BRIDGE MANAGEMENT SYSTEM
A strategy for individual and total maintenance planning

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ABSTRACT**:** The purpose of the bridge management system presented in this paper aims to efficiently maintenance of individual bridges for adequate safety and propose a maintenance budget planning for each individual bridges as a total. The proposed system is able to provide a reasonable basis for decision making of bridge repairing and reconstruction which are generally decided by personal experience or custom. The target of bridge management system focuses at necessity to separately consider individual and total bridges. It is important for considering bridges individually to get deterioration prediction for preventive maintenance and after maintenance. The total bridges management strategy is needed to prospect total repair cost for budged control. This paper consolidates the requirement needed to efficiently manage bridges system in practice, and also considers about the required output for individual and total bridges management.

KEYWORDS: Bridge management systems, decision-making assist module, deterioration prediction, budged control, individual bridges management, chloride attack

1. INTRODUCTION

Huge amount of infrastructures were constructed after World War II, they supported tremendous economic growth in Japan. Various type of deterioration appeared as ageing structures, and it has increased the requirements for management systems to operate the infrastructure in efficient way.

Bridge management system (BMS) becomes a tool to assist maintenance management planning as well as decision-making of individual and total bridges to run efficiently. In general BMS consists of systems components: inspection system, database system and decision-making system that are based on maintenance policy and deterioration prediction.

These systems work as a single module or function in bridge management system. In addition, it is indispensable for practical BMS to improve its usability and reliability.

This paper consists of two parts. First part is the total BMS framework and decision-making assist module. Second part is case study of deterioration prediction for individual bridge.

2. BRIDGE MANAGEMENT SYSTEM

2.1 General overview

Figure 1 shows overall schema of the BMS. It shows the required components and abilities in the order that form the whole system. The first step of BMS is construction of maintenance assist module that is consisted of inspection system and database system. The second step is for repairing, reconstruction planning and budged control. It is necessary to include the decision-making assist module to manage according to maintenance policy and deterioration prediction. The user friendly and multi-function interface to deal with the maintenance assist module determine the practicability in the first step of BMS. In the second step, the reliable result for deterioration prediction and the customizability of BMS is required to be able to sustain the changes the design standard and the improvement of the each components.

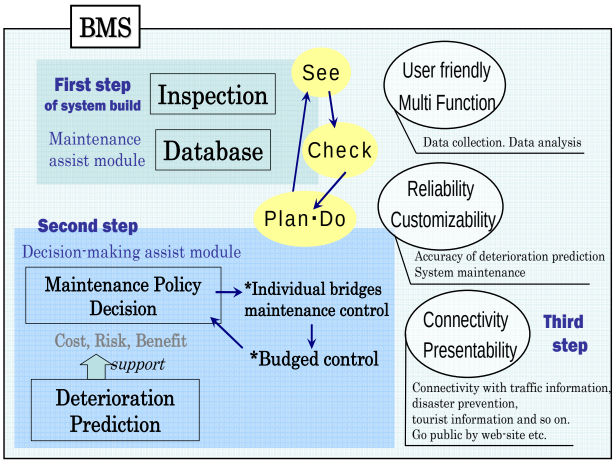

Figure1 Schema of bridge management system

At the present BMS in Japan, MICHI that is a road database system for national highway, is formed and started to be utilize for practice. Then, systematic inspection is conducted by many bridge administrators, and inspection database is growing year by year. However, the user friendly and multi function of these maintenance assist module is not enough for practical management. It is necessary to have the improvement of the system hereafter. The decision-making assist module of second step was just start to be developed. For example, the deterioration prediction models for chloride attack, fatigue of RC slabs and painting deterioration of steel bridges were just purposed to the National Highway BMS in 2006. The accuracy of models is not sufficient. The BMS in Japan is along the way in between the first and second step of BMS.

Efficiency of the decision-making assist module is important for more practical BMS together with improvement of user friendly and multi function interface.

2.2 Decision-making assist module

The decision-making assist module consists of maintenance policy and deterioration prediction sections. The target of decision-making is considered as individual bridge and budged control for total bridges. The decision-making for individual bridge is required when efficiently performing daily maintenance and repair planning based on a given maintenance policy. On the other hands, the decision-making for budged control of total bridges is required for deciding the maintenance policy based on risk assessment.

2.2.1 Budged control -Relationship between maintenance policy and individual bridge-

Figure 2 shows schema of decision-making assist module and the relationship between budged control and individual bridge maintenance. At first, decision of maintenance policy is required for individual bridges maintenance planning. Then, budged for total bridges maintenance is calculated by summing up all costs of each individual bridge belong to the target region. The maintenance policy is changed according to budged constraints. If the total budged is not settled in the budged constrain (dissatisfy), maintenance policy has to be changed or considered for another approach.

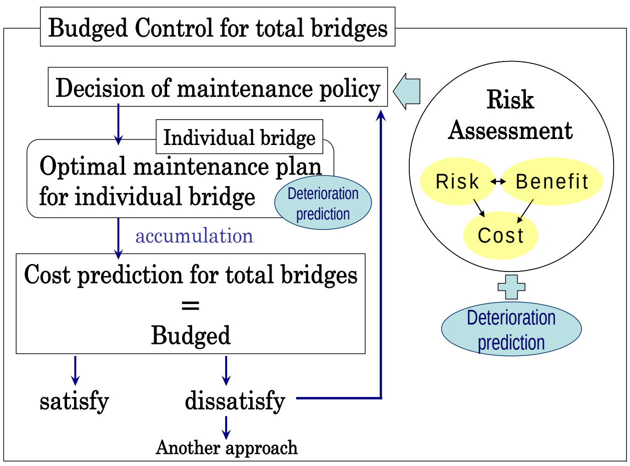

Figure 2 Schema of decision-making assist module and relationship between budged control and individual bridges and maintenance policy

2.2.2 How to decide maintenance policy

This section consider about the determination method of the maintenance policy based on budged calculation. The maintenance policy should be decided by the balance of cost, risk and benefit factors. However, for simplicity, only cost and risk are considered at this step of system development.

At first, it is necessary to prepare material for decision-making and list up number of maintenance type and level. The maintenance type and level that can be listed up are, for example, repairing, reconstruction and repair/reconstruction. Repairing can be decided from several possible combinations of existing repair methods. Each cost can be calculated with decision of some appropriate maintenance type and level. The cost is consisted by repair cost, reconstruction cost and social cost such as loss by traffic jam. The repair cost also should be included inspection cost. Target bridges will be classified according to the expected cost. Bridge size, traffic density and bypass road are considered as the items for classification. Figure 4 shows the mentioned procedure.

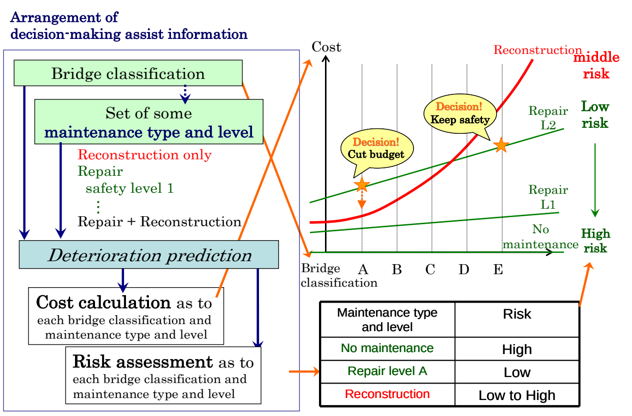

Figure 4 Flow-chart of how to decide a maintenance policy

The horizontal axis in graph of figure 4 represent bridge classifications and the vertical axis is cost. It is possible to decide some line, as in the figure, at each level of maintenance. From this graph, the maintenance policy can be decided by maintaining the balance between cost and risk. The decided maintenance policy based on the appropriate maintenance level is represented by star mark in the graph of Figure 4.

2.2.3 Deterioration prediction , chloride attack

The existing deterioration prediction models are classified by two categories, one is the model based on the statistical regression theory. The other follows the actual deterioration mechanisms. For the deterioration prediction for the RC slabs under fatigue loading and the painting erosion, it may be rational method to predict the deterioration by statistical methodology from traffic density and damage condition at the present time. However, the prediction based on actual deterioration mechanisms is indispensable for enough accuracy of the model such as chloride attack and carbonation that are influenced by complex environmental condition around target bridges.

The deterioration prediction based on actual mechanism consists of 4 steps; first step is giving definition of deterioration process, second is the modeling of each process, third is deciding the probability for each deterioration factor and model, and the last is the calculation for deterioration prediction. In the next section, deterioration prediction model of chloride attack based on actual deterioration mechanism is shown as an example.

Chloride attack

Chloride attack is one of the main deterioration for concrete structures. It is known that strong deterioration and it tends to re-deteriorate after repairing.

Definition of deterioration process

For chloride attack, five deterioration stages are usually defined: stage I is Incubation Stage, stage II is Progress Stage, stage III is Acceleration Stage, stage IV is Deterioration Stage, stage V is Unusable Stage. These stages are corresponding to the following four limit states: limit state 1 is initiation of steel corrosion, limit state 2 is crack opening, limit state 3 is falling of cover and limit state 4 is insufficiency of member strength. Models for deterioration prediction is based on the term of incubation stage, and the after incubation stage is defined as correlation with the time in which corrosion begins.

Deterioration model

The incubation stage is generally assumed as chloride ion diffusion process, which is expressed by Equation 1, Fick's second law.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad (1)$$

Where C represents chloride ion concentration, *t* is elapsed time, D is a diffusion coefficient, *x is* the distance from the surface of concrete.

Equation 2 is the most common equation for the process of chloride penetration into concrete. It is the solution of Equation 1 when assumed that chloride concentration at the surface is constant.

$$C(x,t) = C_0\left\{1 - erf\,(\frac{x}{2\sqrt{D \cdot t}})\right\} + C(x,0) \qquad (2)$$

Where $C(x,\ t)$ represents chloride ion concentration at distance *x* at the time *t* (kg/m^3), C_0 is chloride ion concentration at the surface of concrete (kg/m^3), C(x,0) is initial chloride ion concentration (kg/m^3), *erf* represents an error function. $C(x,\ t)$ should be limited chloride ion concentration for starting corrosion (critical chloride threshold value) to calculate incubation stage. D in Equation 2 is apparent diffusion coefficient (cm^2/y). The value of D is by JSCE [2] as shown in the following equation. It is result from statistical regression from many sampling tests [3].

$$\log D = \left[-3.9(w/c)^2 + 7.2(w/c) - 2.5\right] \qquad (3)$$

Where w/c is water cement ratio of concrete.

After incubation stages, the progress stage, the acceleration stage and the deterioration stage are controlled by the factors those are steel corrosion velocity and cracking resistance of cover concrete. However, research on steel corrosion speed is not enough at the present time. Therefore, after incubation stage, it is assumed as a few times of the incubation stage length for simplicity. The corrosion speed is a function of chloride concentration, oxygen diffusion speed and diameter of steel bar, and the cracking resistance is a function of cover concrete depth, bar spacing and concrete strength. These factors are the same as those affecting the chloride penetration except bar diameter and bar spacing.

The progress stage, the acceleration stage and the deterioration stage are assumed as four times, three times and two times the length of incubation stage, respectively. It is decided by the correlation of inspection data with calculation in preceding paper [1].

Probability for deterioration factors and models

Probabilistic deterioration factors and uncertainty of the models are necessary to be considered for practical deterioration prediction of real bridges.

The probabilistic deterioration factors that should be considered are surface chloride concentration, apparent diffusion coefficient and concrete cover those are the parameters controlling the chloride ingression into concrete. These probabilistic parameters are influenced by the environment and construction process.

Since, the critical chloride threshold value that determines the crack occurring timing still has unknown mechanisms, it is necessary to consider its uncertainty by introducing probabilistic measure.

The other stages of incubation stage also should be determined in a probabilistic manner.

3. CASE STUDY OF DETERIORATION PREDICTION FOR CHLORIDE ATTACK

In this section, case study of deterioration prediction for chloride attack is done for individual bridge. And, it is then compared the real condition with the calculation result. As for illustration the proposed methods, this section shows 2 different approaches. First is the case that use budged control of total bridges as one bridge data. Second is the case of that maintenance planning of individual bridge is decided by using result of deterioration prediction.

3.1 Deterioration prediction for individual bridge

Ananai Bridge is located in Aki-shi, Kochi prefecture, Japan. It is at 150 m away from seashore facing to the Pacific Ocean. Ananai Bridge consists of 2 spans and 5 RC T-shape girders in one span. Sea side 3 girders of each span were constructed before 1953 (clear construction year is unknown), and the others were extended in 1968. The girders named as G1 to G5 from mountain side to sea side, respectively. In this section, deterioration prediction of G2 and G3 girders of right span (figure 3) is shown, since detail data is available for these two girders.

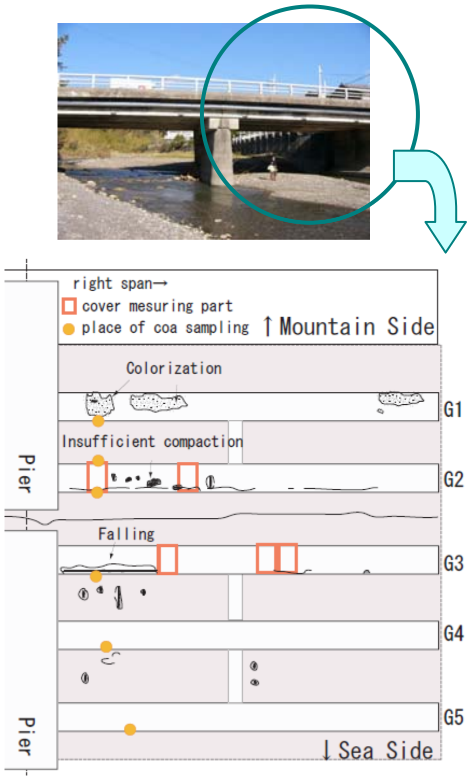

Figure 3 Picture of Ananai Bridge and the deterioration condition at 2005

3.1.1 Probability of each deterioration factors

Table 4 shows the result of core tests, surface chloride ion concentration C_0 and apparent diffusion coefficients D by data fitting between distributions of chloride ion concentration and Equation 2. The initial chloride ion concentration is assumed to be 0.5 kg/m^3. Depth of core is 60 mm, and values of Table 4 are average total chloride ion concentration of each 20 mm.

Table 4 Result of core test and values of C_0 and D

* S: sea side, M: mountain side ** Age of core

Girder No.*	Year**	Chloride concentration kg/m^3			C_0 kg/m^3	D cm^2/y
		10	30	50		
G1/S	37	4.56	6.61	3.42	6.5	1.5
G2/S		3.38	2.25	1.8	3.3	0.4
G2/M		1.35	1.8	0.9	1.3	1.0
G3/S	55	2.53	2.76	1.84	2.5	0.9
G4/S		4.7	3.53	4	4.5	2.0
G5/S		4.74	3.56	2.13	5.0	0.3

Table 5 shows the probability of C_0 and D those are decided by the result from Table 4.Construction year of G3-G5 is assumed as 1950.

Table 5 Probability of the surface chloride ion concentration and apparent diffusion coefficient

	Average	Standard Deviation
C_0 (kg/m^3)	3.9	1.9
Log D (D: cm^2/y)	-0.095	0.344

Cover

Some parts of concrete cover on G2 and G3 were measured by electromagnetic inducing testing method. Number of measured points is 141 points on two locations in G2, and 201 points on three locations in G3. Table 6 shows average of the results and standard deviation calculated from Equation 3. Table 6 shows the probabilistic values of the concrete cover. The standard deviation is decided by Equation 4, inference of population variance.

$$s^2 = \frac{1}{n-1}\sum(x_i - \bar{x})^2 \qquad (4)$$

Table 6 Probability of cover concrete

	Sampling points	Average mm	Standard Deviation
G2	141	46	9.0
G3	201	69	15.0

Critical chloride threshold value

Definition of the critical chloride threshold value is not well defined. However, some researchers reported the value between 1.2 to 2.4 kg/m^3 as the result of exposed tests. In this paper, average of C_{lim} is 1.8 kg/m^3, standard deviation is 0.2 kg/m^3 are adopted.

The average length of the states after incubation stage; i.e. progress, deterioration and unusable stage, are assumed to be 4, 3 and 2 times of that of the incubation stage, respectively. Coefficient of variations that has value of 35% is considered for each probability. Every distribution type is assumed as normal distribution with 99 % confidence.

3.1.2 Result of deterioration prediction

Figure 4 shows the results were obtained from the proposed models and probabilistic values. Upper figure shows the deterioration prediction of G2 girder and below figure is for G3 girder. G2 girder has age of 37 years, and G3 girder is about 55 years. The deterioration speed is differed because of the G3 cover concrete is thicker than of the G2 one.

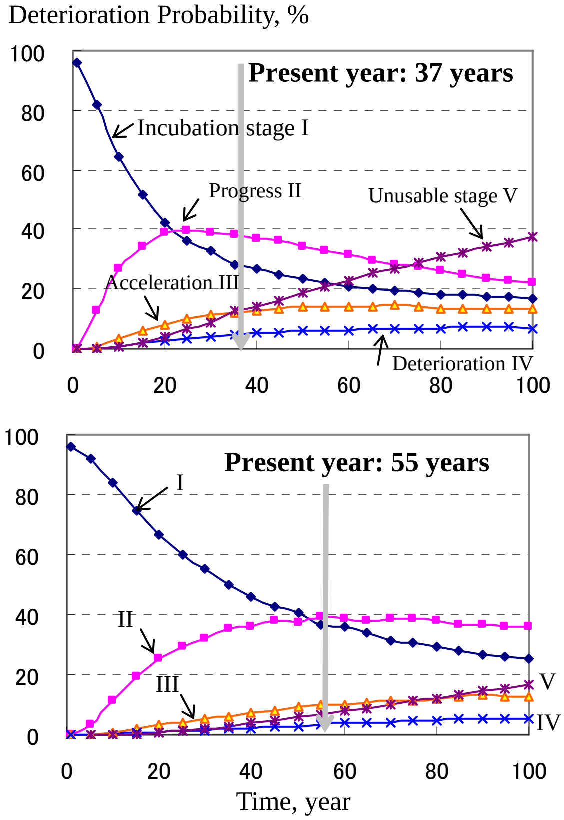

Figure 4 Calculated deterioration prediction (probability of 5 deterioration) of G2 girder (upper) and G3 girder (below)

Figure 5 shows comparison the prediction result and the real condition of G2 (upper) and G3 (below) girders (see Figure 3).

This deterioration prediction is targeted for the deterioration condition on main reinforcing bar by setting the probabilistic distribution of concrete cover regarding to the reinforcing bar. The actual conditions on the main reinforcing bar are investigated; cracking on half of span length and 10% for cover spalling on the G2 girder, cracking on 20% of span length and 20% of cover spalling on the G3 girder. The ratios of each type of deterioration are shown in Figure 5. It is assumed that there are 6 main reinforcing bars inside each girder section. The large reduction of steel bar cross-sectional area was not found on both G2 and G3 girder. Unusable stage cannot be counted.

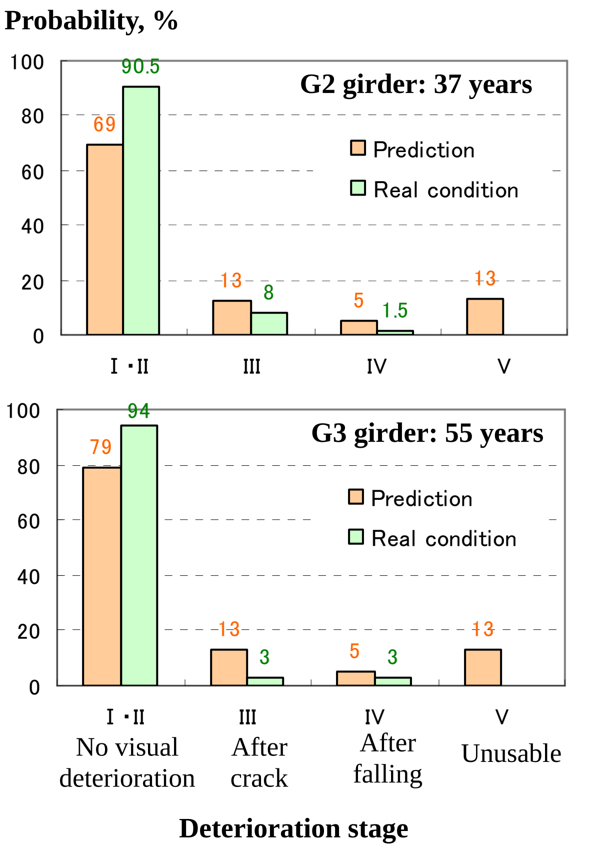

Figure 5 Comparison between calculation result and real condition

The deterioration prediction overestimated the real condition, e.g. the calculated unusable stage is large. The reason is expected that it was caused by assuming the incubation stage length shorter than that of the real one, or the calculation models of after incubation stage are assumed with insufficient deterioration length.

3.2 Image of practical usage of deterioration prediction of bridge and member

Deterioration prediction systems for budged management control and maintenance of individual bridge are different. Deterioration prediction for budged control is the information about the maintenance cost and timing under settled maintenance policy. On the other hands, the deterioration prediction for individual bridge concerns material analysis under various conditions.

3.2.1 Budged control

The following maintenance level is assumed as the maintenance policy for Ananai Bridge.

Example: Maintenance level for Ananai Bridge

Before the unusable stage ratio of any single member of the superstructure become over 20%, fixed repair (e.g. the electrical protection) should be introduced.

For this example, it can be judged from Figure 4 that the G2 girder will reach the target deterioration state in 20 years and the G3 girder is in about 50 years.

It is assumed that G1 girder has the same deterioration prediction with G2, and G4 and G5 girders are same with G3 girder.

The repairing cost is assumed for 10 million yen per girder. The repairing cost for Ananai Bridge is then calculated as 40 million yen (2 girders/2 spans × 10 million yen) in 20 years, 60 million yen (3 girders/2 spans ×10 million yen) in 50 years. It becomes possible to predict the budged for total bridges maintenance by summing the maintenance cost and repair timing of individual bridges.

3.2.2 Individual bridge maintenance and planning

From the previous discussion, the target deterioration state will be reached in 20 years and in 50 years for G1, G2 girders and G3, G4, G5 girders, respectively. The repairing timing and scale will be decided based on this information by bridge engineer.

4. CONCLUSION

This paper proposed the guideline that able to aid the decision-making assist module, deciding for maintenance policy for budged control. Also, the case study to illustrate the general example for deterioration prediction was presented.

As for future development of the BMS, it is necessary to arrange and construct the system that aids the decision-making for the maintenance policy, improve accuracy of the deterioration prediction models.

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