

Estimation of Bridge Life Cycle MR&R Costs Using a Reliability-Based Model

Rong-Yau Huang and I-Shiang Mao

Abstract—This study proposes a systematic approach to estimate the MR&R cost of bridges using a reliability-based model. The approach first identifies a group of similar bridge samples to describe how the target bridge deteriorates in terms of reliability indices. The cost is then accumulated while each MR&R action is assumed to be taken over its lifespan. Afterwards, Monte Carlo Simulation is applied to generate the probability distribution as a stochastic result. Bridge expansion joint is employed as an example to demonstrate and to validate the developed approach. Results show the estimation of maintenance cost for the expansion joint of the bridge example forms a lognormal distribution with a mean of 120,768 TWD.

Index Terms—Bridge, cost estimation, deterioration.

I. INTRODUCTION

Deterioration is an inevitable process which requires maintenance, rehabilitation and repair (MR&R) to maintain at least a minimum satisfactory level of service quality. Proper budgeting for MR&R plan is essential for effective use of very limited government resources. Since the MR&R costs of bridges during their lifespan account for a significant portion of life-cycle cost [1], [2], adequate estimation of the cost will undoubtedly facilitate the priority evaluation of MR&R plans as well as the comparison of alternatives for new bridge projects.

This study proposes a systematic approach to estimate the MR&R cost of bridges using a reliability-based model. Visual inspection data of bridge elements is used for prediction of deterioration. The performance of bridge elements is transformed into the reliability index. A stochastic approach is then introduced and the probabilities for what action should be taken at each time point is determined. The costs associated with different MR&R actions are summarized from past related contracts. Thus, the MR&R cost for each bridge element can be taken as the sum of costs for all actions activated over its lifespan. Afterwards, Monte Carlo Simulation is applied to generate the probability distribution as a stochastic result. Finally, a bridge element, expansion joint, is 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 MR&R cost for a whole bridge.

II. MODEL DEVELOPMENT

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The authors are with the National Central University, Taoyuan, Taiwan (e-mail: rhuang@cc.ncu.edu.tw, i.mao@cute.edu.tw).

The retrieval of "similar" samples is of vital importance to the accuracy of modeling since the deterioration process for different bridge categories can be very different due to a variety of uncertainties (see Fig. 1). For a given target bridge, there should be more or less a set of similar bridge samples stored in BMSs (Bridge Management Systems). The retrieval process generally consists of two steps: (1) attribute extraction and (2) sample retrieval with the common attributes. The purpose of attribute extraction is to extract features that meet criteria of having sufficient clues leading to bridge deterioration implied in databases, then return a set of attributes describing those features. Having attributes identified, bridge samples with attribute values similar to the target one can be retrieved [3].

The performance of bridge elements are usually visually rated based on levels of semantic descriptions. 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 scale, see Table I). By definition, D and E are physical measures of bridge conditions while R is comment made for further action. Therefore, a single condition index, namely NCI (New Condition Index), for prioritizing the condition states composed by D and E was proposed [4]. Since a greater D value indicates a severer condition state regardless of what E value is, NCI is defined as:

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

TABLE I: D-E-R RATING FOR VISUAL INSPECTION

Ratings					
	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

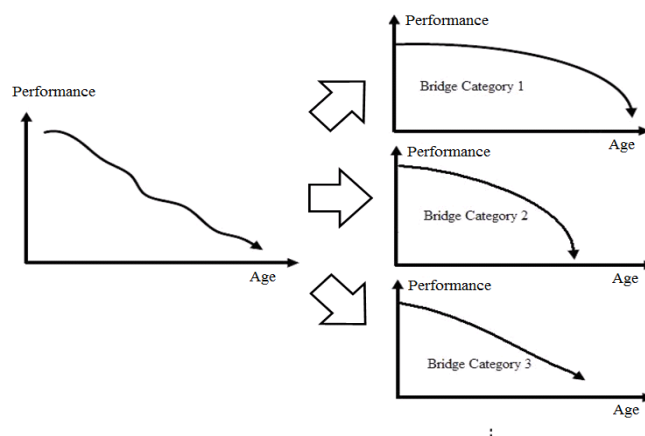


Fig. 1. Deterioration process for different bridge categories

As formulated, NCI ranges from 1 to 4.75. It depicts 13 levels of conditions for bridge elements. As a matter of fact, the measures of performance from the retrieved bridge samples form a probability distribution. The deterioration over time can be modeled by a group of distribution curves as shown in Fig. 2. Each curve in Fig. 2 represents the probability distribution of performance of a bridge element at a specific point of age. It is anticipated that the average performance of bridges grouped by the same ages is getting worse over time while the uncertainty is getting higher.

The results of visual inspection can be used to update the bridge reliability [5]. In this study, the performance model in Fig. 2 can be easily transformed into a reliability index profile. Suppose the acceptable level of NCI is given to be λ , the reliability index, β , of bridge elements can be calculated as follows:

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

of NCI respectively.

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 Fig. 2.

Four levels of MR&R actions including 'do nothing', 'routine maintenance', 'repair' and 'replacement' are taken into account in this study. To evaluate the probabilities for each action, this paper proposes a simple and rational solution solely based on the historic inspection data. First, four scenarios for bridge conditions are defined: (1) good, $\text{NCI} < \lambda_1$; (2) fair, $\lambda_1 < \text{NCI} < \lambda_2$; (3) poor, $\lambda_2 < \text{NCI} < \lambda_3$; (4) severe, $\text{NCI} > \lambda_3$. The $\lambda_1, \lambda_2, \lambda_3$ are threshold levels set to meet the requirement for their corresponding MR&R actions. For each point of time, the probability of taking action i is denoted as p_i .

As the bridge condition for each year is a distribution of NCI values, the probabilities for bridge condition can be best fitted by a beta distribution defined on the interval [1, 4.75]. The $\lambda_1, \lambda_2, \lambda_3$ just divide the area under the PDF into four parts, denoted as A1 to A4 as shown in Fig. 3. For any point of time, the probability for each MR&R level is identical to the probability for what scenario the condition of bridge element is determined. In other words, A1 indicates the probability for "do nothing" (i.e. p_1) while A2 is for "routine maintenance" (i.e. p_2) and so on. Therefore, the PDF for each point of time in Fig. 2 can be used to determine the probability for each maintenance option.

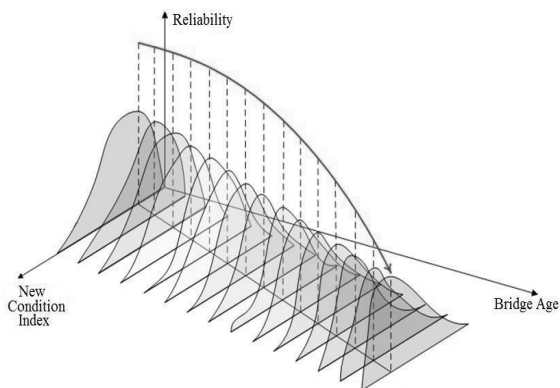


Fig. 2. Schematic deterioration model

As a result, the probability for taking "do nothing" is relatively larger than others at an early age of bridge (see Fig. 4). On the other hand, the "replacement" is gaining a bigger chance while the bridge element is getting worse (see Fig. 5). Some studies showed that the prediction of deterioration could be rather worse if the probability is determined by experts [6]. In this study, the proposed method determines the probability objectively based on data themselves only. It provides a fair approach and reflects the stochastic nature.

III. EXPERIMENTAL EXAMPLE OF COST ESTIMATION

To establish the deterioration model, data on a total of 2,128 bridges in the Taiwan National Freeway Bridge Management System are collected. With attribute value of expansion joint equal to "sliding finger joint" and length of maximum span roughly equal to 30 meters (70% of similarity), 376 bridge samples with expansion joints which have not experienced any maintenance service are retrieved following the approach for searching similar bridges proposed by Huang et al. [7]. Samples with the same age are grouped to form the PDF of performance for each year. The reliability index for each year is then calculated and forms a characteristic curve, the β profile, to represent the deteriorating process. As defined above, three levels of reliability indices, $\beta_1, \beta_2, \beta_3$ can be calculated due to $\lambda_1, \lambda_2, \lambda_3$ respectively, corresponding to different thresholds of performance level. As a result, three β profiles are drawn as shown in Fig. 6.

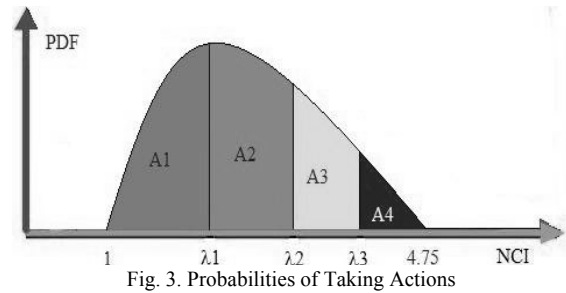


Fig. 3. Probabilities of Taking Actions

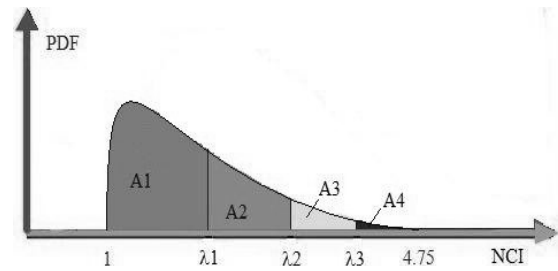


Fig. 4. Probabilities of taking actions for younger bridges

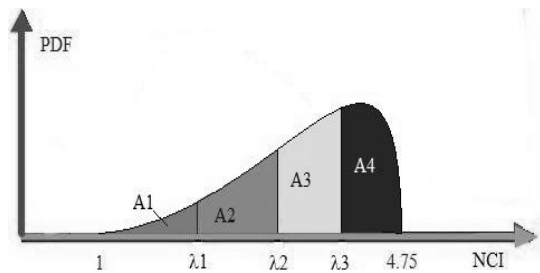


Fig. 5. Probabilities of taking actions for elder bridges

Costs for each level of MR&R actions are summarized

from past contractual documents provided by Taiwan Area National Freeway Bureau. Except for "do nothing," cost for each level of MR&R is represented by a log-normal distribution. Afterwards, Monte Carlo Simulation (MCS) is applied to simulate the deterioration and MR&R process over the lifespan. A 35-year of life span is considered in the working example. The reliability index, β , profile for 250 simulations are plotted. It is noted that "do nothing" and "maintenance" tend to be taken in the early age while "repair" and "replacement" occur more frequently after the middle of lifespan. Besides, "do nothing" can still possibly be taken even though the reliability index is very low, which perfectly reflects the nature of uncertainty. The MR&R 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 Fig. 7. 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 236,116 TWD (1 USD \approx 30 TWD).

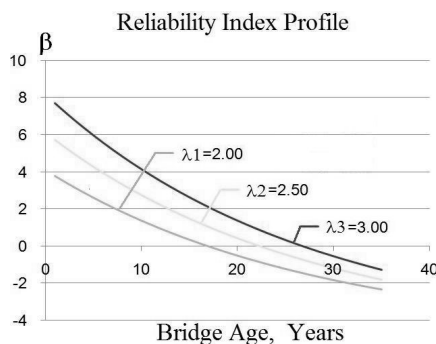


Fig. 6. Reliability index profile for expansion joint

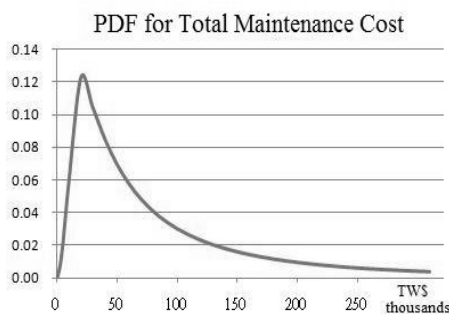


Fig. 7. Life-cycle MR&R cost for expansion joint

IV. CONCLUSION

This paper has proposed a systematic approach to estimate the maintenance costs of bridges during their service life using visual inspection data only. This study uses expansion joint as an experimental example to demonstrate the framework of the model. Monte Carlo Simulation is applied to compute the probability distribution of cost estimation. In a similar fashion, the proposed approach can be utilized to all other bridge elements to further evaluate the MR&R cost for a whole bridge.

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Rong-Yau Huang was born in Chang-hwa, Taiwan in 1963. He received his Bachelor degree in Civil Engineering from National Taiwan University in Taiwan in 1986. He received both his Master and Ph.D. degrees in Construction Engineering and Management from Purdue University in USA in 1991 and in 1994 respectively.

Dr. Huang is currently a professor and Chair of Institute of Construction Engineering and Management at National Central University in Taiwan. After finished his Ph.D. at Purdue, he worked as a research engineer for Mortenson Construction Company at Minneapolis, USA, from 1995-1996. He then returned to Taiwan and worked for Taiwan Construction Research Institute for one year, as an Associate Researcher, before he joined the faculty at National Central University in 1997. In 2003, he took a short leave to be a Visiting Scholar at UC Berkeley to do research in lean and green construction. He has published more than 40 refereed journal papers, and more than 110 conference papers. In addition, he has been the principal investigator of many research projects sponsored by various government agencies as well as private E/C firms in Taiwan. More than 60 research and/or technical reports were generated as a result. His major research areas include sustainable construction, project life cycle management, green building, recycling of construction wastes, lean construction, etc.

Dr. Huang serves in various organizational committees. He is the Regional Chair of Green Building Label (EEWH) Assessment Committee in Taiwan. He is the Chair of Green Construction Committee in Chinese Civil and Hydraulic Association in Taiwan. He also serves as a board member of the Green Building Promotion Association and the Taiwan Concrete Institute in Taiwan.



I-Shiang Mao was born in Tainan, Taiwan in 1969. He earned his MEng in civil engineering from the NCHU in Taichung Taiwan in 1993, his MEngSc in project management from the UNSW in Sydney, Australia in 2000, and is currently a PhD candidate in NCU, Taoyuan, Taiwan.

He is an Associate Research Fellow with the Structure Safety and Hazard Mitigation Center in China University of Technology, Taipei. The main research interests are in the fields of structural safety monitoring and data analysis.