A Study on Optimum Life Cycle Cost Focusing Bridge Maintenance for Japanese Local Governments
-A Case Study in Fukuoka City, Japan-

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Today, there are many local governments in Japan facing the problems of deteriorating public facilities and decreasing budget. Taking their cue from the forerunner, USA, they are now introducing Asset Management practices (hereafter referred to as AM) with regards to maintenance of bridges.

In Fukuoka City, a government-ordinance designated city, there are approximately 2,100 bridges that were constructed as part of large scale road-development projects that have been rapidly implemented during Japan's high economic growth period. Given the city's decreasing budget for public works, it is imperative to lengthen the life of existing facilities and to reduce their maintenance costs.

This paper examines the effects of AM by estimating the Life Cycle Cost (hereafter referred to as LCC) of maintaining existing bridges to be incurred in the future, based upon the result of our investigation into sampled bridges in the city. It also presents challenges and prospects for the promotion of AM.

1.PURPOSE AND BACKGROUND OF THIS STUDY

Infrastructure that rapidly developed during Japan's high economic growth period in post-war years, have deteriorated over the years. Thus, their maintenance costs are expected to grow sharply. Conversely, investment in public works is predicted to fall, as the larger share of available financial resources will be allocated to social welfare programs including one to cope with the falling birth rate. Therefore, the importance of better management and usage of facilities in stock as social infrastructure, has increased for both the national and local governments.

The first and foremost critical action that local governments must take to promote AM, is to investigate into the effects of AM on cutting maintenance costs. Needless to say, the best way to do so is to check and analyze damages of all bridges. The problem is that such an approach is time-consuming and inappropriate considering financial

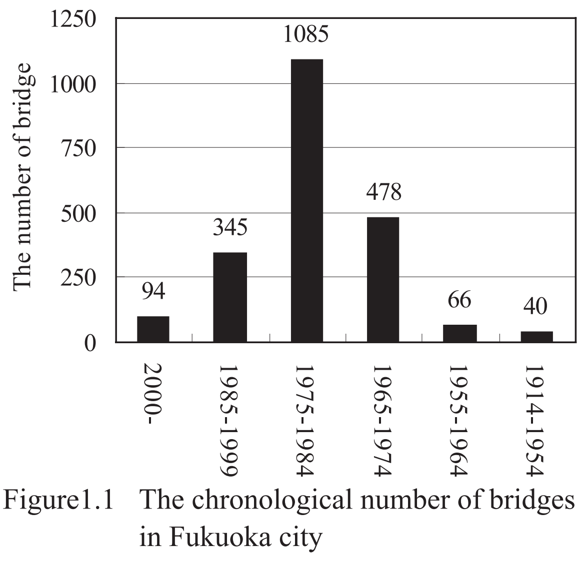

Figure1.1 The chronological number of bridges in Fukuoka city

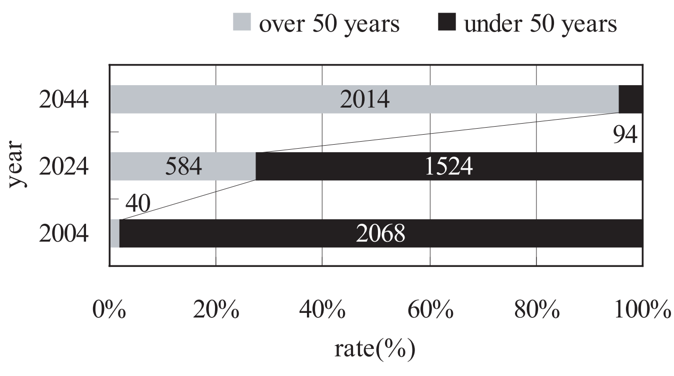

Figure1.2 The rate of the number of bridges over 50 years

difficulties faced by many local governments. The introduction of AM will also be delayed. However, public facilities are steadfastly becoming aged. This requires the government sector to switch to a strategic and systematic maintenance practice from the existing one focusing on fixing damages on a case-by-case basis. This makes it all the more important to ascertain the effect of AM as early as possible. To this end, public facilities should be classified into several categories for sampling purposes. Then, the LCC of sampled facilities can be calculated, so that we can make a comparison with the cost with AM. This process is necessary as it helps the government sector to gain understanding about the AM effects from city councils and citizens.

As is the case with other local governments, Fukuoka City has developed roads within a short period of time. For example, the city has about 2100 road-bridges as of July 2004, of which 1085 bridges or about 74% are believed to have been constructed between 1965 and 1984. (Fig. 1.1) From

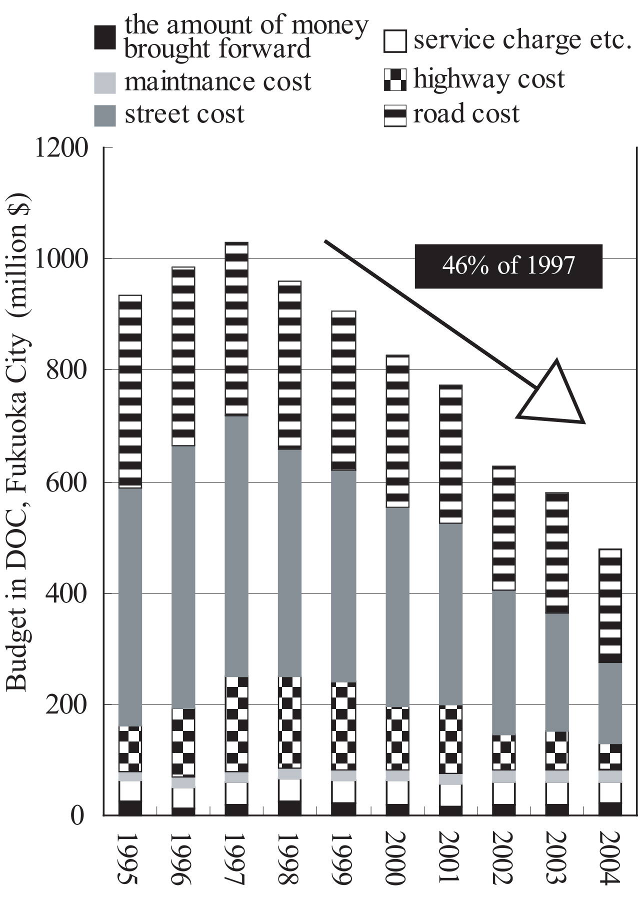

Figure1.3 Budget of Public Works Bureau of Fukuoka City (1$=100yen)

this time forward, the number of bridges that are more than half a century old will increase sharply if no replacements are made. For example, this number will be 15 times in 2024, and 50 times in 2024 as compared with that of 2004. The rapid aging of bridges is of grave concern. (Fig. 1.2)

The city's road-related budget in the city' s general account peaked with $1029 million in the fiscal year 1997, and has continued to drop to $477 million in the fiscal year 2004, which is equivalent to about 46% of the fiscal year 1997. Meantime, the budget for road maintenance has grown only slightly, as it depends on the increase in road length. It was about $22 million in the fiscal year 2004. (Fig. 1.3)

In this study, we sampled several bridges within the city that have a risk of causing a lot of casualties should they fall, in order to prove the effects of AM by obtaining their LCC. In addition, we also identified issues to be examined and made proposals for the promotion of AM.

2.STUDY FLOW

Figure 2.1 shows the flow of our study. The concept and formula of LCC are described in Figure 2.2 and Eq.(2.1). This study focuses on LCC of existing bridges and excludes their construction costs. In other words, the subjects of this study are future expenses for maintenance and repair, and replacement, and LCC is expressed as the sum of these two expenses. The conditions for the calculation are as follows:

1) With regards to the prediction of deterioration, the upper structure of bridges such as the main girder and floor system will be taken into account.
2) Bearings, the sub structure, accessories shall be excluded from prediction.
3) The degree of soundness of a repaired bridge is assumed to have fully recovered. Its aging curve shall be identical to the standard aging curve of the same type of bridge.
4) Maintenance cost per unit area shall be multiplied by the total bridge area to obtain the total maintenance cost.

5) The replacement cost shall consist of the construction cost of upper and lower structures of a bridge, removal fees, and the cost for temporary works required for bridge reconstruction..
6) Social discount rate shall not be taken into consideration. Current commodity prices shall be applied and assumed to remain unchanged)
7) Life-time cost shall be evaluated by current values, and social influences such as traffic congestion as well as environmental load shall not be considered.

Prediction period shall be 50 years from 2006 to 2055.

3.BRIDGE SAMPLING

3.1 Selection of bridges for this study

Sampling was conducted in order ascertain the conditions of about 2100 bridges managed by Fukuoka City. The basic factors that we took into account in selecting bridges to be sampled are as follows,

3.1.1 Salt pollution

Bridges that are located within 200m from the coast line, which the Specification for Highway Bridges defines as an area affected by brine water.

Bridges that are located in areas where anti-freezing agent is sprayed in the winter time.

3.1.2 Types of bridges

Steel, RC (reinforced concrete), and PC (prestressed concrete) bridges, when combined account for about 97% of all bridges in the city.

3.1.3 The time of construction to be covered for sampling and their characteristics

The time of construction to be covered for sampling and their characteristics

1) Prior to 1964: Old bridges.
2) Between 1965 and 1974: There is a possibility that unwashed sea sands was used as fine aggregates during this period.
3) Between 1975 and 1984: Bridges that are believed to be most common in the city.
4) After 1985: New bridges

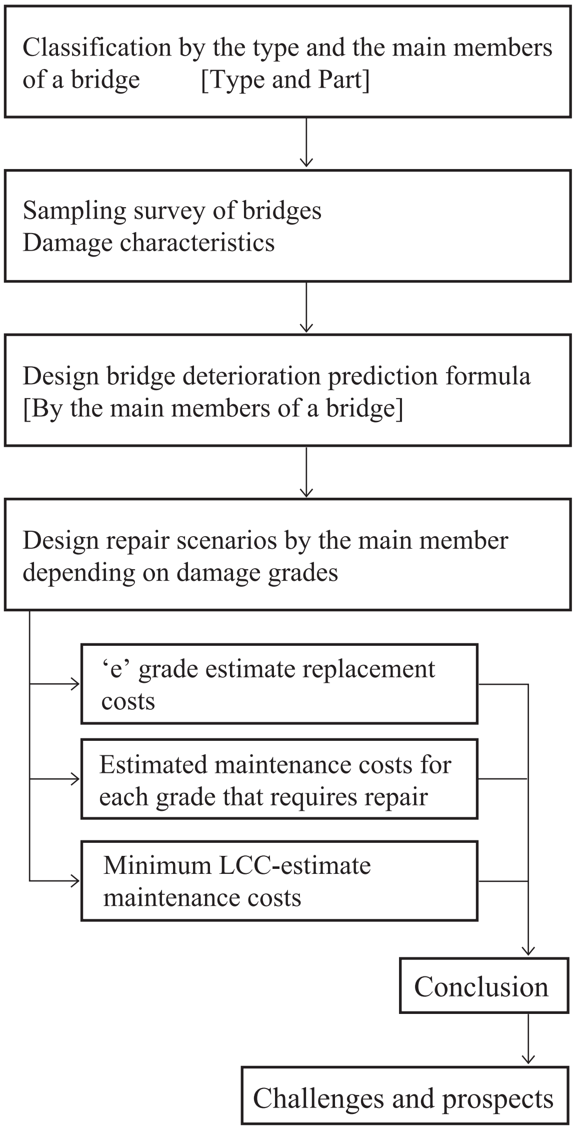

Figure 2.1 The flow of this research

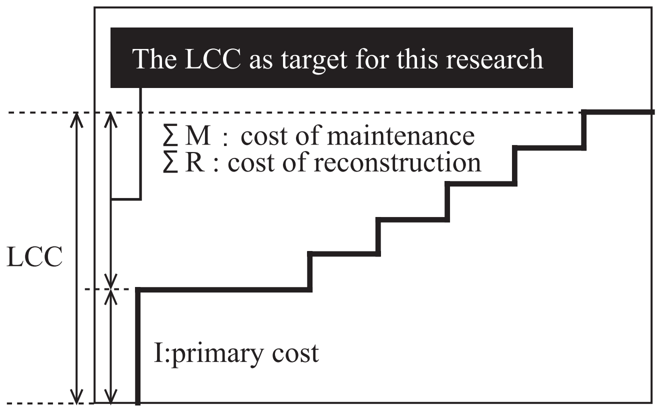

Figure2.2 The image of LCC per bridge

$LCC = I + \Sigma M$ or ΣR
ΣI: primary cost
ΣM: maintnance cost
Σ R: reconstruction cost

Eq.(2.1) Formula of calculation Life Cycle Costs

3.2 Assessment criteria for sampled bridges

The degree of soundness of the upper structure was determined by taking into consideration the results of inspection about the level, location, and distribution of damages caused to its floor system and main girder. We adopted the 5 grade-scale in compliance with the Bridge Periodical.

3.3 Findings and characteristics of damages

The result of sample inspection suggests that damages caused to bridges managed by Fukuoka City has characteristics as follows.(Figure 3.1)

The intensity of damage is ‘b’ (light damage) in the ‘a to e scale’ with more than half of bridges.

PC bridges are relatively in sound condition, while RC bridges are more damaged than other types of bridges. Numerous RC bridges were constructed between 1965 and 1984. In 1978, the use of salt-contained fine aggregate was banned. Therefore, many of those bridges are highly likely to contain sea sand without salinity removed, as fine aggregates for concrete.

The damage intensity of bridges constructed between 1965 and 1984 is found to be more serious than those constructed in other times.

The damage incidence is more 3 times higher with bridges located in seaside areas than those in the rest of city areas.

In Fukuoka City, bridges in the western seaside areas as well as in the western part of Shikanoshima island have developed severe damage. This is believed to have been caused by the salinity distributed during the northwest monsoon season.

4. STANDARD FORMULA FOR DETERIORATION PREDICITON AND REPAIR SCENARIO

4.1 Standard formula for deterioration prediction

The following are basic conditions for the standard formula for deterioration prediction as well

Table3.1 Classification of bridge samples

Type	Time of construction	The number of samples
Iron bridge	before 1955	0
	1955-1964	6
	1965-1974	5
	1975-1984	5
	subtotal	16
Reinforced concrete bridge	before 1955	11
	1955-1964	18
	1965-1974	6
	1975-1984	1
	subtotal	36
Prestressed concrete bridge	before 1955	7
	1955-1964	21
	1965-1974	20
	1975-1984	15
	subtotal	63
total		115

Table3.2 Assensssment criteria for sampled bridges

Grade	Evaluation	Damage description
a	Sound	No damage
b	Light damage	Minor damage
c	Displacemet	Damaged
d	Caution	Serious damage
e	Danger	Too damaged to graduate safety

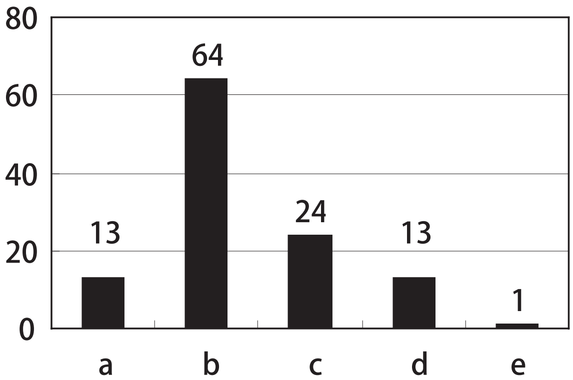

Figure 3.1 The damage of Sample bridges

as the flow of design.

1) The degree of soundness is classified into 5 grades with a full score of 50 points , and each grade increasing by 10 points.
2) Deterioration speed is quantified by looking at how the degree of soundness has dropped over time based upon inspection results.
3) Standard deterioration formula employs primary expression format, and is used to evaluate damages that have been visually observed.
4) Normal distribution format is applied to describe the distribution of each damage intensity by bridge age.
5) To secure reliability of inspection data, data with less than 90% reliability is discarded.
6) Standard formula for deterioration prediction is designed by identifying deterioration factors due to aging.

Standard formula for deterioration prediction involves the type, the upper structure, and the floor system of bridges based upon the concept specified in the Standard Specification for Concrete Structure established in 2001. Bridges are assumed to maintain the initial degree of soundness during latency and progress periods of damage.

The initial degree of soundness is assumed to deteriorate when acceleration period of damage comes. The formula and life expectancy are shown in Table 4.1. An example of the deterioration formula for RC bridges is shown in Fig. 4.1.

Table 4.1 Formula by the type and main members of a bridge

Type of bridges	Parts		Formula of deterioration caluculation	life span (year)
Iron bridge	Slab	(1)	-1.45t+66.45	38.9
	Girder (a-1 paint)	(2)	-1.00t+65.00	55.0
Reinforced concrete bridge	Slab	(3)	-1.98t+99.50	45.2
	Girder	(4)	-1.60t+93.68	52.3
Prestressed concrete bridge	Slab	(5)	-0.79t+69.553	75.4
	Girder	(6)	-1.21t+78.435	56.6

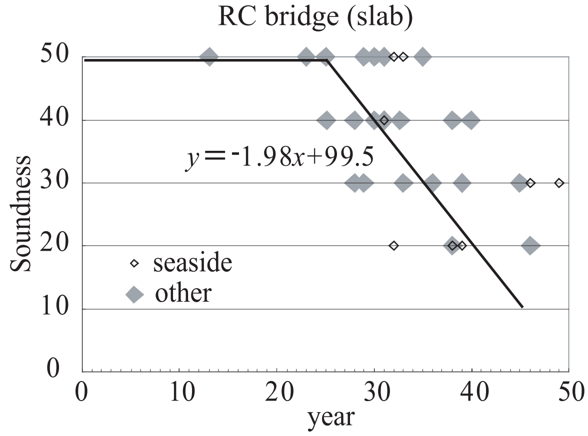

Figure4.1 Design bridge deterioration prediction formula (by the main members of a bridge)

Table4.2 Term of maintnance cycle LCC which minimized LCC and minimum LCC (1$=100 yen)

Type of bridges	parts		first repairment stage	Cycle of LCC minimum maintenance (year)	LCC unit price ($/m²)
Iron bridge	Slab		22.8	11.5	1,494
	Girder	a-1 paint	32.3	17.3	809
		c-1 paint	64.6	34.6	571
Reinforced concrete bridge	Slab(including Slab of Reinforced concrete T-type Girder bridge)		33.2	8.2	2,128
	Girder		38.3	11.0	732
Prestressed concrete bridge	Slab		36.8	13.3	1,252
	Slab of Reinforced concrete T-type Girder bridge		45.5	20.7	855
	Girder		37.6	14.1	1,260

* c-1 paint's durability is two times greater than a-paint's

4.2 Repair scenario

We have conceived repair scenario by the floor system and main girder for all degrees of soundness including ‘b’(light damage), ‘c’ (deformation), ‘d’(caution), and ‘e’(danger) for the purpose of maintaining bridge functions in a sustainable manner.

For repairing the damage caused to the upper structure due to aging, we have obtained the cost per 1 from our repairing scenario which adopted the conventional repair work method and their fees. In this study, ‘e’ (danger)-grade bridges are to be reconstructed when their expected service life ends.

4.3 Examination of optimized repair cycles (minimum LCC)

We estimated the maintenance and replacement costs for 50 years by the type and main members of a bridge based upon each repair scenario, in order to predict the lowest cost for maintenance and reconstruction, resulting in optimized repair cycles for minimizing LCC. As a result, we have concluded that optimum timing of repair for all types of bridges falls on the beginning of the c-grade period in terms of the degree of soundness. Repair cycle years to achieve minimum LCC and the resulting minimum LCC are shown in Table 4.2.

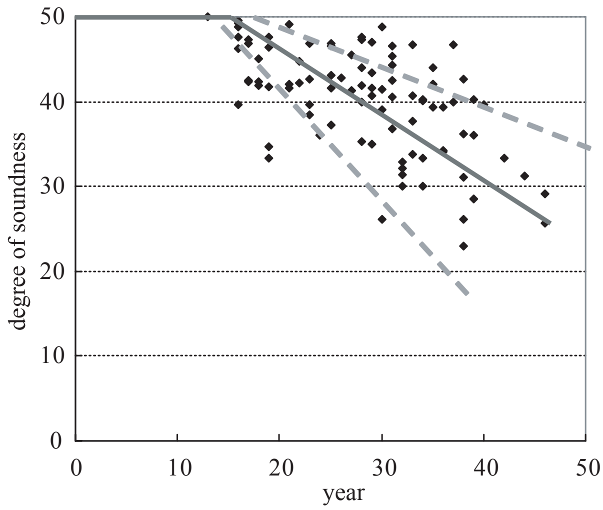

Figure 4.2 Value-dispersion increases as the standard deviation α grows.

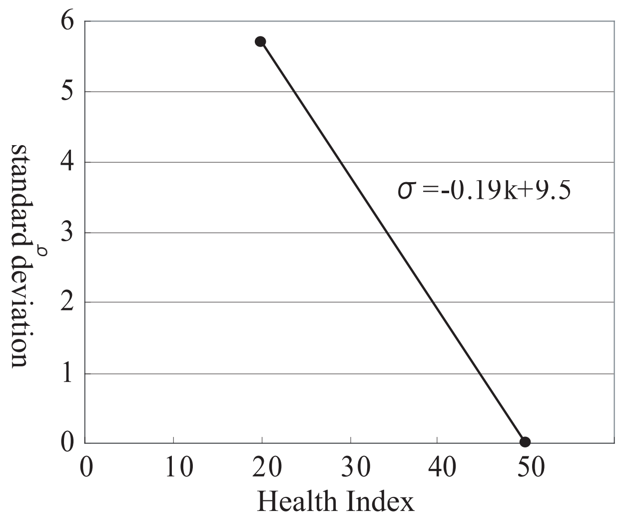

Figure 4.3 Co-relation between the degree of soundness and standard deviation α

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2} \right]$$

$f(x)$:probability
σ:standard deviation
μ:mean

Eq. (4.1) probability

$$\sigma = -0.19k + 9.5$$

k: Degree of Soundness

Eq. (4.2) standard deviation

Table 4.3 Variance in bridge ages requiring repair for each degree of soundness

degree of soundness	standard deviation	Variance in bridge ages (confidence interval 90%) (year)
40	1.9	6.2
30	3.8	12.4
20	5.7	18.7
10	7.6	24.9

4.4 Consideration of variance in deterioration prediction

The level of deterioration in bridge members due to aging is varied depending on the location and traffic intensity of a bridge. In other words, it is difficult to predict the level of deterioration for all bridges by the standard formula that we have formulated in this study.

Thus, normal distribution was used in order to determine the scope of variance in deterioration prediction, thereby simulating more practical maintenance costs. In the normal distribution, the most probable bridge age requiring repair derived from the deterioration prediction formula is expressed as mode values. (Figure 42)

Variance in bridge ages requiring repair for each degree of soundness is defined by the normal distribution method in order to determine the scope of variance in deterioration prediction, which will be used to estimate maintenance costs to be incurred in the future. (Eq.(4.1))

Standard deviation was determined for each degree of soundness by considering the scope of the variance by using data taken from sampled bridges.(Eq.(4.2), Figure4.3, Table 4.3)

5. CONCLUSION

We have estimated LCC of bridges in the city for the next 50 years for each grade of the degree of soundness. As a result, we have found that LCC will be $523 million if optimum repair cycles are used in all bridges, which is about a quarter of LCC if measures are taken only when bridges reach the 'e'

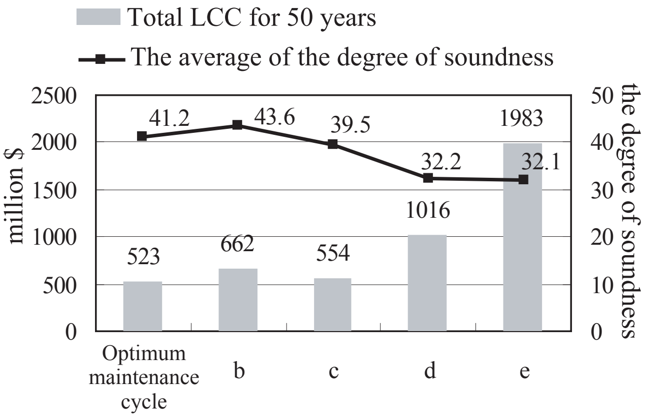

Figure 5.1 LCC and the average of the degree of soundness by maintenance-requiring grade

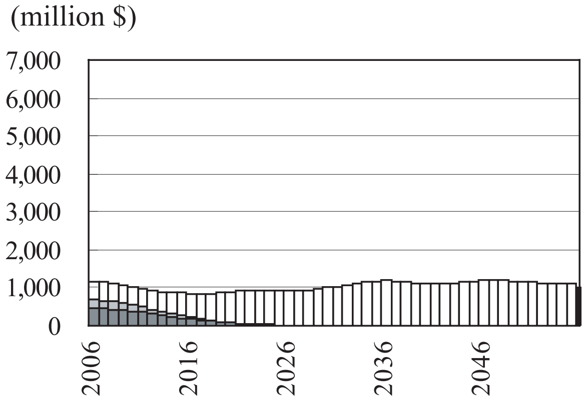

Figure 5.3 Estimated maintenance costs under optimum maintenance scenario (n=2108)

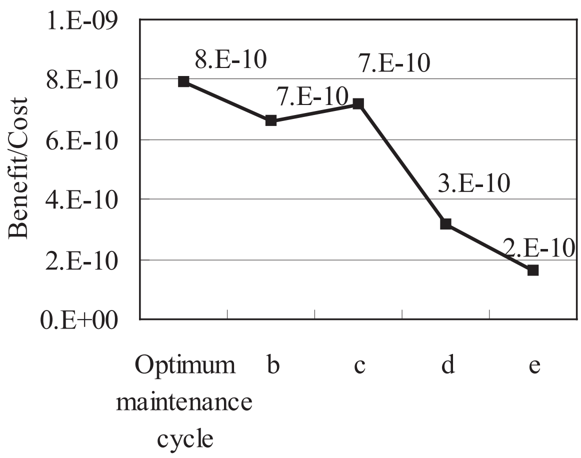

Figure 5.2 Cost-effectiveness for each grade that requires repair

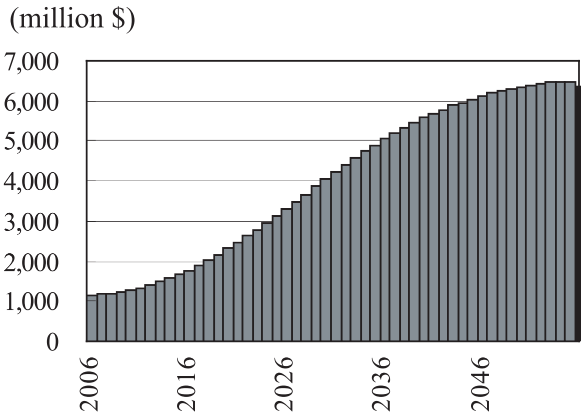

Figure 5.4 Estimated maintenance costs if maintenance is only performed for e-grade bridges

-grade stage (danger). (Fig. 5.1)

We also compared cost-effectiveness for the above two scenarios using the average of the degree of soundness of all bridges. For this purpose, benefits derived from bridges are divided by LCC. The result was the former scenario was about 4 times more cost-effective than the latter. (Fig. 5.2) In addition, the comparison between Figure 5.3 and Figure 5.4 suggests that the optimum repair cycle scenario enables leveling of budget better than the reconstruction scenario for the e-grade bridges.

6. CHALLENGES AND PROSPECT

6.1 Concept of benefit

In this study, for assessing cost-effectiveness, benefits are defined as the average of the degree of soundness. However, bridges offer various benefits. For example, bridges help reduce transit time, fuel costs, and provide more opportunities for interaction among people. In addition, drivers have to travel a long distance in the absence of bridges, causing air pollution, noise, vibration, and aggravating global warming due to increased CO^2 emission. Another benefit can be derived from added values of bridges, as they have a potential of contributing to branding efforts by the city through their unique structures or creating distinctive landscape.

Therefore, it would be worthwhile to study other benefits of bridges and use the findings for setting priorities of investment such as repair works and reconstruction.

6.2 Asset Management as an integrated process from planning to maintenance

This study focused on maintenance for obtaining LCC. From the viewpoint of performing citizen-oriented AM, AM should be comprehensive management of bridges from planning to maintenance. For instance, public participation in the planning stage is important since this approach adds more values to the planned facility and enables to better use it in the long run. At the construction stage of a bridge, consideration into the possible increase in LCC due to changes in the environment may necessitate additional measures to lengthen the life of a bridge, even though it increase the initial construction costs. Reusing bridge railings with historical values and recycled materials could be viable options from the viewpoint of cost reduction and environmental conservation. It is also important to take a selective approach in maintenance by separating facilities into those to be preserved and those to be removed, possibly based upon the result of a questionnaire survey of citizens.

6.3 Investment planning which takes into consideration investment in all public facilities

To perform repair works at the optimum timing is most desirable to minimize LCC of bridges. However, a number of bridges may be at the optimum timing for repair at any given time. In that case, given the city's limited financial resource, it is realistically impossible to maintain all bridges subject to repairing simultaneously. Thus, it is important to produce a master plan for investment in road development including the construction of new roads and fire prevention programs in order to achieve investment leveling. Moreover, to promote city-wide AM, investment planning must also predict investment for all public facilities.

6.4 Monitoring of deterioration

In this study, we have obtained LCC from deterioration prediction resulting from the sampling survey. However, it is important to review deterioration prediction formula alongside the progress in inspection work, and to update formula classified by characteristics of each area including seaside areas as well as the needs of the time, in order to add more accuracy to investment planning.

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