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Efficient reliability-based approach for mechanistic-empirical asphalt pavement design

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HIGHLIGHTS

- An approach for reliability-based mechanistic-empirical pavement design is developed.
- First-order reliability method of asphalt pavement is implemented in a spreadsheet.
- The gamma sensitivity study is performed to identify the key input parameters.
- FORM can yield results comparable with those obtained using Monte Carlo simulation.

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ABSTRACT

An efficient approach for reliability-based mechanistic-empirical pavement design considering fatigue and rutting failures is developed in this study. This efficient approach relies on the first-order reliability method (FORM) and is implemented in a spreadsheet. The gamma sensitivity study is performed to identify the key input parameters in the reliability analysis. This study investigates the effect of the uncertainty in elastic modulus, layer thickness, design traffic as well as the model error of a three-layered pavement system on the reliability analysis. Comparison study shows that this efficient approach using FORM can yield results that are comparable with those obtained using Monte Carlo simulation. The advantages of this efficient approach include: it requires much less computational effort to determine probability of failure; it can be readily adapted for other mechanistic-empirical models for pavement design; it is easy to be adopted in the engineering practice and thus has the potential to become a practice tool in the reliability-based mechanistic-empirical pavement design.

1. Introduction

During the past decades, there has been a transition from the empirical design to the mechanistic-empirical design in the pavement engineering. The implementation of the mechanistic principles has significant benefit to the pavement design. For instance, the mechanistic-empirical pavement design guideline (MEPDG), which is one of the most thorough design methodologies, includes the characterization of traffic, climate effect, structural and material factors and the option to implement the reliability concepts [1].

The conventional pavement design is based on deterministic approaches in which all input parameters are considered as fixed inputs. For example, if the predicted fatigue life is larger than the allowable load repetitions, the design is considered to be a safe design. However, it is well known that the input factors in MEPDG, such as the traffic loads, climate issue, structural and material properties, layer thickness of asphalt, have uncertainty in pavement design and construction. The errors in those empirical components in MEPDG also cause addition uncertainty in the design outcome, e.g., the fatigue life. It is, therefore, advisable to consider those uncertainties in MEPDG through modeling those input parameters as random variables and perform the reliability-based design [2,3]. The reliability-based pavement design can be realized through meeting the required reliability level (R). Table 1 shows such an example suggest by AASHTO 1993 [4]. Design reliability concept of various pavement distresses is presented in Fig. 1. Alternatively, the design can also be performed based on the acceptable probability of failure (p_f), denoted as $p_f = 1 - R$. For instance, in a design against fatigue failure, the probability of fatigue failure, defined as the probability of the predicted

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Table 1
Reliability levels (R) suggested by AASHTO (1993).

Functional classification	Reliability level (%)	
	Urban	Rural
Interstate and other freeways	85–99.9	80–99.9
Principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

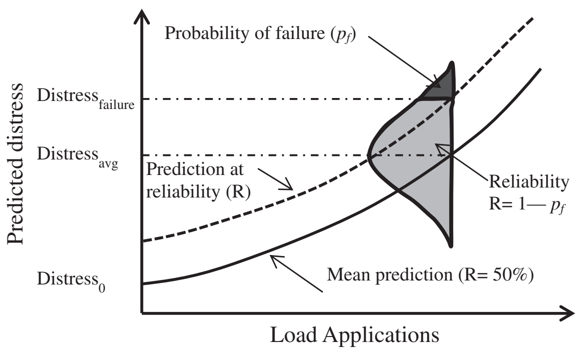

Fig. 1. Design reliability concept of various pavement distresses.

fatigue life less than the liming fatigue life, can be estimated. This failure probability should meet the minimum requirement, say 10^{-3}.

The reliability concepts have been widely adopted in various disciplines in civil engineering, e.g., structural, geotechnical and pavement engineering. AASHTO defines "the reliability of the pavement design-performance process is the *probability* that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period" [4]. In addition, AASHTO uses the reliability concept to account for design uncertainties. Basically, a pavement structure is designed using the most accurate input data available; data are not manipulated or inflated (nor are conservative values used) to compensate for their estimated variability but rather the best value is used. The pavement structural design process is then accounted for in the "reliability" factor which is comprised of two variables: standard normal deviate and combined standard error of the traffic prediction and performance prediction [4].

The current MEPDG is actually not a single closed-form solution and thus the implementation of the available reliability-based approaches is challenging. The current approaches to estimating the reliability in the MEPDG are still insufficient [1]. Nevertheless, many investigators have made significant contributions to develop the reliability-based framework for MEPDG in recent years [1,5–9]. In their research, various available approaches are adopted, including Monte Carlo simulation (MCS), point estimate method (PEM), first-order second-moment method (FOSM), first-order reliability method (FORM), etc. It should be noted that MCS is the most rigorous method for reliability analysis, but the trade-off is that a large amount of computational time and effort is required [2,3]. The previous research shows that the simplified approaches such as FORM can yield reasonably accurate solutions comparing with MCS [5]. The importance of improving the computational efficiency and reducing the computational effort in the reliability-based mechanistic-empirical pavement has also been highlighted [10]. In this regard, the focus of this study is to propose an efficient reliability-based procedure for MEPDG.

In this paper, an efficient approach, FORM, for the reliability-based mechanistic-empirical pavement design is developed and implemented in spreadsheet. The solver option in EXCEL is used for the ease of the computation of probability of failure. Both model and parameter uncertainties are considered in the reliability analysis. The key design parameters are identified using gamma sensitive index and a series of sensitivity study is performed to show the effect of those uncertain parameters as well as the model error on the estimated probability of failure. This developed simple procedure is easy to follow and can be readily adapted for other similar design problems in pavement engineering.

2. Mechanistic-empirical approach for pavement design

In the MEPDG, the design input parameters can be subdivided into four categories: structure, materials, traffic and climate. Using these input parameters, MEPDG incorporates the models to evaluate the stress and strain levels in pavement (both in the vertical and horizontal directions) and the models to assess the distress levels using those stresses and strains. The two key distresses are fatigue cracking and permanent deformation (rutting). The failure criterion for fatigue can be determined by the number of cumulative standard axles (denoted as N_F herein) that yields a certain cracked surface area, say 20% [11]. The failure criterion for rutting can be determined by the number of cumulative standard axles (denoted as N_R herein) that results in a certain amount of rutting, say 20 mm [11]. The number of load repetitions to fatigue failure (N_F) and rutting failure (N_R) can be estimated with empirical models based on regression analysis. In this study, the empirical model for fatigue failure for hot mix asphalt suggested by Asphalt Institute [12] is adopted:

$$N_F = 0.0796 \times \left(\frac{1}{\varepsilon_t}\right)^{3.291} \times \left(\frac{1}{E_1}\right)^{0.854} \tag{1}$$

in which, ε_t is the horizontal tensile strain developed at the bottom of the layer of hot mix asphalt due to traffic loads and E_1 is the modulus of elasticity of the asphalt concrete. For the number of load repetitions to rutting failure (N_R), the following empirical model is suggested by Asphalt Institute [12]:

$$N_R = (1.365 \times 10^{-9}) \times \left(\frac{1}{\varepsilon_v}\right)^{4.477} \tag{2}$$

in which, ε_v is the vertical compressive strain developed at the top of the subgrade layer. In a deterministic analysis, if both N_F and N_R estimated for a certain pavement system are greater than the design traffic (in terms of the allowable number of standard axle repetitions, N_{lim}), no failure will occur; if either N_F or N_R is less than N_{lim}, the pavement failure is said to occur. In the deterministic analysis, the use of factor of safety (FS) can be defined as the ratio of estimated axle load repetition (the smaller of N_F and N_R) the over N_{lim}. The deterministic design can be realized through meeting the minimum required value, say 1.0.

The stress and strain levels induced by traffic loads can be estimated using various approaches such as elastic solution [13], finite element method [14], response surface method [15]. With the estimated horizontal tensile strain (ε_t) and the vertical compressive strain (ε_v), the number of axle load repetition to failure (N_F and N_R) can be readily estimated using Eqs. (1) and (2). However, due to the uncertainty in those input parameters, a factor of safety greater than the minimum required value may not always guarantee safety. It is more rational to model those design parameters as random variables and perform the reliability-based design. The reliability-based pavement design can be realized through meeting the required reliability (R), or the equivalent probability of failure (p_f). The reliability-based pavement design in this study, the limit state function is built as follows:

$$g(x) = FS + \varepsilon - 1.0 \tag{3}$$