EMERGING TRENDS:
Keynote Lectures and Symposia

PROCEEDINGS OF

The Tenth East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-10)

Bangkok, Thailand

EASEC
THE EAST ASIA-PACIFIC CONFERENCE ON STRUCTURAL ENGINEERING & CONSTRUCTION
20th ANNIVERSARY

Edited by
Worsak Kanok-Nukulchai
Sunil Munasinghe
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The Tenth East Asia-Pacific Conference on Structural Engineering and Construction
August 3-5, 2006, Bangkok, Thailand

MAINTENANCE AND MANAGEMENT OF CONCRETE BRIDGES

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ABSTRACT: This paper attempts to improve the existing chloride deterioration simulation system by gathering real structural data and modifying the deterioration processes of existing concrete bridges. Criteria of visual inspection were decided and adopted in the real structures. The chloride ion diffusion process that is obtained from the solution of the Fick's law of diffusion had been altered from constant surface chloride concentration to concentration increasing with time. The new proposal system was confirmed by the result of inspection.

KEYWORDS: Total management system, Chloride attack, Probabilistic prediction, Visual inspection, Reinforced concrete bridge.

1. INTRODUCTION

Huge amount of infrastructures were constructed after World War II, they supported tremendous economic growth in Japan. Various types of deterioration appeared as ageing structures, and it has increased the requirements for management systems to operate the infrastructure in efficient way. Currently, simulation system for concrete deterioration that brings the possibility of evaluating the performance of the concrete structures is now under researching by many institutes. Most of the simulation systems are intended for an individual structure or a single structural member.

Based on these facts, the authors have proposed a system with the methodology to compute the total maintenance costs of the concrete infrastructures under chloride attack by probabilistic way in preceding paper [1].

This total management system consists of deterioration simulation system and optimization system as for rehabilitation planning. In the deterioration simulation system, shape, dimensions, material characteristics of the structure, as well as external deterioration forces, which those values are scattered in ranges, are given as input data for the probabilistic deterioration simulation. All structures that belong to an organization are calculated for the probability to reach each deterioration situation and the performance probability distribution at arbitrary time. Optimum maintenance cost can be obtained by verification of the results after inputting some rehabilitation plans into the probabilistic performance distribution. Technical foundation for budget request, maintenance technique, and a study will be immediately demanded in the near future. Consequently, it should be ensured by establishment of the total management system with proper degree of accuracy.

This paper attempts to improve the existing deterioration simulation system. One is the gathering of reliable data by visual inspection of the real structures, and the other is to improve the chloride

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diffusion process in concrete material. Criterion of visual inspection to verify the total management system was decided, and it was adopted in Kochi prefecture, Japan. The chloride ion diffusion process that presented in the preceding paper are modified, which the solution of Fick's law of diffusion had been altered from constant surface chloride concentration to concentration increasing with time.

2. COMPUTATIONAL MODEL FOR CHLORIDE ATTACK IN PRECEDING PAPER [1]

For chloride attack, five deterioration stages are usually defined: stage I is Incubation Stage, stage II is Progress Stage, stage III is Acceleration Stage, stage IV is Deterioration Stage, stage V is Unusable Stage. These stages are corresponding to the following four limit states: limit state 1 is initiation of steel corrosion, limit state 2 is crack opening, limit state 3 is falling of cover and limit state 4 is insufficiency of member strength. Models for deterioration prediction is based on the term of incubation stage, and the after incubation stage is defined as correlation with the time in which corrosion begins.

2.1 INCUBATION STAGE

The chloride ion diffusion process until initiation of corrosion was assumed as in the Equation (1) which is the solution of the Fick's Second Law where assumed that chloride concentration at the surface is constant.

$$C(x,t) = C_0\left\{1 - erf\left(\frac{x}{2\sqrt{D \cdot t}}\right)\right\} \tag{1}$$

Where x represents the distance from the surface of concrete (cm), t is elapsed time (year), $C(x, t)$ represents chloride ion concentration at distance x at the time t (kg/m^3), C_0 is chloride ion concentration at the surface of concrete (kg/m^3), erf represents an error function, D is an apparent diffusion coefficient (cm^2/year). $C(x, t)$ should be limited chloride ion concentration for starting corrosion (critical chloride threshold value) to calculate incubation stage.

2.2 OTHER STAGES

After incubation stages, as the same with preceding paper [1], the progress stage is defined as the term from corrosion starts to crack opening. The factors affecting this stage are steel corrosion velocity and cracking resistance of cover concrete. The former is a function of chloride concentration, oxygen diffusion velocity and diameter of steel bar. The latter is a function of cover concrete depth, bar spacing and concrete strength. These factors are the same as those affecting the corrosion initiation except bar diameter and bar spacing. For simplicity, the progress stage is assumed as four times as long as the incubation stage. The acceleration stage and the deterioration stage also similar to those in progress stage and for simplicity, these stages are assumed as three times and two times as long as the incubation stage, respectively.

2.3 PROBABILISTIC COMPUTATIONAL MODEL

The factors of deterioration process can not be estimated by the deterministic manner but should be estimated by a probabilistic manner. Following probabilistic values were assumed;

(1) The minimum and maximum values of critical chloride threshold are reported as 1.2 and 2.4 kg /m^3 respectively [2]. The average value was assumed as 1.8 kg /m^3 and standard deviation of 0.2.

(2) The chloride ion concentration at the surface of concrete was assumed according to the environmental zoning proposed by Japan Loads Association recommendation [3]. In 1984, the JRA published the design recommendation for chloride attacks which divided Japan into four Zones according to the severity of chloride attack as shown in Figure 1. The concrete bridges placed in Zone

4 are assumed to be safe against the chloride attack from seashore. The average surface chloride concentration was 8.0, 3.0 or 2.0 kg /m^3 according to the Zone 1, 2 or 3. The minimum values were assumed as 0.5 kg /m^3 for all three zones.

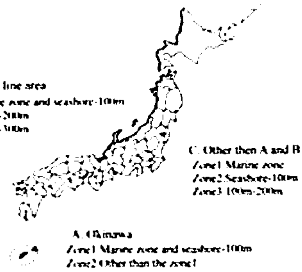


Figure 1. Zoning for chloride attack

(3) The apparent diffusion coefficient is proposed by the JSCE Standard Specification [2] as a function of water cement ratio (w/c) with cement sort as shown in Equation (2).

$$\log D = -3.9(w/c)^2 + 7.2(w/c) - 2.5 \tag{2}$$

Where D represents an apparent diffusion coefficient (cm^2/year), w/c is water cement ratio of concrete. This equation is established for Portland cement. It is an empirical formula obtained from apparent diffusion coefficient database that is calculated by regression analysis of distribution of chloride concentration of concrete inspections or experiments [4]. The range of apparent diffusion coefficient which obtained by the numerical approach has wide range. Log D is assumed to follow the normal distribution function with the standard deviation of 0.4 and the water cement ratio was assumed as deterministic. The water cement ratio was assumed 55% and 35% for reinforced concrete girder and pre-stressed concrete girder respectively.

(4) Concrete cover should be changes according to the structural type and design code. The design recommendation for countermeasure against salt attack was published in 1984 [3], and the resisting ability of bridges were greatly different according to the construction time before or after 1984. The average values are defined as 40mm for reinforced concrete and post-tensioned concrete, and 30mm for pre-tensioned concrete before 1984. After 1984, the average concrete cover is defined as 5mm larger than the minimum value in the code applied [3]. The standard deviations were assumed as 5 for all.

The stages after incubation stage should be determined in a probabilistic manner. In this model the coefficients of variation for the time of stage are temporally assumed as 35% for all cases.The type of probability distribution for all random variables may be different, but for simplicity the probability functions are assumed as normal distribution in this model. Five to ten samples in the range between its minimum and maximum values with same intervals are used for numerical integration.

3. PROPOSED COMPUTATIONAL MODEL FOR CHLORIDE ATTACK

3.1 INCUBATION STAGE

In contrast to the previous methodology, the diffusion equation is assumed to follow the Equation (3). It is a solution of Fick's Second Law where surface chloride concentration is set as a function of time (increasing with time) as shown in Equation (4), [2]. Chloride ion on the concrete surface is assumed to increase with square root of time in year. This kind of increment of surface concentration is more realistic because airborne chloride particles from the sea transport to accumulate on the surface of concrete where an amount of absorbable chloride reduces with the surface concentration.

$$C(x,t) = S\sqrt{t}\left[\exp\left(-\frac{x^2}{4D\cdot t}\right) - \frac{x\sqrt{\pi}}{2\sqrt{D\cdot t}}\left\{1 - erf\left(\frac{x}{2\sqrt{D\cdot t}}\right)\right\}\right] \tag{3}$$

$$C_0 = S\sqrt{t} \tag{4}$$

Where S represent surface chloride coefficient (kg/m$^3\sqrt{t}$), t is elapsed time (year), $C(x, t)$ represents chloride ion concentration at distance x at the time t (kg/m^3). C_0 is chloride ion concentration at the surface of concrete (kg/m^3), erf represents an error function, D is an apparent diffusion coefficient (cm^2/year). The difference with Equation (1) is the definition of surface chloride concentration.

3.1.1 Surface Chloride Coefficient

Environmental condition where the concrete structure is located may affect the surface chloride coefficient, S. The surface chloride coefficient S has large value where the structure is located in severe environmental condition. The main factor that relates to the environmental condition is weather condition such as velocity and direction of wind, distance from seashore and shore condition. Kawamura et al. [5] proposed that surface chloride coefficient is according to the weathering area and the distance from seashore. It was evaluated by the numerical approach using equation (3) based on the chloride profiles in many cases of marine structures. The surface chloride coefficients which proposed by Kawamura et al. are shown in Table 1, and the weathering zone also shown in Figure 2.

Table 1. Surface chloride coefficient

Area	Distance from seashore (m)				
	0	100	250	500	1000
SS	Need an extra consideration				
S1	0.9	0.35	0.20	0.15	0.12
S2	0.9	0.15	0.12	-	-

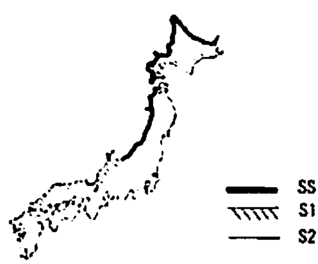


Figure 2. Zone for surface chloride coefficient.

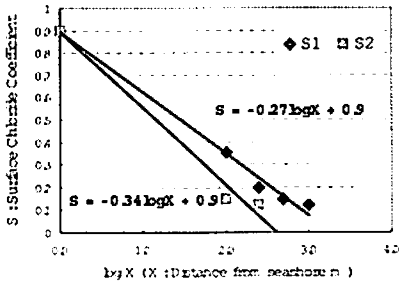


Figure 3. Surface chloride coefficient.

Figure 3 shows the relation between the surface chloride coefficient and distance from seashore of Table 1 in logarithmic scale. It is obvious that there is interrelation between the two factors. Therefore, the surface chloride coefficient can be defined to follow Equation (5) and (6) for the area S1 and S2, respectively.

$$S = -0.27\log X + 0.9 \tag{5}$$

$$S = -0.34\log X + 0.9 \tag{6}$$

3.2 PROBABILISTIC COMPUTATIONAL MODEL

The factors of deterioration process should be estimated by a probabilistic manner. The probabilistic values except of surface chloride coefficient are assumed as the same as chapter 2. The average surface chloride coefficient is assumed as Equation (5) and Equation (6) for S1 area and S2 of Figure 2 respectively, and having coefficients of variation of 0.2.

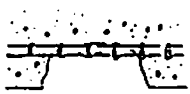
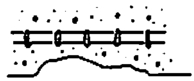
4. VISUAL INSPECTION FOR CHLORIDE ATTACK

4.1 REFER FOR INSPECTION CRITERIA

Manual for inspection published in 1988 [6] was used for national road inspection until it had been revised [7] in the later years. The revised version of manual is adopted for the national road and regional road. Both versions of the manuals show purposes of inspection, timing, and the criteria of evaluating the structural deterioration. Table 3 shows the criterion of visual inspection by the standard [6]. The evaluation is based on the classification of deteriorated structural portion and its severity such cracking and spalling of concrete. Table 4 shows the criterion of visual inspection by the standard [7]. Each classification of structural damage is evaluated as standard evaluation. For example, Table 3,4 show the spalling and exposure of steel bar of the standards.

In the preceding paper, the inspection data that is adopted by the standard [6] was used for verification. Material deterioration such as cracks or spalling caused by chloride attack cannot be evaluated by the standard [6]. Therefore, the data from the standard [6] need some environmental information such a weathering characteristic and distance from seashore. However, it was difficult to gather sufficient amount of data for the verification, since there was lack of data and no record of repair. For this reason, the concrete bridges in Kochi prefecture have been investigated for its structural deterioration data.

Table 3. Criterion of visual inspection [6]

		Effect on durability and load carrying capacity of structure	
		Great	Little
Depth (Y)	Condition	Exposure of steel bar	Spalling only
	Example		
Area (Z)	Condition	Large area	Small area
	Particular	Superstructure: over 0.1m^2 Substructure: over 1 m^2	Superstructure: less 0.1m^2 Substructure: less 1 m^2

Y	Z	Level for main member	Level for sub member
Great	Great	II	II
	Little	III	IV
Little	Great	III	III
	Little	IV	IV

Table 4. Criterion of visual inspection [7]

Category	Condition
a	No visual deterioration
b	-
c	Spalling only
d	Exposure of steel bar, and small corrosion on the steel
e	Exposure of steel bar, and severe corrosion on the steel

4.2 VISUAL INSPECTION IN KOCHI PREFECTURE

Actual bridges that are constructed beside the sea in Kochi prefecture were observed visually. Kochi prefecture is located in the south of Japan, and it faces to the Pacific Ocean. The weather is hot and humid in summer, while typhoons regularly pass through.

In this inspection, it was focused on chloride attack on main girder of the reinforced concrete bridges. The shape of all inspected girders was T-shape.

4.2.1 Evaluation of Deterioration Stage

In order to use the deteriorated conditions of the target structures, it is necessary to propose some numerical methodology for the verification of the deterioration model that is corresponding to the deterioration progress. The deteriorate condition of the concrete girder was evaluated according to the following criteria. Six deterioration categories are defined for this visual inspection.

Category I -II : No visual deterioration
Category II-1 : Corrosion on the surface of concrete with rusty color
Category II-2 : Partially spalling of concrete cover at about less than 20mm
Category III : Partially cracks or spalling of concrete cover at about 20mm or over

Category IV-1 : Cracking or spalling within 30% or greater of the objective area
Category IV-2 : Cracking or spalling within 80% or greater of the objective area or breaking reinforcing bar

Chloride attack is phenomenon that chloride ions caused corrosion on the steel reinforcement, which the corrosion product may expands and cause cracking of concrete. Therefore, it is difficult to judge visually whether steel corrosion is started or not until cracking occur. This stage of corrosion is classified as category I-II. Result of the corrosion appears on the surface of concrete with rusty color, while the steel corrosion is proceeding inside the concrete until cracking. This condition is categorized as category II-1. Category II-2 is classified according to deterioration level of the concrete cover. Category III-1 is defined as partially cracking and spalling of concrete cover at about less than 20mm, and it is assumed that the spalling occur with the cracking at that point (Figure 4 Left). Category III is defined as partially cracking and spalling of concrete cover at about 20mm or over and the condition is under category IV-1 (Figure 4 Left). Category IV is judged by the deteriorated area for the target area. This target area is defined as the area under the surface of girder and the away from the under of side girder 20cm (Figure 5). Most of reinforced concrete T-shape girder is arranged with reinforcing bar in two layers. The reinforcing bars in the second layer are arranged at about 15cm from lower face of the girder. Category IV-1 is defined for the condition that cracking or spalling within 30% or greater of the target area, while the category IV-2 is defined in the case of 80% and over (Figure 4 Right). In this paper, the deterioration level was evaluated for every girder according to the criteria. However, if deterioration classification is mixed, the level will be judged with more severe category (Figure 4 Left).

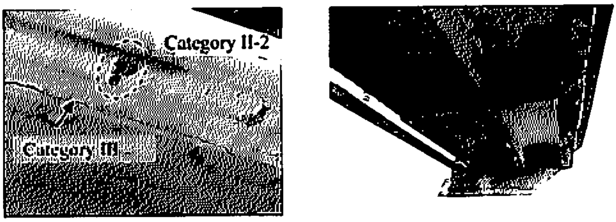


Figure 4. Example of category for inspection. Left is category III, right is category IV-2.

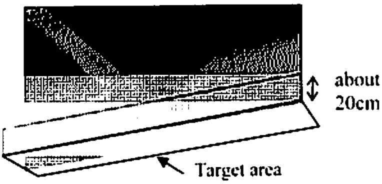


Figure 5. Target area for visual inspection.

4.2.2 Example of Visual Inspection

Table 5 shows an example of the results on visual inspection. There concrete bridges are located within 100m or less from the seashore. In front of the target bridge, there were not any structures or trees to prevent attacking from airborne chloride. Incremental tendency of the deterioration is shown by increasing of exposure time and shorter distance from the seashore.

Table 5. Results of visual inspection

No.	Years of service	Distance from seashore (m)	Total number of girders	Number of girder in each deterioration stage					
				I-II	II-1	II-2	III	IV-1	IV-2
1	37	15	8	0	2	4	2	0	0
2	44	50	3	0	0	0	2	1	0
3	55	100	3	0	0	0	2	1	0
4	70	20	6	0	0	0	0	2	4
5	70	90	3	0	0	0	0	0	3
6	73	80	3	0	0	1	0	2	0

It is counted from inspection categories to deterioration stages as: category II-1,2 is progress stage, category III is acceleration stage, category IV-1,2 is deterioration stage. Table 6 shows percentage of each deterioration stage of Table 5.

Table 6. Data arrangement of Table 5

No	Years of service	Percentage of each deterioration stage (%)		
		Progress stage	Acceleration stage	Deterioration stage
1	37	75	25	0
2	44	0	67	33
3	55	0	67	33
4-5	70	0	0	100
6	73	33	0	67

5. VERIFICATION

Figure 6 shows the comparisons of the computational result and inspection data (Table 6). The average surface chloride coefficient is assumed as 0.9 for calculation.

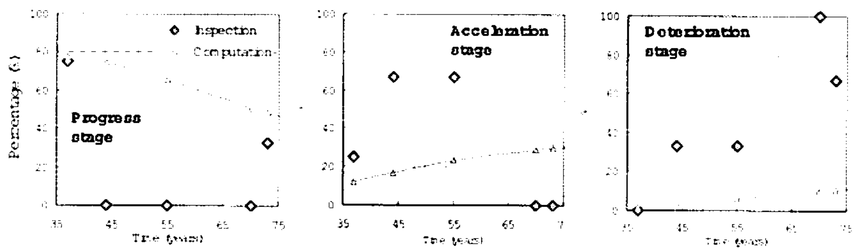


Figure 6. Relation between the inspection results and the computational results. Progress stage, Acceleration stage, Deterioration stage from left figure.

The computational results of the progress stage are quite larger than that of the inspection. While the results of acceleration and deterioration stages are smaller. This may be caused by two reasons: one is the definition to calculate the stage after corrosion starts, and another is the assumed value of the surface chloride coefficient.

Each stage after the corrosion is assumed as proportional to the term of incubation stage as described in chapter 2.2. However, this definition has to be modified since Equation (3) is adopted in this paper instead of Equation (1). Figure 7 shows the time profiles of chloride ion concentration at 4cm of cover and 55% water cement ratio calculated by Equation (1) with the surface chloride concentration (C_0) of 3 kg/m^3, and Equation (3) with the surface chloride coefficient (S) of 0.9 kg/m$^3\sqrt{t}$. C_0=3 kg/m^3 was assumed as the average value of C_0 of environmental zone2 in preceding paper. The calculation by

Equation (3) with the value of S=0.9 overestimates the result calculated by Equation (1) about 20 years. The chloride ion concentration calculated by Equation (3) is greatly increased when comparing with the result calculated by Equation (1) after 20 years period. For this reason, the computational result shows higher concentration than that of when defining the other states based on the incubation state. Therefore, it can be concluded that the proposed system has now limitation on prediction of deterioration stages in the later period.

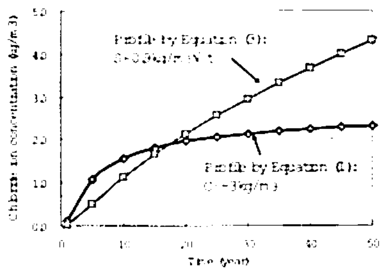


Figure 7. Time profiles of chloride ion concentration at the point of 4 cm from concrete surface.

Figure 8 shows computational probabilities of five deterioration stages. Results in the left figure are calculated by the proposed system assuming that the stages after corrosion start are equal to four times, three times and two times of the incubation stage. Results in the right figure are calculated with a modification on the proposed system. It is assumed as two times, three times and five times of the incubation stage. It shows better simulation result of the inspection data than that of the left figure.

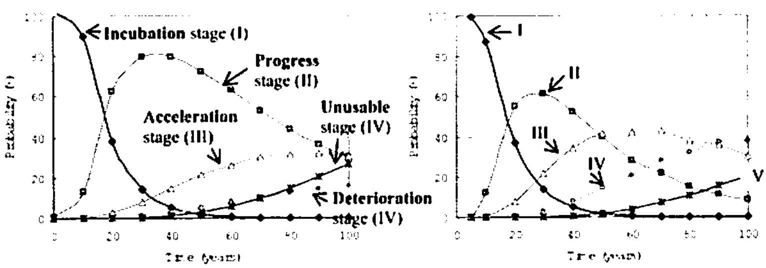


Figure 8.Computational probability of 5 deterioration stages. Left: progress stage, acceleration stage, deterioration stage is four times, three times, two times, respectively. Right: two times, three times, five times, respectively.

Determination of surface chloride coefficient S was based on the proposal by Kawamura et al. However, the value of S proposed by Kawamura et al. was determined from inspected data of the real bridge columns and abutments. While, the target structure of this research is RC main girder of superstructures, which it has high possibility that water cement ratio is lower than that of the substructure. For this reason, chloride ions penetration through lower water cement ratio under similar environmental condition is slower and resulted in higher value of apparent S.

6. FUTURE DETERIORATION LEVEL FORECAST

The deterioration levels of existing bridge girders shown in Figure 9-left can be computed by the proposed system. Figure 9-left shows a number of reinforced concrete girders constructed from 1930 to 1984 by the Ministry of Construction. Figure 9-right shows the computational results for these girders by the proposed system. The computational results offer a safer side of state determining. Specifically, every girder should be more over-deteriorated than this result according to the consideration in chapter 5.

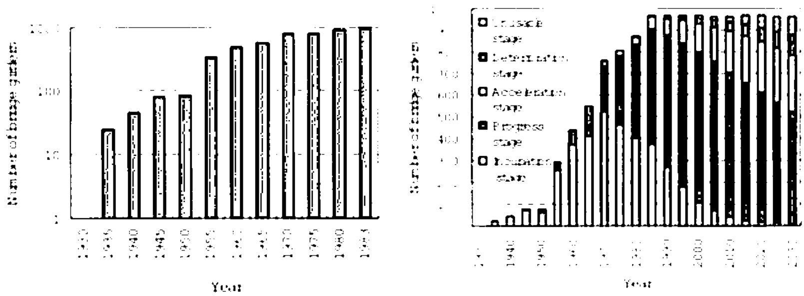


Figure 9. Left: Accumulation number of reinforced concrete bridge girders constructed by Ministry of Construction placed in Zone2. Right: Computational deterioration levels for left figure.

7. CONCLUSION REMARKS

The deterioration simulation system was improved from preceding paper, and it is verified by the visually inspected data. However, precision of the system still needs more improvement for accuracy as practical use in the future. Further inspection data is necessary to improve this system.

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