ESTIMATION OF BRIDGE LIFE CYCLE MAINTENANCE COSTS USING RELIABILITY-BASED MODEL

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Abstract

Bridge life cycle maintenance costs can be estimated more accurately if the deteriorating and maintaining process can be simulated objectively. This paper first proposed a reliability-based model for prediction of deterioration. The performance of bridge elements was quantified by the reliability index. A stochastic approach was then introduced and the probabilities for what action should be taken at any time point can be determined. Afterwards, the costs associated with different maintaining actions were summarized from historical records. Thus, the maintaining cost for a bridge element can be taken as the sum of costs for all actions incurred over its lifespan. Monte Carlo Simulation (MCS) was finally applied to generate the probability distribution of cost estimation. Expansion joint was taken as an example to demonstrate the framework of the model. Likewise, the proposed model can be applied to all bridge elements and in turn, evaluate the maintenance cost for a whole bridge.

KEYWORDS: bridge, deterioration, reliability, cost estimation.

INTRODUCTION

The maintenance costs of bridges during their lifespan account for a major part of total life-cycle cost (LCC). However, the accuracy of estimation relies on how exact we can predict how bridges deteriorate as well as when and what maintaining action is taken. Many bridge management systems (BMSs) have provided with prediction tools to perform the estimation. A fundamental principle is that the costs are assumed to arise as soon as the maintaining actions are taken. As bridges may experience many uncertain times of various maintenances, a stochastic model is usually applied to determine whether an action should be taken or doing nothing at all as well as how the performance will be upgraded after an action is done.

Conditions of bridge elements can be either measured by embedded sensors or simply inspected visually. Although readings from sensors are somehow more convincible compared with inspectors' judgment, some limitations such as the costs and range of installation etc. still discourage us from use of embedded sensors. In fact, visual inspection has been widely applied on most highway and railway bridges in Taiwan since 1990s. As a result of regular proceeding, a significant mass of data has been accumulated. This provides plenty of historical information for deterioration process and facilitates modeling deterioration of bridges.

This study proposed a systematic approach to estimate the maintenance cost of bridges during their service life. A reliability-based model for prediction of deterioration was introduced. For any unique target bridge, a group of bridge samples with similar attributes can be selected from the bridge inventory (Huang, 2008). The deterioration trend can then be presented by the selected samples with a group of characteristic curves over time. Furthermore, the maintenance events were set to trigger if the bridge elements reached the critical performance levels. On the other hand, the costs associated with different maintaining actions were also summarized from the historical records. The maintaining cost for a bridge element can be simply taken as the sum of costs for all actions taken over its lifespan. Since the stochastic processes were involved, Monte Carlo Simulation (MCS) can be applied to generate the probability distribution of cost estimation. Finally, this study used a bridge element, expansion joint, as an experimental example to demonstrate the framework of the model. Similarly, the proposed model can be applied to all bridge elements and in turn, evaluate the maintaining cost for a whole bridge.

RELATED WORK

Cost Budgeting for Public Infrastructures

Budgeting on public infrastructures may suggest how the maintenance costs are estimated in public sectors. One of the most common approaches is the based-budget model, in which the budget is simply increased by a percentage of last year's base. This model tends to rely on the base to justify itself but sometimes cannot match the actual maintenance needs after several years. The zero-based budgeting concept was soon proposed. It requires that the base be rejustified each year, where the based-budget only requires that the increment be justified (Barco, 1994). In general, maintenance cost makes up 20-50% of overall cost for public infrastructure according to past national budgets of many countries (Lin, 2002).

Cost Estimation for Maintaining Bridges

Since most damages of bridge decks are caused by traffic flows, some studies attempted to find out the relation between the maintenance cost and the traffic from historical records. The heavy trucks are generally regarded as one of the major sources leading to damages. Thus, the correlation between truck axel load and maintenance cost was studied (Ni, 1996). Furthermore, a simple linear regression model was soon proposed to predict the maintenance cost over time (Yang, 1998).

An advanced approach was to estimate the maintenance costs based on the deterioration process which requires collection of historical inspection data. In US, conditions of bridge members have been inspected and recorded in a standard manner since the federal government announced the National Bridge Inspection Standards (NBIS) in 1971. Two national-level BMSs, PONTIS and BRIDGIT, were developed later for processing the raw inspection data. Both PONTIS and BRIDGIT have an in-built deterioration model, which uses Markov decision process to simulate uncertainty of deterioration. However, there are some limitations: (1) they use discrete transition intervals and stationary transition probabilities, which are sometimes impractical (Collins, 1972); (2) the future condition depends on the current condition state regardless of the facility condition history, which is unrealistic (Madanat et al., 1997); (3) the calculation of probabilities of deterioration requires a statistically significant number of observation pairs applied to the same bridge, which are not available for new bridges.

In spite of the limitations of Markovian models, the principle of calculating maintenance cost (i.e. the sum of the action costs) still holds. Therefore, the accuracy of estimation relies on the prediction of deterioration and what actions are taken.

Reliability-based Models for BMSs

The goal of design of bridges is to make sure a satisfactory level of reliability, which implies the concept of risks. Thus, the performance of bridge elements should be quantified in terms of reliabilities, which make more sense than discrete condition states do. Thoft-Christensen (1995) proposed to apply reliability theory in BMSs. Frangopol et al. (1997) used the reliability index, β, to represent the performance level of a reinforced concrete (RC) bridge under corrosion. Also, β was used as a measure of bridge safety (Ghosn and Frangopol, 1999). Some more deterioration mechanisms of RC bridges were further summarized by Enright et al. (1999). Their reliability index profiles can be obtained in a similar manner. As a matter of fact, Bridge Management in Europe (i.e. BRIME, 2001) has recommended the use of reliability techniques.

In consideration of uncertainties, probability density functions of random variables were employed with the deterioration process (Frangopol et al., 2001). Kong and Frangopol (2003) introduced a method of analyzing life-cycle performance of deteriorating structures based on reliability. A computer program, Life-Cycle Analysis of Deteriorating Structures (LCADS), was developed to implement the simulation of activities which affecting the reliability profiles. Although the above approaches have provided with a reliability-based framework for prediction of bridge performance and estimation of maintenance costs, the employment of such deterioration mechanisms requires specific nondestructive evaluations (NDE) which are often expensive and not feasible for all bridges. Instead of NDE, Estes and Frangopol (2003) attempted to use the visual inspection data provided from PONTIS to update the reliability of a bridge. However, the visual inspection data are not as perfectly quantitative as provided by monitoring sensors. Some revisions and conservative assumptions would be needed.

In short, the efforts mentioned above suggests: (1) reliability-based model should be incorporated in BMSs; (2) reliability index can be used as a measure of bridge performance; (3) random variables and probability distributions can be used to describe uncertainties associated with deterioration; (4) Visual inspections provide a great source of data for reliability analysis if the format of data can be well transformed.

METHODOLOGY

Measures of Bridge Performance

The performance of bridge elements are usually visually rated by semantic descriptions and recorded in BMSs. A well defined rating scale and experienced inspectors are essential to minimize the ambiguity while condition state for bridge elements is marked. In PONTIS, bridge elements are characterized by five discrete condition states, which describe the type and severity of deterioration in visual terms. An example is shown in Table 1. In Taiwan, conditions of bridge elements are assessed on a rating scale from 0 to 4 with respect to the degree (D) and the extent (E) of deterioration and its relevancy (R) to safety (known as the D-E-R rating, see Table 2).

Table 1: An Example of Condition State Definitions for Bridge Element in PONTIS

State	Name	Description
1	No corrosion	No evidence of active corrosion; paint system sound and functioning as intended.
2	Paint distress	Little or no active corrosion. Surface or freckled rust has formed or is forming.
3	Rust formation	Surface or freckled rust is prevalent. There may be exposed metal but no active corrosion.
4	Active corrosion	Corrosion present but any section loss resulting from active corrosion does not yet warrant structural analysis.
5	Section loss	Corrosion has caused section loss sufficient to warrant structural analysis to ascertain the effect of the damage.

Table 2: D-E-R Rating for Visual Inspection

	Ratings				
Item	0	1	2	3	4
D	No such element	Good	Fair	Poor	Severe
E	Cannot be inspected	<10%	10% ~30%	30%~60%	>60%
R	Cannot be decided	Minor	Small	Medium	High

By definition, D and E are physical measures of bridge conditions while R is comment made for further action. Therefore, we proposed a new condition index (NCI) for prioritizing the condition states composed by D and E. In addition, a greater D value indicates a severer condition state regardless of what E value is. Thus, NCI is proposed and defined as:

$$NCI = \begin{cases} D + (E-1)/4 & \text{, where } D > 1 \\ 1 & \text{, where } D = 1 \end{cases}$$

As formulated, NCI ranges from 1 to 4.75. It depicts 13 levels of conditions for bridge elements. The greater the NCI value, the worse the performance. Despite human error may be minimized there are still many uncertainties or unknown factors influencing the process of deterioration. As a matter of fact, the measures of performance from a number of bridge samples form a probability distribution. The deterioration over time can be schematically modeled by a group of distribution curves as shown in Figure 1. Each curve in Figure 1 represents the probability distribution of performance of a bridge element at a specific point of time. If the performance is measured by NCI, the mean as well as the variance of each distribution normally go increasing as the bridge elements deteriorate over time.

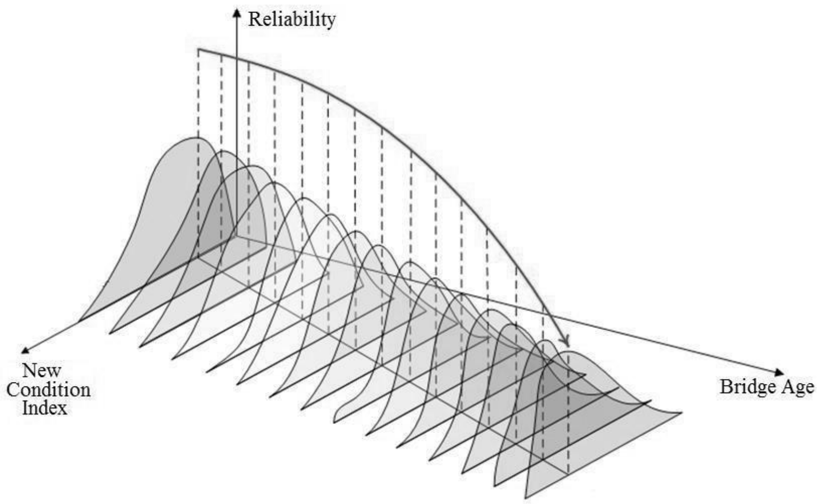

Figure 1: Schematic Deterioration Model

Induction of Reliability Theory

The performance model in Figure 1 can be easily transformed into a reliability index profile. If the acceptable level of NCI is set to be λ, the reliability index, β, of bridge elements can be calculated as follows:

$$\beta = \frac{\lambda - \mu}{\sigma}$$

where β = reliability index; μ = mean of NCI; σ = standard deviation of NCI.

Reliability index, β, represents the number of standard deviations, σ, which separates the mean, μ, of NCI from the critical condition, (i.e. NCI = λ). Figure 3 illustrates the notion of reliability index for bridge performance. For each time point (e.g. each year), the reliability index can be calculated if the probability density functions (PDFs) are determined. Therefore, the reliability index profile can be obtained as the curve over the PDFs shown in Figure 1.

Frangopol et al. (2001) suggested five states for bridge reliability: (1) excellent, $\beta > 9$; (2) very good, $9 > \beta > 8$; (3) good, $8 > \beta > 6$; (4) fair, $6 > \beta > 4.6$; and (5) unacceptable, $\beta < 4.6$. However, the grading usually depends on which part of bridges in consideration and the maintenance policies made by the bridge authorities. There has been always a trade-off between safety and costs. It is understandable that the lower tolerance of risk taking at safety, the higher maintenance cost incurred.

Probabilities for Taking Action

Four levels of maintenance actions including do nothing, preventive maintenance, repair and replacement are taken into account in this study. In PONTIS 4.4 (2005), the decision is made based on a transition probability matrix, which combines expert elicitations and historic observations (i.e. the weighted average). However, historic probabilities of "do something" cannot be evaluated in PONTIS. Their matrices and weighting coefficients in the model are identical to those of the elicitation. To evaluate the probabilities for each action, this paper proposed an innovative solution solely based on the historic inspection data. First, four scenarios for bridge conditions are defined: (1) NCI < λ1; (2) λ1< NCI < λ2; (3) λ2< NCI < λ3; (4) NCI > λ3. The λ1, λ2, λ3 are critical levels set to meet the requirement for their corresponding maintenance actions (i.e. preventive maintenance, repair and replacement). For each point of time, the probability of taking action *i* is denoted as *pi*.

As the scenarios are categorized by NCI value, the probabilities for each action can be best described by a beta distribution defined on the interval [1, 4.75]. The λ1 ~ λ3 just divide the area under the PDF into four parts, denoted as A1~A4 as shown in Figure 2. For any point of time, the probability for each action is identical to the probability for what scenario the bridge element falls into. In other words, A1 indicates the probability for "do nothing" (i.e. p_1) while A2 is for "preventive maintenance" (i.e. p_2) and so on. Therefore, the PDF for each point of time in Figure 1 can be treated as the PDF for taking action. It is anticipated that the probability for taking "do nothing" is relatively larger than taking other actions at an early age of bridge (see Figure 2). On the other hand, the "replacement" is gaining a bigger chance while the bridge element is getting worse (see Figure 3). The shape of the distribution skews rightwards year by year if the bridge elements deteriorate over time without any maintenance.

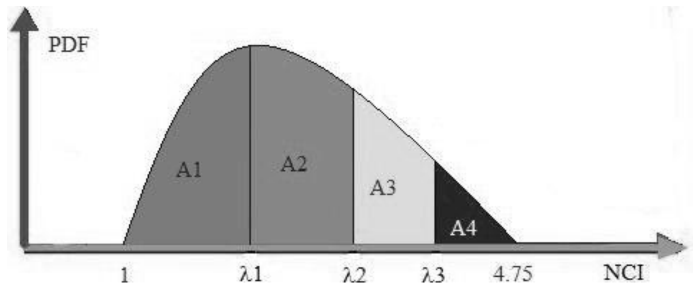

Figure 2: PDF of Taking Actions

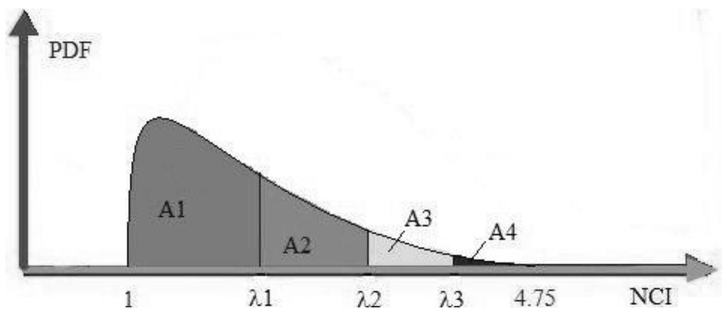

Figure 3: PDF of Taking Actions for Young Bridges

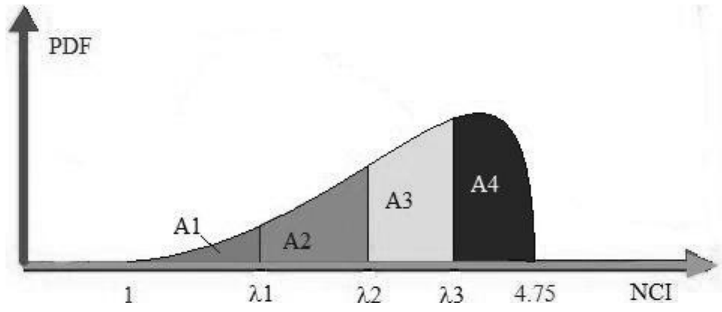

Figure 4: PDF of Taking Actions for Old Bridges

EXPERIMENTAL EXAMPLE OF COST ESTIMATION

Reliability-based Deterioration Model

To establish the deterioration model, 376 samples of expansion joints which have not experienced any maintenance service, were collected from Taiwan National Freeway System. The selection of bridge samples followed the systematic approach for searching similar bridges proposed by Huang et al. (2008). Samples with the same age were grouped to form the PDF of performance for each year. Figure 5 shows the result, the NCI profile, for selected samples.

The bridge samples are assumed to deteriorate in a similar manner since they are selected based on similar attributes which lead to deterioration (Huang et al., 2008). This study uses the reliability index profile to represent the deteriorating process. As defined above, three levels of reliability indices, $\beta1$, $\beta2$, $\beta3$ were calculated due to $\lambda1$, $\lambda2$, $\lambda3$ respectively, corresponding to different thresholds of performance level. As a result, three β profiles can be drawn as shown in Figure 6.

Performance Upgrade and Costs Associated with Action Taken

The reliability of bridge elements should be increased after maintenance action is done. Undoubtedly, "do nothing" gains no improvement while "replacement" brings the reliability back to the initial level (i.e. age = 0). However, the effects for "preventive maintenance" and "repair" can hardly be measured by visual inspection, hence require an advanced evaluation. In this study, 5% and 20% of reliability increment are suggested for "preventive maintenance" and "repair" respectively for expansion joint, but the resulting reliabilities cannot exceed their initial levels. The performance gains can also be replaced by a random variable if a significant number of observations can be accumulated.

Maintenance costs for each level of actions were summarized from past contracts for maintaining bridges of Taiwan National Freeway System during year 2001 to 2006. Except for "do nothing," cost for each level of maintenance was represented by a log-normal distribution. The PDFs and their parameters (i.e. the mean, ψ, and standard deviation, ζ, of the variable’s natural logarithm) are shown in Figure 7.

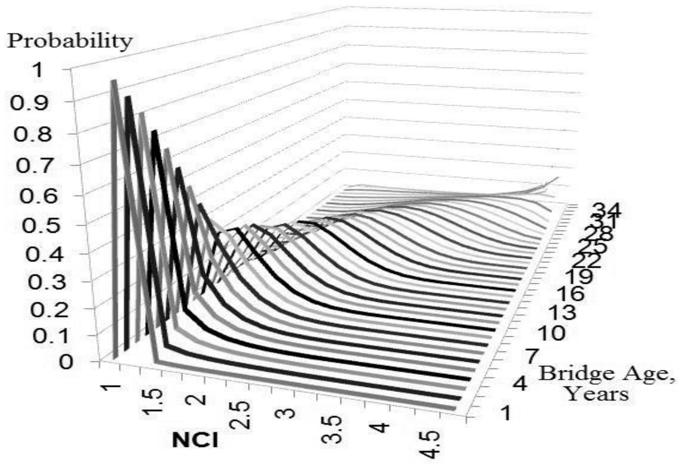

Figure 5: NCI profile for expansion joint

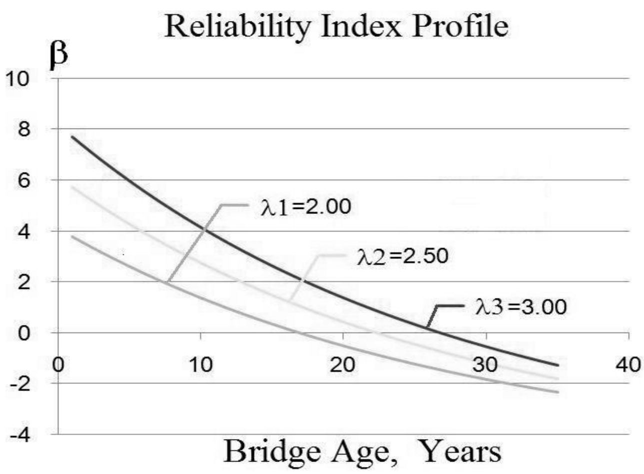

Figure 6: profiles for expansion joint

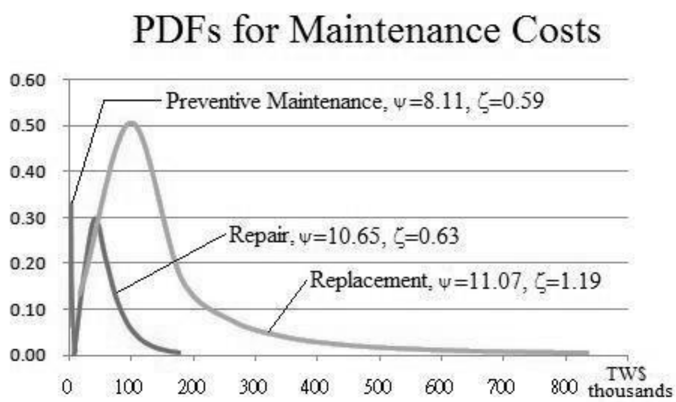

Figure 7: PDFs for Maintenance Costs

Estimation Using Monte Carlo Simulation

Monte Carlo Simulation (MCS) is widely recognized as a powerful tool to obtain an objective estimation under uncertainties. The hundreds or thousands of repetitive calculation can be easily executed by developing a program with spreadsheet software. A 35-year of life span was considered in the working example. The reliability index, β1, profile for 250 simulations were plotted as shown in Figure 8. It can be seen that "do nothing" and "Preventive maintenance" are probably taken in the early age while "Repair" and "Replacement" occur more frequently after the middle of lifespan. Besides, "Do nothing" can possibly happen even the reliability index is very low. The maintenance cost for expansion joint can be accumulated by the costs associated with all actions taken over a 35-year life span. As each cycle of simulation may produce different maintenance history, the sum of cost can be treated as a random variable provided with the mean and standard deviation. The result of cost estimation is presented in Figure 9. As a result, the estimation of maintenance cost for expansion joint forms a lognormal distribution with a mean of 120,768 TWD and standard deviation of standard deviation of 236,116 TWD (1 USD ≈ 33 TWD).

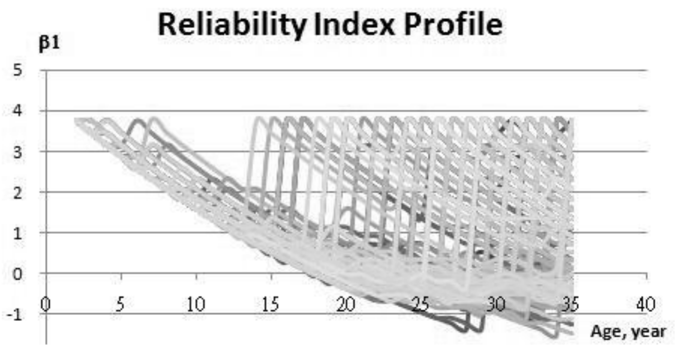

Figure 8: Reliability Index Profile of Expansion Joint for 250 Simulations

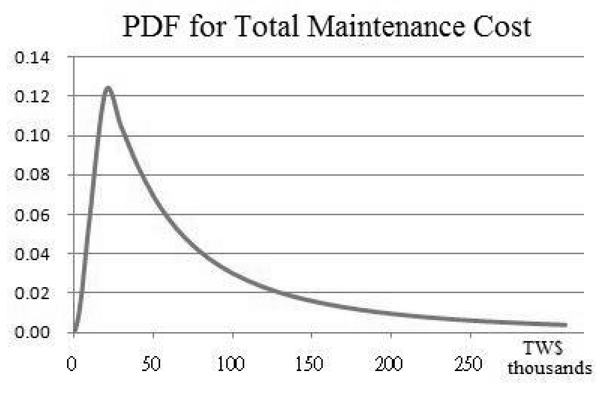

Figure 9: PDF of Total Maintenance Cost for Expansion Joint

CONCLUSIONS

The purpose of this paper is to demonstrate a straightforward approach of using visual inspection data to estimate the maintenance costs of bridges during their service life. The uncertainties for deterioration process are emphasized and treated by reliability theory. Moreover, the probabilities for selecting maintenance action are subtly derived from the probability distribution of bridge performance which can be completely sourced from historic data. The associated costs incurred from each maintenance action can be summarized from past contracts or any other available database. Thus, the maintaining cost for a bridge element is the sum of costs for all actions taken over its lifespan.

Finally, this study used expansion joint as an experimental example to demonstrate the framework of the model. Monte Carlo Simulation was applied to compute the probability distribution of cost estimation. Likewise, the proposed model can be utilized to all bridge elements and further evaluate the maintenance cost for a whole bridge.

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