Life-Cycle Cost Analysis of a Concrete Road Bridge Across Open Sea

R. BHASKARAN, N. PALANISWAMY, AND N.S. RENGASWAMY,
Central Electrochemical Research Institute, Karaikudi, Tamilnadu

A life-cycle cost analysis (LCCA) was made of a 2,345-m-long prestressed concrete road bridge across open sea. The bridge was completed at a cost of $4.2 million and opened to traffic during 1988. It is subject to periodic maintenance such as painting, repair, and replacement of affected parts. The LCCA used the net present value method for a 50-year design life. The annual cost of corrosion is ~$43,000. By adopting galvanic cathodic protection, the annual cost of corrosion can be brought down to ~$40,000.

The U.S. National Aeronautics & Space Administration (NASA) recently discovered an ancient, 30-km-long bridge in the Palk Strait between India and Sri Lanka.[1] The bridge's unique curvature and composition revealed that it was manmade. Legend, as well as archeological studies, indicate that the bridge was built about the time of the first signs of human inhabitants in Sri Lanka, some 1,750,000 years ago.

The concrete road bridge discussed here is very near the site of the ancient bridge, and is thus of historical importance. Apart from the rail bridge, this road bridge is the only link between the mainland and Rameshwaram Island, a famous pilgrim center that attracts tourists throughout the year. Consequently, this road link is also of strategic importance.

A study of this bridge has shown that in spite of adhering to the construction specifications, the life of marine structures can be adversely affected by aggressive environmental conditions, especially the chloride ion concentration on the structure's surface. The corrosion initiation period for various structural components ranges from six to 28 years, depending upon the concrete grade and concrete cover. The life-cycle cost analysis (LCCA) used in this work shows that galvanic protection is a cost-effective technology for this structure.

FIGURE 1

A view of the road bridge along with the rail bridge.

TABLE 1

PRESENT CONDITION OF THE BRIDGE (VISUAL OBSERVATION)

Elements		Period of Actual Construction	Visual Observation
Electric lamppost		1987-1988	Fifteen lampposts have been severely affected by corrosion from the aggressive saline atmosphere prevailing at the bridge site. Figure 3 shows the condition of a corroded lamppost.
Handrails & posts		1987-1988	The majority of them are apparently in good condition. Cracks in the concrete cover have started appearing at a few points. These locations need maintenance repair.
Footpath		1986-1988	The major maintenance problem appears to be related to finger-type expansion joints. Some of the joints need replacement, while some of them need corrosion protection.
Kerb		1986-1988	Even though the majority of kerbs are apparently in good condition, the road kerbs at certain locations need maintenance repair.
Roadway surface		1987-1988	Potholes have started appearing in some locations. Minor cracks have been seen. Obviously, the roadway surface needs periodic maintenance.
Deck slab		1984-1986	Some locations have shown cracks, which need immediate attention.
Expansion joints		1987-1988	Expansion joints have suffered corrosion. In particular, expansion joints at the footpath portion need special attention (Figure 2).
Girders	Box Girder	1984-1986	Some of the portions have shown cracks requiring immediate attention.
	I-Beam Girder	1974-1978 (45 Nos.) 1984-1986 (34 Nos.)	Diaphrams need special attention at certain locations.
Bearings		1985-1986	Some of tetron spherical as well as polytetrafluorethylene sliding bearings need effective corrosion protection treatments. Neoprene bearings also need immediate attention.
Piers		1974-1988 (48 Nos.) 1984-1986 (31 Nos.)	Cracks in the capping beam and column faces. Bottom portions of pier legs need immediate attention.
Foundations		1974-1978 (55 Nos.) 1984-1986 (24 Nos.)	Certain locations need immediate attention.

Structural Details

The structural details are based on published information[2-4] as well as personal observation. The total length of the bridge is 2,345 m. The work commenced in November 1974, was suspended from 1979 until 1983, and the bridge opened to traffic in October 1988. Figure 1 shows the road bridge after completion, along with the 90-year-old steel railway bridge.

The bridge has 79 spans of various lengths, comprising non-navigation spans, anchor spans, the central navigation span, suspended spans, and viaduct spans. The concrete bridge is of prestressed cable construction.

Table 1 describes the present conditions of the various structural elements as visually observed.

Prediction of Design Life for Bridge Components

Design life normally consists of two components—the initiation period and propagation period. The initiation period is the time taken for the chloride to accumulate and reach a threshold value at the steel reinforcement/concrete interface, initiating corrosion of the reinforcement. The propagation period is the time taken for corrosion to proceed and reach an unacceptable level, causing cracking and spalling of the adjoining concrete.

Tuutti[5] observed that the initiation of corrosion in reinforced concrete in chloride environments normally occurs within a period of 10 years. For concrete with a water/cement (w/c) ratio of 0.32 and a compressive strength of ~75 MPa, corrosion attacks began within a period of four years with normal concrete cover. Practical experiments carried out in the United States also confirmed this. Bridges with low w/c values and a concrete cover of 100 mm had been damaged within a period of 20 to 30 years and extremely expensive repairs were required.

In 2000, Pfeifer[6] presented a state-of-the-art paper titled "High Performance Concrete and Reinforcing Steel with a 100-Year Service Life" based on a five-year study (1993 to 1998) by the U.S. Federal Highway Administration. According to this article, type 316 stainless steel (UNS S31600) reinforcing bars should be considered at the design stage as a potential method for obtaining a 75 to 100-year design life. According to the same report, the critical acid-soluble chloride concentration or chloride threshold for black reinforcing bars is ~0.2% of chloride ion by weight of cement for externally applied or admixtured chloride. This is ~0.8 kg/m^3 or 330 ppm (i.e., 0.033% mass weight of the concrete).

For concrete subjected to marine exposure, the chloride ingress into concrete

CALCULATION OF LIFE PERIOD TO REPAIR FOR VARIOUS COMPONENTS IN THE BRIDGE

Component		Concrete Grade	Clear Cover ("x" in cm)	Initiation Period ("t" in Years)	Propagation Period (Years)	Total Life Period to Visual Cracking (Years)
Hand rails & posts		M-30	4	8	25	33
Footpath		M-35	4	8	25	33
Kerb		M-35	5	13	25	38
Deck slab	Non-navigation	M-45	3.5	6	25	31
	Navigation	M-40.5				
Box girders	Inner soffit	M-45	3.5	6	25	31
	Outside of web	M-45	5	13	25	38
	Inner side of web	M-45	4	8	25	33
	Bottom deck	M-45	5	13	25	38
I-Beam girders	Top flange	M-43.5	3.5	6	25	31
	Web	M-43.5	5	13	25	38
	Bottom flange	M-43.5	5.5	16	25	41
Piers	H-shaped	M-35	9	28	25	53
	Rectangular-shaped	M-35	9	28	25	53
Foundations		M-35	9	28	25	53

FIGURE 2

Corroded finger-type expansion joints.

can be described by Fick's Second Law of Diffusion:

$$C_x = C_s\left[1 - \text{erf}\frac{x}{2\sqrt{Dt}}\right] \qquad (1)$$

where C_x = the total chloride level at depth "x" at age "t" in years, C_s = surface chloride level, and D = diffusion coefficient in cm^2/s.

D can be calculated by using the following equation:[7]

$$D = 0.04\,(1{,}166^{w/c}) \times 10^{-12}\ m^2/s \qquad (2)$$

The maximum water cement ratio used in the road bridge was 0.45.

Accordingly, $D = 0.04\,(1{,}166^{0.45}) = 0.9595$ or $\sim 1 \times 10^{-8}\ cm^2/s$. This is in conformity with the value suggested by Broomfield.[8]

Assuming $C_s = 0.4\%$ and $C_x = 0.033\%$ by weight mass of concrete and substituting all these values in Equation (1), it can be shown that

$$\text{"t" in years} = \left(\frac{x^2}{1.8922}\right) \qquad (3)$$

where x is clear cover in cm.

For splash and immersion zones, the surface concentration will be as high as 1% by weight mass of concrete; therefore, assuming $C_s = 1\%$ and $C_x = 0.033\%$:

$$\text{"t" in years} = \left(\frac{x^2}{2.876}\right) \qquad (4)$$

The propagation period for the kind of marine exposure prevailing at this bridge is 25 years to the state of visual cracking. The initiation period plus propagation period equals the total life period or life to repair.

Table 2 shows the life periods to repair for various components of the bridge, calculated as shown earlier.

Hobbs and Mathews[9] have advocated minimum concrete grade M 40/50, maximum w/c ratio 0.45, and minimum cover thickness 50 mm as appropriate parameters for a 50-year design life. The design life of this bridge can be presumed as 50 years and the life-cycle cost analysis made accordingly.

Investment Details

INITIAL COST

The total cost of the bridge excluding the approaches was $4.2 million.

MAINTENANCE COSTS

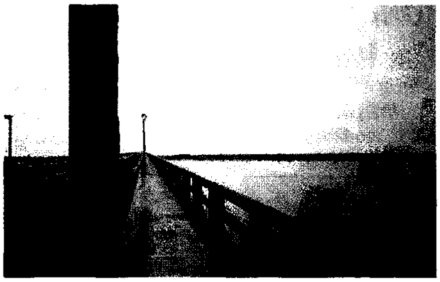
Annual Maintenance

$22,200 has been spent every year to maintain the bridge. Generally, the work consists of the maintenance of the roadway surface, bearings, expansion joints (Figure 2), drainage spouts, dust cleaning, electric lampposts (Figure 3), tollgate, etc.

Maintenance Painting

A four-coat system of anticorrosive paint was applied to the entire bridge

FIGURE 3



Corroded electric lamppost.

during 1992-1993 at a cost of $444,000. The bridge was repainted during 2001-2002 at a cost of $889,000. These data were used while computing the equivalent annual cost of corrosion.

Maintenance Repairs

The repair work normally consists of
1) Sealing of cracks.
2) Repairing spalled portion.
3) Repairing wearing coat, etc.
4) Repair work at expansion joints.
5) Repairing concrete railing.

The repair work is done every three years. The average expenditure is ~$33,000.

Maintenance Replacement

The design life of the metallic components such as expansion joints, bearings, and electric lampposts are 20, 25, and 10 years, respectively. Accordingly, provision has been made for the periodic replacement of them. This factor has been used while computing the equivalent annual cost of corrosion.

User Cost

The user cost arises because lane closures during bridge maintenance work increase travel time. The user cost is calculated as follows:

User cost = Time to cross × increase in travel time × days with user cost × value of time × traffic affected.

Accordingly, 0.05 × (1 + 1.50) × 30 × $2.22 × 500 = $4,167.

REVENUE

Twenty to 25 vehicles cross the bridge every hour. The toll is $0.55 per vehicle. This toll is the only revenue derived from the bridge.

TABLE 3

EQUIVALENT ANNUAL COST OF CORROSION

Details	Year	Expenditure (U.S. Dollars)	Present Worth Factor	Present Value (U.S. Dollars)
Direct Expenditure				
a. Annual maintenance	Annual	22,222	22.470	499,328
b. Maintenance painting	4th	444,444	0.865	384,444
	14th	444,444	0.601	267,111
	24th	444,444	0.418	185,778
	34th	444,444	0.291	129,333
	44th	444,444	0.202	89,778
c. Maintenance repairs	3rd	33,333	0.897	29,900
	6th	33,333	0.804	26,800
	9th	33,333	0.721	24,033
	12th	33,333	0.647	21,566
	15th	33,333	0.580	19,333
	18th	33,333	0.520	17,333
	21st	33,333	0.466	15,533
	24th	33,333	0.418	13,933
	27th	33,333	0.375	12,500
	30th	33,333	0.336	11,200
	33rd	33,333	0.302	10,067
	36th	33,333	0.270	9,000
	39th	33,333	0.242	8,067
	42nd	33,333	0.217	7,233
	45th	33,333	0.195	6,500
	48th	33,333	0.175	5,833
d. Maintenance replacement				
Expansion joints	20th	111,111	0.484	53,778
	40th	111,111	0.234	26,000
Bearings	25th	222,222	0.403	89,555
Electric lampposts	10th	11,111	0.695	7,722
	20th	11,111	0.484	5,378
	30th	11,111	0.336	3,733
	40th	11,111	0.234	2,600
Indirect Expenditure				
a. User cost	Annual	4,167	22.470	93,632
			Total Present Value	**2,077,001**
Less: Income				
Collection from toll gate	Annual	50,000	22.470	1,123,500
			Net Present Value	**953,501**
			Annual Cost Factor	**0.045**
			Equivalent Annual Cost	**42,908**
				~$43,000

Method of Evaluation

Different methods are available to evaluate the financial worth or the return on investment associated with a project or its various alternatives. For the bridge, net present value is the most relevant method and it is used here. The expected long-term inflation of 8% and long-term interest of 12% were used to calculate the discount rate.

$$\text{Discount rate (\%)} = \left[\frac{1+\text{Interest(\%)}}{1+\text{Inflation(\%)}}\right] - 1 = 0.037\% \quad (5)$$

Based on these costs, the LCCA has been made (Table 3). The data in Table 3 show that the annual cost of corrosion, based on a 50-year design life, is ~$43,000.

Preventive Maintenance

A galvanic cathodic protection (CP) system based on strip anodes has been considered. This will be used in conjunction with a single-coat polyurethane (PU) paint system for the concrete surfaces. The concept is that the galvanic protection will prevent further corrosion of embedded steel reinforcement, and the PU coating system on the concrete will prevent further intrusion of chloride ions, thus minimizing deterioration of the concrete. The LCCA is shown in Table 4. The annual cost of corrosion under this scheme, based on a 50-year design life, is ~$40,000.

Conclusions

The LCCA for the road bridge across open sea in the southern-most tip of India has been worked out based on a 50-year design life. The annual cost of corrosion for the 2,345-m-long prestressed concrete bridge is about $43,000. By using a galvanic anode protection system as a preventive maintenance measure, the annual cost of corrosion can be brought down to ~$40,000.

Acknowledgments

The authors gratefully acknowledge the Research Associateship awarded to Dr. R. Bhaskaran by the Council of Scientific & Industrial Research, EMR Division (New Delhi, India), which allowed them to carry out this work at the Central Electrochemical Research Institute (Karaikudi, India). They also gratefully acknowledge the cooperation extended by the National Highway authorities of the Ramnad division.

References

1. http://www.indolink.com/Religion/r091702-130924.php.
2. S.A. Reddi, "Pamban Bridge: Aspects of Project Management—I," Indian Concrete J. 62, 11 (1988): pp. 568-579.
3. S.A. Reddi, "Pamban Bridge: Aspects of Project Management—II," Indian Concrete J. 62, 12 (1988): pp. 629-632.
4. D. Srinivasan, "Bridge Building—A Way of Life; the Story of the Pamban Bridge" (Madras, India: Indian Concrete Institute, 1996).
5. K. Tuutti, "Corrosion of Steel in Concrete" (Swedish Foundation for Concrete Research and Swedish Board for Technical Development, 1982).
6. D.W. Pfeifer, "High-Performance Concrete and Reinforcing Steel with a 100-Year Service Life," PCI J. (2000): pp. 46-54.
7. D.W. Hobbs, ed., "Minimum Requirements for Durable Concrete" (British Cement Assoc., Berks, 1988), p. 52.
8. J.P. Broomfield, Uhligh's Corrosion Handbook, 2nd ed., R. Winston Revie, ed. (New York, NY: John Wiley & Sons, Inc., 2000), pp. 581-600.
9. D.W. Hobbs, J.D. Matthews, "Minimum Requirements for Concrete to Resist Deterioration Due to Chloride-Induced Corrosion," D.W. Hobbs, ed. (Blackwater, UK: British Cement Assoc. Berks, 1988), p. 60.

TABLE 4

EQUIVALENT ANNUAL COST OF CORROSION WITH GALVANIC PROTECTION

Details	Year	Expenditure (U.S. Dollars)	Present Worth Factor	Present Value (U.S. Dollars)
Direct Expenditure				
a. Annual maintenance	1st-14th	22,222	10.775	239,442
b. Annual maintenance	15th-49th	8,889	11.278	100,250
c. Maintenance painting	4th	444,444	0.865	384,444
	14th	444,444	0.601	267,111
d. Maintenance CP and painting	20th	555,556	0.484	268,889
	30th	555,556	0.336	186,667
	40th	555,556	0.234	130,000
c. Maintenance repairs	3rd	33,333	0.897	29,900
	6th	33,333	0.804	26,800
	9th	33,333	0.721	24,033
	12th	33,333	0.647	21,566
	15th	33,333	0.580	19,333
	18th	6,667	0.520	3,467
	21st	6,667	0.466	3,107
	24th	6,667	0.418	2,787
	27th	6,667	0.375	2,500
	30th	6,667	0.336	2,240
	33rd	6,667	0.302	2,013
	36th	6,667	0.270	1,800
	39th	6,667	0.242	1,613
	42nd	6,667	0.217	1,447
	45th	6,667	0.195	1,300
	48th	6,667	0.175	1,167
d. Maintenance replacement expansion joints	20th	111,111	0.484	53,778
	40th	111,111	0.234	26,000
Bearings	25th	222,222	0.403	89,555
Electric lampposts	10th	11,111	0.695	7,722
	20th	11,111	0.484	5,378
	30th	11,111	0.336	3,733
	40th	11,111	0.234	2,600
Indirect Expenditure				
a. User cost	Annual	4,167	22.470	93,632
			Total Present Value	**2,004,274**
Less: Income				
a. Collection from toll gate	Annual	50,000	22.470	1,123,500
			Net Present Value	**880,774**
			Annual Cost Factor	**0.045**
			Equivalent Annual Cost	**39,635**
				~$40.000

R. BHASKARAN is a research associate at the Central Electrochemical Research Institute, Karaikudi, Tamilnadu–630 006, India. He specializes in economic aspects of corrosion control and has done corrosion auditing in the sugar, pulp and paper, fertilizer, and petrochemical industries in India.

N. PALANISWAMY is deputy director and head of the Corrosion Protection Division at the Central Electrochemical Research Institute, Karaikudi. He has 28 years of experience in corrosion and its control, with 93 papers and four patents to his credit. He works in the areas of CP, concrete corrosion, and biological corrosion. He has a doctorate in science from Madurai Kamaraj University, Madurai, and received the NIIS-Meritorious contribution award during 2004 at New Delhi, India.

N.S. RENGASWAMY was an emeritus scientist at the Central Electrochemical Research Institute, Karaikudi. He has 45 years of research and development experience in corrosion and its control, including 30 sponsored projects and 43 consultancy assignments. He has developed a cost-effective CP technology for reinforced concrete bridges and structures. He has a doctorate in engineering from the Indian Institute of Science and received a National Merit Award from the Electrochemical Society of India and the Smt. Annapurna Award for Best Publication from the Society for Advancement of Electrochemical Science and Technology, India. **MP**