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ORIGINAL ARTICLE

The Effects Evaluation of The Deterioration of Bridge Expansion Joints on The Corrosion at Steel Girder End Part

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Abstract: The deterioration of steel girder end parts (steel components above abutment and pier) is the main factor for the administrators' decision making of repair and replacement on the maintenance and management of bridges. Corrosion is one of the main deterioration phenomena at steel girder end parts. Moreover, the primary causes of corrosion are thought to be the water leakage from bridge expansion joint and the ponding on abutment/pier. Therefore, the lifetime improvement of bridges and the reduction of lifecycle costs could be achieved by appropriately establishing the time interval of bridge expansion joints 'inspection and replacement. In this study, using regime switching model and Markov deterioration hazard model, regime switching Markov hazard model is formulated. Using regime switching Markov deterioration hazard model, the effects of the deterioration of bridge expansion joints on the development of the corrosion at steel girder end parts are expressed. Moreover, the relation between the both deteriorations on the bridge expansion joints and the steel girder end parts is able to be quantitatively valuated with the deterioration prediction results. Lastly, the effectiveness of the methodology proposed in this study is empirically validated through the case study focusing on the visual inspection data of highway bridges.

Keywords: asset management, bridge management, corrosion, regime switching model, Markov deterioration hazard model

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1. Introduction

In Japan, about 700 thousand highway bridges had been built intensively after the high economic growth period in the mid-1950s. Half of these bridges will be more than 50 years after constructions in the mid-2020s, it is known that the aging of highway bridges will rapidly develop in the future. The increase in aged highway bridges is directly linked to social unrest due to lower users' safety and an increase in highway bridges' maintenance/management costs. Therefore, it is necessary to regard highway bridges' deterioration as not only engineering problem but also social problem. Moreover, in Japan, the declining birthrate and aging of the population keep on going. Thus, it is thought to be an urgent issue to efficiently maintain and manage highway bridges in limited human resources and austerity finance. Therefore, by inspecting, repairing and renewal at appropriate intervals on the basis of the deterioration state and importance of the bridge, it is necessary to entend the life of the bridge and reduce the life cycle cost.

In this study, the authors focus on the deterioration of the steel girder end parts (steel components above abutment/pier). The deterioration of the steel girder end parts is a main factor in the decision making of repair and renewal especially in maintenance of steel bridge. Corrosion is one of the main deterioration phenomena at steel girder end parts. Moreover, the primary causes of corrosion are thought to be the water leakage from the bridge expansion joint and the ponding on abutment/pier. On the other hand, repair and renewal of the steel girder end parts involve carrying out traffic restrictions, and these repair and renewal are large scale constructions with heavy machinery. As a result, repair and replacement of steel girder end parts can lead to not only reduction of road convenience but also increase of life cycle cost. Therefore, by keeping the bridge expansion joint good condition with the appropriate inspection interval and replacement interval of the bridge expansion joint, it is possible to extend the life of the steel bridge and to reduce the life cycle cost.

Under the above awareness of the issues, in this study, the authors propose a methodology for evaluating the effect of water leakage caused by deterioration of the bridge expansion joint on corrosion of the steel girder end parts. Specifically, the presence or absence of water leakage from the bridge expansion joint above the steel girder end parts are considered as two types of regime. Moreover, Considering the influence of water leakage from the bridge expansion joint on the girder end part, the development process of corrosion at the girder end parts is represented by regime switching Markov deterioration hazard model.

In chapter **2.**, the basic idea of this study is explained. In chapter **3.**, regime switching Markov deterioration hazard model is formulated. In chapter **4.**, the estimation method of regime switching Markov deterioration hazard model is described in detail. In chapter **5.**, the effectiveness of the methodology proposed in this study is empirically validated through the case study focusing on the visual inspection data of highway bridges.

2. Basic idea of this study

2.1 Statistical deterioration prediction method for infrastructure

In this study, the occurrence process of water leakage from the bridge expansion joint and the development process of corrosion at the girder end part are expressed with statistical method, and the model is estimated by using visual inspection data of highway bridges. Administrators of infrastructure vary from nation to local governments, and some facilities are managed by an infrastructure management company. Various inspections have been carried out on infrastructure facilities by each administrator. Thus, vast amounts of inspection data are accumulated. In the past, a lot of Studies on statistical deterioration prediction method using these inspection data has been accumulated. In particular, in case of a facility where deterioration state is observed in binary states (whether it is faulty or not), the developed deterioration prediction method (deterioration hazard model) with survival time analysis[1)] make it possible to use not only data which are obtained from the facilities renewed due to reaching control limit but also data which are obtained from the facilities which preventive repairs and renewals are carried out in the service period. Therefore, the accuracy of deterioration prediction considerably improved[2)]. Furthermore, multistage exponential hazard model (Markov deterioration hazard model)[3)] and multistage Weibull hazard model[4)] express the deterioration process of facilities which are recorded with multistage discrete condition state. These developments make it possible to use the advantages of survival time analysis stated above for transitions of multistage condition states. In addition, more complicated deterioration process (Benchmarking of deterioration process, prediction of composite deterioration process, etc.) can be estimated by mixed probability model and hidden Markov deterioration model which are formulated on the basis of those models stated above[5)-6)]. In this study, the quantitative effect evaluation of the presence or absence of water leakage by bridge expansion joint's deterioration on corrosion at steel girder end part is carried out.

2.2 Development mechanism of corrosion

Corrosion is the phenomenon that the steel material tries to return to the stable oxidized compound by combining with oxygen and water. In steel structures, corrosion is thought to be regarded as one of main deterioration. Corrosion of steel in water or in the atmosphere is caused by water and dissolved oxygen. This chemical reaction formula is expressed by the following Eq. (2.1).

$$\mathrm{Fe} + \frac{1}{2}O_2 + H_2O \rightarrow \mathrm{Fe}(OH)_2 \qquad \text{Eq. (2.1)}$$

In addition, the extent of corrosion development is greatly influenced by the use environment and the type/shape/location of parts. For that reason, various methods for corrosion protection exist depending on each condition, such as painting, anti-corrosion steel and etc. However, painting is the most widespread method in consideration of the points of economic efficiency, landscape and workability. In painted structures, corrosion does not develop as long as paint is not deteriorated. On the other hand, if the paint is left in a deteriorated state, the corrosion of the steel material develops. When corrosion of steel material develops, the cross section of the steel material decreases. Thus, unless any measures are taken against corrosion occurring parts, the structural soundness is greatly affected. Based on this idea, in the case of taking into consideration the reduction of the life cycle cost under the strict budget constraint, it may be more effective method to extend the life of steel material with preventive maintenance such as re-painting at appropriate time points rather than breakdown maintenance such as replacement of steel materials. Furthermore, in order to prevent corrosion of steel materials, it is desirable not only to paint at appropriate time points but also to prevent water, which is the cause of corrosion, from entering into the vicinity of the steel material. That is, when maintenance and management of the steel bridge, appropriate replacements of the bridge expansion joint aimed at preventing the penetration of water to the steel girder end part are considered to be very important for extending the life of the steel bridge and reducing the life cycle cost.

2.3 Occurrence mechanism of water leakage

Corrosion in the lower part of the girder end part is mainly caused by water leakage from the bridge

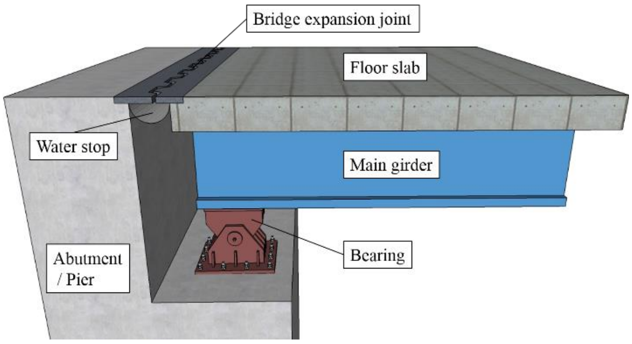

Figure 2.1 non-drainage type's expansion joint

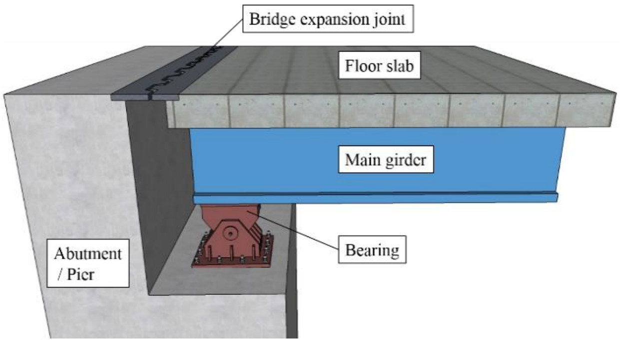

Figure 2.2 drainage type's expansion joint

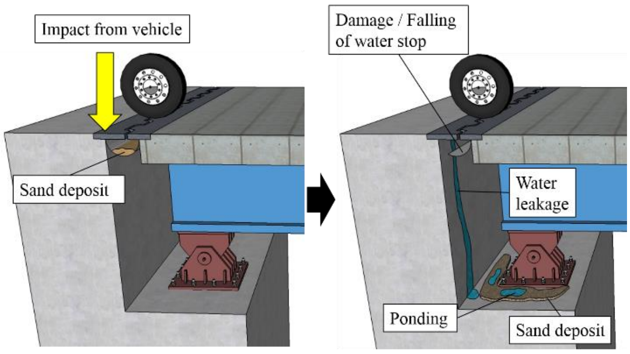

Figure 2.3 damage to the bridge expansion joint

expansion joint [7]. The bridge expansion joint is roughly divided into two types such as non-drainage type and drainage type. In the bridge expansion joint of non-drainage type, as shown in Figure 2.1, a water stop is installed at the bottom of the bridge expansion joint to prevent water from penetrating the lower parts of the girder end part. The causes of damage or falling off of water stop are considered to be sand deposit, repeated impacts by the passing vehicles, excessive impacts by overloaded vehicles, repeated expansions and contractions and aged deterioration as shown in Figure 2.3. When water stop is damaged, water such as rainfall penetrate into the girder end part. Thus, the girder end part becomes to the condition which corrosion tends to develop. For these reasons, the presence or absence of the water stop's damage has deep relation to the corrosion of the girder end part. Therefore, water stop is regularly inspected. In the regular inspections, the presence or absence of water leakage is judged from damage or falling off of the water stop, water traces from the water stop and ponding at the upper part of the abutment/pier. Moreover, the presence or absence of the water leakage is recorded as the inspection results. On the other hand, in the bridge expansion joint of drainage type, as shown in Figure 2.2, a water stop is not installed at the bottom of the bridge expansion joint. Thus, the bridge expansion joint of drainage type has the structure which water penetrates from the seam of the bridge expansion joint into the lower part of the girder end part. Therefore, the inspection results concerning the water leakage are not recorded. From the above, it is conceivable that the water leakage at the girder end part occurs because the water stops of the non-drainage type's bridge expansion joint damage or fall off. Moreover, corrosion develops at points where the painting has peeled off. Therefore, in this study, the deterioration prediction model for quantitative evaluation of the relationship between the damage of the bridge expansion joint and the corrosion of the girder end part is proposed.

3. Formulation of model

3.1 Presupposition for modeling

The bridge administrator starts service of the bridge or renews at the calendar time a_0^l. Thereafter the administrator manages the girder end parts and the bridge expansion joints. $l\ (l = 1, \cdots, L)$ shows the girder end parts' ID. Time series inspection data set (rating data representing corrosion development state and binary data indicating the presence or absence of water leakage from the bridge expansion joint) is obtained for each l.

Discrete time axis t_g^l which calendar time a_0^l is set as initial time point $t_0^l = 0$ is introduced.

$$t_g^l = t_{g-1}^l + z \left(g = 1, 2, \cdots, G^l\right) \quad \text{Eq. (3.1)}$$

$t_{G^l}^l$ shows the end time point of the observation period of l. In this study, the point on the discrete time axis is referred to as the time point. The time point is distinguished from the calendar time. The focusing deterioration process is the composite deterioration process with corrosion development process and water leakage occurrence process. For the sake of simplicity, the girder end part is assumed to have never been renewed from the initial time point. When the girder end part is replaced, the calendar time is assumed to be the initial time point. The corrosion development condition of the girder end part l at the time point t_g^l is expressed by using the discrete state variable $f\left(t_g^l\right) = i \ (i = 1, \cdots, I)$. Rating $i \ (i = 1, \cdots, I)$ shows the corrosion development conditions. Namely, the corrosion development conditions are proportional to the value of i. At the initial time point $t_0^l = 0$, the discrete state variable is shown as $f(0) = 1$. Furthermore, a state variable representing the presence / absence of water leakage from the bridge expansion joint at time point t_g^l is defined as water leakage management mode s_g^l.

$$s_g^l = \begin{cases} 1 \text{ abnormal mode} \\ 0 \text{ normal mode} \end{cases} \quad \text{Eq. (3.2)}$$

In this study, abnormal mode is defined as the state with water leakage. On the other hand, normal mode is defined as the state without water leakage. At the initial time point, the water leakage management mode is shown as $s_0^l = 0$. In this study, the corrosion development process and the water leakage occurrence process are respectively expressed by Markov chain model. The water leakage management mode is a risk management mode indicating whether the corrosion development state which is affected by damage of the bridge expansion joint has occurred or not. Moreover, it is considered that the corrosion developing speed of the girder end part differs depending on the water leakage management mode.

In the water leakage management mode $s_g^l = h \ (h = 0, 1)$, the state-dependent development speed of the corrosion rating i at the girder end part is expressed by $\lambda_{i,g}^l$. At this time, the corrosion development speed $\lambda_{i,g}^l$ in the period $\left[t_g^l, t_{g+1}^l\right)$ is expressed like Eq. (3.3).

$$\begin{aligned} \lambda_{i,g}^l &= s_g^l \lambda_{i,1}^l + \left(1 - s_g^l\right)\lambda_{i,0}^l \\ &= s_g^l x_1 \beta'_{1,i} + \left(1 - s_g^l\right) x_0 \beta'_{0,i} \end{aligned} \quad \text{Eq. (3.3)}$$

Here, $x_h = \left(1, x_{1,h}, \cdots, x_{C,h}\right) \ (h = 0, 1)$ shows explanatory variable vector. On the other hand, $\beta_{h,i} = (\beta_{0,h,i}, \cdots, \beta_{C,h,i})$ shows unknown parameter vector. In the Eq. (3.3), the symbol " $'$ " represents a transposition operation.

3.2 Corrosion development model

The Markov transition probability that the rating of corrosion transits from i to $j \ (j = i + 1, \cdots, I - 1)$ in the period $\left[t_g^l, t_{g+1}^l\right)$ is expressed like Eq. (3.4)[3].

$$\pi^{ij}(l, g, z) = \sum_{m=i}^{j} \prod_{r=i, \neq m}^{j-1} \frac{\lambda_{r,g}^l}{\lambda_{r,g}^l - \lambda_{m,g}^l} \exp\left(-\lambda_{m,g}^l z\right) \quad \text{Eq. (3.4)}$$

Also, $\pi^{iI}(l, g, z)$ can be expressed by the following Eq. (3.5) with the condition of Markov transition probability.

$$\pi^{iI}(l, g, z) = 1 - \sum_{j=i}^{I-1} \pi^{ij}(l, g, z) \quad (s = 0, 1) \quad \text{Eq. (3.5)}$$

As can be seen from these Markov transition probabilities, in this study, it is assumed that corrosion development of the girder end part in the period $[t_g^l, t_{g+1}^l)$ is determined by water leakage management mode s_g^l at the beginning of the period t_g^l.

3.3 State variable model

The transition of the water leakage management mode is thought to be independent of the development of corrosion at the girder end part. The transition from 0 to 1 in the water leakage management mode indicates the deterioration of the water stop. On the other hand, the transition from 1 to 0 indicates the repair of the water stop. In this study, even when the repair records of the water stop are partially accumulated, the transition from 1 to 0 of the water leakage management mode is stochastically expressed. When the repair records of the water stop are completely accumulated, the transition from 1 to 0 should be deterministically set.

In this study, the transition probability of water leakage management mode is thought to be expressed by an exponential hazard model[1)] formulated on the basis of information which is observed at the beginning of the period t_g^l. Now, It is assumed that the normal mode $s_g^l = 0$ is observed at the time point t_g^l. At this time, the hazard ratio which the normal mode $s_g^l = 0$ terminated during the period $\left[t_g^l, t_{g+1}^l\right)$ is expressed by $\theta_{g,0}^l$. Similarly, when the abnormal mode $s_g^l = 1$ is observed at the time point t_g^l, the hazard ratio which the abnormal mode $s_g^l = 1$ terminated during the period is expressed by $\theta_{g,1}^l$. The hazard ratio $\theta_{g,h}^l$ $(h = 0, 1)$ is expressed like Eq. (3.6) with the characteristic vector $y_{g,h}^l = (1, y_{g,h,1}^l, \cdots, y_{g,h,D}^l)$ such as the water leakage characteristic, etc. in the period t_g^l.

$$\theta_{g,h}^l = \exp(y_{g,h}^l \alpha'_h) \qquad \text{Eq. (3.6)}$$

$\alpha_h = (\alpha_{h,0}, \cdots, \alpha_{h,D})$ shows a D dimensional row vector of unknown parameters. The water leakage management mode $s_g^l = h$ $(h = 0, 1)$ is observed at the time point t_g^l. Moreover, the probability which the water leakage management mode $s_g^l = h$ continues until the time point t_{g+1}^l is expressed like Eq. (3.7) with survival probability $\tilde{F}_{g,h}^l(z)$ that the lifetime of each mode becomes z and over.

$$\tilde{F}_{g,h}^l(z) = \exp(-\theta_{g,h}^l z) \qquad \text{Eq. (3.7)}$$

Furthermore, the probability $p_g^l(\theta_{g,0}^l)$ which the water leakage management mode transits from the normal mode to the abnormal mode in the period $\left[t_g^l, t_{g+1}^l\right)$ is expressed like Eq. (3.8).

$$p_g^l\left(\theta_{g,0}^l\right) = 1 - \tilde{F}_{g,0}^l\left(z \middle| \theta_{g,0}^l\right) \qquad \text{Eq. (3.8)}$$

The probability $q_g^l\left(\theta_{g,1}^l\right)$ which the water leakage management mode transits from the abnormal mode to the normal mode in the period $\left[t_g^l, t_{g+1}^l\right)$ is expressed like Eq.(3.9).

$$q_g^l\left(\theta_{g,1}^l\right) = 1 - \tilde{F}_{g,1}^l\left(z \middle| \theta_{g,1}^l\right) \qquad \text{Eq. (3.9)}$$

4. Estimation of model

4.1 Likelihood function

It is assumed that rating $\bar{\imath}_g^l$ of corrosion of the girder end part and the water leakage management mode $\bar{s}_g^l$ are obtained at all time points t_g^l. The symbol "$^{-}$" represents the observation value. At this time, the likelihood function $\mathcal{L}(\bar{\imath}, \bar{s}, \bar{x}, \bar{y}, \alpha, \beta)$ is expressed like Eq. (4.1).

$$\begin{aligned}
&\mathcal{L}(\bar{\imath}, \bar{s}, \bar{x}, \bar{y}, \alpha, \beta) \\
&= \prod_{l=1}^{L} \prod_{g=0}^{G-1} \pi^{\bar{\imath}_g^l \bar{\imath}_{g+1}^l}(l, g, z) \\
&\cdot \left[p_g^l\left(\theta_{g,0}^l\right)^{\delta_g^{l,*}} \left\{1 - p_g^l\left(\theta_{g,0}^l\right)\right\}^{1-\delta_g^{l,*}} \right]^{1-\bar{s}_g^l} \\
&\cdot \left[q_g^l\left(\theta_{g,1}^l\right)^{\delta_g^{l,*}} \left\{1 - q_g^l\left(\theta_{g,1}^l\right)\right\}^{1-\delta_g^{l,*}} \right]^{\bar{s}_g^l}
\end{aligned} \qquad \text{Eq. (4.1)}$$

The dummy variable $\bar{\delta}_g^l$ is defined as Eq. (4.2).

$$\bar{\delta}_g^l = \begin{cases} 0 & (\bar{s}_g^l = \bar{s}_{g+1}^l) \\ 1 & (\bar{s}_g^l \neq \bar{s}_{g+1}^l) \end{cases} \qquad \text{Eq. (4.2)}$$

$\bar{\imath}$ shows the observed rating data set, $\bar{s}$ shows the observed data set of water leakage management mode and $\bar{x}$ and $\bar{y}$ are the observed data sets of the characteristic variables

Here, the situation which rating $\bar{\imath}_g^l$ of corrosion at the girder end part and the water leakage management mode $\bar{s}_g^l$ are observed at all time points t_g^l is not realistic. Therefore, in this study, observed corrosion rating $\bar{\imath}_g^l$ and the water leakage management mode $\bar{s}_g^l$ the girder end part are used as observed values. On the other hand, unobserved rating and water leakage management mode are used as latent variables. Namely, the likelihood function (Eq. (4.1)) is regarded as the completion likelihood function[8)]. In this way, unknown parameters of model and latent variables are simultaneously estimated by using MCMC (Markov chain Monte Carlo) method [9)-10)]. By using above method, the model can be estimated in consideration of the partial unobservability of the rating and the water leakage management mode.

4.2 Unobservable water leakage occurrence situation

In the proposed regime switching Markov deterioration hazard model, the latent variable of water leakage management mode is expressed like Eq. (4.3) because the transition of the water leakage management mode is not affected by rating of corrosion at the girder end part.

$$\Pr\left(s_{g+1}^{l*}\middle|\bar{s}_g^l\right) = \left[p_g^l\left(\theta_{g,0}^l\right)^{\delta_g^{l,*}}\left\{1-p_g^l\left(\theta_{g,0}^l\right)\right\}^{1-\delta_g^{l,*}}\right]^{1-\bar{s}_g^l} \cdot \left[q_g^l\left(\theta_{g,1}^l\right)^{\delta_g^{l,*}}\left\{1-q_g^l\left(\theta_{g,1}^l\right)\right\}^{1-\delta_g^{l,*}}\right]^{\bar{s}_g^l} \quad \text{Eq. (4.3)}$$

The symbol "*" represents a latent variable. The dummy variable $\delta_g^{l,*}$ is expressed like Eq. (4.4).

$$\delta_g^{l,*} = \begin{cases} 0 & (\bar{s}_g^l = s_{g+1}^{l,*}) \\ 1 & (\bar{s}_g^l \neq s_{g+1}^{l*}) \end{cases} \quad \text{Eq. (4.4)}$$

$\bar{\iota}_{-i_g^l}$ represents a rating data set excluding i_g^l.

4.3 Unobservable corrosion development situation

The situation of corrosion development is also unobservable data except the time point of inspection. However, latent variables make it possible to express the situation of corrosion development at the local time point. When rating of corrosion at the time point t_g^l is not observed and the rating of corrosion is sampled as the latent variable $i_g^{l,*}$, the conditional posterior probability of $i_g^{l,*} \in \{\bar{\iota}_{g-1}^l, \cdots, \bar{\iota}_{g+1}^l\}$ is expressed like Eq. (4.5).

Table 5.1 The rating of corrosion

Rating	Condition	
	Depth	Area
1	No damage	
2	Small	Small
3	Small	Big
4	Big	Small
5	Big	Big

Table 5.2 The rating of water leakage

Rating	Condition
1	No damage
2	With Water leakage

$$\Pr\left(i_g^{l,*}|\bar{\iota}_{-i_g^{l,*}}, \bar{s}, \bar{x}, \bar{y}, \alpha, \beta\right) = \frac{\mathcal{L}\left(\bar{\iota}_{-i_g^{l,*}}, i_g^{l,*}, \bar{s}, \bar{x}, \bar{y}, \alpha, \beta\right)}{\sum_{i=\bar{\iota}_{g-1}^l}^{\bar{\iota}_{g+1}^l} \mathcal{L}(\bar{\iota}_{-i}, i, \bar{s}, \bar{x}, \bar{y}, \alpha, \beta)} \quad \text{Eq. (4.5)}$$

5. Empirical analysis

5.1 Overview of database

The effectiveness of the regime switching Markov deterioration hazard model proposed in this study is discussed through the case study with actual bridge inspection data. An administrator which manages the bridges accumulates the visual inspection records such as the rating based on the corrosion development of the steel girder end part and binary data of the presence or absence of water leakage. These visual inspection records are accumulated as rating data on the basis of Bridge periodical inspection guideline [11)] as shown in Table 5.1 and Table 5.2. In this study, these rating data are used as information samples to estimate the regime switching Markov deterioration hazard model. In addition, the information samples are extracted only from the vertically corresponded bridge expansion joint and the main girder end parts. Namely, one of data set of information samples consists of the rating of corrosion of the main girder

Table 5.4 Estimation result of corrosion development process

	β_0						β_1					
	Constant term			Painting specification			Constant term			Painting specification		
	$\beta_{0,1}^1$	$\beta_{0,2}^1$	$\beta_{0,3}^1$	$\beta_{0,1}^2$	$\beta_{0,2}^2$	$\beta_{0,3}^2$	$\beta_{1,1}^1$	$\beta_{1,2}^1$	$\beta_{1,3}^1$	$\beta_{1,1}^2$	$\beta_{1,2}^2$	$\beta_{1,3}^2$
Estimate	-1.7109	-2.7046	-1.1757	-	-0.1793	-0.5945	-3.1221	-5.7946	-1.0335	2.1815	3.2373	-
Upper limit 5%	-1.5025	-2.3494	-0.8144	-	0.1824	0.0205	-2.4521	-3.9867	-0.6519	2.9930	4.6619	-
Lower limit 5%	-1.9007	-3.0442	-1.6781	-	-0.6696	-1.1054	-3.8474	-7.2872	-1.4065	1.3309	1.2470	-
Geweke test statistic	1.7369	-0.4126	0.6227	-	0.2412	-0.1639	0.0532	-0.7962	0.9884	0.2273	0.7242	-

Table 5.3 Overview of database

# of bridges	123
Sample size	866
# of inspections	1~3
Inspection year	2004~2015
Construction year	1926~2005
Characteristics of bridge	Painting specification, Salt damage area classification, Traffic volume

end part, the presence or absence of water leakage from the bridge expansion joint, the characteristics of each bridge and the time interval between the former inspection and the latter inspection. Based on the above assumptions, the overview of the database is shown in Table 5.3.

5.2 Estimation result of corrosion development process of main girder

The information data samples whish are described in section **5.1** are applied to the regime switching Markov deterioration hazard model. In this study, painting specifications and salt damage area classifications are considered as the candidates for explanatory variables of Markov deterioration hazard model because these characteristics are thought to have an effect on the corrosion. Painting specifications are classified into three types such as A paint system, B paint system and C paint system. For these paint systems, A painting system and B painting system are generally classified into general painting system. On the other hand, C painting system is classified into heavy-duty anticorrosion painting system. Thus, the influence of painting specifications on the corrosion development is considered by using binary dummy variable. Table 5.4 shows the estimation result of Markov deterioration hazard model, which represents the development of corrosion of the main girder. The salt damage area is

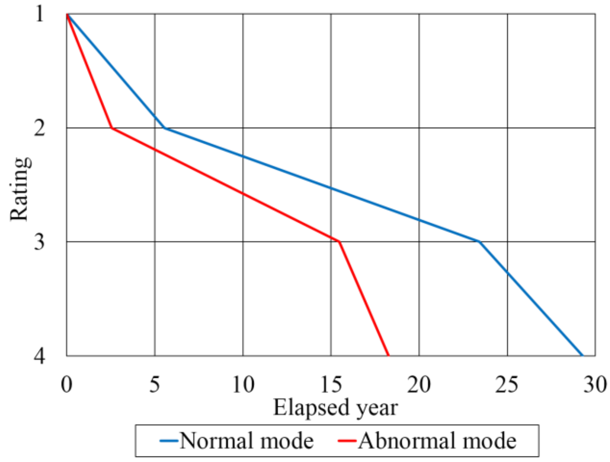

Figure 5.1 Corrosion development processes of the general painting system

classified as A, B, C and D depending on the extent of necessity of taking measures against salt damage. Furthermore, the salt damage area is classified as S, I, II and III depending on the distance from coastline. These details are described in Specifications for highway bridges part III concrete bridge edition[12]. The samples used in this study are divided into four categories such as C-(S), C-(II), C-(III) and D. Therefore, C-(S), C-(II), and C-(III) are classified as salt damage area and D is classified as non-salt damage area. In this way, the influence of salt damage area classification on the corrosion development is considered by using the binary dummy variable. However, because the number of the samples in the salt damage area is small, the significance of salt damage area classification is rejected by Geweke test [13] for the all processes of corrosion development in the abnormal mode. Therefore, the result is not shown in Table 4. Moreover, when paint specifications are adopted as explanatory variable, statistically significant results were obtained in the transitions of corrosion ratings in normal mode from 1 to 2, 2 to 3 and 3 to 4. On the other hand, statistically significant results in the transitions of corrosion ratings in abnormal mode from 1 to 2 and 2 to 3. However, the unknown parameter $\beta_{1,3}^2$ of the transition of corrosion ratings from 3 to 4 in the abnormal mode

Table 5.4 Estimation result of state variable model

	α_0		α_1
	Constant term	Traffic volume	Constant term
	α_0^1	α_0^2	α_1^1
Estimated record	-1.5645	-0.1995	-1.0580
Upper limit 5%	-1.4161	0.3115	-0.9781
Lower limit 5%	-1.7168	-0.7755	-1.1415
Geweke test statistic	1.2813	-0.7369	-1.4929

was rejected by the Geweke test. Furthermore, the unknown parameter $\beta_{0,1}^2$ of the transition of corrosion ratings in the normal mode from 1 to 2 was obtained as positive value. This result indicates that the general painting system is more resistant to corrosion than the heavy-duty anticorrosion painting system. However, this result is contradictory to practical experiences. Therefore, the estimated parameter $\hat{\beta}_{0,1}^2$ was not adopted considering sign condition. By using the above estimation results, it is possible to express the corrosion development processes of the main girder in the normal mode and the abnormal mode as shown in Figure 5.1. However, Figure 5.1 shows the corrosion development processes of the general coating system as an example. Moreover, due to the sample deficiency of corrosion rating 5, Table 5.4 and Figure 5.1 show the estimation result up to corrosion rating 4. It is confirmed from Figure 5.1 that the corrosion in the abnormal mode develops up to rating 4 about 11 years earlier than that in the normal mode. In the future, when inspection data is continued to accumulate, it is speculated that further difference will occur in the deterioration processes between the normal mode and the abnormal mode.

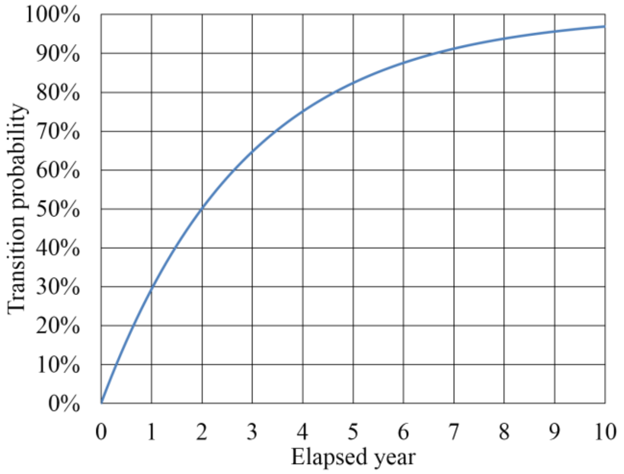

Figure 5.2 Transition probability from abnormal mode to normal mode

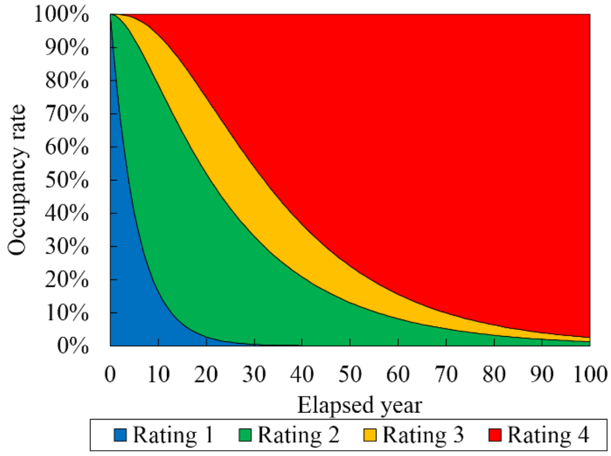

Figure 5.4 Corrosion rating occupancy in normal mode

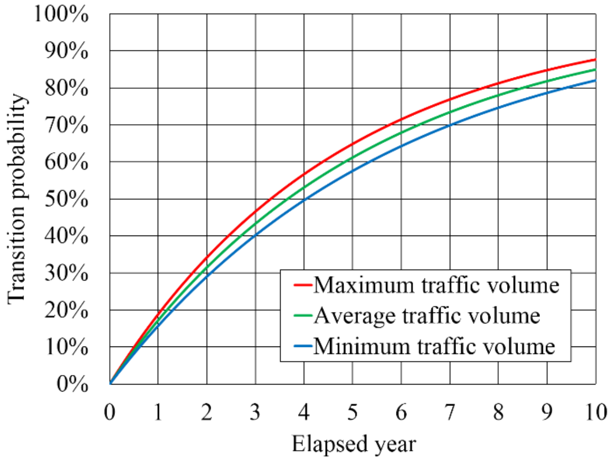

Figure 5.3 Transition probability from normal mode to abnormal mode

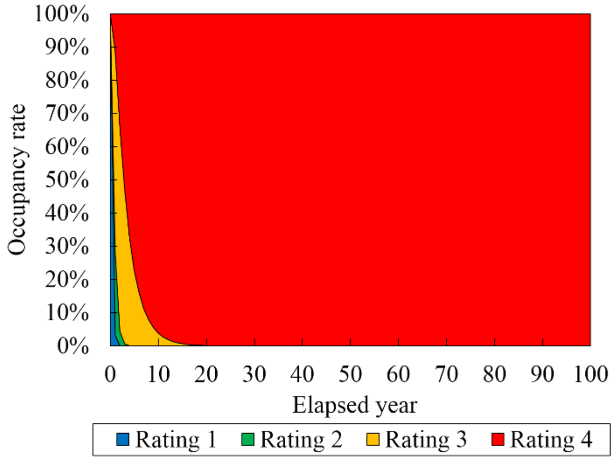

Figure 5.5 Corrosion rating occupancy in abnormal mode

5.3 Estimate result of state variable model

In this study, the Markov deterioration hazard model which expresses the corrosion development process of the main girder and the Markov transition probability which expresses the water leakage management mode transition probability (normal mode and abnormal mode) are simultaneously estimated. In addition to the estimation results of the corrosion development processes of the main girder which are described in section **5.2,** the estimation results of the state variable model are shown in Table 5.4. In this study, considering the traffic volume as the cause of water leakage from the bridge expansion joint, it was adopted as an explanatory variable. The transition probabilities from abnormal mode to normal mode is shown in Figure 5.2 using this estimation result. Figure 5.2 can be thought as the repair probability of the bridge expansion joint with the lapse of time. The transition probability from normal mode to abnormal mode is shown in Figure 5.3. As shown in Figure 5.3, at 50% of the transition probability from normal mode to abnormal mode, the difference of about 0.8 years between the maximum traffic volume and the minimum traffic volume arise. Furthermore, the corrosion rating occupancy of the main girder in the normal mode is shown in Figure 5.4. In addition, the corrosion rating occupancy of the main girder in the abnormal mode is shown in Figure

5.5. From this results, by setting the threshold (administration standard) for the occupancy of rating 4 depending on each water leakage management mode, the road administrator can make a decision for replacement of the bridge expansion joint.

6. Conclusion

In this study, regime switching Markov deterioration hazard model on the based of the concept of Markov switching Poisson occurrence model[14]. Moreover, the effect of the presence or absence of water leakage on the corrosion development of the steel girder end part is quantified. First, the water leakage management modes are defined by setting the normal mode for the case of no water leakage and the abnormal mode for the case of water leakage on the basis of the presence or absence of water leakage from the bridge expansion joint. Secondly, the corrosion development process of the steel girder end part is expressed with Markov degradation hazard model. Moreover, the transition probabilities of each water leakage management mode are expressed with the Markov switching model. In this way, the corrosion development processes in each water leakage management mode are formulated as a regime switching Markov deterioration hazard model. Herewith, the processes of corrosion development of the steel girder end part in each water leakage management mode can be distinguished. Thus, it is possible to determine an appropriate replacement timing of the bridge expansion joint on the basis of the expected lifetime of the steel girder end part in each water leakage management mode. On the other hand, it is possible to express the difference between deterioration processes by adopting the presence or absence of water leakage as an explanatory variable of the conventional Markov deterioration hazard model. However, water leakage from the bridge expansion joint which is confirmed by visual inspection does not necessarily occur near the time point of inspection. Namely, the conventional Markov deterioration hazard model cannot adequately consider the period which the steel girder end parts are exposed to water leakage from the bridge expansion joint. Therefore, the conventional Markov deterioration hazard model has a possibility that the effect of water leakage from the bridge expansion joint on the corrosion development of the steel girder end part may not be sufficiently evaluated. From the above, the model proposed in this study is more valuable than the conventional Markov deterioration hazard model from the viewpoint of expressing the corrosion development process of the steel girder end part in consideration of the probablistic occurrence state and occurrence timing of water leakage from the bridge expansion joint (water leakage management mode). Furthermore, when the traffic volume which is recorded as the time series data is adopted as the explanatory variable of the transition probability in the Markov switching model of the water leakage management mode and the regime switching Markov deterioration hazard model is estimated, it becomes possible to express the transition probability of each water leakage management mode of the bridge expansion joint in increase and decrease of the traffic volume. Thus, this model can be very useful for the bridge maintenance and management. On the other hand, there are still some following future works in terms of this study. First, in the empirical analysis of this study, the authors tried to apply the proposed methodology to limited highway bridges. Thus, the findings obtained from the empirical analysis of this study can be used only for the targeted bridges in this study. In the future, it is necessary to sequentially improve the maintenance and management method of the steel girder end part and the bridge expansion joint at the time of water leakage occurrence by accumulating visual inspection data and the case studies of the model proposed in this study. Secondly, using the corrosion development processes of the steel girder end part in each water leakage mode analyzed in this study, lifecycle cost analysis about the reduction of life cycle costs between the periodic replacements of bridge expansion joint (preventive maintenance) and the breakdown maintenance accompanied by large-scaled renewals needs to be conducted. At that time, it is necessary to consider the road users' social loss due to traffic regulations. Thirdly, at present, the deterioration of anti-corrosion function and the corrosion are classified and recorded as separate deterioration phenomena. Therefore, it is necessary to integrate these deteriorations' ratings by visual inspection because the deterioration of anti-corrosion function and the corrosion are thought to be sequential deterioration phenomenon.

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