OPTIMIZATION OF MAINTENANCE STRATEGY OF PORT MOORING FACILITIES IN TERMS OF COST, BENEFIT AND CARBON DIOXIDE EMISSIONS

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1. INTRODUCTION

Maintenance of port facilities is a serious issue since they are subjected to harsh conditions in terms of corrosion. Mooring facilities play a key role in cargo handling. They are required to be effectively maintained over their service lives to avoid facility breakdowns that adversely affect port operation. Our previous study proposed a Net Present Value (NPV) as an indicator for decision-making of comprehensive maintenance strategies for mooring facilities, based on the cost-benefit analysis[1)]. It was reported that preventive maintenance is required to reduce life-cycle cost (LCC) as well as to avoid the risk of facility breakdown. On the contrary, the environmental impact should be reduced in terms of sustainability. Reduction in CO_2 emission is strongly required for infrastructure sectors. Therefore, optimization in terms of cost, benefit and life-cycle CO_2 emission ($LCCO_2$) is especially important to achieve the goal. Concrete Library No. 134 published by JSCE[2)] offers a possible direction that CO_2 emission not only from construction but also maintenance and repair should be reduced. Such the approach is expected to be accelerated. In this context, this paper presents a trial approach to assess the maintenance strategy from the viewpoint of economic and environmental aspects.

2. METHOD

Several maintenance strategies of the Y port for 50 years from 2015 were assumed and assessed with three indicators, LCC, NPV, and $LCCO_2$. The procedures are described below.

2.1 Outlines of the facilities and calculation of progress of deterioration

Five pile-deck type mooring facilities were selected as a model case. The facility profiles are outlined in Table 1. All of the facilities are comprised of a reinforced concrete (RC) superstructure (beams and slabs) and steel pipe piles. The maintenance strategy of Y port for 50 years from 2015 was drawn up.

2.2 Calculation of deterioration progress

Progress of deterioration can be predicted with the assumption that the deterioration grade follows the simplified Markov chain process using the deterioration grades, which was obtained by visual inspection. The transition probability p_x of each facility, identified by fitting the model to the proportion of the grades, is shown in Table 1. Since the overall deterioration of the facility should be evaluated in consideration with deterioration grades of all structural components of the facility, a numerical index to represent the overall deterioration state, D_p is introduced in this study. D_p can be calculated by using Eq. (1), assuming that the coefficients of 4, 3, 2, and 1 are taken for weighing the corresponding grades of condition.

$$D_{p,t} = 1\times P_{d,t}+2\times P_{c,t}+3\times P_{b,t}+4\times P_{a,t} \qquad (1)$$

For calculating the deterioration progress, the variation of p_x was considered. The probability density of p_x was assumed to conform to a lognormal distribution. The mean values of the p_x for each facility are presented in Table 1, and the standard deviation was 0.638 according to the previous study[3)]. The calculation was performed 10,000 times.

2.2 Maintenance strategy and calculation of LCC, NPV & $LCCO_2$

Six maintenance strategies were set, as shown in Table 2. The threshold for repair was assumed to be a function of D_p. Therefore, when the calculated D_p exceeds the threshold, the repair was performed in the calculation. Note that, after applying the surface coating, p_x was halved from its original value[4)]. According to the strategies, LCC, NPV, and $LCCO_2$

Table 1 Profiles of the mooring facilities (Y port)

Facility		Y1	Y2	Y3	Y4	Y5
Year of construction		1988	1981	1976	1994	2000
Year of inspection		2013	2013	2004	2010	2008
Proportion of grades	d	0.126	0.676	0.695	0.818	0.183
	c	0.566	0.311	0.294	0.179	0.705
	b	0.282	0.013	0.011	0.002	0.112
	a	0.025	0	0	0	0
Overall deterioration index (D_p)		2.206	1.337	1.316	1.184	1.93
Transition probability (p_x)		0.231	0.063	0.069	0.093	0.473
Annual benefit (billion JPY)		1.63	0.2	0.8	0.56	0.39

Keywords: Maintenance strategy, Life-cycle cost (LCC), Net Present Value (NPV), CO_2 emissions
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were calculated. NPV includes benefits as well as cost. During repair work, cargo-handling operations may be restricted, resulting in a benefit loss for the port, which was taken into account, according to the previous study [1]. The repair cost and the annual benefit for each facility were adopted from the previous study[1]. The social discount rate was set at 4.0%. The inventory data of CO_2 emission of each repair method are given in Table 3, based on a reference[2].

Table 2 Maintenance strategies

Type	Repair method
P: D_p=2.0	Surface coating (70%)
C1: D_p=2.2	Patch repair (small:70%) + Type P
C2: D_p=2.4	Patch repair (small:45.5%; large:24.5%) + Type P
C3: D_p=2.8	Patch repair (small:10.5%; large:59.5%) + Type P
C4: D_p=3.0	Patch repair (large:70%) + Type P
R: D_p=3.5	Replacement

3. RESULTS & DISCUSSIONS

The relationship between LCC and $LCCO_2$ of Y port, including 5 facilities, is shown in Figure 1. In terms of minimization of LCC and $LCCO_2$, Type P strategy (preventive maintenance) shows the minimum average values both for LCC and $LCCO_2$, suggestive of the best strategy in this study. Type R is the second-best strategy in terms of minimization of LCC and $LCCO_2$, although the standard deviation of $LCCO_2$ is the largest. When corrective maintenance (Types C1-C4) is applied, both LCC and $LCCO_2$ increases. The standard deviations are also larger than preventive maintenance. Among Types C1-C4, the best strategy in terms of LCC is different from that of $LCCO_2$. For instance, focusing on the average value, Type C1 shows the lowest $LCCO_2$ but the second-worst LCC whilst the opposite tendency can be found in Type C4.

The relationship between NPV and $LCCO_2$ of Y port is shown in Figure 2. It can be interpreted that the data plotted to the bottom right of the graph is the optimum solution since NPV should be maximized whilst $LCCO_2$ minimized. From the figure, Type P turned out to be the best solution in terms of minimizing LCC and $LCCO_2$ and maximizing NPV. On the contrary, Type R strategy, which is the second-best strategy in Figure 1, shows a drastic reduction in NPV, since the facility with higher D_p should suspend the operation during repair works. Also, Type R shows the highest standard deviation. Among corrective maintenance strategies, Type C1 is the best. The standard deviations of Types C1 and C2 are larger than those of Types C3 and C4. This is because the number of repair works during their service lives is different. The distribution of repair cost of Y1 is shown in Figure 3. In Types C1 and C2, depending on the variation of p_x, the facility is required to be repaired two or three times to keep below the threshold D_p. Therefore, larger variations are found in Types C1 and C2.

From the trial calculations, it is emphasized that preventive maintenance is the optimum strategy in terms of minimizing LCC and $LCCO_2$ as well as maximizing NPV. When corrective maintenance strategy is applied, it depends on which cost/benefit indicator is used whilst lower threshold D_p is desirable to reduce $LCCO_2$.

Table 3 CO_2 emission for repair

Repair method	Unit	kg-CO_2/unit
Surface coating	m^2	9.649
Patch repair (small)	m^2	29.86
Patch repair (large)	m^2	59.72
Replacement	m^3	368.81

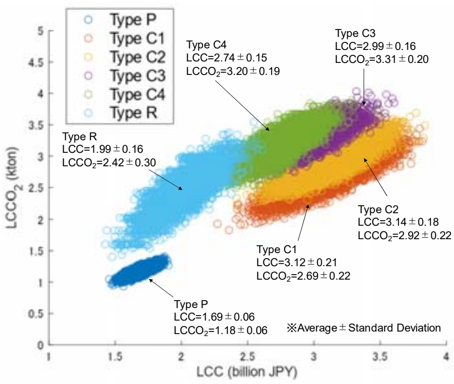

Figure 1 LCC vs. $LCCO_2$ (Y port)

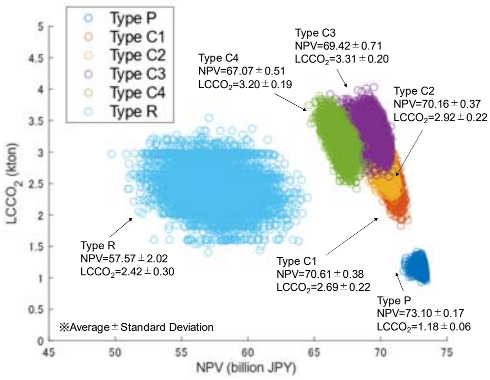

Figure 2 NPV vs. $LCCO_2$ (Y port)

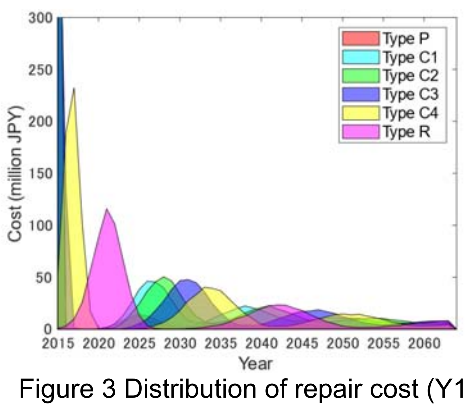

Figure 3 Distribution of repair cost (Y1)

4. CONCLUDING REMARKS

Several maintenance strategies including preventive and corrective maintenance strategies, were assessed with LCC, NPV, and $LCCO_2$. The results showed that preventive maintenance strategy is favored from the viewpoint of $LCCO_2$ reduction. Although refined simulation will be necessary, it should be emphasized that discussions on maintenance strategy in terms of environmental aspect as well as economic one will be more important.

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