APPLICATION OF DETERIORATION MONITORING SYSTEM TO CONCRETE SUPERSTRUCTURE OF OPEN-TYPE WHARF

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ABSTRACT

To improve the reliability of performance evaluation of concrete structures, application of the deterioration monitoring system, which detects initiation of deterioration and deterioration rate quantitatively and non-destructively, is one of the most effective methods. However, applying the deterioration monitoring system to all reinforced concrete (RC) structural members in a structure is very difficult in light of cost-effective maintenance implementation although, ideally, all members should be monitored to ensure the performance evaluation of the target structure.

In this study, the authors analyzed relationships between deterioration rate and location of RC members in the superstructures of 12 open-type wharves. Then, the priority of applying the deterioration monitoring system was examined to determine the RC members that should be monitored for achievement of strategic maintenance. By comparing the deterioration rates of the RC beams and slabs at each location, efficient sensor installation in a superstructure of an open-type wharf was proposed.

Keywords: Open-type wharf, deterioration monitoring system, deterioration rate, location of RC member.

1. INTRODUCTION

The concrete superstructure of an open-type wharf is generally exposed to severe corrosion environmental conditions. These structures need to be maintained appropriately so as to keep the required level of performance throughout their service lives. For this purpose, periodic inspection plays a crucial role in the series of maintenance works to evaluate the present performance of structures. In the general periodic inspection of concrete superstructures, the appearance of the bottom surfaces of RC beams and slabs are visually observed and evaluated to determine the deterioration grade from the viewpoint of corrosion of the reinforcing bars.

To improve the reliability of performance evaluation of a superstructure, application of the deterioration monitoring system, which detects initiation of deterioration and deterioration rate quantitatively and non-destructively by sensors embedded into concrete, such as corrosion sensor, is

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one of the most effective methods. However, the deterioration monitoring system has been applied to only a few port RC structures to date, because the effective and efficient sensor installation in a real structure has not been made clear. Applying the deterioration monitoring system to all RC members in a structure is very difficult in light of cost-effective maintenance implementation although, ideally, all members should be monitored to ensure the performance evaluation of the target structure.

In this study, the authors analyzed the relationships between deterioration rate and location of RC members in superstructures of 12 open-type wharves serviced for more than 20 years. By comparing the deterioration rates for each type and each location of RC members, the priority of applying the deterioration monitoring system was examined to determine the RC members in a superstructure that should be monitored for achievement of strategic maintenance.

2. TARGET STRUCTURE AND EVALUATION METHOD

To detect the RC beams and slabs in which the deterioration rate is high, deterioration grade distributions of the total of 126 blocks in the superstructures of 12 open-type wharves located in several ports were analyzed. Table 1 lists the outline of target structures. Material properties and arrangements of reinforcing bars in the RC members of all the target structures have not been recorded, unfortunately. As additional information, service condition, environmental condition and size of the RC members in those structures were different respectively.

Table 1: Outline of target structure

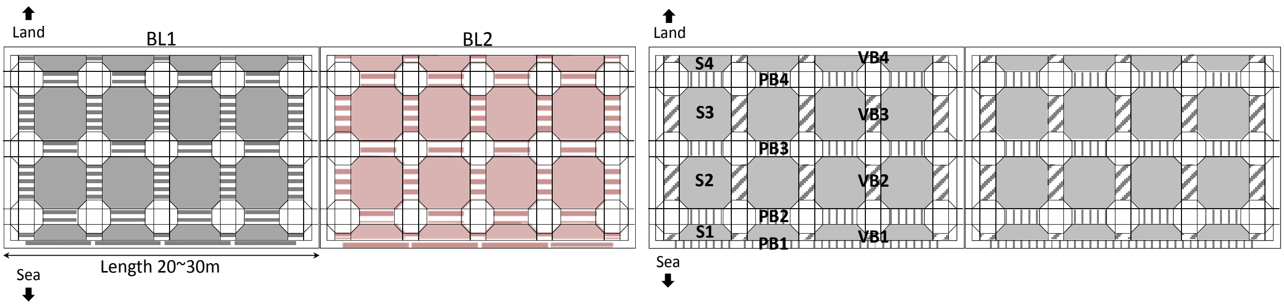
No.	Port	BL	Elapsed service year	Outlines of target facilities			
				Ave. tide level L.W.L (m)	Ave. tide level H.W.L (m)	Direction of quay wall	Ave. temperature
A	O	11	34	0	1.70	E	16.9
B	O	10	34	0	1.70	E	16.9
C	O	12	32	0	1.70	E	16.9
D	O	10	31	0	1.70	E	16.9
E	O	6	30	0	1.70	E	16.9
F	O	6	26	0	1.70	E	16.9
G	M	10	31	0	0.30	NE	14.8
H	HN	9	33	0	0.65	SW	13.6
I	Y	11	31	0	2.00	NW	15.8
J	T	15	29	0	1.50	SE	7.6
K	CN	13	30	0	2.60	E	15.8
L	CN	13	30	0	2.60	E	15.8

Table 2: Criteria of deterioration grade

Grade	0	I	II	III	IV	V
Steel bars' corrosion	No	Localized spotted rust stain	small extent of rust stain	Much rust stain	Heavy rust stain	Large extent of rust stain
Crack	No	Only a few small cracks	Some cracks	Many cracks	Many wide cracks	–
Cover concrete	OK	OK	Partial delamination	Partial spalling	Spalling	Large extent of spalling

Table 2 lists the criteria of deterioration grade for RC members in a superstructure of an open-type wharf, provided in the Maintenance Manual of Harbor Structures (Port and Harbour Research Institute. 1999). Deterioration grades 0~V for RC members in all target structures were visually judged according to the criteria.

In general, maintenance work on the superstructure of an open-type wharf is carried out on each block; that is, the deterioration rates of RC beams and slabs are evaluated in each block as shown in Figure 1a). In this study, the deterioration rate at each relative location in a superstructure, as shown in Figure 1b), was evaluated in addition to the representative deterioration rates of RC beams and slabs for each block. RC members were classified into three types, parallel beams against face line (PB), vertical beams against face line (VB), and parallel slabs against face line (S). The relative location of the RC member from the face line was indicated by number. For example, PB2 is a beam located in the second parallel line from the face line.



a) General evaluation **b) Evaluation in this study**

Figure 1: Unit of evaluation

The distributions of deterioration grades of a superstructure generally show very wide variations. To understand the overall tendency of the deterioration progress, the Markovian chain model was applied (Yokota and Komure. 2003). In this study, each deterioration grade was divided into three sub-grades; then the Markovian chain model with 18 sub-grades was applied to the distributions of deterioration grades of RC members. When the deterioration sub-grades of all RC members are set to grade 0_1 at the commencement and the deterioration sub-grade shifts to the next sub-grade in a time step with a certain transition probability, P_x, fixed to respective constant values for the all RC members, the distribution of the deterioration grades after t years was calculated by Equation (1).

$$\begin{pmatrix} 0_1 \\ 0_2 \\ 0_3 \\ \vdots \\ V_1 \\ V_2 \\ V_3 \end{pmatrix} = \begin{pmatrix} 1-P_x & 0 & 0 & \cdots & 0 & 0 & 0 \\ P_x & 1-P_x & 0 & \cdots & 0 & 0 & 0 \\ 0 & P_x & 1-P_x & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1-P_x & 0 & 0 \\ 0 & 0 & 0 & \cdots & P_x & 1-P_x & 0 \\ 0 & 0 & 0 & \cdots & 0 & P_x & 1 \end{pmatrix}^t \begin{pmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{1}$$

In this study, the most suitable transition probability P_x was found for RC members so that the calculated result by the model, ($0 = 0_1 + 0_2 + 0_3$, …, $V = V_1 + V_2 + V_3$), agreed well with the result of actual distribution of deterioration grades (0, …, V) at the elapsed service year.

The transition probability P_x is one of the indices to express the behavior of deterioration rates affected by environments, materials, and so on (Yokota and Komure. 2003). In the following discussions, the transition probabilities of RC members were employed as the deterioration rate of those. Focusing on the deterioration rates of RC beams and slabs in each block and those of RC members at each location, the priority of applying the deterioration monitoring system in a concrete superstructure of an open-type wharf was discussed.

3. DISCUSSIONS

3.1. Deterioration rate in each block

3.1.1. Deterioration rate of RC beam and slab

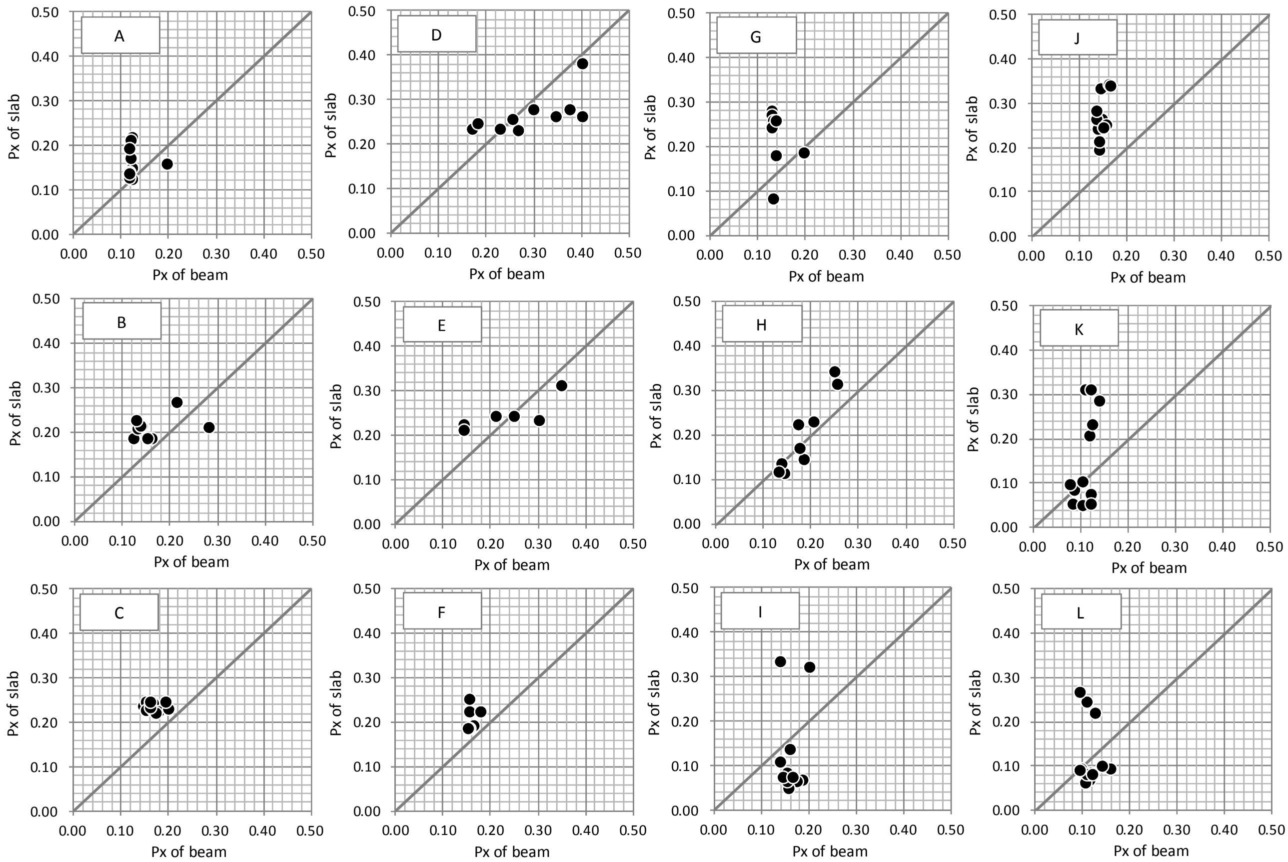


Figure 2: Deterioration rate of RC beams and slabs

Figure 2 shows the deterioration rates of RC beams and slabs in all blocks of each structure. X and Y axes show the deterioration rate of RC beams and that of RC slabs, respectively. When the deterioration rate of RC beams is equal to that of RC slabs in a block, that data is plotted on the straight line shown in Figure 2. In comparing the deterioration rates of RC beams and those of RC slabs, almost all plots are on the line in C, F and H; that is, the deterioration rates of RC beams and those of RC slabs in each block were roughly the same in those structures, respectively. In A, B, G, J and K, deterioration rates of RC beams were smaller than those of RC slabs in almost all blocks in each structure. In D and E, deterioration rates of RC beams were widely distributed compared with those of RC slabs. Whether the deterioration rate of RC beams and that of RC slabs becomes higher was not easily evaluated. It could be concluded that the priority of applying the deterioration monitoring system should not be determined by the type of the RC member, beam or slab.

3.1.2. Influence of overall environmental condition on deterioration rate

In general, the deterioration rate of RC member becomes high when the member is exposed in high environmental temperature. The deterioration rate is also influenced by chloride ion supplying and sunshine. Therefore, it is considered that the average temperature, the tide level and the direction of the face line affect the deterioration rate of RC members in the superstructures. However, the correlation between deterioration rates shown in Figure 2 and the overall environmental conditions of the target structures listed in Table 1 were not clearly found in all target structures in this study. At present, it is very difficult to determine the priority of applying the deterioration monitoring system by considering the overall environmental condition of the structures.

3.2. Deterioration rate at each location

3.2.1. Deterioration rate and distance from sea surface

In the durability verification against corrosion initiation in the RC members of an open-type wharf (Overseas Coastal Area Development Institute of Japan. 2007), the chloride ion concentration at the concrete surface is evaluated by Equation (2), which is based on a site survey and long-term exposure tests (Yamaji et al. 2008).

$$C_0 = -6.0\ X + 15.1 \tag{2}$$

Where, C_0: chloride ion concentration at the concrete surface (kg/m^3), X: distance from the bottom surface of RC member to the high water level (H.W.L.) (m).

Equation (2) suggests that the chloride ion supply to concrete surface linearly increases with decrease in the distance from the bottom surface of RC member to H.W.L.

Figure 3 shows the relationship between deterioration rates of RC members and distance from the bottom surfaces of RC members to H.W.Ls. in each structure. In general, When the type (PB, VB and S) and the relative location from the face line (indicated by number) are the same, the distance from bottom surface and H.W.L. are equal in those RC members. Hence, deterioration rates in Figure 3 show those at each relative location in each superstructure, respectively. Figure 3 clearly shows that deterioration rates were not directly related to the distances from the bottom surfaces of RC members to H.W.Ls. Deterioration grade was judged from the appearance of the concrete surface caused as a result of corrosion of reinforcing bars due to chloride attack. This result indicates that the deterioration rate doesn't necessarily become high by increasing the chloride ion supply to concrete surface. It could be concluded that the priority of applying the deterioration monitoring system should not be determined by the distance from the bottom surface and H.W.L. of the RC member.

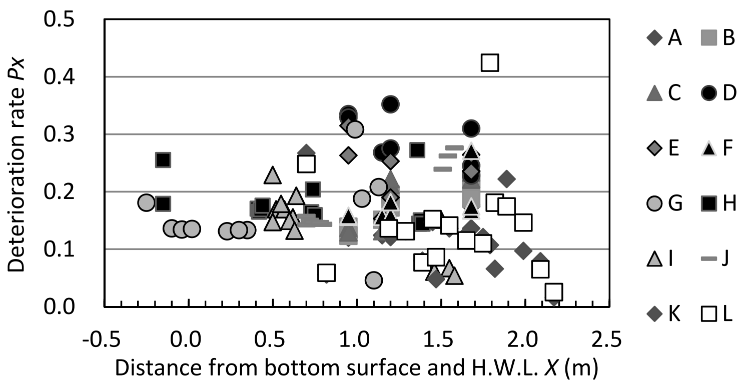


Figure 3: Deterioration rate vs. distance from bottom surface and H.W.L.

3.2.2. Deterioration rate at each relative location in superstructure

Table 3: Deterioration rates at each relative location in superstructure

No.	PB1	PB2	PB3	PB4	PB5	PB6	VB1	VB2	VB3	VB4	VB5
A	No data	0.120	**0.124**	0.120	−	−	No data	**0.126**	0.121	−	−
B	No data	0.139	**0.151**	0.123	−	−	No data	0.172	**0.195**	−	−
C	No data	**0.137**	0.131	0.129	−	−	No data	0.212	**0.222**	−	−
D	No data	**0.335**	0.268	0.329	−	−	No data	**0.352**	0.275	−	−
E	No data	**0.315**	0.153	0.263	−	−	No data	0.190	**0.253**	−	−
F	No data	0.156	0.156	**0.158**	−	−	No data	0.158	**0.182**	−	−
G	**0.181**	0.136	0.134	0.135	0.133	−	0.131	**0.133**	No data	−	−
H	**0.255**	0.170	0.165	0.169	0.176	−	0.179	0.164	**0.204**	0.159	−
I	**0.229**	0.169	0.169	0.155	0.193	−	0.147	**0.179**	0.149	0.132	−
J	**0.157**	0.150	0.146	0.143	−	−	0.142	**0.147**	0.146	−	−
K	**0.267**	0.147	0.136	0.125	0.121	0.107	0.056	0.127	**0.131**	0.080	0.048
L	0.248	0.152	0.141	0.115	0.110	**0.424**	0.059	**0.136**	0.131	0.077	0.086

No.	S1	S2	S3	S4	S5
A	No data	**0.177**	0.174	0.136	−
B	No data	**0.222**	0.217	0.188	−
C	No data	**0.261**	0.233	0.221	−
D	No data	**0.310**	0.245	0.228	−
E	No data	**0.264**	0.236	0.235	−
F	No data	0.167	0.174	**0.271**	−
G	**0.308**	0.188	0.046	0.208	−
H	**0.272**	0.144	0.150	0.144	−
I	0.061	**0.151**	0.067	0.054	−
J	0.239	0.262	**0.276**	−	−
K	0.066	**0.222**	0.097	0.079	0.016
L	**0.181**	0.174	0.146	0.065	0.025

—: No RC member exists.
Bold: highest P_x in each type of RC member.
Underline: highest P_x in a facility.

Table 3 lists the deterioration rates of PB, VB and S at each relative location in the superstructures. The highest P_x in each type and those in the target facility are shown in bold-faced and underlined text, respectively. The distributions of P_x show wide variations in the types and in the target facilities as well. In type PB, the highest P_x was mostly observed in PB1 and PB2. In type VB, the highest P_x was observed in VB2 or VB3. In type S, the highest P_x was mostly observed in S1 and S2. In the case of the highest P_x in the target structures, 4 data in PB, 1 data in VB and 7 data in S were observed, respectively.

Table 4 lists the frequencies of the highest deterioration rate at each relative location and those in each structure. Although the total number of P_x data was different according to the location of the RC member, the authors tried to simply detect the location of the RC member at which the deterioration rate becomes higher in a superstructure of an open-type wharf.

Focusing on C_l/C_{total} listed in Table 4, deterioration rates at PB1, VB3 and S2 tended to be higher than those at other relative locations in each type, respectively. As for C_f/C_{total}, C_f/C_{total} at PB6 shows the highest ratio, although there are only a total of 2 data at PB6. PB6 was located on the landward side; therefore, the reflection wave probably influenced the deterioration rate. Except for C_f/C_{total} at PB6, C_f/C_{total} at PB1, S1 and S2 were higher than those at other locations. In the case of PB1, RC beams were directly exposed to wave splash, wind and insolation. In the case of S1 and S2, it seems that the deterioration rates were influenced by sea breezing from offshore and splashing wave from PB1.

Table 4: Frequency of highest deterioration rate at relative location

	PB1	PB2	PB3	PB4	PB5	PB6	VB1	VB2	VB3	VB4	VB5	S1	S2	S3	S4	S5
C_{total}	6	12	12	12	5	2	6	12	11	4	2	6	12	12	11	2
C_l	5	3	2	1	0	1	0	6	6	0	0	3	7	1	1	0
C_f	2	1	0	0	0	1	0	1	0	0	0	2	3	1	1	0
C_l/C_{total}	83%	25%	17%	8%	0%	50%	0%	50%	55%	0%	0%	50%	58%	8%	9%	0%
C_f/C_{total}	33%	8%	0%	0%	0%	50%	0%	8%	0%	0%	0%	33%	25%	8%	9%	0%

C_{total} :Total number of P_x data.
C_l :Number of highest P_x data in each type of RC member.
C_f :Number of highest P_x data in a structure.

4. DETERIORATION MONITORING SYSTEM FOR COST-EFFECTIVE MAINTENANCE

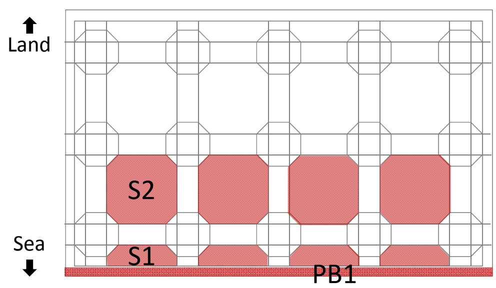


Figure 4: RC member with higher deterioration rate

In this study, it was found that it was possible for PB1, S1 and S2 (shown in Figure 4) to have a higher deterioration rate than other RC members. Therefore, the priority of the deterioration sensor installation in a superstructure of an open-type wharf becomes higher at those RC members. The symptoms of deterioration in a superstructure will be efficiently detected by applying the deterioration monitoring system to those RC members. As a result, remedial measures, such as performing detailed inspection and repair work, can be planned in the early stage of deterioration process. Generally, the earlier appropriate repair work is performed, the higher its effect will be and, in turn, the higher becomes the possibility of cost-effective maintenance implementation on an open-type wharf.

5. CONCLUSIONS

By comparing the deterioration rates of RC beams and slabs at each location in superstructures of 12 open-type wharves, the priority of applying the deterioration monitoring system was discussed for achievement of the strategic maintenance. As a consequence, the following conclusions were obtained:

1. Type and relative location of RC member must be considered in the prioritization of applying the deterioration monitoring system.
2. The first sea-side parallel beam, the first and the second sea-side slabs should be monitored to detect symptoms of deterioration in a superstructure.

The deterioration rates at each location analyzed in this study were obtained from a limited number (12) of facilities in Japan. The deterioration rate of a superstructure is generally different due to its service conditions, environmental conditions, scale, and so on. Therefore, it is difficult to apply the proposed priority of the deterioration sensor installation in a superstructure to all superstructures of various open-type wharves. The prioritization of deterioration monitoring application in RC superstructures needs more investigation and is still open to discussion. However, the authors consider that the simplified prioritization proposed in this study will contribute to promote the strategic maintenance of port concrete structures.

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