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# LIFE CYCLE COST ANALYSIS CASE STUDY ON CORROSION REMEDIAL MEASURES FOR CONCRETE STRUCTURES

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**Abstract.** This paper discusses a short study on life cycle cost analysis (LCCA) on corrosion remedial measures for concrete bridges and marine structures, which are subjected to carbonation or ingress of sodium chloride from sea water and other sources. Life cycle costing software, Bridge LCC 2.0, was used to perform life cycle cost analyses on three case studies, based on net present value method. The analysis of the results showed that LCCA is capable of assisting engineers or transportation agencies to evaluate optimum maintenance decisions in corrosion-related problems. It can be used as an engineering economic analysis tool that helps in quantifying the differential costs and choosing the most cost-effective corrosion remedial measures. Life cycle costs for the remedial measures are influenced by many costing variables such as initial costs, periodic maintenance costs, frequency years and analysis period. The best practice of LCCA should not only consider agency expenditures but also user costs and sensitivity analysis throughout the service life of a remedial measure.

*Keywords*: Life cycle cost analysis, concrete bridges, corrosion, remedial measures, structural rehabilitation, cost-effective, net present value method (NPV)

**Abstrak.** Artikel ini membincangkan kajian ringkas berkaitan analisis kos kitaran hayat terhadap langkah-langkah pembaikan pengaratan bagi jambatan dan struktur marin konkrit yang terdedah kepada karbonasi atau serangan natrium klorida daripada air laut atau sumber-sumber lain. Perisian kos kitaran hayat, Bridge LCC 2.0 digunakan untuk menjalankan analisis kitaran hayat untuk tiga kes kajian melibatkan kaedah nilai bersih kini. Keputusan kajian menunjukkan analisis kos kitaran hayat berkeupayaan untuk membantu jurutera dan agensi pengangkutan dalam menilai keputusan penyelenggaraan yang efektif berkaitan dengan masalah pengaratan. Ia boleh digunakan sebagai alat analisis ekonomi kejuruteraan yang membantu mentaksir kos-kos perbezaan dan membuat pilihan terhadap langkah pembaikan pengaratan yang berkesan. Analisis kos kitaran hayat bagi langkah pembaikan dipengaruhi oleh banyak pemboleh ubah seperti kos permulaan, kos penyelenggaraan, tahun kekerapan, dan jangka masa analisis. Amalan terbaik untuk analisis kos kitaran hayat bukan sahaja mengambil kira perbelanjaan oleh agensi, tetapi perlu mempertimbangkan kos-kos oleh pengguna dan analisis sensitiviti di sepanjang jangka hayat sesuatu langkah pembaikan.

*Kata kunci*: Analisis kos kitaran hayat, jambatan konkrit, pengaratan, langkah pembaikan, pemulihan struktur, keberkesanan kos, kaedah nilai bersih kini (NPV)

## 1.0 INTRODUCTION

Corrosion of reinforcing steel is one of the most prevalent mechanisms of deterioration for concrete bridges and structures in marine environments. It is caused by carbonation

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or ingress of sodium chloride from sea water and other sources. Corrosion affects deterioration of concrete because the corrosion products or rust occupy a greater volume than the steel and exert substantial stresses on the surrounding concrete. The outward manifestations of effects of rusting would include staining, cracking, spalling, and delamination of the concrete.

There are a number of methods for preventing and stopping corrosion in concrete structures and it is often difficult for the engineers and transportation agencies to select the best method in particular circumstances. Choosing the right remedial measures is very important not only to ensure that the problem is totally remedied but also the price should not be too costly in justifying the work. Since remedial measures for bridges are associated with significant costs, therefore, the application of life cycle cost analysis (LCCA) is needed in determining a true cost-effective rehabilitation strategy.

Three case studies are discussed which demonstrate the application of life cycle cost analysis on concrete bridges and marine wharf structures.

## 2.0 METHODOLOGY FOR CASE STUDY

The selection of remedial measures is a crucial decision-making process for corrosion problems of reinforcing steel in concrete bridges and similar structures subjected to marine environment such as wharfs and jetties. Good understanding of the corrosion mechanisms and the advantages and disadvantages of the available remedial measures are needed before any optimum maintenance strategies can be made. Mechanisms of carbonation and chlorides attack require greater attention due to their significant occurrences in Malaysia environment.

Remedial measures used in the repair and protection of corrosion-induced defects are numerous. These include surface impregnation with silane, painting, waterproofing membrane, corrosion inhibitors, crack injection, sprayed concrete, encasement and overlays, patch repair, re-alkalisation, chloride extraction, and cathodic protection. The relative applications, benefits, costs, service life, and effectiveness of each remedial measures have been described in other literature.

Life cycle cost analysis was carried out on three selected case studies in order to demonstrate its use in evaluating the most cost-effective remedial measures based on the minimum life cycle cost. Life cycle costing software (Bridge LCC 2.0) has been used to perform these analysis.

For Case Study I, five preventive techniques employed were painting, waterproofing membranes, coating, silane and cathodic protection. The costs data for these techniques are extracted from the study done by [1]. Unit costs were estimated by [1] for a series of maintenance options, based on data from current experience on 24 bridges in United Kingdom.

The sources of the costs data applied in Case Study II are provided from the work done by [2]. A 15-year old marine wharf with reinforced concrete decking and steel piles has been used by the authors to study the comparative life cycle costs of patch repair, cathodic protection, and chloride extraction.

Lastly, in Case Study III, LCCA was used to compare the life cycle cost of various anode systems normally applied in impressed-current cathodic protection. The anode systems used were catalyzed titanium (Ti) mesh, conductive paints, thermal-sprayed zinc (Zn) coating, and thermal-sprayed Ti coating. The costs data applied in Case Study III are provided from the study carried out by [3].

## 3.0 LIFE CYCLE COST ANALYSIS (LCCA)

### 3.1 Definition and Use

LCCA is defined by Federal Highway Administration of United States of America as a process for evaluating the total economic worth of a usable project investment by analysing initial costs and discounted future costs, such as maintenance, use, reconstruction, rehabilitation, restoring, resurfacing, and disposal costs, over the life of the project segment. In this study, LCCA was used as an economic evaluation for various remedial measures. Net present value (NPV) method has been used to total and convert all cost over the service life of the remedial measures in terms of money values at fixed year, based on the real discount rate, $r$. Total cost, $TC$, was calculated by adding initial cost to annual costs, which is given by:

$$TC = C_1 + \sum_{i=1}^{n} \frac{C_{Ri}}{(1+r)^i} \quad (1)$$

where $C_1$ is the initial cost, $C_{Ri}$ is the annual cost on $i$th year and $n$ is the number of considered years in bridge/structure's service life. Based on the above equation, alternative strategies are compared and the optimum strategy, which gives the minimum total cost over the considered years, is identified.

### 3.2 Basic Steps of LCCA

The life costing software, Bridge LCC 2.0 is developed by the National Institute of Standards and Technology (NIST) in the United States, to help engineers assess the cost effectiveness of new, alternative construction materials. The software uses a life cycle costing methodology based on both ASTM Standard E-917 and Cost Classification developed by NIST.

LCCA in Bridge LCC 2.0 can be carried out in 6 steps as follows:

Step 1: Define project name and alternatives
Step 2: Define project elements
Step 3: Define classifying and quantifying dimensions
Step 4: Estimate costs

Step 5: Compute life cycle costs
Step 6: Compare life cycle costs and select cost-effective alternative

### 3.3 Case Studies

The cost elements used in LCCA for corrosion remedial case studies include the following:

- Initial cost – made up of a number of cost elements that do not recur after an activity is initiated (*e.g*. removal of defective concrete, surface preparation, etc.)
- Rehabilitation/Maintenance cost – group of costs experienced continually over the useful life of the activity (*e.g*. re-applying surface coating, replacement of anodes in CP etc.)
- Disposal cost – the cost of disposing the structure when it is non-repairable.
- Analysis period – time used to evaluate the total cost required for a remedial measure, typically 75 to 100 years for bridges.
- Discount rate – real discount rates reflect the true time value for money with no inflation premium. FHWA recommends using a real discount rate in the range of 3% to 5%.
- Inflation rate – measures the change in the prices of goods and services from one year to the next.

The relationship between various cost elements is diagrammatically shown in a typical expenditure stream diagram for LCCA as in Figure 1. In this project, disposal cost is neglected due to its remoteness from the life cycle and thus tends to be small after discounting. The input data are obtained from three case studies:

- Case Study I – selection of preventive techniques in bridges which include painting, waterproofing membranes, coating, silane, and cathodic protection.

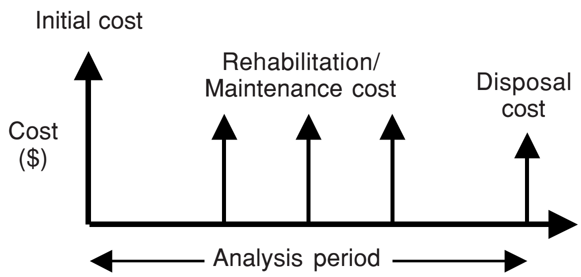


**Figure 1** Typical expenditure stream diagram for a life cycle cost analysis

- Case Study II – selection of repair and maintenance techniques in a wharf structure which include patch repair, cathodic protection, and chloride extraction.
- Case Study III – selection of anode systems in impressed-current cathodic protection for concrete bridges.

The input data for the three case studies are summarised in Table 1, 2, and 3.

**Table 1** Input data for analysis in Case Study I

| Corrosion preventive techniques | |
|---|---|
| Analysis period : 75 years<br>Real discount rate : 3.2 % | Base year : 2002<br>Inflation rate : 2.2% |
| **Alternatives** | **Costs (Pounds, £ and US Dollars, $)** |
| Painting | Initial repair cost = £ 245,000 ($448,350) |
| | On-going cost = £ 25,000 ($45,750) (repeat at 10 years) |
| Waterproofing membranes | Initial repair cost = £ 243,000 ($444,690) |
| | On-going cost = £ 23,000 ($42,090) (repeat at 25 years) |
| Coating | Initial repair cost = £ 242,000 ($442,860) |
| | On-going cost = £ 22,000 ($40,260) (repeat at 25 years) |
| Silane | Initial repair cost = £ 240,000 ($439,200) |
| | On-going cost = £ 20,000 ($36,600) (repeat at 10 years) |
| Cathodic protection | Initial repair cost = £ 560,000 ($1,024,800) |
| | On-going cost = £ 130,000 ($237,900) (repeat at 8 years) |

**Table 2** Input data for analysis in Case Study II

| Corrosion repair/stopping techniques | |
|---|---|
| Analysis period : 20 years<br>Real discount rate : 14 % | Base year : 1989<br>Inflation rate : 10 % |
| **Alternatives** | **Costs (US Dollars, $)** |
| Patch repair | Initial repair cost = $ 282,000 |
| | On-going cost = $ 282,000 (repeat at 5 years) |
| Cathodic protection | Initial repair cost = $ 474,500 |
| | On-going cost = $ 17,750 (repeat at 5 years) |
| Chloride extraction | Initial repair cost = $ 306,500 |
| | On-going cost = $ 57,000 (repeat at 10 years) |

**Table 3** Input data for analysis in Case Study III

| Anode systems | |
|---|---|
| Analysis period : 75 years<br>Real discount rate : 3.2 % | Base year : 2002<br>Inflation rate : 2.2% |
| **Alternatives** | **Costs (US Dollars, $)** |
| Catalyzed Ti-Mesh | Initial repair cost = $ 154,000 |
| | On-going cost = $ 7,700 (repeat at 75 years) |
| Conductive paints | Initial repair cost = $ 234,000 |
| | On-going cost = $ 11,700 (repeat at 14 years) |
| Thermal-sprayed Zn-coating | Initial repair cost = $ 210,000 |
| | On-going cost = $ 10,500 (repeat at 27 years) |
| Thermal-sprayed Ti-coating | Initial repair cost = $ 278,000 |
| | On-going cost = $ 13,900 (repeat at 30 years) |

## 4.0 RESULTS

The results of LCCA for Case Studies I, II, and III are shown in Table 4, 5, and 6 respectively. Figures 2, 4, and 6 illustrate cumulative life cycle costs, in net present value, for the competing alternatives in each case. Life cycle costs by life cycle periods are shown in Figures 3, 5, and 7.

**Table 4** Life cycle costs for Case Study I

| Cost category (UK£ & USD$) | Alternatives | | | | |
|---|---|---|---|---|---|
| | **Painting** | **Water-proofing membranes** | **Coating** | **Silane** | **Cathodic protection** |
| Agency cost<br>Initial cost | £245,000<br>($448,350) | £243,000<br>($444,690) | £242,000<br>($442,860) | £240,000<br>($439,200) | £560,000<br>($1,024,800) |
| Maintenance Cost | £62,001<br>($113,462) | £17,949<br>($32,847) | £17,169<br>($31,419) | £49,601<br>($90,770) | £419,672<br>($768,000) |
| Disposal cost | 0 | 0 | 0 | 0 | 0 |
| Total cost (£) (Net present value) | £307,001<br>($561,812) | £260,949<br>($477,537) | £259,169<br>($474,279) | £289,601<br>($529,970) | £979,672<br>($1,792,800) |

**Table 5** Life cycle costs for Case Study II

| Cost category (USD$) | Alternatives | | |
|---|---|---|---|
| | **Patch repair** | **Cathodic protection** | **Chloride extraction** |
| Agency cost | | | |
| Initial cost | 282,000 | 474,500 | 306,500 |
| Maintenance cost | 432,574 | 27,228 | 33,494 |
| Disposal cost | 0 | 0 | 0 |
| Total cost (Net present value) | 714,574 | 501,728 | 339,994 |

**Table 6** Life cycle costs for Case Study III

| Cost category (USD$) | Alternatives | | | |
|---|---|---|---|---|
| | **Catalyzed Ti-Mesh** | **Conductive paints** | **Thermal-sprayed Zn-coating** | **Thermal-sprayed Ti-coating** |
| Agency cost | | | | |
| Initial cost | 154,000 | 234,000 | 210,000 | 278,000 |
| Maintenance cost | 749 | 19,384 | 6,607 | 7,743 |
| Disposal cost | 0 | 0 | 0 | 0 |
| Total agency (Net present value) | 154,749 | 253,384 | 216,607 | 285,743 |

## 5.0 DISCUSSION

### 5.1 Economic Evaluation

For Case Study I, it is obvious that coating is the most cost-effective preventive technique among the alternatives (Table 4). Cathodic protection (CP) has been proven in this LCCA to be too expensive to be used for prevention of corrosion due to its high initial and maintenance costs (Figure 3). CP, silane, and painting are more expensive than coating and waterproofing membranes because they have shorter frequency years for periodic maintenance (Figure 2).

For Case Study II, LCCA has shown that chloride extraction (CE) has the lowest life cycle cost over the analysis period, making it the most cost-effective repairing technique if compared to the patch repair and CP (Table 5). The frequency year for CE periodic maintenance is longer than the other alternatives (10 years versus 5 years),

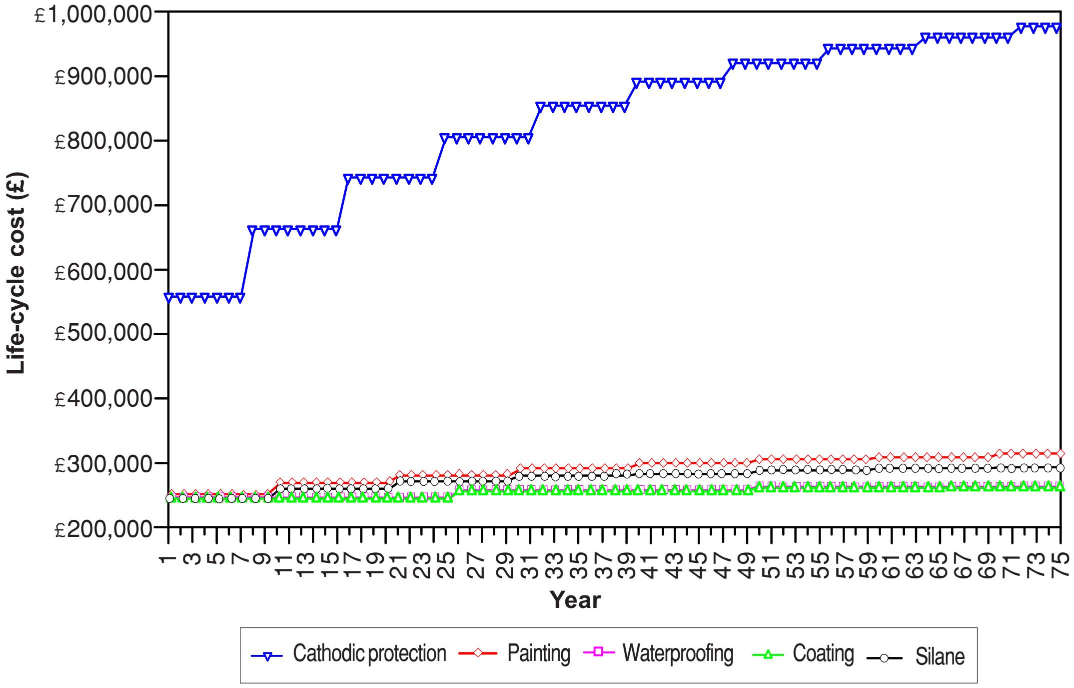


**Figure 2** Cumulative life cycle costs, in present value, for each corrosion preventive techniques in Case Study I

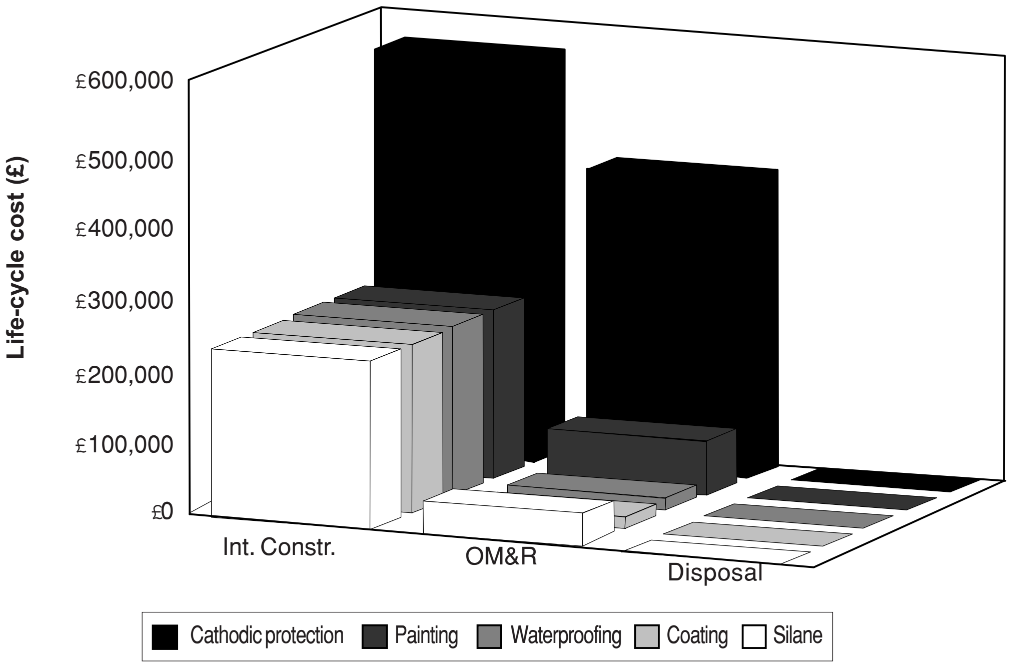


**Figure 3** Life cycle costs by life cycle periods for Case Study I

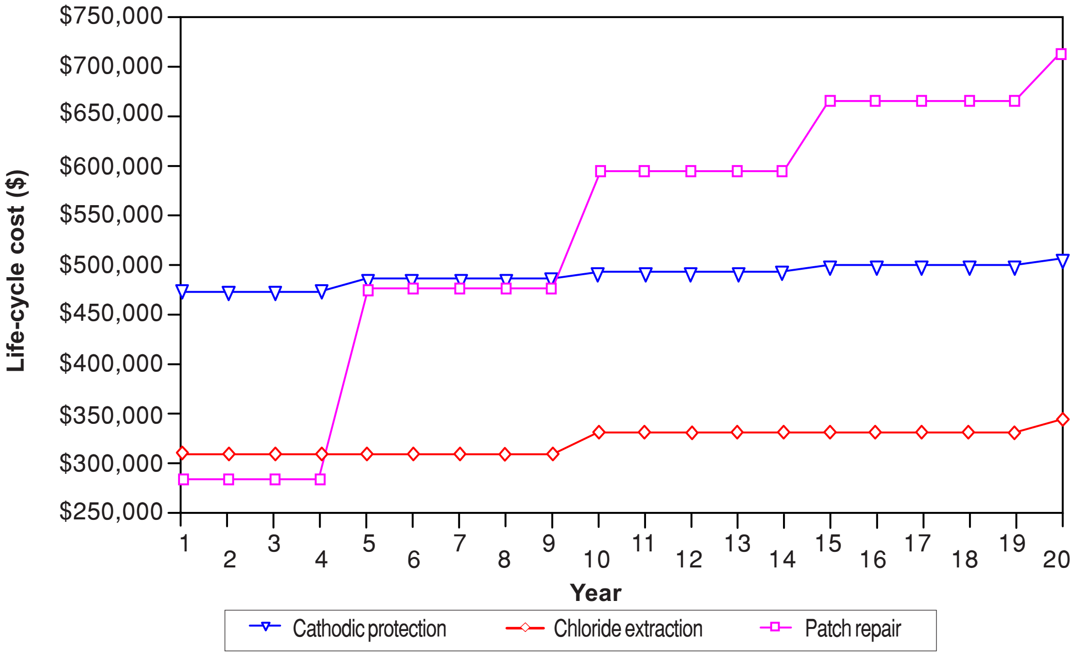


**Figure 4** Cumulative life cycle costs, in present value, for each corrosion maintenance techniques in Case Study II

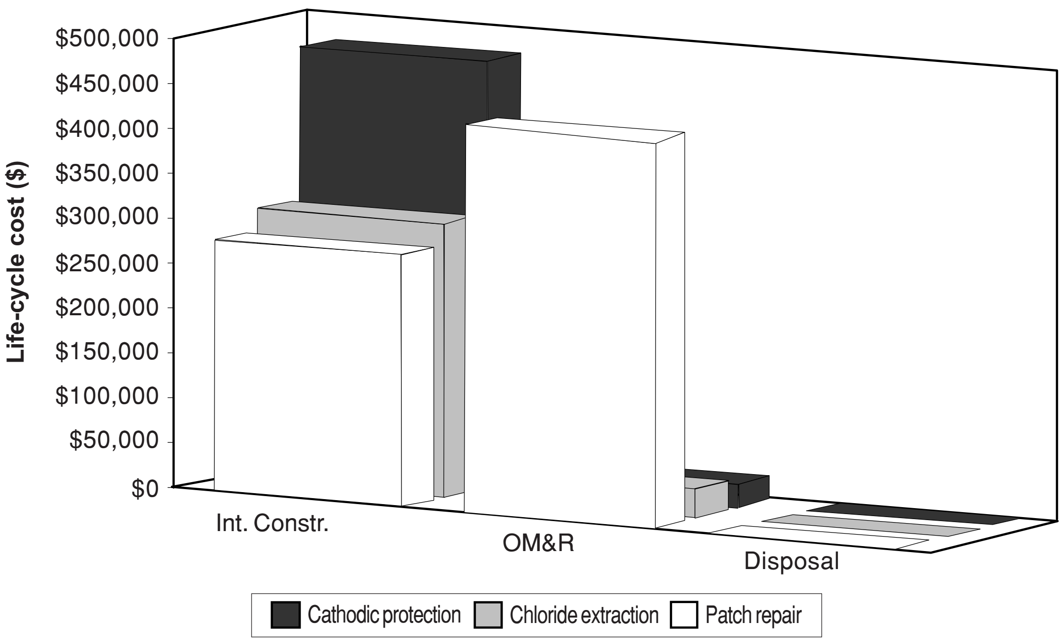


**Figure 5** Life cycle costs by life cycle periods for Case Study II

making it having the lowest total cost (Figure 4). Patch repair is the most costly measure even though it has the lowest initial cost. This is because patch repair requires large amount of expenses for periodic maintenance (Figure 5).

For Case Study III, catalysed Ti-mesh is the most cost-effective anode for impressed-current CP (Table 6). From the results, it is observed that the total costs for impressed-current CP anodes are mainly influenced by their initial cost. This is because the service life for the anodes is relatively long, making the periodic maintenance costs to be far out in the life cycle and thus tend to be small after discounting the present value (Figure 7). Thus, the effect on the life cycle costs is relatively small (Figure 6).

### 5.2 Costing Variable

The results show that life cycle cost is influenced by many costing variables such as initial costs, periodic maintenance costs, frequency years, and analysis period. Initial cost cannot be the only criteria in making selection in LCCA. Normally, the effect of periodic maintenance costs on the life cycle cost will be relatively small if the frequency year and analysis period are long.

### 5.3 Best Practice of LCCA

Although LCCA can be carried out by merely considering all agency expenditures (initial, maintenance & disposal costs), however, the best practice calls for the inclusion of user costs, which consist of vehicle operating costs, user delay costs, and accident costs. This is because in some instances, user costs can overwhelm both initial costs and periodic maintenance costs in the analysis [4]. All the analysis in this project are carried out in 'Basic Mode' in Bridge LCC 2.0 program, which allows the user to assume and conduct only a deterministic analysis, that is, where computed life cycle costs are based on purely deterministic information about real discount rate, timing and cost of construction, repair, and other activities. However, in order to achieve more accurate economic evaluation, these changeable costing variables should be subjected to sensitivity analysis.

### 5.4 Shortcomings in LCCA

The fundamental problem associated with the application of life cycle costing in practice is the requirement to forecast a long time ahead in predicting the related future events. While some of these events can at least be considered, analysed, and evaluated, there are other aspects that cannot even be imagined today. These therefore, remain outside the scope of prediction and probability, and cannot be assessed in the analysis. Besides that, the results of LCCA are highly dependent on the input variables. Many times these inputs are only best estimates. This is due to the difficulty in identifying definite cost information as this varies from job to job, and country to country.

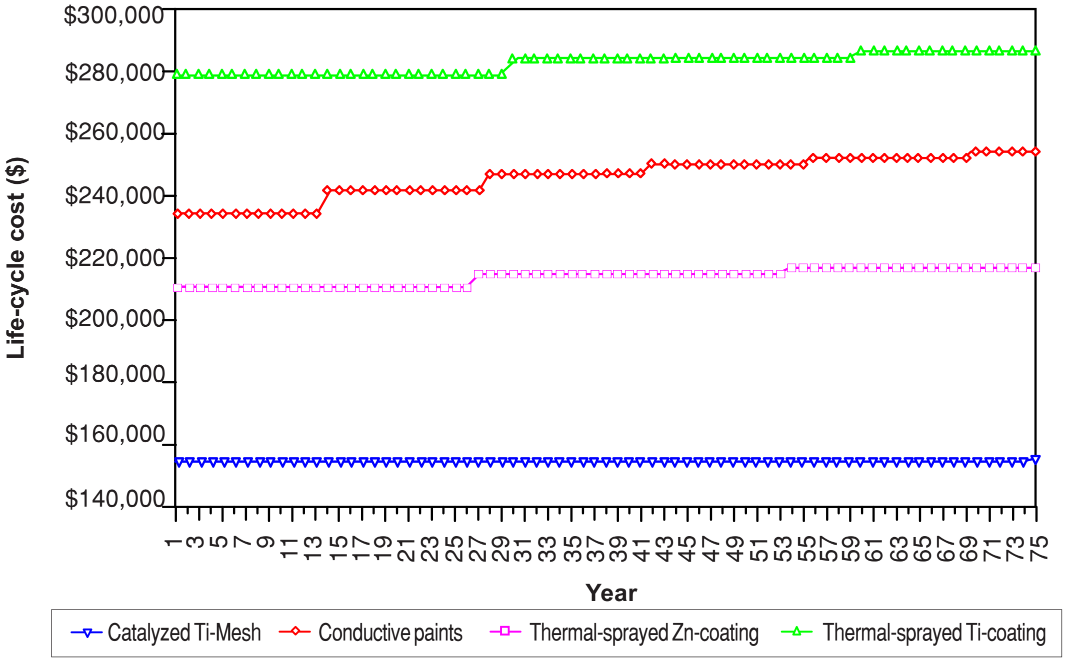


**Figure 6** Cumulative life cycle costs, in present value, for each anode used in impressed-current cathodic protection in Case Study III

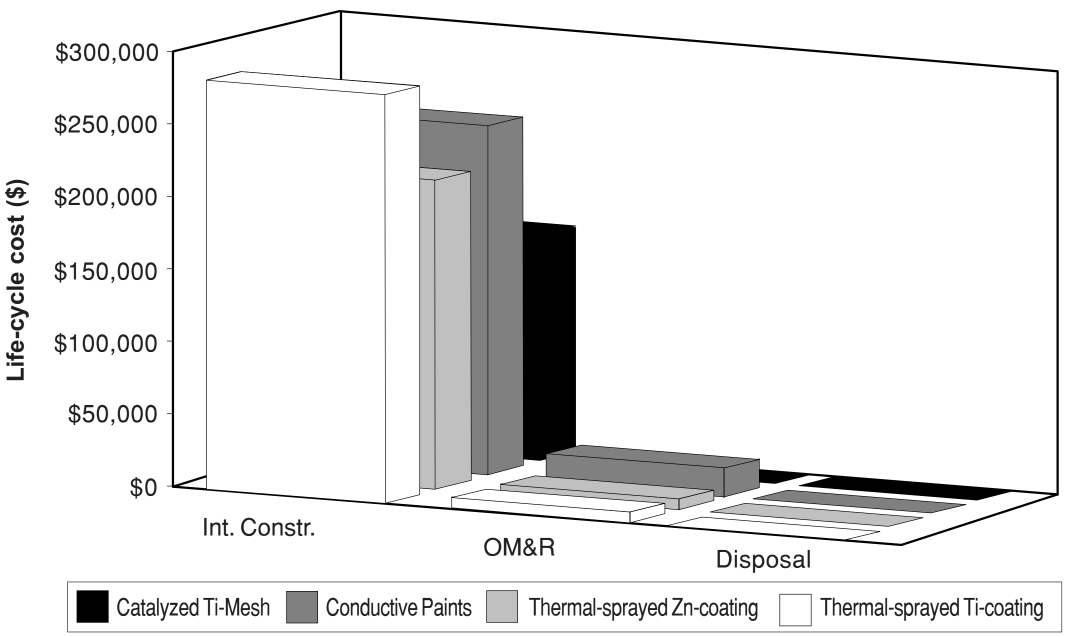


**Figure 7** Life cycle costs by life cycle periods for Case Study III

## 6.0 CONCLUSIONS

The case studies have demonstrated the useful application of Life Cycle Cost Analysis (LCCA) as a decision support tool in analysing investment decision making of repairing corrosion-induced damage and determining optimum maintenance strategies for concrete bridges and wharf structures. LCCA has been shown to be useful in assisting engineers or transportation agencies to evaluate optimum maintenance decisions in corrosion-related problems. It can be used as an engineering economic analysis tool that helps in quantifying the differential costs and choosing the most cost-effective corrosion remedial measures. Life cycle cost is influenced by many costing variables such as initial costs, periodic maintenance costs, frequency years, and analysis period. The analysis of the results in the case studies showed that initial costs should not be the only criteria in selecting remedial measures. Input variables such as periodic maintenance costs and frequency years should be taken into consideration by discounting to the net present value in LCCA. In order to obtain more reliable analysis, the best practice of LCCA should not only consider agency expenditures but also the user costs and sensitivity analysis throughout the service life of a remedial measure.

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## REFERENCES

[1] Atkins, W. S. 1998. Optimum Maintenance Strategies for Bridges – Data Collection. Data Collection Report, December. Bristol. U.K.

[2] Collins, F. G., and P. A. Farinha. 1989. Repair of Concrete in the Marine Environment: Cathodic Protection VS Chloride Extraction. 9th Australian Conference on Coastal and Ocean Engineering. Adelaide. 4-8 December 1989.

[3] Clemena, G. G., and D. R. Jackson. 2000. *Trial Application of Electrochemical Chloride Extraction on Concrete Bridge Components in Virginia*. Charlottesville. Virginia: Virginia Transportation Research Council.

[4] Neff, T. L. 2000. Predicting the Life Cycle Costs of Structures Based on Accelerated Corrosion Testing: A Framework for Incorporating Reliability Concepts. TRB Transportation Research Circular 498.