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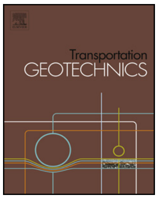

Incorporating spatial variability of pavement foundation layers stiffness in reliability-based mechanistic-empirical pavement performance prediction

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ABSTRACT

Adequate pavement quality and performance are critical for road users' safety, ride comfort, vehicle operation and travel delay costs, and vehicle durability. An accurate and robust pavement design is essential for realistic life cycle cost analysis, as well as overall management of the infrastructure. Compared to deterministic design methods, probabilistic methods are more realistic and can capture the inherent uncertainty in pavement and foundation materials; and loading conditions. In this study, spatial variability and systematic measurement errors in foundation layers' (including the base and subgrade layers) stiffness are incorporated in reliability-based mechanistic-empirical (ME) pavement performance models. Geospatial models are used to characterize both, the spatial variability and systematic measurement errors. To predict the long term pavement performance, the geospatial models were used to construct stochastic finite element (FE) models, which were then used to predict the performance based on the mechanistic-empirical pavement design guide equations (MEPDG). It is found that the typical covariance functions, also known as semivariograms or variograms, should be handled carefully when used in probabilistic performance modeling. Separating the inherent spatial variability from other uncertainties is necessary for performing risk and reliability analysis. Moreover, incorporating the inherent spatial variability in the stochastic FE models can alter the location of the critical response as described in the MEPDG.

Introduction

Adequate pavement performance is critically related to road users' safety, ride comfort, vehicle operation cost, travel delay cost, and vehicle durability [5,7,16]. A robust pavement design should allow for accurate and representative pavement performance predictions, which are essential to perform realistic life cycle cost analysis, and manage the infrastructure [14,36]. Pavement design can be framed either in a deterministic approach, where fixed loading and material conditions are assumed; or a probabilistic approach, where distributions of loading and material conditions are considered [21]. Compared to deterministic design approaches, probabilistic approaches are more realistic and representative of the varying and uncertain nature of pavements, foundation materials, and loading conditions [14,35].

In 1993, the American association of state highway and transportation officials (AASHTO) published a *Guide for Design of Pavement Structures* [1]. The empirical design equations presented in the guide, were derived based on the AASHO Road Test conducted in 1958-60 [15]. Despite the simplicity and practicality of empirical design methods, they are limited to the range of conditions used to derive the design relations [6]. Shortly after the release of the AASHTO 1993 design guide, researchers realized the need to utilize mechanistic-

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empirical (M-E) design methods [40]. M-E design methods can incorporate a wider range of varying design inputs. In 2004, the national cooperative highway research program (NCHRP) published the mechanistic-empirical pavement design guide (MEPDG). The guide provided consistent procedures that can be used as a nationwide design tool [28]. MEPDG, combines the virtue of mechanistic models, which are based on scientific models describing the pavement response to loading, and the empirical calibration that corrects for idealized mechanistic models assumptions [6].

Since the development of the AASHTO 1993 design guide, a reliability-based design approach was recommended to account for design uncertainties. Following the same concepts, and with the ability to consider a wider range of variables, reliability was introduced more extensively in the MEPDG. Despite the effort to incorporate a reliability approach in the MEPDG, design reliability was identified as one of the future needs to improve in the design guide [28]. In the past three decades, many studies have focused on implementing reliability-based M-E design [4,18,20,21,37]. Some of the earliest efforts to apply reliability concepts to pavement structural design were introduced in the 1970s [8,9]. Several studies have utilized reliability-based design methods to optimize flexible pavements design in terms of cost and performance [17,33,37]. Sanchez-Silva et al. [37], presented a reliability-based model to optimize the design of flexible pavements. In their study, it was concluded that reliability-based design optimization can incorporate other aspects besides the mechanical performance, such as construction and rehabilitation costs as well as financial factors including the discount rates, which are relevant to the decision making process.

Various methods have been developed to perform reliability analysis. Typically, reliability-based pavement design is performed using one of the following methods: Monte Carlo (MC) simulation method, point estimate method, first-order second-moment (FOSM) method, Hasofer-Lind first-order reliability method (FORM), and second-order reliability method (SORM) [3,13,20]. In the mentioned reliability methods, excluding the MC simulation method, the reliability index (β) is estimated first and then the probability of failure can be calculated using: $P_f = 1-\Phi(\beta)$, where Φ is the standard normal cumulative distribution function [25].

Alternatively, the MC simulation method derives the probability of failure by generating a large number of models representing the varying material and loading conditions, which makes it computationally expensive. However, MC simulation method is the most robust method since it does not impose assumptions on the distribution of the reliability index. Timm et al. [41] incorporated reliability analysis into the M-E design procedure, developed for Minnesota, by generating 5000 design scenarios for flexible pavements using MC simulations. Dilip et al. [10] performed system reliability analysis for a flexible pavement section designed using the M-E design method. Fatigue cracking and rutting were the failure mechanisms considered due to their significant contribution to flexible pavements performance. Reliability analysis was conducted and validated using FORM, SORM, and MC simulation method. In the study, it was shown that the two failure modes were highly correlated, with a correlation coefficient of approximately 0.80; therefore, the consideration of the joint probability of failure is crucial in the reliability analysis of the pavement system. Several studies have reported the validity of FORM and FOSM for reliability-based M-E flexible pavement design in comparison to the MC simulation method [25,26].

Amongst the uncertainties and variabilities in the pavement design inputs is the foundation conditions variability, such as stiffness [21]. There is a prominent evidence that non-uniform or varying foundation conditions have significant impact on the pavement performance [22,23,24,34,39,42,45]. Several researchers have attempted to quantify and model the spatial variability of the foundation conditions. Phoon and Kulhawy [31,32] presented their extensive investigations on geotechnical uncertainties in two papers. In the papers, it was indicated that the sources of uncertainty in geotechnical properties are due to inherent spatial variability, measurement error, and transformation uncertainty (i.e., model bias). Lua and Sues [23] presented one of the earliest efforts to assess the reliability of airfield pavement response and life prediction using a stochastic finite element (FE) with the inclusion of spatial variability. In their study it was mentioned that probabilistic FE models, with spatial variability, are more accurate representation of the true physical condition, and that research is needed to explore the effect of three-dimensional random spatial variability on pavement response and life. Dilip and Babu [10] generated spatially correlated random fields, following a Latin Hypercube sampling technique, to represent a three layers pavement system; namely AC, base, and subgrade layers. The random fields were then used in finite difference simulations to quantify the pavement response and design reliability at varying conditions. From the study it was concluded that ignoring spatial variability can lead to inaccurate assessment of the pavement performance.

With the recent developments in intelligent compaction (IC), assessing the stiffness of foundation layers with high coverage became a possibility [38,43,47]. Savan et al. [38] presented a benefit-cost analysis on the application of intelligent compaction for transportation construction. The benefit-cost analysis demonstrated that the use of IC reduces compaction costs by as much as 54% and results in a US $15,385 annual savings per 1.6 km throughout the roadway's life. IC technology provides a spatial map of response measures such as machine drive power (MDP), compaction meter value (CMV), and vibratory modulus (E_{VIB}). These measures correlate to the stiffness of the compacted materials. The correlations between the material stiffness and IC measures are variable and project site dependent [46]. One of the questions remains unsolved: how to incorporate the dense data acquired using IC technologies into pavement design or performance prediction [48].

Significant efforts have been carried to address the impact of foundation conditions uncertainty on the pavement performance and design. However, there is a very limited number of studies that could successfully incorporate the impact of spatial variability into reliability-based M-E pavement performance prediction, which controls pavement design. Moreover, there are no clear definitions or procedures describing the process to include different sources of uncertainty in reliability-based pavement performance prediction and design. In this study, a detailed discussion on the uncertainty in foundation conditions will be presented. Furthermore, a mathematically robust procedure to incorporate these uncertainties into reliability-based M-E flexible pavement performance prediction models will be outlined. MC simulations will be implemented to generate stochastic FE models based on actual data acquired from a previous IC study [46]. Due to the limited information provided on the correlation between IC measures and stiffness measures, the implementation will focus on the impact of inherent spatial variability and measurement errors.

Data sources

To incorporate the impact of spatial variability in foundation layers' stiffness on flexible pavement performance, spatial statistics will be utilized to characterize that variability. In this paper, the term foundation layer includes the granular aggregate base/subbase and the subgrade layers. The foundation conditions were simulated based on the results provided in White et al. [46]. In 2009, a research team from Iowa State University performed field testing on the US219 project located near Springville, New York to evaluate Caterpillar and Bomag single drum IC rollers. In their report, test bed 1 (TB1), consisted of compacted embankment granular subgrade material with plane dimensions of approximately 18 m × 200 m. The embankment material was underlain by shredded rubber tires at depths < 1 m below grade. The area was divided into eight roller lanes and compacted with three roller passes using the Caterpillar IC roller. MDP_{40}, a rescaled version of