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DECISION SYSTEM FOR REPAIR/REPLACEMENT OF BRIDGE ELEMENTS

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ABSTRACT

The Bridge Management Systems (BMSs) are applicable for all types of short and long span bridges. The maintenance management of long span bridges of specialized technology, such as cable-stayed bridges or suspension bridges, is complex to meet the functionality level within the limited budget. It includes numerous multidisciplinary tasks such as planning, inspection, maintenance, preparation of procedures and instructions, optimization of resources and interaction with external bodies. An element-level economic decision system for repair/replacement program has been proposed to project level (bridge). The application of repair/replacement decision model has been demonstrated specifically for bridge deck of Vidyasagar Setu cable-stayed bridge (Kolkata, India) and same application to other elements. A hierarchical coding structure has been developed up to five levels. The proposed model incorporates the extended service life due to various rehabilitation alternatives with the discount rates.

CE database subject headings: *Repair/Rehabilitation, Bridge Management Systems, Cable Stayed Bridge, Project level, Element level*

INTRODUCTION

Infrastructure networks of roads and railways play a very important role in the everyday life of a country and its people. They provide mobility so that people can reach their destinations as quickly and safely as possible, and they have major a role in transportation of goods. For these reasons it is important that the infrastructure networks should be maintained at their full functionality with as little inconveniences as possible. To achieve this goal, comprehensive BMSs should be developed; in this view regular maintenance, repair and/or rehabilitation operations must be carefully planned and executed at the proper time (Raghavan and Skettrup, 1999). Generally, the BMSs are essential for all types of short and long span bridges. The maintenance management and installation systems of long span bridges of modern technology such as cable-stayed bridges or suspension bridges are complex to meet the functionality level within the limited budget (Sorensen and Berthelesen, 1990).

The long span bridges e.g. cable-stayed bridges or suspension bridges comprise various complex elements, as compare to other bridges. Hence, these bridges require specialized management system with proper inventory database. So, extensive research is needed to determine the remaining useful service life of long span bridges and what measures can be taken to slow or halt the degradation process. In this regard, present study focused on the formulation of comprehensive maintenance management system for cable-stayed bridges.

The analysis of bridges with distinct deficiency e.g. deficient load rating, involves a decision from available improvement alternatives such as replacement, strengthening, repairs and the do-nothing option. Initially the bridge is down into various elements which have shorter life than the whole bridge life and they constitute enormous costs for repair and replacement program. Hence there is a need for element-level decision system for repair and replacement program for the elements of bridge. This method is based on a cost analysis that considers all the costs involved in designing, constructing, inspecting, maintaining, repairing and strengthening associated within the service life of the bridge.

Project-Level Analysis

Project-level analysis deals with individual bridges. At project-level, the decisions on various repair and reconstruction programs are applicable to a particular bridge. The project-level management system helps the bridge engineer to plan and schedule the repair projects for individual bridges based on the recommendations and the damage data in the database (Soderqvist and Veijola, 1999).

Element-Level Analysis

Element-level analysis deals with various elements of the individual bridge. The procedure mentioned here has been used to evaluate and compare the economic benefits of strengthening/rehabilitating versus replacement alternative at element- level. The element hierarchy is based on breaking down the main elements into smaller elements. The purpose of this hierarchy system is to establish a logical break down of the structure into smaller elements identified for inspection (Henriksen, 1999). Each element has comparable technical properties with respect to materials and maintenance and also identical administrative interfaces. The element hierarchy is used to create a complete list of all the different elements forming the cable-stayed bridge. This list is used to organize all the maintenance related data systematically by relating the information to the element numbers. The element hierarchy also describes the location of each element by using a set of codes referred as the 'Element Location Codes'. The element hierarchy for the structures is based on a break down into maximum six element levels with individual properties. The location of an element and the exact position on a face of the element can be indicated using maximum six location codes, 1 to 6 as described below:

Code 1: Stationing at start (or at centre of element, e.g. at piers) of the element

Code 2: Stationing at end of the element

Code 3: Number of the element

Code 4: Orientation of face, e.g. inner/outer (for piers) etc.

Code 5: Level, height in meters or number of lifts of the scaffold above individual defined levels

Code 6: Co-ordinates on the face characterized by individual co-ordinate systems applied to the different elements and whether the co-ordinates shall be used for horizontal, vertical or circular face

First Cost Analysis

First cost is the simplest and most frequently used analysis, and includes only the initial capital costs. It does not attempt to place a rupee value on future expenditure; hence it is not concerned with the discount rate (Collier and Ledbetter, 1982). This format of analysis is suitable for comparing alternatives with equivalent life expectancy, performance, and maintenance. If significant variations and differences are expected in one of these factors, the first cost analysis will not give a true comparison of cost effectiveness of the various alternatives.

Life Cycle Cost Analysis

In the case of life cycle cost analysis the future costs are also considered. One problem associated with this approach is, the difficulty in accurately assessing future costs as they may apply to most bridge projects (Brito *et al.*, 1997). However, progress has been made in determining element life cycle costs and other economic aspects associated with bridge components through enhanced bridge management systems.

Typically, the future costs include routine maintenance, future rehabilitation expenditures and replacement costs at the end of design life (Figure 1). In lifecycle cost analysis, future costs must be discounted to present worth before they are combined with present costs (Xanthakos, 1995). The maintenance is expected to continuously increase with life of the bridge. It is assumed that the year before rehabilitation or replacement only minimal maintenance will be carried out.

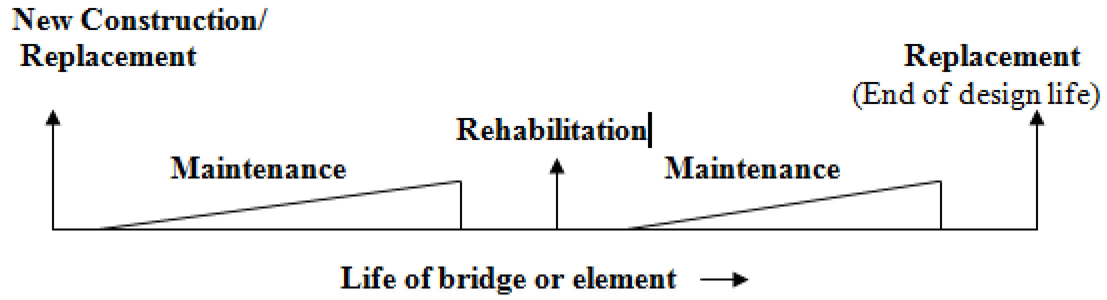


Figure 1: Bridge or Element Life Cycle

Repair/Replacement Model

The comprehensive element-level repair/replacement model has been proposed for comparison of rehabilitation option with respect to the replacement of the various elements of bridge. The procedure discussed here can be used to evaluate and compare the economic benefits of strengthening and rehabilitating versus replacement options. The decision system for repair/replacement model compares the rehabilitation cost with respect to replacement cost considering the extended service life due to rehabilitation alternatives and discount rates. To perform the cost effectiveness comparison of rehabilitation with the replacement option, the methodology is given below.

Replacement case: If the bridge or element is replaced at the end of its design life, as shown in Figure 2, its life cycle cost for perpetual service is:

$LCC_P \text{ (replacement)} = P_{SL} (Pwf_{SL})$

Where, LCC_P = Lifecycle cost (perpetual series)

P_{SL} = Present worth of the cost of one replacement lifecycle (Figure 1)

Pwf_{SL} = Perpetual series present worth factor for service life (Collier and Ledbetter, 1982).

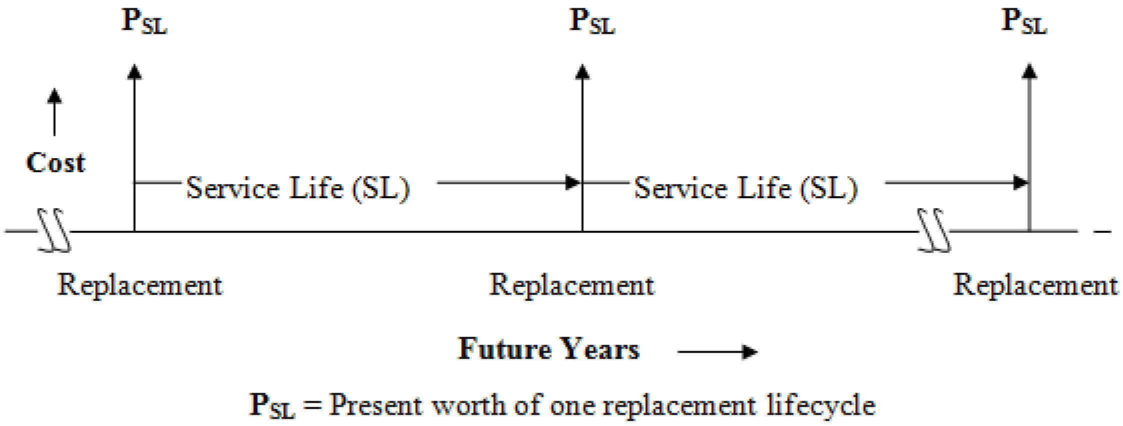


Figure 2: Replacement Case

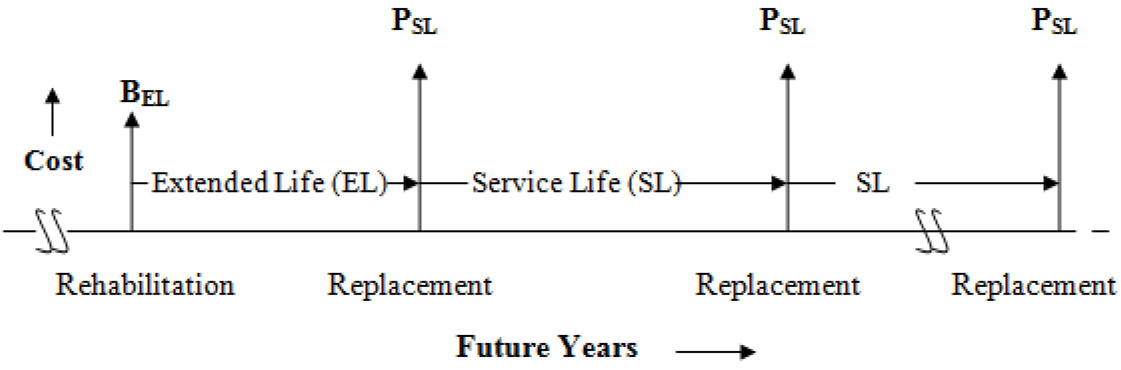
Rehabilitation case**:** Rehabilitation moves replacement by ‘e’ years into the future as shown in Figure 3. In this case the life cycle cost, to perpetuity is

$LCC_P \text{ (rehabilitation)} = B_{EL} + P_{SL} (Pwf_{SL}) (P/F, i, e)$

Where, B_{EL} = present worth of the cost of rehabilitation and maintenance over the extended life of the existing bridge element

e = extended service life of the existing bridge element due to maintenance and rehabilitation (years)

$(P/F, i, e)$ = present worth factor for extended life



P_{SL} = Present worth of one replacement lifecycle
B_{EL} = Present worth of rehabilitation and maintenance costs

Figure 3: Rehabilitation Case

Rehabilitation is cost effective if: $LCC_P\ (rehabilitation) \leq LCCP\ (replacement)$

$$B_{EL} + P_{SL}\,(Pwf_{SL})\,(P/F, i, e) \leq P_{SL}\,(Pwf_{SL})$$

$$B_{EL} / P_{SL} \leq [1 - (P/F, i, e)]\,(Pwf_{SL})$$

$$\text{If} \quad [1 - (P/F, i, e)]\,(Pwf_{SL}) = C$$

$$B_{EL} / P_{SL} \leq C$$

$$\boxed{\text{Repair Index, } (B_{EL} / P_{SL}) \leq C}$$

The Repair Index (RI) represents the ratio of present worth of rehabilitation option (B_{EL}) to replacement option (P_{SL}) costs. It compares the rehabilitation feasibility with respect to replacement option including the extended service life of the element or bridge for a given discount rate.

Model Analysis

The application of the repair/replacement decision model has been demonstrated for the various elements of the Vidyasagar Setu cable-stayed bridge. The bridge is 823 m long and 115 m wide and is supported by 121 wire cables. The design life of this bridge is 70 years. Now just 13 years into the life of the bridge, the elements have started deteriorating and showing premature failures cracks (HRBC Manual, 2005). Hence, there is need for implementation of proper maintenance policy to the bridge as suggested by the design consultants [Leonhardt Und Andrae (LUA) and Freeman Fox and Partners (FFP)]. To ensure uninterrupted traffic movement in future there is a need for major rehabilitation action of the various corroded elements of the bridge in the form of corrective maintenance or replacement. The elements identified for frequent repair/replacement program are given with their design life in Table 1.

Table 1: Elements Identified for Frequent Repair/Replacement

S.N.	Elements	Life in Years
1	Steel Grid System	70
2	Cable System	70

3	Pylon	70
4	Composite Bridge Deck	50
5	Access Facility – Gantry	50
6	Bearing System	30
7	Expansion Joints	25
8	Wearing Surface	20
9	Crash Barriers	20
10	Electrical Installations	20
11	Drainage System	10

Repair/Replacement Analysis for Composite Bridge Deck

Lifecycle cost of bridge deck: The steel and concrete composite decking has been used at Vidyasagar Setu with the design life of 50 years and initial cost recorded during construction was Rs. 200 Million (Accounts Section, HRBC Kolkata). Based on the discussions with the planning and design department of HRBC, Kolkata, the maintenance policy [suggested by Leonhardt Und Andrae (LUA) and Freeman Fox and Partners (FFP)] and the expected maintenance and rehabilitation costs are as given below.

- Construction of deck in the base year (0 year).
- A series of rising maintenance costs gradually varies from Rs.0 at the end of 1st year and to Rs. 4.0 Million at the end of 29th year (by LUA and FFP).
- Rehabilitation cost 100 Million at year 30.
- A series of rising maintenance costs after rehabilitation gradually varies from Rs.0 at the end of 31st year and to Rs. 4.0 Million at the end of 49th year. As suggested by LUA and FFP, the deterioration will be much faster after the rehabilitation so same maintenance policy adopted for rest 20 years.

In the first step in analyzing lifecycle costs, the various costs have to be discounted in present worth terms. An interest rate of 6% has been considered for discounting all the future cost into present worth (Yield Curve, 2005). The inflation has been not taken account because if all cash flows in an economic comparison of alternatives are inflating at the same rate, inflation can be disregarded (Degarmo *et al.,* 1984; Merrett and Sykes, 1976; and Deverell 1970). The breakup of cost calculations are given in Table 2.

Table 2: Lifecycle Cost of Bridge Deck

Year	**Discounting at base year**	**Calculated P.W. Cost (Million Rs.)**
First cost at base year	200	200.00
End of 1st year to 29th	[4/28] * [P/G, 6%, 29]	19.60
At 30th year	100 * [P/F, 6%, 30]	17.41
End of 31st year to 49th	[4/18] * [P/G, 6%, 19]* [P/F, 6%, 30]	3.00
Total Lifecycle Cost [$P_{SL\ (Deck)}$] for Deck at base (0) year		**240.01**

The designed life span of the concrete deck is only 50 years where as the total life span of the whole bridge is 70 years. During the discussion with Hooghly River Bridge Commissioners (HRBC), some of future rehabilitation alternatives and their expected costs were suggested to the damaged composite deck to meet the full life span of whole bridge. In this regard, three rehabilitation alternatives along with their expected costs have been presented as below.

Alternative 1: To remove the full damaged part of the deck concrete and reconstruct with new shear connectors. The initial incurred cost is very high, Rs.150 M (by HRBC after 50th year) with the 20 years of life extension, and the respective maintenance cost is comparatively very less which gradually increases from Rs.0 at year 1 to Rs. 4 M at 19th year.

Alternative 2: Repair of deck with steel plate bonding to the steel section and providing the overlay on the concrete surface. The initial cost of this option is Rs.120 M (by HRBC), the extended life span is same (20 years) as alternative where as the maintenance cost is very high which gradually increases from Rs.0 at year 1 to Rs. Rs. 15 M at 19th year.

Alternative 3: Repair of the deck with concrete patching and providing additional steel bars up to the full supports. The initial cost of this alternative is Rs.140 M (by HRBC) and maintenance cost is slightly lesser than Alternative '2' which gradually increases from Rs.0 at year 1 to Rs. 10 M at 19th year, where as the extension of deck life is same 20 years.

All the future costs of each alternative have been discounted on present worth basis as given below.

Alternative 1: Replacement of concrete with new shear connectors

Total discounted rehabilitation costs [$B_{EL\,(Alt.\,1)}$] = Initial Cost + Maintenance Cost

= 150 + [4/18] [P/G, 6%, 19]

= 168.20 Million Rs.

Total discounted rehabilitation cost [$B_{EL\,(Alt.\,1)}$] for Alternative 1 = 168.20 M Rs.

Alternative 2: Repair of deck with steel plate bonding and overlay

Total discounted rehabilitation costs [$B_{EL\,(Alt.\,2)}$] = 120 + [15/18] [P/G, 6%, 19]

= 187.70 M Rs.

Total discounted rehabilitation cost [$B_{EL\,(Alt.\,2)}$] for Alternative 2 = 187.70 M Rs.

Alternative 3: Repair of deck with concrete patching and additional steel bars

Total discounted rehabilitation costs [$B_{EL\,(Alt.\,3)}$] = 140 + [175/18] [P/G, 6%, 19]

= 185.20 M Rs.

Total discounted rehabilitation cost [$B_{EL\,(Alt.\,3)}$] for Alternative 3 = 185.20 M Rs.

Lifecycle cost for concrete deck has been already computed $P_{SL\,(Deck)}$ = 240.01 M Rs.

Comparison with decision model: Rehabilitation alternative is cost effective if:

Repair Index (RI) $B_{EL\,(Alt.\,i)}/P_{SL\,(Deck)} \leq C$

where $C = [1-(P/F, i, e)]\,(Pwf_{SL})$

$= (1-(P/F, i, e)\,(Pwf_{50})$

$= [1-(1.06)^{-20}]*[(1.06)^{50}/(1.06)^{50}-1]$

$= 0.73$

$B_{EL\,(Alt.\,i)}$ = ***Discounted cost of various rehabilitation alternatives***

$P_{SL\,(Deck)}$ = Present worth of the cost of one replacement cycle of deck

Alternative 1: $B_{EL\,(Alt.\,1)} / P_{SL\,(Deck)} \leq C$

$0.70 < 0.73$

Rehabilitation Alternative 1 is cost effective compared to replacement option.

Alternative 2: $B_{EL\ (Alt.\ 2)} / P_{SL\ (Deck)} \leq C$

$0.78 > 0.73$

Rehabilitation Alternative 2 is costlier than replacement option.

Alternative 3: $B_{EL\ (Alt.\ 3)} / P_{SL\ (Deck)} \leq C$

$0.77 > 0.73$

Rehabilitation Alternative 3 is costlier than replacement option.

The comparison shows that the rehabilitation option with Alternative 1 (replacement of concrete with new shear connectors) is the most cost effective solution.

The parameter "C" is plotted for bridge deck in Figure 4, versus the extended service life due to rehabilitation, "e", assuming service life (SL) equals 50. This graph permits direct comparison of replacement and rehabilitation where the effect of discount rate can be seen. The parameter "C" increases with the discount rate and so Repair Index (B_i/P_{SL}) can be larger as the discount rate increases and still indicate rehabilitation as cost effective.

The higher the discount rate, the more attractive rehabilitation becomes, meaning the low discount rates tend to favor replacement. For the given discount rate, the corresponding line on the graph of Figure 4 is a breakeven line. If the Repair Index (B_i/P_{SL}) point plots below the line, then rehabilitation solution is cost effective; if it falls above the line, it is cost effective to replace. With the '6%' discount rate used, upto 73 percent (C = 0.73) of the replacement cost could spent to extend life to 20 years.

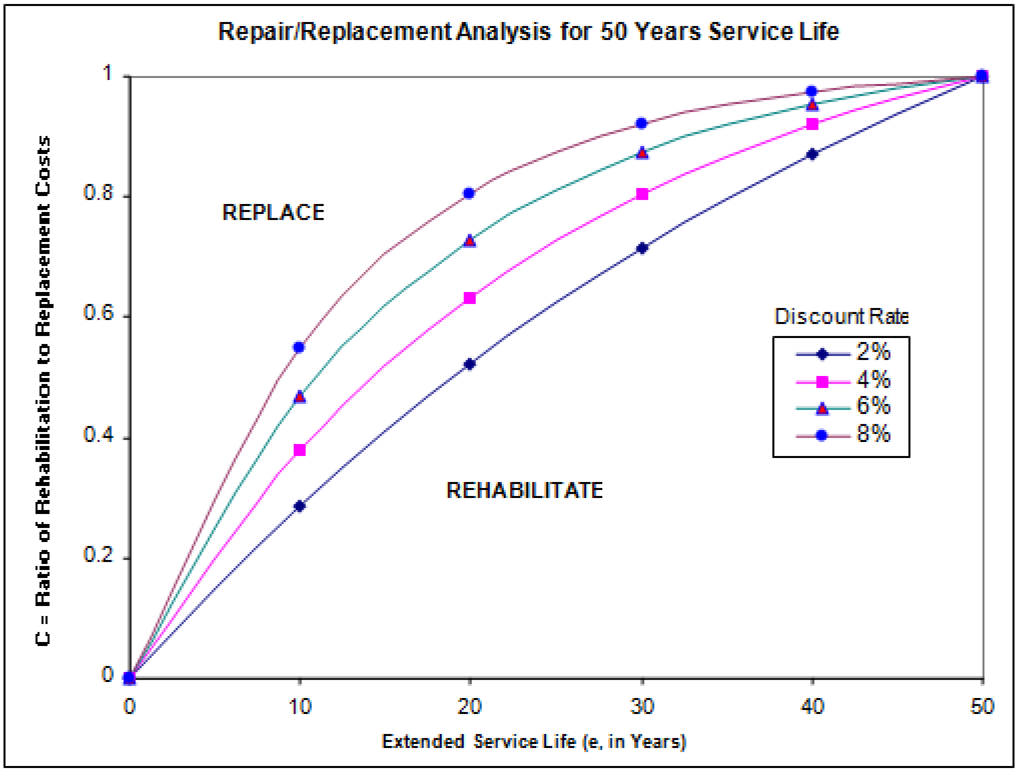


Figure 4: Repair/Replacement Decision Chart for Bridge Deck

In the comparison of bridge deck, rehabilitation option with Alternative 1 extended service life 20 years. For 20 years extension with 6% discount rate, C = 0.73 (Figure 4).

$B_1 / A_D \leq C$

$0.70 < 0.73$

Because Repair Index (B_i/P_{SL}) lies below the breakeven line for a given discount rate, rehabilitation option will be the cost effective compared to replacement of that element and vice versa. But for other rehabilitation alternatives, replacement option will be more cost effective as Repair Index (B_i/P_{SL}) is greater than "C" value.

The similar comparison model charts can also developed for elements identified for frequent repair and replacement works as shown in Table 1. The comparison charts will work as a decision chart to select the most cost effective rehabilitation alternative intervention with respect to replacement option.

Summary

The element-level repair/replacement decision system for the elements used at Vidyasagar Setu cable-stayed bridge across Hooghly River at Kolkata has been presented in this paper. The developed comparison chart evaluates the economic options of whether to rehabilitate or replace the various elements of the bridge based on their extended life and discount rate.

The present worth method is based on the concept of equivalent worth of all cash flows relative to some base or beginning point in time called the present. That is, all cash flows and outflows are discounted to the base point at given interest rate (Collier and Ledbetter, 1982).

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