BRIDGE MANAGEMENT SYSTEM APPLICATION

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Abstract: In this paper, a bridge management system application aiming to assist bridge managers to design optimal rehabilitation/maintenance (R&M) policies is presented. The system provides to the bridge managers the technical information for the planning of optimal R&D as well as managerial accounting information for the asset valuation of the bridges for every fiscal year. The system includes an estimation module that estimates the Markov transition probabilities based on the observation data set from inspections and a module that generates a simulation of the deterioration/rehabilitation processes of the bridge systems in order to evaluate the life-cycle costs of the R&M policies. The system presented in the paper is applied to the bridge systems managed by the Himeji Office of Ministry of Land, Infrastructure and Transport, and the applicability of the systems is tested against real world data.

Keywords **:** bridge management, deferred maintenance accounting, asset management, life cycle costing

1. Introduction

Recently, a large number of studies were conducted on bridge asset management systems. An objective of bridge management is to compute an optimal repair policy with some indexes including the life cycle costing. However, bridge administrators often can not secure a sufficient annual budget to carry out an optimal repair strategy, so they usually have to prioritize the repairs under a budget constraint. The bridge components which can not be repaired at the optimal timing are repaired in the following time period (year).

In Japan a large number of bridges are constructed during a high-growth period, and as a result it is expected that these bridges will be replaced simultaneously in the near future. This results in increasing the demand for bridge repair rapidly. On the other hand, the reduction of the fiscal expenditure resulting from the increase of the social security costs and the decrease of the tax revenues because of the declining birthrate and the "aging society" problem makes it necessary to reduce the maintenance budget of bridges. Under these conditions, in order to respond to the needs resulting from the new provision of social capital, regarding building and maintaining bridges, it is necessary to develop a bridge management system which can estimate the repair demands accurately and aid in planning the budget control efficiently.

This study proposes a comprehensive bridge management system (BMS) which performs rational bridge maintenance. Furthermore, the study developed BMS computer application software to be utilized in real works of bridge maintenance. The BMS application is divided into three systems, 1) inventory system to manage the database, 2) asset management system to plan the repair strategy, and 3) accounting system to record the repair results and control the budget. The asset management system is divided into three sub-systems, a) strategy level, composed of five modules for long term budget planning, b) tactics level which decides the middle-term repair priority according to the outputs of the strategy level, and c) annual level which records the repair results for each fiscal year. The second section of this paper, presents the research fundamentals of the BMS. In the third section some methodologies of the BMS are described. The fourth section describes the usage of the BMS application. Finally, the fifth section presents a case study as it was applied to the bridge systems managed by the Himeji Office of Ministry of Land, Infrastructure and Transport.

2. Research Fundamentals

(1) State-of-the-art

Over the recent years several studies have been conducted on BMS[1),2)] aiming at selecting the repair method, judging the condition rate or the inspection results, and to plan the optimal repair strategy. BMS aimed at the reduction of the long-term life cycle cost (LCC) of a bridge, is put in practical use as in PONTIS, for example, which is one of the typical BMS used in the U.S. When the maintenance of a bridge is considered, it is necessary to simultaneously deal with the problem of managing two different levels, i.e. the project level for each bridge and the system level for all

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the bridges. Among the studies on BMS, there are some about optimal repair models of the bridge components for the project level[3)-7)]. In PONTIS, for example, as mentioned earlier, the LCC is computed using the present value method which converts the cost generated at different times into its current value using a discount rate. Some optimal repair models[12)-17)] using the Markovian decision model[8)-11)] are proposed and applied in practical BMS. On the other hand, there is evidence that the present value method can not estimate adequately the effect of the long-life of bridges[3)]. Related with this finding, Kaito et al. (2005), proposed a Markovian decision model which computes the optimal repair policy using the average cost method by transposing the life cycle cost to an annual average cost. Thus, although there are some methods of determining the repair strategy of a single bridge, in a more realistic bridge management it is necessary to manage simultaneously many bridges where the construction time, the characteristics of the structure and the deterioration differ. When dealing with the maintenance of such a bridge system comprised of several bridges, the development of a managerial accounting system aiming at the asset evaluation of the bridges and the budget control for evaluating the performance of the repair results of the bridge system based on the maintenance repair results in each fiscal year, is required. The BMS developed in this study computes an optimal repair strategy based on average cost method as proposed by Kaito et al. (2005). The LCC evaluation using an average cost method is consistent with deferred repairs and maintenance accounting. The BMS proposed in this study introduces a new approach on the valuation of assets and budget control based on deferred repairs and maintenance accounting that can be simultaneously attained in the bridge system.[19)] In addition, this BMS application is build on the function which estimates the deterioration forecasting model of a bridge component, based on periodical inspection results, and which can update the deterioration forecasting model based on new inspection results.

In this study, the discussion of the BMS is limited to the relation of the "components – bridge system". In the future it is necessary to improve the BMS into a system that takes into consideration the relation of the "components – bridge – bridge system". It should also be added that in this application the information about the condition state of each bridge is collected as physical and managerial accounting information.

(2) Composition of BMS

The BMS of this study can be divided into two classes, the project level and the system level, as mentioned earlier. The BMS is composed of the hierarchical management cycle among the different decision making stages.

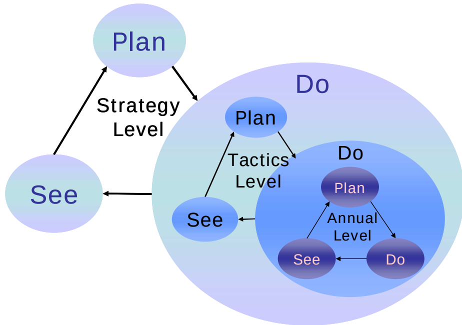


Fig.1 Hierarchical Management Cycle

Fig.1 shows the hierarchical management cycle for the BMS. The BMS can be classified into three main groups, the strategy level (long term planning), the tactics level (short term planning), and the annual level (annual planning). Also in each level, the results of the analysis or the repair in project level are collected as information on the system level.

From the strategy level an optimal repair strategy for each component and the bridge system is extracted. This optimal repair strategy for each bridge is computed based on the condition states of each bridge, and bridges are categorized into groups (grouping module). An optimal repair strategy and a repair method of construction of a bridge are determined for each group. The transition of the deterioration of bridge components is impossible to predict deterministically because of the uncertainty present. Instead a deterioration forecasting model for the bridge's components is expressed by a Markov chain model. This deterioration forecasting model is estimated for every component based on periodical inspection data (estimating transition probability module, **3. (1)**). An optimal repair strategy is computed by the Markovian decision model using the estimated transition probabilities (optimal repair strategy module, **3. (2)**). Furthermore, the simulation of deterioration/repair process for the group as classified according to the whole bridge system or the bridge characteristic is carried out. An optimal repair strategy for every group, a long term budget planning and a maintenance standard, etc. are determined by simulating the transition of the budget and condition states (simulation the deterioration / repair process module, **3. (3)**).

The tactics level is used to generate a list of candidate bridge components that should be repaired in the near future using some outputs from the strategy level (priority module). At this time periodical inspection is carried out. The bridge components in need of immediate repair, as judged from the inspection results, may be divided into groups. The components that need repair during the middle-term and their priorities are examined from several conditions, such as the condition state using the results of the inspection, the target of maintenance level and the budget allocation. The priority of repair is judged by evaluating simultaneously various indices, not only the risk

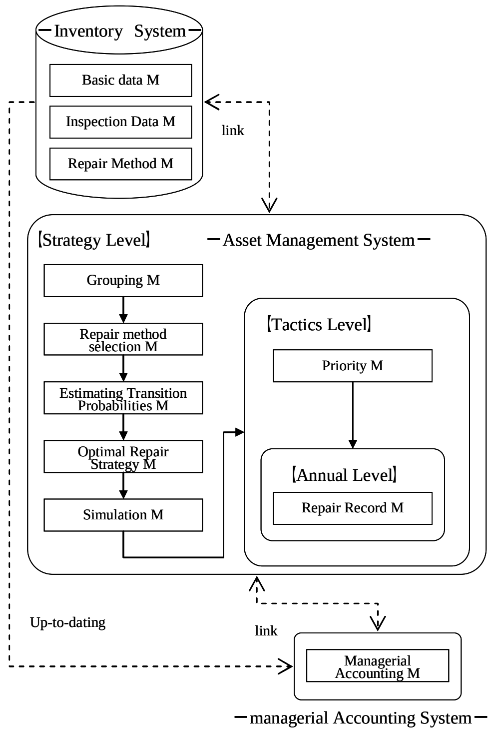


Fig.2 Composition of BMS

of deterioration but the importance of the bridge and/or the management responsibility.

At the annual level, the repair candidate components are processed under the budget allocation according to the priority decided at the tactics level. The information of the bridge components that are flagged as 'repaired' is deleted from repair candidate list (recording module). The records carried out in the fiscal year are then recorded into the managerial accounting system.

The following sections describe the estimation of the transition probabilities, the method of computing an optimal repair strategy, the simulation model for long term budget planning and the managerial accounting system.

3. Methodology of BMS

(1) Estimating Transition Probabilities

A bridge consists of many components and the deterioration process of each of these components has uncertainty, so the life cycle of each bridge is different. The deterioration forecasting model of the bridge components in this research is expressed in a Markov transition probability matrix. The transition from a given state condition of a bridge component is uncertain and forecasting of future states cannot be accomplished deterministically. Assuming that the deterioration process of a bridge component can be formulated by a time-homogeneous Markov chain defined on the state space $S = \{1, \cdots, K\}$ which consists of the condition state $i (i, \cdots, K)$. A Markov transition probability can be defined, given the condition state $h(t) = i$ is observed at time t, as the probability that the condition state at a future time $t+1$ will change to $h(t+1) = j$. That is,

$$\mathrm{Prob}[h(t+1) = j \mid h(t) = i] = \pi_{ij} \tag{1}$$

The Markov transition probabilities matrix can be defined as,

$$\Pi = \begin{pmatrix} \pi_{11} & \cdots & \pi_{1K} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{KK} \end{pmatrix} \tag{2}$$

From the definition of transition probability $\sum_{j=1}^{J} \pi_{ij} = 1$. It is possible to estimate the Markov transition probability matrix using the database of past inspections. More on the methodology of estimating the transition probability can be found on Tsuda et al.[18] In this paper, in order to give facilities to the reader, the outline of the estimation method is discussed.

The Markov transition probability can be defined using a multi-stage hazard model that represents the deterioration process of an individual component. The life expectancy of a condition state i is assumed to be a stochastic variable with probability function $f_i(\zeta_i)$ and distribution function $F_i(\zeta_i)$. The probability density $\lambda_i(y_i)$ is referred to as the hazard function, which means the probability that the condition state at time y_i is assumed to change from i to $i+1$. By using the survival function $\tilde{F}_i(y_i)$ of a transition in the condition state i until the time instance y_i, the hazard function is defined as,

$$\lambda_i(y_i)\Delta y_i = \frac{f_i(y_i)\Delta y_i}{\tilde{F}_i(y_i)} \tag{3}$$

The hazard function $\lambda_i(y_i)$ is the conditional probability that the condition state of a component at time y_i advances from i to $i+1$ during the time interval $[y_i, y_i + \Delta y_i]$. It is assumed that the deterioration process of a bridge component satisfies the Markov property and that the hazard function is independent of the time instance y_i on the sample time-axis. That is, for a fixed value of $\theta_i > 0$

$$\lambda_i(y_i) = \theta_i \tag{4}$$

By using the exponential hazard function it is possible to represent the deterioration process of a bridge component that satisfies the Markov property (independent of the past history). Using the hazard function, the probability $\tilde{F}(y_i)$ that the life expectancy of the condition state i becomes bigger than y_i is expressed by

$$\tilde{F}_i(y_i) = \exp(-\theta_i y_i) \tag{5}$$

Next, the condition state observed by inspection at time τ_A is i. In this case, the condition state at the time instance y_A on a sample time-axis is also i, and the probability that the condition state i will remain constant at a subsequent time instance measured from the time instance y_A by more than $z_i (\geq 0)$ is defined as,

$$\tilde{F}_i(y_A + z_i | \zeta_i \geq y_A) = \mathrm{Prob}\{\zeta_i \geq y_A + z_i | \zeta_i \geq y_A\} \tag{6}$$

dividing the probability by $\tilde{F}(y_i)$ results in,

$$\frac{\tilde{F}_i(y_A + z_i)}{\tilde{F}_i(y_A)} = \frac{\exp\{-\theta_i(y_A + z_i)\}}{\exp(-\theta_i y_A)} = \exp(-\theta_i z_i) \tag{7}$$

In addition, for the condition state i obtained by inspection at time instance y_A the probability that the same condition state will be observed by a subsequent inspection at the time instance $y_B = y_A + Z$ is,

$$\mathrm{Prob}[h(y_B) = i | h(y_A) = i] = \exp(-\theta_i Z) \tag{8}$$

where Z expresses the interval between the two inspection times. The probability $\mathrm{Prob}[h(y_B) = i | h(y_A) = i]$ is the Markov transition probability π_{ii}. That is, when an exponential hazard function is employed, the transition probability π_{ii} is dependent only on the hazard rate θ_i and the inspection interval Z. Furthermore, without using deterministic information on the time instances y_A and y_B, it is still possible to estimate the transition probabilities. Tsuda et al[18] show that the Markov transition probability π_{ij} of the transition of the condition state from i to j during the time interval $[y_A, y_B]$ is,

$$\pi_{ij} = \mathrm{Prob}[h(y_B) = j | h(y_A) = i] = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z) \tag{9}$$

from the definition of the Markov transition probability,

$$\pi_{iK} = 1 - \sum_{j=i}^{K-1} \pi_{ij} \tag{10}$$

More on the methodology of estimating the transition probability using the maximum likelihood estimation method can be found at Tsuda et al[18].

(2) Optimal Repair model

An optimal repair model expresses the deterioration process of a bridge component by the Markov transition probability and derives the optimal repair strategy minimizing the LCC using the Markov decision model. As mentioned earlier, in the LCC evaluation method the, 1) present value method and 2) average cost method are proposed. Kobayashi[20] has pointed out that the average cost method is a more appealing method of evaluating the optimal repair policy of a bridge system which consists of many components. The BMS application utilizes the present value and the average cost methods to compute the optimal repair strategy. This paragraph describes briefly the methodology of LCC evaluation using the average cost method and the optimal repair model using the Markov decision model. For a detailed description of the optimal repair model method, see Kaito et al. [6]

a) The precondition of modeling

Consider a discrete time interval that starts at initial time $t = 0$ up to infinity. Let us focus on a certain component of a bridge. The deterioration process of a bridge component is expressed in the Markov transition probability matrix estimated by the hazard model mentioned earlier. The condition state of a bridge component is evaluated by multi-stage discrete rating indices. The Bridge administrators appraise the condition of a component by inspection, and rehabilitate the condition by repairing the deteriorated component. In that case, the bridge administrators select the optimal repair method according to a repair rule decided in advance. The rule which determines the repair method to be applied in order to rehabilitate the condition of the deteriorated component is called the "repair action." The repair policy $d \in D$ (D is a set of a repair policy) is defined for each condition state i as a series of rules which specify the repair action to be carried out at that time. The repair action $\delta^d(i) \in \Delta(i)$ which comprises of the repair policy d means that the component with condition i is repaired and that condition changes to $\delta^d(i)$. $\Delta(i)$ is a set of the repair method which can be applied when the condition is i. The repair action is defined as,

$$\delta^d = \left(\delta^d(1), \cdots, \delta^d(K)\right) \tag{11}$$

Next a cost vector defines the repair cost which is needed when the repair action $\delta^d(i)$ is carried out.

$$c^d = \left(c_1^d, \cdots, c_K^d\right) \tag{12}$$

where c_i^d is required for the repair to be applied to the component of the condition i, and is defined as the repair cost for restoring the condition of a component from i to

$\eta^d(i) = j \ (1 \leq j \leq i)$.

b) Modeling the deterioration/repair process

The change in the condition state of the component produced by the repair action $\eta^d(i)$ which constitutes the repair policy $d \in D$ is defined as,

$$q^d_{ij} = \begin{cases} 1 & \eta^d(i) = j \\ 0 & \text{otherwise} \end{cases} \quad (i, j = 1, \cdots, K) \tag{13}$$

Now suppose that repair is carried out, when the condition state of a component is evaluated at time t to be i and the condition changes to the condition state j in the next time instance $t+1$ according to the Markov transition probability Π. At that time, even if the component was at the same condition, there are often two different conditions possible, rehabilitation by repair from poor condition and deterioration from the good condition state. In the case of the latter, the condition can be recovered by repair, but in the case of the former a limitation exists in that a repair policy can not be applied and the condition remains at that condition state. In order to take into consideration the repair history in such a deterioration/repair process, the transition probabilities under a repair policy $d \in D$ are defined as,

$$\pi^d_{ij} = \begin{cases} \pi_{ii} & i = j \\ \sum_{k=i+1}^{K} \pi_{ik} q^d_{kj} & \text{otherwise} \end{cases} \quad (i, j = 1, \cdots, K-1) \tag{14}$$

because of the assumption that that component is replaced immediately at condition K, which indicates the worst condition state. After repair is carried out at the beginning of each fiscal year, the component of the condition K does not exist. The transition probability matrix including the effect of repair action is defined as,

$$\Pi^d = \begin{pmatrix} \pi^d_{11} & \cdots & \pi^d_{1K-1} \\ \vdots & \ddots & \vdots \\ \pi^d_{K-11} & \cdots & \pi^d_{K-1K-1} \end{pmatrix} \tag{15}$$

where Π^d has $(K-1 \times K-1)$ dimension.

c) Average cost minimizing principles

A desirable combination of the optimal repair action based on average cost evaluation is calculated. Consider the condition state i is observed at time $t = 0$, and the component deteriorates in the next inspection period, time $t = 1$, and the condition state j is observed just before $t = 1$. Repair action to the condition state j is carried out just before $t = 1$. It is impossible to predict deterministically the repair actions to be carried out at $t = 1$ at $t = 0$, then the expected repair cost which will be needed under the repair policy d until just before $t = 1$ is expressed by,

$$r^d(i) = \sum_{j=i+1}^{K} \pi_{ij} c^d_j \quad (i = 1, \cdots, K-1) \tag{16}$$

Next, consider the condition state changes to j in one period from $t = 0$, that is at $t = 1$. The relation between the expected accumulation life cycle cost in the interval between $t = 1$ and $t = n$ under the repair policy d and the expected accumulation life cycle cost at the initial time is defined recurrently as,

$$u^d(i; n) = r^d(i) + \sum_{j=1}^{K-1} \pi^d_{ij} u^d(j; n-1) \quad (i = 1, \cdots, K-1) \tag{17}$$

The solution of a recursive equation can be approximated to sufficiently big n by[6)],

$$u^d(i; n) = nq^d + v^d(i) \quad (i = 1, \cdots, K-1) \tag{18}$$

That is, the expected accumulation life cycle $u^d(i; n)$ cost can be divided into the term nq^d proportional to the period length n, and the term $v^d(i)$ depending on the initial condition i. The simultaneous equations can be formulated by the relation of equations (17) and (18),

$$q^d + v^d(i) = r^d(i) + \sum_{j=1}^{K-1} \pi^d_{ij} v^d(j) \quad (i = 1, \cdots, K-1) \tag{19}$$

where, q^d in the equation (19) expresses the average cost, redistributed every year as the equivalent cost under the repair policy d. Thereby, the repair/replacement cost required in order to maintain a bridge component semi-permanently can be transposed to the flow of average cost equivalent for each year $(q^d, \cdots, q^d, \cdots)$. The term $v^d(i)$ that depends on the initial condition state is defined as the relative cost, which is required for the large-scale rehabilitation when the condition of components is deteriorated at the current time. By using the expected accumulation life cycle cost, the repair cost to the future time n is aggregated under the repair policy d; the average cost to the time n can be expressed by dividing the expected accumulation life cycle cost by the period length. And the average cost for an infinite period is defined as,

$$w^d(i) = \lim_{n \to \infty} \frac{u^d(i;n)}{n} \quad (i = 1, \cdots, K-1) \tag{20}$$

At this time, the average cost minimization model aiming at the minimization of the average cost can be formulated as,

$$w^{d^*}(i) = \min_{d \in D} \left\{ \lim_{n \to \infty} \frac{u^d(i;n)}{n} \right\} \quad (i = 1, \cdots, K-1) \tag{21}$$

The optimal repair policy based on an average cost minimization model is called the average cost minimization policy. The optimal repair model is an average cost minimization Markov decision model, and the optimal policy is a steady policy about time. This steady optimal solution can be computed by the strategy improving method of Howard[8) etc. See reference (6) about the solution of the average cost minimization model.

The optimal repair policy based on an average cost minimization principle has the desirable property of attaining LCC minimization under a fixed budget constraint every year, when premised on maintaining a bridge semi-permanently. Furthermore, the LCC can be evaluated as a flow of average cost equivalent every year, and the budget control according to the deferred repairs and maintenance accounting of a bridge is evaluated as non-depreciable assets become possible. The managerial accounting system is described at **3.(4)**. The present value minimization model for searching for the optimal repair policy, using a present value method, is also used in the BMS application. It is proved theoretically that an average cost minimization model is equivalent to the special case that makes the discount rate zero in the present value minimization model. More about the present value minimization model can be found at references (6) and (17).

(3) Simulating the Deterioration-Repair Process

a) Procedure of the simulation module

The simulation module analyzes the deterioration/repair process that varies according to the repair policy of the bridge component for which it is computed (using the two different life cycle cost appraisal methods, the average cost minimization model and the present value minimization model) by a simulation that aims at computing the management level (the distribution of the condition state) and a budget standard. The module is designed so that simulation experiments are conducted on various bridges on the repair method and repair cost, taking the heterogeneity into consideration. The purpose of the simulation module is to compute the optimal repair strategy and to analyze the influence the budget constraint has on the management level, generating information for evaluating the bridge repair strategy in agreement with real road management. This paragraph describes the procedure followed for the simulation module.

Suppose that there are M components of a bridge system for management. Each component is expressed by $m (m = 1, \cdots, M)$. Next, the condition state of component m at time t is expressed by the condition state variable $\omega_m(t)$. The condition state of the whole bridge system is expressed by,

$$\omega(t) = (\omega_1(t), \cdots, \omega_M(t)) \tag{22}$$

Next, assume that the bridge system consists of bridges of the same type. This assumption is made in order to simplify the explanation. Note that the BMS application is designed so that many heterogeneous bridge components can be dealt with at the same time. The total number of components having a condition state i at time t is expressed by $\xi^i(t) (i = 1, \cdots, K)$. The vector of the components is defined as,

$$\xi(t) = (\xi^1(t), \cdots, \xi^K(t)) \tag{23}$$

where

$$\xi^i(t) = \sum_{m=1}^{M} \delta_m(t) \quad (i = 1, \cdots, K)$$

$$\delta_m(t) = \begin{cases} 1 & \omega_m(t) = i \\ 0 & \omega_m(t) \neq i \end{cases}$$

Here, the simulation of the process of the condition state of a bridge system is considered when the initial time is at $t = 0$. Because it is impossible to predict deterministically the condition state in the future, the probability distribution of the condition state of component m at the time $t = n$, after n periods from the initial time, is expressed by,

$$\pi_m(n) = (\pi_m^1(n), \cdots, \pi_m^K(n)) \tag{24}$$

where $\pi_m^i(n)$ expresses the probability that the condition of components m becomes i at time $t = n$. Then, the distribution of the condition of component m after n having an initial condition $\omega_m(0) = i$ is defined as,

$$\pi_m(n) = e_i' (P_m)^n \tag{25}$$

where $e_i = (0, \cdots, 0, 1, 0, \cdots, 0)$ is the vector in which only the n-th element takes the value of 1 and all the other elements take the value of 0. Furthermore, $(P_m)^n$ expresses the n-th power of the transition probability matrix P_m.

Next, the case where the repair policy d is applied to a deteriorated component is considered. The distribution of the condition of component m after n periods having an initial condition $\omega_m(0) = i$ is defined as,

$$\pi^d_m(n) = e_i \left(\mathbf{P}^d_m\right)^n \tag{26}$$

where $\pi^d_m(n)$ is the distribution of the condition state of component m, which can be expressed by $\pi^d_m(n) = (\pi^{1,d}_m(n), \cdots, \pi^{K,d}_m(n))$. At this time, the distribution probability of the condition state of the bridge system under the repair policy d is expressed by,

$$\pi^d(n) = \{\pi^d_1(n), \cdots, \pi^d_M(n)\} \tag{27}$$

The distribution probability of the condition state in each period can be computed using the Markov chain model repetitively. The vector of expected components by which each condition is observed at time n is defined as,

$$E[\eta^d(n)] = (E[\eta^d_1(n)], \cdots, E[\eta^d_{K-1}(n)]) \tag{28}$$

The vector of expected components $E[\eta^d(n)]$ by which condition i is observed at time $t = n$ is defined as,

$$E[\eta^d_i(n)] = \sum_{m=1}^{M} \pi^{i,d}_m(n) \quad (i = 1, \cdots, K-1) \tag{29}$$

Furthermore, the expected value of the repair cost of the component m which is in condition i just before time $t = n$ is shown by,

$$E[\xi^d_m(n)] = \sum_{j=i+1}^{K} \pi^{i,d}_m(n-1)\, p_{ij}\, c^d_j \tag{30}$$

The expected value of the annual repair cost of the bridge system in each time instance adding the expected repair cost of each component is computed by,

$$E[\xi^d(n)] = \sum_{m=1}^{M} E[\xi^d_m(n)] \tag{31}$$

This simulation model is given the initial condition of each component $\omega(0) = (\omega_1(0), \cdots, \omega_M(0))$. According to this procedure, the simulation of the deterioration and repair processes of a bridge system can be carried out. In addition, in this simulation module, pseudorandom numbers are generated by the Monte Carlo method, and the sample path expressing the deterioration/repair process of each bridge component is generated. The number of trials for the sample path can be set up arbitrarily. The expected value of the annual repair cost which generates the LCC evaluated on the sample path for each year by performing the equalization operation to several sample paths, and the classification of the components by their condition can be computed.

b) Simulation under budget constraint

When there are no restrictions on the annual repair budget, the repair based on the optimal repair policy computed by the life cycle evaluation is carried. However, in actual bridge management, because the bridge administrators can not often secure sufficient funds to carry out an optimal repair strategy, selected components to be repaired, constrained by the budget, are selected. A cost benefit rule is applied as a standard for determining the priority of repairs. The benefit of the repair work for the damage part of a certain bridge is defined as the difference of "the expected life cycle cost at the time of leaving one period, without repairing at the time concerned, and repairing at the next term", and "the expected life cycle cost computed when it is repaired at the term concerned based on the optimal repair policy." The benefit of the repair work is defined by $LCC^{*}_{i,m} - LCC_{i,m}$, where $LCC^{*}_{i,m}$ expresses the expected life cycle cost of the component m at the time of leaving one period at the condition i under the budget constraint, and, $LCC_{i,m}$ expresses the expected life cycle cost according to the optimal repair policy. Then, the cost-benefit ratio $(B/C)_{i,m}$ is computed by,

$$(B/C)_{i,m} = \frac{LCC^{*}_{i,m} - LCC_{i,m}}{c^{d*}_i} \tag{32}$$

where c^{d*}_i in the denominator is the repair cost for the condition i. When $c^{d*}_i = 0$, that is no repairing action is taken, computing $(B/C)_{i,m}$ is not required. However, the expected life cycle cost is evaluated using the present value of the average cost and the relative cost computed by the average cost minimization model. The LCC can be divided into the average cost q^{d*} equivalent for every year and the relative cost v^{d*}_i to the optimal repair policy d computed by the average cost minimization model. The present value $LCC_{i,m}$ and $LCC^{*}_{i,m}$ of the expected life cycle cost based on an average cost minimization principle are given by,

$$LCC_{i,m} = \sum_{t=0}^{\infty} \frac{q^{d*}}{(1+\rho)^t} + v^{d*}_i \tag{33}$$

$$LCC^{*}_{i,m} = \sum_{j=i}^{K} \frac{p_{ij}(LCC_{j,m} + c^{d*}_i)}{1+\rho} \tag{34}$$

The cost-benefit analysis formulated above shows the priority of repair of the bridge component under the budget constraint. The procedure is shown below,

1) The component for repair is selected for this year.
2) The cost benefit ratio $(B/C)_{i,m}$ for each component is computed and the components which have $(B/C)_{i,m} > 1$ are arranged in increasing order of $(B/C)_{i,m}$.
3) Repairs are carried out according to the priority determined by 1) and 2) and the repair cost is added.
4) Repairs are carried out if the added repair cost does not exceed the budget constraint, and, the component that was not repaired is repaired in the next term.

However, this priority decision model is only applied to the simulation module of deterioration/repair process in the strategy level in this BMS. In the determination of the priority in the tactical level, various factors, such as the importance of the route considered by the bridge administrators and risk for the management along with the cost-benefit analysis, are taken into consideration.

(4) Managerial Accounting

a) Information for managerial accounting

The BMS application includes a bridge managerial accounting system. The objective of the managerial accounting system is to describe the repair cost for each fiscal year as budget control information and to aid in the optimization of the decision making of the bridge asset management for all situations. Although the managerial accounting information is used for various purposes, the following two are considered as monitoring functions of the bridge asset management[19]. First, it is required to compute a sufficient budget for maintenance and to observe whether repair is sufficiently carried out. A bridge deteriorates gradually so severe deterioration often takes very long time to be reached. When the maintenance of such facility is considered, it is not necessary to smooth the repair cost for each fiscal year, and repairs according to a securable budget for each fiscal year should be just carried out. However, even if the change in repair cost is accepted in the short run, the repair candidate components that could be postponed for future repairs must be repaired in the near future. Thus, even if a change in the repair cost is allowed in the short run, the expenditure of the fixed repair cost is needed in the long run. From this viewpoint, it is necessary to monitor the accumulated amount disbursed for the repairs for each fiscal year. Secondly, if many bridge components that need repair were left behind, it is necessary to compute the repair demand and make a maintenance plan for the future. The bridge managerial accounting system will play an important role in the decision of such a maintenance plan.

b) Average cost minimizing principles and deferred repairs and maintenance accounting

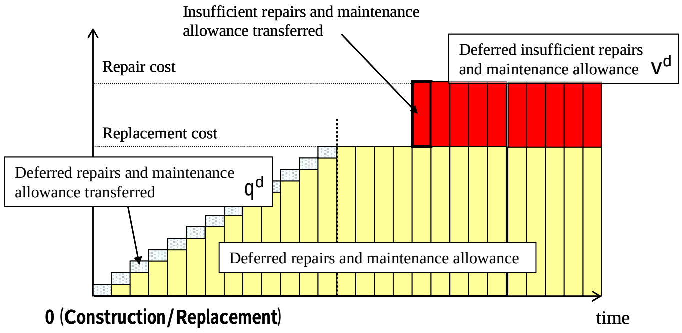


Fig.3 Deferred repairs and maintenance accounting

As mentioned at **3.(2)**, the BMS adopts the average cost minimizing method as the technique of determining the optimal repair policy of a bridge component. The average cost minimizing method indicates that the expected accumulated life cycle cost of repairs required from $t = 0$ to $t = n$ under the repair policy d is approximately defined as,

$$u^d(i;n) = nq^d + v^d(i) \quad (i = 1, \cdots, K-1) \qquad (35)$$

where, n indicates a sufficiently large value. q^d average cost (distributed repair cost) which is considered as a cost equivalent for each year in the management cycle under the repair policy d. The repair cost can be transposed to an equivalent average cost flow for every year. It can be recognized that the deferred repairs and the maintenance allowance to be transferred as repair costs for each fiscal year in deferred repairs as well as the maintenance accounting when it is considered as a non-refunding property are necessary to maintain a structure semi-permanently. That is, in order to determine the average budget for each fiscal year, in deferred repairs and maintenance accounting, the average cost q^d offers important information. The average cost q^d is transferred as the repair cost for every year from the time when a component is replaced. In a current fiscal year, if an allowance is not spent as a repair cost, the allowance is transferred to the reserves for future repairs (reserve fund in deferred maintenance repair accounts). When repairs are carried out, the repair cost is extracted from the saved allowance.

On the other hand, when the deterioration is severe at the initial time, there is a case that the expense for recovering a big damage is short of the average budget allowed for each year. In this case, the relative expense v^d which satisfies equation **(35)** can be made into the deferred insufficient repairs and maintenance allowance which should be saved corresponding to the initial condition. That is, the information for the plan that is capable of carrying out the repair demand, expressed by the relative expense over a period in the future, is offered for the repair demand which cannot be processed only at the average budget allowed for each term. Thus, useful accounting information following the deferred repairs and maintenance accounting from the information derived from the life cycle cost evaluation using the average cost minimization principle can be generated.

4. Design of the BMS Application

(1) Outline of the BMS application

Based on the BMS proposed in this study, the BMS application was designed for the bridge systems managed by the Himeji Office of the Ministry of Land, Infrastructure and Transport. The module which performs the analysis was developed using Microsoft Visual Basic .net; the inventory and output data of the bridges are managed using Microsoft Access. That is, this application can store the electronic management information of a bridge on a personal computer, and can provide to the bridge administrators managerial accounting information and management capability by accessing the inventory information through the BMS application. This section describes the main module's graphical user interface and structure.

(2) Inventory system

The inventory system is used to manage the basic information of the bridges, the inspection data and the basic repair method, collectively (**Fig.4**). The GUI provides a way of checking and manipulating the data of an individual bridge. This basic data module includes an interface that can acquire data from the MICHI-database, which is managed by the Ministry of Land, Infrastructure and Transport. The basic information of the bridge to be used in the asset management system and the managerial accounting system is generated and the bridge data is outputted respectively to the transition probabilities estimation module, the simulation module and managerial accounting module. The inspection data module can check the list as compared to the results of the inspections carried out periodically. After an inspection is carried out, the information on the inspection results for every bridge component (e.g. the inspection day, the bridge's name, the component, the damage form, the condition state, etc.) is added and updated in the database of the asset management and managerial accounting systems. The repair method data module is used to store the basic information of the repair method applied to each component. The module allows the information about the repair method set up for every bridge component or condition state to be checked. Repair method data include the repair method name, the component classification, the component number, the damage form, the condition state, the unit price, and remarks. Moreover, when a new repair method is developed and introduced, the module can add, delete and modify the new information

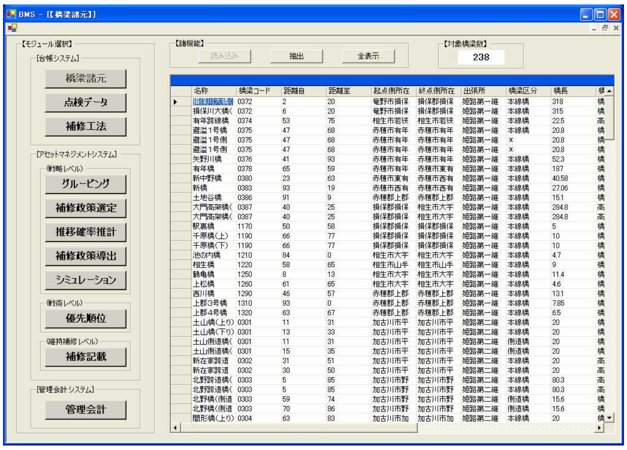


Fig.4 The Inventory System GUI

arbitrarily.

(3) Asset management system

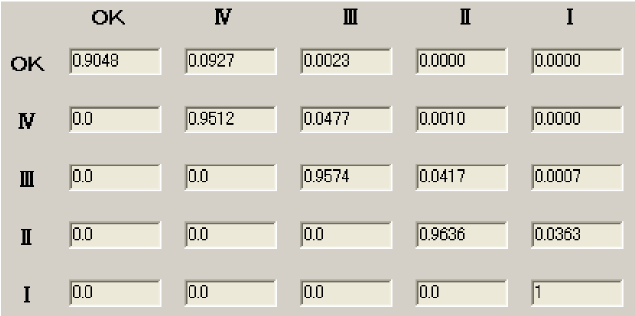
The asset management system delivers useful information to the management based on the inventory system data. First, in the strategy level, the bridge system is classified according to the strategy of the management using the grouping module. Based on the grouping classification, the estimation of the deterioration probabilities and the simulation of the deterioration/repair process are carried out individually. The estimation of the deterioration transition probabilities, the calculation of the optimal repair strategies and the simulation of the deterioration/repair process are carried out for every classified group.

Secondly, in the tactics level, the candidate component to be repaired is selected, preferentially on the short-term. The priority determination method can be selected arbitrarily using two or more determination rules, such as the importance of a route besides the cost-benefit analysis.

In the annual level, the history of repairs according to the priority (list of what should be repaired in the short-term) determined in the tactical level is recorded. Repaired components are then deleted from the list.

a) Transition Probabilities Estimation Module

The deterioration transition probabilities are estimated using the inspection data from the inspection data module as input. The hazard model described at **3.(1)** is used as the estimation model. The data required for the estimation are the inspection date and the condition state. Furthermore, by adding arbitrarily the explanatory variables, which affect deterioration, as input data, sensitivity analysis of the explanatory variables that affect the model can be performed. The estimation of the deterioration transition probability is carried out in the classified groups. Thus, the estimated result is drawn as a transition probability matrix between the discrete condition states. However, the estimation of the deterioration transition probability using the hazard model requires the accumulation of a certain amount of inspection data, and cannot be estimated by the



	OK	Ⅳ	Ⅲ	Ⅱ	Ⅰ
OK	0.9048	0.0927	0.0023	0.0000	0.0000
Ⅳ	0.0	0.9512	0.0477	0.0010	0.0000
Ⅲ	0.0	0.0	0.9574	0.0417	0.0007
Ⅱ	0.0	0.0	0.0	0.9636	0.0363
Ⅰ	0.0	0.0	0.0	0.0	1

Fig.5 Transition probabilities estimation module

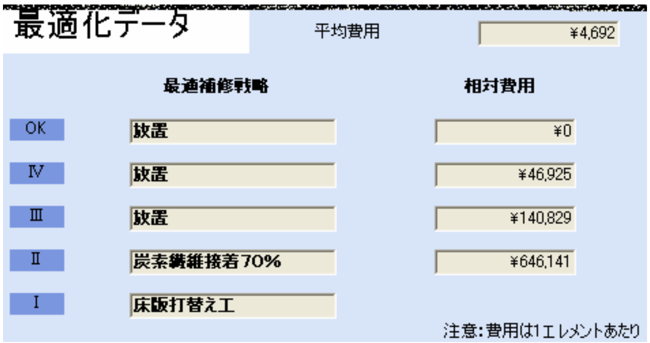


Fig.6 Optimal repair strategy module

model in which checking data is not stored[18].
In this case, the calculation of the Markov transition probabilities was carried out using the expected life length for each condition of the component. Given the expected life length of each condition state forecasted from the previous history and the specific safety guidelines of the component, the hazard rate of each condition $ĺ_i$ is computed by,

$$ĺ_i = \frac{1}{E[RMD_i]}$$

The Markov transition probability matrix can be derived by substituting this hazard rate $ĺ_i$ into equation (9).

(36)

b) Optimal repair strategy module

Using the estimated Markov transition probability matrix and the repair method data, the optimal repair strategy of a bridge component is derived (**3.(2)**). Regarding the optimization method, two different evaluation models, an average cost minimization model and a present value minimization model, can be used, and can be selected arbitrarily. The information derived by the analysis contains the optimal repair policies corresponding to each condition state, the average cost and relative cost, or the life cycle costs from both the optimization models.

c) Simulation module

Based on the optimal repair policy and the transition probability matrix, the deterioration/repair process of a bridge component is simulated and the repair demands for

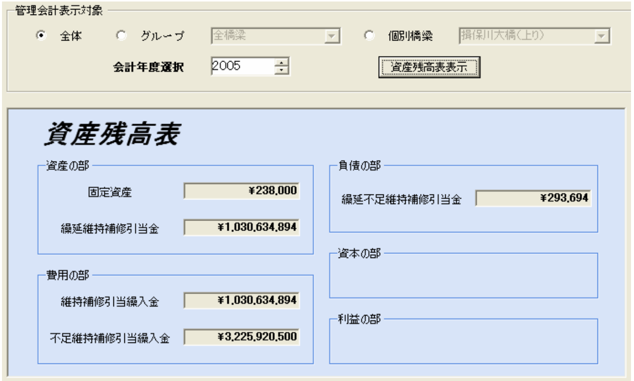


Fig.7 Managerial accounting module

each year as well as the required budget are predicted. The conditions for the Simulation that is the simulation period, the restrictions conditions of annual budget and the number of times pseudorandom numbers are generated by the Monte Carlo method are set up. The result of the simulation can be visually examined by viewing the total values for each component as well as for all components for the past condition state distribution, and cost transition of each year. The number of the components that were repaired within the simulation period or the repairs that were transferred by the budget constraint is computed. In spite of state of progress of the deterioration, the number of the components that their repair was transferred resulting from the budget constraint, is counted and displayed. Moreover, the priority of repairs and the list of candidate components are generated using cost-benefit analysis.

(4) Managerial accounting system

The managerial accounting information for acquiring autonomously the budget required for the maintenance is gathered from the data (mainly basic data and repair history data) that are based on an asset management system and the inventory system. The information for a fiscal year on the fixed assets (replacement cost), deferred repairs and maintenance allowance, transfer amount, insufficient repairs and transfer maintenance allowance is generated using the previous individual bridge account data as input data from previous fiscal years.

5. Empirical Analysis

The BMS application developed in this study was applied in the bridge systems managed by the Himeji Office of Ministry of Land, Infrastructure and Transport. National highway No. 2 bypass, managed by the Himeji Office, has 40km length and about 230 bridges which are approximately 30 years old. Since the traffic volume of the bypass exceeds 100,000 vehicles with a mixture of traffic including large-sized vehicles, it is predicted that the fatigue damage on the bridge deck and on the steel beams

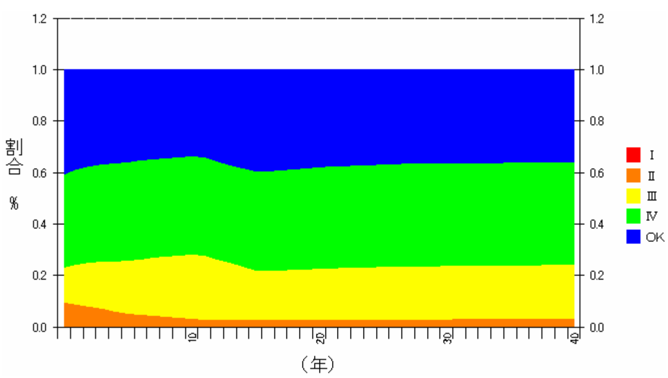


Fig.8 (A) Distribution of the condition state
The case of annual budget constrain to be 200 million yen

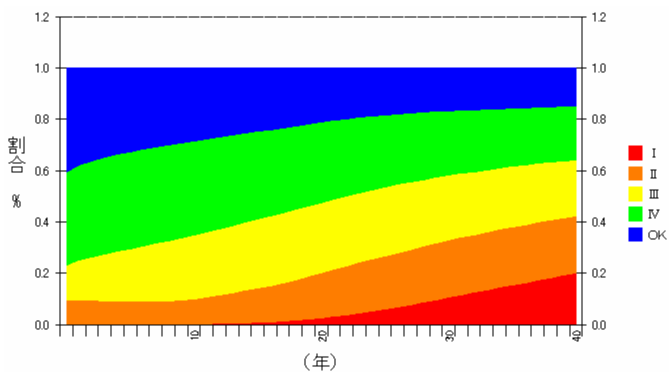


Fig.8 (B) Distribution of the condition state
The case of annual budget constrain to be 175 million yen

by repetitive loading will accelerate the damage progress. This section describes the empirical asset management analysis of the bridge system of the national highway No. 2 bypass. Based on the management method of this office, the main analysis is concentrated on giving results on three items, the crack damage on the concrete deck, the crack damage on the concrete beams and the paint deterioration of the steel beams.

In the Himeji office, the inspection of a bridge is carried out periodically and the inspection results are stored in a database. For example, the results of estimating the transition probability using the inspection data from the crack damage on the concrete deck are shown in **Fig.5** (transition probabilities estimation module). The optimal repair strategy computed by the average cost minimization model for the crack damage on the concrete deck is shown in **Fig.6** (optimal repair strategy module). In this figure, the average cost per component and the relative cost defined for each condition state are shown together. Based on these conditions, the simulation of the deterioration/repair process for the three items was carried out (simulation module). In addition, the following results are based on a simulation period of 40 years, performed 20 times by the Monte Carlo method. Although the number of the simulations can be set up arbitrarily, stability results in about 20 simulation cycles. First, the condition state distribution assuming an annual budget constraint of 200 million yen is shown in **Fig.8 (A)**. In this figure, state “I” which is the worst condition does not appear over a long period of time, and the result that a component maintained over a long period of time is indicated. On the other hand, **Fig.8 (B)** shows the case of assuming an annual budget constraint of 175 million yen. This result indicates that state “I” begins to appear gradually and it is difficult to maintain a component over a long period of time. By performing some simulations as above and analyzing the results, it is showed that repair expenses between 185 and 200 million yen for the managed component are desirable. In such a procedure, decision stems from the long-term management proposals including the budget planning for each module (refer to **Fig.2**) located in the strategy level in an asset management system.

Next, based on the present inspection results and a long-term management proposal, a middle-term repair candidate list is created (priority module). As it was described in **3.(3)**, a priority is automatically determined by B/C. Bridge administrators adjust the priorities of the repair list by referring to the actual management strategy.

Furthermore, if repairs are carried out, it is possible to store the history of the repairs in the database (repair record module), update the repair list, and extract an efficient maintenance scheme.

At the end of a fiscal year, managerial accounting is built using the data stored by the asset management system or the inventory system (managerial accounting module). It becomes possible to grasp quantitatively the stock worth of a component repair demand, and the index when a maintenance plan is modified.

This system can support the long-term management of a component by the management cycle as shown in the above-mentioned example. In addition, when the inventory system is updated, note that it is necessary to improve the results over the complete management cycle.

6. Conclusion

In this study, a BMS application for performing efficient management was developed, and its usefulness was verified using the bridge system of the Himeji Office of Ministry of Land, Infrastructure and Transport. It was verified, that the BMS system can be a very useful tool for bridge management works, such as budget planning and maintenance works. In order to improve the usefulness of this BMS, some points are noted:

1) In actual inspections, visual inspection errors arise from misjudgment. These errors are not dealt with in this system.
2) It is expected that a lot of inspection data will be accumulated in the near future. Therefore, it is necessary to develop a methodology to update the parameters of the hazard model as new information is collected.

3) A bridge system is constituted of many bridges and components, so the relation between deterioration and repair of each bridge and the components cannot be disregarded. It is necessary to develop a system which computes a micro-repair synchronization policy to adjust mutually the repair timing.
4) The data used in this system can be considered to be an electronic form of an inventory system. Bridge systems are located on road networks and they need spatial analysis in consideration with the road network. In order to manage these bridge systems efficiently, grasping the environment of the road spatially is required. It is necessary to acquire spatial information and link them to management information using a GIS. By improving the software in such a way, the application can become an even more useful bridge management tool.

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