Developing A Reliability-based Model for Estimation of Bridge Life Cycle MR&R Costs

Rong-Yau Huang, Ph.D.
Graduate Inst. of Constr. Engineering & Mgmt.
National Central University
Taoyuan, Taiwan
rhuang@cc.ncu.edu.tw

I-Shiang Mao
Graduate Inst. of Constr. Engineering & Mgmt.
National Central University
Taoyuan, Taiwan
i.mao@cute.edu.tw

***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. Likewise, the proposed model can be applied to all bridge elements and in turn, evaluate the MR&R cost for a whole bridge.**

Keywords—bridge;maintenance;cost;estimation;reliability

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. RELATED WORK

A. Estimating Bridge Life Cycle MR&R Costs

A survey showed that the annual MR&R costs of public facilities in various countries accounted for 20%–50% of overall infrastructure expenditures [3]. Although these figures provide a statistical approximation, they lack accuracy for use in estimations. Regarding bridges, truck weight has been regarded as a major source of damages and maintenance costs [4]. Ni [5] found a roughly positive correlation between truck axle load and MR&R costs. Furthermore, Yang [6] proposed a simple linear regression model to predict MR&R costs over time. Such regression models can easily be expanded to include additional factors, leading to a multi-variable regression approach. However, regression models are useful only if the correlation exists. Attaining a reasonable result is typically difficult in multi-variable regression analyses because of a lack of eligible samples or unreliable data quality. Although data cleaning, classification, and grouping similar samples that match the bridge in question can improve the regression model results, classifying bridges by using numerous attributes requires a considered approach.

B. Measures of Bridge Performance

Measuring bridge performance levels is a major purpose of inspection and is typically scored using condition ratings, for which each condition state is predefined using an ordinal scale; most bridge management systems (BMSs) calculate the deterioration rate based on this condition rating. Instead of relying on visual inspection, the conditions of bridge elements can be measured using sensors. Such sensor readings are likely more accurate compared with the judgements of inspectors; however, only a few deteriorating phenomenon can be measured by sensors. Besides, installing sensors on all bridges yields considerable costs, limiting the availability of this method.

Bridge safety often refers to a satisfactory level of reliability. Thus, measuring bridge element performance levels using a reliability index (RI) should be more comprehensive and accurately quantitative compared with using discrete condition states. Thoft-Christensen [7] proposed applying reliability theory to BMSs. Frangopol, Lin and Estes [8] used the RI to represent the performance levels of a reinforced concrete bridge and the deterioration mechanisms of such bridges were further summarized by Enright and Frangopol [9]. To address certain uncertainties, the probability density functions of random variables have been applied to the deterioration process [10]. A computer program, namely the Life-Cycle Analysis of Deteriorating Structures, was developed to simulate activities that affect reliability profiles [11]. Reliability-based approaches can typically be applied to sensor-measured data, which are only available for certain bridges during their monitoring periods. Estes and Frangopol [12] attempted to use the later visual inspection data from PONTIS to update bridge reliability, but determined that certain revisions and conservative assumptions were required, limiting its application. Thus, the relationship between condition ratings and sensor-measured readings is difficult to establish. Although visual inspection data is in an ordinal scale, the RI can be defined if the probability distribution for performance rating is given and the acceptable level of threshold is set regardless of other measurements.

C. Modeling Bridge Deterioration

A bridge deterioration model is used to describe how performance levels change over a bridge's lifespan. Tuutti [13] proposed a model that described the performance levels of concrete structures exposed to chlorides. Destructive load test or non-destructive evaluations have also been proposed to model deterioration [14, 15, 16]. Such models typically focus on a specific chemical or mechanical factor and often require numerous experimental tests to formulate deterioration mechanisms. Alternatively, regression analysis has been applied to historical data to build models based on correlations [17, 18]. Experimental and regression models assume that bridge performance levels have an expected value with time and are thus deterministic. By contrast, a stochastic model treats deterioration as a stochastic process that involves uncertainty; for example, the Markovian model in most BMSs [19, 20] assumes that the probability of transitioning from one condition state to another depends on the current state of a bridge and a predefined probability matrix rather than its age or any other bridge element information. However, using the Markovian model yields the following limitations: (1) it involves discrete transition intervals and stationary transition probabilities, which are sometimes impractical [21]; (2) the future condition of a bridge depends on its current condition state regardless of the facility condition history, which is unrealistic [22, 23]; and (3) calculating transition probability requires that a statistically significant number of observation pairs be applied to the same bridge element and such information is unavailable for new bridges. Although various scholars have attempted to enhance the Markovian model [24, 25], the outcomes of their predictions solely depended on transition probability matrices, and rectifying the probabilities therein such that prediction accuracy can be improved requires substantial effort [26, 27, 22, 28, 29]. Sobanjo [30] showed that the results could be rather conservative if the probability matrix was dominated by expert elicitation models.

In short, the aforementioned efforts suggest the following: (1) a rational approach for estimating bridge MR&R costs should be based on the deterioration process, involving all critical factors; (2) the deterioration process should be described using historical inspection data rather than human judgements; and (3) visual inspections have produced an extensive data source for modeling the deterioration process.

III. MODEL DEVELOPMENT

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 [31].

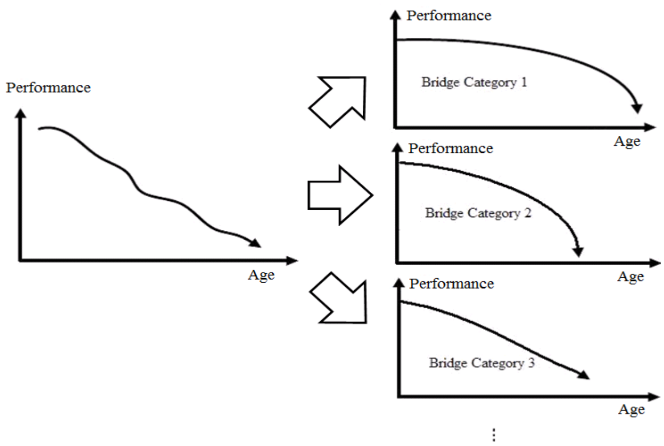

Fig.1. Deterioration Process for Different Bridge Categories

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

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 1). 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 [18]. Since a greater D value indicates a severer condition state regardless of what E value is, NCI is defined as:

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

As formulated, NCI ranges from 1 to 4.75. It depicts 13 levels of conditions for bridge elements. 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.

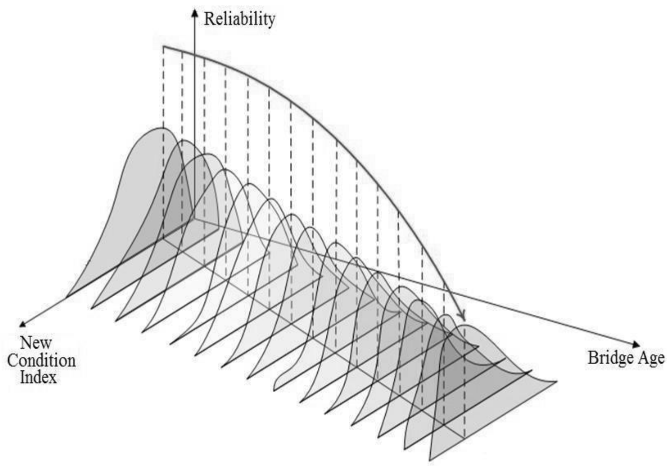

Fig. 2 Schematic Deterioration Model

The results of visual inpection can be used to update the bridge reliability[12]. 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:

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

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

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, NCI < λ1; (2) fair, λ1< NCI < λ2; (3) poor, λ2< NCI < λ3; (4) severe, NCI > λ3. The λ1, λ2, λ3 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 pi.

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 λ1, λ2, λ3 just divide the area under the PDF into four parts, denoted as A1~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. p1) while A2 is for "routine maintenance" (i.e. p2) 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. 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 [30]. 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.

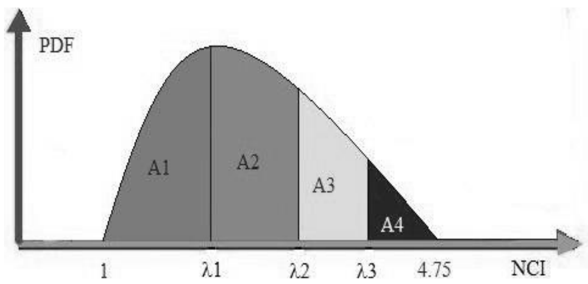

Fig. 3. Probabilities of Taking Actions

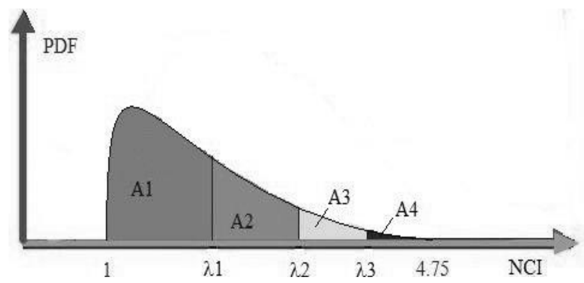

Fig. 4. Probabilities of Taking Actions for Younger BridgeS

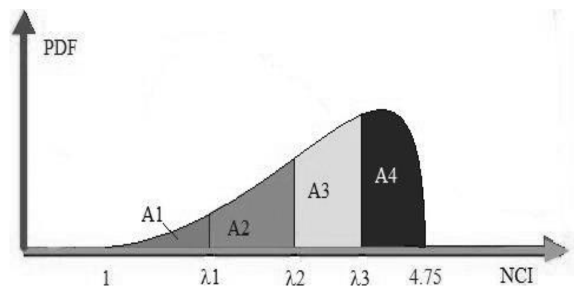

Fig. 5. Probabilities of Taking Actions for Elder Bridges

IV. 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, Mao and Lee [31]. 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, β1, β2, β3 can be calculated due to λ1, λ2, λ3 respectively, corresponding to different thresholds of performance level. As a result, three profiles are drawn as shown in Fig. 6.

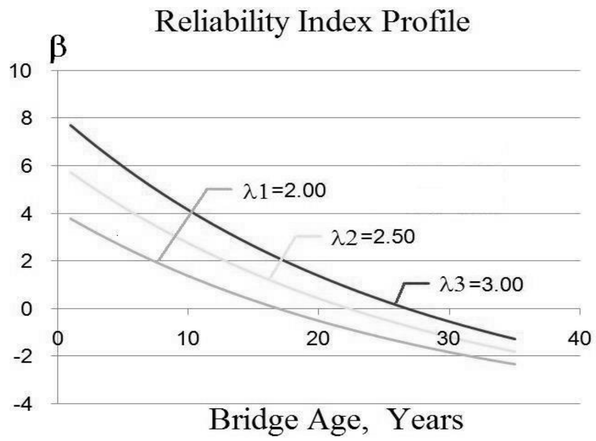

Fig. 6. Reliability Index Profile for Expansion Joint

Costs for each level of MR&Ractions 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, β1, 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 standard deviation of 236,116 TWD (1 USD ≈ 30 TWD).

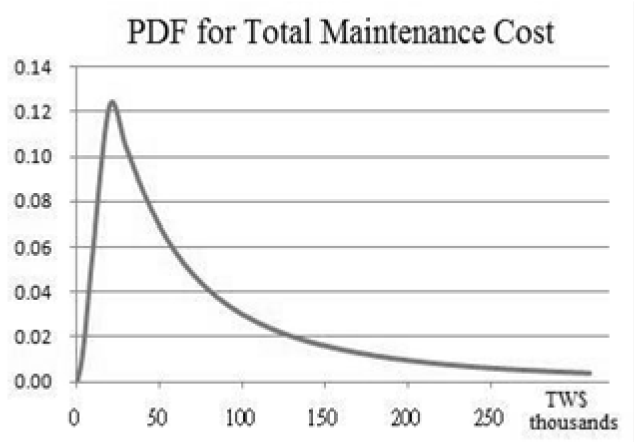

Fig. 7. Life-cycle Maintenance Cost for Expansion Joint

To validate the proposed model, bridge samples that demonstrated similar attributes (i.e., sliding finger joints and a maximal span length of roughly 30 m) were retrieved from the 198 bridges managed by the Mu-Za Section of the Taiwan Area National Freeway Bureau. All bridges were built between 1994 and 1997 and experienced MR&R service during 2000–2011. The average MR&R cost of expansion joints is TWD4,951 per span [33]. To compare the result, 15-year lifespan was set for simulation. After applying the proposed model for five trials of 1,000 simulations, the expected MR&R costs were TWD4,849, TWD5,064, TWD5,399, TWD4,643 and TWD5,358 per span.

V. CONCLUSIONS

This paper has proposed a systematic approach to estimate the maintenance costs of bridges during their service life using visual inspection data only. Expansion joint is used in this study as an experimental example to demonstrate the framework of the model. Monte Carlo Simulation is applied to compute the probability distribution of cost estimation. The initial results demonstrate the soundness of the proposed model. 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. In addition, the application of the developed approach is not limited to bridges and can be applied to other infrastructural facilities.

ACKNOWLEDGMENT

The authors wish to express their gratitude for the support of the work by the National Science Council, Taiwan under the Grant No. NSC102-2221-E-008-057-MY2. In addition, the assistance in the data collection from the Taiwan Area National Freeway Bureau, Taiwan is much appreciated.

REFERENCES

[1] Chang, S. E. and Shinozuka, M. (1996). Lifecycle cost analysis with natural hazard risks. Journal of Infrastructure Systems, ASCE, 2(3), 118-126.

[2] Itoh, Y., Nagata, H., Liu, C. and Nishikawa, K. (2001). Comparative study of optimized and conventional bridges: Life cycle cost and environmental impact. Life-cycle Cost Analysis and Design of Civil Infrastructure Systems, Frangopol D. M. and Furuta, H. ed., ASCE, 130-147.

[3] Lin, J. D. (2002). Budgeting and audit of MR&R cost for public infrastructure, *Final Report*, Taiwan Construction Research Institute, Taiwan

[4] Fu, G., Feng, J., Dekelbab, W., Moses, F., Cohen, H., Mertz, D. and Thompson, P. (2003). *Effect of truck weight on bridge network costs*. National Cooperative Highway Research Program Report 495. Washington, D.C: Transportation Research Board, National Research Council.

[5] Ni, M. R. (1996). *Limit of truck load for the 1st national freeway at Shi-Wu section*. Master thesis, National Taiwan University, Taiwan.

[6] Yang, C. C. (1998). Decision making model for highway bridge management: A case study of 1st national freeway. Master thesis, National Taiwan University, Taiwan.

[7] Thoft-Christensen, P. (1995). Advanced bridge management systems, *Structural Engineering Review*, 7(3), 151–163.

[8] Frangopol, D. M., Lin, K. Y. and Estes, A.C. (1997). Reliability of reinforced concrete girders under corrosion attack. *Journal of Structural Engineering*, ASCE, 123(3), 286-297.

[9] Enright, M. P. and Frangopol, D. M. (1999). Reliability-based condition assessment of deteriorating reinforced concrete bridges considering load redistribution. *Structural Safety*, 21(2), 159-195.

[10] Frangopol, D. M., Kong J. S. and Gharaibeh, E. S. (2001). Reliability-based life-cycle management of highway bridges. *Journal of Computing in Civil Engineering*, ASCE, 15(1), 27-34.

[11] Kong, J. S. and Frangopol D. M. (2003). Life-cycle reliability-based maintenance cost optimization of deteriorating structures with emphasis on bridges, *Journal of Structural Engineering*, 129(6), 818-828.

[12] Estes, A. C. and Frangopol, D. M. (2003). Updating Bridge Reliability Based on Bridge Management Systems Visual Inspection Results. *Journal of Bridge Engineering*, 8(6), 374-382.

[13] Tuutti, K. (1982). *Corrosion of steel in concrete*, Swedish Cement and Concrete Research Institute, Research Report FO 4, Stockholm.

[14] Basheer, P. A. M., Chidiac, S. E. and Long, A. E. (1996). Predictive models for deterioration of concrete structures. *Construction and Building Materials*, 10(1), 27-37.

[15] Roberts, M. and Atkins, C. (1997). Deterioration Modeling, *Concrete Engineering International* 1(1), 38-40.

[16] Rodriguez, J., Ortega, L. M., Casal, J. and GEOCISA (Dragados Group) (1997). Load carrying capacity of concrete structures with corroded reinforcement. *Construction and Building Materials*, 11(4), 239-248.

[17] Veshosky, D., Beidleman, C. R., Bueton, G. W. and Demir, M. (1994). Comparative analysis of bridge superstructure deterioration. *Journal of Structural Engineering*, ASCE, 120(7), 2123-2136.

[18] Huang, R. Y. (2006). A performance-based bridge LCCA model using visual inspection inventory data. Construction Management and Economics, 132(10), 1069-81.

[19] Thompson, P. D. and Shepard, R. W. (1994). PONTIS, *Transportation Research Circular*. No. 423, Transportation Research Board, National Research Council, Washington, D.C., 35-42.

[20] Lipkus, S. E. (1994). BRIDGIT bridge management software, *Transportation Research Circular*. No. 423, Transportation Research Board, National Research Council, Washington, D.C., 43-54.

[21] Collins, L. (1972). *An introduction to Markov chain analysis*. CATMOG, Geo Abstracts Ltd., Univ. of East Anglia, Norwich, U.K .

[22] Madanat, S., Kalaftis, M. G., and McCarthy, P. S. (1997). Probabilistic infrastructure deterioration models with panel data, *Journal of Infrastructure Systems*, 3(1), 4-9.

[23] Mishalani, R. G. and Madanat, S. M. (2002). Computation of infrastructure transition probabilities using stochastic duration models. *Journal of Infrastructure Systems*, ASCE, 8(4), 139-148.

[24] Ng S. K. and Moses. F. (1998). Bridge deterioration modeling using semi-Markov theory. Structural Safety and Reliability, Shiraishi, Shinozuka & Wen (Eds.), Proceedings of 7th International Conference on Structural Safety and Reliability (ICOSSAR). Kyoto, Japan.

[25] Robelin C. and Madanat S. M. (2007). History-dependent bridge deck maintenance and replacement optimization with Markov Decision Processes. *Journal of Infrastructure Systems*, ASCE, 13(3), 195-201.

[26] Jiang, Y., Saito, M. and Sinha, K. C. (1988). Bridge performance prediction model using the Markov chain. *Transportation Research Record 1180*, National Research Council, Washington D.C., 25-32.

[27] Cesare, M. A., Santamarina, Carlos, Turkstra, Carl and Vanmarcke, E. H. (1992). Modeling bridge deterioration with Markov chains. *Journal of Transportation Engineering*, ASCE, 118(6), 820-833.

[28] DeStefano, P. D. and Grivas, D. A. (1998). Method for estimating transition probability in bridge deterioration models. *Journal of Infrastructure Systems*, ASCE, 4(2), 56-62.

[29] Mauch, M. and Madanat, S. (2001). Semiparametric hazard rate models of reinforced concrete bridge deck deterioration. *Journal of Infrastructure Systems*, ASCE, 7(2), 49-57.

[30] Sobanjo J.O. and Thompson, P. D. (2011). Enhancement of the FDOT's project level and network level bridge management analysis tools, Final Report.

[31] Huang, R. Y., Mao, I. S. and Lee, H. K. (2008). Dynamic classification of reinforced concrete bridges based on the deterioration patterns. Electronic proceedings for 11th International East Asia-Pacific Conference on Structural Engineering & Construction, C04-02.

[32] Huang, R. Y., Mao, I. S. and Lee, H. K. (2010). Exploring the deterioration factors of RC bridge decks: A rough set approach. Journal of Computer-Aided Civil and Infrastructure Engineering, 25(7), 517-529.

[33] Huang, R. Y. (2012). *The Investigation of Bridge Life-Cycle Cost Analysis*. Final Report, China Engineering Cousultants, Inc.