspection of Kakamigahara Bridge and report the results of quantitative evaluation of the ability of RT to detect bridge defects.

2. PRELIMINARY SURVEY UTILIZING RT [4,5]

2.1. Periodic Inspection of Kakamigahara Bridge

Kakamigahara Bridge, a prestressed concrete bridge spanning 594m, is managed by Kakamigahara City, Gifu Prefecture, Japan. The 3m-wide paths of the bridge for pedestrians/cyclists posed difficulties in using a general large-scale bridge inspection vehicle with a 4m boom (Figure 1) to inspect the under-surface of the bridge. The paths for pedestrians/cyclists are partially widened to 5m near the P5 and P7 piers. The bridge therefore required special inspection methods including the use of an ultra-large inspection vehicle with a 5m boom, ropework, and inspection scaffolding.

For this reason, Gifu University SIP, which had conducted field testing twice before, supported the preliminary survey prior to the close visual observation of the periodic inspection of Kakamigahara Bridge (Figure 2). An inspection consultant with expertise in periodic inspection of bridges undertook the close visual inspection based on the results of the preliminary survey. The goal of the preliminary survey was to acquire information regarding defective events on target members (under-surfaces of slabs, main girders, and substructure) through the eyes of a camera-equipped robot, etc., to support the subsequent close visual inspection. As to the close visual inspection, the efficiency of the work was enhanced by allowing inspectors to ascertain the members and ranges to be subjected to close observation based on the defect information detected by the preliminary survey.

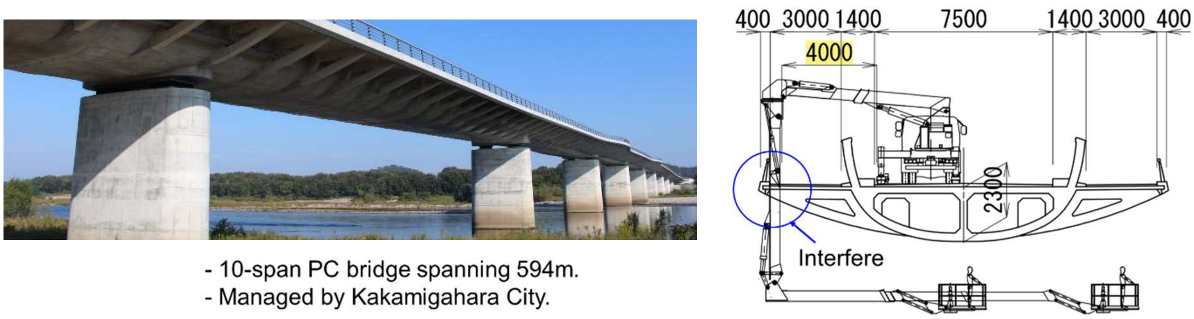

Figure 1. Kakamigahara Bridge where it is difficult to use general large-scale bridge inspection vehicles.

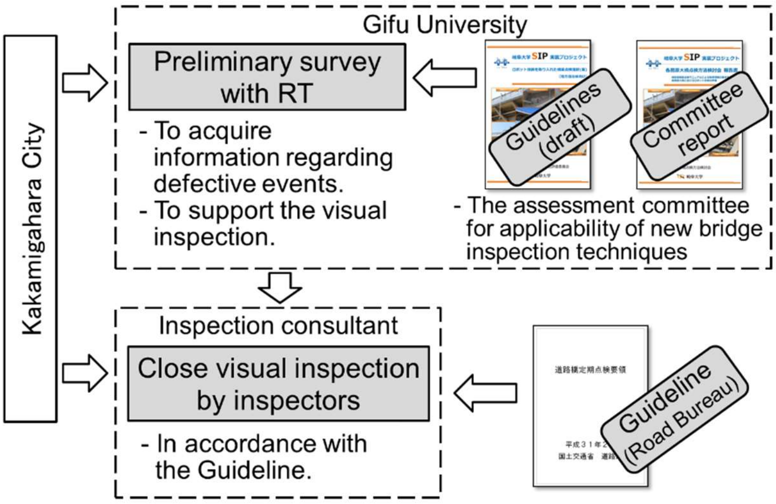

Figure 2. Preliminary survey and close visual inspection.

2.2. Preliminary survey utilizing RT

2.2.1. RTs used 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. It was therefore decided that the six types of RTs listed in Figure 3 were to be used in combination for the present preliminary survey, which consisted of a wide area survey, narrow area survey and hammering inspection by RT. Figure 4 shows the role allotment of each RT for members under the preliminary survey. Figure 5 shows the inspection schedule.

2.2.2. Wide area survey

A wide area survey was conducted for ascertaining the state of the entire bridge, capturing various defects and their positional relations, and creating orthophotographs and 3D models of the bridge. The entire bridge was continuously photographed 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 survey satisfies this performance requirement. The wide area survey took full advantage of the high speed of drone-type robots, curtailing the time of work on site.

As to the results of the wide area survey, the orthophotograph of each structural unit (a span in the superstructure and a pier in the substructure) was divided into a 5m by 5m mesh as shown in Figure 6, 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 and preparation of materials for planning subsequent close visual inspection.

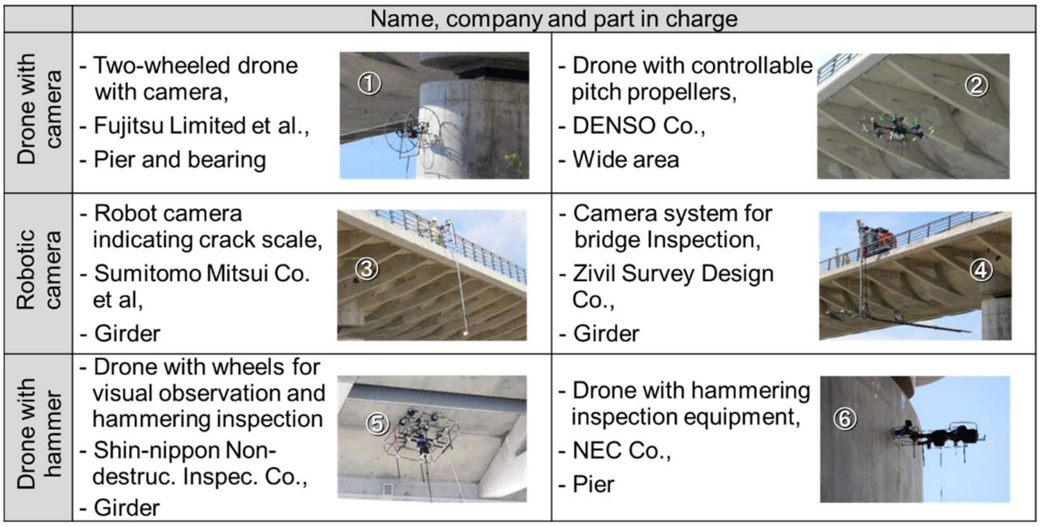

Figure 3. Six kinds of RTs used in combination for preliminary survey.

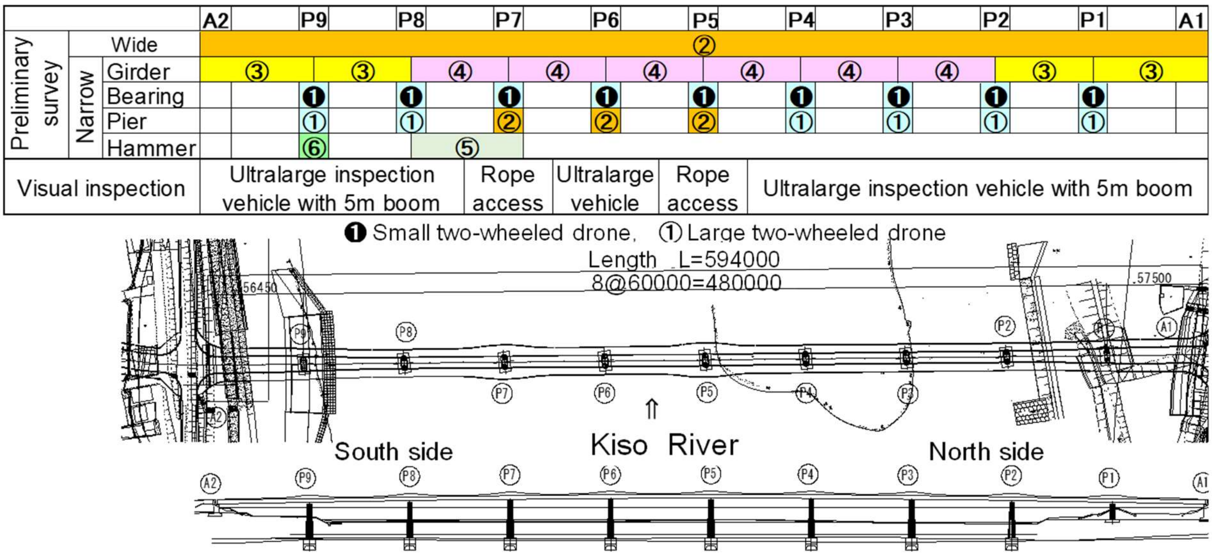

Figure 4. Role allotment of each RT for members under preliminary survey.

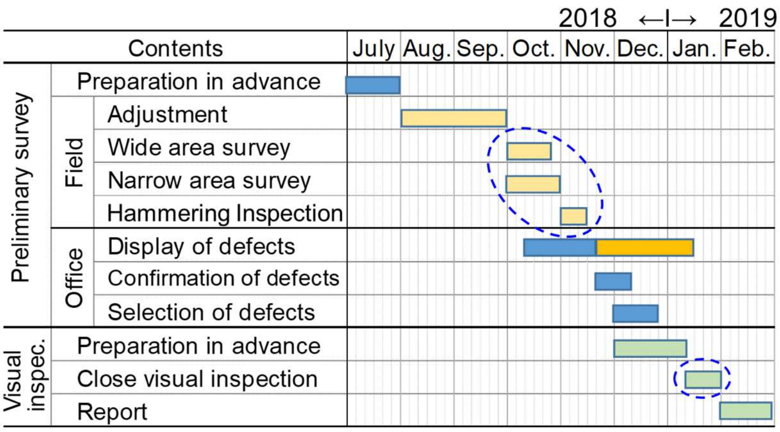

Figure 5. Inspection schedule.

Figure 6. Result example of wide area survey.

2.2.3. *Narrow area survey*

A narrow area survey was conducted for detecting various defects including cracks 0.2 mm or more in width. Detailed images of members were shot 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 survey meet the performance requirements shown in Table 1 [2] which were formulated based on Gifu Prefecture's Bridge Inspection Manual [3].

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.
	Location	Defect can be detected in a manner to allow sketching of defect portions in relation to other members.	
	Size	The overall image can be obtained to judge whether the defect is localized or extensive.	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.
	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 recorded by visual inspection from a short distance or of artificially created accuracy verification marks are roughly within the tolerances shown in the left column.
		Crack length, peeling, rebar exposure, water 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 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 survey to facilitate understanding of the positional relations between defects and the structure. Furthermore, 3D structural models were displayed on a tablet device as shown in Figure 7 to show the location of each defect detected. This was also linked to its photograph, along with the soundness judgment, to be available at the site of close visual inspection for enhancing the work efficiency.

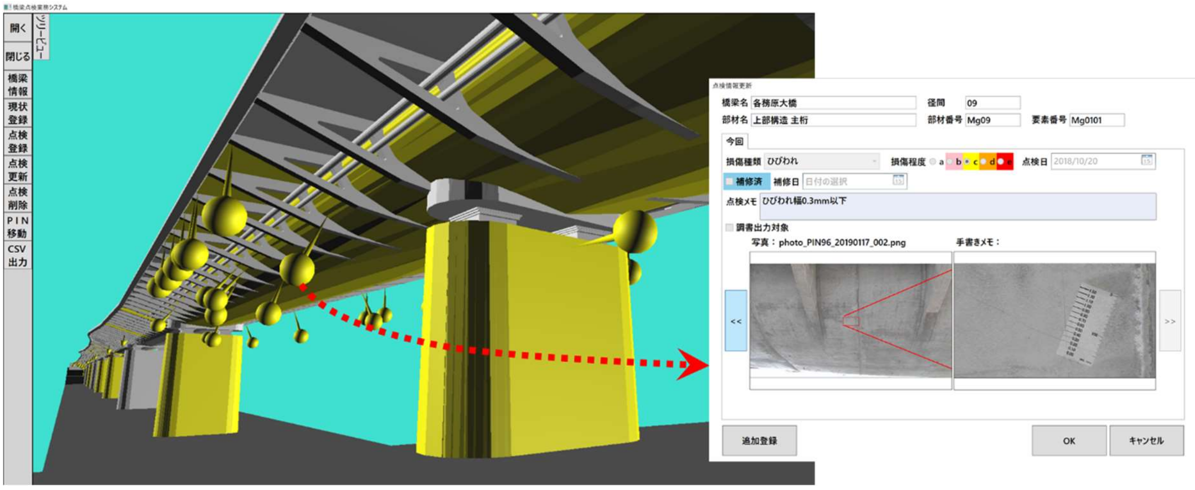

Figure 7. Result example of narrow area survey.

2.2.4. Hammering inspection by RT

A hammering inspection by RT was conducted on segments with discoloration, etc., which suggest peeling or lifting of concrete, found during the wide and narrow area surveys. Note that segments where peeling or lifting was suspected were extracted from all sections of the bridge, but the RT hammering inspection was 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. Other segments were subjected to confirmation by close visual observation.

3. CLOSE VISUAL INSPECTION BASED ON PRELIMINARY SURVEY RESULTS

3.1. Selection of locations for intensive close visual observation

Based on the defect map created by the preliminary survey by RT, an intensive close visual inspection of the standard parts of Kakamigahara Bridge was conducted using an ultra-large inspection vehicle, and the widened parts near the P5 and P7 piers were accessed with rope access. The focus was on the following:

- where the Soundness Class is II (stage of damage requiring preventive maintenance) or higher (for example, cracks with a width of 0.3 mm or more)
- where cracks (narrower than 0.3 mm) are densely found
- where peeling or lifting is suspected
- where survey with RT is difficult (blind spots for camera, piers near the water surface, etc.)..

3.2. Defect extraction by preliminary survey and close visual inspection

Table 2 shows a summary table of the results of the preliminary survey and the close visual inspection for defect extraction. "Defect detection omission" in the table indicates the number of defect locations newly detected by the close visual observation. “Detection error (no defects)” indicates the number of locations where no defects were found in the confirmation by the close visual observation.

"Priority locations for close visual observation" means locations where there was a possibility of the Soundness Class II or higher, where hammering inspection was required due to suspected lifting, where inspection was difficult with RT and where chalking and crack width measurement were performed. Defects elsewhere were considered to be minimal or unlikely to evolve and would not affect the determination of the Soundness Class. Close visual observation was performed at these locations, but basically no chalking nor crack width measurements was carried out. "Locations listed in inspection record" means locations where the defects were expected to progress, requiring continued inspection, with marks made on the damage maps of the periodic inspection report.

Compared with the defect detection locations of the preliminary survey by RT (479 and 378 locations in the super- and substructures, respectively), the priority locations for close visual inspection (146 and 60 locations in the super- and substructures, respectively) are as low as 30% and 16% for the super- and substructures, respectively. This is because, in the preliminary survey by RT, the minimum defect size for detection was not specified in advance. Detection of such small defects was due to the high detection performance of RT. Therefore, the defect record provides evidence that "a survey was performed, but no major defects were detected." Nevertheless, it is important to set the extraction level in advance, considering the high costs of defect extraction and image analysis.

Table 2. Results of defect extraction in preliminary survey and close visual inspection.

	Items examined		Cracks	Water leakage, free lime	Peeling, rebar exposure	Lifting	Others	Total defect number	Lifting suspected
Superstructure	Pre-liminary survey with RT	Defect detection	269	168	17	-	25	479	22
		Defect detection omission	2	3	0	-	4	9	-
		Detection error (no defects)	6	0	4	-	1	11	-
	Close visual inspection	Priority locations for close visual inspection	90	26	6	-	24	146	22
		Locations listed in inspection record	24	29	0	2	9	64	-
Substructure	Pre-liminary survey with RT	Defect detection	374	4	0	-	0	378	40
		Defect detection omission	0	0	0	-	0	0	-
		Detection error (no defects)	0	0	0	-	0	0	-
	Close visual inspection	Priority locations for close visual inspection	56	4	0	-	0	60	40
		Locations listed in inspection record	16	4	0	2	0	22	-

3.3. Crack detection evaluation in preliminary survey

Table 3 shows the results of the crack detection evaluation in the preliminary survey. The performance required for RT is that it can measure crack widths of 0.2 mm or more with an error margin of 0.0 to + 0.1 mm [2]. In the preliminary survey, cracks of 0.1 to 0.2 mm or more were detected as defects, with 269 and 374 locations being detected in the super- and substructures, respectively. Among them, 14 locations were detected with a measurement error exceeding 0.1 mm in the superstructure (the width was overestimated), and 1 location in the substructure (underestimated). The proportions of those locations were 5.2% and 0.3% for the super- and substructures, respectively. Most detection errors overestimate the width of the cracks, erring on the side of caution. From this, it can be concluded that the RT used had a detection accuracy sufficient to replace close visual observation.

Table 3. Results of crack detection evaluation in preliminary survey.

		Crack detection		
		Total locations detected	Overestimated in width	Underestimated in width
Superstructure	Number	269	14	0
	(%)	-	5.2 %	0.0 %
Substructure	Number	374	0	1
	(%)	-	0.0 %	0.3 %

3.4. Defect detection evaluation in preliminary survey

Table 4 shows the evaluation results of the defect detection omissions and the detection errors of the defects in the preliminary survey. The detection omission of defects such as cracks, water leakage and free lime, all occur at the blind spots of the camera mounted on the robot.

“No defects” in “cracks” mean that a spider's web adhering to the concrete surface and mortar leaking from formwork joints of the prestressed concrete superstructure were erroneously detected as cracks, with the number of false detections being 6 (2.2% of the total). “No defects” in “peeling and rebar exposure” mean that the discontinuous shape of the formwork joints of the prestressed concrete superstructure was erroneously detected as peeling, with the number of false detections being 4 (23.5% of the total). This is probably due to the special cylindrical shape of the main girder of this bridge, which made it difficult to finish the joints of overhang blocks.

Since there is no detection omission except for the blind spots of the camera, the RT used has a defect detection accuracy sufficient to replace close visual observation, provided sufficient care is exercised for the blind spots. In addition, determining a non-defect part as a defect is not a detection omission, and is not an error requiring a change in the determination of the Soundness Class, either. Therefore, it can be concluded that the RT used had no practical problems.

Table 4. Results of defect detection evaluation in preliminary survey.

		Superstructure		Substructure	
		Number	(%)	Number	(%)
Cracks	Detection	269	-	374	-
	Detection omission	2	0.7	0	0.0
	No defects	6	2.2	0	0.0
Water leakage, free lime	Detection	168	-	4	-
	Detection omission	3	1.8	0	0.0
	No defects	0	0.0	0	0.0
Peeling, rebar exposure	Detection	17	-	0	-
	Detection omission	0	0.0	0	-
	No defects	4	23.5	0	-

3.5. Efficiency of bridge inspection utilizing RT

By conducting the close visual inspections based on the results of the preliminary survey using RT, the traffic control period on one side of the bridge surface by a bridge inspection vehicle was reduced from 10 days to 4 days. Performing close visual inspection only where they are needed can further reduce inspection work. As mentioned above, spider webs, traces of mortar leaking from formwork joints and formwork joint lines on the concrete surface were sometimes extracted as cracks in the RT imaging results. However, the advantage of recording defects such as cracks without overlooking them is significant. "We have been relieved of the risk and pressure of performing reliable inspection in a limited amount of time," said an inspector who was responsible for the close visual observation.

Since the direct cooperation between the public and private sectors is difficult, the support of universities connecting them was highly effective, when implementing new technologies such as RT in municipalities.

4. AFTERWORD

As the first case in Japan, Gifu University SIP provided support using RT for the periodic inspection of Kakamigahara Bridge (Figure 1) conducted by Kakamigahara City from July 2018 to February 2019. In this periodic inspection, the preliminary survey was first conducted using RT, and based on the results, the close visual inspection was performed by inspectors. The RT used had a defect detection accuracy sufficient for allowing replacement of close visual inspection when used with care for the blind spots of the camera. The performance of the RTs that participated in the inspection of Kakamigahara Bridge has improved dramatically. Furthermore, it became clear that the use of RT could significantly reduce the traffic restriction period on one side of the bridge surface, and that the information obtained by RT was very useful.

In the future, the following approaches are desired to spread the RT in bridge inspection as a general technology.

- Develop supply and ordering systems for using RT
- Clarify applicability to steel bridge inspection and inspection among main girders of multi-girder bridges
- Publish examples of various RT combinations
- Actively use RT in areas other than periodic bridge inspections, such as defect size survey in repair design, initial inspection of new bridges, long-term monitoring after repair, etc.

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