Minimum expected cost-oriented optimal maintenance planning for deteriorating structures: application to concrete bridge decks

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Abstract

Civil engineering structures are designed to serve the public and often must perform safely for decades. No matter how well they are designed, all civil engineering structures will deteriorate over time and lifetime maintenance expenses represent a substantial portion of the total lifetime cost of most structures. It is difficult to make a reliable prediction of this cost when the future is unknown and structural deterioration and behavior are assumed from a mathematical model or previous experience. An optimal maintenance program is the key to making appropriate decisions at the right time to minimize cost and maintain an appropriate level of safety. This study proposes a probabilistic framework for optimizing the timing and the type of maintenance over the expected useful life of a deteriorating structure. A decision tree analysis is used to develop an optimum lifetime maintenance plan which is updated as inspections occur and more data is available. An estimate which predicts cost and behavior over many years must be refined and reoptimized as new information becomes available. This methodology is illustrated using a half-cell potential test to evaluate a deteriorating concrete bridge deck. The study includes the expected life of the structure, the expected damage level of the structure, costs of inspection and specific repairs, interest rates, the capability of the test equipment to detect a flaw, and the management approach of the owner towards making repairs.

Keywords: Deteriorating structures; Cost-based optimal maintenance; Inspection/repair planning; Probability; Updating

1. Introduction

The lifetime maintenance of a deteriorating structure can comprise a far greater portion of the total lifetime cost than the original cost of construction. The cost of construction, while high, is a one-time cost while the cost of maintenance can span decades. The infrastructure of the United States consists of thousands of deteriorating structures and the national cost of maintaining them is a substantial portion of the budget. Of the almost 600,000 bridges and culverts in the National Bridge Inventory, over 35% of the bridges are either structurally deficient, functionally obsolete, or both. The estimated cost to eliminate the backlog of bridge deficiencies and maintenance repair levels is about $80 billion [1]. With such huge expenditures, any realized efficiency or optimization can result in significant savings.

It is difficult to make a reliable estimate of these lifetime costs when the future is unknown and structural deterioration and behavior are assumed from a mathematical model or previous experience. This paper is based on a methodology developed by the writers [7,9] for optimizing the lifetime inspection and repair of any deteriorating structure based on the information available at the time using a decision tree analysis. The optimized strategy is revised and updated as new inspection information becomes available and repair/no repair decisions are made on the structure. The methodology is illustrated using a concrete bridge deck whose steel reinforcement is corroding. The results are a series of optimum strategies throughout the life of the structure which specify the inspection technique, the number and timing of the inspections, and the expected lifetime maintenance cost of the structure.

The general methodology for optimizing the lifetime maintenance of a deteriorating structure is as follows [9]:

- Define the structure and the criteria which constitute failure of the structure.
- Develop a deterioration model which predicts how the structure will change over time.
- Specify the inspection methods available to detect this deterioration. Quantify the inspection costs and capability

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Table 1
Three inspection techniques and their associated costs

Inspection techniques	Spacing of readings	Total readings	Inspection cost ($)
A	5 ft (1.52 m)	$8\times27=216$	1027
B	10 ft (3.05 m)	$4\times13=52$	604
C	20 ft (6.10 m)	$2\times6=12$	408

of these methods to detect the relevant flaws or changes in the structure.

- Define the available repair options, their effect on the structure, and their costs.
- Quantify the probability of making a repair if a defect is detected.
- Formulate the optimization problem based on the optimization criterion, failure constraints, expected life of the structure, and any other imposed constraints.
- Use an event tree to account for all of the repair/no repair decision possibilities that occur after every inspection. The event tree shows the probability of taking a particular path and provides the expected value of the optimization criterion.
- For a discrete number of lifetime inspections, optimize the timing of these inspections for a specific inspection technique.
- Repeat the problem for other inspection techniques and numbers of lifetime inspections. The optimum strategy is the one which provides the best expected value of the optimization criterion.
- As inspections are conducted and the repair/no repair decisions are actually made, use the new information to update the optimum strategy.

2. Concrete bridge deck

The structure whose lifetime inspection and repair strategy is optimized is a 42.1 m × 12.2 m concrete bridge deck which deteriorates over time as spalls and delaminations appear in the concrete. The deterioration is caused by corroding reinforcing steel in the bridge deck. Consistent with the Colorado Department of Transportation (CDOT) repair policy, deck failure occurs when active corrosion is underway in at least 50% of the deck [4].

The concrete deteriorates as chlorides from deicing salts penetrate the concrete and reach the steel reinforcing. At a critical chloride concentration, the reinforcing corrodes which causes the concrete deck to spall. The corrosion initiation time which is the amount of time between the application of surface chloride and the onset of corrosion is expressed as [11]

$$T_{\mathrm{I}}=\frac{(d_{\mathrm{I}}-D_{\mathrm{I}}/2)^2}{4D_{\mathrm{c}}}\left(\mathrm{erf}^{-1}\left(\frac{C_{\mathrm{cr}}-C_0}{C_{\mathrm{i}}-C_0}\right)\right)^{-2} \quad (1)$$

where d_{I} is the concrete cover, D_{I} the initial diameter of the reinforcing bar, C_0 the equilibrium chloride concentration on the concrete surface, C_{i} the initial chloride concentration, D_{c} the chloride diffusion coefficient, and C_{cr} is the critical chloride concentration that will initiate corrosion. Using the distributions and parameters listed in Ref. [6] for all of these random variables, T_{I} was calculated to be normally distributed with a mean value $\mu_{T_{\mathrm{I}}}=19.6$ years and standard deviation $\sigma_{T_{\mathrm{I}}}=7.51$ years. The deterioration model can predict the percentage of corrosion in the deck at any time.

There are a variety of tests which may be performed individually or used in combination to detect concrete deterioration. These include measured crack widths, chain drag to detect delaminations, percentage of spalls, observed efflorescence, and chloride content. This study uses the half-cell potential test because it remains the most useful source of information regarding active corrosion in the deck [3]. It is inexpensive, simple, and non-destructive. The half-cell potential survey measures the electrical potential difference between a standard portable half-cell placed on the surface of the concrete and the embedded reinforcing steel. The voltage readings are compared to empirically derived values which indicate relative probabilities of active corrosion [8].

The correlation between the half-cell readings and the presence of active corrosion has been the subject of considerable research. The ASTM guideline prescribes that half-cell readings more positive than −0.20 V indicate at least 90% probability of no corrosion activity. Similarly, values more negative than −0.35 V indicate at least 90% probability of corrosion activity. Marshall [10] studied the data from 89 bridges to determine the probability density functions of the half-cell potentials for both sound and damaged deck areas. The half-cell potentials in areas where the deck was known to be undamaged was a normal distribution with a mean of $\mu=-0.207$ V and a standard deviation $\sigma=0.0804$ V and the half-cell potentials in areas where the deck was known to be damaged was a normal distribution with a mean of $\mu=-0.354$ V and a standard deviation $\sigma=0.0697$ V.

The uncertainty associated with assessing the condition of the entire deck from a finite number of half-cell readings was considered. Three different inspection techniques were used where the number of readings varied from one every 5 ft (1.52 m) to one every 20 ft (6.10 m). Table 1 shows the techniques and their associated costs. The inspection costs, developed in consult with CDOT [5] included fixed costs such as travel time to site, traffic control, equipment set-up, and writing the final report and variable costs such as marking the grid pattern, prewetting the test locations,

Table 2
Expected cost of repair for concrete bridge deck with 45 year service life, three lifetime inspections, proactive approach, inspection technique A, and 2% discount rate

Event tree	Discounted cost of repair ($)				Probability of taking branch	Expected cost of repair ($)
	Repair 1 $t_1 = 10.05$	Repair 2 $t_2 = 19.76$	Repair 3 $t_3 = 35.45$	Total		
Branch 1	184,887	152,455	111,805	449,147	0.001	449
Branch 2	184,887	152,455	0	337,342	0.003	1,012
Branch 3	184,887	0	111,805	296,692	0.058	17,208
Branch 4	184,887	0	0	184,887	0.005	924
Branch 5	0	152,455	111,805	264,260	0.160	42,281
Branch 6	0	152,455	0	152,455	0.589	89,796
Branch 7	0	0	111,805	111,805	0.183	20,460
Branch 8	0	0	0	0	0.001	0
Total expected cost of repair						172,130

probabilities of occurrence that determine the optimum (i.e. least-cost) inspection strategy. In reality, none of these eight paths will be taken. While the optimum strategy at this time is for three lifetime inspections at 10.05, 19.76, and 35.45 years, the plan will be updated after each inspection to account for the new information that the inspection provides.

3. Optimizing and updating

After the first inspection, the deterioration model can be updated, the first decision to replace or not replace the deck is made, and half of the eight paths are eliminated. With that additional information, a revised optimum inspection plan is developed. To illustrate this process over the life of the structure, let us assume that the inspection results accurately reflect the deterioration model and that the decision-maker follows the most probable path at every opportunity.

At the time of the first inspection (10.05 years), the expected damage to the deck is 10.2%. Assuming the inspection results confirm this, Branch 6 from Fig. 3 is the most likely path (58.9%) and the decision is to not replace the deck at this time. It is also assumed that for practical management purposes, the inspections are moved back to the next lowest even numbered year to coincide with the biennial visual inspection, although this is not a requirement.

The optimization problem is solved again for a bridge deck that is now 10 years old and has a remaining service life of 35 years. The optimum updated strategy shown in Fig. 5 suggests two lifetime inspections at 8.96 and 24.51 years, which is 18.96 and 34.51 years after the bridge has been put in service. The expected damage over time for each of the four branches of the event tree is shown in Fig. 6. The expected lifetime cost is $194,500 in dollars 10 years after the bridge was put in service (i.e. in 2010 dollars) which with a discount rate $r = 2\%$ is a lifetime cost of $159,558 in year 2000 dollars. The expected cost, as shown in Table 3, was reduced from $174,175 to $159,558 once the actual decision was made not to repair the deck after the first inspection.

The most probable path is Branch 2 (55.7% probability of occurrence) from Fig. 6 which replaces the slab after the 8.96 year inspection, but not after the 24.51 year inspection. Assuming the inspection results are consistent with the deterioration model, the deck will be damaged over 46.6% of the deck and will be replaced after the inspection at 8.0 years (the next lowest even numbered year), which is year 18 of service life. The deck is replaced at a cost of $157,956 in year 2000 dollars. When added to the inspection cost, the cumulative cost to date of the deck is $159,517 as shown in Table 3. None of these four paths will actually be followed because once the decision to replace the deck is known, the optimization process is completed again and the inspection strategy is updated.

Table 3 summarizes the initial lifetime strategy (step 1)

Table 4
Updated optimization results for inspection of a deck with a 45 year service life using an updated deterioration model (Note: Data separated by a slash (/) indicates before replacement/after replacement of the deck. Data in parenthesis indicates revised deterioration model (previous deterioration model))

Step	Time (years)	Number inspections	Inspection times (years)	Percent damage (%)	Time since repair (years)	Remaining service life (years)	Projected remaining cost (year 2000 $)	Actual cumulative cost (year 2000 $)
1	0	3	10.05 19.76 35.45	0	0	45	174,175	0
2	10	1	10.80	10.2 (5.5)	10	35	7,493	842
3	20	1	19.6	6.4 (16.9)	20	25	17,126	1533
4	38	1	2.0	37.5	38	7	43,882	2017
5	40	0	–	42.0/0	40/0	5	50,180	104,654
6	45	0	–	2.8	5	0	0	104,654

cost of the structure and owners are not unexpectedly surprised when this is done in a progressive, rational manner.

The initial expected cost is not necessarily accurate, but it presents the best information available at the time. This study evaluated a deteriorating concrete bridge deck with a 45 year service life to illustrate the methodology. The original expected lifetime cost of the deck was $174,175. During the updating process, the actual lifetime cost ranged from $271,575 down to $2,928 based on inspection results and decisions made. The difference in costs however was not unexpected. The successive strategy iterations show how and why this was occurred and gives planners time to prepare.

The analysis was also performed for different expected service lives of the structure, other management repair approaches, alternative repair policies, and different discount rates. The method requires a great deal of input data that is not readily available and demands investment of time and research. Additional research is needed in the areas of quantifying the probabilistic capability of NDE inspection techniques, probability of making repairs, and the modeling of deterioration. An optimization strategy that considers the results of several different inspection techniques also merits further study.

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