

Asset Management Systems for the Facilities on the Highways

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Abstract: This paper presents an asset management system (Fasys-AM) that is used to optimize maintenance/repair activities for highway facilities. The Fasys-AM can be used to estimate the optimal inspection/repair/replacement policies that minimize the life-cycle cost and failure risks using a database containing the inventories and inspection history. The system contains a simulation model in its core module that investigates the medium-long term budget plans and the service levels of the facilities given the budgetary constraints. The deterioration processes of the facility systems are modeled by the aggregated time-dependent Markov process model. In order to investigate the validity of the Fasys-AM system, a case study was conducted and is presented in the paper. The case study was carried out for the lighting system on the Tohoku expressway.

Keywords : asset management, life cycle cost, optimal inspection/repair/replacement policy

1. Introduction

The deterioration of some highway facilities such as lighting systems and equipment for emergencies (e.g. hydrants), is advancing with time and results in increases of not only the maintenance cost but also the inconvenience caused to the highway users due to the traffic restrictions accompanying the repair and replacement activities. Furthermore, when the highway lighting equipment deteriorates and it falls on the road it may cause a serious accident so a maintenance management that prevents such a danger beforehand is required. For this reason, in order to control the existing equipment effectively and efficiently and to appropriately maintain them, great importance is attached to the development of a "Road Facility Asset Management System."

This research proposes a road facility asset management system (Fasys-AM) that can be used for the maintenance management of a road facility. Furthermore, in order to utilize this system in the maintenance works of road facility management, a computer application (Fasys-AM application) that generates useful information to be used by the facility management administrators in the decision-making during the maintenance operation was developed. The Fasys-AM application developed in this research aims to be used for the management of highway tunnel lighting systems. In a tunnel lighting assembly, steel as well as stainless steel plates are broadly used. The plates

are vulnerable to corrosion which advances with time. As corrosion progresses, the probability of having a lighting assembly collapse due to deterioration becomes high. For this reason it is required to check the state of the tunnel's lighting assembly periodically and to store and manage inspection data in a database. This application computes an optimal inspection and repair/replacement policy using mid-term and long-term deterioration and repair simulation models, and the estimation of a deterioration forecasting model which is based on a database of scheduled inspections, so as to generate information for determining the medium-term and long-term budget planning and control level (deterioration risk level). The paper is organized as follows. The second section of the paper presents the research fundamentals. In the third section, some methodologies of the Fasys-AM are described. The fourth section describes the usage of the Fasys-AM application. Finally, the fifth section presents a case study as it was applied to a tunnel lighting system.

2. Research Fundamentals

(1) State-of-the-Art

A large number of studies were conducted on optimal repair models of engineering-works and structures at the project level in asset management systems and for the development of operating support system applications that utilize these techniques. For example, many Bridge

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Management Systems (BMS) aiming at the reduction of long-term life cycle costs are proposed. A typical example of a BMS is PONTIS which is widely used in the U.S.¹⁾ In the management of a civil engineering structure, it is necessary to deal with various hierarchical management levels, such as the management at the project level that considers the repair plan of each structure component and the management at the network level which considers the repair policy and the budget planning of the complete structure. In the case of the project level of a single structure, the model that derives the optimal repair policy is built by performing the life cycle cost evaluation using the Markov decision model²⁾⁻⁶⁾. In life cycle cost evaluation when the cost to be generated at a future time is accumulated, it is important to consider the cost on a different time-axis. The PONTIS application software adopts the discounted present value method which is used to convert into current value using a discount rate to the cost generated on a different time-axis. On the other hand, Kaito *et al.*⁵⁾ proposed a method of determining the optimal repair policy using the average cost method for transposing the life cycle cost to be generated in the future to an annual average cost, and evaluating it assuming that a life cycle cost evaluation using a discount rate cannot evaluate the effect of the formation of a long-life²⁾. Furthermore, Aoki *et al.* proposed a BMS that was built based on the optimal repair policy model utilizing the average cost method⁷⁾. The BMS proposed by Aoki *et al.* has an administrative-accounting system aiming at the bridge valuation of assets for evaluating the performance of the maintenance repair record of the whole bridge system based on the maintenance repair record in each fiscal year and the budget control, when regarding control of maintenance of the complete bridge system. Moreover, some studies are found in the literature regarding the repair plan optimization of road pavement and asset management systems⁸⁾⁻¹²⁾. However, in this research, a system that supports the facility management's decision-making to compute the timing of inspection and repair simultaneously was not developed. The Fasys-AM proposed in this research utilizes a road facility system model that has several facilities installed on the road and implements a system which derives the optimal inspection and repair policy. Furthermore, the Fasys-AM application includes a budget planning functionality when managing the whole facility and it analyzes the maintenance of the actual road facility of a highway.

(2) Management Scheme of the Road Facilities

A road facility system, which usually consist of groups of components installed on the road such as lighting systems (e.g. road light fixtures and tunnel lighting), tunnel emergency equipment (e.g. fire hydrants), air ventilation systems (e.g. jet air fans) and road information boards, is an important infrastructure that is provided for the safety of the road users. The failure or deterioration of a road facility has a great impact to the road users and as a result it must be promptly repaired. In road facilities, just like other infrastructure systems, the deterioration of a component advances and the cost for restoring functionality is increasing with time. Therefore, there is a necessity of reducing the life cycle cost, which is increasing with maintenance, to secure a satisfactory level of safety to the users and to find the optimum inspection, repair and replacement timing.

This study proposes an asset management system for road facility groups having identical components that are installed on the road. Specifically, a road lighting system was used as an application example of this research. The purpose of a road lighting system is to provide to the users road illumination in low visibility conditions thus allowing the users see and avoid any obstacles, properly evaluate the speed of other vehicles, see the geometry of the road, etc. In addition to that, a tunnel lighting system plays an important role in the safety of road traffic by providing, 1) mitigation of the loss of traffic functionality due to the special ambient conditions inside the tunnel, 2) stable visibility conditions to the drivers during the entrance, while inside and at the exit of the tunnel, 3) a constant flow of clean air inside the tunnel via the tunnel's ventilation system.

The road facility consists of a functional and a structural part, so it is necessary to clarify the definition of the deterioration and to clearly comprehend the condition. For example, functional deterioration of lighting equipment is defined as the misalignment of light fixtures, surface dirt and illumination deterioration. On the other hand, corrosion is considered as structural degradation, for example. Replacement of parts is necessary during functional deterioration and preventive repair and replacement is needed during structural deterioration.

(3) Asset Management for Road Facilities

Many equipment of the same kind are installed on the road, such as lighting implementations and equipment for tunnel emergencies (e.g. fire hydrant). The fixed cost which accompanies inspection and repair/replacement works of

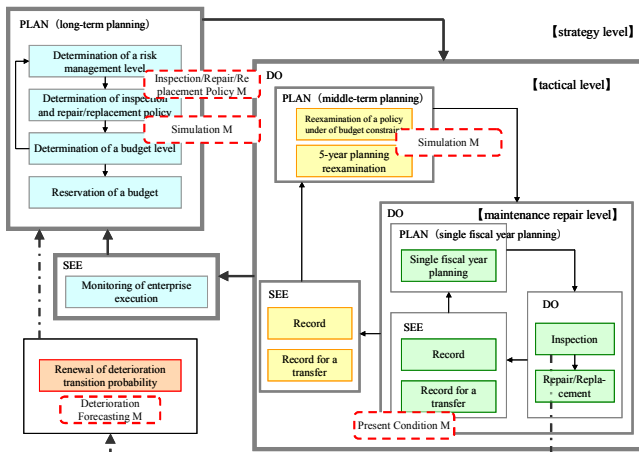


Fig.-1 structure of road facility asset management system

such equipment can be reduced by synchronizing the inspection and repair/replacement works.

Checks are conducted in certain fixed time intervals and repair and replacement is done according to the inspection results. In deterioration process of the facilities there is uncertainty, so the deterioration risk of the components at the inspection time has to be considered. The relation between the deterioration risk (risk management level) of the components at the time of inspection, repair, and replacement and life cycle cost is shown as the management index of the road facility system. This deterioration risk and life cycle cost have a trade-off relation. Fig.-1 shows the structure of a road facility asset management system.

At the strategy level (i.e. long-term planning), predictions in the long term about optimization of the policy of the inspection, repair, and replacement and budget transition, and a required budget are supplied. In that case, the stationary policy of inspection, repair, and replacement which is needed in order to attain a control level is determined by providing a certain risk management level. As a result, it is very important to search for a long-term budget level using simulation. Moreover, when the annual budget has restrictions, it is also necessary to analyze the influence a restrictive budget has on the deterioration/repair process.

At the tactical level (i.e. middle-term planning), the distribution of the budget for each facility group and the candidate for management is considered according to each year budget as determined on the strategy level. Within the limits of the distributed budget, re-examination of the desired value of the control level and inspection and repair/replacement policy is performed.

On the maintenance repair level (single fiscal year planning), the facility that inspection, repair and

replacement is to be carried out during a fiscal year is chosen from the optimal plan. Within the limits of the budget of each year, when all inspection, repair, and replacement according to the plan cannot be carried out, it is recorded as a transfer amount of the repair and renewal of the concerned fiscal year and is reflected in the plan of the following fiscal year, and a re-examination of 5-year plans is performed.

In order to perform life cycle cost evaluation in asset management, it is necessary to predict the deterioration performance of a facility. The reliability of the life cycle cost evaluation greatly depends on the accuracy of the deterioration forecasting model. In this system, the deterioration process is predicted using a multi-stage Weibull degradation hazard model utilizing data collected during inspections. The following sections of the paper describe the estimation of the deterioration model, the model of computing an optimal repair strategy and the simulation model for long term budget planning.

3. Methodology of Fasys-AM

(1) Optimal Inspection/Repair/Replacement Model

Aoki *et al.* have already developed a model of optimal inspection/repair policy for a system which consists of many components of the same kind¹³). Regarding the empirical study of a tunnel lighting system in this research, two kinds of replacement policies were considered, 1) replacement at the inspection time of only the components that reached their terms at the scheduled inspection time (i.e. individual replacement rule), 2) collective replacement of all the components that constitute the system in every fixed period independently of their condition (i.e. simultaneous replacement rule). Considering the simultaneous replacement rule, since all components are replaced at a fixed interval independently of their condition, components that have not deteriorated will also be replaced and as a result the replacement cost increases. On the other hand, since the number inspections as well the verification of deteriorated components decreases, the social cost also decreases. On the contrary, when the individual replacement rule is considered, while it becomes possible to reduce the replacement cost to a minimum, the social cost increases. In order for a decision maker to choose a replacement rule, i.e. individual or simultaneous replacement, the external cost such as the property of deterioration, repair/replacement cost and the social cost related to the traffic demand must be taken into account. In this system, the optimal replacement policy by comparison

of the life cycle cost in consideration of the social cost including the losses incurred to the user by traffic congestion besides repair / replacement cost is estimated.

The deterioration/repair process of a system that includes a large number of simultaneous inspections and repairs periodically is formulized as the aggregated time-dependent Markov process model. The deterioration process of a component is expressed by the Weibull deterioration hazard model which is dependent on time, and the repair history of each facility and the number of times of repairs taking into consideration the influence from the action from the next repair. So, unlike a usual the Markov process model, the state variable in the deterioration/repair process is defined by the expected relative frequency classified by the repair history exception in the system and the number of inspections in addition to each condition. The expected relative frequency is in the state of each facility in the discrete time t_ϵ^d , when a scheduled inspection interval is set to d , and it is expressed by $\pi_{klim}^\xi(t_\epsilon^d)$, when ξ indicates the rule of repair and replacement, and k, l, i and m show the latest repair (defined as the condition of recovery) history of the facility concerned defined after inspection/repair, the number of times recovered by repair to the condition of recovery, the condition, and the number of times of inspection after the latest replacement (time of use). The condition of an object is expressed by I discrete rating indices, and condition I expresses the worst condition. The following formula materializes at this time.

$$\sum_{k=1}^{I-2} \sum_{l=0}^L \sum_{i=k}^{I-1} \sum_{m=0}^{M-1} \pi_{klim}^\xi(t_\epsilon^d) = 1 \quad (1)$$

Furthermore, when the deterioration/repair process of an institution is modeled, the transition probabilities $P_{klim}^{k''l''i''m''}(\xi)$ which indicate the state conditions from the states (k, l, i, m) before repair activities at time t_ϵ^d to the state (k'', l'', i'', m'') after repair activities at time $t_{\epsilon+1}^d$ should be defined. $P_{klim}^{k''l''i''m''}(\xi)$ is expressing the condition transition probability between the time t_ϵ^d under inspection/repair policy ξ , and time $t_{\epsilon+1}^d$. At this time, the deterioration process of a facility can be expressed with the following three kinds of formulas. First, when repair is not carried out in time $t_{\epsilon+1}^d$, it is expressed by;

$$\pi_{k''l''i''m''}^\xi(t_{\epsilon+1}^d) = \sum_{i=1}^{i''} P_{k''l''i''m''}^{k''l''i''m''}(\xi) \pi_{k''l''i''m''}^\xi(t_\epsilon^d) \quad (2)$$

$(k'' = 1, \dots, I-2; l'' = 0, \dots, L; i'' = k'', \dots, I-1; m'' = 0, \dots, M-1)$

Next, when repair is carried out at the scheduled inspection time $t_{\epsilon+1}^d$, it is expressed by:

$$\pi_{k''l''i''m''}^\xi(t_{\epsilon+1}^d) = \sum_{k=1}^{k''} \sum_{l=0}^L \sum_{i=k}^{I-1} \sum_{m=0}^{M-1} P_{klim}^{k''l''i''m''}(\xi) \pi_{klim}^\xi(t_\epsilon^d) \quad (3)$$

Finally, when an object is replaced, the number of times of repair history, the number of times of repetitions, the condition state, and the inspection time are reverted to 0, and expressed by;

$$\pi_{1010}^\xi(t_{\epsilon+1}^d) = \sum_{k=1}^{I-2} \sum_{l=0}^L \sum_{i=k}^{I-1} \sum_{m=0}^{M-1} P_{klim}^{1010}(\xi) \pi_{klim}^\xi(t_\epsilon^d) \quad (4)$$

The above deterioration/repair process is arranged in the form of a determinant. We will express the transition probability matrix under inspection/repair policy ξ with $P(\xi)$. At this time, the stationary probability vector about the institution share classified by repair history, condition, and the number of inspection when deterioration/repair process is repeated for a long period of time and reaches a stationary state over a long period of time is expressed by;

$$\bar{\pi}^\xi = \bar{\pi}^\xi P(\xi) \quad (5)$$

The stationary probability $\bar{\pi}^\xi$ is calculable by solving the simultaneous equations which are added to the definitional equation (1) of stationary probability while deleting one arbitrary equation from equation (5).

From the drawn stationary probability vector, the life cycle cost under inspection/repair policy ξ and the stationary probability (failure risk) that the condition I will be observed become computable. The risk management level is expressed by \bar{U} , and the set of $\Omega(\bar{U})$ of inspection and replacement policy which can be held down to below the risk management level \bar{U} is defined using the failure risk $\Pi_I(d, \eta^\xi)$ is defined by;

$$\Omega(\bar{U}) = \{(d, \eta^\xi) | \Pi_I(d, \eta^\xi) \leq \bar{U}\} \quad (6)$$

The optimal inspection/repair policy model which minimizes the life cycle cost when the risk management level \bar{U} is considered given at this time is defined by;

$$\min_{d, \eta^\xi} \{C(d, \eta^\xi)\} \quad (7)$$

subject to $(d, \eta^\xi) \in \Omega(\bar{U})$

On the other hand, when adopting the simultaneous replacement rule, since the condition of all facilities is updated to 1 at the time a replacement is carried out, the stationary probability cannot be defined. When the time interval of the replacement time of simultaneous is set to Md as a check interval d , risk management level is a failure risk $\tilde{\Pi}_I(M, d, \eta^\xi)$ in the M th check time (replacement time of simultaneous). The set $\tilde{\Omega}(\bar{U})$ of inspection/replacement policy which can keep the failure risk $\tilde{\Pi}_I(d, \eta^\xi)$ below the risk management level \bar{U} is defined by;

$$\tilde{\Omega}(\bar{U}) = \left\{ (M, d, \eta^\xi) \mid \tilde{\Pi}_I(M, d, \eta^\xi) \leq \bar{U} \right\} \quad (8)$$

At this time, the optimal inspection and repair model which can compute simultaneously the optimal inspection and replacement policy $\xi^*(\bar{U})$ and the optimal simultaneous replacement interval that minimizes the life cycle cost is formulated by;

$$\begin{aligned} & \min_{M, d, \eta^\xi} \left\{ \tilde{C}(M, d, \eta^\xi) \right\} \\ & \text{subject to } (M, d, \eta^\xi) \in \tilde{\Omega}(\bar{U}) \end{aligned} \quad (9)$$

(2) Deterioration Forecasting Model

In order to compute the optimal inspection/repair/replacement policy, the transition probabilities are expressed by a multi-stage Weibull deterioration hazard model. Aoki *et al.* have already developed a deterioration forecasting model which the deterioration process depends on the time of use. Please refer to the paper about the basic concept and methodology of estimation of the multi-stage Weibull deterioration hazard model¹⁴⁾. Here, the model which derives the optimal repair policy is briefly explained using the estimation result of the multi-stage Weibull deterioration hazard model.

The conditional probability $p_{klim}^{kli'(m+1)}$ that a component with a repair history k , the condition i , and the number of inspection times m will change to the state of the repair history k' , the condition i' , and the number of inspection times $m+1$ at inspection time $t_{\epsilon+1}^d$ is defined by;

$$p_{klim}^{kli'(m+1)} = \frac{\pi_{ii'}^k(md, (m+1)d)}{\rho_{ki}(m)} \quad (10)$$

The denominator $\rho_{ki}(m)$ in formula (10) shows the probability that the condition will change to i , after the component has recovered to condition k by repair and replacement at time $t_{\epsilon-m}^d$ goes through the usage time md . Moreover, the numerator $\pi_{ii'}^k(md, (m+1)d)$ shows the simultaneous probability that the condition i is observed at the inspection time t_ϵ^d passed the time md after condition is recovered to k , and condition i' is observed at the inspection time $t_{\epsilon+1}^d = t_{\epsilon-m}^d + (m+1)d$. The transition probability defined by the formula (10) will be impossible to be evaluated analytically, so multiple integration by numerical computation is used for deriving the solution. The 5th section discusses the transition probabilities estimated using tunnel lighting system inspection data. Furthermore, in order to modify the deterioration transition probability, computation of the function for the deterioration transition probability for the expected life length as input conditions is carried in this system. It is desirable to develop and adopt a methodology that modifies the parameters of the Weibull hazard model using the Bayesian theory when the survey data based on new inspections are acquired. The updating problem is beyond the scope of this research and is considered as a topic for future research.

(3) Simulating the Inspection / Repair / Replacement Processes

a) Procedure of Simulation

The purpose of the simulation module is to predict the transition of the required budget for managing the whole group of facilities, and the condition transition through a simulation. The optimal stationary policy given a certain risk management level based on the results computed from the inspection repair optimization module is inputted as simulation conditions. This stationary policy is a guideline for the maintenance works, and gives useful information for micro management, such as the interval of inspection and replacement, and repair information (judgment of preclusive repair or ex post repair etc). On the other hand, the components have various conditions, such as different installation year and deterioration process, repair history; that condition state is not stationary. The future cost transition and condition will be greatly dependent on the present management situation. Furthermore, since it assumes that the future deterioration process changes according to the deterioration probability estimated by the Weibull deterioration hazard model, great uncertainty in deterioration process exist which also influences the forecasting of future demand. This module predicts the cost

and the condition through a simulation, after taking the present controlled state of a component into consideration under such uncertainty. Moreover, it also makes it possible to predict the influence of the condition by the restrictions of an annual budget. These outputs are used as explanatory material for supplying the required budget when the facility group is managed for future events.

The total number of the systems components is set to N and each component is expressed by $n(n = 1, \dots, N)$. Here, the condition of component n at time t is expressed by $\omega_n(t)$. At this time, the condition of the system is expressed by the vector;

$$\boldsymbol{\omega}(t) = (\omega_1(t), \dots, \omega_N(t)) \quad (11)$$

The total number by which the condition of a component was estimated as i in time t is expressed as $\eta^i(t)$. At this time, the vector of the number of components is defined by;

$$\begin{aligned} \boldsymbol{\eta}(t) &= (\eta^1(t), \dots, \eta^I(t)) \\ \text{when} \\ \eta^i(t) &= \sum_{n=1}^N \delta_{in}(t) \quad (i = 1, \dots, I) \quad (12) \\ \delta_{in}(t) &= \begin{cases} 1 & \text{if } \omega_n(t) = i \\ 0 & \text{if } \omega_n(t) \neq i \end{cases} \end{aligned}$$

The initial time $t = 0$ is regarded as the standard time and the simulation of the deterioration process of the system is considered. In the present time, it is impossible to accurately predict the condition in the future, so the probability distribution of the state of the object n in the time $t = m$ which passed m terms from initial time is expressed by;

$$\boldsymbol{\kappa}_n(m) = (\kappa_n^{1010}(m), \dots, \kappa_n^{(I-2)L(I-1)(M-1)}(N)) \quad (13)$$

where, $\kappa_n^{klm}(n)$ is the probability that the repair history is k , the number of times l of repair, the condition i , and the number of inspection times m (elapsed time). The state distribution after m term of component n which had the condition (k, l, i, m) at the initial time can be expressed by;

$$\boldsymbol{\kappa}_n(m) = \mathbf{e}_i (\mathbf{P}_n)^m \quad (14)$$

where, $\mathbf{e}_i = (0, \dots, 0, 1, 0, \dots, 0)$ is the row vector which

the i th element is 1 and others are all 0. The term $(\mathbf{P}_n)^m$ expresses the m th power of the transition probability matrix \mathbf{P}_n . The term \mathbf{P}_n is the transition probability matrix defined for component n .

Next, consider the case of adopting the inspection and replacement policy ξ to deteriorated components. The state distribution after m term of the component n whose state of initial time was (k, l, i, m) is expressed by;

$$\boldsymbol{\kappa}_n^\xi(m) = \mathbf{e}_i (\mathbf{P}_n^\xi)^m \quad (15)$$

where, $\kappa_n^\xi(m)$ is the condition distribution of component n , and it can be expressed by $\boldsymbol{\kappa}_n^\xi(m) = (\kappa_n^{1010, \xi}(m), \dots, \kappa_n^{(I-2)L(I-1)(M-1), \xi}(m))$. At this time, the state distribution probability of the whole system realized under the inspection and repair policy ξ is expressed by;

$$\boldsymbol{\kappa}^\xi(m) = \{\boldsymbol{\kappa}_{1010}^\xi(m), \dots, \boldsymbol{\kappa}_{(I-2)L(I-1)(M-1)}^\xi(m)\} \quad (16)$$

The condition distribution of each term can be computed using a Markov chain model repetitively. The expected number of components vector by which each condition is observed at time m is defined by;

$$E\boldsymbol{\eta}^\xi(m) = (E\eta_1^\xi(m), \dots, E\eta_I^\xi(m)) \quad (17)$$

The expected number of components $E\eta_i^\xi$ judged at time $t = m$ to be of condition i is defined by;

$$E\eta_i^\xi(m) = \sum_{n=1}^N \kappa_n^{i, \xi}(m) \quad (i = 1, \dots, I) \quad (18)$$

Moreover, the expected cost to recover to condition i'' from condition i' is expected by $c_{i'}^{i''}$. The expected repair cost for component n having condition is i at time $t = m$ is formulated by;

$$E\zeta_n^\xi(m) = \sum_{k'=1}^{I-2} \sum_{k''=1}^{I-2} \sum_{l'=0}^L \sum_{l''=0}^L \sum_{i'=k''}^{I-1} \sum_{i''=k''}^I \sum_{m'=0}^{M-1} \sum_{m''=0}^{M-1} \kappa_n^{klim,\xi}(m-1) p_{klim}^{k'l'i'm'} q_{k'l'i'm'}^{k''l''i''m''}(\xi) c_{i''}^{i''} \quad (19)$$

$$(k = 1, \dots, I-2; i = k, \dots, I-1; \\ l = 0, \dots, L; m = 0, \dots, M-1)$$

The expected value of the annual repair cost of the whole system adding the expected repair cost for each object is expressed b;

$$E\zeta^\xi(m) = \sum_{n=1}^N E\zeta_n^\xi(m) \quad (20)$$

When performing a simulation, initial states, such as the condition states, a repair history, and the number of inspection times (hour of use), are set up as conditions. The deterioration/repair process of a system can be simulated with the above procedure. In addition, in the simulation of this module, pseudorandom numbers are generated by the Monte Carlo method, and the sample path expressing deterioration/repair process of each object is generated. The number of times of trial of a sample path can be set up arbitrarily. The expected value of the annual repair budget and the number classified by the condition which generates the LCC evaluated on the sample path in the time of each year by performing equalization to many sample paths can be computed.

b) The simulation under budget constraint

When there are no restrictions in the budget of each year, repair and replacement works based on the optimal policy computed by life cycle assessment are carried out. However, the budget for carrying out the optimal policy actually cannot necessarily be secured every year, so the object which should be preferentially carried out in the secured budget frame is selected and repair and replacement are carried out. The priority for repair and replacement is determined by the condition state. When the condition I is observed (the worst ranking), the component is replaced. First, within the limits of the budget frame, 1) replacement is carried out and then the component having a bad condition is preferentially repaired. Namely, 2) repairing of the components which has condition $(I-1)$, 3) repairing of the component which has condition $(I-2)$, \dots and finally the component which has condition 2 is repaired. The result that component by which repair was not carried out in the fiscal

year will be recorded by shortage of a budget, and repair demand will be transferred after the following fiscal year.

4. Design of the Fasys-AM Application

(1) Outline of the Fasys-AM Application

The application software developed in this researched is based on Fasys-AM which is an asset management system for highway facilities. This application was developed in Microsoft Visual Basic 6.0 (GUI and coding) and MSDE (SQL Server Engine) for the DBMS. The GUI was designed to provide functionality to the system users. The application for this system was reviewed using examples from the GUI of other existing systems. The system includes user authentication by requesting users to login with ID and password. Following are more detailed information about the system and its modules.

(2) Database System

The database system is the main repository of information of the basic repair method, the inspection data and some data of controlled facilities. The data groups in this system can roughly be classified into the following, 1) optimal repair policy calculation, 2) simulation, 3) historical data and 4) master data. In historical data, the processed results of each user are stored to time series and the database system allows reading access and further processing of information. The database system attributes were based on another related data management system and adjusted for the needs of this system. There was also effort to match some of the structure and inspection data with other relevant data control systems. The interface was also designed to allow data in CSV-form to be imported in and from the database.

(3) Present Condition Module

In this module, the results of inspection and repair are utilized from the database. The module is intended to aid the user to visually comprehend the management conditions of the facilities. A user can extract samples in order to analyze the facilities from data such as the name of management office, the name of line, the facility classification and others. The distribution of the current condition state of subject to the facilities that was sampled is displayed to user allowing him to comprehend and evaluated the situation. Moreover, the data regarding past states is controlled by the historical data,

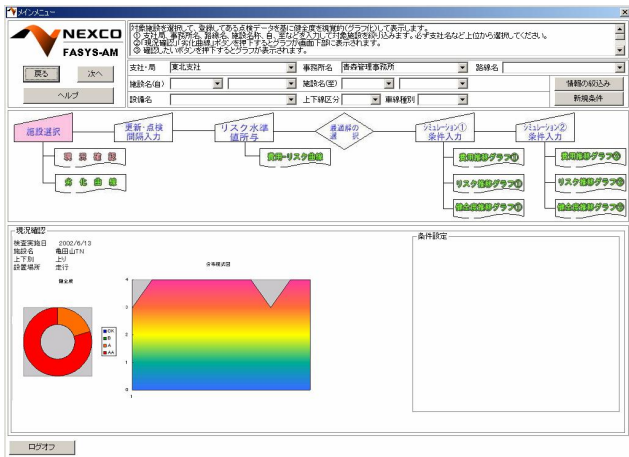


Fig.-2 Present Condition Module

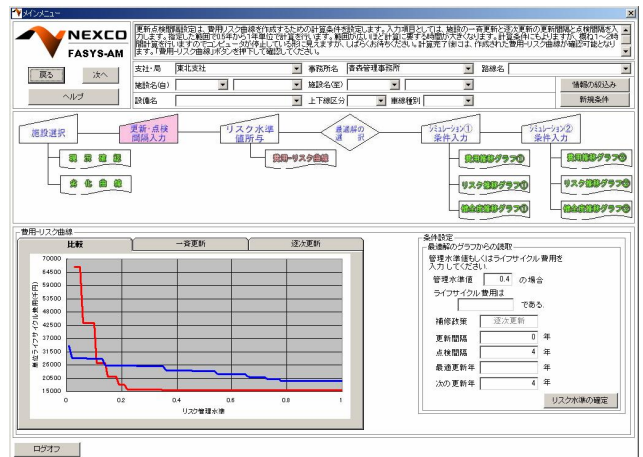


Fig.-4 Inspection/Repair/Replacement Policy Module

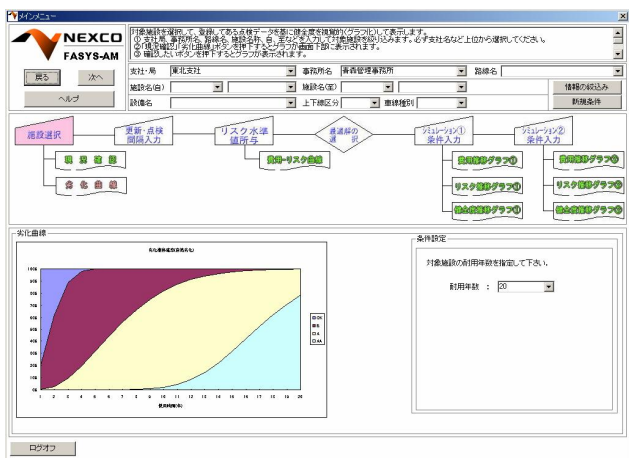


Fig.-3 Deterioration Forecasting Module

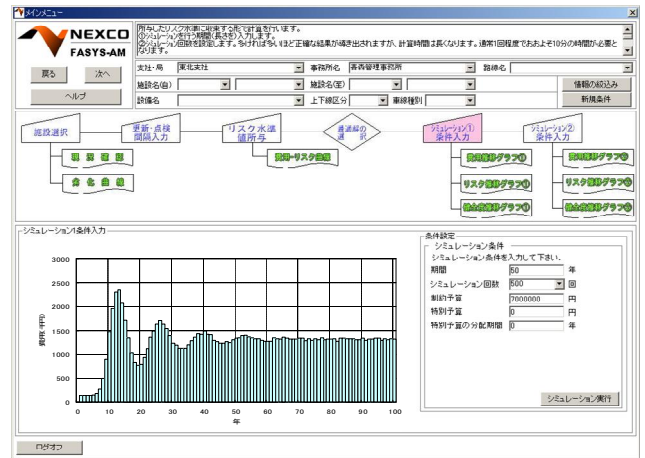


Fig.-5 Simulation Module

thus allowing a possible comparative analysis of the past as can be seen in Fig.-2.

(4) Deterioration Forecasting Module

The deterioration characteristic of facilities are analysed using the Weibull deterioration hazard model. The deterioration transition probabilities can be seen in Fig.3, which presents the relationship between the past times from first utility time and the transition probabilities. In this system, the estimated results from the Weibull deterioration hazard model are set up as an initial value. In the case analysis, because the deterioration characteristics of the structures differ, it must be a revision of the Weibull deterioration hazard model. But, because the module for the estimate of the multi-stage deterioration hazard model that is using real data from inspections needs a lot of time to give results, it is not appropriate to be used as a module of the system. Therefore, the system uses a simpler approach that allows the system user to revise the Weibull hazard model from the hazard rate of the corresponding structures. To comply with the what is presented, the hazard rate has

to be inferred from the existing works or the specific safety guidelines of the corresponding structures, the parameter θ_i on the Weibull deterioration hazard model is revised. In the Weibull hazard function, the expected time $E(T)$ until the breakdown is:

$$E(T) = \theta_i^{-\frac{1}{\alpha_i}} \Gamma \left(1 + \frac{1}{\alpha_i} \right) \quad (21)$$

This $E(T)$ is defined by the hazard rates which are given in order to revise the parameters. Additionally, the parameters of the Weibull hazard function are used as the criteria for the prior information θ_i , α_i , $E(T)$ represent the hazard rate at this time, the parameter θ_i of the Weibull hazard function that makes revisions from the hazard rate subjects to:

$$\bar{\theta}_i = \theta_i \left(\frac{E(T)}{\bar{E}(T)} \right)^{\alpha_i} \quad (22)$$

(5) Inspection/Repair/Replacement Policy Module

Fasys-AM is able to simultaneously calculate the optimal repair policy and optimal interval of inspection and replacement. Moreover, in order to estimate the life-cycle-cost, the system allows a choice among two types of replacement rules (i.e. the simultaneous replacement and the individual replacement rule). A user of the system can choose the structure type (subject of analysis), the Weibull deterioration hazard model of the structure, and at the input stage, the date of the repair method (method, repair cost, repetition limit of repair, recovery level) and the basic units for the social cost. The inspection interval (when all repair is occurring at the replacement interval) of the optimal estimate limits is also inputted. The cost-risk curve is then computed to compliance with the input requirements. The optimal inspection/repair/replacement rule that is satisfied with the risk management standards or the life cycle cost limits are chosen from only one the results of the cost-risk curve (Fig.-4).

(6) Simulation Module

a) Set up Conditions on Simulation

Optimal inspection/repair/replacement policy from the cost-risk curve is sampled, and based on weibull deterioration hazard model, the simulation about deterioration/repair process of structure is performed, the estimate for repair needs at each time, the necessary budgeted, the effect to condition state is analyzed from the budgeted of limit. Under the conditions of simulation, the simulation term (years), the limit condition of yearly budgeted, the number of times about random numbers are generated from the Monte-Carlo simulation (Fig.-5).

b) Output of Simulation Module

The simulation generates the following results: the expected values of the sum of the group and the expected yearly values of every tunnel that are about 1) the transition of condition states, 2) the transition of every term, 3) the transition of condition state before repair, 4) the quantity of repair needs of every term, 5) the quantity that is transferred to the next period due to inability of repair (shortage). Regarding 1) the transition of condition states, 2) the transition of every terms, 3) the transition of condition state before repair are represented by the catalog of result and the graph, and about 4) the quantity of repair needs of every terms, 5) the quantity are moved up repair by shortage, are represented by the catalog.

c) Simulation model for a simple tunnel

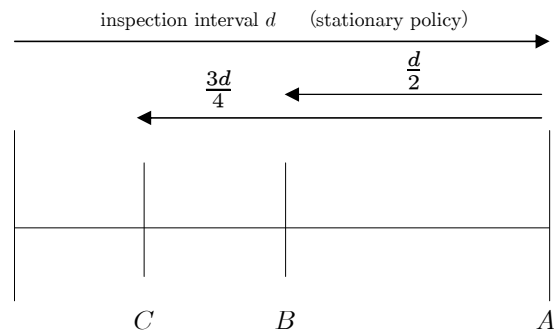


Fig.-6 Advanced Inspection Policy

In the tactics levels, the inspection/repair/replacement policy is decided, and the risk value is needed in order to manage the tunnel. At this time, when the “repair all rule” is adopted, there is repair/replacement demand that accumulates at a certain time, by the condition state of the tunnel’s facilities and the distribution of the service age, in the normal policy that was decided through the cost-risk curve. Therefore, when the demand of the repair/replacement is concentrated at at a certain point, the policy tends to lean towards smoothing the cost distributions and as a result risk is imposed. When the repair/replacement moves up, additional inspection is needed to be carried out during other times other than the original periodic inspection intervals. In this study, such a policy is called the . The following illustrates the basic idea of the policy of simulatneous inspections.

- Additional policy is set up for management standards that are not decided by the normal policy.
- About additional policy, the repair policy does not change. Instead the simultaneously repair/replacement is carried out by narrower inspection intervals.
- The inspection intervals are never made wider than those of the normal policy.

From the following, it is shown that the basic rule of inspection’s timing is carried out.

- The compliance with the inspection interval is decided by the normal policy. The expected value of risk value is estimated for a point in time is estimated at exactly that point.
- Regarding the risk over the management standards at a point in time and the expected value of risk value in case inspection carried out at B point in time, the inspection interval is shortened.
- Additionally, similar to the above and regarding the management standards, there is a return back to point C.

Table-1 Appraisal standard of deterioration ranking

inspection result	conditions	physical meaning
OK	1	no damage
B	2	A there is damage but functional fall is not seen. The progress of damage are observed.
A	3	there is damage, a functional fall is seen and repair is required, but urgent repair is not required.
AA	4	Damage is remarkable, Urgent repair is required.
	5	replacement is required.

Table-2 Estimated results of hazard model

conditions	α_i	β_{i0}	β_{i1}	$E[\theta_i]$
1 (<i>t-value</i>)	2.039 (477.54)	0.548 (6.14)	-0.323 (-3.49)	0.367 -
2 (<i>t-value</i>)	1.623 (469.92)	0.0812 (32.90)	- -	0.0812 -
3 (<i>t-value</i>)	5.709 (1486.69)	0.000011 (15.10)	- -	0.000011 -
Initial log-likelihood	-811,804.79			
log-likelihood	-7,041.67			
likelihood ratio	0.991			

Table-3 Repair method and cost parameter

conditions	type (method)	recovery level	repetition limit
B	Rust removal and prevented	OK	1
A	Rust removal and prevented	B	1
AA	fall prevention	A	1
AA	replacement	OK	-

The deterioration/inspection/repair/replacement process is simulated at the tactics level, based on the above rules. When the fixed value that has risk management standards from simulation is regarded, additional inspection is carried out and the simultaneous policy of repair/replacement is adopted.

5. Empirical Study

(1) Summary of Empirical Study

The road facility management system proposed by this research is applied to facility management works in highways. Facilities management works on the highways are generally made up of many facility types. This study out of all of those facility types, considers the management problems of a tunnel lighting system. The tunnel lighting system considered in this case study has two types material:

Table-4 Optimal Inspection/repair/Replacement policy

inspection interval		1 year
repair policy	condition B	Rust removal and prevented
	condition A	Rust removal and prevented
	condition AA	Replacement
Replacement Policy		Individual

steel and SUS: stainless. There are very few studied cases that consider having SUS. As a result, the inspection data of SUS are very limited. Therefore, in this study we chose to analyze only lighting system having steel. In addition to that, when there were insufficient data (e.g. SUS data), the deterioration forecasting model can be instructed about that fact and the input for the expected condition state hazard rate from formula (21) can be analyzed. The condition states of the lighting system were estimated using a rating of 4 levels (OK, B, A, AA) as seen in **Table-1**. A correspondence relation of the condition states as used in the application case in this study are set up as seen in **Table-1**. The estimated results of the multi-weibull deterioration hazard model are shown in **Table2**⁽¹⁴⁾. In this demonstration test, $E(\theta_i)$ is used as a controlled average to the parameter of the weibull deterioration hazard model. The applied repair method is shown in **Table-3**.

(2) Computing the Inspection, Repair and Replacement Policy

The case study utilizes data from the lighting system of the Kamedayama tunnel which is under the Towada office of the Tohoku expressway. The number of light fixtures in the tunnel is 276. The length of tunnel is 3.0km. Furthermore, when the life cycle assessment is performed, the social cost due to the regulation at the time of inspection, repair, and replacement is computed. While the regulation time at the time of inspection is grouped by the extension of the tunnel, the regulation time of repair/replacement is decided from the number of components subjected at each repair/replacement. Regarding the regulatory time at replacement, the management level is not the same to the simultaneous replacement and individual replacement. When the simultaneous replacement is considered, the fixed time is can be reduced by carrying out replacement works using many workers. In estimating the social cost s , we used the social cost estimate model adopted by Tohoku's regional

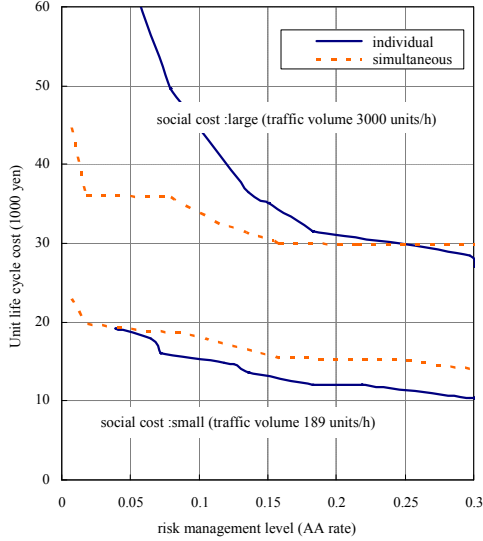


Fig.-7 Cost – Risk Curve

office.

$$s = \begin{cases} BT & \text{one-way} \\ BT + BR & \text{facing-pass} \end{cases}$$

$$BT = T \left(\sum_j Q_j L / V_s \gamma_j - \sum_j Q_j L / V \gamma_j \right) \quad (24)$$

$$BR = T \left(\sum_j Q_j L'' \psi_j - \sum_j Q_j L' \psi_j \right)$$

Here, Q_j is traffic volume (volume/h) of type j of car, L is tunnel extension (extension of regulatory term) (Km), L' , L'' is the distances are inter-Exit that including each pertinent tunnels and the distance of bypass to general load. V , V_s s are the traffic speed (Km/h) for normal time and regulatory, γ_j is the basic unit of value of time (Yen/min \times volume) of car type j . ψ_j is the basic unit of traffic cost (Yen/volume \times km) of car type j .

For the Kamedayama tunnel, an effective traffic volume of 189 units is considered. **Fig.-7** shows the cost-risk analyzed result of the tunnel's light system. Additionally, **Fig.-7** shows the effects the change of replacement has on the social cost in the line for a different traffic volume (3000 unit/h). The cost-risk curve shows the matching of the repair policy when one management standard is achieved while considering the "one risk management" standards as the optimal repair policy; the minimizing life cycle cost policy was chosen from just 1 point from this plots. **Fig.-7** is providing only results from the optimal repair strategy. When it is set up to a risk management level

of 0.08 the optimal inspection/repair/replacement policy is indicated at **Table.4**.

(3) Simulating the Inspection, Repair and Replacement Processes

Next, for the light system of the Kamedayama tunnel, the inspection/repair/replacement process is simulated and the cost shift and condition distribution are analyzed. The 276 light fixtures of the Kamedayama tunnel are 16 year old since the installation time. They condition of the light fixtures is nearly at state AA. The light fixtures group can be improved to state A if they are treated for safety. In the existing repair policy, i.e simultaneously adopted, it is considered that repair service was executed and the next repair period is approaching. At this state, the life cycle cost evaluation not only depends on the judgment when reagrding a change in the replacement policy, but it's often the case that is left to the managerial judgment. Subject to the simulation analysis in this study, the condition states of all of Kamedayama tunnel's light fixtures that were replaced simultaneously (i.e. the light system is OK), the state is then reset to operational life 0 as in the initial condition. After the simultaneous replacement, from the results of the cost-risk analysis, the responsive replacement policy based on the replacement policy of the light system is adopted. The simulation period is 50 years, and the number of simulationa is 500. The number of simulations is chosen arbitrarily, but from several trials it was established that in order to get good results a value of about 500 should be adopted.

Fig.-8 shows the state immediately after the repairs and the condition state distribution with time. The percentage of condition state "A" is increasing. From the deterioration probability that is adopted from the Weibull deterioration hazard model that depends a time, regarding the operational life of all light fixtures at the initial condition of the simulation, there is a tendency to get centered on during a given period of time that has a repair timing in the next period, as seen in **Fig.-8**.

Meanwhile, **Fig.-9** shows the state immediately before the repair of the condition state distribution with time. In normal policy, the risk management standard is set at 8%. From the results (**Fig.-9**), the elapsed time from 10 to 30 years temporarily exceed the risk management standards. this is responsible for the aggregate replacement when the repetitious replacement policy is adopted. For the facilities that are managed on field works, it is requested to hold the risk level of facilities below a certain level. For this reason, when the repair demand gets centered and incremental

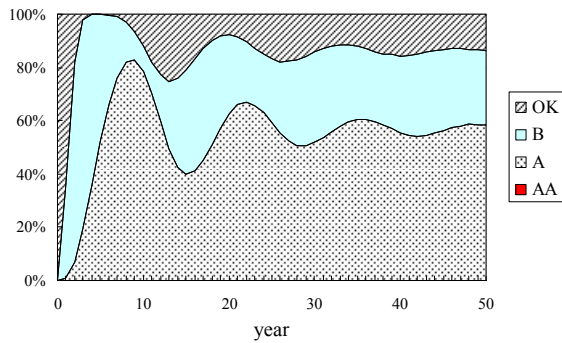


Fig.-8 Transition of the condition state after repair

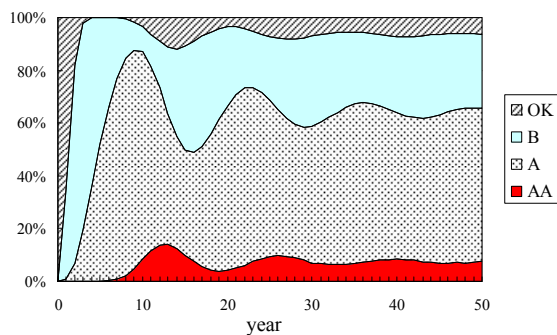


Fig.-9 Transition of the condition state before repair



Fig.-10 Comparative transition of the risk value

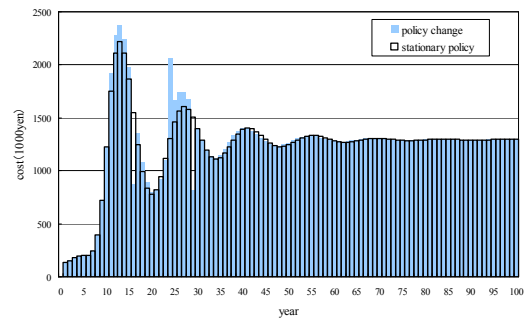


Fig.-11 Comparative transition of the cost

inspection is carry out, the data that do not show exceedance of the risk management standard such as strategy are required. This case is explained with 4 (5) c), the smoothing of the replacement demand can be implemented and the inspection front-loading policy is adopted. For this types of result, **Fig.-10** shows the comparison of the transition of risk value after the policy switch. The risk standard is decided by a normal policy of 0.08. The adopted normal policy is more than 0.08 in about 15 year and 25 year since the beginning of the service. On the other hand, when the simultaneous inspection policy is adopted, it does not exceed a risk management standard of 0.08. **Fig.-11** shows the comparison of the cost transition in case of a changed policy with the cost transition before change policy. The full line shows the cost transition when it follows the normal policy. On the other hand, a dashed line indicates the cost transition when the simultaneous policy is adopted. When the changed policy is considered, the cost is reported at the front-loading.

In this case, as explained in **Table-4**, the optimal inspection term is 1 year. But, when the simultaneous inspection policy is adopted, in the period from year 10 to year 16, inspection of 0.5 year intervals is needed. From the above analysis, in the field works of facilities management, when a chance results in an over-the-risk management

standard that causes an accumulation to the repair demand, this study reveals that using this system it is possible to provide the information for deciding for implementing additional inspection.

The results of this demonstration analysis expresses the output that analyzed just one part of a tunnel’s light system management works. In reality though, simulation tests for a variety of conditions will be need for the management that is intended for many tunnels

In this case, the effects of a changed policy was analyzed from the simulation test that was repeatedly carried out in this system.

6. Conclusions

This study proposed an asset management system that can analyze the relation of the life cycle cost and the repair management level when administering several facilities simultaneously using the statistical deterioration forecasting model and the Fasys-AM application that was developed for the management works of tunnel lighting systems. The usefulness of the system was also verified. As a result of this analysis, the application revealed a useful tool that can be used in practice for works for the budgeted-planning of higher ranking facilities.

There is a need for improvements to the system in order to be used and expand for other system application. There also remain unanswered problems regarding the following:

- 1) Public assets have many complicated structures that are in turn made out of many elements. For example, the facilities for extinguishing fires are classified into several parts that can be categorized as structural and/or functional. In public assets, there are quite a few cases that the relationship among the structures or deterioration/repair among elements can not be ignored. Thus, a methodology needs to be developed that will find a micro repair synchronized policy, e.g the adjustment of the repair timing of elements.
- 2) the method of searching for the optimal repair policy proposed by this study is by searching for the policy that minimizes the life cycle cost when a given risk management standard is attained, and the relation between the life cycle cost and risk is evaluated quantitatively. The risk management level defined here shows the deterioration probability for all of the managed structures. These have specified the result as the “output” of a repair policy. The deterioration probability as the “output” must express the effect and the result for users as the “outcome”, for the executive department of structures is decided on the optimal risk management level. In order to achieve accountability to the road users, a logic model which clarifies the relation between the output and the outcome needs to be developed.
- 3) in the application that is actually utilized by this study case, the present management works are analyzed, and it is necessary to establish a method of evaluating the output data from the system. The budget planning or the optimal inspection/repair/replacement policy is calculating based on the future deterioration estimate. The deterioration process of public assets involves uncertainty; a criterion that improves the system continuously is needed by the continuous management cycle. For example, when new inspection data are acquired, it is possible to introduce a model based on the Bayesian theory thus renewal of the deterioration estimate model will become possible. Additionally, the method for reviewing the plan and the evaluation method of the difference between the estimated results and the practice needs to be examined and established.

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