- Technical Paper -

UTILIZATION OF INSPECTION RESULT OF RC STRUCTURE IN THAILAND TO PLAN MAINTENANCE FOR CHLORIDE ATTACK

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ABSTRACT

Currently, the importance of maintenance work for deteriorated RC structures increases significantly. In order to ensure safety and serviceability, maintenance has to be planned in advance based on the prediction result. In this study, examples of RC structures in Thailand was inspected the actual variation of their conditions. The method to plan the maintenance work by utilizing these actual inspection results is discussed. Finally, benefit of using actual inspection results in maintenance planning over an ordinary method considering the safety factor is also discussed.

Keywords: maintenance, deterioration, corrosion, life cycle cost, non-destructive testing, inspection, probability, uncertainty

1. INTRODUCTION

Corrosion of reinforcing steel due to chloride attack is one of main mechanisms deteriorating RC structure. There are great efforts to maintain deteriorated structures to ensure their safety and serviceability. In 2002, JSCE [1] regulated the durability design to ensure the performance of structure during their service life based on the performance based design. In this specification, safety factor is considered to deal with the variation and uncertainties of actual condition from design condition. This leads to the over-design and higher cost than the actual requirement. In addition, JSCE [2] also regulates the guideline for maintenance the RC structure and have already recommended to periodically inspect the structure to ensure their safety and serviceability. Therefore, there are a lot of useful inspection results available. However, they are rarely used to planning the maintenance program in the future.

In this study, RC structures attacked by marine environment in Thailand were inspected and inspection result of the actual structures is used to plan the maintenance program based on probability theory. Finally maintenance program is decided by the lowest life cycle cost including repairing and failure cost. When maintenance planning considers the actual variation of structure properties, maintenance cost is expected to be lower than that of the method considering only general safety factor.

2. INSPECTION PROGRAMS

In order to investigate the variation of properties of actual RC structure against steel corrosion due to chloride, RC structures located close to marine environment in Thailand were inspected by both of destructive testing and non-destructive testing.

2.1 Sites of inspection

Sites of inspection are mainly road bridges located nearby Bangkok, Thailand as shown in the Fig.1. Totally 3 bridges were inspected. Age of these structures is 1 year, 5 years and 43 years at the time of inspection in November 2006. Picture of one of the structures is shown in Fig. 2. The deterioration level due to chloride attack can be classified from no damage to severely damaged. Concrete spalling can be clearly seen in one of these bridges as shown in Fig.3. Average day-time temperature during the inspection program was about 34˚C without any rain. Concentration of

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NaCl in surrounding sea water is about 3.0% except the site in Samutprakan province that is attacked by brackish water which concentration of NaCl is about 0.03%. Used cementitious material is not only ordinary Portland cement but some structures were used also sulfate resistant cement or coal fly ash cement as a cementitious material. In order to prevent the deterioration due to chloride, designer specified minimum covering depth, compressive strength, and unit cement content. Background information of each structure is shown in Table 1.

2.2 Parameters of inspection

Previous research [3] revealed that variable of parameters, including steel covering depth, chloride diffusion coefficient, surface chloride content, and concrete compressive strength, significantly affect the performance of RC structure against chloride attack as well the prediction result of maintenance planning. Therefore, inspection program conducted in this study was mainly focused to determine the random variable of those parameters and are explained below.

Fig.1 Area of inspection

Fig.2 Picture of actual inspected structure

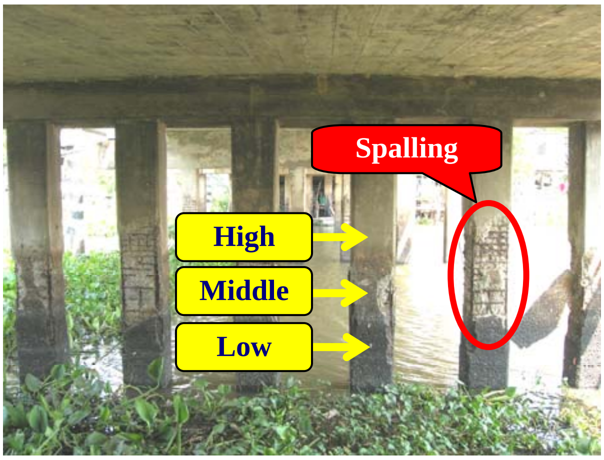

Fig.3 Example of deterioration condition and location of collecting concrete powder sample

(1) Covering depth of reinforcing steel

Covering depth of stirrup was measured by commercial rebar detector of which principle of detecting steel is based on techniques of electromagnetic wave. Scanning was conducted on Quickscan mode to many small sections with the length of each section around 1.5 meters. Only concrete with smooth surface was inspected. Then all of data is collected together for each structure to finalize its variations.

(2) Chloride diffusion coefficient and surface chloride content

Chloride diffusion coefficient was calculated from the profile of chloride content. Sample of concrete powder was collected on site by drilling machine with the diameter of drilling bit of 14mm based on the method of JSCE G573 [4]. Sample powder was collected from three adjacent holes with the depth of 0-2cm, 2-4cm, 4-6cm, 6-8cm, and 8-10cm from the surface to minimize the effect of aggregate size. Sample was collected not only at the same level from sea water level but also at different height in order to determine the effect of height from the sea level. Total chloride content in powder was measured based on method of JCI SC5. Then chloride diffusion coefficient and surface chloride content were calculated from the profile of chloride content.

(3) Concrete compressive strength

In order to inspect the variation of concrete quality, concrete compressive strength was measured by rebound hammer. Although there are other NDT methods such as air permeability test., rebound hammer is still one of the methods that are most convenient to be conducted. Twenty points were tested for one set of sample. Only smooth concrete surface was tested. From Eq. 1, concrete compressive strength can be calculated from rebound number JSCE [5].

Table 1 Information of inspected structures

Bridge No.	Location	Age, years	Cementitious material
1	Samutprakan Province	43	OPC cement
2	Chonburi Province	5	Sulfate resistance cement
3	Chantaburi Province	1	Coal fly ash cement

$$f_c' = -18 + (1.27 \times RN) \qquad (1)$$

where, f_c' is concrete compressive strength (MPa), and RN is rebound number.

2.3 Distribution fitting

As explained, inspections were conducted at many locations on each structure. In order to conclude the distribution of all inspected data, they are combined together for each structure as one set of data. Then distribution fitting program called Bestfit was used to select the most fitting distribution to our set of data based on chi-square goodness of fit test. Distribution type, mean value, and coefficient of variation are reported in following section.

3. INSPECTION RESULTS

In order to determine the distribution and random variable of properties of structures, inspection results were processed as explained and will be discussed. Table 2 concludes total number of samples being inspected for each inspection item and bridges.

3.1 Covering depth of reinforcing steel

Results of scanning from many small sections of structure are combined together and the distribution fitting is conducted. From the combined inspection data, the distribution fitting was conducted as explained earlier. Fig. 4 shows the example of comparison between distribution of actual inspection result and the fitting curve. The results of type of distribution, random variable are shown in Table 3 as well as the specified covering depth. Most of mean value of measured covering depth is significantly less than the required value as shown in the design drawing. Also their coefficient of variation is more than 20%. It should be noted that assigned safety factor should also be high to compensate this high variation of actual measured value. As a result, the life cycle cost of maintenance is expected to be more expensive than the actual requirement of the structure and will be discussed in the later section.

3.2 Chloride diffusion coefficient and surface chloride content

As explained, powder of concrete sample was collected and analyzed for chloride content. However, the number of samples is limited due to difficulties of sample collection. Therefore, it is difficult to reliably determine their random variable. As a result, only actual variations of the data are shown in Table 4. Very high variation is observed in both of surface chloride content and chloride diffusion coefficient. Local effects of chloride attack due to location of members, wind direction, etc., can be seen from this result. Also variation of the concrete permeation due to effects of casting and curing can be seen from the result.

Table 2 Number of sample

Bridge No.	Item	Level	No. of Sample
1	Covering depth	Middle	916
	Chloride analysis	Middle	3
	Compressive Strength	Middle	252
2	Covering depth	Middle	1252
	Chloride analysis	Low	4
		Medium	12
		High	4
	Compressive Strength	Middle	713
3	Covering depth	Middle	334
	Chloride analysis	Middle	6
	Compressive Strength	Middle	1493

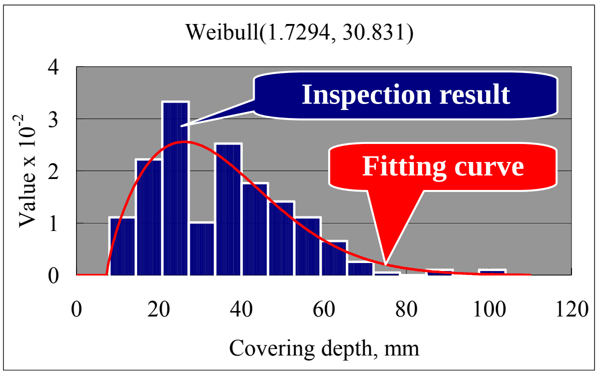

Fig.4 Distribution fitting of the inspection result

Table 3 Inspection result of covering depth

No	Required covering depth	Type of Distribution	Mean (mm)	COV
1	50mm	Gamma	24.21	0.38
2	70mm	Gamma	41.61	0.46
3	70mm	Weibull	88.34	0.22

In one of the bridges, concrete samples were collected from different height from the water level. Results of chloride analysis are shown in Fig. 5 and 6. As expected, results of samples closer to the water level show higher surface chloride content than samples from the higher position. Average surface chloride content of low, middle, and high level are 15.33, 9.40, and 3.42 kg/m^3, respectively. This shows that the effect of local variation of chloride attack can be considered in both of horizontal and vertical directions in each structure. But the effect of distance from water level cannot be clearly seen on the variation of the properties of concrete. The chloride diffusion coefficient is in the similarly wide range for all of three levels of measurements.

3.3 Concrete compressive strength

Due to handiness of rebound hammer, it was conducted on a large number of members to determine the variation of the concrete compressive strength used to represent the concrete quality. The results of reading rebound number as well as the calculated concrete compressive strength are shown in Table 5 together with the minimum required concrete compressive strength in design drawing. All of calculated compressive strength is higher than regulated value. This may be due to regulated value is based on compressive strength at 28days but the inspection was conducted at a minimum of 1 year after the casting. Variations of concrete quality are in the range of 10 to 20%; however, they are significantly lower than that of covering depth.

Due to difficulties of collecting the concrete powder sample for chloride analysis, the variation of concrete compressive strength is also applied as the variation of chloride diffusion coefficient.

4. MAINTENANCE PLANNING

From the obtained inspection results shown in the last section, maintenance program will be decided by using the obtained results as the actual conditions of each structure. Comparison of the maintenance life cycle cost between consideration of safety factor and actual uncertainties is given in this section. However, only inspection results of bridge No. 3 is used as an example.

Table 4 Inspection results of surface chloride content and chloride diffusion coefficient

No	Results	No. of Data 1	2	3	4
1	C_s (kg/m^3)	11.17	7.82	7.14	-
	D_{cl} (cm^2/year)	0.82	2.00	1.19	-
2	C_s (kg/m^3)	10.60	14.10	17.10	19.50
	D_{cl} (cm^2/year)	0.75	0.58	0.39	0.36
3	C_s (kg/m^3)	8.60	5.58	14.39	6.52
	D_{cl} (cm^2/year)	0.35	0.73	0.75	1.01
	C_s (kg/m^3)	3.95	11.13	-	-
	D_{cl} (cm^2/year)	1.32	1.38	-	-

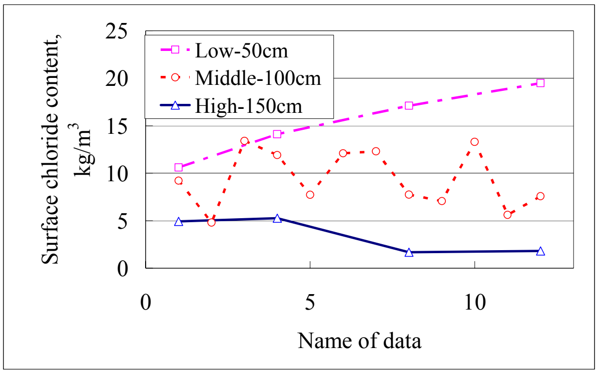

Fig.5 Effect of height from sea water level on surface chloride content

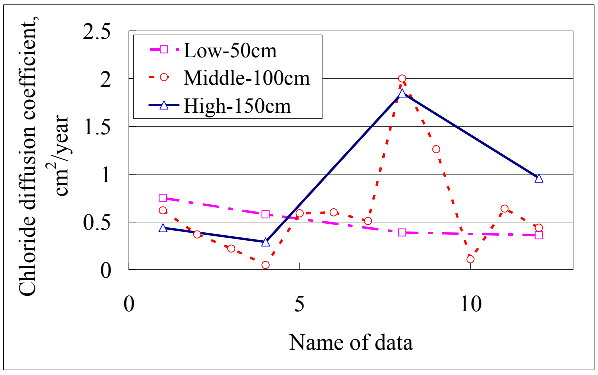

Fig.6 Effect of height from sea water level on chloride diffusion coefficient

Methods of deterioration prediction and life cycle cost calculation are reported previously by Sancharoen and Uomoto [6]. Random variables of parameters used in the prediction are concluded in Table 6. Please be noted that distribution of surface chloride content is assumed to be uniform within the range of 3.95 to 14.39 kg/m^3. Also it is assumed that deterioration rate of the structure after being repaired is same with that of original structure.

Table 5 Inspection results of concrete compressive strength

No	Required strength	Type of Distribution	Mean (MPa)	COV
1	24MPa	Ext Value	34.47	0.17
2	30MPa	Beta General	44.66	0.16
3	30MPa	Normal	36.22	0.16

Life cycle cost analysis is one of tools that decision makers normally used to decide the best solution for their objectives. In this study, life cycle cost is calculated from undiscounted fixed repairing cost, variable repairing cost, and failure cost. They are assumed as 1000, 2000, and 5000, respectively for a service life of 100 years. The formula to calculate life cycle cost is shown in Eq. 2. Properties of structures after being repaired are assumed to be similar to that of original structure. Official primary credit discount rate of 6.25% (Federal Reserve [8]), is considered. Safety factor is 1.0 in case of considering actual inspection results in the prediction. However, in case of considering a safety factor, safety factor is set to be 1.3, 1.5, 2.0, 2.5 and 3.0. High safety factor is set to compensate large variation of inspection results.

$$LCC = \sum_{i=1}^{n} \frac{(R_f + R_v \times p_{r,i}) + (C_f \times p_{f,i})}{(1+\nu)^{t_i}} \quad (2)$$

where LCC is expected life cycle maintenance cost, R_f is fixed repairing cost, R_v is variable repairing cost, $p_{r,i}$ is probability of repairing ith time at time t_i, C_f is expected failure cost, $p_{f,i}$ is probability of failure at time t_i, ν is discount rate, and t_i is time of repairing ith time.

As shown in Fig.7, the number of repairing mainly depends on value of safety factor. Higher value of safety factor requires more times of repairing as well higher life cycle cost. In contrast, there are three alternative results of repairing program in case of actual variation of concrete properties is considered. As shown in Fig.8, repairing can be conducted 1 time at 77th year, 2 times at 42nd, and 80th year, or 3 times at 4th, 42nd, and 80th year. Please be noted that the cost of these schedule of repairing is optimized by considering both of number of repairing time and time of repairing. Due to effect of discount rate, the repairing conducted early shows very high life cycle cost.

Table 6 Random variables

Parameters	Mean	Coefficient of variation (Distribution Type)
x	88.34mm	0.22 (Weibull)
D_{cl}	0.92 cm^2/year	0.16 (Normal)
C_{lim}, [9]	0.05 % by mass of concrete	0.10 (Log normal)
C_s	0.35 % by mass of concrete	0.43 (Uniform)
D	1.6 cm	0.015 (Normal)
f_c'	34.3 MPa	0.16 (Normal)
i_{corr}, [7]	2 μA/cm^2	Constant
d_0, [7]	12.5 μm	Constant
α_{rust}, [7]	0.57	Constant
ρ_{rust}, [7]	3600 kg/m^3	Constant
ρ_{st}, [7]	7850 kg/m^3	Constant
f_t', [1]	$0.23 f_c'^{2/3}$	-
E_c, [1]	30.1 GPa	Constant
φ_{cr}, [1]	1.1	Constant
υ_c, [1]	0.20	Constant

The results show that life cycle cost of maintenance program of the structure predicted by considering the actual variation of the inspection results is lower than that of the prediction by considering safety factor.

Fig. 9 shows the reliability of the structure along its service life. In case of considering safety factor, reliability of structure becomes zero at year before repairing. In case of considering variation of structure properties, the actual reliability of the structure can be predicted. Reliability is maintained over 60% of the original performance.

5. CONCLUSIONS

As shown in the inspection results, there are very large uncertainties in the properties of the structures, especially the covering depth. The reason can be lack of quality control, knowledge, or mistake of construction lead to large variation of the result. However, not only the quality of construction but also environment causes uncertainties in durability of RC structure. As shown, the variation of surface chloride content can be seen in both of horizontal direction as well vertical direction. Uncertainties are very significant in the actual condition.

Comparison of life cycle cost of repairing between predictions based on safety factor and prediction by using variation of actual inspection result. It can be concluded that method considering variation of inspection result shows lower life cycle repairing cost than that considering safety factor.

In conclusion, the benefit of the method of maintenance planning with considering the variation of structure properties based on the actual inspection result can be seen over the method of considering safety factor.

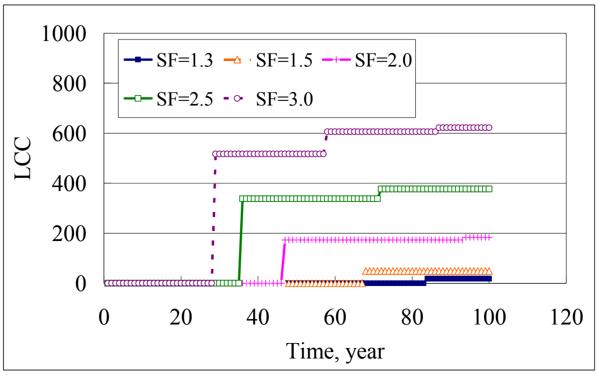

Fig.7 Life cycle cost based on using safety factor

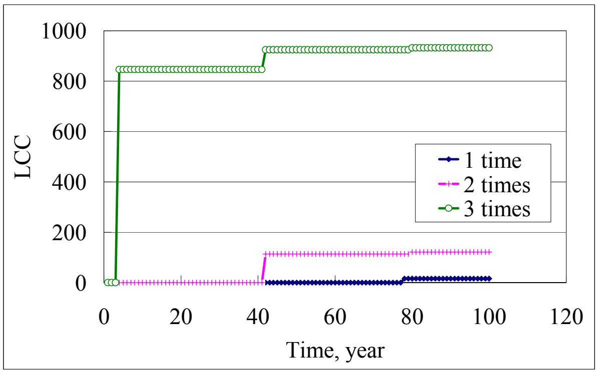

Fig.8 Life cycle cost based on using actual inspection result

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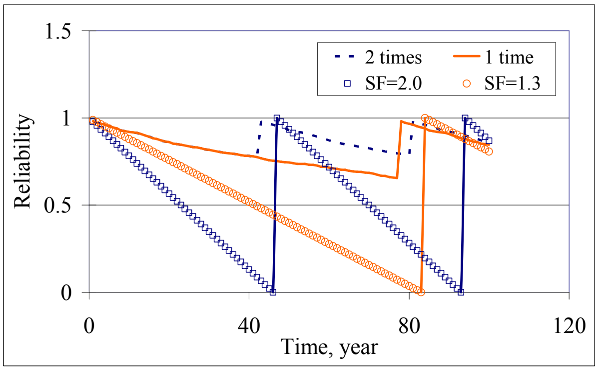

Fig.9 Reliability of structure along service life

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