Observation Maintenance for Bridges Using Early Detection of Deterioration Progress

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ABSTRACT

In Japan, the results of inspections show that many bridges require repairs. However, Japanese municipalities do not have sufficient time and budget, and the progress of bridge repair is insufficient. Almost all the bridges managed by municipalities are short-span bridges. Therefore, a management system that selects and focuses on bridge repair based on performance evaluation would be effective. This paper presents an overview of a bridge management system that applies observational maintenance based on the early detection of deterioration, and its effectiveness is demonstrated.

1. INTRODUCTION

Bridge administrators should implement effective maintenance to maintain bridges in proper condition because the safety of bridges degrades as they deteriorate. The structural performance of reinforced-concrete (RC) road bridges decreases as the reinforcing bars deteriorate, and the passage of some bridges can be restricted. In Japan, the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT, 2019) reported that the number of passage-restricted bridges and maintenance costs has increased as more bridges begin to age. In addition, human resources for maintenance work are decreasing. These budget and time limitations affect bridge maintenance and are the reasons unmaintained bridges exist in Japan. Consequently, bridge administration requires a method that reduces maintenance costs and improves efficiency.

Municipalities in Japan that manage most bridges encounter significant challenges. Table 1 lists the grades of the bridge conditions during inspection (MLIT, 2014). The administrators plan to repair G3 or G4 bridges. However, these municipalities lack sufficient repair resources. The MLIT has reported the progression of repair work. From 2014 to 2019, 71% of G3 or G4 bridges and 96% of G2 bridges were not repaired. The repair work is delayed owing to the lack of time and effort (resources) required to maintain bridges. Two approaches can be used to solve this resource shortage problem, as shown in Figure 1. About 80% of bridges owned by municipalities are short-span bridges with

Table 1. Bridge condition grades

Condition grade		General condition guideline
G1	Good	The bridge has no functional problem.
G2	Preventive maintenance stage	The bridge has no functional problem, but it requires countermeasures for prevention.
G3	Corrective maintenance stage	The bridge has a functional problem, and it requires early countermeasures.
G4	Emergency stage	The bridge has a functional problem, and it requires emergency countermeasures.

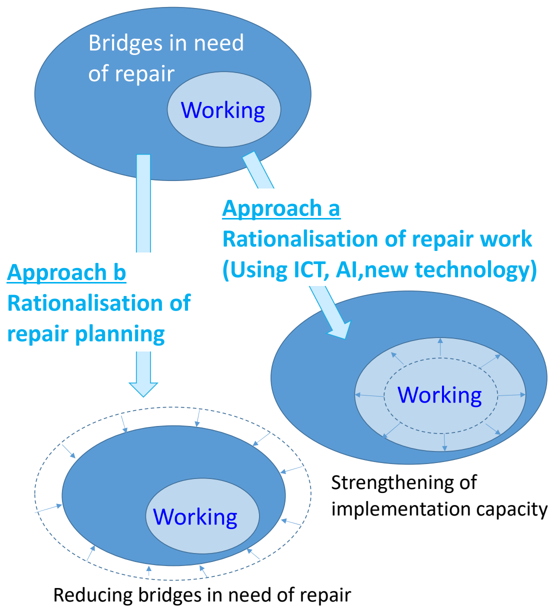

Figure 1. Approaches to resource shortage.

lengths of less than 15 m. Although the amount of maintenance-related work per bridge is small for short-span bridges, the number of bridges is high. Therefore, in this paper, the focus is on 'Approach b', which reduces the number of bridges requiring repair.

To implement Approach b, we are developing a method for the early detection of deterioration in short-span salt-damaged RC bridges managed by municipalities. We have introduced this method for bridge maintenance management in a previous paper (Ito & Mizobuchi, 2022). In this paper, the results of a case study of an existing bridge are presented.

2. PROPOSED BRIDGE MANAGEMENT

The bridge condition grade is a representative indicator of bridges. However, the progression of deterioration generally differs on a bridge. Therefore, even if repairs are required according to the inspection results, we consider that some bridges do not require to be repaired by evaluating the progress of deterioration in detail.

2.1. Early Detection of Deterioration Progress

Bridge A, located in a salt-damaged area, is managed by a Japanese municipality (Table 2). According to the most recent periodic inspection results, the bridge condition is G3, and it has an area with exposed reinforcing bars (deformation pictures are shown in Figure 2). Bridges in coastal areas have deteriorated owing to salt damage. Therefore, the deformation factor was estimated to be salt damage because Bridge A is located close to other salt-damaged bridges. Bridge A has the possibility of salt damage at locations other than where deformation occurred. However, only the visual inspection results are available, and the progression of salt damage was not evaluated.

During salt-damage deterioration, steel corrosion occurs and progresses because of the permeation of chloride ions. According to the experimental results of Oyado, Kanakubo, Yamamoto, and Sato (2006) and the analytical results of Saito, Takahashi, and Higai (2008), up to a cross-sectional reduction ratio of 0.2 for the reinforcing bar, the load-bearing performance is relative to the cross-sectional reduction ratio of the reinforcing bar. Therefore, in this paper, a cross-sectional reduction ratio of 0.2 for the reinforcing bar is adopted as an index to determine whether to implement repair.

We have reported the results of applying an early detection method for performance changes in Bridge A (Ito & Mizobuchi, 2021). Electromagnetic-wave radar and fluorescent X-ray methods were applied to Bridge A, and chloride-ion permeation, which is the initial stage of salt damage deterioration, was detected. Figure 2 shows the estimation results of the average chloride-ion distribution at the reinforcement-bar position using this method. According to the most recent periodic inspection results, the bridge condition is G3, indicating that Bridge A requires repair.

Table 2. Specifications of Bridge A

Years after construction	59
Most recent inspection year	2015
Condition grade	G3
Distance from coastline	100 m
Bridge type	Simple slab
Span length, width (m)	5.4, 11.1

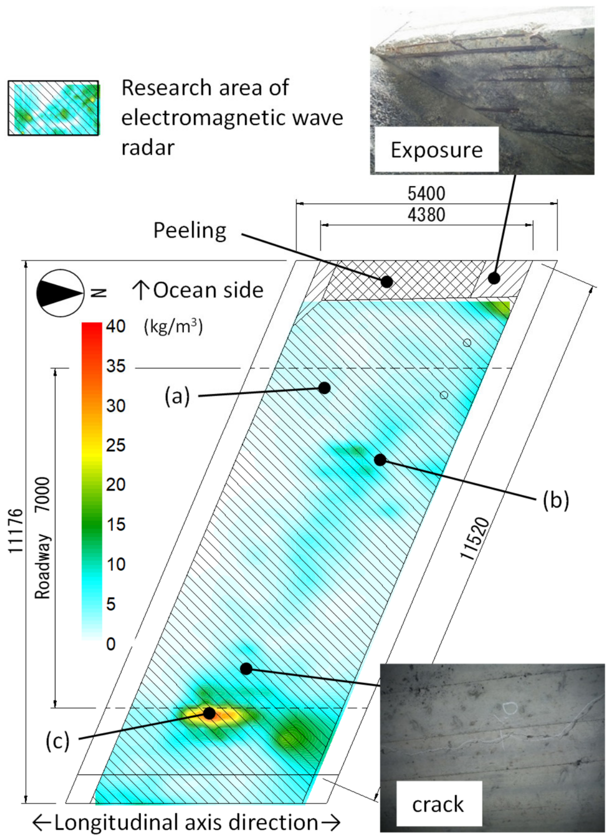

Figure 2. Distribution of estimated amount of chloride ions on the surface of the reinforcing bars.

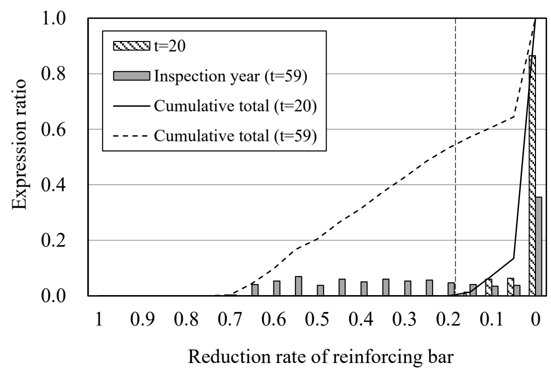

Figure 3. Reduction rate of reinforcing bar (Case 1).

Table 3. Maintenance type assumptions.

Case	Maintenance type	Countermeasure as preventive maintenance	Countermeasure (future prediction)
1	Corrective maintenance	No measure	Repair of cross section (30 mm)
2	Preventive maintenance 1	Surface coating	Repair of cross section (30 mm)
3	Preventive maintenance 2	Chloride ion removal around surface	Repair of cross section (30 mm)
4	Preventive maintenance 3	Surface coating (80%*) + Chloride ion removal around surface (20%*)	Repair of cross section (30 mm)
5	Preventive maintenance 4	Surface coating (50%*) + Chloride ion removal around surface (50%*)	Repair of cross section (30 mm)

* Ratio of countermeasures to bridge area

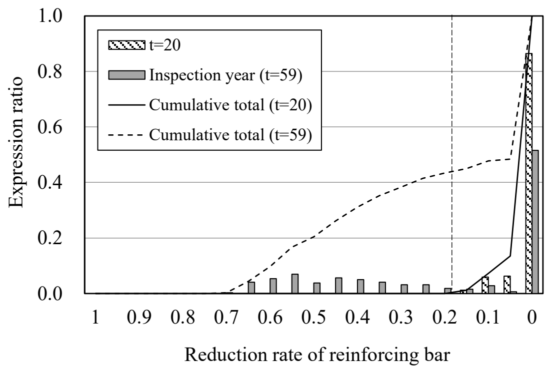

Figure 4. Reduction rate of reinforcing bars (Case 2).

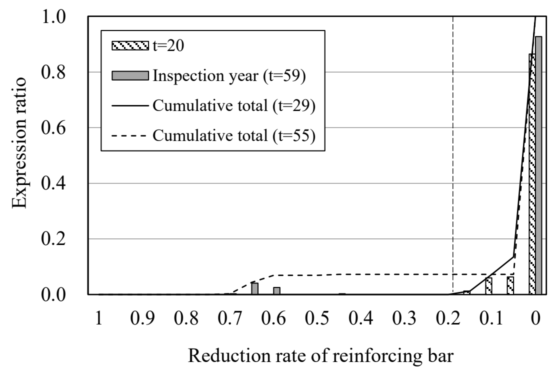

Figure 5. Reduction rate of reinforcing bars (Case 3).

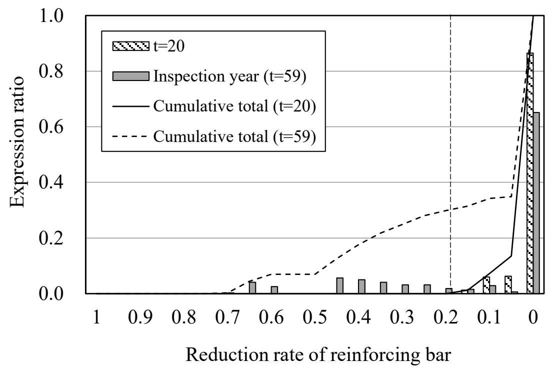

Figure 6. Reduction rate of reinforcing bars (Case 4).

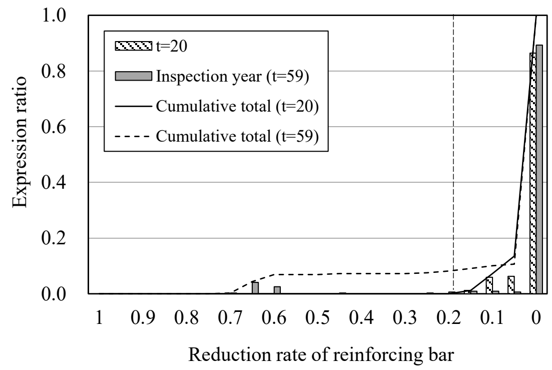

Figure 7. Reduction rate of reinforcing bars (Case 5).

However, as shown in Figure 2, the chloride-ion content is relatively low in most areas, although it is high near damaged areas. Although the estimation is based on Figure 2, the prediction of the steel cross-sectional reduction rate is estimated using the method of Ito and Mizobuchi (2021). The steel cross-sectional reduction rate at the time of inspection (t = 59) was calculated based on the survey results (Figure 2). The steel cross-sectional reduction rate at t=20 was calculated by analysing the chloride-ion content at t=20 from the conditions related to the chloride-ion penetration estimated based on the survey results (Figure 2). Figure 3 shows the prediction of the steel cross-sectional reduction rate, at the time of inspection (t=59), the steel cross-section reduction rate exceeded 0.2 in 55% of the bridge area.

However, the assessment of G3 is based on peeling and exposure confirmed by external appearance and not on the amount of chloride ions (Figure 2) and the steel cross-sectional reduction rate (Figure 3). In addition, because areas other than the peeling and exposure areas are not targets of repair work, insufficient load-bearing capacity even after repairs and future damage in areas other than the repaired areas are also problems. A solution to this problem is preventive maintenance, which is not only more economical than corrective maintenance but can also suppress the progress of deterioration from an early stage.

2.2. Preventive maintenance

In preventive maintenance, if deterioration is expected to become apparent in the future, preventive measures are necessary. According to Figure 3, at t=20, no areas exceeded 0.2 of the steel cross-sectional reduction rate; however, at the time of inspection (t = 59), the steel cross-sectional reduction rate exceeded 0.2 in the range of 55% of the bridge area. Therefore, if preventive maintenance is performed before t=20, the range at which the steel cross-sectional reduction rate at t=59 exceeds 0.2 will decrease. However, at t=20, damage has not occurred, and determining whether countermeasures should be implemented based on appearance is difficult. In addition, because preventive measures assume various countermeasures, it is difficult to select the optimum measures.

Table 3 and Figures 4–7 show the results of predicting the steel cross-sectional area reduction rate for four cases (cases 2 to 5) to assess the effectiveness of preventive maintenance. Although the amount of chloride-ion penetration at the time of the preventive maintenance measures was the same, the results of the steel cross-sectional reduction predictions differed by case. Therefore, the amount of chloride-ion permeation was predicted considering the effect of the countermeasure. The prediction of chloride-ion penetration in Figures 2 (a)–(c), which indicate different salt-damage conditions, was performed using the method by Asakura & Taguchi (2004) involving numerical analysis using the difference method. Figures 8–10 show the variations in the chloride-ion amount at the position of the reinforcing bar during the life cycle for the cases of no measures, surface coating, and chloride-ion removal around the surface (repair of cross-section).

- Surface coating is sufficient at (a).
- No measures might be sufficient at (a).
- Even if countermeasures are taken at (c), the chloride-ion amount is high, and repairs will be necessary in the future, similar to the no-measure scenario.
- Surface coating will require repair in the future at (b)

With the method of Ito and Mizobuchi (2021), the critical chloride concentration for the initiation of steel corrosion (C_{lim}) is 2.13 kg/m^3.

According to the proposed method for the early detection of the deterioration progress, the evaluation described above is possible even if no damage is apparent. Therefore, it is effective for preventive maintenance in scenarios that are difficult to determine whether countermeasures should be implemented. In addition, with this method, the optimum preventive maintenance measures can be selected based on the information obtained.

2.3. Observational maintenance

According to Table 3, countermeasures for preventive maintenance would be required for the entire Bridge A. However, according to Figure 8, in places with a lower predicted amount of chloride-ion permeation, the chloride-

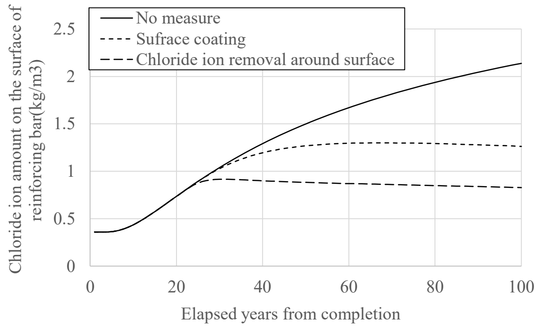

Figure 8. Chloride-ion amount on the surface of reinforcing bars at (a).

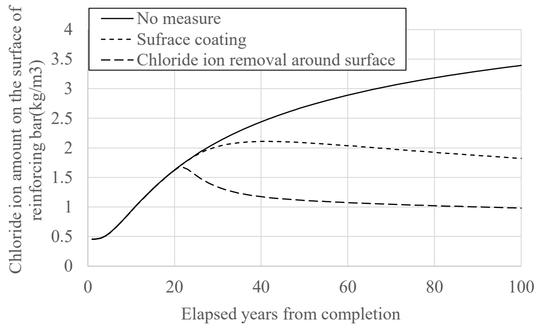

Figure 9. Chloride-ion amount on the surface of reinforcing bars at (b).

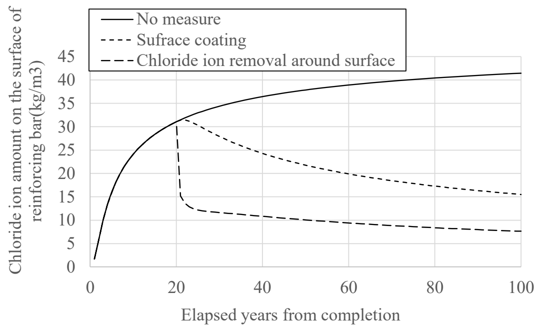

Figure 10. Chloride-ion amount on the surface of reinforcing bars at (c).

Table 4. Unit price of repair work.

Scaffold	9,300 yen/m^2
Surface coating	14,100 yen/m^2
Chloride ion removal around the surface *1	43,483 yen/m^2
Chipping (10 mm) *2	13,080 yen/m^2
Chipping (30 mm)	39,241 yen/m^2
Section repair (10 mm) *2	30,403 yen/m^2
Section repair (30 mm)	91,209 yen/m^2
Inspection (once every 5 years)	1,000 yen/m^2
Proposed method (once every 5 years) *3	2,000 yen/m^2

*1 sum of chipping (10 mm) and section repair (10 mm)
*2 set by us based on report (JCI research committee, 2021)
*3 early detection method of deterioration progress

Table 5. Cost estimate of repair work.

Case	Maintenance type	Cost estimation (million yen/bridge)				
		Countermeasure as preventive maintenance	Anticipated future countermeasure	Survey	LCC total	Rank
1	Corrective maintenance	0	3.87	0.54	4.41	5
2	Preventive maintenance 1	1.15	2.94	0.54	4.63	6
3	Preventive maintenance 2	2.58	0.48	0.54	3.60	3
4	Preventive maintenance 3	1.43	2.05	0.54	4.02	4
5	Preventive maintenance 4	1.86	0.55	0.54	2.95	2
-	Observational maintenance	1.29	0.55	1.08	2.92	1

ion amount does not exceed C_{lim} even with no measures. Approximately 50% of the area of Bridge A has low chloride-ion penetration. In this area, safety can be ensured without the implementation of preventive or corrective maintenance measures. In other words, fewer repair works can be expected. However, periodic observations (soundness monitoring), instead of countermeasures, are required. The proposed method is effective for observation because it detects performance changes at an early stage and evaluates the performance even if no damage has occurred. Therefore, in this paper, if the proposed method (observational maintenance) is implemented during periodic inspections, we consider that this will reduce the number of bridge repair works as well as costs.

2.4. Cost estimation

The maintenance costs for Cases 1–5 (Table 3) are compared. Table 4 (JCI Research Committee, 2021) shows the unit price used for the estimation, and Table 5 shows the results. Table 5 also shows the estimation results for observational maintenance. The observational maintenance required was assumed to be no-measure for 50% of the bridge area, and chloride-ion removal around the surface for other areas. In addition, as the survey costs are once every five years, Cases 1–5 include periodic inspection costs, and the observational maintenance costs include the costs of the proposed method.

The cost of preventive maintenance is 1.15–2.58 million yen, which is more economical than the cost of corrective maintenance (3.87 million yen); however, in some cases that include subsequent measures, the LCC (Life Cycle Cost) is high. In general preventive maintenance, cases 2 and 3 can be applied; however, by applying the early detection method of deterioration progress, cases 4 and 5 can be applied, and the amount of repair work is expected to be reduced. In addition, further cost and work reductions could be achieved by applying observational maintenance. Although the cost of the proposed method is approximately twice that of periodic inspections, it is expected to be reduced through generalisation in the future.

3. Conclusions

The conclusions are as follows.

- Even if the amount of chloride-ion permeation at the time of preventive maintenance is the same, the prediction of the steel cross-sectional reduction differs depending on the measure.
- In some preventive maintenance cases, LCCs are more costly than corrective maintenance.
- Effective preventive maintenance can be selected by applying early detection of deterioration progress.
- In some cases, safety can be demonstrated by periodic observation (soundness monitoring) instead of preventive or corrective maintenance, depending on the amount of chloride ions.
- By applying the early detection of the deterioration progress, observational maintenance can be applied, which may be more economical than preventive maintenance.

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