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Title	STATISTICAL SELECTION OF DETERIORATION FACTORS IN RC SLAB OF URBAN EXPRESSWAY
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Description	The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan.
Relation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan, F-2-3.
Citation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), F-2-3
Issue Date	2013-09-12
Doc URL	https://hdl.handle.net/2115/54381
Type	conference paper
File Information	easec13-F-2-3.pdf

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STATISTICAL SELECTION OF DETERIORATION FACTORS IN RC SLAB OF URBAN EXPRESSWAY

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ABSTRACT

Precedents for statistical selection of deterioration factors in RC slabs of urban expressway have not been accumulated very much. In this study, the authors focus on the deterioration of RC slab in urban expressway and clarify its deterioration process using statistical methods. In this study, the detailed visual inspection data of RC slabs inspected each panel which compose a single RC slab are adopted. The authors employ the Markov deterioration hazard model as a concrete method to select deterioration factors and to estimate the expected lifespan of each panel. Regarding to deterioration factors, 15 kinds of characteristic variables are considered as candidates of the factors, and by comparison of *t*-value and AIC, the factors having the significant interpretability can be selected. In addition, by estimating the Markov deterioration hazard model, Markov transition probability can be estimated. Then, using the Markov transition probability and Monte Carlo simulation, the expected lifespan of each RC slab can be calculated. By using the result of this study, when we determine the number of panels per a RC slab, the number of construction joint panels and the characteristic variables, expected deterioration path of the RC slab can be obtained.

Keywords: RC slab, statistical deterioration prediction, Markov deterioration hazard model.

1. INTRODUCTION

In this study, the authors especially focus on RC slab among various infrastructures with highway. Up to now, regarding to RC slab, many experimentations and analyses have been carried out. However, results of these experimentations and analyses were reflected in design of RC slab and were not reflected in management of RC slab very often due to difference between experiment condition and service condition. In the case of management of RC slabs, for safety and comfort of drivers and local residents, daily inspections are carried out and vast inspection results are accumulated. Regarding to statistical deterioration prediction methods using these inspection data, Markov deterioration hazard model (Tsuda et al. 2006) was developed and they conducted the case study using the inspection data of RC slabs in city of New York. However, case studies applying

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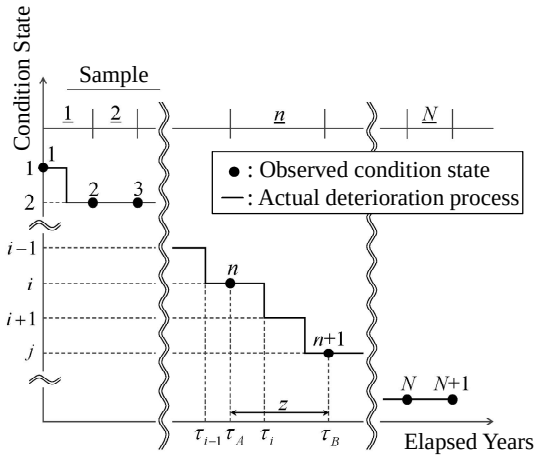

Figure 1: Visual inspection data and its deterioration process.

Markov deterioration hazard model to RC slabs are few in number. Therefore, in this study, the authors apply Markov deterioration hazard model to the inspection data of RC slabs with urban expressway and conduct calculation of expected life spans, selection of deterioration factors and determination of optimal model in practical business.

2. MARKOV DETERIORATION HAZARD MODEL

2.1. Preconditions for modelization

Visual inspection data of RC slabs are generally evaluated as discrete data, such as that shown in Figure 1. In the figure, the vertical axis is the condition state of the luminaire, with condition state 1 as the sound condition. As deterioration proceeds, the number increases. State I is the serviceability limit state. In the figure, the condition state changes from i-1 to i at time $\tau_{i\text{-}1}$, and from i to i+1 at time τ_i. This transition of states can be observed completely when using monitoring system such as sensors. On the other hand, times τ_A and τ_B ($=\tau_A+z$) are when visual inspections were carried out. As we can clearly see, the information regarding the deterioration process that can be obtained from visual inspections is that the condition state is i at time τ_A, the first inspection, and j at time τ_B, the second inspection.

Now, consider the transition of states between two time points. The state at time τ_A is $h(\tau_A)$, and the state at time τ_B is $h(\tau_B)$. If $h(\tau_A)=i$ and $h(\tau_B)=j$, the Markov transition probability is Prob[$h(\tau_B)=j|h(\tau_A)=i$]. The condition for this Markov transition probability is that the state is i at time τ_A, and the conditional transition probability that the state will be j at time τ_B can be defined as:

$$\text{Prob}[h(\tau_B) = j \mid h(\tau_A) = i] = \pi_{ij} \tag{1}$$

Naturally, if the inspection intervals differ, the transition probability will also differ. The Markov chain model satisfies the Markov property that, regardless of the time at which the state transitions from i-1 to i , the probability of the transition taking place between time τ_A and time τ_B depends only on the condition state at time τ_A.

2.2. Markov deterioration hazard model

The deterioration process of RC slab can be expressed superposing hazard models. When it is assumed that hazard rate does not depend upon time point y_i and has constant value θ_i (>0) on each state, the Markov property of deterioration process of RC slab can be expressed, using exponential hazard rate, as:

$$\lambda_i(y_i) = \theta_i \tag{2}$$

At this time, the probability $F_i(y_i)$ that the life expectancy of state i is more than y_i can be expressed, using hazard rate $\lambda_i(y_i)=\theta_i$, as (Lancaster 1990):

$$F_i(y_i) = \exp(-\theta_i y_i) \tag{3}$$

Therefore, the probability $\pi_{ii}(z)$ that the state will be i at inspection τ_A, as well as at the following inspection τ_B ($=\tau_A+z$) can be expressed as:

$$\pi_{ii}(z) = \exp(-\theta_i z) \tag{4}$$

Moreover, the probability $\pi_{ij}(z)$ that the state will be i at inspection τ_A and j at inspection τ_B ($=\tau_A+z$) can be expressed as (Tsuda et al. 2006):

$$\pi_{ij}(z) = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k z) \tag{5}$$

And, due to the Markov probability's condition, $\pi_{iI}(z)$ can be:

$$\pi_{iI}(z) = 1 - \sum_{j=i}^{I-1} \pi_{ij}(z) \tag{6}$$

By using the Markov deterioration hazard model, the expected remaining duration RMD_i of deterioration from when the state first reaches i to when it reaches the next i+1 can be expressed, considering Equation (2), as:

$$RMD_i = \int_0^\infty \tilde{F}_i(y_i)\,dy_i = \int_0^\infty \exp(-\theta_i y_i)\,dy_i = \frac{1}{\lambda_i} \tag{7}$$

2.3. Estimation of Markov deterioration hazard model

When the K number of inspection samples can be obtained from RC slab, the inspection sample k (k=1,…,K) includes two inspection times τ_A and τ_B ($=\tau_A+z$), the observed states $h(\tau_A)$ and $h(\tau_B)$. Now, based on the observed inspection information, the dummy variable $\delta_{ij}^{\ k}$ (i=1,…,I-1; j=1,…,I; k=1,…,K) is defined as:

$$\delta_{ij}^{k} = \begin{cases} 1 & when \;\; h(\tau_A)=i, h(\tau_B)=j \\ 0 & otherwise \end{cases} \tag{8}$$

Table 1: Notation of condition states

State	Rating	Physical meaning
D	1	There is no damage and deterioration or they are extremely slight and it is not necessary to record them.
C	2	There is damage and deterioration and it is necessary to record them.
B	3	There is damage and deterioration and it is necessary to repair them.
A	4	There is conspicuous damage and deterioration. If they are left as it is, they proceed to critical damage and deterioration and prompt consequential damage. It is necessary to immediately deal with them.
S	5	There is possibility that they hinder traffic and cause injury of third party. It is necessary to urgently deal with deterioration and damage.

Moreover, the characteristic vector which influences deterioration rate of RC slab is expressed as $\boldsymbol{x}^k=(x_1{}^k,\ldots,x_M{}^k)$. However, $x_m{}^k$ (m=1,…,M) is the mth observed characteristic value of inspection sample k. Now, the information of sample k can be arranged as $\boldsymbol{\Xi}^k=(\delta_{ij}{}^k, z^k, \boldsymbol{x}^k)$. Also, the hazard rate θ_i depending upon the characteristic vector of RC slab can be expressed as:

$$\theta_i^k = \boldsymbol{x}^k \boldsymbol{\beta}_i' \tag{9}$$

However, $\boldsymbol{\beta}_i$ ($\boldsymbol{\beta}_i=\beta_{i,1},\ldots,\beta_{i,M}$) is row vector of unknown parameter $\beta_{i,m}$(m=1,…,M), and the symbol " ' " signifies transposition. At this time, if the number K of deterioration phenomenon are multiple independent, the log likelihood function ln[$L(\boldsymbol{\beta})$], which expresses the joint occurrence probability of all inspection samples, can be defined as:

$$\ln\left[L(\boldsymbol{\beta})\right]=\sum_{i=1}^{I-1}\sum_{j=i}^{I}\sum_{k=1}^{K}\delta_{ij}^k \ln\left[\pi_{ij}\left(z^k, \boldsymbol{x}^k \mid \boldsymbol{\beta}\right)\right] \tag{10}$$

By using the maximum likelihood estimation, the unknown parameters which maximize the log likelihood function ln[$L(\boldsymbol{\beta})$] can be estimated.

3. EMPIRICAL STUDY

3.1. Outline of visual inspection data

In this study, the authors carry out selection of deterioration factors and statistical deterioration prediction using the inspection data of RC slabs in urban expressway. The characteristic of the inspection data in this empirical study is that the observed condition states are recorded in not each RC slab but each panel which configures RC slab.

Table 1 shows the evaluation criteria for the 5 condition states: D, C, B, A and S, in the visual inspection of RC slabs. The best condition state is D, which moves to C, B, then A as deterioration proceeds. Especially, state S needs urgent measures but there is no samples having state S in this study. Therefore, the ratings for this paper are classified as shown Table 1. : D as rating 1, C as rating 2, B as rating 3 and A as rating 4. When the ratings are classified in four steps, the hazard rate of rating 1, rating 2 and rating 3 (excluding rating 4) can be defined with the Markov deterioration hazard model.

Table 2: Data specifications

Start of service	1975-2007					
Inspection years	2004-2010					
No. of inspection data	71,455					
No. of construction data	40,387					
No. of repair data	Total: 849, simultaneous repairs: 308 and individual repairs: 541					
No. of panels	39,429					
No. of samples	55,802					
Average inspection intervals	13.11 years					
Sample breakdown			Posterior state			
			1(D)	2(C)	3(B)	4(A)
	Prior state	1(D)	41,157	11,106	932	280
		2(C)	-	1,650	304	17
		3(B)	-	-	330	16
		4(A)	-	-	-	10

Table 3: Candidates of characteristic variable *x*

No.	Items	x	Dummy variable	
1	Minimum slab sickness (mm)	x_1^{1}		
2	Length of span (m)	x_1^{2}		
3	Length of bridge (m)	x_1^{3}		
4	Cumulative usage count of antifreeze	x_1^{4}		
5	Annual average usage count of antifreeze	x_1^{5}		
6	Cumulative heavy traffic	x_1^{6}		
7	Annual average of heavy traffic	x_1^{7}		
8	Material	x_1^{8}	1	Ordinary RC
			0	Lightweight RC
9	Structural type	x_1^{9}	1	Monolithic structure
			0	Isolation structure
10	Under girder bridge condition	x_1^{10}	1	River
			0	Except river
11	Division of up or down line	x_1^{11}	1	Up and down line
			0	Except up and down line
		x_2^{11}	1	Ramp
			0	Except ramp
12	Joint of concrete	x_1^{12}	1	Construction joint
			0	Ordinary part
13	Division of start of service	x_1^{13}	1	Before 1984
			0	On and after 1984
		x_2^{13}	1	Before 1993
			0	On and after 1993
14	Division of cumulative heavy traffic	x_1^{14}	1	45 million or more
			0	Less than 45 million
		x_2^{14}	1	30 million or more and less than 45 million
			0	Less than 30 million or 45 million or more
		x_3^{14}	1	15 million or more and less than 30 million
			0	Less than 15 million or 30 million or more
15	Inspection method	x_1^{15}	1	Visual inspection at close
			0	Visual inspection from a distance

The data specifications used in the empirical study are shown in Table 2. The RC slabs used in this study started service between 1975 and 2007. The visual inspections of each panel were carried out between 2004 and 2010 and the number of their data is 71,455. Also, the construction data of

Table 4: Top ten *t*-values

Characteristic variable		State	*t*-value	Estimated value of β
$x_{1,1}^{2}$	2) length of span	1	43.366	2.479
$x_{1,1}^{3}$	3) length of bridge	1	43.314	1.734
$x_{1,1}^{12}$	12) joint of concrete	1	38.965	1.019
$x_{1,1}^{4}$	4) cumulative usage count of antifreeze	1	-34.412	-1.065
$x_{2,1}^{12}$	12) joint of concrete	2	33.823	1.872
$x_{1,1}^{13}$	13) division of start of service	1	-32.074	-0.848
$x_{1,1}^{9}$	9) structural type	1	27.053	0.490
$x_{1,1}^{5}$	5) annual average usage count of antifreeze	2	24.256	5.097
$x_{1,2}^{14}$	14) division of cumulative heavy traffic	1	-22.366	-0.507
$x_{1,1}^{1}$	1) minimum slab sickness	1	22.320	2.935

Table 5: AIC

No.	Characteristic variables	AIC
12	Joint of concrete	74,180
3	Length of bridge	74,725
2	Length of span	74,831
13	Division of start of service	75,378
4	Cumulative usage count of antifreeze	75,509
9	Structural type	75,742
1	Minimum slab sickness	75,973
14	Division of cumulative heavy traffic	76,119
8	Material	76,167
11	Division of up or down line	76,286
5	Annual average usage count of antifreeze	76,293
15	Inspection method	76,322
6	Cumulative heavy traffic	76,349
7	Annual average of heavy traffic	76,428
10	Under girder bridge condition	76,446
	Only constant term	76,526

40,387 panels can be obtained. Regarding to the construction data, they are added to the estimation samples as the rating is 1 when the panel were constructed. Moreover, 849 repair data can be obtained: the number of simultaneous repairs is 308 and the number of individual repairs is 541. In this study, the authors assumed that the ratings of RC slabs just after repair are 1 and, regarding the individual repairs, the ratings of RC slabs just before repair are 3: 849+541=1,390 data can be added to the estimation samples. When the estimation samples are made using these observed data, 55,802 samples on 39,429 panels can be obtained. As mentioned in Section 2.3, each inspectionsample includes information on the two visual inspection results (i, j), inspection interval (z), and characteristic variable (x). The average inspection interval is 13.11 years and Table 2 includes the breakdown of samples for each pair of states.

3.2. Establishment of characteristic variables

In Markov deterioration hazard model, the influence of each factor upon deterioration process of RC slab can be evaluated quantitatively by embedding the factors as the characteristic variables. In this study, the number of candidates of characteristic variables is 15 items (19 kinds) as shown in

Table 6: Estimation result [β^{12}: joint of concrete]

Rating i	Constant term $\beta_{i,0}^{12}$	Joint of concrete $\beta_{i,1}^{12}$	Expected life span [years]	
			Construction joint	Ordinary part
1	-4.034 (-412.155)	1.019 (38.965)	20.399	56.486
2	-4.579 (-129.529)	1.872 (33.823)	14.983	97.397
3	-3.177 (-52.439)	- (-)	23.972	23.972

Table 3. Regarding to Table 3, 7 items painted red are quantitative variables which can be observed as continuous value and one item has one kind of characteristic variable. In quantitative variables, for subsequent analysis, all quantitative variables are normalized so that the maximum of each variable becomes 1. On the other hand, 8 items (12 kinds) of characteristic variables which painted blue are discrete variables. Regarding to discrete variables, the dummy variables are set as Table 3 shows.

3.3. Estimation of 15 kinds of hazard models

The 15 kinds of Markov deterioration hazard models can be defined to each characteristic variable shown in Table 3. The hazard rate of each model can be expressed, using Equation 10, as:

$$\theta_i^j = \beta_{i,0}^j + \sum_{m=1}^{M} \beta_{i,m}^j x_{i,m}^j \ , \ M = \begin{cases} 1 & j \neq 11,13,14 \\ 2 & j = 11,13 \\ 3 & j = 14 \end{cases} \tag{11}$$

And, 57 (=3ratings*19 parameters) kinds of unknown parameters were estimated, and the parameters having *t*-value higher than 1.96 (significance level is 5%) in absolute value can be applied. The higher the absolute value of *t*-value is, the higher the parameter has statistical interpretability. In Table 4, the variables having top ten value of absolute value of *t*-value are shown. After the determination of characteristic variables using *t*-value, Akaike information criterion (AIC) can be implemented in order to compare the optimality of each model. AIC can be defined as:

$$\mathrm{AIC} = -2\ln(L) + 2k \tag{12}$$

AIC is defined using the likelihood L and the number of unknown parameters k. The smaller AIC is, the more the model is optimal from the perspectives of number of unknown parameters and goodness of fit between the observed data and the model. Table 5 shows AIC of all 15 kinds of Markov deterioration hazard models. The characteristic variable “12) joint of concrete” has the minimum AIC and the model including it is the optimal model in the models considering only one item. Moreover, both of the parameters of the characteristic variable “12) joint of concrete” in rating 1 and rating 2 have top ten *t*-values shown in Table 4 and they have high interpretability. Now, Table 6 shows the estimated parameters of the characteristic variable “12) joint of concrete” as one example. Because both of the parameters $\beta_{1,1}^{12}$ and $\beta_{2,1}^{12}$ are positive values, the panel in

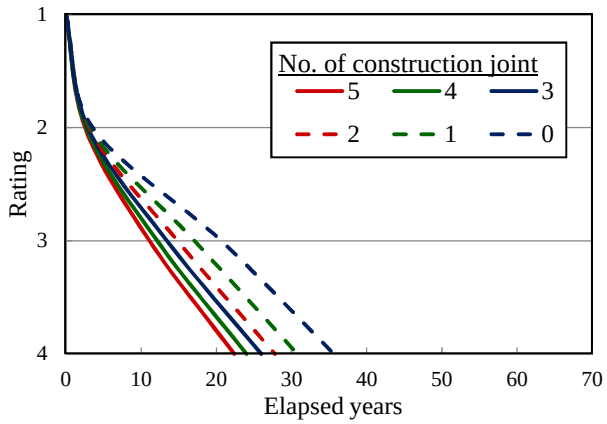

Figure 2: Change of expected deterioration paths due to number of construction joints.

construction joint deteriorate fast. However, the parameter $\beta_{3,1}^{12}$ of rating 3 has t-value less than 1.96 in absolute value and is rejected.

3.4. Evaluation unit and expected deterioration path

In order to visualize the estimation result, the expected life span is calculated using the estimated parameters in Section 3.3. In this study, the estimation unit is each panel of RC slab. Figure 6 also shows the estimated life spans. Moreover, by using the estimated parameters, the Markov transition matrix can be calculated. By Monte Carlo simulation using the Markov transition matrix, the random numbers from the distribution of the expected life span can be generated. In this study, the life span of each RC slab (each span) can be calculated using the random numbers. When one RC slab includes the plural panels and the state of the panel most proceeding deterioration is the state of the RC slab, the expected deterioration path of each RC slab can be expressed. Figure 2 shows the changes of the deterioration paths due to the difference of the number of construction joint when one RC slab includes 17 panels.

4. CONCLUSIONS

In this study, by using Markov deterioration hazard model, the authors carried out the selection of deterioration factor and the estimation of the expected life span of urban expressway. Especially, focusing whether construction joint or not, the quantitative evaluation of deterioration processes which was difficult hitherto. Regarding to the candidates of characteristic variables which is not judged statistical significance, by accumulating the inspection data hereafter, there is possibility that they will be judged significance, hence it is desirable that continuous acquisition of inspection data will be carried out.

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