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Evaluation System for Lifecycle Environmental Impact and Cost of Bridges

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Abstract: Bridges consume a great number of resources during their lifecycle for construction, maintenance and demolition activities. Recently global warming has been considered as a serious threat to the human society that is caused due to emission of greenhouse gases by anthropogenic activities. In this study, a system is developed to estimate the lifecycle CO_2 emissions and costs of bridges using available database and information. This study aims to find the proportions of environmental impact and cost of each lifecycle stage of the bridge.

[Key words] lifecycle, evaluation system, environmental impact, CO_2 emission, maintenance frequency

1. Introduction

Lifecycle studies are being more important in the field of infrastructure planning and management in recent years. Several aspects of bridge lifecycles are being investigated by a number of researchers. Study on the basis of deterioration of existing bridges is one detailed approach. Such studies are carried out by Cady and Weyers (1984), Frangopol et al. (1997), and Tam and Steimer (1996). Development of conceptual models is another approach of lifecycle study. Ellis et al. (1995) and Chang and Shinozuka (1996) have developed such models. Ehlen (1997) has considered cost of new construction materials. Most of these studies focussed on the lifecycle cost as the basis for the lifecycle performance. Recently, environmental problems are being important in the infrastructure management in addition to the cost. Horvath and Hendrickson (1998) in their recent work have focussed on the difference of steel and steel-reinforced bridge with respect to environmental assessment. The problems of global warming have drawn attention of whole world to find various ways of reducing greenhouse gases. Bridge is one of major infrastructures that use significant amount of resources during its lifecycle.

This study considers lifecycle environmental impact of bridges as supplementary parameter additional to the conventional criteria such as cost and safety. Major maintenance activities are accounted in evaluating lifecycle environmental impact and cost in addition to construction and demolition activities. Carbon dioxide (CO_2) emission is considered as the indicator for environmental impact. Because maintenance stage is associated with various uncertainties like bridge service life and maintenance frequencies, probability distributions are considered for these uncertain parameters on the basis of available information from various sources including previous lifecycle studies and interview with practical maintenance engineers. This study aims to find the proportions of environmental impact and cost from construction, maintenance and demolition activities. This work focussed on dealing with difficulties in gathering and processing of lifecycle information of bridge infrastructure and shows a methodology to deal with available information.

2. Development of Evaluation System for Lifecycle Environmental Impact and Cost

The lifecycle cost is the total cost accrued to the facility during its construction, maintenance and demolition stage. Similarly, the lifecycle environmental impact is the total environmental impact from construction, maintenance and demolition stage. The environmental impact and cost from construction stage of a bridge can be evaluated with the system developed by Itoh et al. (1996) and later improved by Sunuwar et al. (1997). The environmental impact and cost from the demolition stage are determined by finding the equipment and materials used during the bridge demolition activities. The materials and equipment used during maintenance vary depending upon various factors such as quality of construction, traffic condition, surrounding

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environment and so on. To account such numerous factors, the age of the bridge and frequencies of major maintenance activities are dealt in the probabilistic manner. At this stage, various parameters of proposed distributions are calculated and included in this study.

Fig. 1 shows the structure of the lifecycle evaluation system developed in this study. According to the deterioration rate of the bridge components and possible intervention from the maintenance agency the maintenance frequency can be decided. CO_2 emission from the maintenance is found by estimating the material usage and equipment usage during maintenance stage. For the demolition stage, appropriate method is considered and the material and equipment usage are estimated to find the total CO_2 emissions from demolition activities. The materials are used in demolition stage for making temporary structures. The demolition cost is also found depending upon the demolition methods and equipment used.

The lifecycle environmental impact **I** is the total environmental impact from construction, maintenance and demolition stage as shown in Eq. (1):

$$\mathbf{I} = I_C + I_M + I_D \tag{1}$$

where I_C = environmental impact from construction stage; I_M = environmental impact from maintenance stage and I_D = environmental impact from demolition stage. The environmental impacts from construction and demolition stages are for a single event and can be calculated by considering various bridge components. The environmental impact from maintenance has to be summed for several years occurring at various intervals. It can be calculated by summing all the impacts from maintenance activities of various bridge components as:

$$I_M = \sum_{n=1}^{N}\sum_{t=1}^{T} I_m(n,t) \tag{2}$$

where I_m (n,t) = environmental impact from n-th maintenance activity at t-th year; N = total number of maintenance activities; and T = bridge service life in year.

The lifecycle cost **C** is the total cost accrued to the facility during its construction, maintenance and demolition stage and can be estimated as shown in Eq. (3):

$$\mathbf{C} = C_C + C_M + C_D \tag{3}$$

Where, C_C = construction cost at present value; C_M = present value of all maintenance cost and C_D = present value of demolition cost. The construction cost and demolition cost occur within fixed duration of time. But the

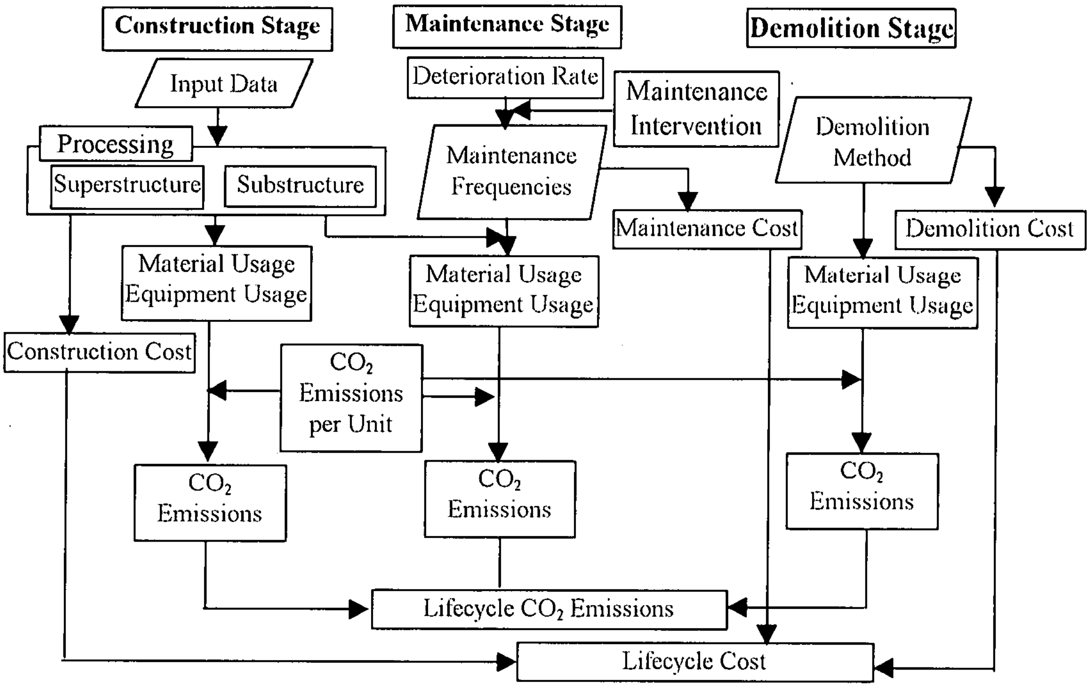

Fig. 1 Structure of the Lifecycle Impact Evaluation System

maintenance cost will occur over the whole bridge service life at several intervals. Since the value of money changes over time, a certain discount rate has to be considered to find the present value of money. Following equation estimates the cost from various maintenance activities to be carried out at several events:

$$C_M = \sum_{n=1}^{N} \sum_{t=1}^{T} C_m(n, t) \times (1 + r)^{-t} \tag{4}$$

where C_m (n, t) = cost of *n*-th maintenance activity at *t*-th year; N = total number of maintenance activities; and r = discount rate. The demolition cost occurs at the end of the service life that has to be converted into present value with following equation:

$$C_D = C_d \times (1+r)^{-T} \tag{5}$$

where C_d = estimated future value of the demolition cost.

3. Environmental Impact and Cost from Bridge Maintenance

3.1 Probabilistic Approach for Bridge Maintenance

During the bridge lifecycle the maintenance activities vary tremendously depending upon the quality of the construction, traffic condition and the surrounding environment. Because there is very limited database available for the performances of infrastructures from maintenance activities, various parameters are attempted to include in range with probability distributions. Fig. 2 shows the methodology followed in deciding the major maintenance activities and range of maintenance frequency. Routine maintenance activities are not included in this study. Major maintenance activities and frequencies are considered based upon the results of interviews with bridge maintenance engineers from Nagoya City and similar previous studies by Kitada et al. (1996) and PWRI (1997). Table 1 shows the most common bridge maintenance activities with corresponding frequencies considered. Assuming these minimum and maximum values as pessimistic and optimistic values for maintenance frequencies, the standard deviation s for these ranges is evaluated by Eq. (6) as proposed in Tung (1992).

$$s = \frac{f_{op} - f_{pe}}{k} \tag{6}$$

where f_{pe} and f_{op} = the pessimistic and optimistic values of the maintenance frequencies respectively; and k = a constant. The value of k can be determined assuming the values between f_{pe} and f_{op} cover a certain confidence interval. In this case, k is taken as 4 to cover about 95% value in log-normal distribution.

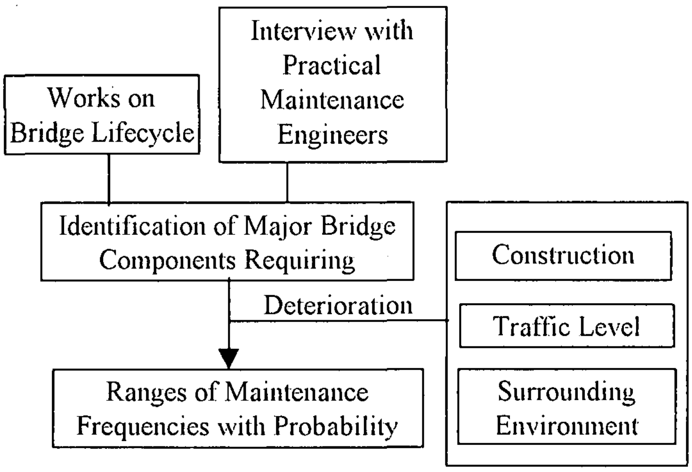

Fig. 2 Procedure Adopted in Considering Frequencies for Major Maintenance Activities

Table 1 Major Bridge Maintenance Activities and Frequencies

Maintenance Activities	Frequency Range (years)	Proposed Distribution	Mean Value (year)	Standard Deviation (year)
(1)	(2)	(3)	(4)	(5)
(1) Pavement Replacement	5-20	Log-normal	12	3.75
(2) Superstructure Painting	5-20	Log-normal	10	3.75
(3) Deck Rehabilitation	15-25	-	20	-
(4) Deck Replacement	30-50	-	40	-
(5) Expansion Joint Replacement	5-20	Log-normal	12	3.75
(6) Support and Bearings Replacement	20-30	-	25	-

Log-normal distribution has been considered for maintenance frequencies and log-normal curves corresponding to frequencies assumed in Table 1 are shown in Figs. 3 (a) and 3 (b). The log-normal densities and cumulative probabilities are shown as line (1) for the frequencies of pavement and expansion joint replacement. The line (2) in these figures show the log-normal densities and cumulative probability for superstructure painting in case of steel girder bridges. For other activities, fixed values of frequency are considered lying within the range.

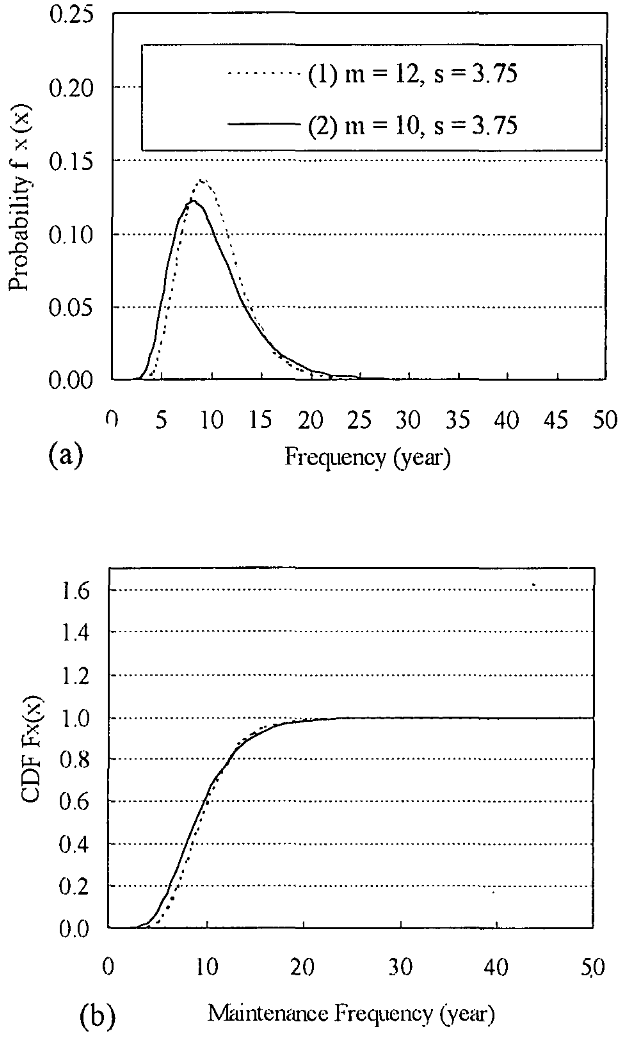

Fig. 3 Log-normal Distributions Considered for Maintenance Frequencies
(a) Probability Distribution Functions
(b) Cumulative Distribution Functions

3.2 Case Studies for Environmental Impact and Cost from Maintenance

Two types of bridges are considered to show the evaluation of the lifecycle environmental impact and cost. These bridge types are Prestressed Concrete (PC) Simple Post-Tension T-Girder Bridge and Steel Simple Non-Composite I-Girder Bridge. The details of these bridges are shown in the Table 2. The environmental impact and cost from construction are obtained by the running the bridge type selection system described in Sunuwar et al. (1997). The materials and equipment used in maintenance activities for single event is obtained by using available manual for material and equipment (Budget 1997). The same manual gives the material and equipment requirement for demolition activity including unit cost for construction activities. The unit impact values for finding emissions values are referred from PWRI (1994).

The points for calculation are considered at *m-2s*, *m-s*, *m*, *m+s*, *m+2s*. Here *m* is the mean frequency value and *s* is the standard deviation of the frequency value. These five points are designated as case 1 to case 5 respectively as indicated in the Table 3. The average service life of the bridge is considered to be 50 years for this calculation. Table 3 shows the details of maintenance intervals considered.

Figs. 4(a) and 4(b) show the environmental impact from construction, maintenance and demolition stage to the total life cycle environmental impact at five points. In case of PC Simple Post-Tension T-Girder Bridge, the maintenance stage is contributing about 19% impact in slowest deterioration rate and 50% in highest deterioration rate. In case of Steel Simple Non-Composite I-girder Bridge, the environmental impact from maintenance activities varied from 22% to 63%. The environmental impact from demolition stage is found very low in comparison to construction and maintenance stages. This is because the demolition activities are carried out mostly with manpower and equipment requiring only small quantities of construction materials for temporary structures such as staging.

Table 2 Details of Bridges Considered for Evaluation of Lifecycle Performances

Superstructure Type	Steel Simple Non-composite I-girder	PC Simple Post-tension T-Girder
(1)	(2)	(3)
Bridge Length (m)	100	
Width (m)	17	
Effective Width (m)	16	
Span Arrangement	33m + 34m + 33m	
Type of Abutments	Inverted T-type	
Type of Piers	Inverted T-type	
Type of Piles	Reverse Piles	

Table 3 Details of Cases for Estimation of Lifecycle Environmental Impact and Cost

Maintenance Activities	Maintenance Frequencies (in year)				
	Case1 (m-2s)	Case 2 (m-s)	Case 3 (m)	Case 4 (m+s)	Case 5 (m+2s)
(1)	(2)	(3)	(4)	(5)	(6)
Pavement replacement	4.50	8.25	12.0	15.8	19.5
Superstructure Painting	2.50	6.25	10.0	13.8	17.5
Deck Rehabilitation	20.0	20.0	25.0	30.0	30.0
Deck Replacement	30.0	30.0	40.0	50.0	50.0
Expansion Joint Replacement	4.50	8.25	12.0	15.8	19.5
Support and Bearings Replacement	20.0	20.0	25.0	30.0	30.0

Figs. 5(a) and 5 (b) show the cost for construction, maintenance and demolition stages of bridges. In these figures, the maintenance cost is varying as the maintenance frequencies change from high to low. An annual discount rate of 2% is considered to convert the future costs to present value. In the case of PC Simple Post-tension T-Girder Bridge, the maintenance stage is contributing about 14% of total lifecycle cost in slowest deterioration rate and 34% in highest deterioration rate. In case of Steel Simple Non-Composite I-Girder Bridge, the maintenance cost varied from 15% to 47%. It can be observed that the demolition activity contributes larger proportion of lifecycle cost than lifecycle environmental impact.

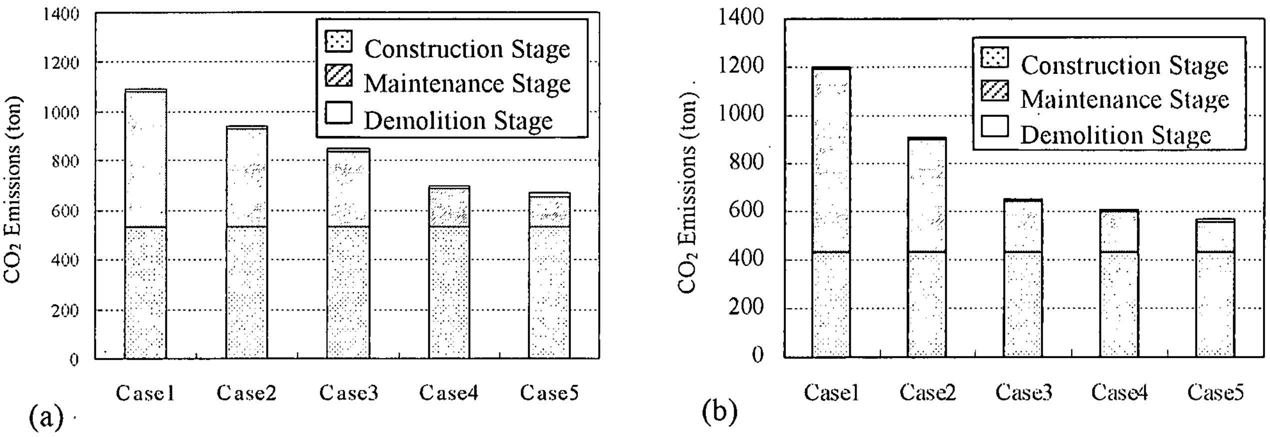

Fig. 4. Lifecycle Environmental Impact from Varying Maintenance Frequencies
(a) PC Simple Post-Tension T-Girder Bridge (b) Steel Simple Non-Composite I-Girder Bridge

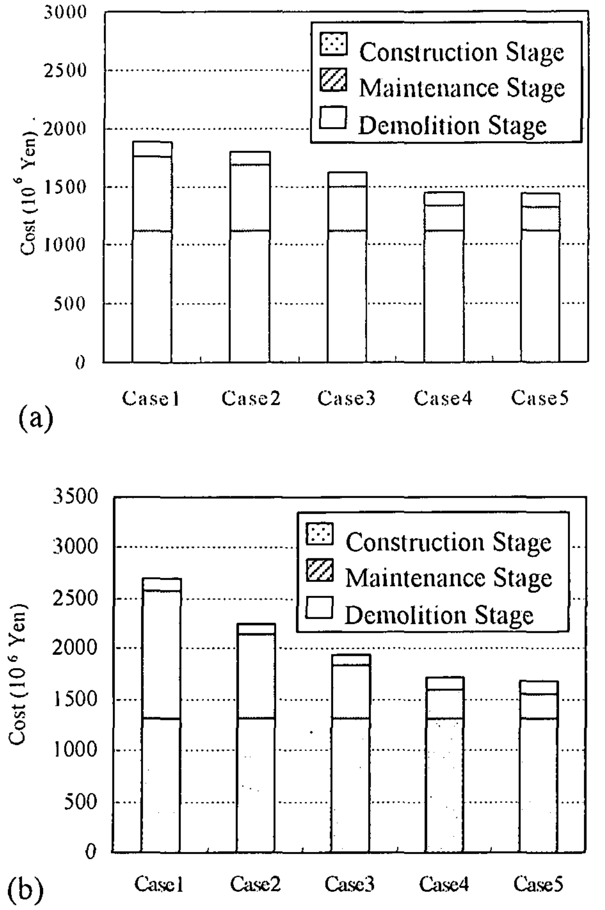

Fig. 5 Lifecycle Cost from Varying Maintenance Frequencies
(a) PC Simple Post-Tension T-Girder Bridge
(b) Steel Simple Non-Composite I-Girder Bridge

4. Effect of Bridge Service Life on Lifecycle Environmental Impact and Cost

4.1 Probabilistic Treatment of Bridge Service Life

Bridge service life is one uncertain parameter in lifecycle study depending upon numerous factors such as quality of construction, traffic condition and surrounding environment. To account all these uncertainties the bridge service life has to be considered in a range with probability distribution. Weibull distribution is fitted for the data available in Fujiwara (1992) for the bridges replaced in Japan during September 1977 - June 1986. Among the various reasons for replacement, only 90 bridges demolished due to insufficient load carrying capacity have been considered. The shape of Weibull distribution obtained is shown in Figs. 6(a) and 6(b). From this the life of the bridge is found to be between 35-65 years with most likely value of 52 years. However, other study PWRI considers service life for conventional bridges of Japan as 60 years. Similarly, Frangopol et al. (1997) have considered service life of concrete bridges in USA as 75 years. Therefore this study examines various lifecycle performances assuming the bridge service life to be in between 35-75 years.

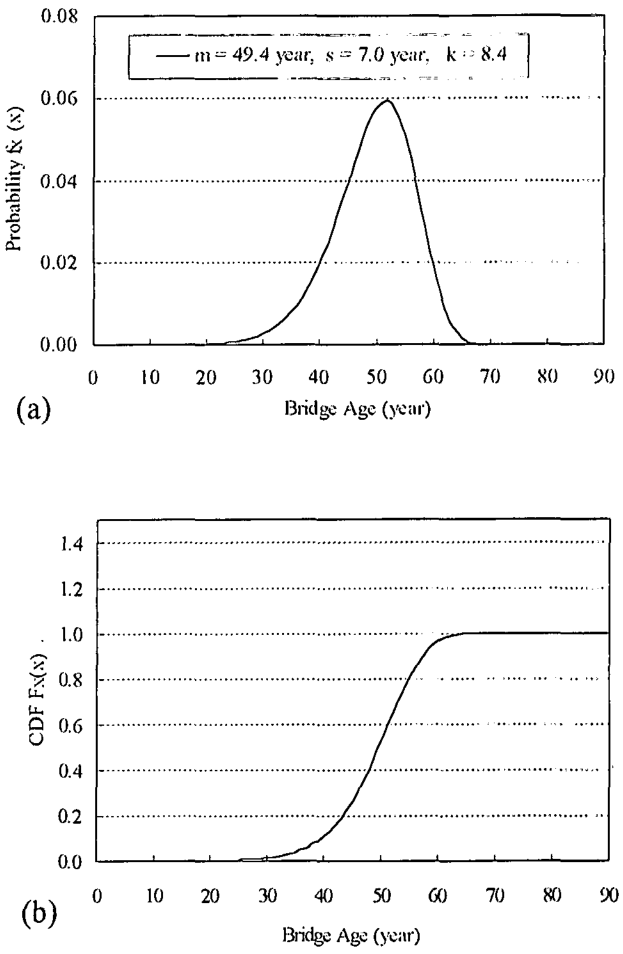

Fig. 6 Weibull Distribution Fitted for Bridge Service Life
(a) Probability Distribution Function
(b) Cumulative Distribution Function

4.2 Scenarios for Different Bridge Service Life

In order to observe the environmental impact and cost, Figs. 7(a) and 7(b) show the total lifecycle environmental impact for different service lives of PC Post-tension T-girder bridge and Steel Non-Composite I–Girder bridge considering the average maintenance frequency. There is gradual increase in total lifecycle environmental impact as the bridge life increases. Since no discount rate is considered for environmental impact, the environmental impact from demolition is the same for all cases of bridge life. The environmental impact from demolition activity is relatively small as almost no construction materials are consumed during this stage except for temporary structures.

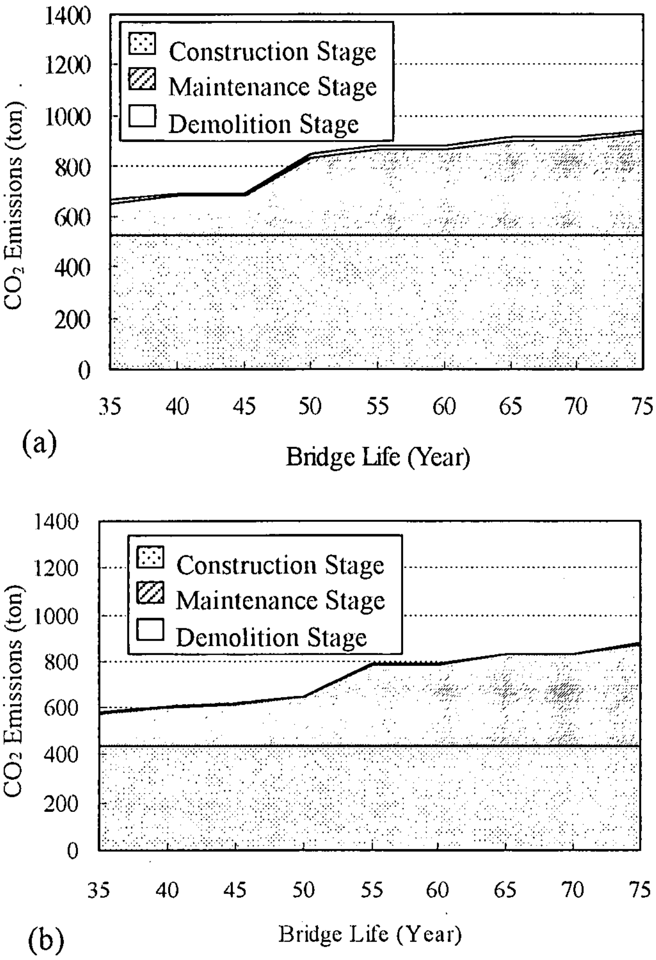

Fig. 7 Effect of Bridge Service Life on Lifecycle Environmental Impact
(a) PC Post-Tension T-Girder Bridge
(b) Steel Non-Composite I-Girder Bridge

It is obvious that the environmental impact from maintenance is variable among lifecycle environmental impact. Further calculations are made by considering various cases of maintenance frequencies and different ranges of bridge service lives. The trends of environmental impact from various cases of maintenance frequencies for different bridge service lives are shown in Figs. 8(a) and 8 (b). The environmental impact is increasing for bridges having longer service lives. In the case of steel bridge more frequent maintenance cases, the environmental impact from maintenance stage is quite higher than less frequent cases. This is because steel bridge has to be painted more frequently in higher maintenance requirement.

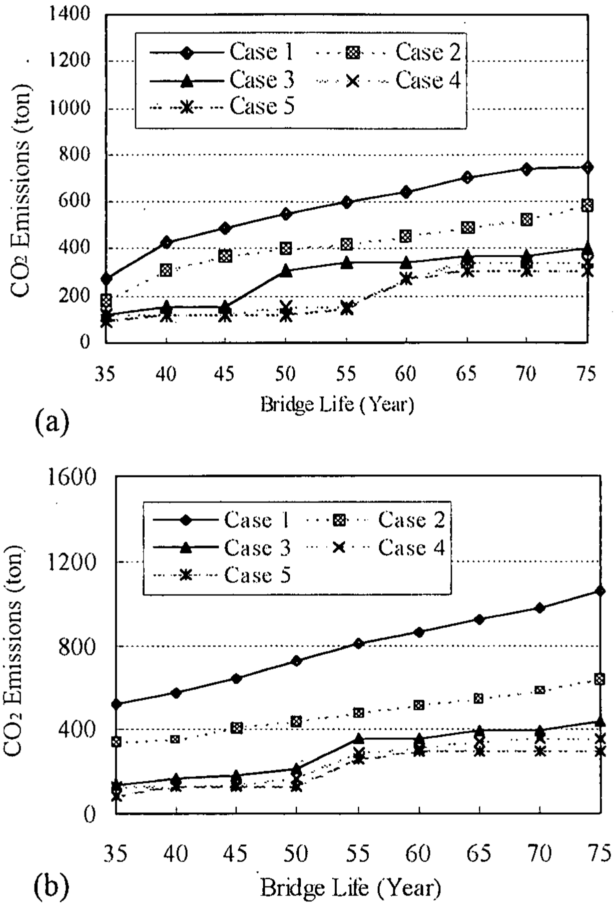

Fig. 8 Effect of Changing Maintenance Frequencies and Bridge Service Life on Impact from Maintenance
(a) PC Post-Tension T-Girder Bridge
(b) Steel Non-Composite I-Girder Bridge

5. Conclusions

This study described the development of a system for the estimation of lifecycle environmental impact and cost including major maintenance and demolition activities in addition to construction activity of bridges. The estimation procedures are illustrated with various types of bridges. Following conclusions can be stated from this study:

(1) A system is developed by considering a range of bridge service life and maintenance frequencies in probabilistic basis from the available information from various sources.

(2) The environmental impact and cost from major maintenance activities of bridges vary significantly depending upon the maintenance frequencies. The environmental impact from maintenance is between 19-63% of total lifecycle environmental impact depending upon the maintenance frequency and bridge types. The variation in maintenance cost is between 14-43% of total lifecycle cost.

(3) The increase in lifecycle environmental impact and cost is gradual as bridge service life increases. From this observation, it can be implied that extension of the bridge service life may be one effective way to reduce the lifecycle environmental impact as well as cost.

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