Pavement Management for a Life Cycle Cost Analysis

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As the Framework Act on Sustainable Infrastructure Management has recently been enacted in Korea, it has become mandatory to establish a medium-and long-term plan for managing social infrastructure and evaluating the feasibility of maintenance projects. Road agencies are experiencing problems due to a lack of deterioration models which are essential to conducting a life cycle cost analysis. The deterioration model subdivided pavement materials into asphalt, conventional concrete, and latex-modified concrete.

asset management | bridge | pavement | life cycle cost analysis | life expectancy | deterioration model | Markov chain | pavement material

1. Introduction

As social infrastructure that had been built in Korea (Republic of Korea; ROK) since the 1970s became superannuated [1] and failures (i.e., events) occurred therefrom, Korea enacted the Framework Act on Sustainable Infrastructure Management (hereinafter, the Infrastructure Management Act) in 2020. This Act focuses on reorganizing a system that manages the social infrastructure and requires the following: to re-establish criteria for maintenance; to set up a long- and short-term management plan; and to evaluate the feasibility of maintenance projects. This Act specifies, as one of its fundamental principles, to "minimize the life cycle cost incurred by deterioration" [2] and prescribes to apply a Life Cycle Cost Analysis (LCCA) as an evaluation of the economic feasibility of performance improvement projects [3].

The LCCA derives future budgetary demands necessary to anticipate a change in a state of assets retained by an organization and secure a targeted service level. To conduct the LCCA, a deterioration model with an asset register is essential for anticipating a future condition of the assets. Based on the "Special Act on the Safety Control and Maintenance of Establishments (hereinafter, the Infrastructure Safety Act)" enacted in 1990s [4], Korea has endeavored to develop data on the status, condition, and history of social infrastructure for the last 30 years. As a result, Korea has developed detailed data on major social infrastructure in a systematic way [5]. However, no deterioration model and LCCA techniques have been established so far for each type/member of social infrastructure, which are officially applicable. That is, even if it is forced to conduct an LCCA by enacting new legislation, it is not prepared to respond thereto in the real world.

Thus, here is to develop a bridge pavement deterioration model for the LCCA as the first step to secure a power of execution of the Infrastructure Management Act. Herein, it subdivided deterioration models by pavement materials (asphalt, concrete, and Latex-Modified Concrete (LMC)) to develop a direction for the development of deterioration models presented by ISO 55001 and International Infrastructure Management Manual (IIMM) which could respond to deterministic/probabilistic LCCA. To sufficiently secure empirical bases, data on inspection and diagnosis conducted for the last 12 years in Korea were applied. As analytical tools, the Bayesian Markov Hazard (BMH) model combining a Markov chain, a multi-state exponential hazard model, and a Markov Chain Monte-Carlo (MCMC) technique were introduced. As its findings, life expectancy by condition grade, deterioration curve, probability density and distribution of the life expectancy, confidence intervals of life expectancy at the 3-sigma rule, and Markov Transition Probability (MTP) as Probability of Failure (POF) were suggested.

2. Pavement Management for a Life Cycle Cost Analysis

ISO 55001, an international standard for managing assets, states that it is essential to predict events likely to occur in the future [6]. It is a basis for sustainable organization management to define in advance the types of events and characteristics of risk which will obstruct an organization from achieving its objectives and establish strategies in preparation. The IIMM developed by applying ISO 55000 series and classifying types of deterioration models into deterministic models and probabilistic models [7]. Furthermore, ISO 55001 (Clause 10.2) requires the identification of a potential failure of assets and uses the same for preventive measures [1]. This means the application of Risk Centered Maintenance (RCM). It is required to investigate in advance the POF to realize the RCM, which would be able to be developed only through a probabilistic model. Thus, it is intended to develop a deterioration model which could support both functions to apply the requirements of ISO 55001.

Internationally, many studies are being conducted on social infrastructure deterioration modelling with a focus on pavement and bridges with various statistical techniques are applied thereto [8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41]. Do et al. [8] classified deterioration modelling techniques into six types and presented their advantages, disadvantages, and selection methods, respectively. Here, they are classified into the citation of useful life in accounting standards, simple calculation of elapse time between maintenances, multiple regression analysis, reliability analysis, traditional Markov chain, and advanced Markov chain application theory. It is presented that the appropriate methodology (or model) shall be selected based on the type, scale, and characteristics of obtained data and the information to be obtained through the deterioration model. Han and Lee [9] presented the conditions of deterioration model for asset management, as follows: (1) description of the transition of the deterioration speed, (2) derivation of information of uncertainty in the deterioration process, (3) derivation of influence of explanatory variables, (4) direct application of the Level of Service (LOS), and (5) resolution of lack of samples and presumption of model parameters. As a result, the BMH model was presented as a model optimized to meet these conditions.

The BMH model was proposed by Kaito and Kobayashi [10] and it overcomes the limitations of a model proposed by Tsuda [11] by applying the MCMC which is a non-parametric method. Thereafter, Bayesian Markov Mixed Hazard Model (hereinafter, the BMMH) that represents the heterogeneity of samples with a benchmark curve and heterogeneity factor was presented [12][13]. Herein, it is compared and examined the BMH Model and the BMMH Model to select the most appropriate deterioration modelling technique herein. The BMMH Model satisfies the ideal conditions for the deterioration model proposed by Han and Lee [9], and is able to develop and compare deterioration models for various sample groups all at once [14][15]. However, the BMMH Model assumes that deterioration models have the similar shape of deterioration curve (i.e., a process in which a deterioration rate changes) due to their nature to utilize a benchmark approach. Such an assumption may not be significant in studies that simply compare the performance of design/material alternatives based on life expectancy. However, such an assumption may become fatal in studies on the LCCA where a process in which deterioration rate change acts as an optimization variable. Thus, herein it is determined that it would be appropriate to apply the BMH Model considering the possibility that a deterioration curve may vary depending on pavement materials.

Studies on pavement management conducted since the mid-1960s are being conducted more actively in the 21st century [16][17]. Significant results were derived even in Korea in relation to pavement deterioration characteristics from information accumulated through the operation of the Pavement Management System (PMS) [9][14][15][18][19][20][21]. However, it is impractical to apply the findings on general road pavement to the LCCA of bridge pavement. This is because it is difficult to assume that their deterioration characteristics are similar due to their different pavement design, materials, and understructure. Furthermore, a condition of pavement is internationally represented with cracking, rutting, and International Roughness Index (IRI). However, Korea regards bridge pavement as a bridge component and thus its condition is evaluated based on its grade in accordance with the Infrastructure Safety Act [22]. Naturally, the road pavement deterioration models cannot be applied to the LCCA of bridge pavement in Korea and it would be reasonable to derive models by historical performance data of bridge pavement.

A bridge is a complicated structure composed of many components. The American Society for Testing and Materials (ASTM) defines 48 detailed components (at Level 3: individual elements) [23]. Previous studies on bridges have focused on the structural defects in abutment, pier, deck and so on, or the safety of components having a direct effect on collapse [24][25][26][27][28][29][30][31]. Of course, as there are a variety of studies on the deterioration characteristics of bridge pavement [11][32][33][34][35][36], it is impractical to apply the findings of studies conducted in other countries to the LCCA in Korea without change. This is because the LCCA shall reflect thoroughly the deterioration characteristics of its own assets.

Next, the subdivision of the deterioration model is also of interest. It would be convenient to develop a network-based model which represents the whole bridge pavement. However, such a model would not be able to reflect a difference in life expectancy resulting from deviation of technology or materials of pavement. Even the IIMM stated that it would be able to secure the accuracy of prediction only considering the deviation of these assets in terms of technology and environment [7]. In general, asphalt and concrete are used as materials for bridge pavement. However, it takes too long to cure the concrete pavement (28 days or more) [42] and civil complaints are frequently raised due to work zones. To mitigate the problem, the LMC is used as the main material in Korea, which reduces the curing period significantly. The LMC pavement has physical characteristics different from those of conventional concrete and asphalt pavement and has high installation costs [32][33][34]. Thus, it is necessary to confirm its difference from conventional concrete pavement in terms of life expectancy.

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