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Paper:

Variability in an Optimal Infrastructure Management Policy by Internalization of Seismic Risk

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During recent years, the possibility that damage at the time of earthquake could change depending on the deterioration condition of infrastructure has been noted through analytical analyses. Faced with such a possibility, management policy should be optimized by internalizing the external elements of earthquake damage, evaluating the appropriateness of management policy for infrastructure, and optimizing the system. In this study, the deterioration process for infrastructure was modelled using the Markov process model, and a methodology to determine the optimal management policy is proposed by considering the two risks: i) the risk that infrastructure fails because of deterioration independent of external elements such as an earthquake, and ii) the risk that changes due to deterioration fails the infrastructure at the time of earthquake. Using an example of the application the following two points are demonstratively shown: i) the optimal management policy would change in the case in which earthquake risk is not considered, and ii) the optimal management policy would change depending on the earthquake occurrence probability in the case in which earthquake risk is considered.

Keywords: disaster risk management, infrastructure management, optimization, Markov process

1. Introduction

It is essential, for social and economic activities, to keep infrastructure and its network always usable. The influences exerted by deterioration of infrastructure and the risk caused by external influences of a disaster such as earthquake lower the user safety of infrastructure. To minimize such risk, it is important to rationally and optimally maintain infrastructure. Furthermore, the time has come in Japan when considerable infrastructure constructed during the period of high economic growth has deteriorated. Considering the difficulty in securing a budget for responding to deterioration of such infrastructure, a certain level of management which could keep the level of risk below a certain degree should be adopted, while decreasing the management cost as much as possible.

During recent years the possibility has been noted through analyses, simulations, etc., that damage at the time for earthquake could be different depending on the deterioration condition of the infrastructure (in other words, deterioration could lower earthquake resistance). Faced with such a possibility, it is possible that damage at the time for earthquake could change according to a level of management of the deterioration condition of the infrastructure; therefore, the damage under an unusual condition such as a disaster could be mitigated by changing the management policy under normal conditions. Furthermore, as for earthquake occurrence probability, research has accumulated in the fields of science and technology for quantification such as "the probability of earthquake occurrence in certain years in the future (earthquake occurrence probability) [1]," although there still remains the problem of accuracy. In the case that damage by an earthquake would differ depending on the deterioration condition of the infrastructure, the optimal management policy under normal conditions would also change according to the earthquake occurrence probability. For example, the optimal management policy would gradually change by updating the earthquake occurrence probability over time. Or, the optimal management policy would drastically change on the assumption that the occurrence probability of a consolidated type of earthquake would significantly increase because of a partial occurrence of a plate boundary earthquake in the Nankai Trough.

In this study, the deterioration process for infrastructure is expressed using the Markov process model and the condition in which the decisions on inspection and repair are made by a management policy that is unchangeable over the years is considered. In this study, the management policy consists of the condition state[1] and the interval of inspection[2] in conducting a repair. Then, the superiority of a management policy is evaluated based on the expected cost consisting of i) the cost expressing the risk caused by the deterioration of infrastructures, ii) the cost expressing the risk at the time of an earthquake chang-

1. In this study, the deterioration condition of infrastructure was determined and evaluated using discrete condition state. In terms of condition state, the soundest condition corresponding to that of newly established infrastructure is set as 1 and the value of condition state increases as deterioration increases.
2. In this study, it is assumed that a management policy is defined as the rules depending on the deterioration situation.

ing with the deterioration condition of the infrastructure, and iii) the cost of inspection and repair. The optimal management policy for infrastructure is derived, considering the difference in damage at the time of an earthquake depending on the deterioration condition (condition state), by solving the optimization problem assuming the expected cost is an objective function and the individual variable consisting of a management policy as a manipulated variable. A review was completed fundamentally on the variability of the management policy for infrastructure considering the risk at the time of an earthquake and the change in the risk at the time of an earthquake.

Previous studies are reviewed in Section 2, the methodology used is explained in Section 3, and the application of the methodology introduced in this study to the problem of management, assuming existing infrastructure and its availability, are discussed in Section 4.

2. Literature Review

2.1. Optimal Management Policy for Infrastructure

Since the 1990s various studies have explored the optimal management policy for infrastructure. As for the Markov process model used in this study, Madanat [2] addressed the optimization problem on repair actions for infrastructure as the Markov Decision Process [3] and proposed a solution using dynamic programming [4]. Jido et al. [5] applied the methodology of Madanat [2] to a description of the deterioration of infrastructure in a continuous state space. Studies have also explored the optimization of a management policy using the Latent Markov Decision Process (LMDP) in the case that the random error is included in the inspection results for infrastructure [6, 7]. A study on the steady state of the Markov process model was also considered in this research [8]. A study on the further application of this model to a continuous state space and continuous time axis was completed [9]. Moreover, an unsteady Markov process model [10] using the time-dependent Markov transition probability of the multistage Weibull hazard model [11] and the mixed Markov process model [12] using multiple unsteady Markov transition probabilities of the hierarchical hidden Markov deterioration model has been developed. A methodology has also been developed to determine the optimal synchronization policy for the timing of inspection and repair for composite facilities consisting several types of facilities [13]. Methodologies [14, 15] that not only determine the lifecycle cost and the risk management index also incorporate the Markov decision model into an accounting system for infrastructure and Fault Tree Analysis have been developed. A model [16] that quantifies an economic analysis of an inspection action by using Real Options Analysis together, and an optimal model for scrapping and repair [17] considering a policy for disposal of infrastructure have been also developed. Furthermore, during recent years, studies [18–21] on the optimization problem at a network level considering the linkage to a network for infrastructure have also been completed. However, in the aforementioned studies, a management policy for infrastructure was optimized by solving the optimization problem setting the cost for management such as inspection, repair, and updating as an objective function and the management level for the risk caused by deterioration as limiting conditions, or the optimization problem in which the objective function is defined as the user cost consisting of the management cost and the risk caused by deterioration. Therefore, in these studies the earthquake risk that changes in correspondence with the deterioration condition of infrastructure is not considered. Although there is a study [22] that qualifies the variation in the vulnerability of a network for infrastructure depending on the deterioration condition of the infrastructure, the previous studies do not include the methodology that would optimize a management policy under normal conditions considering the relevance between the deterioration condition and the damage caused by an earthquake.

2.2. Deterioration Condition and Damage at the Time of an Earthquake

Numerous studies have been completed evaluating the earthquake resistance of a facility with advanced deterioration through simulations and experiments. Simon et al. [23] analyzed the earthquake resistance of reinforced concrete (RC) bridges with advanced corrosion of the reinforcement bar by using a finite element model. It was concluded that although a decline in the adhesion between the reinforcement bar and concrete is not considered, corrosion of the reinforcement bar influences the proof stress per unit element, but does not influence the earthquake resistance of the bridge itself as much. However, Ibarra et al. [24] evaluated the earthquake resistance of an RC element of a nuclear facility with deterioration over many years using the finite element method and concluded that a concrete crack and corrosion of the reinforcement bar caused by deterioration over many years could significantly influence the earthquake resistance of an RC element. As for a lead rubber bearing (LRB) with deterioration over many years, a study demonstratively verified the residual performance [25]. It was concluded that deformability is secured in a deteriorated LRB, but the influence of deterioration can be recognized in the horizontal shearing strain during the ultimate limit test. However, the earthquake resistance was covered in the study, but it was avoided because of the difficulty in reproducing the LRB used in the experiment to assert whether there would be any decline in earthquake resistance or not. In an analytical study [26] on the LRB conducted thereafter by the incremental dynamic analysis using many seismic motion input waves indicated that the change in failure probability of a bridge with a deteriorated bearing is smaller compared to that with a bearing that is not deteriorated in the case of a small-scale earthquake, while the failure probability of a bridge caused by deterioration of a bearing could increase in the case of an earthquake of more than 1000 gal. Furthermore, Onodera et al. [27] also analyzed, using Incremental Dynamic Analysis, the influence of deterioration of a seismic bearing over many years on the earthquake response of an RC bridge system with a seismic bearing. It was shown that the decrease in damping performance with deterioration of a seismic bearing would cause a prominent advancement of plasticization of an RC pier in an RC bridge system using a seismic bearing such that the strength to seismic motion would be lowered. Thanapol et al. [28] proposed a methodology to update the earthquake resistance of RC structures in a coastal area depending on the advancement of corrosion of the reinforcement bar using inspection data and the results of non-destructive inspection. However, even if the type of infrastructure to be covered is limited by these previous studies, it is difficult to obtain unified information on whether deterioration over many years would influence the damage at the time of an earthquake and the earthquake resistance, or not. Studies on this theme should be completed in the future. Nevertheless, as shown in the previous studies, a difference in the damage at the time of an earthquake caused by deterioration of infrastructure over many years cannot be completely denied. Therefore, usefulness of this study is in building a framework to support decision making on management, considering the difference in damage at the time of an earthquake.

3. Methodology

A methodology is formulated to derive the optimal management policy for infrastructure, considering the difference in damage at the time of an earthquake depending on the deterioration condition of the infrastructure. In this study the following conditions are supposed to be known: i) the Markov transition probability expressing the deterioration process, ii) the condition state before and after each repair action consisting of the repair policy to be examined; iii) the cost of each repair action; iv) the cost of inspection; v) the probability of each condition state that an infrastructure would fail at the time of earthquake; vi) the earthquake occurrence probability; vii) the probability that infrastructure would fail determined only depending on the deterioration condition (condition state) regardless of an earthquake; and viii) the user cost when infrastructure fails. The aforementioned input values should be determined by statistically estimating from actual data, referring to the cost of the actual inspection and repair, and using information generally available and other methods. As for the conditions of "v) the probability of each condition state that infrastructure would fail at the time of an earthquake" and "vii) the probability that infrastructure would fail determined only depending on the deterioration condition (condition state) regardless of an earthquake," it is possible to use the knowledge obtained by simulations and the experiments as mentioned in Section 2.2. As for the condition of "vi) the earthquake occurrence probability," it is possible to use the values published by a public organization such as [1]. However, it should be kept in mind that the earthquake occurrence probability calculated in [1] was based on the renewal process in which it increased with a lapse in time and that it was calculated based on the steady Poisson process which is not dependent on time. It should also be kept in mind that the situation supposed in this study, where an increase in arrival rate slowly progresses over time[3] even in the case that an earthquake occurrence process follows a Poisson process or in the case that it follows a renewal process, the static "vi) the earthquake occurrence probability" is adopted. If a temporal variation in arrival rate of the renewal process which the earthquake occurrence probability follows is remarkable, a methodology adopting the renewal process should be developed. This is a problem to be solved in the future. As a matter of course, the possibility cannot be denied that indices other than "vi) the earthquake occurrence probability" would also dynamically change. In this study, the possibility that the input values of such indices would change is not discussed, and the newest information obtained at the time of the selection of the management policy is used as the definitive value.

3.1. Precondition

To express the deterioration and repair process and the earthquake occurrence probability, the discrete time axis with the beginning point of time of $t_0 = 0$ is defined as:

$$t_{z+1} = t_z + a \; (z = 0, 1, 2, \ldots) \quad \ldots\ldots\ldots \quad (1)$$

The point on the discrete time axis in Eq. (1) is termed the "point of time" as distinguished from calendar time. a is the length of the unit period. It is assumed that the deterioration condition is expressed with I stages of condition state $1, 2, \ldots, I$. The soundest condition is set as 1 and the deterioration advances with an increased number of condition state. βa (β is natural number) indicates an inspection interval.[4] The rules, depending on the condition, assume that a decision on repair and updating shall be immediately made[5] based on the inspection results at the point of time of the inspection $t_{g\beta}$ $(g = 0, 1, 2, \ldots)$.

It is supposed that the condition state of infrastructure at the point of time t_0 is 1. If the probability that the infrastructure has a condition state of i $(i = 1, \ldots, I)$ at the point of time t_z is $\zeta_{z,i}$, the state vector at the point of time t_z is defined as $\boldsymbol{\zeta}_z = (\zeta_{z,1}, \ldots, \zeta_{z,I})$. $\sum_{i=1}^{I} \zeta_{z,i} = 1$ holds. It is supposed that the infrastructure comes into service at the point of time t_0 and $\zeta_{0,1} = 1$.

3. As for an earthquake caused by an active fault, as mentioned in [1], the average active time of the main active fault is approximately a few thousand years. It is thought that this hypothesis would not significantly limit the applicability of this study. However, it should not be applied to a subduction-zone earthquake. Therefore, this possibility should be kept in mind as noted in this paper that the methodology would need to be modified depending on the planning period and the active cycle of earthquakes.
4. β is defined by normalizing the actual inspection interval by the length of the unit period a, termed the "inspection interval," and β is set as a manipulated variable for the optimization problem.
5. An increase in the risk and the deterioration generated by the time lag of the point of time of inspection, repair, and updating is regarded as relatively small compared to the risk and the cost to be mainly analyzed in this study.

3.2. Deterioration and Repair Process

The deterioration process of the infrastructure is modeled using the time-homogenous Markov process. In the case that the condition state of the infrastructure is i at the point of time t_z, the probability that the condition state becomes j at the point of time t_{z+1} is expressed using the Markov transition probability $\pi_{i,j}(a)$. Supposing that neither a repair nor replacement is conducted, it is assumed that the condition state is not recovered, i.e., $\pi_{i,j}(a) = 0$ under a condition of $i > j$. This means that a measurement error of condition state at an inspection is not treated in this study. $\sum_{j=i}^{I} \pi_{i,j}(a) = 1$ holds. The Markov transition probability matrix setting the Markov transition probability $\pi_{i,j}(a)$ as its $i \times j$ element is expressed as $\mathbf{\Pi}(a)$. The deterioration process for the infrastructure to be reviewed is expressed as:

$$\boldsymbol{\zeta}_z = \boldsymbol{\zeta}_{z-1}\mathbf{\Pi}(a) \quad \text{(2)}$$

Furthermore, it is supposed that the Markov transition probability matrix satisfies the time adjustment condition [29], i.e., $\mathbf{\Pi}(na) = \{\mathbf{\Pi}(a)\}^n$. Here, n is an arbitrary natural number.

Now the case is considered, where a repair policy η has been adopted. The repair policy consists of the repair action for each condition state. If a condition state for infrastructure at the point of time of inspection is i in the repair policy η, a repair action is completed to restore the condition state to $\phi_\eta(i)$. In other words, the policy is defined so that the condition state would change after the repair depending on the condition state before the repair. Here, in the case that the repair is not conducted to condition state i, $\phi_\eta(i) = i$. The $i \times j$ element $q_{\eta,i,j}$ of a repair matrix $\boldsymbol{Q}_\eta$ in repair policy η is expressed as:

$$q_{\eta,i,j} = \begin{cases} 1 & \phi_\eta(i) = j \\ 0 & Otherwise \end{cases} \quad \text{(3)}$$

At this time, supposing $\boldsymbol{\zeta}_z$ indicates the state vector after the repair at the point of time $t_{g\beta}$ $(g = 0, 1, 2, \ldots)$, an inspection and repair process for the infrastructure is expressed as:

$$\boldsymbol{\zeta}_z = \begin{cases} \boldsymbol{\zeta}_{z-1}\mathbf{\Pi}(a)\boldsymbol{Q}_\eta & z \bmod \beta = 0 \\ \boldsymbol{\zeta}_{z-1}\mathbf{\Pi}(a) & Otherwise \end{cases} \quad \text{(4)}$$

Using the state vector $\boldsymbol{\varepsilon}_{g\beta} = (\varepsilon_{g\beta,1}, \ldots, \varepsilon_{g\beta,I})$ whose i-th element is the probability that the condition state of the infrastructure before the repair at the point of time of repair of $t_{g\beta}$ is i, $\boldsymbol{\zeta}_{g\beta}$ can be defined as:

$$\boldsymbol{\zeta}_{g\beta} = \boldsymbol{\varepsilon}_{g\beta}\boldsymbol{Q}_\eta \ (g = 0, 1, 2, \ldots) \quad \text{(5)}$$

3.3. Optimization

3.3.1. Precondition

A discussion is conducted based on the principle to minimize an average cost, and the social discount rate is not considered. The case is the subject of this study, in which the following Markov process satisfies the complete ergodicity and the cost is defined by using the state vector of the steady state.[6]

$$\boldsymbol{\zeta}_{(g+1)\beta} = \boldsymbol{\zeta}_{g\beta}\mathbf{\Pi}(\beta a)\boldsymbol{Q}_\eta \quad \text{(6)}$$

The state vectors before the repair and that after the repair at the point of time of repair $t_{g\beta}$ in the steady state under the conditions that the repair policy is η and the inspection interval is β (βa) are defined as $\boldsymbol{\varepsilon}^*_{\eta,\beta} = (\varepsilon^*_{\eta,\beta,1}, \ldots, \varepsilon^*_{\eta,\beta,I})$ and $\boldsymbol{\zeta}^*_{0,\eta,\beta} = (\zeta^*_{0,\eta,\beta,1}, \ldots, \zeta^*_{0,\eta,\beta,I})$, respectively. They can be expressed as:

$$\boldsymbol{\varepsilon}^*_{\eta,\beta} = \boldsymbol{\varepsilon}^*_{\eta,\beta}\boldsymbol{Q}_\eta\mathbf{\Pi}(\beta a) \quad \text{(7)}$$

$$\boldsymbol{\zeta}^*_{0,\eta,\beta} = \boldsymbol{\zeta}^*_{0,\eta,\beta}\mathbf{\Pi}(\beta a)\boldsymbol{Q}_\eta \quad \text{(8)}$$

The state vector at the point of time between the points of time under the steady state $t_{g\beta+f}$ $(f = 1, 2, \ldots, \beta-1)$ is expressed as $\boldsymbol{\zeta}^*_{f,\eta,\beta} = (\zeta^*_{f,\eta,\beta,1}, \ldots, \zeta^*_{f,\eta,\beta,I})$. This can be expressed as:

$$\boldsymbol{\zeta}^*_{f,\eta,\beta} = \boldsymbol{\zeta}^*_{f,\eta,\beta}\mathbf{\Pi}((\beta-f)a)\boldsymbol{Q}_\eta\mathbf{\Pi}(fa) \quad \text{(9)}$$

3.3.2. Inspection and Repair Costs

The repair cost in the repair policy η is expressed as $c_{\eta,i}$ $(i = 1, \ldots, I)$. Where $c_{\eta,i}$ indicates the repair cost that restores the condition state of the infrastructure i to j in the repair policy η with $\phi_\eta(i) = j$. If $\phi_\eta(i) = i$, $c_{\eta,i} = 0$. The repair cost vector is expressed as $\boldsymbol{c}_\eta = (c_{\eta,1}, c_{\eta,2}, \ldots, c_{\eta,I})$. The cost to conduct an inspection once is ι. At this time, the inspection and repair cost per unit period can be defined as:

$$w_{\eta,\beta} = \frac{\iota + \varepsilon^*_{\eta,\beta}\boldsymbol{c}'_\eta}{\beta} \quad \text{(10)}$$

The symbol "$'$" indicates transposition.

3.3.3. User Cost Caused by Deterioration

The user cost to be needed when the infrastructure in service fails is expressed as u. It is assumed in this study that a user cost is used, and is calculated by converting the direct damage, such as casualties of the users who use the infrastructure, into a currency unit. The user cost u can be determined, for example, by the amount of compensation that shall be paid by a manager of infrastructure for casualties of users caused by the infrastructure. At this time, the methodology to be proposed in this study can be regarded as a solution of the cost minimization problem that is a subproblem of a profit maximization problem for a manager of infrastructure. However, the economic

6. In this study the case is treated, in which the Markov process in Eq. (6) has reached a steady state. However, in the following cases the methodology proposed in this study should be modified as appropriate: i) if the Markov process has not reached a steady state; ii) if it is desirable to consider the social discount rate depending to the type of infrastructure; and iii) if the analysis aims to a develop a management plan and budget for outsourcing the management such that the planning period needs to be determined. However, considering the permanent management of infrastructure, the cost and risk during the period until the Markov process has reached a steady state are relatively small. Nonetheless, as a matter of course, as for the management policy for infrastructure during the period until the Markov process has reached a steady state, it is also desirable to determine the cost to be optimized. At this time the non-steady optimal management policy should be reviewed using a methodology such as that from [30].

loss caused by interruption, etc., of a network because of the unavailability of the network is not considered in this study. If the loss caused by interruption of a network is considered, only the value of u changes. To quantify such a loss of value of time for a user, the route selection by the user or the economic effect of the avoidance of interruption of a network at the time of the disaster should be considered. Even if such elements of the cost were included in u, it would be possible to analyze the user cost by modifying the methodology of this study. It would also be possible to solve a loss minimization problem that is a subproblem of a social total surplus maximization problem instead of a solution of a profit maximization problem for a manager of infrastructure, a single economic agent. The aforementioned various economic effects should be considered in calculating the user cost, but this is not the case in this study.

It is assumed that the failure probability caused by the deterioration changes depending on the condition state, and let p_i be the failure probability when the condition state i continues for a unit period. It is assumed $p_i \le p_{i+1}$ $(i = 1, \dots, I-1)$ holds. $\boldsymbol{p}$ is defined as $\boldsymbol{p} = (p_1, \dots, p_I)$. Supposing that the state vector of the period can be approximated as the state vector at the end of the period $(t_z, t_{z+1}]$, the user cost caused by deterioration per unit period, $y_{\eta,\beta}$, can be defined as:

$$y_{\eta,\beta} = \frac{\left(\sum_{f=1}^{\beta-1} \boldsymbol{p}\boldsymbol{\zeta}^{*\prime}_{f,\eta,\beta} + \boldsymbol{p}\boldsymbol{\varepsilon}^{*\prime}_{\eta,\beta}\right) u}{\beta} \quad \dots\dots (11)$$

3.3.4. User Cost Caused by Composite Factors of Earthquakes and Deterioration

Let s be the earthquake occurrence probability per unit period.[7] For example, if the information is available that the probability of an earthquake occurrence within k years is l, s can be determined such that $\ell = 1-(1-s)^k$ holds. The user cost when the infrastructure in service fails, u, is also used to define the user cost caused by composite factors of earthquakes and deterioration.[8] The probability that the infrastructure with a condition state i fails at the occurrence of an earthquake is ξ_i. It is assumed $\xi_i \le \xi_{i+1}$ $(i = 1, \dots, I-1)$. Let $\boldsymbol{\xi}$ be $\boldsymbol{\xi} = (\xi_1, \dots, \xi_I)$. The user cost caused by the composite factors of earthquakes and deterioration, $x_{\eta,\beta}$, can be expressed as:

$$x_{\eta,\beta} = \frac{\left(\sum_{f=1}^{\beta-1} \boldsymbol{\xi}\boldsymbol{\zeta}^{*\prime}_{f,\eta,\beta} + \boldsymbol{\xi}\boldsymbol{\varepsilon}^{*\prime}_{\eta,\beta}\right) su}{\beta} \quad \dots\dots (12)$$

7. The uncertainty of the earthquake occurrence probability and the modeling of the earthquake occurrence process are not covered in this study.
8. In this study, the loss caused by the interruption of the network because of the unavailability of infrastructure is also not considered at the time of earthquake.

Table 1. Markov transition probability $\pi_{i,j}(a)$.

	j			
i	0.980	0.015	0.004	0.001
	0	0.987	0.010	0.003
	0	0	0.995	0.005
	0	0	0	1

3.3.5. Objective Function

As the total expected cost, the objective function can be defined as:

$$b_{\eta,\beta} = w_{\eta,\beta} + y_{\eta,\beta} + x_{\eta,\beta} \quad \dots\dots\dots (13)$$

The values of η and β are determined such that the value of $b_{\eta,\beta}$ is minimized. The value of the objective function varies depending on the repair policy η and the inspection interval β.

3.3.6. Optimization Model

The combination of repair policy η and inspection interval β is termed the management policy. η can be defined by determining $\phi_\eta(i)$ for all the condition state i. A set of the repair policies that are the candidates for the optimal repair policy $\hat{\eta}$ is termed $\boldsymbol{\Psi}$. A set of the inspection intervals that are the candidates for the optimal inspection interval $\hat{\beta}$ is termed $\boldsymbol{\Omega}$. All of the elements of $\boldsymbol{\Omega}$ are natural numbers. A set of the candidates for the management policy is expressed as $\boldsymbol{\Theta} = \boldsymbol{\Psi} \times \boldsymbol{\Omega}$. The symbol "×" indicates a Cartesian product. The optimal management policy $\hat{\boldsymbol{\Lambda}} = (\hat{\eta}, \hat{\beta})$ is given by:

$$\hat{\boldsymbol{\Lambda}} = \arg\min_{(\eta,\beta)\in\boldsymbol{\Theta}} b_{\eta,\beta} \quad \dots\dots\dots\dots (14)$$

In this study the values of $b_{\eta,\beta}$ are calculated for all the elements of $\boldsymbol{\Theta}$, and then $\hat{\boldsymbol{\Lambda}}$ is determined with the exhaustive enumeration to determine the pair of η and β such that the value of $b_{\eta,\beta}$ is minimized.

4. Example of Application

4.1. Outlines

Supposing infrastructure that is supposed to provide long-term service, such as a lubber bearing (a bridge structure), the proposed methodology is applied. Concretely, a bridge structure at a scale of a national road in Japan is assumed and the conditions are set such as the Markov transition probability, cost, and other probabilities. Let a and I be 1 year and 4, respectively. In general, the Markov transition probability of the Markov process model indicating the deterioration process for infrastructure is estimated using the inspection data of the existing structure, but here we consider the situation where the Markov transition probability $\pi_{i,j}(a)$ is provided as shown in **Table 1**. $\boldsymbol{\Pi}(na)$ is calculated as $\{\boldsymbol{\Pi}(a)\}^n$ (n

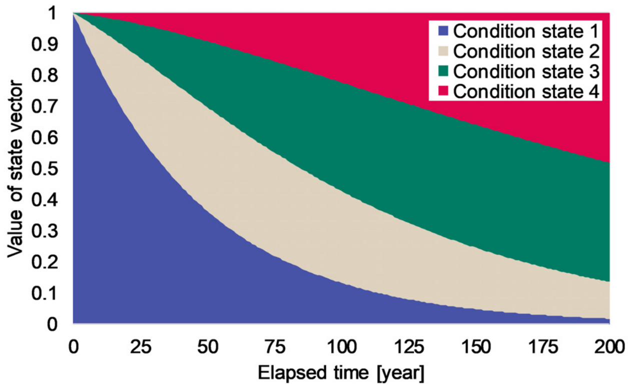

Fig. 1. Deterioration process.

Table 2. Repair action $\phi_\eta(i)$.

$\eta=1$		$\eta=2$	
i	$\phi_1(i)$	i	$\phi_2(i)$
1	1	1	1
2	2	2	2
3	3	3	1
4	1	4	1

Table 3. Cost.

Item	Variable	Value [m.u.]
Inspection cost	ι	16
Repair cost	$c_{1,1}$	0
	$c_{1,2}$	0
	$c_{1,3}$	0
	$c_{1,4}$	940
	$c_{2,1}$	0
	$c_{2,2}$	0
	$c_{2,3}$	940
	$c_{2,4}$	940
User cost	u	65,000

Table 4. Probability.

Item	Variable	Value
Failure probability (deterioration)	p_1	0
	p_2	0
	p_3	0
	p_4	0.001
Failure probability (earthquake)	ξ_1	0
	ξ_2	0
	ξ_3	0
	ξ_4	0.5
Earthquake occurrence probability	s	0.07

is a natural number). Under these conditions, supposing $\boldsymbol{\zeta}_0 = (1,0,0,0)$, the deterioration process for infrastructure can be expressed as a temporal transition of the value of the element of the state vector $\boldsymbol{\zeta}_z$, as shown in **Fig. 1**.

Then, the set of the manipulated variables of the optimization model is defined. Because the inspection interval is determined to be 5 years for the bridges according to the guidelines [31] in Japan, it is set as $\boldsymbol{\Omega} = \{1,2,3,4,5\}$. As for the repair policy, a corrective management policy (Policy 1, $\eta = 1$) and a preventive management policy (Policy 2, $\eta = 2$) are considered. That is to say, $\boldsymbol{\Psi} = \{1,2\}$. The repair action in each policy is defined as shown in **Table 2**. The repair cost is set as listed in **Table 3**. In this application, only a replacement is considered as a repair in both Policies 1 and 2. The condition state is restored to 1, if the repair (replacement) is conducted. The repair (replacement) cost is uniformly set as 940 m.u.[9] for the both Policies 1 and 2. The inspection cost and the user cost are also set as listed in **Table 3**. The human loss accompanying a failure of infrastructure is supposed as the user cost. These costs are determined by referring to [32, 33], considering the actual management problem as much as possible and standardizing the cost in Japanese Yen as a constant. The individual probabilities are set as listed in **Table 4**. The earthquake risk is supposed as relatively high (the probability that an earthquake occurs within 30 years in the future is $1-s^{30} = 1-(1-0.07)^{30} = 0.8866$). For example, in the case of $\eta = 1$ and $\beta = 5$, supposing $\boldsymbol{\zeta}_0 = (1,0,0,0)$, the deterioration and repair process of the infrastructure can be expressed as a temporal transition of the value of the element of the state vector $\boldsymbol{\zeta}_z$ as shown in **Fig. 2**. Illustrating the deterioration and repair process in such a manner, the Markov process is determined to have reached a steady state, if the maximum value of the difference between the right side and the left side of the vector elements in Eqs. (7)–(9) are less than 10^{-6}.

9. Monetary unit (arbitrary currency unit).

4.2. Results

4.2.1. Optimal Management Policy

Under the conditions mentioned in Section 4.1, the optimal management policy $\hat{\boldsymbol{\Lambda}}$ is calculated. The cardinality of $\boldsymbol{\Theta}$ is 10. The value of the objective function in each management policy is calculated, and then the optimal management policy is drived by using the exhaustive enumeration. The results are shown in **Fig. 3** as the values of 10 types of candidates for the optimal management policy. The optimal management policy is a combination of $\eta = 2$ and $\beta = 3$ with the value of objective function being 23.71 m.u.

4.2.2. Influence of Earthquake Risk

The values of the objective function in each management policy in the case that earthquake risk is not considered (namely, in the case that the earthquake occurrence probability in **Table 4** changes to $s = 0$) are shown

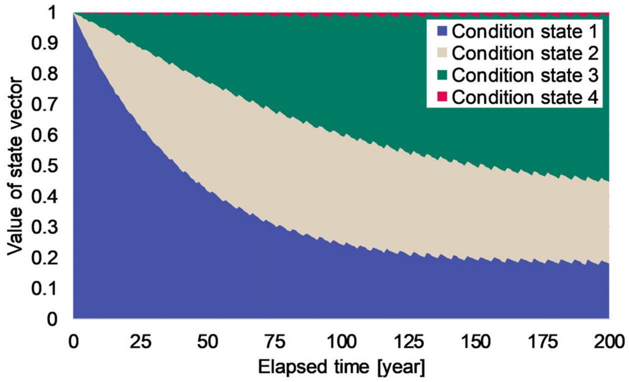

Fig. 2. Deterioration and repair process.

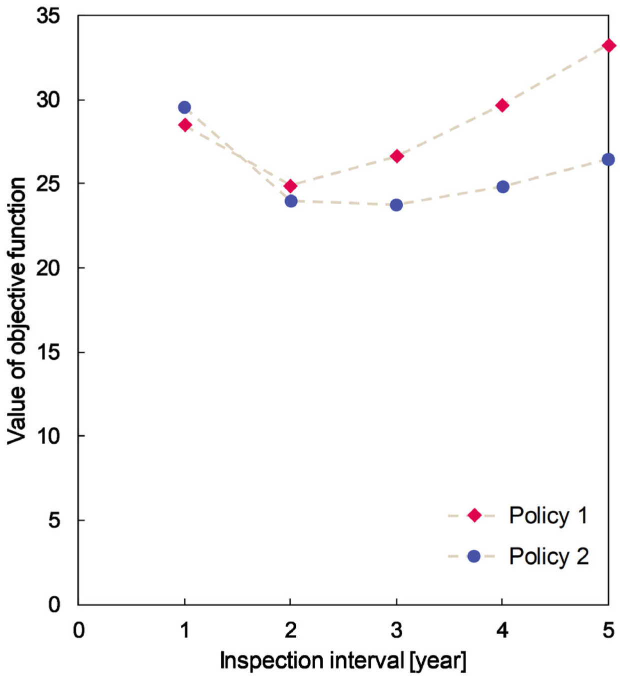

Fig. 3. Difference in the objective function depending on the inspection interval, in the case that the earthquake risk is considered.

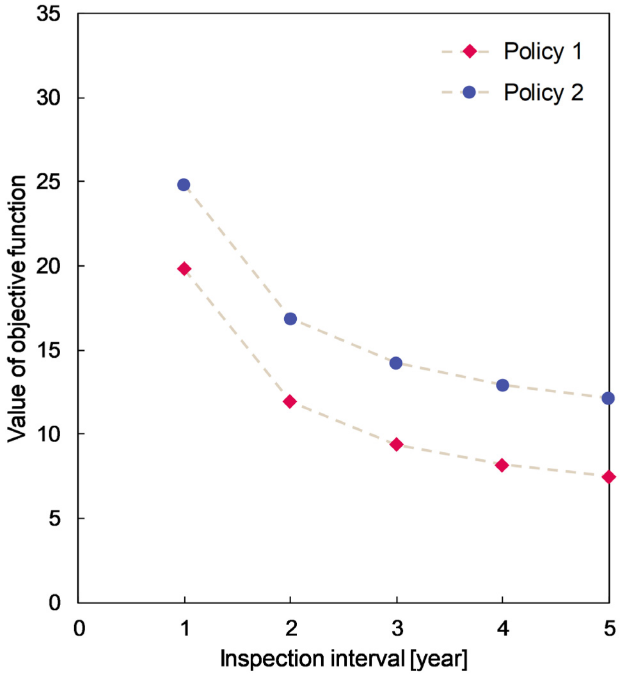

Fig. 4. Difference in the objective function depending on the inspection interval in the case that the earthquake risk is not considered.

in **Fig. 4**. As a matter of course, because the earthquake risk is not considered, the value of the objective function is much smaller compared to that shown in **Fig. 3**. Importantly, in the case that the earthquake risk is not considered in the optimal management policy, a combination of $\eta = 1$ and $\beta = 5$ is different from the optimal management policy in the case that earthquake risk is considered. Furthermore, not only the inspection interval, a policy that can be relatively easily changed, but also a repair policy that have the different optimal solutions depending on whether the earthquake risk is internalized or not. This indicates the possibility that the repair matrices differ between a case considering the earthquake risk and that without considering such a risk, even if the optimization model has the constraint that the repair action is determined depending on the management policy assuming the element of the repair matrix has a value of neither 0 or 1 for the practical convenience (i.e. the repair action to be executed is automatically decided, if the condition state of the infrastructure is observed). In Section 4.2.3, the sensitivity analysis is to be conducted to verify how the optimal management policy would change depending on the earthquake occurrence probability and the failure probability at the time of an earthquake.

4.2.3. Sensitivity Analysis in Terms of Earthquake Occurrence Probability

Let us confirm how the optimal management policy would change by varying ξ_4 and s which are shown in **Table 4**. The difference in the objective functions (the objective function of Policy 1 minus that of Policy 2) in which the optimal inspection interval is adopted in the repair policy $\eta = 1$ and $\eta = 2$, respectively, is shown in **Fig. 5**,[10] when the earthquake occurrence probability s varies from 0 to 0.15 and the failure probability at the time of the earthquake, ξ_4, from 0 to 1. If the value of the z axis shown in **Fig. 5** becomes negative, Policy 1 is selected as the optimal management policy, and if the value becomes positive, Policy 2 is selected. With an increase in the earthquake occurrence probability s, it becomes desirable to adopt a preventive management policy (Policy 2) to avoid in advance a condition state 4 where damage would

10. Plane with the value 0 of the z axis shown in gray.

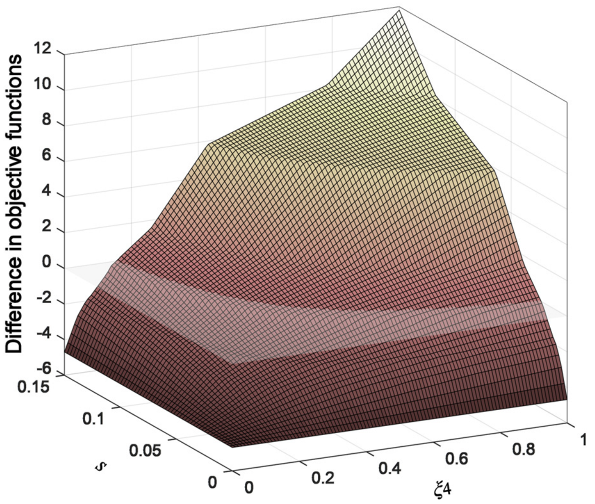

Fig. 5. Difference in objective functions.

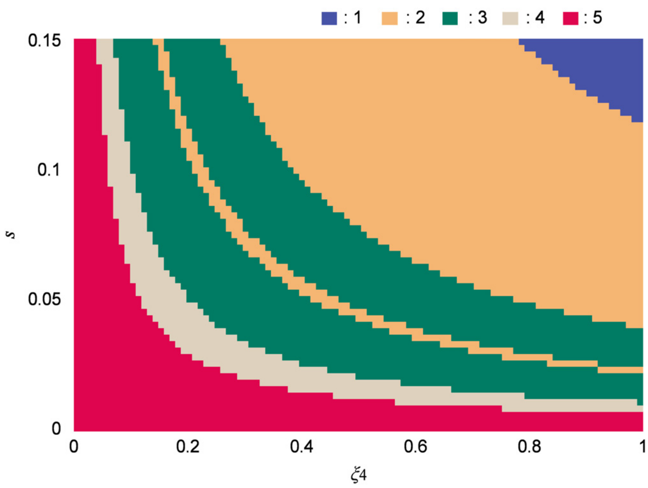

Fig. 7. Optimal inspection interval.

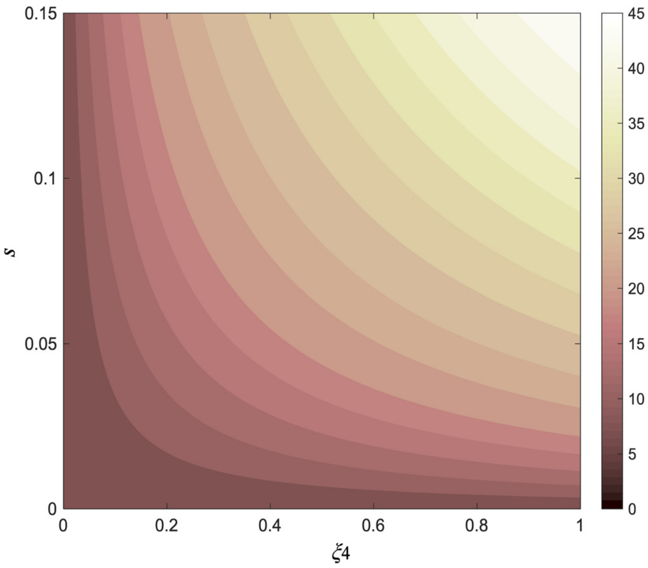

Fig. 6. Objective function under the optimal management policy.

occur at the time of an earthquake. Similarly, an increase in the failure probability at the time of earthquake, ξ_4, it becomes desirable to adopt Policy 2. The values of the objective function when the earthquake occurrence probability s varies from 0 to 1 and the failure probability at the time of earthquake, ξ_4, varies from 0 to 1, and the optimal management policy has been adopted are shown in **Fig. 6**. Furthermore, the optimal inspection interval in the optimal management policy is shown in **Fig. 7**. As the earthquake occurrence probability s and the failure probability at the time of earthquake, ξ_4, decrease, the total expected cost as an objective function also decreases. In addition, as the earthquake occurrence probability s and the failure probability at the time of earthquake, ξ_4, increase, the optimal inspection interval shortens except for a period when the optimal inspection interval increases from 2 to 3 years in changing from $\eta = 1$ to $\eta = 2$. They imply that the optimal management policy under normal conditions would be changed, if the earthquake occurrence probability and the failure probability of the infrastructure at the time of an earthquake vary.

5. Conclusions

In this study, focusing on the possibility that damage and risk at the time of an earthquake can change depending on the deterioration condition of the infrastructures, a basic examination was completed by investigating the possibility of a change in the optimal management policy for infrastructures used in normal (daily) situations depending on the earthquake occurrence probability. Concretely, the deterioration process of an earthquake was modelled using the Markov process model, then a methodology was proposed to determine the optimal management policy, considering i) the risk caused by the deterioration of infrastructure itself, and ii) the risk at the time of an earthquake changing with the deterioration condition of infrastructure. Then, in the application the example, supposing actual infrastructure (rubber bearing), the following points were found: i) the optimal management policy can be changed between a case considering the earthquake risk and that without considering such a risk, and ii) the optimal management policy can be changed depending on the earthquake occurrence probability, if the risk of an earthquake is considered.

However, the followings are listed as future works.

- The methodology proposed in this study can be also used for optimizing strategies of antiseismic reinforcement of infrastructures and management policies antiseismic reinforcement facilities. The methodology proposed in this study should be applied to such various problems.

- The modelling of the deterioration process for infrastructures and the calculation of a failure probability for infrastructures at the time of an earthquake should be refined.

- A discussion of how to address the earthquake occurrence probability is needed. A large number of studies have been completed in the field of science on earthquake occurrence probability, but it is desirable to use such knowledge in modeling the uncertainty of earthquake occurrence probability and the earthquake occurrence process as well as conduct a practical analysis. It should be continuously examined how to consider the unsteady earthquake occurrence probability mentioned in Section 3 among others.

- A discussion as to what extent the uncertainty of the failure probability of infrastructure at the time of an earthquake and the earthquake occurrence probability should be lowered to make such information useful from the viewpoint of infrastructure management is needed.

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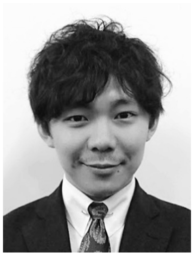

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Selected Publications:

• D. Mizutani, K. Matsuoka, and K. Kaito, "Statistical deterioration prediction model considering the heterogeneity in deterioration rates by hierarchical Bayesian estimation," Structural Engineering International, Vol.23, No.4, pp. 394-401, 2013.
• D. Mizutani, K. Obama, K. Kaito, and K. Kobayashi, "Multidimensional infrastructure deterioration process model," J. of Japan Society of Civil Engineers, Series D3 (Infrastructure Planning and Management), Vol.72, No.1, pp. 34-51, 2016 (in Japanese).
• D. Mizutani, M. Burkhalter, B. T. Adey, C. Martani, and V. Ramdas, "Initial investigations into the use of three heuristic algorithms to determine optimal intervention programs for multiple railway objects," Int. J. of Architecture, Engineering and Construction, Vol.6, No.3, pp. 1-20, 2017.

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