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Strategies for Minimising the Whole of Life Cycle Cost of Reinforced Concrete Bridge Exposed to Aggressive Environments.

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ABSTRACT

In design of bridge structures, it is common to adopt a 100 year design life. However, analysis of a number of case study bridges in Australia has indicated that the actual design life can be significantly reduced due to premature deterioration resulting from exposure to aggressive environments. A closer analysis of the cost of rehabilitation of these structures has raised some interesting questions. What would be the real service life of a bridge exposed to certain aggressive environments? What is the strategy of conducting bridge rehabilitation? And what are the life cycle costs associated with rehabilitation? A research project funded by the CRC for Construction Innovation in Australia is aimed at addressing these issues. This paper presents a concept map for assisting decision makers to appropriately choose the best treatment for bridge rehabilitation affected by premature deterioration through exposure to aggressive environments in Australia. The decision analysis is referred to a whole of life cycle cost analysis by considering appropriate elements of bridge rehabilitation costs. In addition, the results of bridges inspections in Queensland are presented.

KEYWORDS: Reinforced Concrete Bridges, Aggressive Environments, Life Cycle Cost, Rehabilitation Costs.

1.1 INTRODUCTION

Bridges represent a substantial investment of public funds, and are expected to provide satisfactory performance and remain in service for many years. For new bridges, design specifications typically require 75- or 100-year design life. Bridges deteriorate with time due to several causes such as environmental effects, possible overloading, and other factors. Moreover, even bridges not suffering from any serious deterioration may become obsolete with time because of increases in legal load standards and modifications of bridge design codes. Consequently, as the age of existing bridges increases, more resources need to be allocated for their maintenance, rehabilitation, and replacement.

Approximately 100 of the 2800 bridges in Queensland are concrete structures of which many are exposed to aggressive environmental conditions such as saline water or aggressive soils. These environmental conditions have contributed significantly to many of the bridge structures requiring significant repairs within the first 50 years with 1% or less reaching a 100-year design life (Carse, 2005). As a result, maintaining the service delivery for these assets has become a major issue facing the Queensland Department of Main Roads (QDMR) (Venkatesan, *et al.*, 2006). In many cases, the repair of bridges often has been a reactive activity, initiated only when deterioration threatens the safety or tolerance of the public (Hearn *et al.*, 2006). The option of demolishing a bridge and re-building seems to have practical implications. In many cases, approaches to the new bridges cannot be constructed due to land constraints. Furthermore, re-routing the traffic or closing down a service bridge might involve public dissatisfaction and political implications (Venkatesan *et al.*, 2006a)

Before conducting any action towards existing bridges deteriorations careful analyses such as an understanding of the symptoms and the causative problems are essential in the condition assessment of bridge structures. Both site investigations and laboratory tests and followed up by an appropriate life cycle cost analysis need to be carried out properly before selecting the most efficient solution for treatment of the bridge.

Whole life cycle costing (WLCC) is rapidly becoming a standard method for the long-term cost appraisal of building and civil infrastructure projects. In the context of bridges rehabilitation, the purpose of a Life Cycle Cost Analysis (LCCA) is to estimate the overall costs of treatment methods or options and select the best one that ensures the facility will provide the lowest overall cost of ownership consistent with its quality and function. With clients now demanding projects that demonstrate value for money over the long term, WLCC has become an essential tool for those involved in the design, construction, operation and risk analysis of construction projects. It takes into account all costs of acquiring, owning, and disposing of a system. The analysis is especially useful when treatment alternatives that fulfil the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximises net savings (Fuller, 2006). If all parameters affecting bridge performance are known (and deterministic), then the decision-making process is relatively straightforward (Val *et al.*, 2000). In practice, however, there are uncertainties in materials properties, structural dimensions, loads, and environmental conditions.

Decisions for rehabilitation based on initial cost can inhibit innovation since generally innovative solutions have high initial cost. A probabilistic whole life cycle costing analysis can be used to obtain a more realistic assessment of the benefits of innovative materials and technologies, whilst giving asset manager a basis to arrive at an acceptable level of risk, taking into account the reliability of proven/traditional solutions weighed against innovative solutions (Venkatesan *et.al.*, 2006a).

This ongoing research project presents a concept map which indicates a useful strategic method for assisting decision makers to appropriately choose the best option or treatment for bridge rehabilitation affected by premature deterioration through exposure to aggressive environments in Australia. The decision analysis is referred to a whole of life cycle cost analysis. Elements of bridge rehabilitation costs developed as part of the whole of life cycle cost analysis are provided. In addition, a summary result of bridges inspections in Queensland is presented in order to identify the real service life of a bridge exposed to aggressive environments.

1.2 DETERIORATIONS DUE TO AGGRESSIVE ENVIRONMENTAL CONDITIONS

Reinforced concrete has proven to be a durable material in comparison with steel or other structural materials. However, early deterioration of concrete due to aggressive environments or poor construction quality has also occurred in many reinforced concrete structures (Venkatesan *et al.*, 2006a). When exposed to sufficiently aggressive environmental conditions, structural concrete members will eventually deteriorate and lose strength (ACI, 2006). Aggressive environmental conditions for bridges can be described as cycles of freezing and thawing, and cycles of wetting and drying, with or without the presence of chloride. The time required for deterioration to occur varies considerably, depending on the severity of the exposure conditions and the characteristics of the structural concrete.

Corrosion of reinforcing steel is one of the most important and prevalent mechanisms of deterioration for concrete structures in marine environments (Daily, 2005). High permeability concrete, poor design detailing, and construction defects, such as inadequate depth of cover, are quality control problems, which allow the ingress of salt and moisture into the concrete. The higher concentrations of salt and moisture can result in accelerated corrosion of the reinforcing steel and significant deterioration to the concrete structure. In other words, the corrosion of reinforcing steel spalls the cover concrete, reduces the cross-sectional area of the reinforcing steel, and therefore, its strength.

According to Daily (2005) concrete structures in marine environments can be divided into two categories of exposure; direct and indirect. The direct category includes structures that are partially or fully submerged, and the indirect category includes structures along the coastline, which do not come into direct contact with seawater. Bridge substructure elements and retaining walls are some examples of structures in the direct exposure category, whereas buildings along the coast are examples of structures in the indirect exposure category.

Although the results of the corrosion process are similar for all reinforced concrete structures, the process by which corrosion occurs, the corrosion rate and the appropriate repair method can be very different. Reinforced concrete structures that are partially or fully submerged in seawater are especially prone to reinforcing steel corrosion due to a variety of reasons. These include high chloride concentration levels from the seawater, wet/dry cycling of the concrete, high moisture content and oxygen availability (Daily, 2005). Three areas on concrete structures in marine environments can be distinguished regarding corrosion:

- The submerged zone (always below seawater);
- The splash and tidal zone (intermittently wet and dry); and
- The atmospheric zone (well above mean high tide and infrequently wetted).

The characteristics of the corrosion differ from one zone to another. The corrosion level on reinforced concrete structure located below water level is limited by low oxygen availability, and on the other hand lower chloride and moisture content in the atmospheric zone limit the corrosion level above high tide. Corrosion is most severe within the splash and tidal zones where alternate wetting and drying result in high chloride and oxygen content.

1.3 BRIDGES INSPECTION AND MAINTENANCE

Bridge deterioration usually occurs slowly at first and is often overlooked (ACI, 2006). In later stage of deterioration, however, sudden catastrophic events can occur, demanding immediate action. Progressive deterioration can be retarded and sometimes avoided if proper systematic maintenance is practiced (Carter and Kaufman, 1990). In addition, it is believed that continuous and systematic maintenance of a bridge will extend its service and reduce its overall operating cost. Concrete bridge maintenance involves relatively inexpensive, repeatable activities that either prevent or minimise concrete life of bridge elements or are minor repairs that extend the service of the structural concrete members. A decision of conducting systematic maintenance is normally based on a systematic inspection. The current QDMR bridge management practice is based on three levels of inspection (Venkatesan *et.al.*, 2006):

- Routine maintenance inspection;
- Bridge condition inspections; and
- Detailed engineering inspections.

Inspection or assessment of an existing reinforced concrete bridges is usually required when one or a combination of the evidences occurred (Val *et al.*, 2000):

- Some form of deterioration is observed (e.g., cracking, spalling, staining).
- Structural weakness or distress is evident (e.g., large deflections, cracking).
- The bridge has been damaged by accident (e.g., impact, explosion, or earth quake).
- A defect is suspected in the bridge.
- A change of load rating is being considered.
- The bridge is changing ownership.

- It is part of a routine monitoring program.

Report No.	Build	Inspec	Defect and location	Causes	Recommen-dation

During the inspection it is necessary to quantify the structural defects, identify a suitable repair strategy and estimate the residual service capability of the affected elements of the bridge. While structural defects are normally quite evident in the form of cracking, delamination, rusting and spalling, determination of the underlying causative mechanisms usually requires further investigation.

Over the last few years, QDMR has conducted several inspections at bridges in Queensland. The reports indicated that bridges studied have been affected by alkali silica reaction (ASR) and chloride induced corrosion. The chloride attack was confirmed as the most serious deterioration problem effecting reinforced concrete bridges substructures in Queensland. The presence of the chloride in the concrete did not directly affect the concrete but it promoted corrosion of the steel reinforcement. The bridges studied were classified as exposed to aggressive environmental conditions as they were situated in coastal areas. Detailed inspection reports of substructure of the reinforced concrete bridges in Queensland can be viewed in Table 1.1.

Data from Table 1.1 indicated that the actual design life of the bridges which typically required 75-100 years old was significantly reduced due to premature deterioration resulting from exposure to aggressive environments. Cracking and spalling defects occurred in pier piles and pile caps around tidal zone. These were causes mainly by chloride contamination and alkali silica reaction to concrete. In addition, some cracking defects occurred on headstock and abutments. Site investigations and laboratory tests have been conducted to find out the most causative mechanisms. For several bridges, diving inspections were carried out to investigate bridge substructures conditions. In laboratory, several tests were conducted. These included core test, chloride profiles analysis, petrographic analysis, testing of strength, density and carbonation measurement and cover measured of the core samples in order to identifying the concrete deterioration. As the rate of concrete deterioration at any given time is dependent on many factors including corrosion rate, reinforcing steel concentration, concrete properties, cover and the environment (Scannell and Sohanghpurwala, 1993), recommendations for bridge rehabilitation will depend on the causes of the defects. Treatments could be applied either by using cathodic protection systems or encasement and or pile jacketing systems.

Table 1.1 Inspection Reports Summary of reinforced concrete bridges in Queensland

1	1978-1980	2004	Cracking and spalling defects in pier piles and pile caps around tidal zone.	Chloride contamination and alkali-silica reaction to concrete.	Cathodic protection and repair of pile caps and encasement of piles.
2	N/A	1999	Large cracks between reinforcing bars and within the cover concrete in pier piles.	Chloride contamination.	Pile encasement.
3	1966	2000	Cracking and spalling defects in piles concrete.	Chloride contamination.	ICCP and the installation of protective coatings for the areas not covered by CP. Silane treatment of the remaining areas of piles an headstocks.
4	1964	2003	Vertical cracking and spalling of the pier columns and headstock.	Chloride contamination.	Install an impressed current cathodic protection system.
5	1947	2003	Cracking and spalling on abutments and pier walls; and minor cracking and spalling in the substructure	Chloride contamination and alkali-silica reaction to concrete.	Concrete repair
6	1966	2002	Spalling in the reinforced concrete abutment headstock/capping beam. Corrosion to the steel sheet pile walls.	Chloride contamination and alkali-silica reaction to concrete.	Concrete repair

The study of the existing bridges in Queensland confirmed that estimating the future service life of a structure (and the life extension provided by a corrosion protection system) is perhaps the most subjective aspect for life cycle cost analysis of corrosion protection systems, but also, the most important. To predict future service life with any accuracy, important determinants of performance for any given protection/treatment system need to be identified properly.

The costs associated with repair and rehabilitation, and with disruption to the public's use of the facility, can be very high and in certain circumstances often exceed the original of the construction cost (Neff, 2003). To avoid highly rehabilitation costs, it is important to note that maintenance activities performed at the proper time are extremely cost effective.

Bridge maintenance can be subdivided into preventive and responsive maintenance (ACI, 2006). Preventive maintenance procedures are done before deterioration is visible and the structural concrete member is still in good condition, and are usually planned at the design stage and started accordingly. Responsive maintenance procedures are usually more extensive, and are done in the early stages of the visible deterioration cycle and to extend the service life of the structural concrete members in bridges.

It is always more cost-effective in the long run to perform preventive maintenance activities than allow a known condition get progressively worse until the entire member or structure has to be replaced (NN, 2006). Similarly, maintenance activities conducted at the wrong time can be a poor investment. The wrong time for maintenance is after significant damage has occurred.

Increasingly, maintenance has become a discretionary activity within many organisations, because it is often the first victim of budgetary shortfall (Yanev *et al.*, 2003). In light of this, those responsible for the maintenance need reliable methods for productively allocating the resources they are given. Cost-benefit assessment of bridge maintenance strategies is possible if related expenditures can be correctly evaluated over an appropriate life cycle and if they produce a known effect on structural performance.

Given the relationship between bridge deterioration and maintenance level, bridge life can be computed once a repair protocol and a condition for replacement or rehabilitation are specified (Yanev *et al.*, 2003). Then all costs for maintenance, repairs, and replacement are annualised over that model. That is not to say such costs are well defined, but rather, that their potential effect can be observed. Total annual costs and annual costs of the expenditures can thus be computed as functions of the maintenance level.

1.4 DECISION MAKING PROCESS MAP AND WHOLE LIFE CYCLE COST ANALYSIS

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 bridges structure have become major issues (Setunge *et al.*, 2005). In selecting a treatment option for reducing corrosion of reinforced concrete bridges, four key tasks have been developed and need to be conducted:

- Identify concrete and corrosion condition by conducting a field investigation and collecting the available data of the existing bridge.

- Define causes and extend of the damage by conducting several laboratory tests and evaluating data from the condition surveys and tests.
- Determine option of repair and protection method to use.
- Evaluate the options by conducting whole of life cycle cost analysis.

The four key tasks are identified as a decision making process map which assists decision maker to select an appropriate option for bridges rehabilitation. Detailed decision making process map is viewed in Figure 1.1

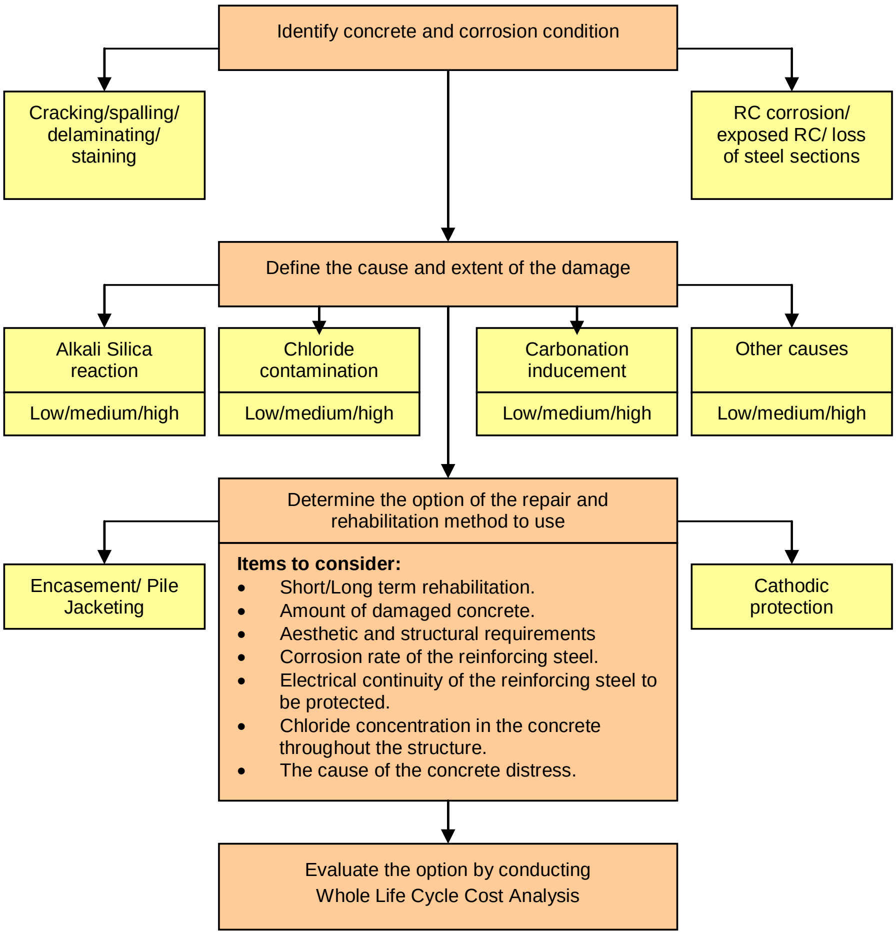

Figure 1.1 Decision Making Process Map

The extent of the damage of the bridges in a certain condition such as low, medium or high has been developed by Venkatesan *et al.* (2006). The explanation of the level of the damage is beyond the scope of this paper.

In general, 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 (Setunge *et al.*, 2005). In this research project, the WLCCA evaluates each option of the repair and rehabilitation method 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 (NPV) 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).

The first and most challenging task of an LCCA, or any economic evaluation method, is to determine the economic effects of alternative option of bridge rehabilitation and to quantify these effects and express them in dollar amounts. Traditionally, life cycle cost analysis has been done without regard for variability of input parameters for LCCA (Neff, 2003). Best guesses are commonly used for input values, yielding a single life cycle cost result. Unfortunately, while this approach is simple and straightforward, it falls to recognise the significant effect the inherent variability input parameters can have on structure performance and analysis. In a LCCA, these uncertainties should be considered.

Variability and uncertainty result from assumptions, estimates, and projections used as inputs for the LCCA (Neff, 2003). These inputs vary both within a structure and from project to project. With respect to corrosion protection of reinforced concrete structures, variability can come from any areas such as bridge conditions, treatment selection, and the resources which include labour, materials, equipment, traffic control and engineering. The costs associated in a bridge rehabilitation project can be divided into four categories:

- Initial cost,
- Maintenance and repair cost,
- Monitoring cost, and
- User and failure cost

These cost elements are used as input parameters for conducting life cycle cost analysis properly. There is no standardised or definitive list of cost elements that should be included in the life cycle cost analysis since this would reduce the flexibility of the approach to modelling different scenarios. The four categories of the cost elements associated with bridge rehabilitation have been developed and can be seen in more details in Figure 1.2. These all cost elements need to be included whilst calculating life cycle cost analysis.

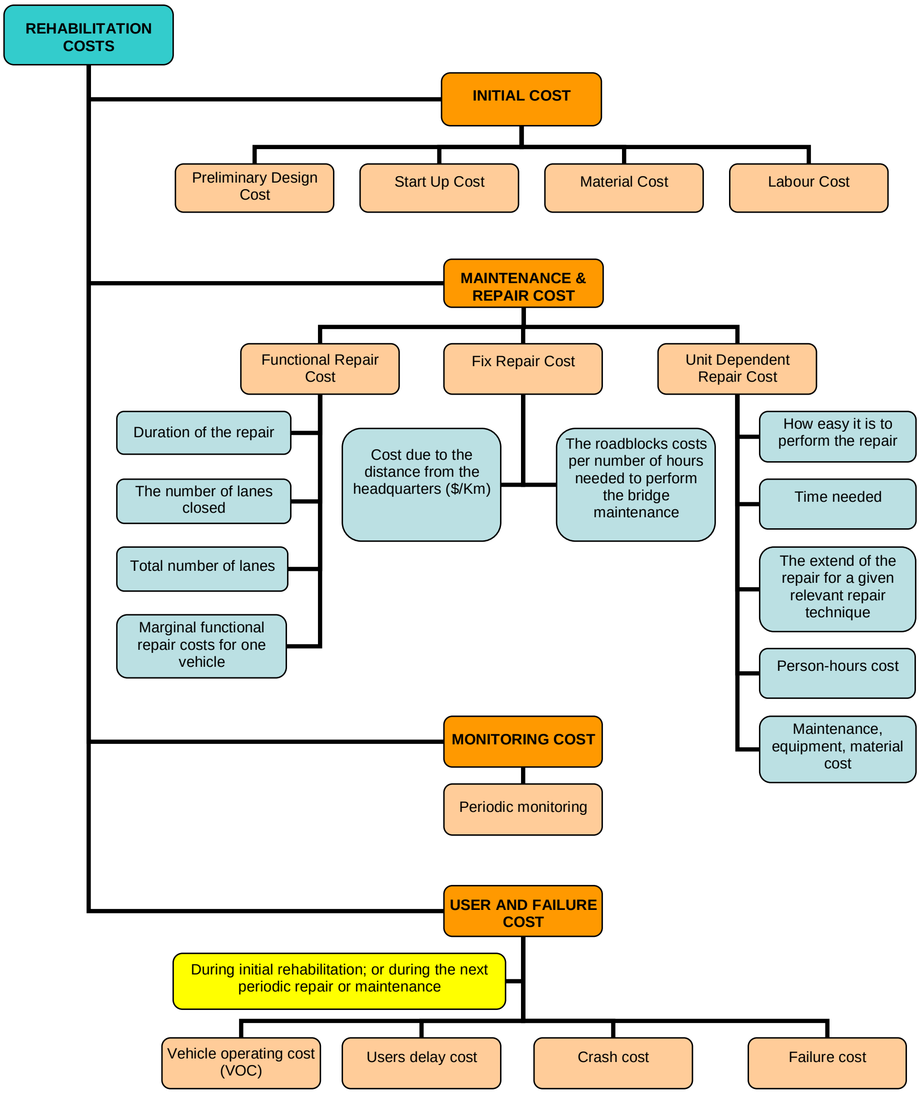

Figure 1.2. Rehabilitation Cost Elements

1.5 CONCLUSIONS

Premature deterioration such as corrosion of reinforced concrete bridge structures due to aggressive environment condition in Queensland affected the real life of bridge services. The actual design life of the reinforced concrete bridge was reduced to between 26 and 50 years and the level of deterioration depended on many factors including corrosion of reinforcing steel, condition of concrete and external environments. One of the critical issues causing reduced service life of the bridge was a delay of conducting bridge maintenance. Furthermore, delaying bridge maintenance can result in increased cost due to repair and rehabilitation.

The time to repairing and selecting corrosion protection system are the most critical decision-making step strategies and will usually have a major impact on the life cycle cost. Decision making process map developed was found to be a useful strategic method to assist decision maker in selecting an appropriate treatment for bridges rehabilitation followed up by conducting life cycle cost analysis. This task is made difficult without considering variability of input parameters. Rehabilitation cost elements were developed as input parameters and used for minimising the whole of life cycle cost analysis.

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