INNOVATIVE ASSET MANAGEMENT

Full Paper

RELIABILITY BASED OPTIMAL SOLUTION FOR REHABILITATION OF EXISTING BRIDGE STRUCTURES

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ABSTRACT

Many countries are experiencing problems in management of rehabilitation of aged concrete bridges due to increasing demand on load-carrying capacity combined with fast rate of deterioration and limited budgets for rehabilitation and strengthening of older bridges. The strengthening, rehabilitation or retrofitting of an existing structure can be accomplished using different materials and construction techniques, which often lead to a situation where officials are faced with a decision to select an optimum solution. Decisions are typically made based on a cost basis analysis. However, determination of the cost of each alternative is not straightforward simply because of uncertain nature of the future of most repair schemes and risks involved. Probabilistic time-dependant analyses can be used to evaluate and optimize life-cycle costs associated with each strengthening or rehabilitation alternative. This is often referred to as risk-cost benefit analysis or whole-life costing. By incorporating risk information into the cost benefit analysis, a bridge rehabilitation decision can be made on the basis of comparison of risks against benefits. The optimal strengthening/rehabilitation solution, chosen from multiple options, can then be found by minimizing life cycle costs. This paper describes a methodology for development of a decision support tool that relies on the life cycle cost analysis.

Keywords: Bridges, rehabilitation, strengthening, risks, life cycle cost and probabilistic time dependent analysis.

1 INTRODUCTION

In Australia, over 60% of bridges for local roads are over 50 years old and approximately 55% of highway bridges are over 20 years old (Stewart 2001). Structural deterioration increases with the age of the bridge structure due to corrosion, fatigue, wear and tear and other causes of material deterioration. At the same time, loads, vehicles and legal load limits for bridges have been increasing. When the ageing bridge structures are subjected to these kinds of excessive loads, then the structural capability of it reduces. Therefore keeping bridges in a good operation condition is a continuous challenge faced by transportation agencies. Fast rate of deterioration and the high cost of repair, rehabilitation and replacement of bridge structures have become major issues in road asset management. Even when the resources have been allocated, completing rehabilitation tasks with minimal interruptions to traffic flow and inconvenience to the public has been a major issue in identifying a given method of rehabilitation. This paper presents a decision support methodology developed for selecting the optimal rehabilitation method for a deteriorated bridge using the whole life cost analysis of each potential treatment option.

2 DECISION SUPPORT FRAMEWORK

Almost every organization faces the need to evaluate several program proposals or projects competing for scarce resources. Most of the time, the decision maker is trying to satisfy conflicting objectives or cater for opposing group interests. The challenges faced in developing an integrated decision making framework are both procedural and conceptual. In operational terms, the framework should be easy to be understood and employed.

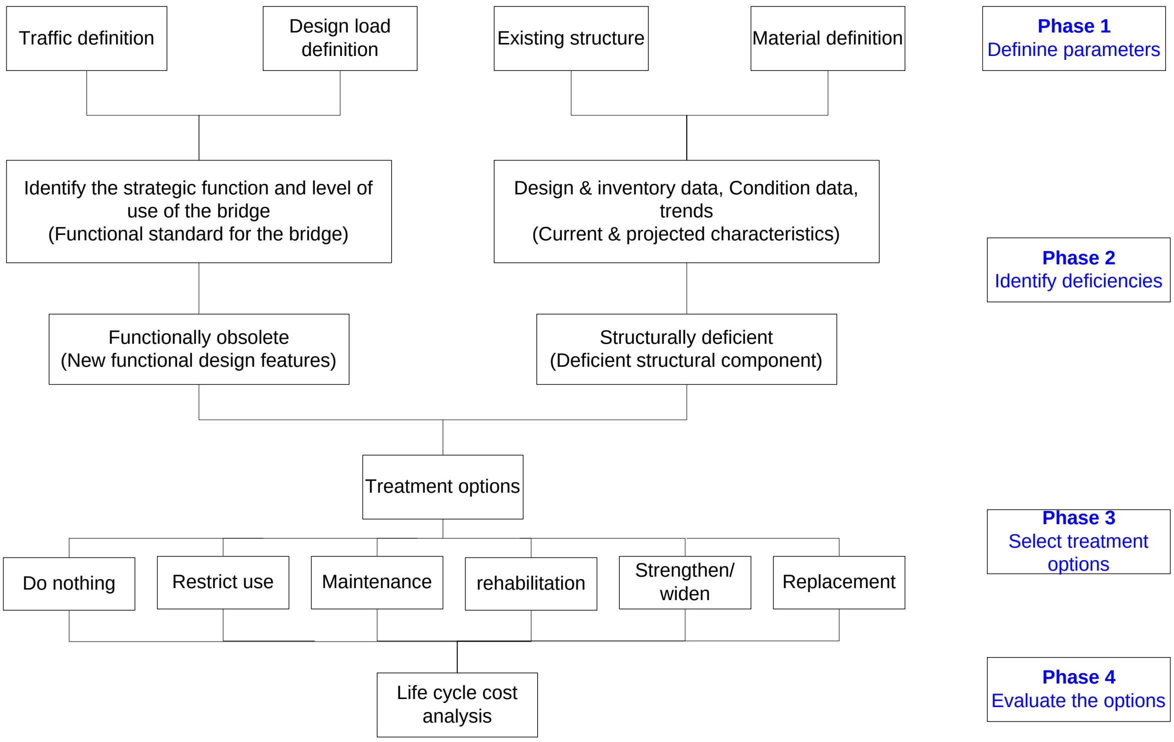

Figure 1: Proposed decision making framework for rehabilitation of bridges

In philosophical terms, the framework should be able to deal with challenging issues, such as uncertainty, time frame, network effects, model changes, while integrating cost and non-cost values into the evaluation. The choice of evaluation techniques depends on the feature of the problem at hand, on the aims of the analysis, and on the underlying information base (Nezamian & Setunge 2004). A decision support framework was developed after identifying the most important factors to be covered (Figure 1). The framework was developed around three key tasks: Identification of deficiencies, establishing available treatment options and then conducting a life cycle cost analysis for each of the options. These tasks were identified through industry consultation

3 IDENTIFICATION OF THE DEFICIENCIES

Identification of the deficiencies of the bridge structure is the first step in addressing the issue of rehabilitation. This requires clear identification of performance requirements of the bridge structure and then evaluating the performance based on existing information of the bridge.

Condition assessment of the structure is the first step in determining the rehabilitation methodology. Clear identification of the performance level needed and deficiencies requires design load definition, definition of traffic, material properties and design documentation of the existing structure. Project specifications and identified strategic function and level of use of the route can be used to establish some of the above information. Evaluation of the structure should commence by conducting a systematic field assessment and recording details of previous repair or rehabilitation task undertaken and accident and traffic overloading data if available. This would be followed by a structural analysis and design calculations complying with the recommendations of the relevant codes and standards. At the end of this phase, the bridge structure can be categorised as “Structurally Deficient” or “Functionally Obsolete”, with a clear understanding of the deficiency. Structures can also be considered “adequate for current use” and simply kept under surveillance.

4 TREATMENT OPTIONS

This is an extremely important component of the framework. Options available to the authorities have been expanded over the years with new developments in materials and structural technology. However, a lack of availability of complete information, which facilitates a fair comparison, makes it difficult for the decision maker to make an informed decision. The broad range of higher-level options identified by the authorities is given below.

- Do nothing
- Restrict use
- Maintain and monitor
- Rehabilitate
- Strengthen/widen
- Replace super-structure
- Replace entire bridge

Recent developments related to materials, methods and techniques for structural strengthening and rehabilitation of the deteriorated bridges have been significant. In addition to well established and proven technologies such as steel plate bonding, external post tensioning, concrete encasing, etc., innovative technologies such as use of fibre reinforced polymer composites are appearing in the market place.

Evaluation of different options requires the asset manager to find a basis for comparison of the options. Evaluation process needs to include uncertainties associated with the innovative methods as opposed to well-understood and established methods.

5 EVALUATION OF THE OPTIONS

Presenting clear and concise information to the decision maker regarding the available options will enable him/her to make a higher level decision from the list identified above. Detailed discussions with the industry revealed that the “cost” is the prime deciding factor in making a decision in selecting a particular strengthening scheme. Authorities prefer to be presented with the whole of life cost of a selected treatment option and incorporate other factors through their own judgement using a broader framework covering social and environmental issues.

6 LIFE CYCLE COST ANALYSIS

Whole of Life cycle cost analysis (WLCCA) is an evaluation method, which uses an economic analysis technique that allows comparison of investment alternatives having different cost streams. WLCCA evaluates each alternative by estimating the costs and timing of the cost over a selected analysis period and converting these costs to economically comparable values considering time-value of money over predicted whole of life cycle. The analysis results can be presented in several different ways, but the most commonly used indicator in road asset management is net present value of the investment option. The net present value of an investment alternative is equal to the sum of all costs and benefits associated with the alternatives discounted to today’s values (Darter and Smith 2003).

Making a decision for selection of the rehabilitation method will be done by minimizing the life cycle costs. Such a decision analysis is referred as a whole of life cycle costing, cost-benefit or cost-benefit-risk analysis. Life cycle costs will assess the cost effectiveness of design decisions, quality of construction or inspection, maintenance and repair strategies (Stewart 2001). The costs associated in a rehabilitation project may initially include:

- Initial cost
- Maintenance, monitoring and repair cost
- Costs associated with traffic delays or reduced travel time (Extra user cost)
- Estimated cost of failure

As shown by Austroads (1996), all of these costs are valued in resource cost terms (i.e. Market prices + subsidies - taxes). If monitoring, repair, extra user cost are considered as the maintenance cost then the cash flow for any rehabilitation method can be shown as in Figure 2.

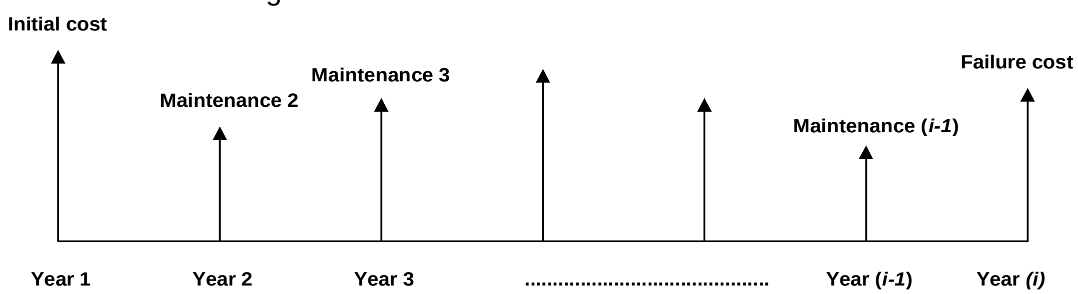

Figure 2: Cash flow for the rehabilitation of bridge

In order to be able to add and compare cash flows, these costs should be made time equivalent. It can be presented in several different ways, but the most commonly used indicator in road asset management is the Net Present Value (NPV). The present value analysis has to be considered together with Internal Rate of Return (IRR).

6.1 STUDY PERIOD

The study period begins with the base date, that is the date to which all cash flows are discounted. Because the cost of each alternative rehabilitation strategy can be compared reasonably only if the benefits gained are the same, the alternatives should be compared over the same operational time period which is known as study period. As a rule of thumb, the analysis period should be long enough to incorporate all or significant component of each alternative's life cycle including one rehabilitation in each alternative. Generally study period or the evaluation period is based on the economic life of major asset in the project. For bridges, the study period is normally longer than the pavements (more than 40 years). Assets with economic life longer than the evaluation period should be given a residual value (resale value).

6.2 DISCOUNT RATE AND INFLATION

The costs are incurred in a project in different times. The interest rate used to discount is a rate that reflects an investor's opportunity cost of money over time. Discount rate is defined as "the rate of interest reflecting the investor's time value of money (Mearig et al. 1999). It is the interest rate that would make an investor feel the same way if he receives a payment now or a large payment at sometime in the future. The LCCA can be performed in constant dollars or current dollars. Constant dollar analyses exclude the rate of general inflation. Current dollar analyses include the rate of general inflation in all costs, discount rates and price escalation rates. Both methods give the identical present value.

It is obvious that the discount rates are normally influenced by the economic, social and political factors. Discount rates used by various countries are different. For example Australia 4%, US 2-3%, UK Department of Transport 8%, Sweden 4% and Finland 6% (Val and Stewart 2003). The discount rates normally are updated and published. Therefore a standard discount rate can be obtained from such published data. For AUSTROADS or national work, the recommended discount rate is 7% (Austroads, 1996). However it is recommended to calculate the NPV based on borrowing rate (bank interest on loans) minus inflation rate.

6.3 FORMULATION OF WHOLE OF LIFE CYCLE COST

Objective function for the optimal bridge rehabilitation can be formulated as the maximization of,

$$W = B_{lifecycle} - C_{lifecycle} \qquad \text{Eq. 1}$$

Where $B_{lifecycle}$ is the benefit which can be gained from the existence of the bridge after rehabilitation and $C_{lifecycle}$ is the cost associated with the bridge during its whole life. Since the benefit from the bridge will be the same irrespective of the rehabilitation method considered, it is possible to consider only the cost component. Therefore the new objective function will be the minimization of the total cost during its whole life cycle subjected to reliability and other constraints. The whole of life cost can be estimated as,

$$C_{lifecycle} = C_{initial} + C_{repair} + C_{user} + C_{failure} \qquad \text{Eq. 2}$$

When all these input costs are defined it is straightforward to calculate the present value of them. However all the input costs have a high degree of uncertainty. In order to deal with such uncertainties it is necessary to include the probabilistic behaviour of the input costs.

6.3.1 Modeling of the initial cost

Initial rehabilitation cost will include preliminary design cost, start up, material and labour costs (supervisors, skilled and unskilled). All these costs will incur in the base time of the project.

6.3.2 Modeling of the maintenance (repair) cost

Modelling of the future maintenance cost is complicated. Thoft-Christensen (2000) divided this cost into three categories namely, functional repair cost $C_1(t_{r,i})$, fixed repair cost $C_2(t_{r,i})$, and unit dependent repair cost $C_3(t_{r,i})$, if a repair is to be taken place at the time $t_{r,i}$. r is the discount rate and i is the number of occurrence of repair. Therefore the corresponding maintenance cost may be defined as (Thoft-Christensen 2000),

$$C_{maintenance}(t_{r,i}) = C_1(t_{r,i}) + C_2(t_{r,i}) + C_3(t_{r,i}) \qquad \text{Eq. 3}$$

The expected repair cost discounted to the time $t=0$ is the summation of the single repair cost.

$$C_{repair} = \sum_{i=1}^{n} \left(1 - P_f(t_{r,i})\right) C_{maintenance}(t_{r,i}) \frac{1}{(1+r)^{t_{r,i}}} \qquad \text{Eq. 4}$$

where n is the number of failures during the life cycle of the bridge and P_f is the updated failure probability at each repair time.

6.3.3 Modeling of user cost

User cost may be of two types, during initial rehabilitation and during the next periodic rehabilitation. User cost may be calculated in terms of costs associated with traffic delay, and in case of using alternate routes wear and tear of user vehicle. The expected user cost may be formulated as,

$$C_{user} = \sum_{i=1}^{n} C_{user}(t_{r,i}) \frac{1}{(1+r)^{t_{r,i}}} \qquad \text{Eq. 5}$$

6.3.4 Modeling of the failure costs

Expected cost of failure (E_c) may be defined as (Stewart et al. 2000),

$$E_c = \sum_{j=1}^{M} p_{f,j} C_{f,j} \qquad \text{Eq. 6}$$

where p_{fj} is the probability of failure for limit state i and C_{fj} is the cost associated with occurrence of limit state i. Failure cost will include the damages, injury and loss of life costs.

6.3.5 Life cycle cost

The life cycle cost can be formulated in an excel spreadsheet. All the possible cost components need to be then added to this spreadsheet for each and every rehabilitation option considered. Cash flows can be given as input variables for the respective year and finally the calculation of present value is performed using the built in financial function for NPV.

The probabilistic behaviour (mean and standard deviations) of any of the input cost should be entered to the respective cells of the spreadsheet in terms of the considered distribution function.

In a similar way each cost component can be given as input parameters and include the probabilistic behaviour. Eventually the decision analysis should be subjected to a sensitivity analysis to make sure that the decision is not unreasonably affected due to the uncertainties of the costs associated.

7 SENSITIVITY ANALYSIS

LCCA estimations should be checked for the sensitivity to the uncertain parameters of the analysis such as analysis period, discount rate, traffic growth rates, traffic speeds, capital costs and accident predictions. Austroads (1996) has suggested the variables and ranges for a road project as shown in Table 1.

Table1: Sensitivity tests – variables and ranges (Austroads, 1996)

Variable	**Suggested minimum value**	**Suggested maximum value**
Capital cost (final costing)	-10% of estimate	+10 to 20% of estimate
Operating and maintenance cost	-10% of estimate	+10% of estimate
Total traffic volume	-10 to 20% of estimate	+10 to 20% of estimate
Proportion cars in work time	-5 percentage points	+5 percentage points
Average car occupancy	-0.3 from estimate	+0.3 from estimate
Normal traffic growth rate	-2% pa (absolute) of the forecast rate	+2% pa (absolute) of the forecast rate
Traffic generated or diverted by project	-50% of estimate	50% of estimate
Traffic speed changes	-25% of estimated change in speed	+25% of estimated change in speed
Accident changes	-50% of estimated change	+50% of estimated change

@RISK 4.5 for Excel can be used to evaluate the impact of uncertain model parameters on the final result. For assumed values for input costs, the sensitivity of the net present value can be identified using @RISK software. It calculates the NPV for a base input parameter and then for a range of values (base value ± 10%). Similarly for all the input cost values the sensitivity of the NPV can be determined and compared.

8 RISK RANKING

All the input variables in the LCCA are uncertain for a particular project. For example time to first rehabilitation may occur in a range of years, the bid cost of the materials is not fixed and discount rate can be varying (Darter and Smith, 2003). Therefore the resulting mean LCCA value is always probability based. As a result there is a risk involved in calculating LCCA value for any of the rehabilitation methods. As shown by Darter and Smith, 2003 it is necessary to include a risk analysis or risk ranking in any LCCA calculation.

Risk ranking can be used to compare the relative risks of various alternatives. This can also be used to evaluate effect of the deterioration rates, relative frequency of overload, costs of failure, cost and efficiency of repair strategies etc (Stewart et al. 2000). The traffic delays or the increased travel time depends on the traffic volume. Therefore estimated cost of failure is a more meaningful measure for the risk ranking. Thoft-Christensen (2000) defined the risk for a failure mode as the product of the failure cost and the probability associated with that. Damage cost and costs associated with loss of life and injury can be considered as the cost of failure. Cost of failure must be discounted to a present value. The probability associated with the failure is related to structural reliability. In this approach, the reliabilities for each option of rehabilitation can be ranked from higher risk to lower risk and a decision of selecting the optimal rehabilitation method can be based on both life cycle cost analysis and risk ranking.

It has been proposed by Thoft-Christensen (2000) that for a bridge rehabilitation program a risk based structural optimization is more suitable than reliability based optimization.

9 CONCLUSIONS

Availability of innovative materials and new technologies of structural rehabilitation has opened up opportunities for more efficient structural rehabilitation. However, lack of decision support tools which facilitate comparison of these options has stalled ready application of these technologies in the field. The work reported herein presents a decision-making framework for rehabilitation of reinforced concrete bridge structures. The major components of the framework have been identified as, capacity analysis, identification of treatment options and whole of life cost analysis of each of the options using a reliability-based methodology.

Probabilistic life cycle costing together with the risk ranking offers prominent improvements in selecting the most suitable rehabilitation strategy. This approach is superior to the deterministic approach used in traditional bridge management systems. The basic steps involved in the LCCA estimation are shown in Figure 2.

The mean and standard deviations of the inputs are entered into the spreadsheet for the simulation. Frequency distribution of the predicted LCCAs of each alternative and some LCC statistics (mean, standard deviation, coefficient of variability, range) are illustrated as the outputs. It is then possible to continue the calculations in spreadsheets including a sensitivity analysis using Monte Carlo Simulations with the aid of @RISK 4.5 software Professional version for simulations and risk analysis.

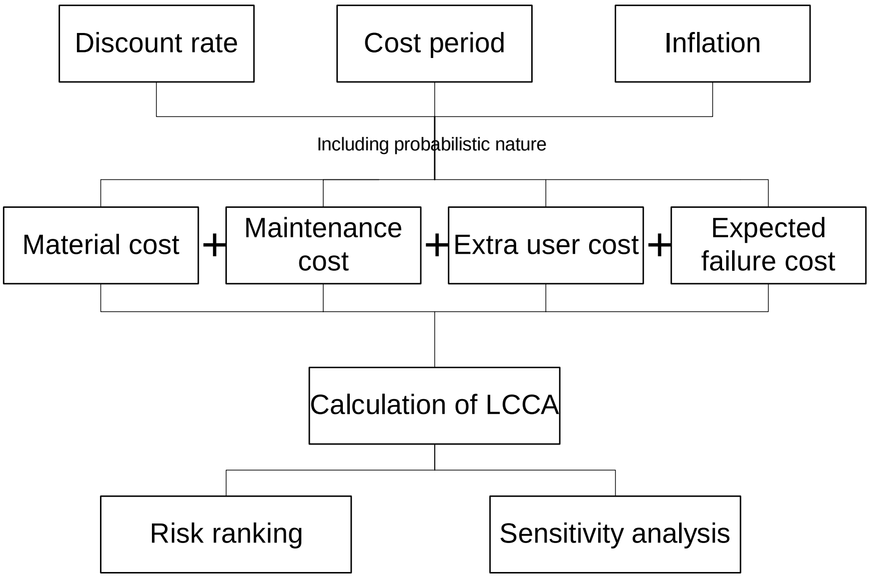

Figure 2: Flow-chart for the LCCA estimation

10 ACKNOWLEDGEMENTS

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