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Bridge Maintenance Planning: Probabilistic Approach

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Abstract: Due to technical difficulty or lack of resources, it is not feasible to monitor a bridge system continuously. Hence, in this case, bridge condition can be detected only by discrete inspections through bridge lifetime. Based on these inspections, different maintenance actions, ranging from doing-nothing to system-replacement, can by assigned. Combining inspection policy with age of maintenance and degradation process, taken from previous experience and available database of similar structures, can be used as an effective process in decision making among different maintenance actions. The aim of this study was to develop a statistical-oriented method of managing and predicting maintenance actions and choosing the suitable inspection time interval at different bridge ages based on distributions of the time of maintenance obtained from the past experience and available database.

Key words: Bridge maintenance, inspection intervals, maintenance strategy, preventative maintenance, rehabilitation programs, probabilistic approach

INTRODUCTION

Monitoring a bridge system continuously to determine its condition and then apply the suitable maintenance action is not a feasible task. So, bridge condition is detected through discrete inspections during bridge lifetime. In practice, five different types of inspections are applied to most highway bridges. These inspections are[1]: Initial inspection, routine inspections, in-depth inspection, damage inspection and special inspection. The most common used type is the routine inspection that is a regularly scheduled to determine the condition of a bridge and to identify any changes since previous inspections and to ensure that a bridge continues to satisfy all applicable serviceability requirements.

Based on these regular inspections, different decisions that lead to various maintenance actions, ranging from doing-nothing (i.e., waiting for another scheduled inspection) to system-replacement, can by assigned to each inspected structure. Furthermore, this process is time consuming with high associated maintenance cost that affects the total rehabilitation budget. On the other hand, the maintenance cost is highly influenced by the condition of the maintained bridge and the total number of maintenance actions made throughout the bridge lifetime.

In literature, the inspection-maintenance relation was usually obtained using Markov Chain technique in which the beginning of the Markov Chain is represented by the tree diagram that shows the inspection-decision tree and their associated probabilities[2,3]. Thus, every node will have a condition state and a number of possible maintenance options represented by branches that are emanating to the right. (Increasing time). The Markovian approach has several important limitations, such as: (a) severity of deterioration is described in visual terms only; (b) condition deterioration is assumed to be a single step function; (c) transition rates among condition states of a bridge element are not time dependent and (d) bridge system condition deterioration is not explicitly considered. On the other hand, the number of branches is very high (a two-option tree over 20 inspections would have 2^{20} branches) and although the calculations are simple a large amount of computer time would be needed[4].

The aim of this study was to develop a statistical-oriented method of managing and predicting maintenance actions and choosing the suitable inspection time interval at different bridge ages based on distributions of the time of maintenance obtained from the past experience and available database.

Rehabilitation programs: The main objective of bridge management was to maintain bridge structures in a safe condition during their lifetime. This is usually done through bridge rehabilitation programs. These programs are mainly divided into three groups[2]:

- Routine maintenance: Minor work carried out on a regular basis, such as cleaning of drains.
- Preventive Maintenance: Maintenance work which repairs defects, replaces components or otherwise slows the rate of deterioration and may enhance the strength of the structure to some extent, such as steelwork repainting, expansion joint replacement and small concrete repairs.

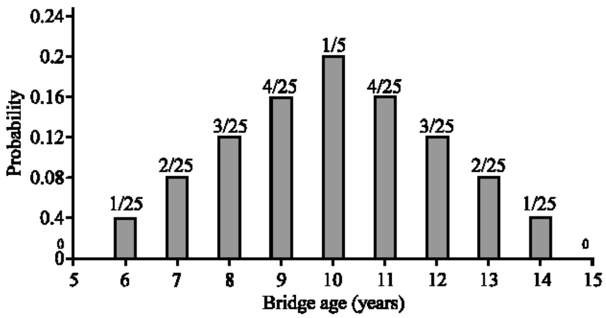

Fig. 1: PDF of first rehabilitation

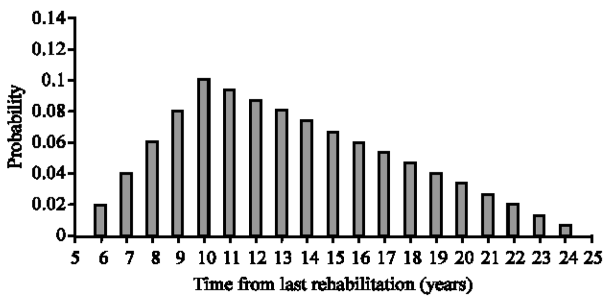

Fig. 2: PDF of subsequent rehabilitation

- Essential Maintenance: Rehabilitation work undertaken when a structure is considered to be structurally inadequate such as major concrete repairs, replacement of structural elements.

Results presented at the University of Colorado[2,4,5] show the crucial role of preventive maintenance actions in reducing the overall maintenance costs and the need for essential maintenance actions in keeping structures safe and serviceable, during their entire service life.

Based on opinions of experienced engineers, it was noticed that the preventive maintenance actions could be considered as a single package[2,4,5]. Also, the Probability Density Functions (PDFs) of the age at which this package should be reapplied can be modeled by a triangular distribution. Using the available data provided in bridge management database, the properties of this type of distributions can be obtained and thus the rehabilitation occurrence time can be modeled.

Rehabilitation probability distributions: In literature, probability distributions of first rehabilitation and subsequent rehabilitation were developed for four main bridge types[4]. These types are: steel-concrete composite, reinforced concrete, pre-stressed concrete and post-tensioned concrete bridges.

In this study, only one of these bridge types is taken to illustrate this methodology and a triangular distributions T(5,10,15) and T(5,10,25) were assumed as probability distributions of the first and subsequent preventive maintenances, respectively[2]. The numbers in parentheses represent lowest age, mode and highest age associated with triangular distributions. Figure 1 shows the PDF of the age of bridge at which first preventative maintenance is done. Figure 2 shows the PDF of the time at which subsequent preventative maintenance is done measured from last preventative action.

INSPECTION-MAINTENANCE RELATION

The inspection-maintenance relation found in literature, usually obtained using Markov Chain technique[2,3] in which the beginning of the Markov Chain is represented by the tree diagram that shows the inspection-decision tree and their associated probabilities[2,3]. Thus, every node will have a condition state and a number of possible maintenance options represented by branches that are emanating to the right. (Increasing time). The Markovian approach has several important limitations, such as: (a) severity of deterioration is described in visual terms only; (b) condition deterioration is assumed to be a single step function; (c) transition rates among condition states of a bridge element are not time dependent and (d) bridge system condition deterioration is not explicitly considered. On the other hand, the number of branches is very high (a two-option tree over 20 inspections would have 2^{20} branches) and although the calculations are simple a large amount of computer time would be needed[4].

A new probabilistic method was developed at the University of Colorado uses the probability distribution of the age of each maintenance action instead of the branches of the decision tree of Markov chain[2,5]. This study elaborates on this approach and uses the translated probability distribution of the age of preventative maintenance merged with the scheduled routine inspections to predict and manage the maintenance actions for a bridge stock.

Knowing that the preventive maintenance action comes after a scheduled inspection, therefore, merging the probabilistic nature of maintenance occurrence with inspection timetable, the probabilities of a maintenance decision in any inspection can be predicted. Figure 3 illustrates the PDF of first rehabilitation time (approximated as triangular distribution) and the scheduled inspections in time domain.

The PDF's of the first and subsequent rehabilitation can be transformed to a PDF's of number of inspections to the first or subsequent rehabilitation. These transformed PDF's are shown in Fig. 4 for two inspection intervals (3 year interval and 5 year interval, respectively).

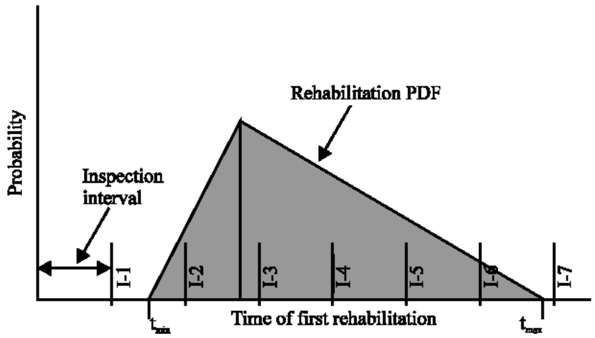

Fig. 3: PDF of first rehabilitation with scheduled inspections

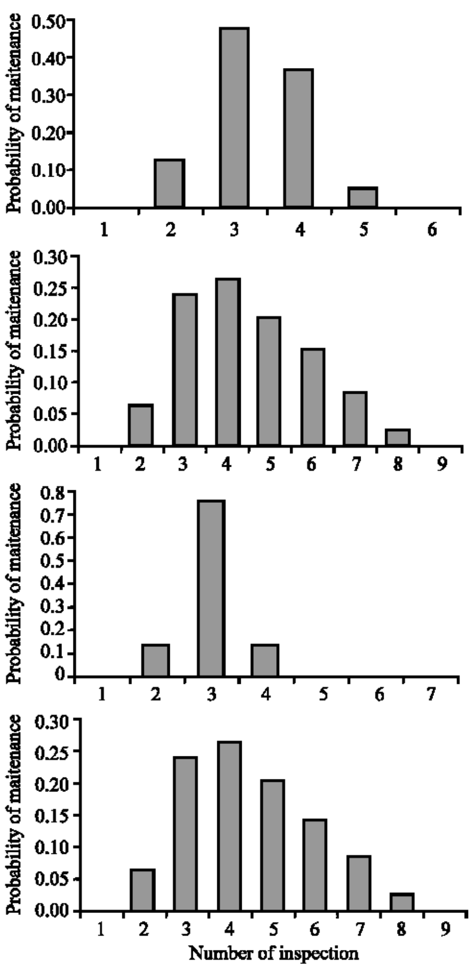

Fig. 4: Number of scheduled inspections to first and subsequent rehabilitation assuming 3 and 5 year inspection intervals: (a) First rehabilitation, 3 year interval; (b) Subsequent rehabilitation, 3 year interval; (c) First rehabilitation, 5 year interval; (d) Subsequent rehabilitation, 5 year interval

Note that in subsequent rehabilitation, the number of scheduled inspections is taken from the last maintenance (i.e., relative inspection numbers).

Table 1: Calculation of subsequent maintenance probabilities

	Subsequent maintenance				
First	1	2	3	4	5
maintenance	0.0625	0.416667	0.333333	0.166667	0.020833
1	1+1	1+2	1+3	1+4	1+5
0.125	0.007813	0.052083	0.041667	0.020833	0.002604
2	2+1	2+2	2+3	2+4	2+5
0.75	0.046875	0.3125	0.25	0.125	0.015625
3	3+1	3+2	3+3	3+4	3+5
0.125	0.007813	0.052083	0.041667	0.020833	0.002604

Then, the transformed PDFs are used to generate the probability density of the number of inspections to any subsequent rehabilitation. A simple calculation sheet shown in Table 1 shows how to generate the second rehabilitation distribution from the first and subsequent distributions. Therefore, the second preventive maintenance PDF is generated from the first and subsequent rehabilitation PDFs, the third rehabilitation PDF is generated from the second and the subsequent rehabilitation PDFs and so on.

The probability of the second preventative maintenance, P^2, after a number of inspections, n, can computed from the first maintenance distribution, P^1 and the subsequent maintenance distribution, S, as follows:

$$P^2(n) = \Sigma P^1(n_p. S(n_s) \quad \text{for all } n_p + n_s = n \tag{1}$$

where, n_p is the number of inspections to the previous maintenance and n_s is the number of inspections to the subsequent maintenance.

As an example, the probability of the second preventative maintenance after (n=7) inspections is calculated as:

$$P^2(n{=}7) = P^1(n_p{=}1).S(n_s{=}6) + P^1(n_p{=}2).S(n_s{=}5) + P^1(n_p{=}3).S(n_s{=}4) + P^1(n_p{=}4).S(n_s{=}3) + P^1(n_p{=}5).S(n_s{=}2) + P^1(n_p{=}6).S(n_s{=}1)$$

In general, the probability distribution of the number of inspections to the (kth) preventative maintenance, P^k, can be generated from the (kth-1) preventative maintenance distribution, P^{k-1} and the subsequent maintenance distribution, S, as follows:

$$P^k(n) = \Sigma P^{k-1}(n_p). S(n_s) \quad \text{for all } n_p + n_s = n \tag{2}$$

Where, n_p is the number of inspections to the previous maintenance and n_s is the number of inspections to the subsequent maintenance.

Figure 5 and 6 present the probability of having a maintenance action after certain number of scheduled inspections measured from the time of construction for three and five years inspection intervals, respectively.

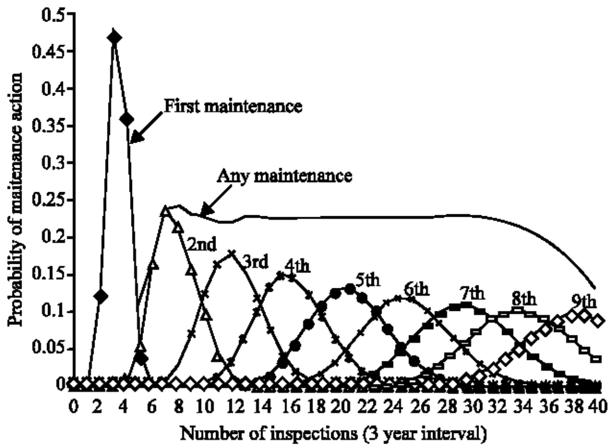

Fig. 5: PDFs of successive rehabilitations with respect to number of scheduled routine inspections (inspection interval is assumed = 3 year)

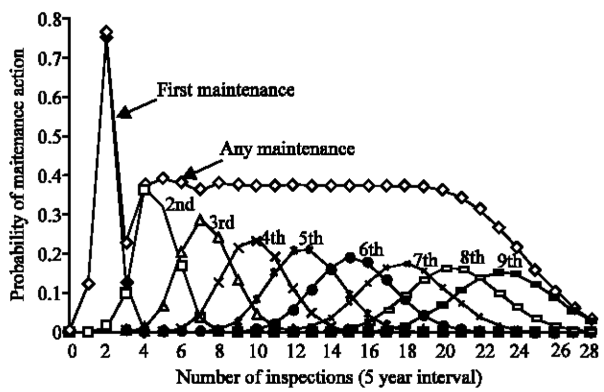

Fig. 6: PDFs of successive rehabilitations with respect to number of scheduled routine inspections (inspection interval is assumed = 5 year)

Figure 5 and 6 also show the probabilities of the first nine rehabilitations and the probability of having any rehabilitation. The probability of having a rehabilitation at any inspection is found from the summation of all probabilities of first, second, third rehabilitation... etc.

Results show that after about 20 years (7 3-year inspections or 4 5-year inspections) from construction, the probability is converging to almost a constant number. Figure 5 indicates that for a three-year inspection intervals there will be about 0.225 of the bridge stock need to be rehabilitated after each inspection. On other words, each bridge needs a rehabilitation after 1/0.225 = 4.444 inspections (about 13 years). Similarly, Figure 6 indicates that for a five-year inspection intervals there will be about 0.375 of the bridge stock need to be rehabilitated after each inspection. On other words, each bridge needs rehabilitation after 1/0.375 = 2.6667 inspections (about 13 years).

CONCLUSIONS

The method presented in this study represents a probabilistic way of managing and predicting maintenance actions that help dealing with maintenance planning. The a statistical-oriented method presented was successful of treating inspections and predicting future maintenance actions using the available database. This method showed that the integration of life-cycle maintenance and scheduled inspections is a practical possibility. However, more investigations are needed on the optimal network-level bridge maintenance planning.

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