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Development of optimal bridge management system considering practical usefulness

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Abstract: Several bridge management systems (BMS) have been developed to estimate the future expenditure for bridge management, but those have not been sufficiently applied to the practical bridge management for the reason of complex problem that the damaged bridge members should be repaired at one time as much as possible considering the whole bridge system. In this study, a useful BMS for practical bridge management is developed without special techniques. The deterioration transfer curves for slab, girder and abutment are introduced for three classifications of rapid deterioration, standard deterioration and no degradation members. The most economical repair plan is determined by comparing the life cycle costs for nine cases considering the annual budget limit. The effectiveness and practical usefulness of the system are illustrated by applying it to the bridge management of 1381 bridges in Fukui city, Japan.

Keywords: Bridge management system (BMS), deterioration transfer curve, optimum repair plan

1. Introduction

Each Japanese local government has developed the own bridge management system (BMS) for the bridge maintenance management according to the guideline established in the local government. It has been mainly used to estimate the future expenditure for bridge management, but it has not been sufficiently applied to the practical bridge management. On the other hand, the guideline for periodic bridge inspection was re-established for bridge maintenance management by the ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan [1] in 2014. The local governments are requested to develop the BMS according the guideline established by the MLIT.

In the past researches, some papers proposed to use optimization techniques such as mathematical programming and GA for determination of optimum repair plan for each member element in the bridge. Kaito et al. [2] studied optimal maintenance strategies of bridge components based on an average cost minimizing principle presented by Haward [3]. One of author proposed to determine the optimum repair plan by using the mathematical programming and 2 stage optimization process [4,5]. Many contributions have been made to development of expert systems for bridge management by using the genetic algorithm [6-9].

However, those contributions have not been applied to the practical bridge maintenance for the reason that the system dealt with the management of a member element without considering the repair of whole bridge system. In the practical bridge repair, the damaged bridge members should be repaired at one time as much as possible for the reduction of cost for scaffolding and shortening period of closing traffic. Therefore, development of effective bridge management system according to the guideline by MLIT is awaited for the complex problem in the practical bridge management expectantly. In this study, a useful BMS for practical bridge management is developed without special techniques. The deterioration transfer curves for slab, girder and abutment are introduced for estimation of future deterioration. The distributions of condition ratings are characterized with three deterioration transfer curves for rapid deterioration, standard deterioration and no degradation members in this study. The most economical repair plan is determined by comparing the life cycle costs for nine cases considering the annual budget limit, in which the damage degree is introduced to determine the priority of repair. The effectiveness and practical usefulness of the system are illustrated by applying it to the bridge management of 1381 bridges in Fukui city, Japan.

2. Introduction of deterioration transfer curves

According to the Fukui prefectural policy the maintenances of special bridges such as truss, arch and cable-stayed bridges are managed in the post maintenance. The normal bridges such as slab, PC, RC and steel plate girder bridges are managed in the preventive maintenance. The defects in member elements of slab, girder and abutment influence the life span of a bridge, and the deterioration transfer curves of those member elements are introduced for estimation of future defects using the inspection data of 284 bridges(Lv.1 bridge and Lv.2 bridge) in Fukui city, Japan shown in table 1. The number of bridges that the ages are unknown(unknown bridge) is 1097 bridges in total 1381 bridges. The inspection was executed in the simplified manner established in Fukui prefecture. According to the guideline by Fukui Prefecture the result of inspection is classified into the three stages of no defects, minor defects and serious defects. Lv.1 bridges indicate that no defects were founds for main members and Lv.2 bridges indicate that minor or serious defects were found. On the other hand, the 4 stages of rating condition established by the MLIT in 2014 is shown in table 2. In this study the result in inspection, no defects, minor defects and serious defects, are assigned to the stages I (1.0), II (2.0) and III (3.0) respectively. The real number from 1.0 to 4.0 is used to express the transition of condition rating hereafter.

In this study, the cubic equation $y = at^3 + 1$ is applied to express the deterioration transfer curves for all member elements. The coefficient *a* is calculated by the equation (1) using the least squares method.

$$a = \frac{\sum_{i=1}^{n} \left(\bar{y}_i \cdot t_i^3 - t_i^3 \right)}{\sum_{i=1}^{n} t_i^6} \tag{1}$$

where $\bar{y}_i$ is the condition rating of the member element in the *i*th bridge. *n* is the number of bridge. t_i is the age of the *i*th bridge at the time of the inspection.

Figure 1 shows the deterioration transfer curves for concrete slab. The standard equation indicates the deterioration transfer curve obtained by eq. (1) using the condition ratings for concrete slab in all bridges that their ages are known. The condition ratings are widely distributed, and it is not suitable to express the characteristics of deterioration with the standard equation only. Therefore, in this study the following border equations are introduced to determine the allowable range for the standard equation.

$$y^f(a) = \beta a t^3 + 1 \tag{2}$$

$$y^S(a) = \frac{1}{\beta} a t^3 + 1 \tag{3}$$

y^f, y^S are respectively the faster and slower deterioration limit equations in the allowable range. β is set at 1.8 in this study. The allowable range is drawn in a pattern of slanted lines in figure 1. The characteristics of rapid deterioration, which shows that the deterioration is faster than the deterioration limit y^f, are expressed with the rapid equation calculated by using the condition ratings for concrete slabs in the bridges out of the deterioration limit y^f. The rapid deterioration curve shows that the concrete slab will deteriorate up to the condition rating 4.0 in about 55 years. The characteristics of slow deterioration, which shows that the deterioration is slower than the deterioration limit y^S, indicate that the concrete slab will not deteriorate. In this study, the no degradation equation is applied to the concrete slabs which have not deteriorated for more than 30 years.

Figure 2 shows the deterioration transfer curve for steel floor slab. In this case, the number of steel floor plate girder bridge is not so many and the characteristics of deterioration are expressed with the standard deterioration curve only. This curve shows that the steel floor slab will deteriorate up to the condition rating 4.0 in about 40 years for the cause of corrosion.

The deterioration transfer curves for slabs, girders and abutments are summarized in table 3. The deterioration transfer curve for RC girder is also expressed with the standard equation only for the reason that the number of bridge with RC girder is not many. The deterioration transfer curves for PC girder, steel girder and abutment are characterized

Table 1 : Configuration of the bridges considered in this study

Bridge type	Lv.1 bridge	Lv.2 bridge	Bridge which the ages are unknown	Unknown bridge
RC slab bridge	9	23	964	996
RC girder bridge	0	3	46	49
PC bridge	55	128	58	241
Steel plate girder bridge	10	35	28	73
Steel floor plate girder bridge	0	21	1	22
Total	74	210	1097	1381

Table 2 : 4 stages in the condition rating

Condition rating		Maintenance immediacy of action
Ⅰ (1.0)	Good condition	No structural defects
Ⅱ (2.0)	Preventive maintenance	Minor structural defects without failure of function of structure, but special attention from viewpoint of preventive maintenance
Ⅲ(3.0)	Early repair	Structural defects with need of early repair in order to prevent failure of function of structure
Ⅳ(4.0)	Urgent repair	Serious structural damage with need of urgent repair in order to restore function of structure

Table 3 : Coefficient of deterioration transfer curves for member elements

Member element	Kind	Deterioration speed	Equation	Coefficient a
Slab	Concrete slab	Slow	$y = at^3+1$	0 (In the case that the condition rating has been 1.0 for more than 30 years)
		Standard	$y = at^3+1$	4.40521E-06
		Rapid	$y = at^3+1$	1.65922E-05
	Steel floor plate girder bridge	Standard	$y = at^3+1$	4.34201E-05
Girder	RC girder	Standard	$y = at^3+1$	2.87650E-06
	PC girder	Slow	$y = at^3+1$	0 (In the case that the condition rating has been 1.0 for more than 30 years)
		Standard	$y = at^3+1$	7.14042E-06
		Rapid	$y = at^3+1$	2.16099E-05
	Steel plate girder bridge	Slow	$y = at^3+1$	0 (In the case that the condition rating has been 1.0 for more than 30 years)
		Standard	$y = at^3+1$	1.53946E-05
		Rapid	$y = at^3+1$	4.49396E-05
Abutment	Concrete	Slow	$y = at^3+1$	0 (In the case that the condition rating has been 1.0 for more than 30 years)
		Standard	$y = at^3+1$	6.40834E-06
		Rapid	$y = at^3+1$	2.13383E-05

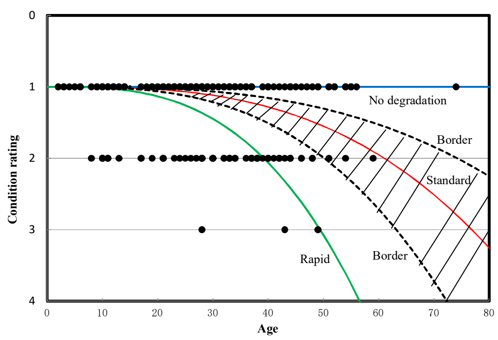

Figure 1: Deterioration transfer curves for concrete slab

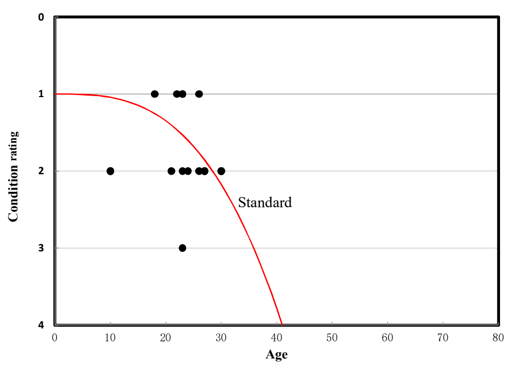

Figure 2: Deterioration transfer curve for steel floor slab

in three equations for no degradation, standard and rapid deteriorations.

In the inspection data the ages for 1097 bridges are unknown. In this study the ages of those bridges are estimated by investigating the age of each member element. The age for each member element is derived from the deterioration transfer curve for each member element. The bridge age is taken the youngest age among the ages for slab, girder and abutment considering the lower and upper limits of the ages

3. Assumptions for determination of optimum repair plan

For determination of optimum repair plan we assume the repair works and their unit prices, extension of bridge life span due to the preventive maintenance, and inspection, repair and rebuilding costs.

3.1 Repair method for slab

The repair methods, repair areas and unit prices for the condition rating 2.0 are shown in table 4. The crack injection method or section repair method is selected for the repair work of concrete slab. The area of repair is assumed at 25 % of area of concrete slab. The painting method is set for corrosion of steel floor slab and the area of repair is the whole area of steel floor slab. The efflorescence in filling concrete between PC girders is observed for the main defect of concrete slab in PC bridge. Therefore, the filling processing method is selected and the repair area is assumed at 50% of the length of filling concrete.

The repair methods, repair areas and unit prices for the condition rating 3.0 are shown in table 5. The crack injection method or section repair method is selected for the repair at 50% of area of concrete slab. The repair area of painting method for steel floor slab is the whole of steel floor slab. The area of filling processing method is set at the full length of filling concrete in PC bridge. The steel sheet adhesion method is also the alternative of repair methods for future progress of deterioration.

In case of the condition rating 4.0, the concrete slab needs reinforcement across the whole slab. The replacing method or steel sheet adhesion method is chosen as shown in table 6. The painting method is also applied to the repair of corroded steel floor. The filling processing method is also applied to the repair for whole of filling concrete in PC bridges.

3.2 Repair method for girder

It is clear from the inspection data that the cause of deteriorations for steel girders in steel plate girder bridges is corrosion. The painting method is chosen for repair of steel girders at the condition ratings 2.0, 3.0 and 4.0 as shown in tables 4-6. The average circumference length for painting in the steel girder is assumed at 2m. The crack injection method and section repair method are applied to the repair of girders in RC and PC bridges. The average circumference lengths in the cross sections of RC and PC bridges are assumed at 2m. The areas of repair are assumed at 25 % and 50% of girders in RC and PC bridges for the condition ratings 2.0 and 3.0 respectively. The section repair method is applied to the repair of whole girders at the condition rating 4.0.

3.3 Repair method for abutment

The crack injection method and section repair method are applied to the repair of abutments in all bridges at the condition ratings 2.0 and 3.0 as shown in tables 4 and 5. It is assumed that the height of repair area in the abutment is 2.0 m at the condition ratings 2.0 and 3.0. The wide of repair area is the half of the bridge wide at the condition rating 2.0 and the bridge wide at the condition rating 3.0 respectively. The section repair method is applied to the repair of abutment at the condition rating 4.0 and the repair area is the same as that at the condition rating 3.0.

3.4 Assumptions in the repair plan

Repair cost for the condition rating at the middle from 2.0 to 3.0 is calculated by the linear interpolation method using the repair costs for the condition ratings 2 and 3. The inspection cost is set at 50000 yen per bridge. Bridges are inspected once in 5 years. The bridges shall be inspected at the same time when the bridges are repaired. The rebuilding cost is the sum of new construction cost and removal cost, in which the new construction costs for superstructure, abutment and pier in each bridge type are assumed as shown in table 7. The removal cost is assumed at 40% of the new construction cost. The bridge life span shall be extended from 10 to 50 years for each bridge type considering the preventive maintenance as shown in table 8 following the policy of bridge management in Fukui prefecture, Japan. In the repair plan, the bridge shall be rebuilt when the bridge age reaches at the extended life span.

4. Determination of optimum repair plan

Table 4 : Repair works and unit prices in the condition rating Ⅱ(2.0)

Member element	Bridge type	Condition rating Ⅱ (2.0)		
		Repair method	Assumption of area of repair	Unitprice
Slab	Concrete slab	Crack injection method	25% of area of slab	1.7(10^4 yen/m²)
		Section repair method	25% of area of slab	5(10^4 yen/m²)
		Filling processing method	50% of {bridge length×(number of girder＋1)}	0.5(10^4 yen/m)
	Steel floor plate girder bridge	Painting method	Area of slab	0.3735(10^4 yen/m²)
Girder	RC girder	Crack injection method	25% of (2m×bridge length×number of girder)	1.7(10^4 yen/m²)
		Section repair method	25% of (2m×bridge length×number of girder)	5(10^4 yen/m²)
	PC girder	Crack injection method	25% of (2m×bridge length×number of girder)	1.7(10^4 yen/m²)
		Section repair method	25% of (2m×bridge length×number of girder)	5(10^4 yen/m²)
	Steel plate girder bridge	Painting method	2m×bridge length×number of girder	0.3735(10^4 yen/m²)
Abutment	All bridges	Crack injection method	50% of (2m×Width)	1.7(10^4 yen/m²)
		Section repair method	50% of (2m×Width)	5(10^4 yen/m²)

Table 5 : Repair works and unit prices in the condition rating Ⅲ(3.0)

Member element	Bridge type	Condition rating Ⅲ(3.0)		
		Repair method	Assumption of area of repair	Unitprice
Slab	Concrete slab	Crack injection method	50% of area of slab	1.7(10^4 yen/m²)
		Section repair method	50% of area of slab	5(10^4 yen/m²)
		Filling processing method	Bridge length×(number of girder＋1)	0.5(10^4 yen/m)
		Steel sheet adhesion method	Area of slab	8(10^4 yen/m²)
	Steel floor plate girder bridge	Painting method	Area of slab	0.3735(10^4 yen/m²)
Girder	RC girder	Crack injection method	50% of (2m×bridge length×number of girder)	1.7(10^4 yen/m²)
		Section repair method	50% of (2m×bridge length×number of girder)	5(10^4 yen/m²)
	PC girder	Crack injection method	50% of (2m×bridge length×number of girder)	1.7(10^4 yen/m²)
		Section repair method	50% of (2m×bridge length×number of girder)	5(10^4 yen/m²)
	Steel plate girder bridge	Painting method	2m×bridge length×number of girder	0.3735(10^4 yen/m²)
Abutment	All bridges	Crack injection method	2m×Width	1.7(10^4 yen/m²)
		Section repair method	2m×Width	5(10^4 yen/m²)

Table 6 : Repair works and unit prices in the condition rating Ⅳ(4.0)

Member element	Bridge type	Condition rating Ⅳ(4.0)		
		Repair method	Assumption of area of repair	Unitprice
Slab	Concrete slab	Replacing method	Area of slab	13.5(10^4 yen/m)
		Steel sheet adhesion method	Area of slab	8(10^4 yen/m²)
		Filling processing method	Bridge length×(number of girder＋1)	0.5(10^4 yen/m)
	Steel floor plate girder bridge	Painting method	Area of slab	0.3735(10^4 yen/m²)
Girder	RC girder	Section repair method	2m×bridge length×number of girder	5(10^4 yen/m²)
	PC girder	Section repair method	2m×bridge length×number of girder	5(10^4 yen/m²)
	Steel plate girder bridge	Painting method	2m×bridge length×number of girder	0.3735(10^4 yen/m²)
Abutment	All bridges	Section repair method	2m×Width	5(10^4 yen/m²)

Table 7 : Unit cost for rebuilding of bridge

Bridge type	Super structure(unit cost)	Abutment (unit cost)	Pier (unit cost)
RC slab bridge	8 (10^4 yen/m^2)	45 (10^4 yen/m)	0 (yen/m)
Steel plate girder bridge	15 (10^4 yen/m^2)	100 (10^4 yen/m)	100 (10^4 yen/m)
RC girder bridge	10 (10^4 yen/m^2)	60 (10^4 yen/m)	0 (yen/m)
PC girder bridge	13 (10^4 yen/m^2)	100 (10^4 yen/m)	100 (10^4 yen/m)

Table 8: Extension of bridge life span due to the preventive maintenance

Bridge type and conditions of construction site	Year of preventive repair after bridge construction	Period remained before rebuilding	Extension of bridge life span
Steel plate girder bridge	In case of no preventive repair	60 years	—
	In case of preventive repair in 41 to 59 years after bridge construction	70 years	+10 years
	In case of preventive repair within 40 years after bridge construction	100 years	+40 years
Concrete bridge locate in the salt damage region	In case of no preventive repair	50 years	—
	In case of preventive repair in 31 to 49 years after bridge construction	60 years	+10 years
	In case of preventive repair within 30 years after bridge construction	100 years	+50 years
Concrete bridge locate out of the salt damage region	In case of no preventive repair	75 years	—
	In case of preventive repair in 41 to 74 years after bridge construction	85 years	+10 years
	In case of preventive repair within 40 years after bridge construction	100 years	+25 years

The preventive repair is executed at the condition rating from 2.0 to 3.0. The repair at 3.0 is recognized as the post maintenance and the condition rating at more than 3.0 is not allowed. The optimum repair plan is the most economical case obtained by comparing the life cycle costs for the following nine cases.

① Repair is executed at the condition that the condition rating of slab is 2.0 or more, or one of other element is 3.0 or more.

② Repair is executed at the condition that the condition rating of girder is 2.0 or more, or one of other element is 3.0 or more.

③ Repair is executed at the condition that the condition rating of abutment A1 is 2.0 or more, or one of other element is 3.0 or more.

④ Repair is executed at the condition that the condition rating of abutment A2 is 2.0 or more, or one of other element is 3.0 or more.

⑤ Repair is executed at the condition that the condition rating of slab is 2.5 or more, or one of other element is 3.0 or more.

⑥ Repair is executed at the condition that the condition rating of girder is 2.5 or more, or one of other element is 3.0 or more.

⑦ Repair is executed at the condition that the condition rating of abutment A1 is 2.5 or more, or one of other element is 3.0 or more.

⑧ Repair is executed at the condition that the condition rating of abutment A2 is 2.5 or more, or one of other element is 3.0 or more.

⑨ Repair is executed at the condition that the condition rating of one of member element is 3.0 or more.

In the above nine cases all member elements that the condition rating is 2.0 or more shall be repaired at the same time considering the repair of whole bridge system. The condition rating for a member element in the multi-span bridge takes the maximum value among those for the element in each span. In the case that the bridge is rebuilt within 5 years later from the nearest repair time, the nearest repair shall be replaced by the rebuilding.

The annual budget limit must be taken into account for the determination of optimum repair plan. In this study, the flow chart shown in figure 3 is proposed for the determination of optimum repair plan considering the annual budget limit. At first the optimum repair cases in nine cases are determined for all bridges without considering the annual budget limit. After then, focusing on the youngest year where the annual budget limit is violated, the repairs in this year are postponed to the next year. To determine the turn of bridge that the repairs are postponed, the following defect degree, D_f, is calculated and the bridges are arranged in ascending order of D_f.

$$D_f = \sum_{i=1}^{n} \left\{ (D_G^i - 1.0) + (D_S^i - 1.0) + (D_{A1}^i - 1.0) + (D_{A2}^i - 1.0) \right\} + W \qquad (4)$$

where $D_G^i, D_S^i, D_{A1}^i, D_{A2}^i$ are, respectively, the condition ratings of the girder, slab, abutments A1 and A2 in the ith span. W is the weight of the bridge and n is the number of span.

The smaller value of D_f indicates that the bridge has less defects, so that the repairs are postponed to the next year in turn in the ascending order of D_f until the annual budget limit is satisfied. In the case that the corresponding repair time t is the first time of repairs, the first repair time is fixed at t+1 years, and then, the following repair times are determined again while keeping the condition of the optimal case without considering the annual budget limit. In the case that the corresponding repair time t is after the first time, the corresponding repair time is fixed at t+1 years and the following repair times are also postponed to the next year. This process is repeated until the annual budget limit is satisfied during the management period

5. Numerical examples

The bridge inspections were executed in the years from 2004 to 2014 and the repair plan is implemented in 2015. The initial condition ratings are revised considering the progress of deterioration after the inspections. The maintenance management period is set at 75 years. The annual budget limit for maintenance and management of bridges is set at 1.3×10^8 yen.

Figure 4 shows the repair cost in each year during the management period (75 years). During the first 11 years the number of repair bridge is limited so as to satisfy the annual budget limit. After then, the repair cost required in a year is less than the half of annual budget limit.

Figure 5 shows the comparison of the cumulative repair costs for the optimum repair plan and the post maintenance plan (the repair case ⑨). The optimum repair plan requires the larger repair cost than that for the post maintenance plan during the first 11 years. Then, the repair cost for the optimum maintenance plan is smaller than that for the post maintenance plan from 12 to 39 years. In 40 years both the repair costs are almost the same for the reason that many bridges have to repair again for the optimum repair plan. In 75 years 7.6 % reduction can be observed in the cumulative repair cost for the optimum repair plan compared with that for the post maintenance plan.

The repair history of PC bridge (No.75) is shown in figure 6. The optimum repair case for PC bridge is the repair case ②. The initial bridge repair is postponed to 7 years later considering the repair priority, and both the girder and slab are repaired in the initial repair. The second repair of girder is executed in 43 years for the reason that its condition rating reaches at 2.0. The repairs in three members of slab, abutments A1 and A2 are executed for the third repair simultaneously in 56 years. The bridge is rebuilt in 71 years for the reason of the maximum life span of PC bridge (100 years old).

The repair history of steel floor plate girder bridge (No.171) is shown in figure 7. The optimum repair case is the repair case ③. The initial bridge repair is executed for the abutment A1 in 10 years. The second bridge repair is executed for the slab in 31 years. The third repair is executed for both the girder and abutment A2 in 40 years. The forth repair is executed for the abutment A1 in 45 years. The bridge is rebuilt in 66 years for the reason that the fifth repair is so close to the rebuilding within 5 years and the repair is replaced by the rebuilding.

6. Conclusions

In this paper, a useful BMS is developed for the practical bridge management. The BMS can determine the most economical repair plan considering the repair of whole bridge system. The proposed system can repair the members that the condition ratings are 2.0 or more simultaneously so as to satisfy the annual budget limit, in which the defect degree is introduced to determine the priority of repair. The cumulative repair cost for the optimum repair plan is reduced by 7.6 % of that in the post maintenance plan. The final optimal bridge repair plan can be determined by comparing the optimum repair plans for several annual budget limits and management periods.

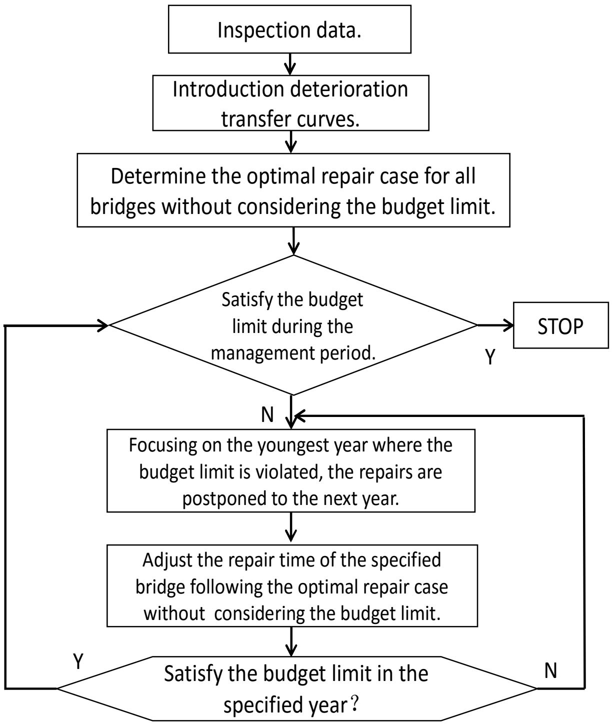

Figure 3: Decision process of the optimal repair time considering the annual budget limit

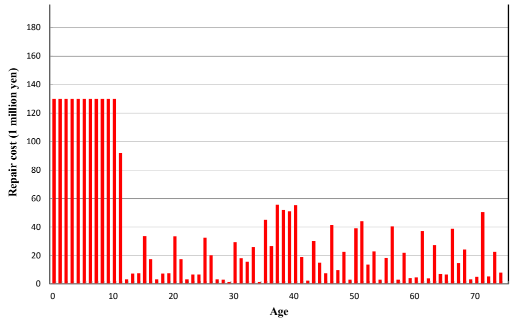

Figure 4: Repair cost in each year

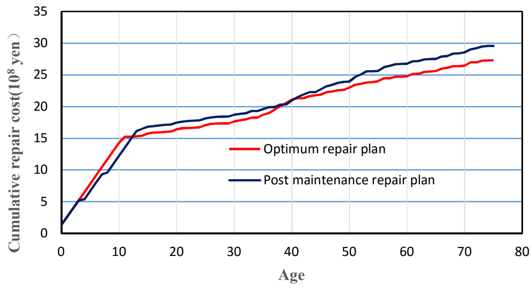

Figure 5: Comparison of cumulative repair costs for optimal repair plan and post maintenance repair plan

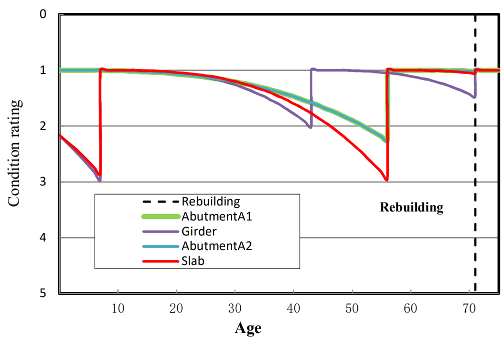

Figure 6: Repair history of pc bridge (no.75)

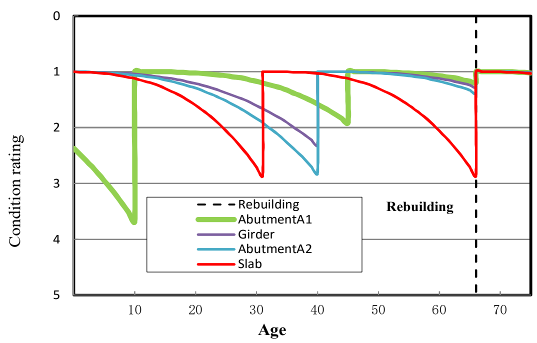

Figure 7: Repair history of steel floor plate girder (no.171)

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