DEVELOPMENT OF ESTIMATION METHOD FOR DETERIORATION FACTORS OF CONCRETE BRIDGE AND ITS PRACTICAL APPLICATION

Hideaki NAKAMURA*1, Hiroyuki ONIMARU*2, Ayaho MIYAMOTO*1
and Kei KAWAMURA*3

ABSTRACT

The authors have been developing Bridge Management System (BMS) that can manage inclusively the bridge maintenance. In order to maintain effectively the bridges, it is necessary not only to rehabilitate bridge damage but also to suppress the deterioration factors which generate damage.

This paper describes the estimation method of deterioration factors which is one of the sub-systems in bridge management system (BMS). The main purpose of this sub-system is to presume deterioration factors from the inspection data of the bridge damage by using a cause-effect network. From the comparison of the results based on this sub-system applying for some actual in-service bridges with the results of questionnaire surveys to domain experts, it is found that the estimation of deterioration factors can be predicted accurately.

KEY WORDS: *Bridges maintenance, BMS(Bridge Management System), Cause-Effect Network, Maintenance Measures*

1.INTRODUCTION

In Japan, many concrete bridges were constructed in the highly economic growth period. However, many of theses bridges have seriously deteriorated in resent years and some accidents caused by the fall of flaking concrete have occurred. It is necessary to maintain the concrete bridges appropriately to use them for a long period. Many bridges must be repaired or strengthened depending on the severity of their deterioration. However, due to the limited budget for maintenance, it is impossible to perform all the demanded maintenance works [1]. Therefore, it is necessary to maintain the bridges rational and effectively within the limited budget. In order to maintain bridge effectively, it is important to restore the bridge damage as well as to suppress the deterioration factors.

Under such background, authors have been developing Bridge Management System (BMS) as an integrated system which enables to support the bridge maintenance works [2]. In this study, a new sub-system was developed as a part of BMS. This extended system presumes the deterioration factor from the inspection data and non-destructive testing and it allows a maintenance strategy to be determined using the output of the estimation function [3]. Moreover, the extended system is applied to existing concrete bridges so as to demonstrate the validity of the proposed system.

*1 Department of Computer Science & Systems Engineering, Yamaguchi University
*2 Graduate Student, Department of Computer Science & Systems Engineering, Yamaguchi University
*3 Venture Business Laboratory, Post Doctoral Fellow, Yamaguchi University

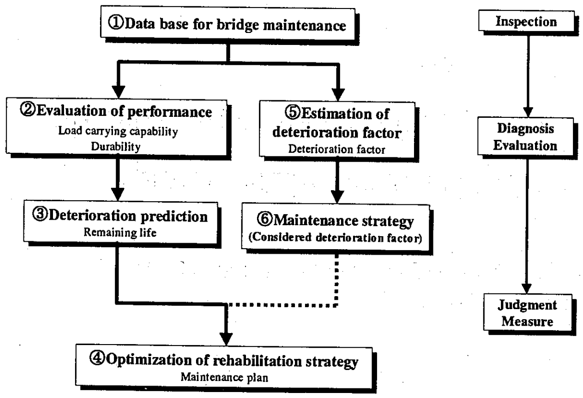

Fig. 1 Position in the BMS

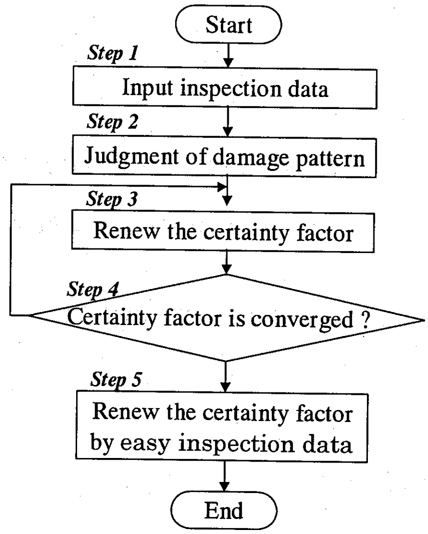

Fig. 2 Flow chart of inference process

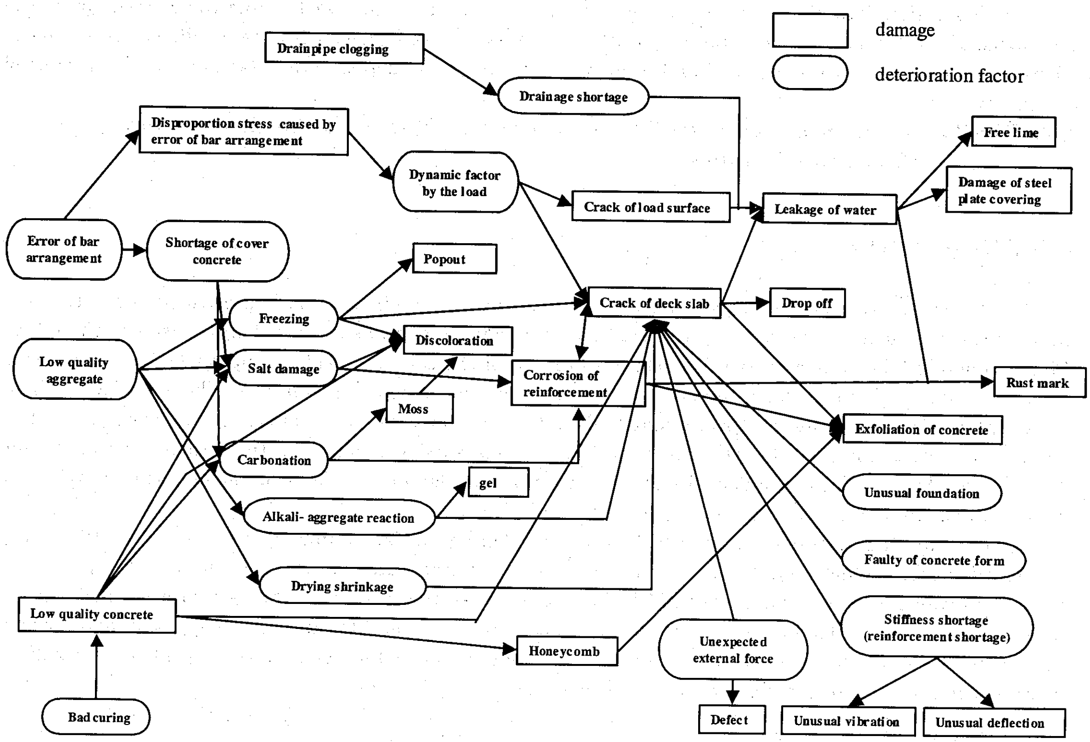

Fig. 3 Image of cause-effect network (deck slab)

Table 1 Deterioration factors considered with this system

Member	No	Deterioration factor	Member	No	Deterioration factor
Deck slab	1	dynamic facor by the load	Main girder	15	bending stress
	2	bad curing		16	sharing stres
	3	error of bar arrangement		17	bad curing
	4	shortage of cover concrete		18	shortage of cover concrete
	5	reinforcement shortage		19	reinforcement shortage
	6	alkali-aggregate reaction		20	alkali-aggregate reaction
	7	salt damage		21	salt damage
	8	carbonation		22	carbonation
	9	freezing damage		23	freezing damag
	10	low quality aggregate		24	low quality aggregate
	11	drainage shortage		25	drainage shortage
	12	unexpected external force		26	unexpected external force
	13	faulty of concrete form		27	faulty of concrete form
	14	unusual foundation		28	unusual foundation

2. OUTLINE OF THIS SYSTEM

This system is developed as a function of BMS, and the position of this system in the BMS is shown in Figure 1. The BMS is an integrated system which enables support of bridge maintenance works. Technical specification data, inspection data and various data concerning bridge maintenance are stored in the data base (①). The performance of the bridge members is evaluated using the obtained inspection data and the technical specifications of the target bridge. This evaluation is performed using a program referred to as the Concrete Bridge Rating Expert System (②). Then, based on the results of the expert system, present deterioration can be characterized and the remaing life of the bridge can be estimated using the predicted function of deterioration (③). If the present remaing life calculated by BMS does not exceed the expected service life, the rehabilitation strategy is obtained from the prediction curve according to the cost and effect of repairs and strengthening. This strategy includes various maintenance plans provided by the cost minimization or quality maximization (④). However, the maintenance strategy planned here does not consider the deterioration factor. Therefore, the deterioration factor keeps acting even if damage is restored, so the same damage might happen again, and the output maintenance strategy by the system is inefficient. To solve this problem, the deterioration factor estimation system which presumed the deterioration factor from the inspection data was newly constructed (⑤). Furthermore, the maintenance strategy was planned from the maintenance strategy planning system (⑥). This system involves arranging various causal relations of the damage occurring in the bridge and the acting deterioration factor. The deterioration factor is reasoned according to the causal network expressed as the causal relation [4]. The causal network for the bridge slab is shown in Figure 3 as an example of the causal network. The square shows damage, and the circle shows the deterioration factor in the figure. The flow of the inference is as follows (see Figure 2).

[Step 1]

It is examined whether damage occurs in the target bridge. If damage occurs, the level of damage is input.

[Step 2]

If specific damage with the crack occurs, the crack pattern is input.

[Step 3]

The inference is started when the data input is ended, and the certainty factor is renewed according to the rule of the causal network.

[Step 4]

The inference is ended when the certainty factor is converged, advanced to Step 5.

[Step 5]

In step 5, the result of easy inspection and the environmental condition of the bridge are input.

Table 2 Professional engineers' answer criterion

Evaluation	Criterion
1	no act
2	very little act
3	unknown
4	little act
5	strong act

The effect on the damage for general maintenance work is arranged in the maintenance strategy planning system. The best maintenance strategy for the damage which occurs in the target bridges is solved as a combinational optimization problem. Refer to reference [2] and [3] for details of each system of BMS.

3. OUTLINE OF APPLICATION BRIDGE AND VERIFICATION OF APPLICATION RESULT

In this study, in order to acquire the input data of this system, five existing bridges (ten spans) in Yamaguchi prefecture were inspected. The bridge inspection was basically carried out according to the Ministry of Construction Pubic Works Research Institute material "Maintenance guide (draft)"[5]. The inspection items which improved in this laboratory were also carried out. The addition and the improved inspection item by our idea were included. The bridge inspection was carried out by professional engineers who have been maintaining bridges for 20 years or more. Moreover, in order to verify the validity of this system, the questionnaire survey is set out to professional engineers who inspected the bridge so as to investigate the deterioration factor which had acted on the target bridge. In this chapter, the outline of the application bridge is mentioned, and the damage confirmed by bridge inspection is shown. After that, the output result obtained by inputting the confirmed damage to this system is shown in order to verify the validity of this system. The deterioration factors considered in this system are shown in Table 1. "No" of Table 4, 6, 8, 10, and 12 corresponds to "No" of Table 1. The number enclosed with a circle shows the span number. And, the score in this table is the inference result of the output of this system, and these score show certainty factor (0.0-1.0) on which the deterioration factor has acted. If this certainty factor is large, the possibility that the deterioration factor has acted on the bridge is high. In addition, the score in ( ) is the result of the questionnaire survey set out to the professional engineers. The criterion is shown in Table 2.

3.1 OUTLINE OF TARGET BRIDGE AND APPLICATION RESULT OF THIS SYSTEM

(1) Ko bridge (Yamaguchi Pref. N engineering works office jurisdiction)

The Ko bridge (five main girders and eight spans) is a RC T-girder type bridge constructed in February 1917. The age of the bridge is 82 years. This bridge is constructed in a main prefectural highway with light traffic. In the main girder, some cracks were found under the surface in the bridge axial direction. Moreover, some free limes were found at the joint part of the deck slab. A lot of free limes of the bridge axial direction were found in the floor slab, and some of them extended. In the pavement, cracks were seen at the dummy joint. The damage confirmed by each member of the inspection of "Ko bridge" is shown in Table 3. Moreover, the application result of this system is shown in Table 4. The professional engineers judged that the deterioration factor such as a dynamic factor by the load, defective construction, a defective design, a defective material, and drainage shortage and the carbonation had acted on this bridge. On the other hand, this system can presume a dynamic factor by the load and drainage shortage as well as a deterioration factor. However, deterioration factors such as defective construction and defective design cannot be presumed.

(2) Mi bridge (Yamaguchi Pref. H engineering works office jurisdiction)

The Mi bridge (four main girders and three spans) is a RC T-girder type bridge constructed in March 1952. The age of the bridge is 47 years. This bridge is constructed in a main prefectural highway. In the main girder, some cracks were found under the surface in the bridge axial direction. Moreover, reinforcement exposures were found. In the deck slab, the reinforcement exposures were especially found at the sponson part. It seems that concrete filling shortage due to defective execution caused reinforcement

Table 3 Damage of Ko Bridge

Member span No.		Damage
Deck slab	③	pavement crack, free lime
	⑧	crack, pavement crack, honeycomb･cavity,separation･reinforcement exposure, free line
Deck slab	③	crack, separation･reinforcement exposure
	⑧	separation･reinforcement exposure, free lime

Table 4 Application result of this system (Ko Bridge)

No	③	⑧	No	③	⑧
1	0.60 (4)	0.40 (4)	15	0.40 (4)	0.24 (3)
2	0.13 (4)	0.36 (3)	16	0.40 (3)	0.24 (3)
3	0.10 (3)	0.07 (3)	17	0.36 (3)	0.22 (3)
4	0.04 (4)	0.10 (4)	18	0.10 (3)	0.10 (4)
5	0.14 (3)	0.40 (3)	19	0.40 (4)	0.24 (3)
6	0.14 (2)	0.40 (3)	20	0.40 (2)	0.24 (3)
7	0.09 (2)	0.24 (3)	21	0.24 (2)	0.24 (3)
8	0.09 (3)	0.24 (3)	22	0.24 (3)	0.24 (4)
9	0.14 (2)	0.40 (3)	23	0.40 (2)	0.24 (3)
10	0.13 (3)	0.36 (4)	24	0.36 (3)	0.22 (3)
11	0.54 (4)	0.54 (4)	25	0.24 (4)	0.54 (4)
12	0.14 (2)	0.40 (2)	26	0.40 (2)	0.24 (2)
13	0.14 (3)	0.40 (3)	27	0.40 (3)	0.24 (3)
14	0.14 (3)	0.40 (3)	28	0.40 (3)	0.24 (3)

Table 5 Damage of Mi Bridge

Member span No.		Damage
Deck slab	①	crack,pavement crack,honeycomb･cavity,separation,separation･reinforcement exposure,free lime
	③	separation･reinforcement exposure,free lime
Main girder	①	crack,reinforcement exposure
	③	crack,defect,separation･reinforcement

Table 6 Application result of this system (Mi Bridge)

No	①	③	No	①	③
1	0.60 (2)	0.24 (2)	15	0.40 (2)	0.40 (2)
2	0.36 (5)	0.22 (5)	16	0.60 (3)	0.40 (3)
3	0.11 (4)	0.04 (4)	17	0.36 (5)	0.36 (5)
4	0.10 (4)	0.10 (4)	18	0.10 (4)	0.10 (4)
5	0.40 (3)	0.24 (3)	19	0.40 (3)	0.40 (3)
6	0.40 (3)	0.24 (3)	20	0.40 (3)	0.40 (3)
7	0.24 (1)	0.24 (1)	21	0.24 (1)	0.24 (1)
8	0.24 (2)	0.24 (2)	22	0.24 (2)	0.24 (2)
9	0.40 (2)	0.24 (2)	23	0.40 (2)	0.40 (2)
10	0.36 (5)	0.22 (5)	24	0.36 (5)	0.36 (5)
11	0.54 (3)	0.54 (3)	25	0.24 (3)	0.24 (3)
12	0.40 (2)	0.24 (2)	26	0.40 (2)	0.90 (2)
13	0.40 (4)	0.24 (4)	27	0.40 (4)	0.40 (4)
14	0.40 (3)	0.24 (3)	28	0.40 (3)	0.40 (3)

exposure. Water leak marks were found at the pier and the abutment. Furthermore, extensive damage caused by erosion and wear were found. The damage confirmed by each member of the inspection of "Mi bridge" is shown in Table 5. Moreover, the application result of this system is shown in Table 6. The professional engineers judged that deterioration factors such as defective execution, defective design, and defective material had acted on this bridge. However, the output result of this system outputs low values to these deterioration factors. Moreover, dynamic factors by the load, drainage shortage, and the unexpected external force indicate high values.

(3) Tu bridge (Yamaguchi Pref. H engineering works office jurisdiction)

The Tu bridge (three main girders and four spans) is a RC T-girder type bridge constructed in May 1963. The age of the bridge is 36 years. This bridge is constructed in a main prefectural highway, and a lot of construction vehicles pass this bridge. In the main girder, bending cracks, shearing cracks and cracks caused by reinforcement corrosion were found. A lot of repair parts (recovery of cross-section) were found, and many of them were deteriorated again by the crack. In the deck slab, the crack of a right-angled direction of the bridge axis was found and the free lime was also found. In addition, the expansion and the drainpipe were clogged with sand. The damage confirmed by each member of the inspection of "Tu bridge" is shown in Table 7. Moreover, the application result of this system is shown in Table 8. The professional engineers judged that the deterioration factor such as a dynamic factor by the load, a defective design, a carbonation and a drainage shortage had acted on the third span of this bridge and a defective execution and a drainage shortage had acted on fourth span. On the other hand, this system produced a high score for the dynamic factor by the load and the drainage shortage. However, this system outputs a low score for defective design and defective execution.

(4) Ha bridge (Yamaguchi Pref. N engineering works office jurisdiction)

The Ha bridge (four main girders and two spans) is a RC T-girder type bridge constructed in March

Table 7 Damage of Tu Bridge

Member span No.		Damage
Deck slab	③	crack,drainpipe clogging,defect,free lime
	④	free lime
Main girder	③	crack,drainpipe clogging
	④	discoloration·detarioration

Table 8 Application result of this system (Tu Bridge)

No	③	④	No	③	④
1	0.40 (4)	0.22 (2)	15	0.60 (4)	0.14 (3)
2	0.36 (3)	0.13 (4)	16	0.60 (3)	0.14 (3)
3	0.07 (3)	0.04 (3)	17	0.36 (3)	0.36 (3)
4	0.10 (3)	0.04 (3)	18	0.10 (4)	0.16 (3)
5	0.40 (4)	0.14 (3)	19	0.40 (4)	0.14 (3)
6	0.40 (3)	0.14 (2)	20	0.40 (3)	0.14 (2)
7	0.24 (2)	0.09 (2)	21	0.24 (3)	0.40 (2)
8	0.24 (3)	0.09 (3)	22	0.24 (4)	0.24 (3)
9	0.40 (3)	0.14 (2)	23	0.40 (3)	0.40 (2)
10	0.36 (3)	0.13 (3)	24	0.36 (3)	0.16 (3)
11	0.90 (4)	0.54 (4)	25	0.90 (4)	0.09 (4)
12	0.40 (2)	0.14 (2)	26	0.40 (2)	0.14 (2)
13	0.40 (3)	0.14 (3)	27	0.40 (3)	0.14 (3)
14	0.40 (3)	0.14 (3)	28	0.40 (3)	0.14 (3)

Table 9 Damage of Ha Bridge

Member span No.		Damage
Deck slab	①	drainpipe clogging,pavement crack,leakage of water,free lime
	②	drainpipe clogging,leakage of water,free lime
Main girder	①	crack,discoloration·detarioration,drainpipe clogging,free lime
	②	drainpipe clogging,separation·reinforcement exposure

Table 10 Application result of this system (Ha Bridge)

No	①	②	No	①	②
1	0.24 (3)	0.60 (4)	15	0.40 (3)	0.24 (3)
2	0.14 (2)	0.13 (2)	16	0.40 (3)	0.24 (3)
3	0.04 (3)	0.11 (3)	17	0.36 (3)	0.22 (3)
4	0.04 (3)	0.04 (3)	18	0.16 (3)	0.10 (3)
5	0.16 (4)	0.14 (4)	19	0.40 (3)	0.24 (3)
6	0.16 (2)	0.14 (2)	20	0.40 (2)	0.24 (2)
7	0.10 (3)	0.09 (3)	21	0.40 (3)	0.24 (3)
8	0.10 (2)	0.09 (2)	22	0.24 (2)	0.24 (2)
9	0.16 (3)	0.14 (3)	23	0.40 (3)	0.24 (3)
10	0.14 (3)	0.13 (3)	24	0.36 (3)	0.22 (3)
11	0.90 (5)	0.54 (5)	25	0.90 (5)	0.90 (5)
12	0.16 (3)	0.14 (3)	26	0.40 (3)	0.24 (3)
13	0.16 (3)	0.14 (3)	27	0.40 (3)	0.24 (3)
14	0.16 (3)	0.14 (3)	28	0.40 (3)	0.24 (3)

1967. The age of the bridge is 32 years. This bridge is constructed in a main prefectural highway, and traffic is comparatively heavy. Especially, a lot of large sized motor vehicles pass this bridge. In the main girder, a crack, and a reinforcement exposure were found in the center part. In the deck slab, a water leak caused by drainpipe damage was found at the sponson part. Moreover, free lime was generated, too. The damage confirmed to each material by the inspection in "Ha bridge" is shown in Table 9. Moreover, the application result of this system is shown in Table 10. The professional engineers judged a defective design and drainage shortage as the deterioration factors which acted on this bridge. This system outputs high score to the drainage shortage. The defective design is reasoned well in the main girder, however, this system outputs a low score for the defective design in the deck slab, and so the defective design is not reasoned well. The inference result of this bridge was the best result in the five bridges examined.

(5) Ho bridge (Yamaguchi Pref. N engineering works office jurisdiction)

The Ho bridge (four main girders and four spans) is a RC T-girder type bridge constructed in March 1941. The age of the bridge is 58 years. This bridge is constructed on a general road and traffic is heavy. The bridge axial direction crack and the axis right-angled direction crack were found under the surface of the main girder. In the deck slab, a honeycomb and a crack at the sponson part were found. Also, a water leak was found in the sponson part. A radial crack was seen in the road surface. The damage confirmed to each member by the inspection in "Ho bridge" is shown in Table 11. Moreover, the application result of this system is shown in Table 12. The professional engineers judged that the deterioration factor such as a dynamic factor by the load, defective designs, and carbonation had acted on this bridge. On the other hand, this system outputs a high score for the dynamic factor by the load. However, this system outputs a low score for the defective designs and the carbonation, and some items cannot be reasoned well.

3.2 CONSIDERATION OF OUTPUT RESULT OF THIS SYSTEM

In the deterioration factor judged by the professional engineers, this system outputs a high score for a

Table 11 Damage of Ho Bridge

Member span No.		Damage
Deck slab	①	pavement crack
	④	crack
Main girder	①	crack,honeycomb・cavity,separation,reinforcement exposure
	④	crack

Table 10 Application result of this system (Ho Bridge)

No	①	④	No	①	④
1	0.60 (4)	0.40 (4)	15	0.60 (4)	0.60 (4)
2	0.13 (3)	0.36 (3)	16	0.40 (4)	0.40 (4)
3	0.11 (3)	0.07 (3)	17	0.36 (3)	0.36 (3)
4	0.04 (4)	0.16 (4)	18	0.10 (4)	0.10 (4)
5	0.14 (4)	0.40 (4)	19	0.40 (4)	0.40 (4)
6	0.14 (3)	0.40 (3)	20	0.40 (3)	0.40 (3)
7	0.09 (3)	0.40 (3)	21	0.24 (3)	0.24 (3)
8	0.09 (4)	0.40 (4)	22	0.24 (4)	0.24 (4)
9	0.14 (3)	0.40 (3)	23	0.40 (3)	0.40 (3)
10	0.13 (3)	0.36 (3)	24	0.36 (3)	0.36 (3)
11	0.09 (3)	0.24 (3)	25	0.24 (3)	0.24 (3)
12	0.14 (2)	0.40 (2)	26	0.40 (2)	0.40 (2)
13	0.14 (3)	0.40 (3)	27	0.40 (3)	0.40 (3)
14	0.14 (3)	0.40 (3)	28	0.40 (3)	0.40 (3)

dynamic factor by the load and the deterioration factor such as drainage function shortage as compared with the result of the questionnaire completed by the professional engineers. This system reasoned well. However, this system outputs a different score for the deterioration factor such as defective construction, defective design and defective material. As a result, it seems that the rule concerning the deterioration factors such as defective construction, defective design and defective material are few in this system. Especially, a defective deterioration factor for construction has only one rule to calculate the certainty factor. As for other deterioration factors, the certainty factor is calculated by a lot of rules. Therefore, it will be necessary to add the rule of the deterioration factor in the future. Moreover, it is necessary to increase the rule about other deterioration factors as much as possible, and improve the rule in order to improve the accuracy of the inference. Finally, it seems that the deterioration factor with high accuracy can be presumed by incorporating traffic and environmental conditions of the target bridge into the inference.

4. CONCLUSION

In this study, a new support system which enabled the deterioration factor to be presumed from the inspection data and non-destructive testing was developed as a part of the BMS. The new support system was applied to existing concrete bridges so as to demonstrate the validity of the proposed system. The questionnaire survey was set out to the professional engineers who inspected the bridge and the deterioration factor which had acted on the target bridge was investigated. As compared with the result of the questionnaire to the professional engineers, this system outputs a different score for the deterioration factor such as defective construction, defective design and defective material. This system outputted an almost similar score for other deterioration factors, and could reason well. In order to solve this problem in the future, a rule is added or improved to the system for the deterioration factor which is not reasoned well. In addition, not only the causal relation between damage and the deterioration factor but also rules concerning traffic and the environmental condition are added to this system.

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