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CHLORIDE-INDUCED DAMAGE EVALUATION OF CONCRETE BRIDGES

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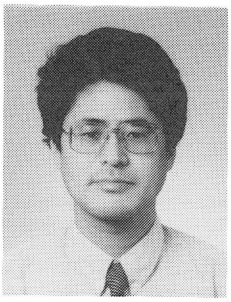
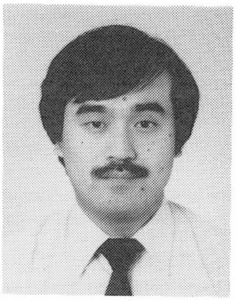

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SYNOPSIS

Factor analysis for chloride-induced damages is conducted on concrete bridges along or near coast line. Ten factors related to a structure and environment are considered. Among structural factors, pretensioning prestressed concrete, slab and small bridges show relatively minor damages. As for environmental factors, concrete bridges located within 100 meter from coast line are prone to suffer damages. Based on the results of factor analysis, a damage prediction system is proposed. The system will enable one to estimate a degree of damage that a bridge will suffer in the future from its structural and environmental data. To establish a discriminant criteria, a concept of loss function is introduced in the system so as to make an assessment on safe side.

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CHLORIDE-INDUCED DAMAGE EVALUATION OF CONCRETE BRIDGES

By Hiroshi SEKI, Kunihito MATSUI**, Manabu MATSUSHIMA*** and Yuichi KANEKO****

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Based on the results of factor analysis, a damage prediction system is proposed. The system will enable one to estimate a degree of damage that a bridge will suffer in the future from its structural and environmental data. To establish a discriminant criteria, a concept of loss function is introduced in the system so as to make an assessment on safe side.

Keywords : *concrete bridge, chloride-induced damage, factor analysis, damage prediction*

1. INTRODUCTION

Deterioration of concrete structures has been drawing a greater social attention. The deterioration is mainly caused by corrosion of reinforcements and PC wires due to the action of chloride-ion. Various investigations and researches on the deterioration have been conducted such as :

1) Sources of structural deterioration
2) Deterioration mechanism
3) Inspection methodologies and evaluation techniques
4) Adequate repairing methodologies.

Corrosion of steel material in concrete is commonly caused by electrochemical reaction and main cause attributes to the penetration of chloride-ion. Some work has been conducted on characteristics of migrating-in-air chloride and its measuring procedure[1], chloride-ion concentration in actual structures[2] and the relationship of the concentration and steel corrosion in actual structures[3]. It is very important to estimate the amount of deterioration that a structure will suffer during its life time from the view points of design and construction.

Bažant[4),5)] proposed a prediction method of structural life span based on a physical model of steel corrosion in concrete materials. Browne[6] and Browne et al.[7] presented an evaluation of structural integrity and prediction of its life span.

Aside from the above mentioned conceptual approaches, other methods based on such as an expert

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system[8] and damage analysis due to statistic theory have been examined. Furuta et al.[9] used a production system to evaluate a structural integrity. Nishimura et al.[10] attempted a durability diagnosis of actual bridges based on hierarchy model. These researches aimed to carry out judgements on structural integrity and durability by computers, which have been primarily made by specialists.

Data on actual structures are often vague and qualitative. Quantification theory[11] is conveniently utilized to make a quantitative analysis on mixed data with some vagueness. The theory is based on descriminant analysis of sample space with both quantitative and qualitative data and is applied to risk analysis on potential slope failure[12] and seismic damage[13].

As is aforementioned, chloride-induced structural deterioration is greatly affected by the amount of migrating-in-air chloride. Although careful design and construction practices along with adequate inspection and maintenance could prolong the lives of many structures, they are not free from deterioration. Consequently, it is extremely important to establish a simple damage assessment and prediction system by which even less experienced engineers can judge properly on structural integrity and durability.

This paper seeks to develop a simple and reliable procedure of assessing the damage and of predicting the ongoing deterioration of concrete bridges due to the migrating-in-air chloride. Discriminant analysis for the categorical data (Quantification theory II) is conducted on the data of physical parameters, environmental conditions and damage levels obtained from actual bridges, in order to make investigations on the factors that contributes to structural damages. Then based on the obtained results, also developed is a procedure to predict a damage level which a structure, of a given type in a given environment, will experience in the future. Assessment of structural integrity and prediction of deterioration provide useful information to designing of a structure, especially when a durability design or repairing schedule in the duration of its service life is required.

2. STATE OF DAMAGE AND ITS CONTRIBUTING FACTORS

Ministry of construction has inspected 920 concrete bridges along the coast of Japan on their states of damages[14]. The report states that severe damages are observed in a northwestern part of Japan (Hokkaido

Table 1 Items and Categories.

Items	Categories				
1. Bridge Type	RC	PC (pretensioning)	PC (post tensioning)		
2. Shape of Cross Section	T-section	Slab			
3. Bridge Length	15 ~ 50m	51 ~ 100m	101 ~ 340m		
4. Number of Spans	1 ~ 2	3 ~ 5	6 ~ 17		
5. Span Length	7.0 ~ 10.0m	10.1 ~ 15.0m	15.1 ~ 20.0m	20.1 ~ 25.0m	25.1 ~ 38.8m
6. Number of Main Girders	1	2 ~ 4	5 ~ 14		
7. Environments	Fields	Factory Area	Residential Area	Farmland	Mountainous Area
8. Under Bridge	Sea	River	The Others		
9. Distance from Sea	Above Sea ~ 0m	1 ~ 50m	51 ~ 100m	101 ~ 200m	201 ~ 500m
10. Splash	Splashed	Unsplashed			
11. Girder Type	Simple Girder	Continuous Girder	The Others		
12. Bridge Width	1.5 ~ 8.0m	8.1 ~ 10.0m	10.1 ~ 17.2m		
13. Design Load	T - 20	The Others			
14. Elevation from Sea Surface	2 ~ 3m	4 ~ 6m	7 ~ 33m		
15. Clearance below Girders	1 ~ 3m	4 ~ 6m	7 ~ 21m		

and Japan Sea side of Tohoku region) and in Okinawa.

This paper focuses on bridges in the northwestern area of Japan where geographical conditions are similar and structures show conspicuous damages. Fifteen parameters (called items hereafter) which seem to influence chloride-induced damages are taken into consideration. They are "bridge type" (X_1), "shape of cross section" (X_2), "bridge length" (X_3), "number of spans" (X_4), "span length" (X_5), "number of main girders" (X_6), "environments" (X_7), "under bridge" (X_8), "distance from sea" (X_9), "splash" (X_{10}), "girder type" (X_{11}), "bridge width" (X_{12}), "design load" (X_{13}), "elevation from sea surface" (X_{14}) and "clearance below girders" (X_{15}). Items from X_1 to X_6 and from X_{11} to X_{13} are associated with structure and the others are related to the environment that the structure is located. The items are composed of qualitative variables (X_1, X_2, X_7, X_8, X_{10}, X_{11} and X_{13}) and quantitative variables (X_3, X_4, X_5, X_6, X_9, X_{12}, X_{14} and X_{15}). Each item is divided into from two to five small groupes (a groupe is called category). A set of data on a bridge is assigned to a category of each item. Items and the corresponding categories are listed in Table 1. A degree of damage is indicated by five levels from 0 to 4, as shown in Table 2, in which the larger, the severer. The judgement is made by visual observations.

Table 2 Damage levels of concrete bridges.

Damage levels	Description
0	No damage
1	Sympton of damage appearance of rust stains due to corrosion of spacer etc.
2	Slight damage appearance of local cracks and increasing amount of rust stains
3	Medium damage cracks and delaminations over all main girders
4	Severe damage wider cracks and more serious delaminations than those of damage level 3

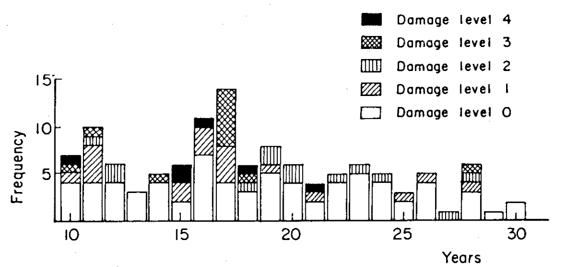

Fig. 1 Distribution of damage levels versus years from completion.

The data used in this analysis are obtained from 120 concrete bridges in the region mentioned above, and satisfy the following conditions :

1) a bridge located within 500 meters from sea
2) a bridge of ten to thirty years old
3) a bridge which has not been repaired in the past.

The conditions are adopted due to the reasons as follows :

1) Bridges away from sea are free from chloride-induced damages.
2) The period is selected to eliminate effects due to the changes of design philosophy and construction materials characteristics.
3) Although an evaluation of structural repairs is extremely important, it is impossible to understand their effects properly from small number of samples with repairing history. Furthermore since the aim is to relate items with damage levels, the cases with some repairing work are removed from the original data.

Since the amount of migrating-in-air chloride and chloride penetrating into cover concrete will increase with time, the damage induced by chloride will be expected to increase. Thus structural deterioration proceeds gradually, as a time passes. A deterioration rate, however, is considered to differ depending on structural factors and environmental conditions. Fig. 1 illustrates a distribution of damage levels with ages of structures. Since the figure shows no eminent relationship between damage levels and structural ages, other factors seem to given contributions to the damage than ages. This paper deals with an estimation for deterioration of concrete bridges aged between 10 and 30 years from the observed data.

3. EVALUATION OF FACTORS CONTRIBUTING TO CHLORIDE-INDUCED DAMAGES

The flow of factor analysis on structural damage and damage prediction system based on the analysis is presented in Fig. 2. This chapter states steps 4 and 5 in Fig. 2 and the quantitative relationship between each item and damage level is studied. The prediction system (steps 6-8 in Fig. 2) is explained in the following chapter.

(1) Investigations on major factors

If categorical divisions of an item is not properly made (i. e. if categorical difference does not clarify the distinction of damage levels), the corresponding item will become insignificant. Before applying "Quantification theory Ⅱ", it is examined whether categorical division of each item are significant. Significance of each item is examined by an analysis of variance method[15]. In this paper, based on a variation of the data in a category, it is tested whether categorical divisions in each item are adequately made. In another words, the test is made to find whether variance of the data is caused by a difference of damage levels or simply by error involved in the data. Five percent level of significance is most frequently used, which is described by $F_{0.05}$ in F distribution. If the variance ratio F_0 obtained from sample data is greater than $F_{0.05}$, there exist meaningful difference among categories and that the corresponding item contributes to damage levels in some significance.

Table 3 shows the results of the analysis of variance. Among fifteen items, "girder type", "bridge width", "design load", "elevation from sea surface" and "clearance below girders" are judged insignificant. The symbol * in the column of significance in Table 3 indicates that the item meets the condition for 1 % level of significance. Among the remaining ten items, eight items except "number of spans" and "environments" satisfy the condition mentioned above.

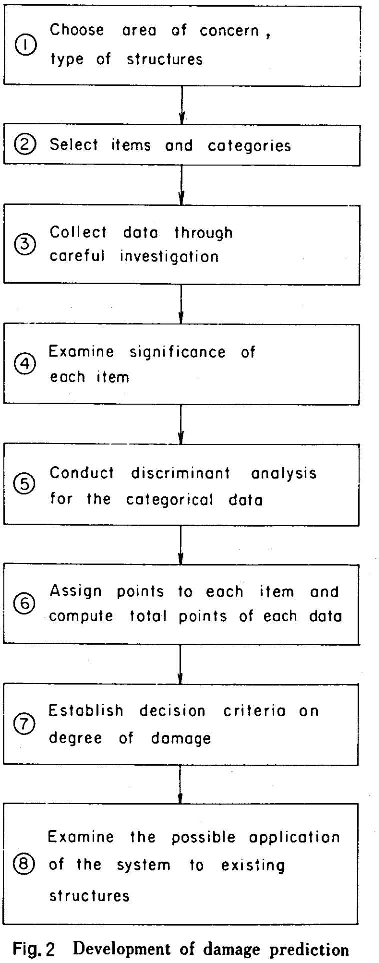

Fig. 2 Development of damage prediction system for concrete bridges.

(2) Discriminant analysis of chloride-induced damage

a) Method of analysis

Quantitative analysis is made to find a contribution of each item to damage levels. "Quantification theory Ⅱ" is used on ten items which are judged significant based on the analysis of variance. When categorical data on each item is known, the theory enables one to judge which damage level the data belong to.

Item X_j ($j=1, 2, \cdots, 10$) has l_j categories expressed by $C(j, k)$ where k runs from 1 to l_j. A weight $x(j, k)$ is assigned to each category $C(j, k)$ such that actual damage level shows a good agreement with the damage level estimated from "Quantification theory Ⅱ", and a magnitude of the weight,

Table 3 Analysis of variance.

Items	Number of Categories	$F_{0.05}$	F_0	significance
1. Bridge Type	3	3.07	9.44	O*
2. Shape of Cross Section	2	3.92	7.83	O*
3. Bridge Length	3	3.07	7.52	O*
4. Number of Spans	3	3.07	3.79	O
5. Span Length	5	2.44	6.01	O*
6. Number of Main Girders	3	3.07	5.07	O*
7. Environments	5	2.44	3.07	O
8. Under Bridge	3	3.07	5.68	O*
9. Distance from Sea	5	2.44	5.11	O*
10. Splash	2	3.92	7.70	O*
11. Girder Type	3	3.07	0.03	×
12. Bridge Width	3	3.07	0.16	×
13. Design Load	2	3.92	2.56	×
14. Elevation from Sea Surface	3	3.07	2.50	×
15. Clearance below Girders	3	3.07	3.04	×

Notes O* significance for 1% significance level
O significance for 5% significance level
× unsignificance

herein, implies a degree of its contribution to damage level. Then a quantity Y is defined by a summation of weights as,

$$Y=\sum_{j=1}^{10}\sum_{k=1}^{l_j}\delta(j,\ k)\,x(j,\ k) \qquad (1)$$

in which

$$\delta(j,\ k)=\begin{cases}1 : \text{when data correspond to } C(j,\ k)\\ 0 : \text{when data do not correspond to } C(j,\ k)\end{cases} \qquad (2)$$

If all items for a bridge are known, Y can be computed from eq. (1), from which a damage level of bridge can be estimated. The difference between max. $x(j,\ k)$ and min. $x(j,\ k)$ is called a range and plays a roll of relative indicator to damage level. The range of each item is tabulated in Table 4.

b) Discussions on items

Table 4 shows the results of discriminant analysis. As to the distribution of $x(j,\ k)$ in the table the one extending to the right implies that a structure with the category is more likely to be damaged, and the one to the left implies the contrary. Contribution of each item to damage level is represented by a magnitude of the corresponding range. Fig. 3 demonstrates the ranges of items in decreasing order. The figure indicates that five items i. e. ; "number of girders", "shape of cross section", "distance from sea", "span length" and "environments", show marked contribution to structural damage.

Examining structure-related items, the following can be stated :

1) For "bridge type", pretensioning prestressed concrete is superior in quality control and the use of higher strength concrete prevent penetration of chloride-ion.
2) For "shape of cross section", slab type structure suffer less damage than T-type girder does. It can be regarded that T-type girder tend to accumulate more chloride at its concave parts of flange-web intersection.
3) "Bridge length", "number of spans", "span length" and "number of girders" are the items all

Table 4 Discriminant analysis for the categorical data.

Items	Categories	$x_{j,k}$	Distribution of $x_{j,k}$	Range
1. Bridge Type	RC	0.2387	-0.5 +0.5	0.6644
	PC(pretensioning)	-0.4055		
	PC(post tensioning)	0.2589		
2. Shape of Cross Section	T-section	0.5203		1.4520
	Slab	-0.9317		
3. Bridge Length	15 ~ 50m	-0.1532		0.7124
	51 ~ 100m	-0.0215		
	101 ~ 340m	0.5592		
4. Number of Spans	1 ~ 2	-0.1630		0.5629
	3 ~ 5	0.0660		
	6 ~ 17	0.3999		
5. Span Length	7.0 ~ 10.0m	-0.6451		1.1947
	10.1 ~ 15.0m	-0.0297		
	15.1 ~ 20.0m	0.3157		
	20.1 ~ 25.0m	0.5496		
	25.1 ~ 38.8m	-0.0872		
6. Number of Main Girders	1	-0.9419		1.6324
	2 ~ 4	0.2214		
	5 ~ 14	0.6905		
7. Environments	Fields	0.7434		1.1868
	Factory Area	-0.0801		
	Residential Area	-0.1260		
	Farmland	-0.1260		
	Mountainous Area	-0.4434		
8. Under Bridge	Sea	0.4400		0.6261
	River	-0.1358		
	The Others	0.4902		
9. Distance from Sea	Above Sea ~ 0m	0.6716		1.3957
	1 ~ 50m	0.4850		
	51 ~ 100m	0.1893		
	101 ~ 200m	-0.7241		
	201 ~ 500m	-0.5992		
10. Splash	Unsplashed	-0.0472		0.0928
	Splashed	0.0456		

related to a structural size. It can be said that the larger structures are, the more vulnerable to damage they are. Slab type bridges are considered herein as one main girder in classification of "number of main girders". The reason that x (6, 1) assumes a negative of large value is likely to be caused by the second category of item no. 2.

The following observations can be made on environmental items :

1) Distance from sea has the widest range among environment-related items. A marked change in the values of x (j, k) takes place between third and fourth categorical divisions. It implies bridges within 100 meters from sea tend to be more damaged due to the effect of chloride-ion.
2) As for item "under bridge", bridges over sea are more affected by chloride-ion than those in other conditions.
3) As compared with items no. 8 and no. 9, it is contrary to our expectation that item no. 10 "splash" takes a narrow range of 0.0928, implying a little effect on the damage. This inconsistency seems to be caused by a doubtful accuracy of the data on "splash", because some of the bridges at 0 meter from sea are judged "unsplashed", which is very unlikely.
4) "Environments" come second in magnitude of ranges. Particularly categorical data x (7, 1) assumes a large value. Since categorical division of the item is not clearly explained, discussions in details will be withheld.

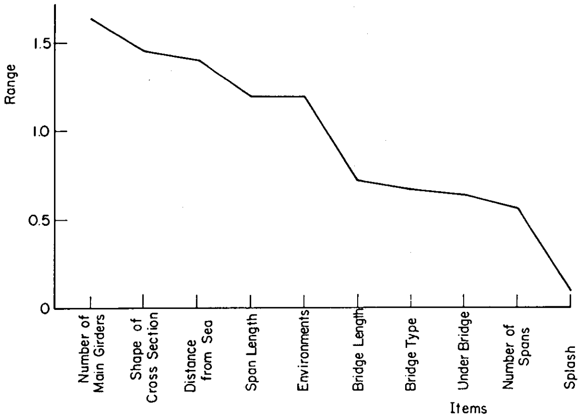

Fig. 3 Range for Items.

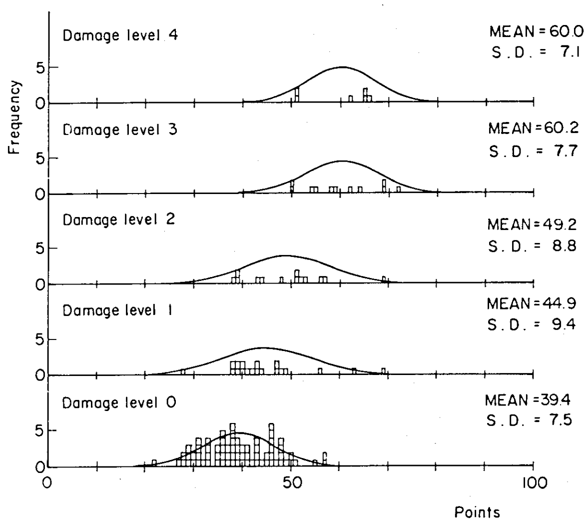

Fig. 4 Point distribution for each damage level.

Table 5 Points for each category.

Items	Categories	Points
1. Bridge Type	RC	7
	PC (pretensioning)	0
	PC (post tensioning)	7
2. Shape of Cross Section	T-section	15
	Slab	0
3. Bridge Length	15 ~ 50m	0
	51 ~ 100m	2
	101 ~ 340m	7
4. Number of Spans	1 ~ 2	0
	3 ~ 5	3
	6 ~ 17	6
5. Span Length	7.0 ~ 10.0m	0
	10.1 ~ 15.0m	7
	15.1 ~ 20.0m	10
	20.1 ~ 25.0m	13
	25.1 ~ 38.8m	6
6. Number of Main Girders	1	0
	2 ~ 4	12
	5 ~ 14	17
7. Environments	Fields	12
	Factory Area	4
	Residential Area	3
	Farmland	3
	Mountainous Area	0
8. Under Bridge	Sea	6
	River	0
	The Others	7
9. Distance from Sea	Above Sea ~ 0m	15
	1 ~ 50m	13
	51 ~ 100m	10
	101 ~ 200m	0
	201 ~ 500m	1
10. Splash	Unsplashed	0
	Splashed	1

4. DAMAGE PREDICTION SYSTEM

(1) Outline of the system

To begin with, we describe a procedure to establish assessment model. As stated in chapter 3, ten items are considered in relation to observed damage level. The difference of max. and min. points within an item is set in proportion to its corresponding range, and points are assigned to categories within an item based on $x\ (j,\ k)$ distribution. Points for each category are indicated in Table 5. They are chosen so that a sum of the largest point among each item yields a hundred. Damage level index Z for chloride-induced damage can be given as

$$Z=\sum_{i=1}^{10} S_i \cdots\cdots (3)$$

in which S_i is points for a category selected from item X_i. Z could vary from 0 to 100 depending on a degree of damage. Using eq. (3), Z is computed for each bridge. Distribution of Z for every damage level is illustrated in Fig. 4. Normal distribution curves are added to the figure to approximate Z distribution curves. The figure shows a trend that the larger the value of Z is, the larger the damage level is. However as can be observed in case of damage levels 3 and 4, a clear distinction of Z distribution is not necessarily made. This reason could be due to lack of data and low quality of data.

Presented next is how to establish classification criteria. As can be seen in Fig. 4, Z distribution does not show complete separation on each damage level. Hence no matter how we set up classification criteria, there are some cases that actual damage levels do not coincide with predicted ones. A concept of loss function[15] is introduced to establish classification criteria.

To facilitate explanation, two damage levels are considered. Their typical probability density is given in Fig. 5. Table 6 shows a loss function, in which a row indicates actual damage level (variable θ is used) and columns, expected damage level ϕ which depends on the value of Z. A loss in the table means as follows : if expected damage level is I and actual damage level is II, a loss is L_2; if vise versa, a loss is L_1; and if expected damage level coincide with actual damage level, a loss is zero. Since damage level II is severer than damage level I, a loss function should be $L_2 > L_1$. In another words, L_2 implies the judgement is wrong and in dangerous side. L_1 means wrong but in safe side. Since we cannot expect perfect coincidence, it should be in safe side, if our estimation turns out wrong. Then an expected loss will be small.

For a value of Z, probability of actual damage level I is given as

$$P_{\mathrm{I}}(Z)=\frac{\int_{Z}^{\infty} P_{\mathrm{I}}(z)dz}{\int_{Z}^{\infty} P_{\mathrm{I}}(z)\,dz+\int_{-\infty}^{Z} P_{\mathrm{II}}(z)\,dz} \qquad (4)$$

and probability of actual damage level II is

$$P_{\mathrm{II}}(Z)=\frac{\int_{-\infty}^{Z} P_{\mathrm{II}}(z)\,dz}{\int_{Z}^{\infty} P_{\mathrm{I}}(z)\,dz+\int_{-\infty}^{Z} P_{\mathrm{II}}(z)\,dz} \qquad (5)$$

where $P_{\mathrm{I}}(z)$ and $P_{\mathrm{II}}(z)$ are probability densities of damage levels I and II respectively. From Table 6, a loss function $l(\theta, \phi)$ becomes

$$\begin{cases} l(\mathrm{I}, \mathrm{II})=L_1 \\ l(\mathrm{II}, \mathrm{I})=L_2 \end{cases} \qquad (6)$$

$E(\phi)$ is an expected loss when a damage level is estimated as ϕ. If a wrong estimation is made, expected losses $E(\phi)$ are,

$$E(\mathrm{I})=P_{\mathrm{II}}(Z)\,L_2 \qquad (7)$$

in case that predicted damage is level I and

$$E(\mathrm{II})=P_{\mathrm{I}}(Z)\,L_1 \qquad (8)$$

in case that predicted damage is level II. The most adequate classification criterion satisfies $E(\mathrm{I})=E(\mathrm{II})$, from which the delimiting value Z_{cr} can be obtained. However it is difficult and not essential to make objective evaluation of losses L_1 and L_2. Since an obvious relationship $L_1 < L_2$ exists, classification delimitting values are determined assuming $2L_1 \simeq L_2$, which are presented in Table 7.

(2) Results and discussions

The data from a report of investigations on concrete bridges are used to estimate damage levels and the

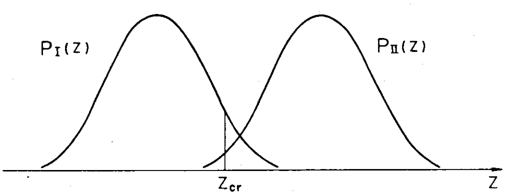

Fig. 5 Determination of delimitor between two adjacent damage levels.

Table 6 Value of loss function.

ϕ \ θ		Actual damage level I	Actual damage level II
Predicted damage level	I	O	L_2
	II	L_1	O

Table 7 Classification of damage levels.

Damage levels	Range of Z
0	0 - 42
1	43 - 47
2	48 - 54
3	55 - 60
4	61 - 100

Table 8 Results from the prediction system.

		Calculated damage level				
		0	1	2	3	4
Actual damage level	0	46	14	8	3	0
	1	9	5	2	1	2
	2	3	2	5	2	1
	3	0	0	3	3	5
	4	0	0	2	0	4

results are presented in Table 8. The row and column of Table 8 are computed and actual damage levels respectively, and frequency of each combination of damage levels is also presented in the table. The table shows correct classification is 52.5 % (62 cases correct out of 120 cases). Among misclassified cases, 19 cases (15.3 %) are estimated in a dangerous side and 38 cases (31.7 %) falls in a safe side. Classification criteria used herein appear to be reflected on the results.

5. CONCLUSIONS

Based on the data obtained by visual inspection, factor analysis is conducted to find effects of structural and environmental factors on chloride-induced damages of concrete bridges. And using the results of the factor analysis, a prediction system of damageability due to chloride penetration is presented. The research focuses on concrete bridges of from 10 to 30 years old and located in northern region of Japan. Findings are stated as follows:

From the results of factor analysis,

1) Pretensioning prestressed concrete girders recieve relatively minor damages.
2) Slabs show less damages than T-girders do.
3) Larger bridges are, in general, more likely to be damaged.
4) Distance from sea is a key factor which affects chloride-induced damages. Within 100 meters from sea coast, bridges are more likely to suffer damage by chloride effect.

As regards the prediction system, the use of Tables 5 and 7 enable one to assess a damage level from data on structural and environmental factors. Approach such as factor analysis and prediction system presented in this paper will be useful for establishing durability design of structures considering their long time deterioration. The results presented still contains some ambiguity partly because the data lack in quantity and quality. But careful examination and accumulation of data will bring us possible to estimate a degree of chloride-induced damage in good accuracy.

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