Proceedings of US-Japan Workshop on
Life Cycle Assessment of Sustainable Infrastructure Materials
Sapporo, Japan, October 21-22, 2009

EXAMPLES OF LIFE-CYCLE MANAGEMENT FOR COASTAL CONCRETE STRUCTURES

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ABSTRACT

Reinforced concrete structures built in coastal areas have to keep their structural performance over required levels in extremely severe marine environments. This can be achieved both with sufficient durability design and maintenance work based on the concept of life-cycle management. Focusing on a reinforced concrete superstructure of open-type wharf, this paper presents the concepts and methodologies of strategic maintenance work based on the life-cycle scenario formulated in relation to the initial durability design.
Keywords: life-cycle management, life-cycle cost, maintenance strategy, coastal concrete structure, prediction, Markovian model.

1 INTRODUCTION

Since Japan is an island country with long coastlines of more than 30 000 km, it is very easy to understand the importance of structures built there. As one of the coastal structures, a port and harbor structure has a long lifetime and must be expected to meet demands during its lifetime that cannot be foreseen. While many port and harbor structures are newly built every year, a great numbers of existing structures require interventions including repair, strengthening, upgrading, or renovation.

Marine areas are very severe for structures from the viewpoints not only of mechanical actions but also of environmental actions. Materials tend to deteriorate relatively rapidly in marine environments and loss of structural performance or even structural collapse may be consequences. The most common and costly deterioration occurring in reinforced concrete (RC) structures in coastal areas is chloride-induced corrosion of steel reinforcement. At the initial design of an RC structure, designers must have several assumptions, in which probably worst conditions are considered, so that the structure can keep its structural performance over required levels. Serious deterioration of structural members may be caused by insufficient durability design with optimistic assumptions against material deterioration and by lack of proper maintenance work after construction of the structure.

To meet these facts, it is extremely important to pursue collaboration between durability design and strategic maintenance. Furthermore, to realize the strategic maintenance, the comprehensive life-cycle management [1] is one of the key technologies. The life-cycle management formulates scenarios for future maintenance work based on the initial durability design level and is followed by verification and/or modification of the scenarios. The life-cycle management includes a series of actions to evaluate the grade of deterioration and structural performance degradation by inspection, to predict the future progress of performance degradation, and to propose the alternatives of appropriate intervention based on life-cycle cost (LCC) minimization or performance maximization under budget capping. This paper introduces the life-cycle management system for an RC superstructure of an open-type wharf that is one of the most vulnerable structures in coastal areas. The methodologies of rational and efficient maintenance work are also mentioned based on scenarios formulated in relation to durability design based on the LCC estimation.

2 MAINTENANCE STRATEGY

It is usually very hard to keep structural performance of a coastal RC structure over required levels for the whole service life because it is exposed to marine environments with rich chloride ion supply. Chloride-induced corrosion and consequent damage can be often seen in RC beams and slabs of open-type wharf. Therefore, sufficient durability design has to be done at the initial design stage, in which some kinds of mitigating measures are needed. One simple measure that anyone can realize is to increase concrete cover, but it seems distant because a concrete cover of about 200 mm or even larger is required. Instead of taking actions only by means of durability design, maintenance work during service period should be linked with it to ensure the structural performance. With thorough durability verification at the design stage and performance assessment at the maintenance work, the structure can keep its structural performance over the requirement.

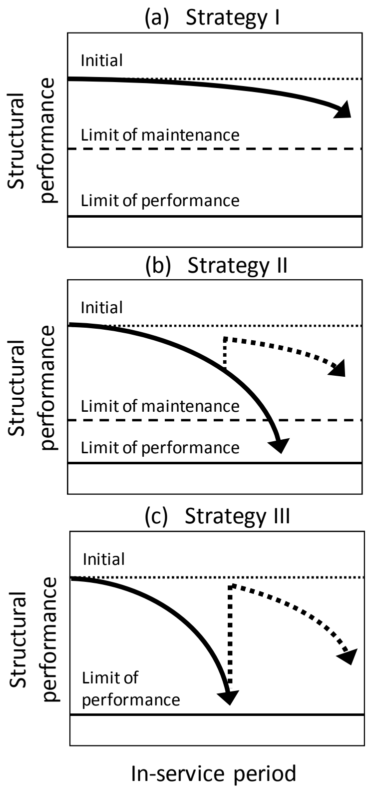

Figure 1: Definition of three maintenance strategies.

For realizing rational and effective maintenance work, a maintenance strategy or scenario should be properly formulated during the durability design of structure before construction or after regular inspection for already existing structure. Importance and substitutability of structure and difficulty of maintenance work should be well taken into account for the strategy-making. Figure 1 shows three kinds of maintenance strategies indicating basic concepts of how structural performance will be guaranteed beyond the performance limit or the maintenance limit. Strategy I is defined that the structural performance is always kept above the maintenance limit during the design working life. This strategy is realized by use of highly durable materials and/or preventive measures. Examples of durable materials and measures are stainless reinforcement, highly durable permanent formwork, extremely high quality concrete, etc. Maintenance work in this strategy is not ignorable even serious deterioration is not expected to occur. Instead, the maintenance is required on the regular-basis including careful monitoring to avoid unexpected deterioration. Strategy II is defined that even performance degradation is expected in the design stage, minor interventions are repeatedly applied before the maintenance limit is reached. In Strategy II, it is necessary to predict the progress of deterioration and formulate maintenance plan based on the result of prediction. Maintenance in this category allows performance degradation due to deterioration at the design stage, but minor intervention should be taken as early as possible when deterioration exposes. Strategy III is a kind of corrective maintenance, in which performance degradation is allowed to occur but major intervention may be applied once or twice for performance recovery.

3 LIFE-CYCLE MANAGEMENT

3.1 Overall Concept

The maintenance work is carried out to assess the present conditions of structure and to quantify the level of structural performance. In addition, by predicting future progress of structural performance degradation, the most appropriate method of intervention is chosen for minimizing the LCC or maximizing structural performance recovery under budget capping. A general procedure of maintenance work is shown in Figure 2, which is based on the life-cycle management (LCM) concept. The life-cycle management system is composed of the following main components:

- Inspection of the present conditions of structural members,
- Assessment of structural performance,
- Prediction of future progress of performance degradation,
- Proposal of method and timing of intervention, and
- Decision-making among proposed alternatives of interventions.

3.2 Judgment of Deterioration

Judgment of deterioration is generally made by a two-step inspection system: the primary (preliminary) inspection and the detailed inspection. The state of deterioration is visually evaluated and judged using the deterioration grade: Grade *d* to *a* [2] or Grade V to O. Grade *d* or O refers to a sound condition without any signs of deterioration, while Grade *a* or V is the most severe deterioration state. For proper judgment, inspection should be carried at with regular intervals.

When the primary inspection is insufficient to provide proper data for assessment, the detailed inspection is recommended to carry out.

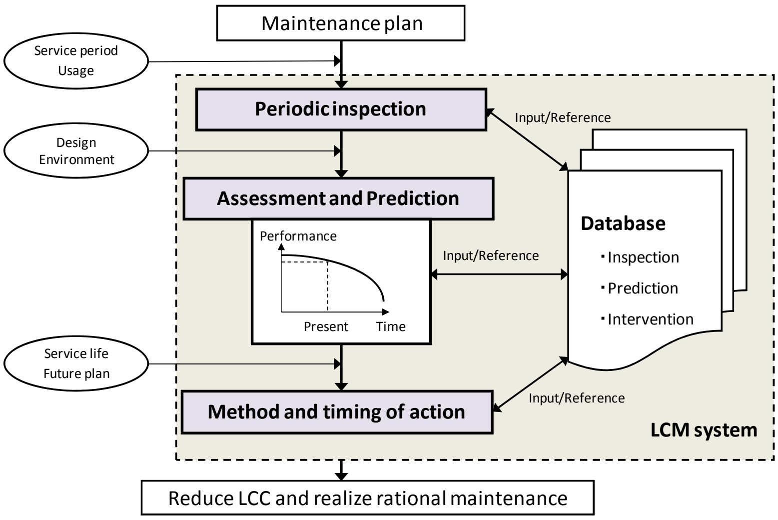

Figure 2: Procedure of life-cycle management.

The detailed inspection includes visual inspection by well-trained divers for submerged parts, measurement with non-destructive or destructive techniques, etc. After the onset of corrosion of steel reinforcement, structural performance will be degraded rapidly. Therefore, material deterioration should be captured before its appearance on the surface of member.

3.3 Assessment

For the life-cycle management, the concept of assessment should be upgraded from condition assessment to performance assessment. Therefore, it is required to quantitatively make overall assessment of a structure from the viewpoint of structural performance. The visual inspection is only able to provide the change in appearance of structural member, but structural performance has to be evaluated as precisely as possible.

The relationship between structural performance (structural capacity) and the grade of deterioration has been studied on RC beams. In particular, the relationship between load-carrying capacity and the deterioration grade has been roughly made clear for the RC beam and RC slab in open-type wharf [3]. When the deterioration grade reaches Grade *b*, structural performance tends to become lower than the design requirement level. These facts are well considered for the overall assessment from the viewpoint of structural performance.

3.4 Prediction

Since deterioration of an RC member is induced and accelerated by chloride ion provided by sea water, the chloride ion profile inside concrete and the volume loss of reinforcement are predicted as main indices for durability performance. The calculation theory based on Fick’s second law of diffusion of chloride ion in concrete has been widely used for the prediction of deterioration progress. For simulating the diffusion of chloride ion in concrete with this theory, it is necessary to quantify four fundamental parameters: threshold value for the onset of reinforcement corrosion; chloride ion content on the surface of concrete, an apparent diffusion coefficient of chloride ion in concrete, and the concrete cover depth.

As the progress of deterioration of a structure differs widely by its location because of inhomogeneous characteristics of materials and diversity of environmental conditions, the proper determination of the surface chloride ion content and the apparent diffusion coefficient is not so easy [4]. For example, the surface chloride ion concentration and diffusion coefficients widely vary with location. The maximum differences of measured results between the adjacent points were about 70 % in the surface chloride ion concentration and more than double in the diffusion coefficient. Therefore, even in one structural member, variability in chloride ion profiles may appear significantly. In the practical investigation of existing structures subjected to marine environments, chloride ion profile of concrete has generally been estimated according to one or a few samples. However, it seems that such a few numbers of concrete cores may not be representative.

These facts indicate that it is practically rather difficult to accurately predict the progress of deterioration and remaining structural capacities by using the diffusion theory. Instead of this, the authors have tried to investigate the applicability of a calculation model to predicting the progress of deterioration by analyzing the variation of visually observed deterioration grades with the Markovian model [5]. This approach is of use to understand the overall tendency of deterioration in consideration of its variation by the experienced progress of deterioration.

In the model, the state and the transition are main components, and a probability of shifting from a certain state to the next state is expressed by a transition probability as shown in Figure 3. The assumptions of the prediction are as follows:

- A structural member belongs to a certain grade of deterioration,
- The grade of deterioration shifts to the next grade in a time step with a certain transition probability, p_x, while the other structures remain in the present deterioration grade with the remaining probability, $1-p_x$,
- These calculations continue step by step during the life span of structure. At the commencement of calculation, the deterioration grades of all structural members are set at Grade *d* or O, and
- Grade *a* or V is the worst condition; that is, the final stage of deterioration.

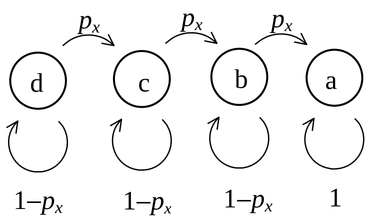

Figure 3: The Markovian model for the prediction.

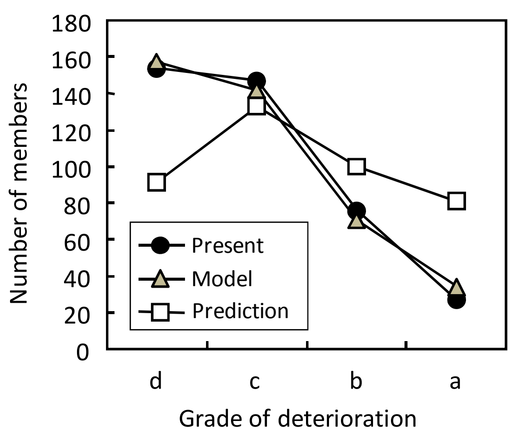

Figure 4: Prediction by the Markovian model.

When a transition probability is determined with good accuracy, the overall trend of future deterioration can be predicted. The transition probability is one of the indices to express the behavior of deterioration progress affected by environments, materials, and so on. When the years in service of each structure were substituted to the number of calculation steps, the most suitable transition probability was found for members so that the calculated result by the model agreed well with the result of actual distribution of deterioration Grades.

The example of application is shown in Figure 4 [6]. This figure shows collected data from all the RC members in a specific port, in which the transition probability is obtained through fitting the actual distribution and simulated distribution. Based on the prediction result after 15 years, the number of members probably judged as Grade *a* may increase up to about 3 times. For the application of the Markovian model to prediction, many data have to be collected and accumulated for members under almost the same environmental, material, and structural conditions.

4 LIFE-CYCLE COST ESTIMATION

4.1 Calculation of Life-Cycle Cost

To determine the maintenance strategy or to consider the appropriate timing and the method of intervention, estimation of LCC is one of the best indices. LCC is calculated for several maintenance scenarios among maintenance strategies. In the calculation, the initial cost, maintenance cost including primary and detailed inspection costs, and the cost of planned intervention are totaled.

An example of estimated LCC is shown in Figure 5 [7]. In Strategy II, all concrete surfaces of slabs and beams are coated, and they are re-coated at the end of the life of the coating material (assumed at 10 years in this figure). In Strategy III, the timing of repair is deferred as much as possible. When the second half of the acceleration period begins 25 years after the completion of the structure, section repair and surface coating are carried out extensively for the relatively deteriorated parts of the structure. It is assumed that the cross sections of 95% of all members are section-repaired. The LCC, thus, calculated is expressed in terms of the ratio to the initial construction cost in the case that a general RC superstructure within Strategy III is constructed. The social discount rate is not taken into account in the calculation.

At the end of design working life (50 years in this calculation), Strategy I has the smallest LCC even its initial cost is largest. It should be confirmed here that the more durable structure in construction, the lower LCC achieved. Since Strategy I is not likely to cause deterioration resulting in performance degradation and only primary inspection is needed, the LCC over a period of 50 years after construction is not significantly higher than the original construction cost. For the scenario considered in Strategy II, one option is to carry out coating at the beginning of construction because deterioration of structures exposed to severe environmental conditions is very fast. It should be noted that this scenario based on Strategy III shows the largest LCC and the amount of incremental increase in cost is so large that single-year costs are far larger than those for the other two scenarios.

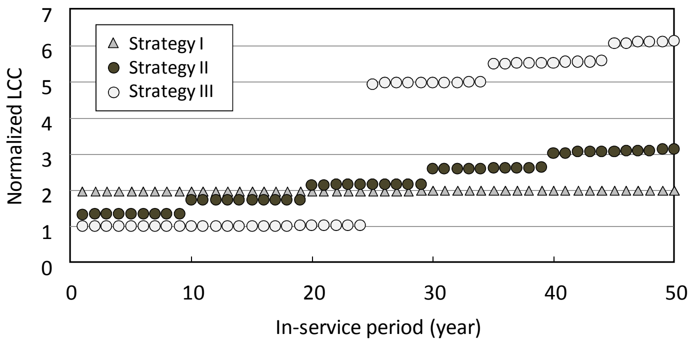

Figure 5: Example of LCC estimation for 50 years.

Table 1: Measured results of polarization resistance and corrosion current.

Kind	Grade before the repair	R_p, kΩcm^2		I_c, μA/cm^2		$I_{c,after}/I_{c,before}$
		Before	After	Before	After	
Section repair	II	91.7	237.0	0.284	0.110	0.387
	III	180.3	1251.9	0.144	0.021	0.144
	IV	135.7	360.6	0.192	0.072	0.376
Cathodic protection	III	42.6	487.9	0.611	0.053	0.087
	IV	261.7	10655.7	0.099	0.002	0.025

R_p: Polarization resistance and I_c: Corrosion current

Table 2: Effects of intervention (repair) to the transition probability.

Kind of intervention \ Grade before repair		O	I	II	III	IV	V	Transition probability after repair
Grade after repair	Section repair	-	-	I	II	II	II	Reduced to 50%
	Cathodic protection	O	O	I	II	II	II	Reduced to 10%
	Partial replacement	-	-	-	O	O	O	Not changed

Table 3: Costs and effects of repair in calculation.

	Section repair	Cathodic protection	Partial replacement
Cost of execution in JPY/m^2	100 000	120 000	400 000
Annual maintenance cost in JPY/m^2	-	300	-
Grade before repair	IV-V	III-IV	V
Design life of repair in year	20	40	-

4.2 Maintenance Strategy Based on LCC

As an example, estimation of LCC and further maintenance strategy based on the estimated LCC is presented [5]. The target structure is an open-type wharf. The RC superstructure has been exposed to chloride rich environment; therefore, the structure suffered from very severe chloride-induced deterioration only 15 years after the construction.

The wharf was inspected two times in 2000 and 2003 and some beams were experimentally repaired in 2002 based on the deterioration grades judged by the inspection. That is, three beams having deterioration grades of II, III and IV were repaired by section repair. Concrete of 150 mm thick from the bottom surface of each beam was removed. The removed part was filled with non-shrinkage mortar after applying rust-proof coating to the reinforcement. Two beams with the deterioration grades of III and IV were repaired by cathodic protection. In the beam having deterioration grade of III, concrete of 150 mm thick was removed in which titan ribbon mesh anodes were then installed. The removed part was filled with non-shrinkage mortar. Almost the same technique was applied to that of Grade IV except being covered by FRP panels. The current density of the both repaired beams was about

25 mA/m^2.

The most suitable transition probabilities, p_x were found for slabs and beams respectively so that the predicted results agreed well with the inspected results in 2000. The most reliable transition probabilities, p_x were found to be 0.113 and 0.213 for slabs and beams respectively. The predicted results agreed well with the inspected results from the viewpoints of their peaks and tendencies. Therefore, the prediction method based on the Markovian model was confirmed to its applicability with reasonable accuracy to the existing wharf.

When the safety and the serviceability of a wharf are presumed to fall below their required levels because of deterioration during the service periods, some interventions should be implemented. Two kinds of interventions are available to use:

(a) To enhance structural capacities as well as to draw back the apparent grade of deterioration, and
(b) To reduce the rate of deterioration.

To predict the future progress of deterioration after taking some interventions, the grade of deterioration, the transition probability, and design service life are required to quantify as precisely as possible.

The effect of interventions to recover or to improve structural performance can be estimated depending on the kind of interventions. The effect of interventions to reduce the rate of deterioration has not been well examined to date, which is depending of the kind of interventions. In this paper, the rate of deterioration was tried to estimate by measuring the polarization resistance at the part of interventions (repair) taken. The polarization resistance was measured by the AC impedance method at the timings of before the repair and 6 months after the repair. The results are summarized in Table 1. The corrosion currents, which is relating to the corrosion rate of reinforcement in concrete, were decreased to less than 0.4 for section repair and less than 0.1 for cathodic protection. These results indicated that the cross section repair is effective to reduce the rate of corrosion of reinforcement. In the prediction, the transition probabilities were assumed to be reduced to 0.5 for section repair and 0.1 for cathodic protection.

In this paper, section repair, cathodic protection, and partial replacement were selected as the alternatives of interventions. The partial replacement was considered as method (a) and the other techniques were categorized in method (b). Table 2 summarizes the effect of each intervention (repair). The assumptions of prediction are as follows:

a) The section repair is applicable when the grade of deterioration is III or higher. After doing section repair, grade II is recovered to Grade I and Grades III or higher are to Grade II by removing chloride contaminated concrete and heavily corroded part of reinforcement. The transition probability after section repair is reduced to 50% of its original probability before the repair.
b) The cathodic protection is applicable to all grades. By taking cathodic protection, the grade of deterioration is recovered as listed in Table 4. In case that the cathodic protection is effectively used, the transition probability is changed to 10 % of its value before the repair.
c) The partial replacement will be done when the grade becomes III or higher. It should be most effective to draw back the structural performance to the almost initial stage, thus the grade of deterioration returns to O, but the transition probability does not change because of the same materials as original ones.

In calculation of the LCC, the unit costs and design life of interventions are assumed as listed in Table 3. Other assumptions in the calculation are summarized as follows:

– The first repair was done in 18 years after the commencement of service,
– The further repair was undertaken when the number of structural members graded V became 20% or more,
– The service period of the member depended on the design life of the repair,
– The repair cost is calculated by multiplying the number of members repaired and the average cost of a typical structural member, and
– The discount rate was not considered in the calculation.

Te results of LCC estimation are shown in Figures 6 and 7 for the slab and the beam respectively. The cost effectiveness greatly varied depending on the kind of repair with its service life. As shown in Figure 6, the slab was required to implement repair once or twice during 50 years even if any kinds of interventions were taken. This was because the deterioration of non-treated slabs progressed resulting in 20 % or more of members having Grade V. Through the comparison of the initial costs, section repair was most economical and cathodic protection was most costly, but from the viewpoint of LCC, section repair was the lowest.

On the other hand in the beam as shown in Figure 7, the cost effectiveness greatly varied depending on the kind of repair with its service life. In the early stage of the service life, the order of the cost was the same as those of the slab. During 50 years, however, the cost of cathodic protection became the lowest. The LCC of partial replacement were about 5 times and of section repair was about 1.7 times as much as that of cathodic protection. Moreover, the frequency of taking repair with the cathodic protection was only 1 time, while those with the sectional repair and the partial replacement were 4 and 7 times respectively. Since the rate of deterioration of the beam was very high, the intervention enabling to reduce the rate of deterioration rate was greatly effective from the viewpoint of LCC minimization.

Figure 8 shows the influence of the threshold grade to implement the cathodic protection on the LCC. In this calculation, the cathodic protection was applied when the deterioration grades were higher than Grades III and IV (Case 1) and Grades IV and V (Case 2). In the early stage of the service life, the cost-effectiveness of Case 2 was higher than that of Case 1. However, in 50 years, Case 1 was more effective than Case 2.

From these calculated results, it was recognized that the deterioration rate, the remaining life of the structure, and the threshold grade for conducting repair work had large influences on the calculated LCC. The most suitable life-cycle scenario can be chosen based on the estimated LCC.

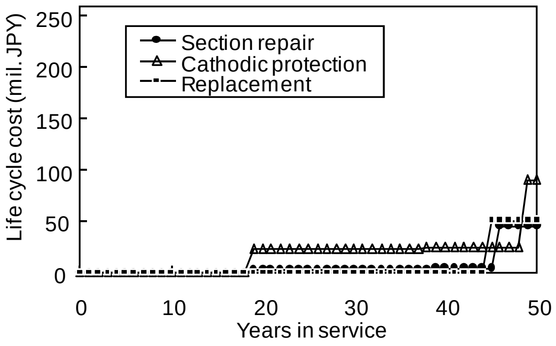

Figure 6: Estimated LCC of slabs.

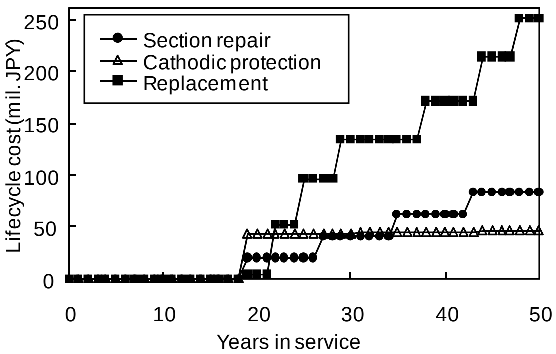

Figure 7: Estimated LCC of beams.

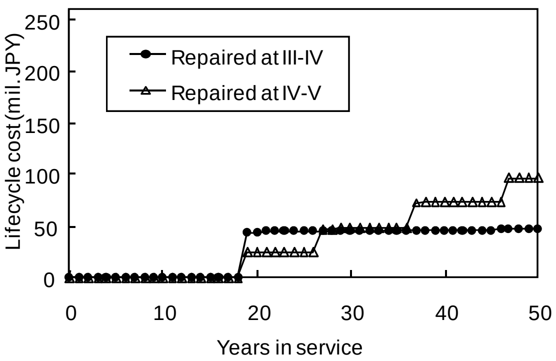

Figure 8: Influence of the timing of repairs taken on LCC.

5 CONCLUDING REMARKS

The life-cycle management system including prediction of the progress of deterioration was developed and being implemented for maintenance of civil infrastructure including port and harbor structures in Japan. After modification of the original system, the authors expect that rational and effective maintenance is realized so that LCC reduction and performance maximization can be attained.

The deterioration grade has not been judged objectively in fact, because lots of local inspectors have been involved in the investigation done by their eyes. However, considering with the probabilistic approach may produce reasonable outputs for the estimation. The nationwide survey is now still continued for collecting the deterioration states of concrete members in various conditions. By utilizing the accumulated data, the more accurate modelling on the deterioration progress is expected to realized, which will be published in the future.

REFERENCES

[1] H. Yokota, M. Iwanami, T. Yamaji, and E. Kato: Maintenance Strategy of Harbor Structures in Japan Based on Life-Cycle Management, Lifetime Engineering of Civil Infrastructure, No. 2, pp. 229-238 (2008)

[2] Port and Airport Research Institute: Manual on Maintenance and Rehabilitation of Port and Harbor Facilities, Coastal Development Institute of Technology (2007)

[3] H. Yokota and E. Kato: Performance Evaluation of Corroded RC Beams, Proceedings of 2008 KCI-JCI-TCI Symposium on Assessment of Existing Structures and Recent Advancements in Concrete Engineering, Ilsan, pp. 10-18 (2008)

[4] H. Yokota: Variability in Chloride-Induced Deterioration of Marine Concrete Structures", Proceedings of International Seminar on Durability and Lifecycle Evaluation of Concrete Structures-2006, Higashi-Hiroshima, pp. 41-50 (2006)

[5] H. Yokota, K. Komure and H. Takahashi: Lifecycle Management of Concrete Deck by Markov Model, Lifetime Engineering of Civil Infrastructure, pp. 137-149 (2006)

[6] H. Yokota and K. Komure: Estimation of Structural Deterioration Process by Markov-Chain and Costs for Rehabilitation, Life-Cycle Performance of Deteriorating Structures, ASCE, pp. 424-431 (2003)

[7] Japan Society of Civil Engineers: Example of Design Calculations Based on JSCE Standard Specifications for Concrete Structures. JSCE Guidelines for Concrete, No.10 (2007)