Bridge maintenance system based on asset management

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ABSTRACT: This paper describes a decision supporting system for scheduling the maintenance program of many damaged RC bridge decks. Emphasis is placed on the decision process for repairing the damaged RC decks, considering the highway network, traffic condition, and functional constraints. The concept of asset management including life-cycle cost evaluation is adopted in order to obtain the optimal maintenance plan. A practical numerical example is presented to demonstrate the applicability of the proposed system.

1 INTRODUCTION

In Japan, a lot of highway bridges have been constructed over past 50 years. At present, these are aging and suffering from damage, deterioration and environmental attack. The number of deteriorating bridges is likely to increase in the near future. Then, it is very important to maintain those existing bridges in satisfactory safety and serviceability levels (Frangopol & Furuta, 2001). Reinforced Concrete (RC) bridge decks, being directly subjected to wheel loads of vehicles, are much more damaged than other structural elements in highway bridges. It is, then, necessary to make appropriate decisions on how to repair, rehabilitate and/or replace the RC bridge decks, taking into account the type of bridges, road network, traffic condition, and functional constraints (Furuta et al. 2002, 2003, 2004). This paper describes a decision supporting system for scheduling the maintenance program of many damaged RC bridge decks. Emphasis is placed on the decision process for repairing the damaged RC decks, considering the highway network, traffic condition, and functional constraints. The concept of asset management including life-cycle cost evaluation is adopted in order to obtain the optimal maintenance plan. A practical numerical example is presented to demonstrate the applicability of the proposed system.

2 ASSET MANAGEMENT

Asset management aims to improve the productivity and efficiency of infrastructures by quantifying the priority of budget allocation. In this study, the concept of asset management is applied to the establishment of optimal maintenance program. The process of asset management is illustrated as shown in Figure 1. Asset evaluation consists of the following factors:
physical value
economical value
social value
The physical value is calculated as

$$A_p = D_p(A_0 - A_d)(1 - C_d/10) \quad (1)$$

where A_0 : area of Reinforced Concrete (RC) deck, A_d : its damaged area, D_p : unit cost of RC deck, and C_d : crack density. The economical value is related to the loss of traveling time, traveling cost, and traffic accident. The social value is concerned with air pollution, noise and vibration, and global warming.

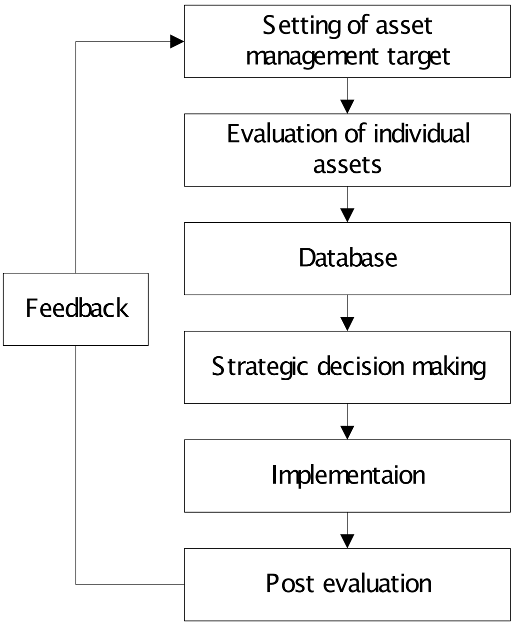

Figure 1. Process of asset management

4) frost damage
5) chemical corrosion

For the damage condition, the followings are considered:
1) crack
2) spalling
3) exposition and corrosion of reinforcing bar
4) leakage of water, lime and rust
and so on.

3.2 *Damage evaluation of RC deck*

The damage and deterioration of RC decks greatly depend on the traffic and environmental conditions. Referring to the result of inspection, the deteriorating degree of damaged RC decks is classified into some categories specified by some authorities (MLTI, 2002). According to such manuals, the damage rank of RC decks may be classified into five categories of I, II, III, IV, and V, corresponding to the magnitude of crack density on their surfaces, i.e., crack length per unit surface (m/m^2) as shown in Table 1, in which the level I is the well-conditioned, i.e., no repair at all. On the other hand, the level V is the most severe state and some repair must be done. In this table, the deterioration degree D_c of RC decks is also given, which is defined by Matsui and Maeda (Matsui and Maeda, 1978) as follows:

Table 1. Damage rank of RC decks

Damage state	Deteriorating state of RC decks		Need of maintenance
	Deterioration degree D_c	Crack density C_d (m/m^2)	
I	0.0-0.3	0-3	No rehabilitation
II	0.3-0.6	3-6	Possible rehabilitation
III	0.6-0.8	6-8	Rehabilitation or upgrading
IV	0.8-0.9	8-9	Rehabilitation, upgrading, or replacement
V	>0.9	>9	Upgrading or replacement

$$D_c = \frac{C_d}{10} \tag{2}$$

in which C_d = crack density.

3 REPAIR AND REINFORCEMENT OF RC BRIDGE DECKS

3.1 *Damage causes and damage conditions*

The following damage causes are considered for RC bridge decks:
1) excessive wheel load
2) excessive impact force
3) large moment force
4) lack of design capacity
5) quality of concrete and poor construction
6) lack of reinforcement and deck depth
7) lack of rigidity of deck
8) effects of negative moment and tensile force
9) excessive moment of free edge

Actually, the above factors cause the damage in a combined manner. In addition to the above traffic load and design and construction errors, the environmental effects should be considered as follows:
1) chloride attack
2) alkaline aggregate reaction
3) neutralization

3.3 *repair methods*

There are various repair methods for the rehabilitation, reinforcement, and replacement, corresponding to the deterioration degree of damaged RC decks. For instance, twelve maintenance methods in Table 2 can be adopted for some kinds of damages on the RC bridge decks, in which the maintenance cost per unit slab area is presented.

Table 2. Effects and costs of repair methods

Action	Method	Matrix recovers quantity	Cost (yen/m^2)
Rehabilitation	①Injection method	60%	23,000
	②Spraying method	60%	14,000
Reinforcement	③Steel plate attaching method	45%	73,000
	④FRP attaching method	45%	75,000
	⑤Stringer adding method	35%	44,000
	⑥Slab thickness increasing method	40%	45,000
Replacement	⑦Partial replacement	45%	47,000
	⑧Overall replacement	100%	47,000
Combination of Rehabilitation and Reinforcement	⑨Steel plate attaching method and Rehabilitation	75%	③+①or②
	⑩FRP attaching method and Rehabilitation	75%	④+①or②
	⑪Stringer adding method and Rehabilitation	65%	⑤+①or②
	⑫Slab thickness increasing method and Rehabilitation	70%	⑥+①or②

4 GENETIC ALGORITHM

In the natural world, every living being exhibits its current appearance through such iterative process as heredity, generation, adaptation, mutation, and so on. A genetic algorithm (GA) is one of the simulation models. That imitates the evolution process of living beings. It is an approach for obtaining insights into the adaptation and evolution of living beings. It may be thought of as an optimization method applicable to engineering problems (Goldberg, 1989). GA was invented to solve the combinatorial optimization problems. That is the same process as the evolution process of living beings. GA has such a high ability that it can pursue an optimum solution even for optimization problems with vague and imprecise objective functions. Therefore, the present paper attempts the application of elite preserve strategy, that is a kind of GA, to the complex and combinatorial optimization problem for planning a rational maintenance scheduling of damaged RC decks within some financial constraints.

The process of elite preserve strategy is as follows:

1) A set of individuals, i.e., the combination consisting of a maintenance method applied to each damaged RC deck, is assumed.
2) The fitness of maintenance plan, i.e., each individual is evaluated.
3) The process of selection and multiplication, i.e., elite preserve of high score individuals, is applied to a set of current individuals.
4) The crossover process for some couples among all individuals is carried out.
5) The mutation process for some individuals is carried out.
6) The fitness of maintenance plan is evaluated.
7) Whether the evaluation process is terminated or not is judged.

5 OPTIMAL MAINTENANCE PLANNING USING ASSET MANAGEMENT

Figure 2 shows the flow chart of maintenance planning using asset management. As an example the north east part of Osaka city is employed, in which

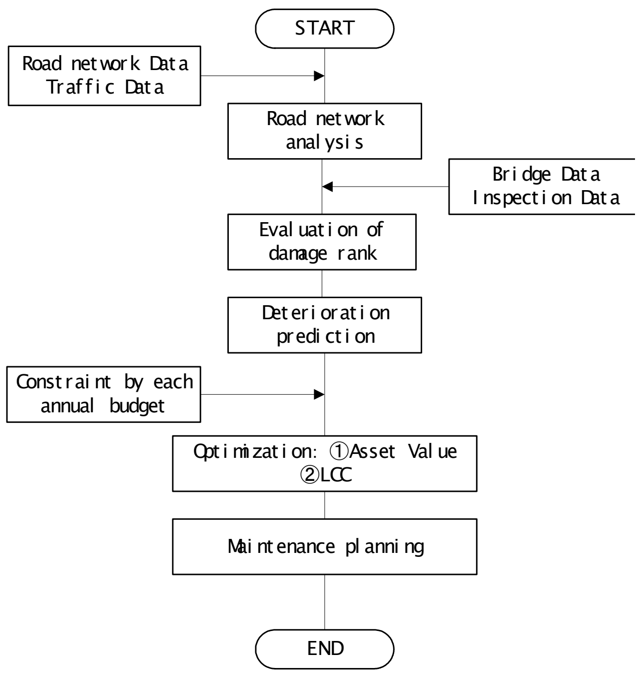

Figure 2. Procedure of maintenance work

an optimal maintenance schedule is determined for each bridge involved in the road network. The

Table 3. Conditions of damaged bridges

Bridge No.	Length (m)	Area of deck (m^2)	Damage area (m^2)	Crack density (m/m^2)	State of damage	Cause of damage	Area
1	150	3,600	1,440	4.2	Two-dimensional cracks	Action of excessive wheel loads	DID
2	145	3,770	754	7.1	Leak of water, Outflow of water, Peeling	Action of excessive bending loads	DID
3	188	4,410	882	3.2	Two-dimensional cracks	-	DID
4	155	2,710	543	6.9	Honeycomb crack, Hollow	Action of excessive wheel loads, Poor material and construction	DID
5	42.5	1,060	531	8.2	Cave	Lack of strength at design	DID
6	479	10,300	2,060	3.2	Two-dimensional cracks, Honeycomb crack	Lack of reinforcement	Urban district
7	42.1	1,030	82.6	2.1	One-dimensional crack	-	DID
8	35.9	327	106	6.1	Honeycomb crack	Action of excessive bending loads	DID
9	65.8	461	300	8.5	Free lime, Leak of water, Outflow of water	Action of excessive wheel loads	Urban district
10	561	10,900	2,190	6.2	Honeycomb crack	Lack of rigidity of deck	Urban district
11	43.2	1,040	104	5.1	One-dimensional crack	Action of excessive wheel loads	DID
12	56.3	1,240	124	8.3	Leak of water, Outflow of water	Lack of reinforcement	Urban district
13	48.2	1,120	224	3.2	Two-dimensional crack, Peeling	-	Urban district
14	41.6	936	94.1	8.1	Free lime	Action of excessive wheel loads	DID
15	36.1	199	39.7	4.4	Two-dimensional cracks	-	DID
16	42	966	242	8.7	Expose of reinforcement, Cave	Action of excessive bending loads	DID
17	36.2	260	35.3	2.9	One-dimensional crack	-	DID
18	42.3	850	233	6.2	Honeycomb crack, Hollow	Action of excessive bending loads	Urban district
19	55.6	1,280	153	3.7	Two-dimensional crack	Action of excessive wheel loads	Urban district
20	48	1,060	212	6.1	Honeycomb crack	Action of excessive wheel loads	Urban district

maintenance plans are made for the middle term such as 5- year plan.

5.1 *Road network*

The road network as shown in Figure 3 is assumed to demonstrate the applicability of the decision supporting system for determining the rational maintenance program of many damaged RC decks. There are 14 main- and sub- roads including 20 bridges, as shown in Figure 3. Table 3 shows the length of each bridge, the whole and damaged areas of each RC deck, the state and cause of damage, the crack density of each deck, and the environmental conditions of construction site. The traffic volume and speed for each link are assumed to be Q_c=36,000cars/day, and V_{max} = 50km/h for four line road, and Q_c = 12,000cars/day and V_{max}=40km/h for two line road and one line road for one way, respectively. The unit requirement of driving time is assumed to be α =82yen/car/min.

As mentioned above, GA has such an ability that it can provide us with useful solutions for large and complex combinatorial scheduling problems with discontinuous or vague objective functions. In this paper, GA technique is applied to obtain the optimal solution for repairing some decks among many damaged RC bridge decks. In the GA procedure, the GA operators shown in Table 4 are used. These values are optimal ones and could be determined after some trial computations.

It is assumed that the budget is limited 500 million yen for a year and the weights of economical asset value and social asset value are equivalent. Table 5 presents the plan with the minimum maintenance cost, whereas Table 6 presents the plan with the maximum asset value.

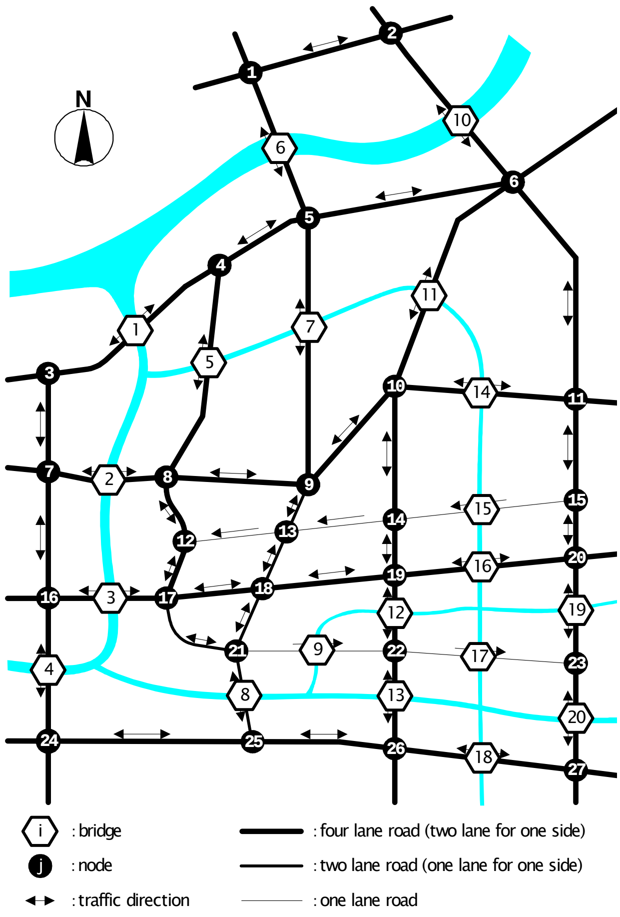

Figure 3. A road network

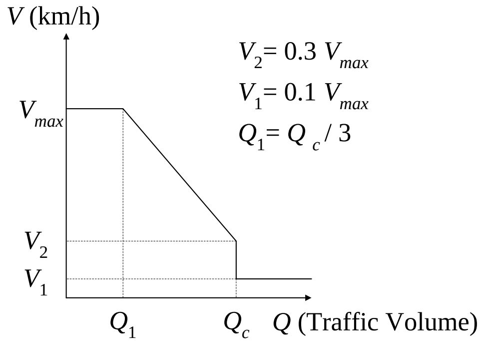

Figure 4. Q-V Curve

Table 4. GA parameters

GA Parameter	Value
Number of individuals	100
Crossover rate (%)	40
Mutation rate (%)	1

Table 5. Plan with minimum maintenance cost

Bridge No.	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year	10th year
1	⑧	-	⑨	⑥	-	-	-	-	-	-
2	-	-	-	-	-	-	②	-	①	-
3	-	-	⑨	-	-	-	-	-	-	-
4	⑦	⑫	⑦	⑦	⑦	③	⑦	-	⑦	-
5	-	⑦	⑦	-	③	-	⑦	-	⑦	-
6	-	-	-	-	-	-	-	-	-	-
7	⑧	①	-	-	⑥	③	⑤	-	-	-
8	⑨	-	-	-	⑤	-	-	-	-	-
9	③	⑧	-	-	-	⑧	-	-	⑤	⑥
10	-	-	-	-	-	-	-	-	-	-
11	⑨	-	-	⑧	-	-	-	⑧	-	⑤
12	-	⑤	-	⑦	④	-	-	-	-	-
13	④	-	-	-	-	-	⑥	-	-	-
14	⑤	④	-	-	-	-	-	-	-	-
15	④	-	-	-	-	⑥	-	-	-	-
16	⑫	-	⑧	-	④	⑧	-	⑧	-	-
17	③	-	-	-	-	-	-	⑧	-	-
18	②	③	⑦	-	-	-	⑤	-	-	-
19	①	⑨	-	-	-	-	-	-	-	-
20	-	①	⑫	⑥	③	⑥	-	-	⑤	-
Maintenance Cost	\402,628,090	\284,028,574	\389,985,449	\298,765,070	\174,699,353	\177,807,971	\205,981,996	\114,171,187	\145,705,169	\72,704,567

Bridge No.	Physical assets value	Economical assets value	Social assets value
1	\20,906,100	\2,340,412,365	\11,242,077
2	\3,170,570	\2,349,329,723	\11,302,255
3	\28,059,857	\2,349,329,723	\11,765,629
4	\7,340,839	\2,402,640,901	\8,801,842
5	\1,663,875	\2,275,098,730	\11,242,077
6	\67,760,542	\2,280,767,033	\11,293,229
7	\8,152,326	\3,424,486,482	\11,221,014
8	\1,271,582	\2,259,775,260	\10,874,989
9	\656,925	\2,238,230,913	\11,230,041
10	\21,631,865	\2,248,567,046	\11,199,952
11	\4,650,635	\2,973,584,359	\11,347,389
12	\1,926,642	\2,298,305,024	\12,322,279
13	\7,604,032	\2,421,049,860	\12,599,099
14	\1,723,270	\2,399,517,086	\11,476,773
15	\1,111,880	\2,300,196,764	\11,266,148
16	\1,255,800	\2,248,203,591	\13,294,159
17	\1,850,260	\2,239,917,910	\11,181,899
18	\3,159,795	\1,698,073,502	\418
19	\8,056,440	\2,912,485,967	\20,160,500
20	\3,789,284	\2,920,806,375	\20,160,500

Total maintenance cost	\2,266,477,426
Total asset value	\49,104,727,270

Total physical assets value	\195,742,519
Total economical assets value	\48,697,729,339
Total social assets value	\233,982,268

Table 6. Plan with maximum asset

Bridge No.	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year	10th year
1	⑧	①	①	⑨	⑤	-	-	-	-	-
2	-	-	-	-	-	-	②	-	①	-
3	-	-	⑨	-	-	-	-	-	-	-
4	⑦	-	⑦	⑦	⑦	③	⑦	-	⑦	-
5	-	-	⑤	-	⑫	⑨	-	⑥	-	-
6	-	-	-	⑫	-	-	-	-	-	-
7	①	①	-	-	⑥	-	⑫	⑫	⑫	③
8	⑨	-	-	-	-	-	⑥	-	⑧	⑤
9	③	⑥	-	-	-	-	-	-	⑤	⑥
10	-	-	⑧	⑤	-	-	-	-	-	-
11	⑨	-	-	-	-	-	-	-	-	⑤
12	-	⑤	-	⑦	⑩	-	-	-	-	⑦
13	-	-	-	-	-	-	-	④	-	-
14	⑧	④	-	-	-	⑤	⑧	⑥	-	-
15	④	-	-	-	⑧	-	-	⑧	⑥	-
16	-	-	-	-	⑤	⑧	①	⑧	①	⑩
17	-	①	-	-	①	⑥	①	-	③	-
18	-	⑦	-	-	③	-	-	-	⑦	-
19	⑪	-	-	-	⑥	-	-	-	-	⑧
20	-	①	③	⑥	⑤	⑥	-	-	-	-
Maintenance Cost	\300,572,020	\135,321,754	\734,358,359	\1,238,112,077	\490,661,508	\243,465,085	\158,550,453	\224,754,277	\167,531,679	\192,899,017

Bridge No.	Physical assets value	Economical assets value	Social assets value
1	\20,906,100	\2,340,412,365	\11,242,077
2	\3,170,570	\2,349,329,723	\11,302,255
3	\28,059,857	\2,402,640,901	\11,765,629
4	\8,408,750	\2,275,098,730	\8,801,842
5	\1,415,250	\2,280,767,033	\11,242,077
6	\49,840,399	\3,424,486,482	\11,293,229
7	\7,467,531	\2,259,775,260	\11,221,014
8	\1,247,373	\2,238,230,913	\10,874,989
9	\660,383	\2,248,567,046	\11,230,041
10	\15,807,901	\2,973,584,359	\11,199,952
11	\5,099,381	\2,298,305,024	\11,347,389
12	\800,136	\2,421,049,860	\12,322,279
13	\7,360,703	\2,399,517,086	\12,599,099
14	\1,723,270	\2,300,196,764	\11,476,773
15	\1,101,873	\2,248,203,591	\11,266,148
16	\767,294	\2,466,280,448	\13,294,159
17	\1,796,602	\2,239,917,910	\11,181,899
18	\2,287,459	\1,698,073,502	\418
19	\8,056,440	\2,912,485,967	\20,160,500
20	\3,624,173	\2,920,806,375	\20,160,500

Total maintenance cost	\3,886,226,229
Total asset value	\49,150,185,684

Total physical assets value	\169,601,444
Total economical assets value	\48,697,729,339
Total social assets value	\233,982,268

Table7. Balance of maintenance cost (plan with minimum maintenance cost)

	1st year	2nd year	3rd year	4th year	5th year
Maintenance Cost	\402,628,090	\284,028,574	\389,985,449	\298,765,070	\174,699,353
Balance	\102,628,090	\-15,971,426	\89,985,449	\-1,234,930	\-125,300,647

6th year	7th year	8th year	9th year	10th year
\177,807,971	\205,981,996	\114,171,187	\145,705,169	\72,704,567
\-122,192,029	\-94,018,004	\-185,828,813	\-154,294,831	\-227,295,433

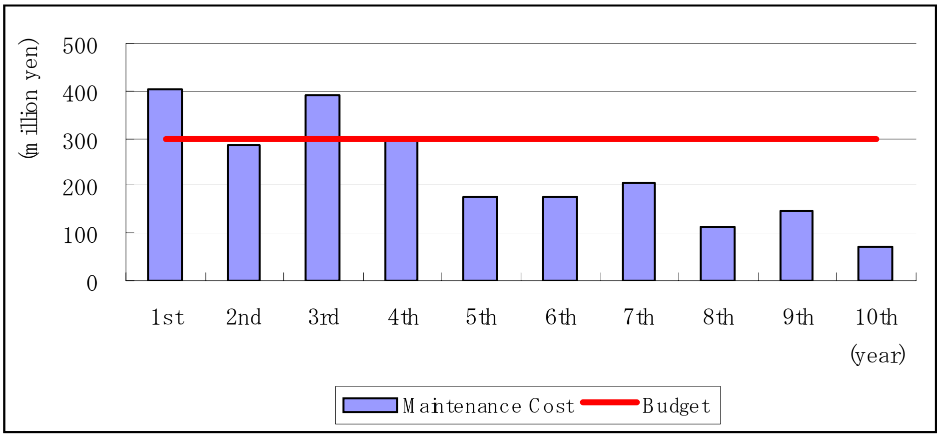

Figure 5. Maintenance cost for each year (plan with minimum maintenance cost)

Table8 Balance of maintenance cost (plan with maximum asset).

	1st year	2nd year	3rd year	4th year	5th year
Maintenance Cost	\300,572,020	\135,321,754	\734,358,359	\1,238,112,077	\490,661,508
Balance	\572,020	\-164,678,246	\434,358,359	\938,112,077	\190,661,508

6th year	7th year	8th year	9th year	10th year
\243,465,085	\158,550,453	\224,754,277	\167,531,679	\192,899,017
\-56,534,915	\-141,449,547	\-75,245,723	\-132,468,321	\-107,100,983

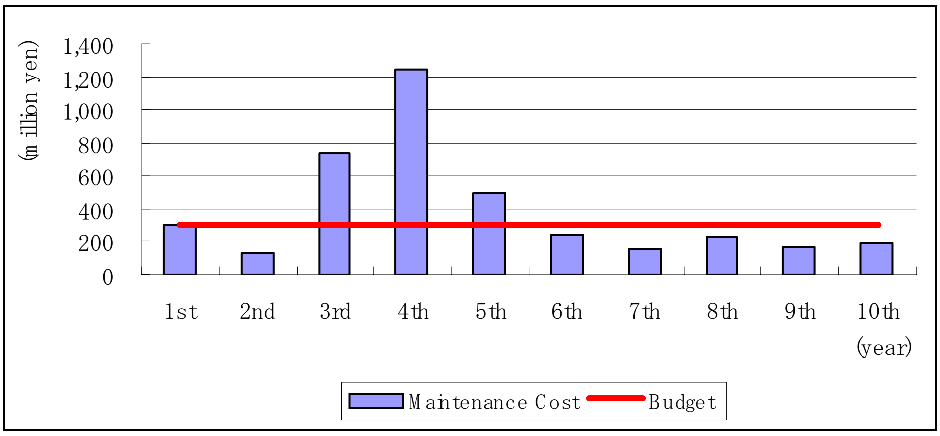

Figure 6. Maintenance cost for each year (plan with maximum asset)

The maintenance costs for the first to 10th year from the beginning of the plan are presented in Table 7 and Figure 5. Table 7 also shows the balance between maintenance cost obtained by the proposed system and the budget assumed to be 300,000,000 yen. Table 8 and Figure 6 show the maintenance costs for the plan with the maximum asset value and the balance between the budgets.

The plan with the minimum maintenance cost shows the lowest maintenance cost for each bridge. Bridge 18 has the highest asset value. This is due to the fact that the 18th bridge is evaluated to be the most important. The order of importance of bridges are as follows: bridge 18, bridge 4, bridge 8, bridge 9, bridge 17, bridge 15, bridge 5, bridge 14, bridge 11, bridge 2, bridge 7, bridge 12, bridge 16, bridge 13, bridge 3, bridge 1, bridge 10, bridge 20, bridge 19, and bridge 6. Since bridges 19 and 6 are evaluated to be less important, these bridges are not repaired.

On the other hand, the maintenance plan with the maximum asset has larger maintenance cost than the plan with the minimum maintenance cost. In this case, the order of importance of the bridges are as follows: bridge 18, bridge 8, bridge 9, bridge 15, bridge 17, bridge 4, bridge 5, bridge 14, bridge 2, bridge 11, bridge 7, bridge 12, bridge 16, bridge 13 bridge 1, bridge 3, bridge 10, bridge 20, bridge 19, and bridge 6. This result also shows that bridge 18 is the most important, because the bridge has the large economical and social asset values. Comparing both these two plans, it is obvious that the plan with the minimum maintenance cost has a tendency that maintenance cost required for each year does not differ so much. However, the plan with the maximum asset shows the large difference in the maintenance cost required for each year. This is natural, because the former plan is obtained by paying attention to the maintenance cost itself. whereas the latter plan is obtained by maximizing the total asset value.

6 CONCLUSIONS

A decision-support system was developed for determining a rational and economic maintenance scheduling that selects some RC decks among many existing damaged bridges and their appropriate repair methods, considering the traffic characteristics of highway network. The concept of asset management was introduced to evaluate the fitness of maintenance methods for the damaged RC decks. GA was adopted to solve the large and complex combinatorial scheduling problems for the maintenance of damaged RC bridge decks.

As a result of numerical computation, it can be concluded that the proposed decision-support system for determining the maintenance scheduling of many damaged RC decks is available and effective. It can be seen that GA procedure is useful and powerful to search the optimal repair order. The influence of the traffic characteristics of highway network, surrounding condition at the construction site, manufacture and construction conditions, and financial constraints on the optimal repair program are taken into account.

Asset management aims to enhance the productivity and efficiency of infrastructures. By quantifying the asset of each infrastructure, it becomes possible to explain the overall view of maintenance program for existing various structures.

According to this direction, an attempt was made in this paper to introduce the concept of asset management into the maintenance planning of RC bridge decks. Comparing the maintenance plan based upon the life-cycle cost, the asset management can provide us with more clear explanation for the accountability. For the future problems, there still remain several issues to overcome; the accuracy of network analysis, the evaluation of asset values, the estimation of repair and reinforcement effects, and the evaluation of seismic risk in asset management (Furuta & Koyama, 2003a, 2003b).

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