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Infrastructure Asset Management System for Bridge Projects in South Korea

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Abstract

While there have been many studies on life cycle cost analysis and preventive maintenance planning, this study proposes an innovative method of bridge asset management in South Korea. Two different levels of approaches were used in this study. First, in the level of bridge elements, deterioration modeling and optimized maintenance repair and rehabilitation (MR&R) planning on bridge assets are proposed, using the bridge historical data of Han River in the city of Seoul. Second, the network level of bridge asset management is suggested, using historical MR&R cost and budget, overall-condition assessment results, and health index data. These two levels of approaches were developed into an Internet-based application so that facility managers can use them to review their past budgets and to plan their future budget based on historical data.

Keywords: *bridge management system, asset management, markov chain, life cycle costs, deterioration modeling*

1. Introduction

The purpose of infrastructure maintenance is to prevent casualties and significant loss of Social Overhead Capital (SOC) and to offer stability, thereby ensuring a balanced service to the users. In other words, the core of infrastructure maintenance is preventive maintenance through the performance of timely maintenance actions. The basic procedure for preventive maintenance is, first, to predict the deterioration of the elements of the infrastructure, and then, to establish a maintenance plan for the infrastructure (Hong and Hastak, 2005; Hong and Hastak, 2007).

Many studies have been conducted to develop a method for the deterioration prediction of infrastructure. Early studies focused mainly on deriving the deterioration rate of an element from the viewpoint of material research. Cady and Weyers (1984) suggested a procedure for calculating the deterioration rate of a concrete bridge deck based on the test data of the corrosion process. Veshosky *et al*. (1994) conducted a comparative research focusing on the deterioration rates of various materials of the upper structure of a bridge, via regression analysis. These researches, however, which were based on the deterioration rate, had limitations in terms of the accuracy of their prediction. As an alternative, Cesare *et al.* (1992) suggested a deterioration prediction framework based on real bridge data, through the Markov chain method, where the accuracy of the deterioration prediction model depends on the reliability of the data regarding the deterioration process of the infrastructure. Therefore, high-quality data are required for this method (Durango-Cohen, 2004). Due to the difficulty of obtaining such high-quality data, the researches that used the Markov method are limited, such as researches on the development of a deterioration model of an element (Hong and Prozzi, 2006; Morcous *et al*., 2003; Veshosky *et al*., 1994) and researches focusing only on theoretical methods for the development of the deterioration model (DeStefano and Grivas, 1998; Morcous *et al*., 2002; Ortiz-Garcia *et al*., 2006). In addition, for the same reason, it is difficult to predict the detailed maintenance cost via Life Cycle Cost Analysis (LCCA) (Cesare *et al.,* 1992).

The Markov Decision Process (MDP) has been applied in the popular software PONTIS and in existing bridge asset management systems made by the IABMAS Bridge Management Committee and PIARC during the last decade. Generally, the MDP is used for modeling deterioration in civil engineering facilities, such as bridges, pavements, and waste water systems. The MDP means the process of solving the problem with the concept of the zone (infinite horizontal time) and a statistical dynamic programming (Winston, 1994). In the MDP, the next state depends on the decisions made in the current state rather than the previous state.

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The MDP consists of four steps: (i) state space; (ii) decision set; (iii) transition probability; and (iv) expected costs.

However, various problems need to be solved based on the five perspectives enumerated below (Butt *et al.*, 1987; Cesare *et al.*, 1992; DeStefano and Grivas, 1998; Jiang and Sinha, 1989; Morcous *et al.*, 2002; Morcous *et al.*, 2003; Ortiz-Garcia *et al.*, 2006; Thompson and Johnson, 2005).

1. A bridge as a single structure needs to be divided into several elements to develop a transition probability matrix. It should also be able to estimate the deterioration curve.
2. The deterioration curve should be developed based on historical data of the bridge element, and its future performance needs to be accurately predicted using the curve. Therefore, the element breakdown structure for data collection needs to be established properly.
3. Since the environment affecting the deterioration of an infrastructure changes with time, the zoning concept needs to be applied to address this problem. The entire life cycle of the infrastructure can be divided into several periods, referred to as "zones." In each zone, the transition period and the transition probability are supposed to be homogeneous.
4. A variety of causes for deterioration in bridge elements need to be identified, and the degree of their impact analyzed. Therefore, a monitoring system should be developed to collect data on the cause of deterioration by bridge element.
5. It is necessary to understand how deterioration of one element impacts the others in the process of deterioration. The transition probability matrix for the MDP should be developed.

2. Bridge Asset Management Framework

The recent Asset Management (AM) trend stresses preventive or proactive management. In general, preventive management consists of three steps: condition assessment, deterioration prediction, and intelligent maintenance (Chae and Abraham, 2001). To develop a preventive management system, the framework of the asset estimation process for bridge asset maintenance is suggested in this study, as shown in Fig. 1. The suggested framework is for a bridge structure, but it can be applied to all types of infrastructure. The main purpose of a budget estimation process for bridge maintenance is to estimate the analysis period of LCCA based on the performance measurement of bridge elements, to perform LCC analysis of the infrastructure during the predicted period, and to predict the cost of the required annual maintenance.

The estimation system of the bridge maintenance cost, which is based on the deterioration prediction model, consists of four steps, as shown in Fig. 1.

The first step is to construct a deterioration prediction model for each bridge element. Cady and Weyers (1984) and Veshosky *et al.* (1994) suggested a deterioration estimation method based on the manufacturers' instructions. They suggested that the longevities of each element be determined using the manufacturers' instructions, and that the MR&R actions be carried out according to the longevities of each element. This method has a limitation, however, with respect to the measurement of the practical and realistic longevity of a bridge element (Durango-Cohen, 2004). Therefore, in this study, a method that practically predicts the timing for the MR&R actions was adopted, which involves the use of a deterioration prediction model of a bridge element based on real deterioration data.

The second step is to predict the performance improvement of each bridge element based on the collected data with regard to the type, timing, and cost of the bridge MR&R actions. The optimum MR&R actions for each bridge element are determined via dynamic programming. The deterioration prediction model of each bridge element is calibrated based on the effects of each MR&R action through time.

The third step is to predict the practical maintenance cost using the cost database of the MR&R actions of each bridge element. In this step, the bridge maintenance cost estimation system predicts the future state of each bridge element using the deterioration prediction model, and estimates an appropriate budget based on the cost of the MR&R actions.

Finally, the system provides the procedure for the estimation of the Health Index (HI). Developed by the California Department of Transportation, HI can be useful for a single bridge or a group of bridges, thus providing an excellent performance measure and management tool for bridge AM. As shown in Eq. (1), HI is one of the most efficient AM methods because it allows the prediction of the future health of the inventory based on various funding levels. Namely, HI provides the damage status of bridge

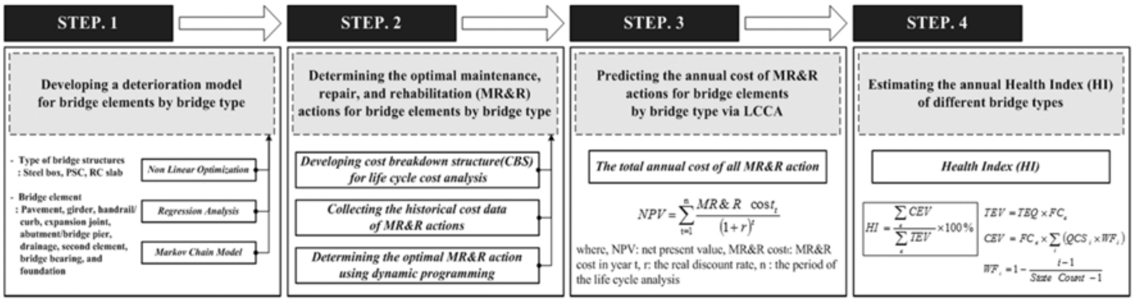


Fig. 1. Framework of the Asset Estimation Process for Bridge Asset Maintenance

elements and the corresponding maintenance cost (Shepard, 2005; Shepard and Johnson, 2001). In the case of South Korea, there are five condition states from "*A*", the highest condition state, to "*E*", the lowest condition state. Accordingly, by using the following equation, WF^i, the weight factors of *A*, *B*, *C*, *D*, and *E* are calculated as 1.0, 0.75, 0.5, 0.25, and 0 respectively.

$$HI = \left(\frac{\sum_e CEV}{\sum_e TEV}\right) \times 100\% \tag{1}$$

$$TEV = TEQ \times FC_e, CEV = FC_e \times \sum_i (QCS_i \times WF_i),$$

$$WF_i = 1 - \frac{i-1}{State\ \ Count - 1}$$

where,

CEV = Current element value
FC_e = Failure cost of the element
HI = Health index
TEQ = Total element quantity
TEV = Total element value
QCS_i = Quantity in the condition state i
WF_i = Weight factor for the condition state i

2.1. Step 1: Developing a Deterioration Model for Bridge Elements by Bridge Type

Main bridge structures are categorized into decks, superstructures, and substructures. To decide the deterioration level of a bridge, it is reasonable to consider the deterioration analysis results of each element based on the main bridge structure. In the previous literature reviews related to bridge maintenance, three main bridge structures were generally used to develop deterioration curves. The core structure of the PONTIS program, one of the most widely used bridge maintenance systems, is a performance test module for each type of bridge element. Therefore, it is appropriate to develop the performance deterioration curves of each element (pavement, deck, girder, handrail/curb, expansion joint, abutment/bridge pier, drainage, second element, bridge bearing, and foundation).

To develop a deterioration model for each type of bridge element, the historical data of bridge MR&R actions were extracted from the data obtained regarding the bridge maintenance system of Han River since 1994. Then, the data were categorized according to the three types of bridge structures: steel box bridges, Pre-Stressed Concrete (PSC) bridges, and Reinforced-concrete (RC) slab bridges. Each category had the historic data of ten elements. The deterioration model was developed using the Markov chain model. A nonlinear-optimization model commonly used in the transition probability prediction of bridges and other facilities (e.g., roads and drainages) was used in the development of the deterioration model using the Markov chain (Bulusu and Sinha, 1997). A nonlinear-optimization method consists of two steps: regression analysis and nonlinear optimization. A regression analysis model was developed based on the historic data. Then, the transition probability of the Markov chain was predicted by finding the minimum total absolute value from the differences between the developed regression analysis model and the value expected from the Markov chain model. Through regression analysis, the interrelationship between the performance of the elements by bridge type and time can be defined. As shown in Eq. (2), the nonlinear-optimization method is used for estimating the transition probability of the Markov chain.

$$Z = \min \sum_{t=t_s}^{t_e} \sum_{n=1}^{N} |y(t) - E(n,p)| \tag{2}$$

where, $0 \le P_{ij} \le 1$ (i, j = 1, 2, ..., m),

$E(n, p)$ = Expected value of the bridge test level for the transition period of the predicted n level using the Markov chain model
m = Status (test level)
n = Amount of transition time (level)
N = Total number of transition periods in each zone
t = Year (time)
t_s = Starting year (time) of each zone
t_e = Ending year (time) of each zone
$y(t)$ = Average test level at predicted time t from a regression analysis model

In Eq. (2), however, it should be noted that the environment affecting an infrastructure's deterioration changes with time; this goes against the assumption that the transition period is fixed during the life cycle of an infrastructure (Butt *et al.*, 1987). The "zoning" concept was applied to address this problem, which pertains to grouping certain time periods. The entire life cycle of an infrastructure can be divided into several periods, referred to as "zones." In each zone, the transition period and the transition probability are supposed to be regular, and each zone is supposed to have a homogeneous Markov chain. The period of this zone is determined by bridge maintenance experts or based on the inspection interval of the bridge. For example, in general, in the case of pavements and bridges, a six-year period is considered one zone (Butt *et al.*, 1987; Jiang and Sinha, 1989). Therefore, as shown in Eq. (3), E(n, p) in Eq. (2) is calculated by multiplying the condition vector of stage n by the condition rating vector S.

$$E(n,p) = Q^{(n)}S^T = Q^{(0)}P^{(n)}S^T \tag{3}$$

where, $P^{(n)}$ = Probability matrix after n-step transition
$Q^{(n)}$ = Condition vector at stage n
$Q^{(0)}$ = Initial condition vector at stage 0
S^T = Transpose of condition rating vector S.

In Eq. (3), the *n*-step transition probability matrix, $P^{(n)}$, is predicted using the nonlinear optimization from Eq. (2). For instance, if a five-year "zone" is used, the optimization in the first zone begins with $t_s = 1$ and ends with $t_e = 5$, and that in the second zone begins with $t_s = 6$ and ends with $t_e = 10$. Once the transition probability for the first zone is estimated, $Q^{(n)}$ is calculated using Eq. (3). If the five-year zone is applied, P^1 will represent the transition probability matrix in the first zone, and the condition vector of each stage will be as follows:

Zone 1
First transition
: Q (1) =Q (0) × P1
Second transition
: Q (2) =Q (1) × P1 = Q (0) × P12 (4)
…
Fifth transition
: Q (5) =Q (4) × P1 = Q (0) × P15

The condition vector for the fifth transition will be used as the initial condition vector in the second zone. The condition vector in the second zone can be calculated using the transition probability matrix in the second zone (P2).

Zone 2
First transition (total sixth)
: Q (6) =Q (5) × P2 = Q (0) × P15 × P2
Second transition (total seventh)
: Q (7) =Q (6) × P2 = Q (0) × P15 × P22
… (5)
Fifth transition (total tenth)
: Q (10) =Q (9) × P2 = Q (0) × P15 × P25

The state vectors of the rest of the zones can be estimated in the same way as that stated above. Using this method and the zoning concept, the deterioration model of each bridge element was derived from the obtained data. For example, in the case of the deterioration model of abutments and piers for a PSC bridge,

Table 1. Transition Probability of Abutments and Piers for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7367	1	1	1	1
6-10	P2	0.9008	0.9133	0.7864	0.8159	1
11-15	P3	0.9382	0.8924	0.7839	0.7777	1
16-20	P4	0.8277	0.7948	0.7171	0.7724	1
21-25	P5	0.4863	0.4924	0.4785	0.5908	1
26-30	P6	0	0	0	0	1

Table 2. Cost Data of Each MR&R Action (Ex: A Steel Box Bridge)

Division	MR&R action		Standard	Quantity	Unit	Cost (USD)		Remark
						Unit Cost	Total Cost	
Pavement	LMC method		40 mm	10,080	m^2	71.86	724,333.06	
	SMA method		80 mm	1,260	m^2	36.83	46,411.68	
	Sidewalk pavement		5 mm	3,240	m^2	70.25	227,609.00	
Pavement for water edge	South of river	Concrete	150 mm	4,050	m^2	30.59	123,869.48	Concrete pavement (15-cm cutting, 15-cm pavement)
		Asphalt	150 mm	900	m^2	22.70	20,434.24	
	North of river	Asphalt	150 mm	1,552.5	m^2	22.70	35,249.06	
	Equip. trans. cost			1	Package	12,568.34	12,568.34	
	Equip. rent			8	Day	2,094.72	16,757.79	
Bottom side of slab	Low-viscosity epoxy injection		0.2 mm and less	3,721.03	m	40.85	151,993.31	
			Over 0.3 mm	11.28	m	72.27	815.18	
	Section restoration		50 mm	409.46	m^2	379.77	155,501.14	
	Section restoration + rebar anticorrosion coating		50 mm	159.81	m^2	451.26	72,116.02	
Pier	Section restoration		50 mm	209.91	m^2	379.77	79,717.78	
			100 mm	2.18	m^2	651.59	1,420.47	
			200 mm	0.19	m^2	1,303.18	247.60	
	Section restoration + rebar anticorrosion coating		50 mm	15.14	m^2	451.26	6,832.09	
			100 mm	2.66	m^2	723.08	1,923.39	
			200 mm	1.70	m^2	1,446.16	2,458.47	
Steel box	Bolt change		F10T-M20	1,459	EA	20.95	30,562.01	
Temporary equipment	Barge		540 P	12	Month	5,341.54	64,098.54	
	Towboat		370 Hp	12	Month	4,775.97	57,311.63	
	Hardware production			1	Package	10,473.62	10,473.62	Workbench installation
	Cargo crane			1	Month	5,236.81	5,236.81	Workbench moving
	Ladder car			25	Day	523.68	13,092.02	Epoxy injection
Total cost							1,861,000.00	Cutting under USD1,000

Note: Based on the exchange rate in fiscal year 2006 (USD1 = KRW954.78)

Y(t) of Eq. (2) was predicted using Eq. (6) via regression analysis, and the transition probability is given in Table 1. The transition probability for developing the deterioration model for the other elements of a PSC bridge can be found in Tables A1 to A10 of Appendix.

$$Y(t) = 1.369 \times EXP(0.053t),\ R^2 = 0.363 \tag{6}$$

2.2 Step 2: Determining the Optimal Maintenance, Repair, and Rehabilitation (MR&R) Actions for Bridge Elements by Bridge Type

Various types of MR&R actions can be carried out, and their effects vary with time. Therefore, the level of performance improvement of a bridge element through MR&R actions depends on and varies with time. To identify the level of performance improvement of a bridge element through MR&R actions, the Markov chain transition was adopted in this study.

Towards this end, LCC analysis of the MR&R actions on each bridge element is required. First, the Cost Breakdown Structure (CBS) was organized, and the historical cost data of MR&R actions were collected. Table 2 shows the MR&R action cost data of one steel box bridge of Han River. Using these data, dynamic programming was conducted to determine the optimal MR&R action. Dynamic programming is an optimization technology used for finding an optimum proposal to make a decision. Other optimization methods, such as linear programming, simultaneously find the best alternative, while dynamic programming disassembles the overall problems into subsets. In other words, optimization through dynamic programming includes every subset to find the best alternative. This breakdown procedure is called "decomposition", and the disassembled subsets are called "stages." Every stage has its own states and decisions.

If the present stage does not figure out the cost or a state change in the next stage, it can be expressed in terms of probability calculated via probabilistic dynamic programming. This can be applied to the problem of finding an optimum MR&R action among various MR&R actions for each bridge element. In other words, the method can figure out the maintenance cost in the present stage but not in the next stage. Therefore, the uncertainty of state change is described in a transition probability of the Markov model. The transition probability drawn from step 1 is based on the assumption that there are no MR&R actions performed (the naturally deteriorating status). When performing preventive or corrective MR&R actions, the deterioration transition probability of the infrastructure changes depending on the performed MR&R actions. For example, if the transition probability derived from the deterioration model of step 1 is described as Eq. (7), this transition probability implies that there is no MR&R action.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 & 0 \\ 0 & 0 & p_{33} & 1-p_{33} & 0 \\ 0 & 0 & 0 & p_{44} & 1-p_{44} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Therefore, based on the transition probability of Eq. (7), the transition probability of when the MR&R actions are performed is derived from statistical dynamic programming. Bridge MR&R actions can be categorized into five kinds: (i) routine, (ii) minor repair, (iii) major repair, (iv) rehabilitation, and (iv) replacement (Hong and Hastak, 2005).

The transition probabilities of these MR&R actions are derived from the judgment of bridge maintenance experts or from the existing transition matrixes. For example, Eq. (8), the transition matrix of minor repair maintenance, implies that condition states 2, 3, 4, and 5 of the transition probability matrix in Eq. (7) will change into condition states 1, 2, 3, and 4 after minor repair.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 & 0 \\ 0 & 0 & p_{33} & 1-p_{33} & 0 \\ 0 & 0 & 0 & p_{44} & 1-p_{44} \end{bmatrix} \tag{8}$$

In the case of major repair maintenance, as shown in Eq. (9), condition states 2 and 3 will be enhanced into condition state 1, and condition states 4 and 5 will be enhanced into condition states 2 and 3, after major repair maintenance.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 & 0 \\ 0 & 0 & p_{33} & 1-p_{33} & 0 \end{bmatrix} \tag{9}$$

If rehabilitation maintenance is applied as shown in Eq. (10), condition state 2 will be upgraded by one step, and condition states 3, 4, and 5 will be enhanced by two steps. The deterioration rate after rehabilitation action will follow the deterioration pattern of condition state 1.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{11} & 1-p_{11} & 0 & 0 \\ 0 & 0 & p_{11} & 1-p_{11} & 0 \end{bmatrix} \tag{10}$$

In the case of the replacement and remodeling actions, the transition probability will return to the initial state after replacement maintenance, as shown in Eq. (11) (Cesare *et al.*, 1992).

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

According to the above four types of transition probabilities, the effectiveness of each MR&R action will be assessed. Towards this end, probabilistic dynamic programming is applied as Eq. (12).

$$f_n(i) = \min\left\{ C_n(i, a) + \alpha\sum_j p(j|i, a, n) f_{n-1}(i) \right\} \tag{12}$$

where, a = Feasible MR&R actions if the state is "i" in "n" year during the life cycle
$C_n(i, a)$ = Expected cost generated in "n" year if the state is "i" and if feasible MR&R action "a" is selected
$f_n(i)$ = Minimum expected cost required from "n" year during the life cycle
α = Interest rate
$P(j|i, a, n)$ = The probability of next year's state will be "j" if the present year's state is "i" and if feasible MR&R action "a" is selected

Using the above probability model, the optimum MR&R action of a bridge element is decided through the MDP, which consists of the following four steps: (i) state space, (ii) decision set, (iii) transition probability, and (iv) expected costs.

(i) State space (S): Described in $S = \{1, 2, \ldots, \mathrm{I}\}$, where I is a state level of elements
(ii) Decision set: Includes all the feasible MR&R actions for bridge maintenance management (For example, in the case of bridge abutment, the decision set includes the following alternatives: low-viscosity crack repair, reinforcing-rod antifouling, anticorrosive technology, replenishment, etc.)
(iii) Transition probability: Estimated in step 1
(iv) Expected costs: The required maintenance cost when the state level is "i" and if the feasible MR&R actions are chosen

The purpose of the MDP is to find the optimum action from among the various MR&R actions. In the MDP, three methods (policy iteration, linear programming, and value iteration) are used to find the optimum action (Winston, 1994). The value iteration method was used in this study because it is effective in calculating the minimum discounted maintenance cost and because it is simpler than the other two methods in terms of calculation. For instance, if the state level of the bearing element for a PSC bridge is described as S = {1 (best state), 2, …, 5 (worst state)}, the decision set, which consists of all the feasible MR&R actions of the bearing element for a PSC bridge, is as given in Table 3.

Table 3. Feasible MR&R Actions of the Bearing Elements of a PSC Bridge

Alternative	Method	Type
A1	Bolt change	Minor repair
A2	Painting	Major repair
A3	Welding	Major repair
A4	Reinforcement	Rehabilitation management
A5	Bearing change	Replacement management

The transition probability of each MR&R action of each bridge element is derived using Eqs. (7) to (11). For instance, if the transition matrix that there is no MR&R actions is as given in Eq. (13), the transition matrix of a minor repair like A1 (bolt change), given in Table 3, can be drawn as that in Eq. (14) using Eq. (8).

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0.9078 & 0.0922 & 0 & 0 \\ 0 & 0 & 0.8211 & 0.1789 & 0 \\ 0 & 0 & 0 & 0.5004 & 0.4996 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0.9078 & 0.0922 & 0 & 0 \\ 0 & 0 & 0.8211 & 0.1789 & 0 \\ 0 & 0 & 0 & 0.5004 & 0.4996 \end{bmatrix} \tag{14}$$

The expected cost is the required maintenance cost when the given state level is "i" and if a feasible MR&R action is chosen. In the case of the PSC bridge bearing element, the expected cost of each MR&R action is as shown in Table 4, where the gray part means that the MR&R action is not applicable at the given condition state because it is assumed that minor repair is applied to condition states 1 to 3.

As mentioned above, to decide the optimum MR&R action

Table 4. Expected Repair Costs for Each State Level and the Results of Value Iteration

Condition State (i)	$f_1(i) = \min\left\{ C_1(i, a) + \alpha\sum_{j=1}^{5} p(j|i, a, 1) f_0(i) \right\}$					$f_1(i)$ ($)	a
	A1 ($)	A2 ($)	A3 ($)	A4 ($)	A5 ($)		
1	28.97	106.31	139.31			28.97	A1
2	28.97	106.31	139.31			28.97	A1
3	28.97	106.31	139.31	502.58		28.97	A1
4		106.31	139.31	502.58	2,973.34	106.31	A2
5				502.58	2,973.34	502.58	A4

Note: Based on the exchange rate in fiscal year 2006 (USD1 = KRW954.78)

Table 5. Optimum MR&R Actions for the Bearing Elements of a PSC Bridge in Each Condition State

MR&R alternative	Method	Type
A1	Low-viscosity crack repair	Minor repair
A2	Reinforcing-rod antifouling	Minor repair
A3	Anticorrosive technology	Minor repair
A4	Deck restoration	Major repair
A5	Replenishment technology	Major repair

using dynamic programming, the value iteration method is applied for the optimization, as described in Eq. (15). As the initial minimum expected cost is zero, $f_0(i)$ will be zero in Eq. (15). The expected cost of a feasible MR&R action "*a*" in state level "*i*" will be the resulting iteration value, as shown in Table 4.

$$f_n(i) = \min\left\{ C_n(i,a) + \alpha \sum_{j=1}^{5} p(j|i,a,n) f_{n-1}(i) \right\} \tag{15}$$

$$f_0(i) = 0$$

where $f_0(i)$ denotes the minimum expected cost in "0" year in the life cycle.

Likewise, through the above procedure, finally, the optimum MR&R action of each condition state for each bridge element is derived. For example, in the case of the bearing element for a PSC bridge, the optimum MR&R action is as shown in Table 5.

2.3 Step 3: Predicting the Annual Cost of MR&R Actions for Bridge Elements by Bridge Type via LCCA

Through steps 1 and 2, the annual cost of the MR&R actions for each bridge type was derived based on the deterioration model and MR&R actions of each bridge element. Table 6 shows the annual available optimum maintenance cost for the PSC-bridge-bearing elements. In Table 6, condition state refers to the state level (1 to 5) of the bridge, and MR&R actions indicate the feasible MR&R actions for the bearing elements of the PSC bridge. As described in Table 3, alternative 1 is bolt change, alternative 2 is painting, alternative 3 is welding, alternative 4 is reinforcement action, and alternative 5 is bearing change. "F × S" is the maintenance cost of the optimum MR&R action among the feasible MR&R actions (alternatives 1-5) for every year and for every condition state. For instance, in the case of condition state 2 in the first year of the analysis period, the optimum MR&R action will be alternative 1 (bolt change), and the required MR&R cost will be 57.95 $/m. If the optimum MR&R action is alternative 2 (painting) in the case of state level 4 in the same analysis period, the required MR&R cost will be 135.29 $/m.

The optimum MR&R costs for each bridge type for a 40-year life cycle were estimated in this study. Table 6 shows only the two-year life cycle within 40 years. The system that was developed in the study was enhanced to more precisely and more easily predict the annual optimum MR&R costs for a bridge element given that the user collects more accurate unit cost data of MR&R actions.

2.4 Step 4: Estimating the Annual HI of Different Bridge Types

As a last step, HI is estimated, which shows the current performance status for a particular bridge type for the efficient management of the asset. HI is calculated using Eq. (1). In this process, from the viewpoint of the asset manager, CEV is considered the current value of the infrastructure, and TEV is the value in the best state. TEV and CEV, however, can be different from the asset value. As the value of the infrastructure is separately calculated from the manager's and user's viewpoints, from the manager's viewpoint, the estimation methods differ depending on the infrastructure type. Therefore, in this research,

Table 6. Prediction Results of the Maintenance Costs of the Bearing Elements of a PSC Bridge

Analysis Period	Condition State	MR & R actions					F × S	Optimum MR&R action
		A1 ($)	A2 ($)	A3 ($)	A4 ($)	A5 ($)		
0	1	28.97	106.31	139.31			28.97	A1
	2	28.97	106.31	139.31			28.97	A1
	3	28.97	106.31	139.31	502.58		28.97	A1
	4		106.31	139.31	502.58	2,973.34	106.31	A2
	5				502.58	2,973.34	502.58	A4
1	1	57.95	135.29	168.28			57.95	A1
	2	57.95	135.29	168.28			57.95	A1
	3	57.95	135.29	168.28	531.55		57.95	A1
	4		135.29	168.28	531.55	3,002.31	135.29	A2
	5				552.76	3,002.31	552.76	A4
2	1	86.92	164.26	197.25			86.92	A1
	2	86.92	164.26	197.25			86.92	A1
	3	86.92	164.26	197.25	560.52		86.92	A1
	4		164.26	197.25	560.52	3,031.29	164.26	A2
	5				581.74	3,031.29	581.74	A4

Note: Based on the exchange rate in fiscal year 2006 (USD1 = KRW954.78)

TEV and CEV were considered tools for calculating HI. In other words, they are the means to estimate the maintenance costs required to maintain a certain performance level of the infrastructure, irrespective of the type.

The Weight Factor (WF) indicates the weight value for each condition state. In the case of South Korea, there are five condition states (A, the highest, to E, the lowest). As a level for HI estimation, A is first, B is second, and the rest follow in the same order. For the calculation of CEV, the weight values of A, B, C, D, and E are 1.0, 0.75, 0.5, 0.25, and 0, respectively, considering the infrastructure's depreciation. Therefore, the better the infrastructure status is, the more similar CEV and TEV are, and then HI reaches 100%. If the status is bad, HI will have a lower value. For example, if the status level of a bridge element is C, HI will be 50%.

3. Development of a Prototype of the Bridge Asset Management System

A bridge asset management system prototype was developed based on the server-client, using the bridge asset management framework (refer to Fig. 1). The asset management system provides a future maintenance cost prediction model through the deterioration model, HI, based on the actual cost data. This

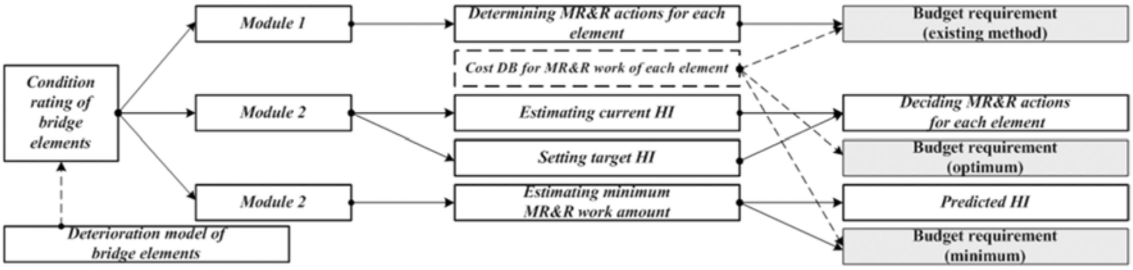
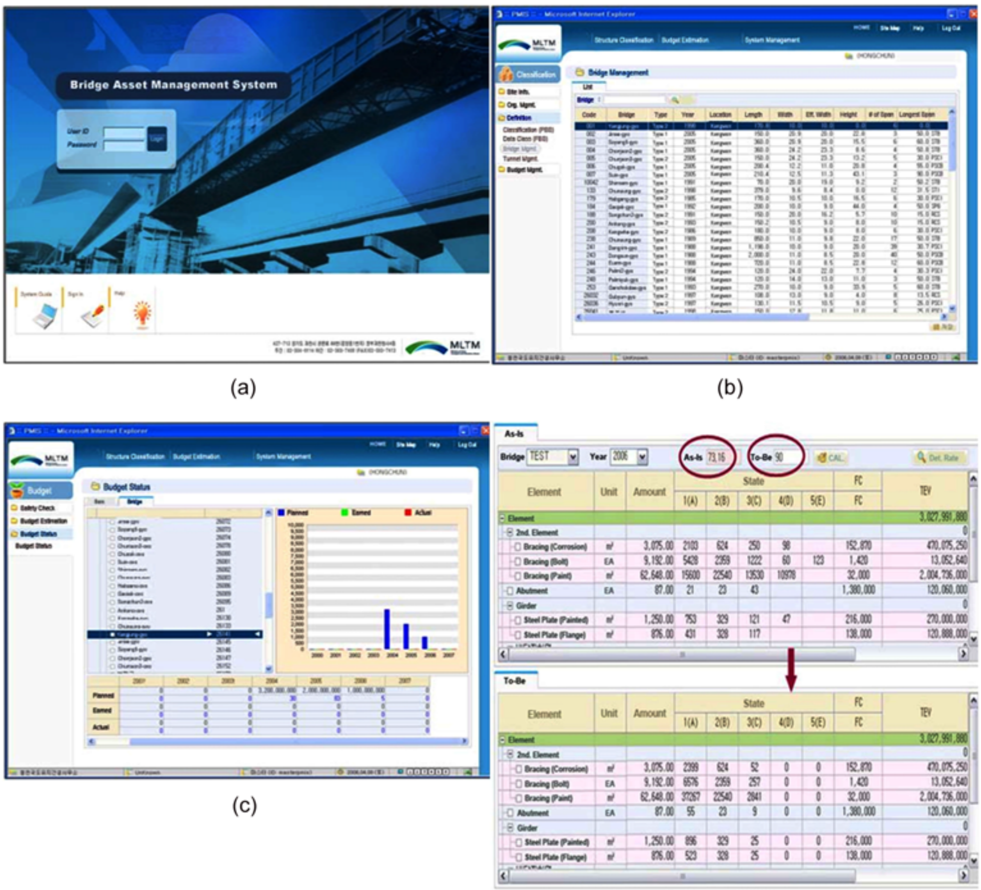


Fig. 2. Overall Data Stream of the System



(a)

(b)

(c)

(d)

As-Is

Bridge TEST Year 2006 As-Is 73.16 To-Be 90

Element	Unit	Amount	State					FC	TEV
			1(A)	2(B)	3(C)	4(D)	5(E)	FC	
Element									3,027,991,880
2nd. Element									0
Bracing (Corrosion)	m²	3,075.00	2103	624	250	98		152,870	470,075,250
Bracing (Bolt)	EA	9,192.00	5428	2359	1222	60	123	1,420	13,052,640
Bracing (Paint)	m²	62,648.00	15600	22540	13530	10978		32,000	2,004,736,000
Abutment	EA	87.00	21	23	43			1,380,000	120,060,000
Girder									0
Steel Plate (Painted)	m²	1,250.00	753	329	121	47		216,000	270,000,000
Steel Plate (Flange)	m²	876.00	431	328	117			138,000	120,888,000

To-Be

Element	Unit	Amount	State					FC	TEV
			1(A)	2(B)	3(C)	4(D)	5(E)	FC	
Element									3,027,991,880
2nd. Element									0
Bracing (Corrosion)	m²	3,075.00	2399	624	52	0	0	152,870	470,075,250
Bracing (Bolt)	EA	9,192.00	6576	2359	257	0	0	1,420	13,052,640
Bracing (Paint)	m²	62,648.00	37267	22540	2841	0	0	32,000	2,004,736,000
Abutment	EA	87.00	55	23	9	0	0	1,380,000	120,060,000
Girder									0
Steel Plate (Painted)	m²	1,250.00	896	329	25	0	0	216,000	270,000,000
Steel Plate (Flange)	m²	876.00	523	328	25	0	0	138,000	120,888,000

Fig. 3. Captured Screen of the System: (a) Front Page, (b) Registration of the Basic Bridge Data, (c) Asset Status of the Infrastructure, (d) Automatic Estimation of the Proposed HI Decision

system shows a practical application of asset management by defining the relationship between the maintenance cost and the performance of the infrastructure. In this system, the asset value is estimated using HI, and then, based on the targeted HI level, the system estimates the annual maintenance cost using cost database of MR&R actions for each bridge element.

As shown in Fig. 2, the system is divided into Modules 1 and 2. As Module 1 was designed to be applied immediately to the present budget estimation duty, it raises the efficiency of the work process by analyzing the existing budget estimation process. Moreover, it enables the monitoring of the cost change for each facility, with the help of a tool, to collect and analyze the history data. Module 2 is the asset management system, which estimates HI based on the state data, and which automatically calculates the quantity of the MR&R actions required for each element so that an optimum MR&R plan can be formulated based on the MR&R action cost data included in Module 1. If the appropriate management level is set by HI, a change in HI will be estimated given that the user selects the quantity as well as calculates the optimum cost and quantity. Therefore, the proposed system can check not only the maintenance cost history but also the HI history.

The overall data stream of the system is shown in Fig. 2. The budget estimation of the asset begins with the result of the state test for each element. The state level for an element is predicted using the mentioned deterioration prediction model. Module 1 focuses on collecting data in the database and on collecting cost data for an element because it follows the current work process of the maintenance budget estimation duty. Using Module 1, users can calculate the budget following the current work process. In the case of Module 2, the present HI is automatically calculated according to the state test level. Module 2 has not only a basic maintenance rule based on the HI criteria but also an immediate-repair-or-replacement rule when the state level of an element is D or E under the Act of Infrastructure Safety Management, and then automatically estimates the maintenance cost and HI changes.

Figure 3 shows the captured screen of the system. Fig. 3(a) is the login page. The program runs on the Web, and multiple users can access the system. The maintenance and management team members have access to the system. Fig. 3(b) is the registration of bridge data for inputting new data into the system. Fig. 3(c) shows the historical HI data for each bridge. Based on the historical data, users can review the previous budgets and health indices. In Fig. 3(d), by setting the HI for the next year, the expected budget to meet the HI can be calculated based on the historical cost and HI data.

4. Conclusions

This study describes the development of a bridge asset management system. It includes the following: (i) a deterioration prediction model at the element level of bridge management using the Markov chain model, (ii) the optimization of MR&R actions using dynamic programming, (iii) prediction of the annual maintenance cost, and (iv) estimation of the health index. At the element level of MR&R action planning, the available deterioration data are very limited. Thus, it is not sufficient to make a realistic forecast for effective bridge management at the network level. To forecast the long-term financial planning of 20 large bridges at Han River in the city of Seoul, some broad methods were needed, and the health index was used in this work. As a result, an Internet-based system was developed using both element-level maintenance planning and a network-level budget forecast model.

Several highlights in this research are as follows: (i) extensive literature reviews were carried out, and the real data from bridges located at Han River in Seoul, South Korea were collected, and then using them, the MDP was developed, (ii) the result of this study is not only applied to specific area but also expanded to all types of infrastructure. As an Internet-based system was developed based on the result, the foundation for continuous and systematic management was established, (iii) there are several limitations such as low accuracy of the model due to insufficient data, uncertainty of causes affecting a deterioration of the bridge elements and its interaction between each other. With regard to the limitations of this research, authors understood it is necessary to develop monitoring system for inspecting individual elements, and (iv) to overcome the limitations of regression model due to insufficient data, new approach such as Support Vector Machine (SVM) needs to be applied to develop the model.

This study, on the other hand, did not cover the level of service, which is an important aspect of infrastructure asset management. To define the service levels, an in-depth review of the user and community needs should be performed. The performance measurements should also be defined before the levels of service could be defined. In this study, the focus was on element-level bridge management and on a primitive form of asset management through the use of the health index and of historical cost and condition assessment data. The follow-up research, which is already being performed, covers the systematic methods of the service levels for infrastructure asset management and defines the missing links between the service levels, performance measurements, and budget forecast.

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Appendix. Dataset used for Calculating Transition Probability for PSC Bridge

Table 7. Transition Probability of Pavement for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7358	1	1	1	1
6-10	P2	1	0.9435	0.1614	0.7969	1
11-15	P3	0.9439	0.9035	0.7170	0.8607	1
16-20	P4	0.8956	0.8539	0.7490	0.8593	1
21-25	P5	0.7867	0.7289	0.6937	0.7704	1
26-30	P6	0.2043	0.2441	0.3002	0.4568	1
31-35	P7	0.0998	0.0873	0	0	1

Table 8. Transition Probability of Deck for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7288	1	1	1	1
6-10	P2	0.9456	0.9218	0.7044	0.9134	1
11-15	P3	0.9430	0.8988	0.7765	0.8444	1
16-20	P4	0	0.3110	0.8921	0.7585	1
21-25	P5	0.1000	0.1790	0.7950	0.7338	1
26-30	P6	0.1000	0	0	0	1

Table 9. Transition Probability of Girder for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7588	1	1	1	1
6-10	P2	1	0.9477	0.1741	0.7044	1
11-15	P3	0.9517	0.9097	0.7286	0.8014	1
16-20	P4	0.9114	0.8642	0.7578	0.8433	1
21-25	P5	0.8093	0.7647	0.7055	0.8050	1
26-30	P6	0.4864	0.4754	0.4766	0.6245	1
31-35	P7	0	0	0	0	1

Table 10. Transition Probability of Handrail/curb for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7446	1	1	1	1
6-10	P2	1	0.9502	0	0.6798	1
11-15	P3	0.9547	0.9111	0.7231	0.7444	1
16-20	P4	0.7942	0.8810	0.8535	0.7981	1
21-25	P5	0.8000	0.7802	0.7348	0.7125	1
26-30	P6	0.4492	0.4693	0.4858	0.5483	1

Table 11. Transition Probability of Expansion Joint for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7237	1	1	1	1
6-10	P2	1	0.9058	0.8575	0	1
11-15	P3	0.9583	0.9039	0.8211	0.6060	1
16-20	P4	0.8731	0.8281	0.7662	0.7434	1
21-25	P5	0.6754	0.6224	0.6128	0.6667	1
26-30	P6	0	0	0	0.0379	1

Table 12. Transition Probability of Abutment/bridge Pier for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7367	1	1	1	1
6-10	P2	0.9008	0.9133	0.7864	0.8159	1
11-15	P3	0.9382	0.8924	0.7839	0.7777	1
16-20	P4	0.8277	0.7948	0.7171	0.7724	1
21-25	P5	0.4863	0.4924	0.4785	0.5908	1
26-30	P6	0	0	0	0	1

Table 13. Transition Probability of Drainage for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.5198	1	1	1	1
6-10	P2	0.6535	0.9177	0.8999	0.2941	1
11-15	P3	0.9608	0.9187	0.8434	0.6897	1
16-20	P4	0.8884	0.8623	0.7893	0.7646	1
21-25	P5	0.1651	0.6755	0.6270	0.6696	1
26-30	P6	0.1000	0	0	0.0205	1

Table 14. Transition Probability of Second Element for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7525	1	1	1	1
6-10	P2	1	0.9246	0.5861	0.8601	1
11-15	P3	0.9460	0.8970	0.7521	0.8747	1
16-20	P4	0.8750	0.8335	0.7608	0.8585	1
21-25	P5	0.7353	0.6920	0.6581	0.7681	1
26-30	P6	0.0151	0.1091	0.1884	0.3777	1
31-35	P7	0	0	0	0	1

Table 15. Transition Probability of Bridge Bearing for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7257	1	1	1	1
6-10	P2	1	0.9078	0.8211	0.5004	1
11-15	P3	0.9510	0.9009	0.8147	0.7278	1
16-20	P4	0.8710	0.8249	0.7656	0.7851	1
21-25	P5	0.6670	0.6284	0.6114	0.6919	1
26-30	P6	0	0	0	0.0659	1

Table 16. Transition Probability of Foundation for PSC Bridges

Year	Transition matrix of the zone	p_1	p_2	p_3	p_4	p_5
1-5	P1	0.7359	1	1	1	1
6-10	P2	0.9908	0.9161	0.8392	0	1
11-15	P3	0.9528	0.9031	0.8262	0.6471	1
16-20	P4	0.8823	0.8282	0.8100	0.7440	1
21-25	P5	0.7276	0.6797	0.6802	0.6821	1
26-30	P6	0	0	0	0	1