A METHOD OF PREDICTING SURFACE CONDITION OF CONCRETE STRUCTURES

Prediction of corrosion of reinforcing bars and surface condition of concrete and revision of prediction based on concrete surface conditions

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1. INTRODUCTION

The JSCE Standard Specifications for Concrete Structures "Maintenance" states that systematic maintenance based on deterioration prediction is important to the appropriate maintenance of concrete structures and that accuracy of deterioration predictions should be enhanced by the effective use of visual inspections and detailed survey results. The penetration of chloride ions and the progress of carbonation into the concrete are indexes used in predicting deterioration. These are used indirectly to evaluate corrosion of the concrete reinforcement bars. Additionally, the Standard Specifications for Concrete Structures "Materials and Construction" defines the limit state of reinforcement bars subject to corrosion**.** This means the state in which corrosion occurs and cannot be used in predictions that define the limit state as the state in which cracking occurs. Accordingly, it is necessary to develop a method of predicting not only reinforcement bar corrosion factors but also directly the development of reinforcement bar corrosion. Corrosion development can be expressed as the change over time in remaining cross-sectional area of a reinforcement bar calculated from the cross-sectional area lost by corrosion. Alternatively, this can be considered as the progress of reinforcement bar corrosion through various degrees. Rationally, the remaining cross-sectional area of reinforcement bars needs to be predicted accurately so as to determine the load-bearing capacity of the structure. However, no method of estimating remaining cross-sectional area has yet been established and, even if one were established, it would be impractical to predict the development of corrosion in actual structures because the data collected to make the prediction would contain many uncertainties. For example, suitable methods would be needed for evaluating environmental conditions to be input into the prediction, variations in mixing conditions and the effects of construction conditions. In this paper, with regard to the corrosion of reinforcement bars, changes over time in degree of corrosion are investigated.1)

In inspecting actual structures, the basic process is to observe and record the surface conditions of the concrete making up the structure. Inspection results are used to evaluate deterioration, judge the need for countermeasures and calculate quantities. Further, the degree of reinforcement bar corrosion is thought to correlate with changes in the concrete surface: floating and peeling are observed on the concrete surface when corrosion is serious while no change in the surface is observed if the bars are un-corroded. Accordingly, it should be possible to predict changes in the surface condition of concrete from the degree of corrosion and vice versa by formulating the correlation. It is important to revise the predicted

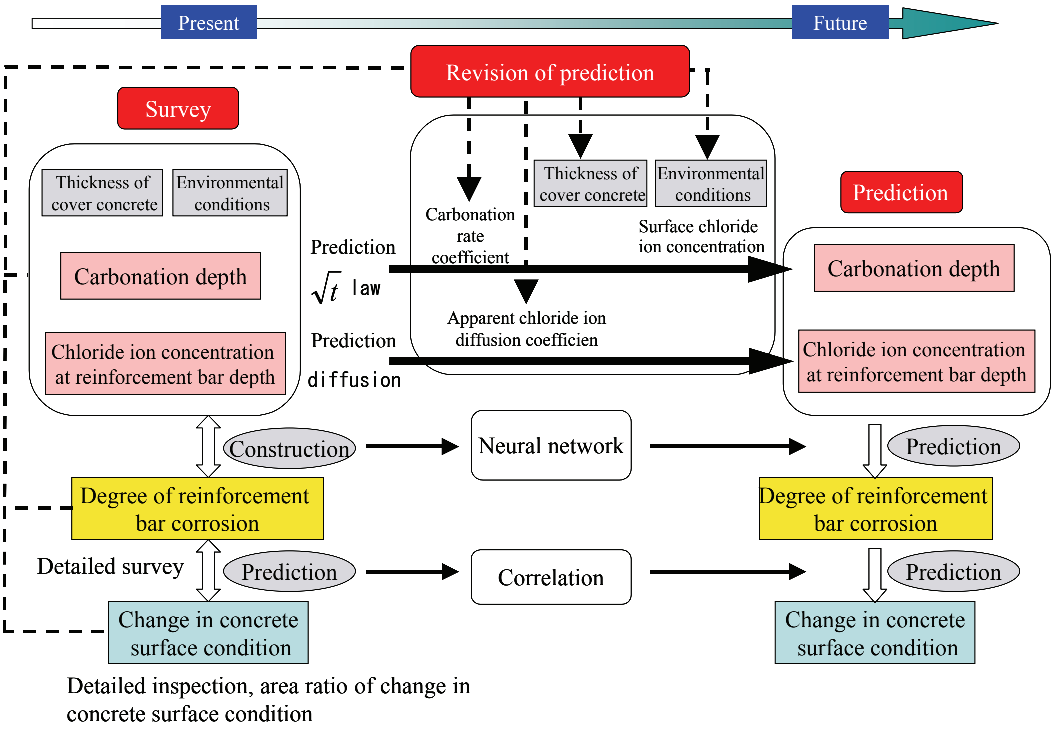

Figure 1 Concept of prediction and revision of concrete structure durability

deterioration through inspection and survey data, but similarly no method of using changes in surface condition to revise predictions has been established, although a method of predicting deterioration using a chloride ion diffusion coefficient calculated from detailed survey results is available.

Against this background, this paper outlines the results of a study based on a probabilistic and stochastic methodology for the evaluation of inspection and detailed survey results, with the objectives of quantifying the correlation between degree of reinforcement bar corrosion and changes in the concrete surface, predicting the degree of corrosion and changes in concrete surface from visual inspections and detailed survey results (such as the concentration of chloride ions at reinforcement bar depth) and establishing a method of revising the prediction based on the condition of the concrete surface. The key feature of the method is that prediction results consist of a probability distribution of degree of reinforcement bar corrosion and area ratio of changes in the concrete surface. These are general inspection items that can be used as indexes for calculating locations where countermeasures are necessary and the cost of taking the measures.

2. BASIC PREDICTIVE CONCEPT

2.1 Prediction of degree of corrosion and changes in surface condition

Figure 1 shows the concept behind making effective use of inspection and survey results to predict deterioration. The Standard Specifications give a method of predicting the corrosion of reinforcement bars due to the progress of carbonation and chloride ions based on estimating the progress of carbonation, the diffusion of chloride ions and the time at which corrosion begins using the carbonation depth (remaining depth) or the chloride ion concentration at the depth of the reinforcement bars (thickness of cover concrete).$^{2)}$ In the inspection of structures, the parameters needed for this prediction, such as carbonation rate coefficient, chloride ion diffusion coefficient and surface chloride ion concentration required to calculate the progress of carbonation and the diffusion of chloride ions, cannot always be obtained by carrying out a detailed survey. Accordingly, the practical approach is to record the degree of corrosion and the location and extent of changes in the concrete surface, including floating, peeling and cracking.

The corrosion rate of reinforcement bars in a concrete structure is affected by the supply of oxygen and chloride ions as well as the pH, all of which vary with environmental conditions and the quality of the concrete. According to previous research3), the degree of reinforcement bar corrosion correlates with cover concrete thickness, carbonation depth (that acts as an index for the quantity of oxygen supplied to the reinforcement bars), and chloride ion concentration at the depth of the reinforcement bars. The authors formulate the correlation using a neural network model using detailed survey data from bridges. In addition, the authors formulate the correlation between degree of corrosion and visual inspection data close to locations where detailed surveys were carried out.

Accordingly, the future degree of corrosion and changes in the concrete surface can be predicted from the predicted value of carbonation depth, the predicted value of chloride ion concentration at the depth of the reinforcement bars, the thickness of the cover concrete, and the environmental conditions around the structure.

2.2 Revision of prediction

To make use of predicted future degree of corrosion and changes in concrete surface condition in structure maintenance, it is necessary to revise the predicted results based on inspection and survey results and provide future predictions. In general, carbonation depth and chloride ion concentration at the depth of the reinforcement bars are predicted using the carbonation rate coefficient and apparent chloride ion diffusion coefficient, which are calculated from the distributions of carbonation depths and chloride ion concentrations.1)

It is also possible to revise the prediction using the area ratio of the concrete where the surface condition has changed, without actually measuring the carbonation depth and chloride ion concentration distributions. This is done using the following steps: the correlation between the area ratio of change in surface condition, as obtained from an inspection, and the probability distribution of corrosion degree is quantified in advance; the area ratio of actual changes in surface condition, as obtained in an inspection, is converted to give the probability distribution of corrosion degree; and the carbonation rate coefficient and chloride ion diffusion coefficient are estimated to match the probability distribution.

3. CORRELATION BETWEEN CORROSION DEGREE AND CHANGES IN CONCRETE SURFACE CONDITION

3.1 Concept of correlation model

To determine the correlation between changes in concrete surface condition and the degrees of corrosion defined in Table 1, actual survey results of changes and corrosion degree are necessary, but in this study they are assumed. The authors studied a stochastic method of converting changes in concrete surface condition into a corrosion degree and vice versa. The correlation between corrosion degree and surface change can be expressed using the concept of a two-dimensional probability variable and a probability distribution. Let the value x of probability variable X be the degree of reinforcement bar corrosion and the value y of probability variable Y be the concrete surface condition. The corrosion of a reinforcement bar is classified into four degrees (I, II, III, and IV) and the concrete surface condition is classified into two categories (unchanged and changed).

Table 1 Degrees of corrosion

Degree of reinforcement bar corrosion	Condition of reinforcement bars
I	Mill scale remains on the surface of reinforcement bars; rust forms but is thin and the bar is solid overall; rust is not deposited on concrete surfaces.
II	There is partly floating rust but it is spotty and covers a small area.
III	Floating rust is observed over the entire circumstance or length of the reinforcement bars, although there is no observable loss of cross-sectional area.
IV	Loss of cross-sectional area of reinforcement bars is observed.

The marginal probability function that expresses the distribution of degrees of corrosion is given by Equation (1).

$$p_x(x) = \sum_{y_j} p_{X,Y}(x, y_j) \qquad (1)$$

where y_i = concrete surface condition (unchanged or changed)

The marginal probability function that expresses the distribution of surface changes is given by Equation (2).

$$p_Y(y) = \sum_{x_i} p_{X,Y}(x_i, y) \qquad (2)$$

where x_i = degree of reinforcement bar corrosion (I, II, III and IV)

These are shown in Figure 2.

Next, in a case where the probability of $Y = y$ depends on the value of X (that is, the probability of $Y = y$ is subordinate to other probability events), we have Equation (3) in the form of a conditional probability. In a case where the probability of $X = x$ depends on the value of Y, we have Equation (4).

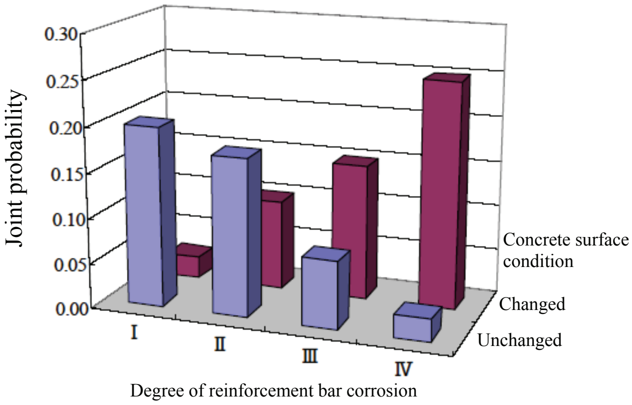

Figure 2 Joint distribution of probability on condition of concrete surface and corrosion

$$P_{Y|X}(y|x) \equiv P(Y = y|X = x = \frac{p_{x,y}(x, y)}{p_x(x)} \qquad (3)$$

$$P_{X|Y}(x|y) \equiv P(X = x|Y = y = \frac{p_{x,y}(x, y)}{p_Y(y)} \qquad (4)$$

3.2 Conversion from corrosion degree to concrete surface condition

Table 2 lists the absolute frequency of concrete surface condition arranged by the degree of reinforcement bar corrosion, as listed in Table 1. In Table 2, peeling, floating and reinforcement bar exposure fall into the category "changed" while concrete in sound condition or cracked is defined as "unchanged". The reason for categorizing cracked concrete as "unchanged" is that cracking due to bending rather than corrosion would likely be counted in the frequency of cracking observed during a survey. Further, cracking that occurs around floating concrete would be counted as floating, so concrete with this kind of cracking would be correctly counted as "changed".

The marginal probability function that expresses the distribution of degree of corrosion is given by Equations (5) to (8) below from Equation (1). Table

3 shows the data in Table 2 in the form of relative frequencies, as obtained using these equations.

Table 2 Frequency of concrete surface

Degree of reinforcement bar corrosion	Number of concrete surface condition observations		
	Unchanged	Changed	Total
I	40	5	45
II	35	20	55
III	15	30	45
IV	5	50	55
Total by concrete surface condition	95	105	200

Table 3 Frequency of reinforcement bar corrosion

Degree of reinforcement bar corrosion	Concrete surface condition		
	Unchanged	Changed	Total
I	0.200	0.025	0.225
II	0.175	0.100	0.275
III	0.075	0.150	0.225
IV	0.025	0.250	0.275
Total by concrete surface condition	0.475	0.525	1.000

$$\text{I:}\quad p_x(I) = 0.200+0.025=0.225 \tag{5}$$

$$\text{II:}\quad p_x(II) = 0.175+0.100=0.275 \tag{6}$$

$$\text{III:}\quad p_x(III) = 0.075+0.150=0.225 \tag{7}$$

$$\text{IV:}\quad p_x(IV) = 0.025+0.250=0.275 \tag{8}$$

From Equation (3), if the degree of corrosion of a reinforcement bar is I, for example, the conditional probabilities that the concrete surface is categorized as "unchanged" and "changed" can be obtained from Equations (9) and (10), respectively. Similarly, the conditional probabilities of concrete surface condition for corrosion degrees II, III and IV are listed in Table 4.

$$P_{Y|X}(Unchanged|I) = \frac{p_{x,y}(I,Unchanged)}{p_x(I)} = \frac{0.200}{0.225} = 0.889 \tag{9}$$

$$P_{Y|X}(Changed|I) = \frac{p_{x,y}(I,Changed)}{p_x(I)} = \frac{0.025}{0.225} = 0.111 \tag{10}$$

Table 4 Conditional probability of surface condition to corrosion

Degree of reinforcement bar corrosion	Concrete surface condition		
	Unchanged	Changed	Total
I	0.889	0.111	1.000
II	0.636	0.364	1.000
III	0.333	0.667	1.000
IV	0.091	0.909	1.000
Total by concrete surface condition	1.949	2.051	4.000

Table 5 Probability of surface condition to corrosion

Corrosion of reinforcement bars		Concrete surface condition		
Degree	Probability P	Condition	Conditional probability $P_{Y\|X}$	Probability of concrete surface condition $P \times P_{Y\|X}$
I	a	Unchanged	0.889	0.889a
		Changed	0.111	0.111a
II	b	Unchanged	0.636	0.636b
		Changed	0.364	0.364b
III	c	Unchanged	0.333	0.333c
		Changed	0.667	0.667c
IV	d	Unchanged	0.091	0.091d
		Changed	0.909	0.909d

Table 6 Table for converting degree of corrosion to surface condition

Probability distribution of corrosion degree		Concrete surface condition		Total
		Unchanged	Changed	
I	a	0.889a	0.111a	a
II	b	0.636b	0.364b	b
III	c	0.333c	0.667c	c
IV	d	0.091d	0.909d	d
Total		0.889a + 0.636b + 0.333c + 0.091d	0.111a + 0.364b + 0.667c+ 0.909d	1.0

If the degree of corrosion is given by a probability distribution, or if the probability of corrosion degree I is *a*, the probability of corrosion degree II is *b*, the probability of corrosion degree III is *c*, the probability of corrosion grade IV is *d*, and $a+b+c+d = 1$, the categorization of the concrete surface as "unchanged" and "changed" can be determined as listed in Table 5 using the values in Table 4. Table 6 is a table for conversion from degree of corrosion to concrete surface condition. If the probability distributions of corrosion degree are given, the probability distributions of the concrete surface condition categories "unchanged" and "changed" can be determined from the table.

3.3 Conversion from concrete surface condition to corrosion degree

The conditional probabilities that corrosion is of degree I, II, III, and IV when the concrete surface condition is "unchanged" and "changed" can be obtained from Table 3 and Equation (4), as listed in Table 7.

Table 7 Conditional probability of corrosion to surface condition

Degree of reinforcement bar corrosion	Concrete surface condition		
	Unchanged	Changed	Total
I	0.421	0.048	0.469
II	0.368	0.190	0.559
III	0.158	0.286	0.444
IV	0.053	0.476	0.529
Total by concrete surface condition	1.000	1.000	2.000

Table 8 Probability of reinforcement corrosion

Concrete surface condition		Corrosion of reinforcement bars		
Condition	Probability P	Grade	Conditional probability $P_{Y\mid X}$	Probability of concrete surface condition P x $P_{Y\mid X}$
Unchanged	m	I	0.421	0.421m
		II	0.368	0.368m
		III	0.158	0.158m
		IV	0.053	0.053m
Changed	n	I	0.048	0.048n
		II	0.190	0.190n
		III	0.286	0.286n
		IV	0.476	0.476n

If the concrete surface condition is given by a probability distribution, or if the probability of category "unchanged" is *m*, the probability of category "changed" is *n*, and *m*+*n* = 1, corrosion degrees I, II, III, and IV can be determined as listed in Table 8. Table 9 is a table for converting from surface condition to degree of corrosion. If the probability distributions of surface condition categories "unchanged" and "changed" are given, the probability distributions of the corrosion degrees can be determined from the table. The probability distribution of concrete surface condition is taken to be the area ratio of change in concrete surface condition.

Table 9 Table for converting surface condition to degree of corrosion

Concrete surface condition		Degree of reinforcement bar corrosion				Total
Unchanged	m	0.421m	0.368m	0.158m	0.053m	m
Changed	m	0.048n	0.190n	0.286n	0.476n	n
Total		0.421m +0.048n	0.368m +0.190n	0.158m +0.286n	0.053m +0.476n	1.0

4. PREDICTION OF CORROSION DEGREE AND CORROSION STATE PROBABILITY OF REINFORCEMENT BARS

4.1 Prediction of corrosion degree of reinforcement bars

The probability that the reinforcement bars have reached a particular degree of corrosion (I, II, III or IV) is expressed quantitatively as the corrosion state probability. It is assumed that the corrosion state probability follows the probability distribution (log-normal distribution) with the degree of reinforcement bar corrosion taken as the probability variable, as shown in Figure 3, and can be obtained as the area ratio of the distribution, i.e. the probabilities of four exclusive events. As time advances, the probability distribution shifts to the right in the figure and at the same time the corrosion state shifts from I to II, from II to III, and from III to IV. The probability that reinforcement bars are in a particular state of corrosion can be expressed as the corrosion state probability. In the figure, α_1 to α_3 are the thresholds of corrosion state. These thresholds, including variations in the distributions, can be determined from inspection and survey data.

To predict the degree of corrosion, the predicted value of the corrosion degree is calculated from the predicted value of a corrosion factor using the network of relations between corrosion factor and corrosion degree constructed using a neural network.[3)] This can be expressed as Equation (11). The neural network used in this study is a 3-tier network consisting of 8 input layers, an intermediate layer, and a corrosion degree output layer.

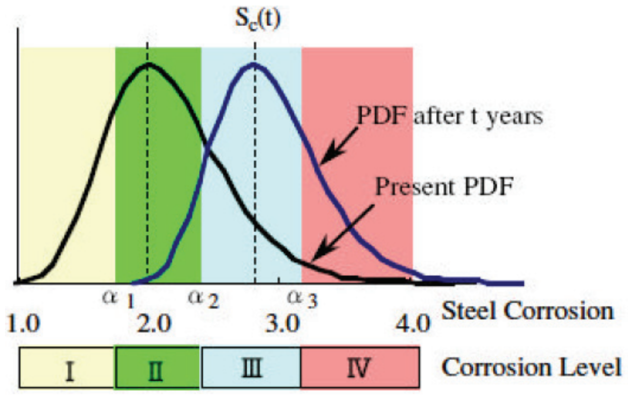

Figure 3 Distribution of probability of corrosion

$$S_C(t) = NW(d, C_t(t), C_d(t), T_{ave}, RH, Rain) \qquad (11)$$

where $S_c(t)$ = degree of reinforcement bar corrosion; t = in-service period, years; NW = neural network model; d = thickness of cover concrete over reinforcement bar, mm; $C_t(t)$ = concentration of chloride ions at the depth of the reinforcement bars, kg/m^3; $C_d(t)$ = carbonation depth, mm; T_{ave} = annual mean air temperature, °C; RH = annual mean relative humidity, %; and Rain = annual rainfall, mm. The concentration of chloride ions at the depth of the reinforcement bars and the carbonation depth in the equation can be determined from the prediction equations[2)] and other variables can be set using design values or inspection and survey results.

The statistical values and density functions for 252 data points used for the construction of the neural network, with the values of all deterioration factors described, are listed in Table 10 and shown in Figure 4, respectively, by degree of corrosion.

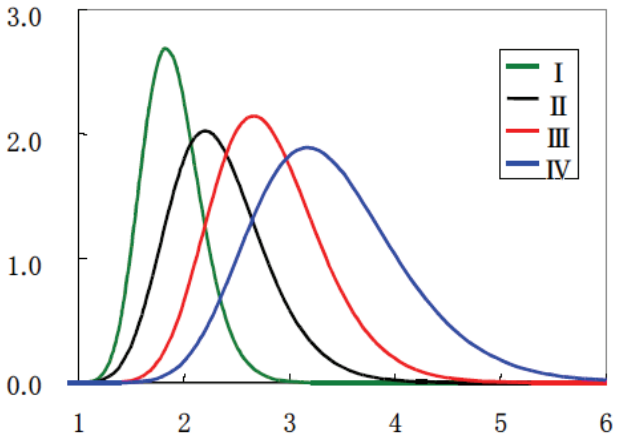

Figure 4 Distribution of statistical quantity on corrosion

In Table 10, μ = mean; σ = standard deviation; n = number of samples; λ = mean of LnX; ζ = standard deviation of LnX. Thresholds between corrosion degrees are calculated from Equation (12) with different variations based on discrimination from a single variate, using the statistical quantities in Table 10.

Table 10 Statistical quantity on corrosion

Degree of reinforcement bar corrosion	μ	σ	n	λ	ζ
I	1.85	0.28	29	1.83	0.148
II	2.25	0.46	119	2.20	0.197
III	2.70	0.49	61	2.66	0.186
IV	3.23	0.63	43	3.17	0.211

Threshold I-II:

$$E_{xp}\{(\lambda_1\zeta_2 + \lambda_2\zeta_1)/(\zeta_1 + \zeta_2)\} = 2.0$$

Threshold II-III:

$$E_{xp}\{(\lambda_2\zeta_3 + \lambda_3\zeta_2)/(\zeta_2 + \zeta_3)\} = 2.47$$

Threshold III-IV:

$$E_{xp}\{(\lambda_3\zeta_4 + \lambda_4\zeta_3)/(\zeta_3 + \zeta_4)\} = 2.93 \qquad (12)$$

4.2 Prediction of corrosion state probability of reinforcement bars

The probabilities of reinforcement bar corrosion of degree I to IV, $P(E_1)$ to $P(E_4)$, can be expressed by

Equation (13) using the corrosion thresholds α1, α2, and α3, and the probability variables (i.e. the mean of degree of reinforcement bar corrosion, μ, and the logarithmic standard deviation, ζ. Although it is assumed that corrosion degree follows the log-normal distribution in this study, the input conditions of the neural network model are also thought to follow a probability distribution.

$$
\begin{aligned}
P(E_1) &= \Phi\left(\frac{1n\alpha_1 - 1n\mu}{\zeta}\right) \\
P(E_2) &= \Phi\left(\frac{1n\alpha_2 - 1n\mu}{\zeta}\right) - \Phi\left(\frac{1n\alpha_1 - 1n\mu}{\zeta}\right) \\
P(E_3) &= \Phi\left(\frac{1n\alpha_3 - 1n\mu}{\zeta}\right) - \Phi\left(\frac{1n\alpha_2 - 1n\mu}{\zeta}\right) \\
P(E_4) &= 1 - \Phi\left(\frac{1n\alpha_3 - 1n\mu}{\zeta}\right) \qquad (13)
\end{aligned}
$$

where Φ = standard normal probability distribution function.

5. METHOD OF REVISING PREDICTIONS

Methods that can be used to change the parameters of the prediction equations so as to match the predicted corrosion state of the reinforcement bars to the actually observed corrosion state include regression analysis methods, such as the least-squares method, and the Bayesian probability method. The Bayesian probability method is a significant method of solving engineering problems where the available information is limited and a subjective judgment is required. Values of parameters related to deterioration factors can be obtained by making use of design documents, information provided by public institutions, or the intuition or experience of an engineer. Further, the parameters can be updated using Bayesian theory as given by Equation (14) by the addition of information obtained from inspections and tests.

$$\int^{n}(\theta) = \mathrm{k}L(E_i 1\theta)\int^{f}(\theta) \qquad (14)$$

where f''(θ) = posterior distribution; f'(θ) = prior distribution; κ = normalization factor; L(Ei | θ) = likelihood function.

$$\int^{'}(\theta) = \frac{1}{\sqrt{2\pi\zeta\theta}}\exp\left[-\frac{1}{2}\left(\frac{1n\theta - \lambda}{\zeta}\right)\right] \qquad (15)$$

Assuming a log-normal distribution, the posterior distribution is expressed as Equation (15), where ζ = $\zeta = \sqrt{\mathrm{var}(1n\theta)}$ and λ= *E*(lnθ).

The likelihood function is a conditional probability that the degree of corrosion (I to IV) given by the inspection data become E_i (i = 1 to 4) when the thickness of the cover concrete becomes θ. It is expressed as the function given by Equation (16).

$$L(E_i|\theta) = \prod_{i-1}^{4} P(E_i|\theta)^{qi} \qquad (16)$$

where q_i =probability of occurrence of E_i (i = 1 to 4).

For example, when the thickness of the cover concrete is assumed to be a log-norm distribution with the design thickness of 35 mm taken as the mean, the prior distribution, likelihood function, and posterior distribution are as shown in Figure 5.

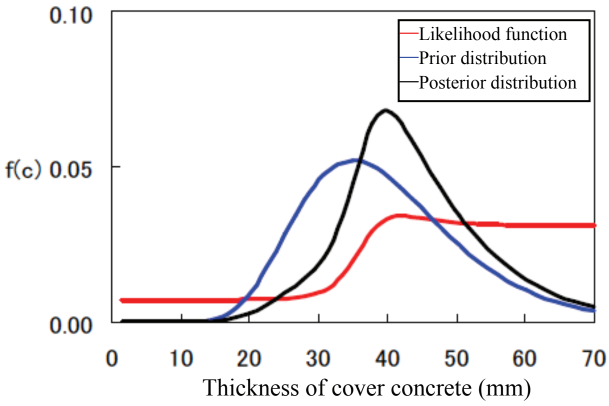

Figure 5 Distribution of probability of corrosion

6. CASE STUDIES OF PREDICTION AND PREDICTION REVISION WITH ACTUAL STRUCTURE

6.1 Prediction using design values

Prediction using design values is a method used in the planning and design phases or in a case where no inspections or surveys are conducted for an existing structure. In this case, the parameters for deterioration factors need to be set from existing data or using standards available from various institutions. The parameters for damage from salt water and carbonation are set from the literature and other sources.

6.1.1 Prediction of chloride ion penetration and the corrosion of reinforcement bars

Table 11 lists the surface chloride ion concentration, initial chloride content, thickness of cover concrete, carbonation rate coefficient, and environmental conditions used to predict the chloride ion penetration and reinforcement corrosion.

Table 11 Parameters for prediction

Item	Set value
Year of construction	1975
Air temperature	20°C
Rainfall	1,500 mm/year
Humidity	70%
Initial chloride content	0 kg/m^3
Thickness of cover concrete	50 mm
Surface chloride ion concentration	4.5 kg/m^3
Chloride ion diffusion coefficient	1.5468 cm^2/year
Carbonation rate coefficient	1.110 mm/$\sqrt{Year}$

The surface chloride ion concentration is set at 4.5 kg/m^3 and the initial chloride content at 0 kg/m^3. The apparent chloride ion diffusion coefficient is calculated from the equation in the Standard Specifications for Concrete Structures "Materials and Construction" based on the assumption that the water-to-cement ratio of the concrete is 52%.[4)] Similarly, the carbonation rate coefficient is calculated from the equation in the Standard Specifications. The predicted degrees of corrosion over the 70 years following completion using the conditions listed in Table 11 and Equation (11) based on the neural network are shown in Figure 6. As can be seen from the figure, corrosion develops as time advances.

6.1.2 Prediction of concrete surface conditions

The results of converting Figure 6 into the surface condition of the concrete based on the correlation model between corrosion degree and surface condition are shown in Figure 7.

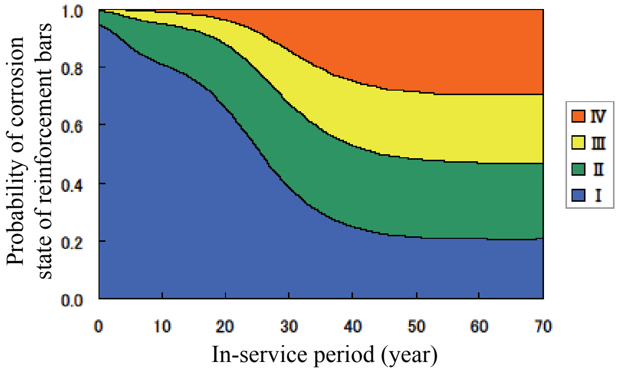

Figure 6 Time dependence of probability of corrosion

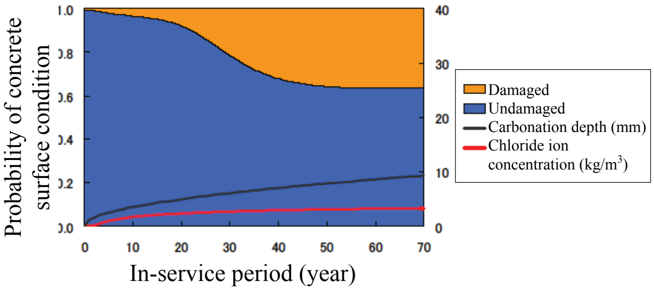

Figure 7 Time dependence of probability of surface condition

6.2 Revision of prediction based on survey results

6.2.1 Revision conditions

The change in surface condition of the concrete is assessed by block from the results of a visual inspection, and the area ratio of change in surface condition is calculated. The chosen block is a region surrounded by beams in the superstructure of a pier. The ratio of area where the surface condition has changed, obtained from a survey conducted 25 years after completion, is measure for two cases as listed in Table 12. These values are substituted for q_i in Equation (16) and the Bayesian probability method is applied. The cover concrete thickness is selected as the probability variable subject to revision and deterioration is predicted in the case where the probability variable is revised optimally.

Table 12　Parameters for prediction

	Results of prediction using set values		Survey result (in 25 years)	Values after revision	
	Thickness of cover concrete (mm)	Ratio of area of a change in concrete surface conditions (unchanged, changed)	Ratio of area of a change in concrete surface conditions (unchanged, changed)	Thickness of cover concrete (mm)	Ratio of area of a change in concrete surface condition (unchanged, changed)
Case 1	50	(0.86, 0.14)	(0.8, 0.2)	46	(0.72, 0.28)
Case 2			(0.4, 0.6)	43	(0.64, 0.36)

6.2.2 Results of revision

With the thickness of the cover concrete taken as the deterioration factor to be updated, the results of updating after application of the Bayesian probability method are listed in Table 12. The probability distributions of the degrees of corrosion after the update are shown in Figures 8 and 9. The probability distributions of concrete surface changes after the update are shown in Figures 10 and 11. As previously noted, the cover concrete thickness is selected for revision in these case studies. The Bayesian probability method can also be used with the carbonation rate coefficient or surface chloride ion concentration adopted as the object of revision. In place of the Bayesian probability method, regression analysis of the parameters used for the prediction or the judgment of an engineer can be used to obtain the parameters.

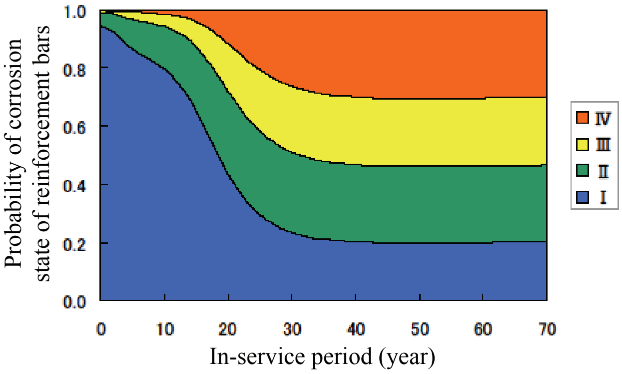

Figure 8　Time dependence of probability of corrosion after revision (Case 1)

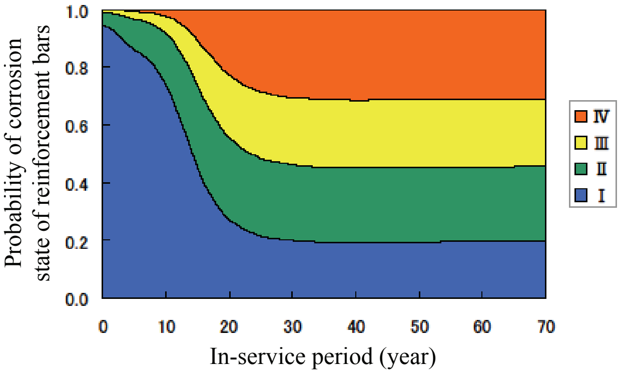

Figure 9　Time dependence of probability of corrosion after revision (Case 2)

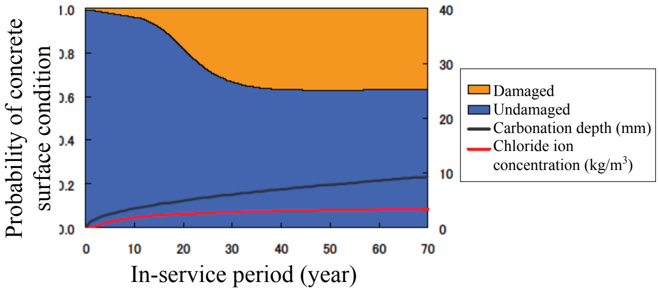

Figure 10　Time dependence of probability of corrosion after revision (Case 1)

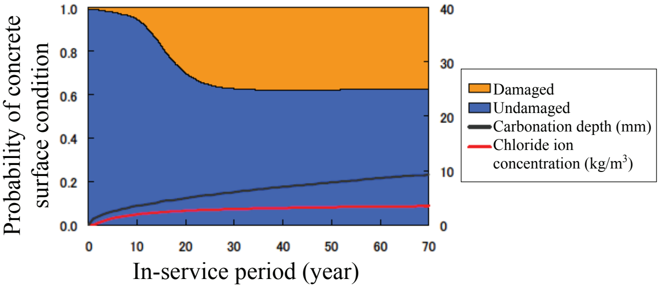

Figure 11　Time dependence of probability of corrosion after revision (Case 2)

7. CONCLUSIONS

The authors have studied methods of predicting the deterioration of actual structures and revising the predictions by making effective use of inspection results. The main feature of this research is that the data used for the study are all obtained from detailed inspections and surveys of actual structures. The following conclusions become clear from the work:

(1) The degree of corrosion of reinforcement bars in concrete correlate with the condition of the concrete surface. The correlation can be expressed quantitatively based on the theory of probability.

(2) The condition of the concrete surface can be predicted by estimating the degree of corrosion and using the correlation between corrosion degree and concrete surface condition.

(3) Results obtained from inspections of concrete surface condition can be converted into a probability distribution of degree of corrosion by categorizing the concrete surface area as changed or unchanged and using the correlation between corrosion degree and concrete surface condition.

(4) The predictions obtained can be revised using the actual results of inspections of the concrete surface by determining the carbonation rate coefficient, cover concrete t thickness, surface chloride ion concentration and apparent chloride ion diffusion coefficient using the Bayesian probability method or a regression analysis method so as to match the probability distribution of corrosion degree obtained from inspections.

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