Technical Note

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Incorporation of Subgrade Modulus Spatial Variability in Performance Prediction of Flexible Pavements

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Abstract: Recent efforts under the auspices of the National Cooperative Highway Research Program (NCHRP) have resulted in the development of a Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. The recently developed Mechanistic-Empirical Pavement Design Guide (MEPDG) employs an iterative procedure for accumulating damage over the entire design period. It follows by mechanistically computing the pavement response (i.e., stresses and strains) and empirically translating these responses into individual distresses and pavement roughness. In the current procedure, the subgrade is divided into several sublayers, and an average modulus is used to define the mechanical behavior of each sublayer, without any consideration of the spatial variability in the subgrade modulus. This paper aims to evaluate the effect of such variability on the overall performance of flexible pavements. To achieve this objective, actual field data were collected and analyzed to determine the frequency distribution of the subgrade modulus, which was incorporated in three-dimensional (3D) finite element models of typical flexible pavement structures. The response obtained from the 3D finite element analysis was used to predict the pavement performance using the MEPDG transfer functions. The results of this study showed that the higher the variability is in the subgrade resilient modulus, the higher the variability is in the pavement response. Furthermore, the effect of the spatial variability in subgrade modulus was more pronounced on the prediction of rutting than that of the fatigue cracking.

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Key words: *Finite element modeling; Mechanistic-empirical pavement design; Pavement performance; Probabilistic modeling; Subgrade stiffness variability.*

Background

Various numerical methods have been utilized to analyze the mechanical response of flexible pavement structures. Among these methods, the layered elastic analysis method is the most commonly used. However, this method is based on the assumption that the material property within each layer is homogeneous. Therefore, this method is incapable of modeling the spatial variability in the subgrade stiffness. This can be accomplished using an alternative numerical method that is the finite element analysis.

Several researchers have conducted finite element studies to investigate the effect of base and subgrade materials on the performance of flexible pavements. For instance, Dondi [1] developed a static three-dimensional finite element model using a commercial package named ABAQUS. In his model, Dondi [1] simulated granular bases by utilizing the Drucker-Parger elastoplastic model and the subgrade layer as Cam Clay elastoplastic strain hardening. In addition, Tutumluer and Thompson [2] developed a cross-anisotropic nonlinear elastic finite element model to compare the response with the linear elastic analysis for the granular bases. Tutumluer and Thompson [2] concluded that the anisotropic model resulted in lower tensile stresses when compared to the linear isotropic approach. Udin and Ricalde [3] have developed a three-dimensional finite element model to simulate microcrack initiation and propagation. In their model, they simulated the pavement layer as a viscoelastic material and the base and subgrade were simulated as linear elastic materials, which resulted in better of pavement behaviour. Furthermore, Zaghloul and White [4] developed a three-dimensional finite element model in which the asphalt pavement layer was simulated as a viscoelastic material, the base was simulated using the Drucker-Prager model, and the subgrade was simulated using the Cam Clay model.

The previous studies incorporated different constitutive models to simulate the behavior of the subgrade layer. However, they did not address the impact of the inherent variability in material properties within this layer on the performance of flexible pavement structures. The effect of such variability is investigated in this paper through the use of three-dimensional finite element models to analyze the stress-strain response of the pavement structure and to characterize fatigue cracking and permanent deformation using the MEPDG permanent deformation and fatigue cracking models.

Determination of Field Stiffness Distribution

To determine the most suitable distribution of subgrade stiffness values, resilient modulus data were collected from eight different sites, as shown in Table 1. This data was then used to generate probability plots using various potential distributions that included Normal, LogNormal, Exponential, and Weibull distributions. A goodness-of-fit test was then conducted to determine the most

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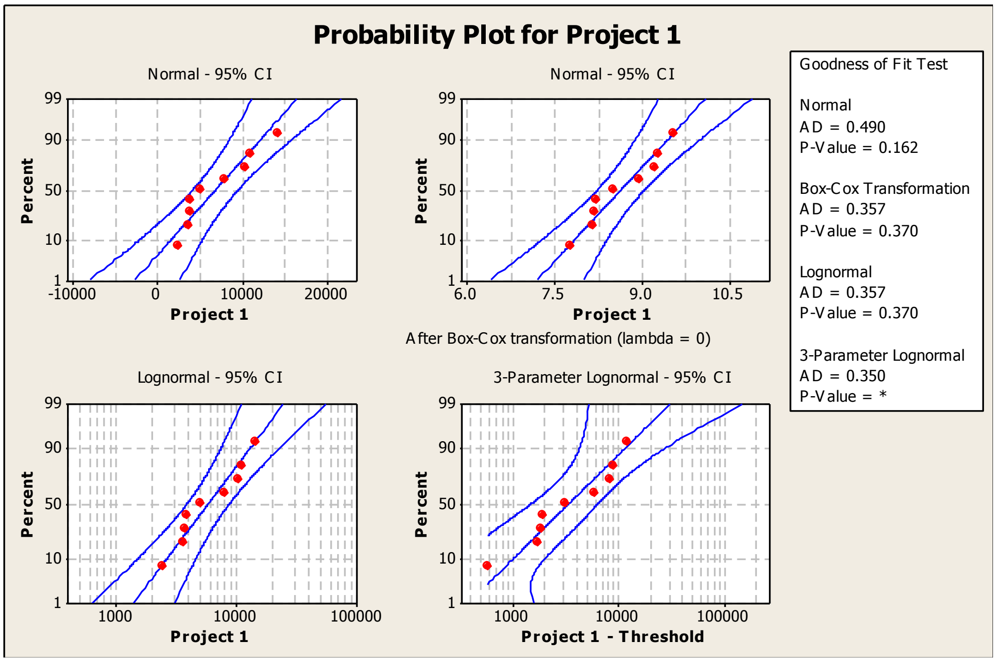
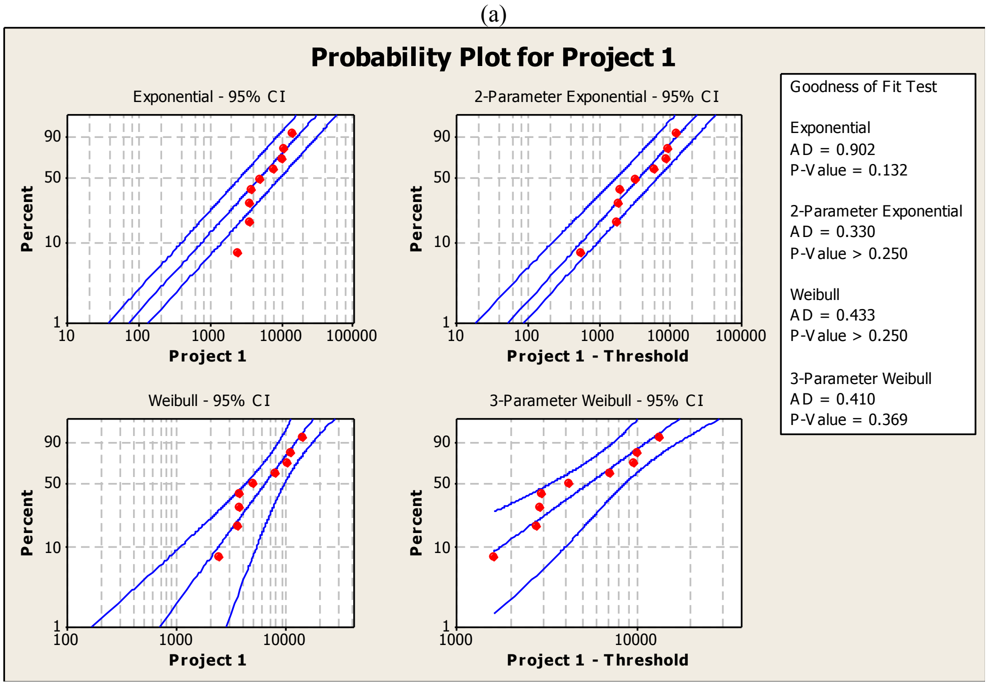
Table 1. Field Collected Subgrade Stiffness Values (ksi)*.

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
2.4	3.8	9.4	4.1	6.9	4.3	6.4	9.4
3.5	3.6	13.4	4.9	5.0	4.3	9.4	13.4
3.7	4.7	6.4	5.1	6.4	4.2	13.4	6.4
3.7	3.9	12.5	13.3	6.3	5.7	11.3	12.5
7.8	5.5	11.3	13.1	4.1	5.8	11.3	11.3
5.0	4.2	11.3	14.2	3.2	5.9	12.5	11.3
14.1	2.9	8.6	10.2	4.1	4.6	8.0	8.6
10.8	3.4	8.0	13.3	7.8	4.6	8.9	8.0
10.3	2.8	8.9	14.2	5.0	4.4	8.6	8.9

* 1 ksi = 6.9 MPa



(a)



(b)

Fig. 1. Probability Plots for Site 1 Data.

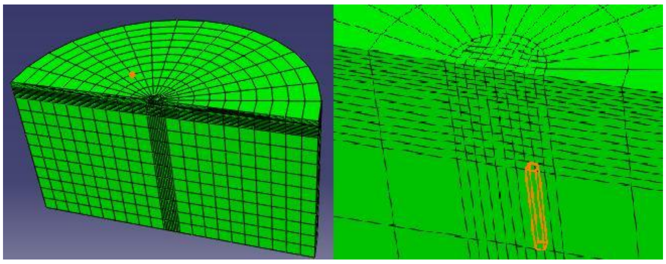


Fig. 2. Cross-sectional View of the Finite Element Mesh.

Table 2. Material Properties Used for Each Layer

Layer	Elastic Modulus, E ksi (MPa)	Poisson's Ratio, ν
Asphalt Layer	400 (2760)	0.35
Base Layer	20 (138)	0.45
Subgrade Layer	Variable*	0.45

* LogNormal Distribution with mean of 5 ksi (34.5 MPa) and three standard deviations of 0.75, 1.5, and 4.5 ksi (5.2, 10.3, and 31 MPa), having a maximum and a minimum stiffness values of 2 and 14 ksi (13.8 and 96.5 MPa), respectively.

suitable distribution representing the data. Fig. 1 shows a sample of the probability plots generated for the data collected from site one. This figure shows that the most suitable distribution fitting the data is the LogNormal distribution, since it has the highest p-value when compared to the other distributions considered. A similar observation was seen in the probability plots of the other sites. Therefore, the LogNormal distribution was selected and used as the basis for analysis.

Finite Element Model

A three-dimensional finite element model was developed to simulate the layered pavement structure using a commercial finite element package called ABAQUS. The development of the model was accomplished in two stages. The first stage involved the development of a linear elastic three-dimensional finite element model, which was verified using a layered elastic analysis software called EverStress. The second stage involved assigning different subgrade stiffness values to the various elements within the subgrade layer to obtain a lognormal distribution. Although the three-dimensional analysis would require more time than the two-dimensional analysis, the two-dimensional analysis is incapable of simulating the spatial variability in subgrade stiffness. Therefore, the latter was not used in this study.

Model Geometry

Fig. 2 shows the three-dimensional finite element model used in this study. The flexible pavement structure was modeled as a cylinder having a radius of 100 inches (2.5 m). The model consisted of three layers, including a 4-inch (0.1-m) asphalt layer, an 8-inch (0.2-m) base layer, and a 100-inch (2.5-m) subgrade layer. The height and radius of the model were selected to ensure minimal error resulting from the boundary conditions located at the edge surfaces of the cylinder, while keeping the model size manageable in terms of computation time and storage.

Boundary and Loading Conditions

Two types of boundary conditions were used in the analysis. The first type was roller supports constraining the edges of the model, while the second type was a fixed a support constraining the bottom of the model.

A 9000 lb (40 kN) load with a tire pressure of 80 psi (552 kPa) was adopted in this study. This load level corresponds to one side of the 18,000 lb (80 kN) standard axle load. The actual tire loading imprint was simulated as a circle with uniform pressure distribution.

Material Properties

A linear elastic model was used for all three asphalt, base, and subgrade layers. Table 2 shows the elastic properties used in the analysis. As can be seen from this table, constant elastic moduli were defined for the asphalt and base layers. However, the elastic properties of the subgrade layer were randomly varied using three different lognormal distributions having a mean of 5 ksi (34.5 MPa) and a standard deviation of 0.75, 1.5, and 4.5 ksi (5.2, 10.3, and 31 MPa). These standard deviations were selected to account for different soil variability levels.

Meshing

Fig. 2 shows a cross-section of the mesh. A total of 2,912 elements were used in the asphalt layer, 3,328 elements were used in the base layer, and 4,160 elements were used in the subgrade layer. All elements were 3D, 8-node block elements (C3D8R).

Pavement Performance Prediction

Upon the completion of the 3DFEM analyses, the MEPDG equations were used to predict the performance of the selected pavement structure with regard to permanent deformation and fatigue cracking. The permanent deformation of the pavement structures was determined by first dividing each pavement layer into sub-layers. Damage models were then used to relate the vertical compressive strain, computed from the 3DFEM analysis, at the mid-depth of each sub-layer and the number of traffic applications to layer plastic strains. The overall permanent deformation was computed using Eq. (1) as sum of permanent deformation for each individual sub-layer.

$$PD = \sum_{i}^{NS} \varepsilon^{i}{}_{p} \cdot h^{i} \tag{1}$$

where

PD = Pavement permanent deformation

NS = Number of sub-layers

$\varepsilon^{i}{}_{p}$ = Total plastic strain in sub-layer i

h^{i} = Thickness of sublayer i

Three main damage models were used in this study; one for the asphalt concrete material (Eq. (2)), one for the base (Eq. (4)), and one for subgrade materials (Eq. (5)). The parameters of these models were determined through national calibration efforts using the Long-Term Pavement Performance (LTPP) database and laboratory tests conducted on the different pavement materials used.

$$\frac{\varepsilon_p}{\varepsilon_v} = k_1 10^{-3.4488} T^{1.5606} N^{0.473844} \text{ (Asphalt concrete layer)} \qquad (2)$$

where
ε_p = accumulated plastic strain at N repetitions of load
ε_v = vertical strain of the asphalt material
N = number of load repetitions
T = pavement temperature
k_1=function of total asphalt layer(s) thickness and depth to computational point, to correct for the variable confining pressures that occur at different depths and is expressed as:

$$k_1 = \left(C_1 + C_2 * depth\right) * 0.328196^{depth} \qquad (3)$$

where
C_1= -0.1039*h_{ac}^2+2.4868*h_{ac}-17.342
C_2= 0.0172*h_{ac}^2-1.7331*h_{ac} - 27.428
h_{ac}= asphalt layer thickness

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_{BG}\left(\frac{\varepsilon_o}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \text{ (Base course layer)} \qquad (4)$$

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_{SG}\left(\frac{\varepsilon_o}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \text{ (Subgrade layer)} \qquad (5)$$

where
β_{GB} = national model calibration factor for unbound base course material and is equal to 1.673
β_{SB} = national model calibration factor for subgrade material and is equal to 1.35
ε_0, β, and ρ = material parameters
ε_r = resilient strain imposed in laboratory test to obtain material properties

The other major distress type that was considered in this study was fatigue cracking. The model used in this study for the prediction of the number of repetitions to fatigue cracking was the national field calibrated model adopted in the MEPDG that was determined by numerical optimization and other modes of comparison. This model is expressed as follows:

$$N_f = 0.00432 \cdot k_1 \cdot C\left(\frac{1}{\varepsilon_t}\right)^{3.9492}\left(\frac{1}{E}\right)^{1.283} \qquad (6)$$

where
N_f = traffic repetitions to AC fatigue
ε_t = resilient horizontal tensile strain from the response model taken as the maximum tensile value with the AC layer
C = a laboratory to field adjustment factor
E = AC complex modulus used in the response model (psi)
k_1 = correction factor to adjust for AC layer thickness (h_{ac}) effects and can be expressed in the following form:

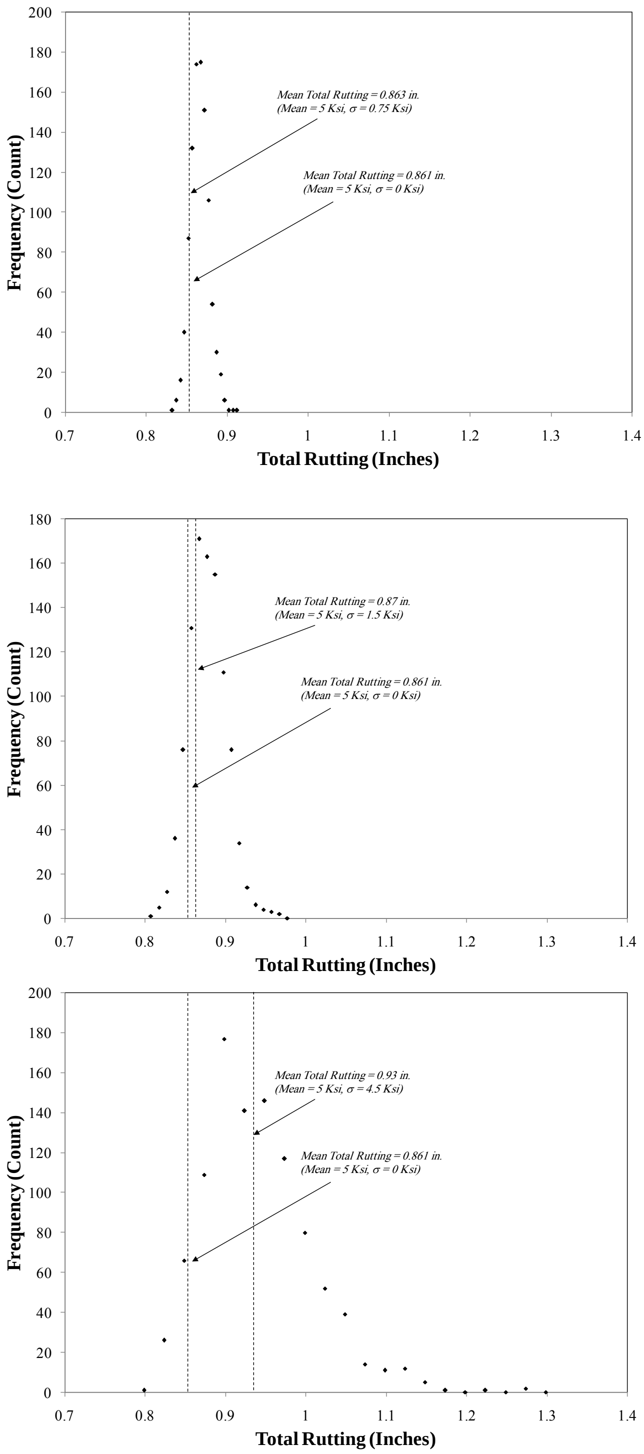


Fig. 3. Distribution of MEPDG Predicted Total Rutting.

$$k_1 = \frac{1}{0.000398 + \dfrac{0.003602}{1 + e^{\left(11.02 - 3.49 h_{ac}\right)}}} \qquad (7)$$

Results and Discussion

Figs. 3 and 4 show the distributions of the permanent deformation

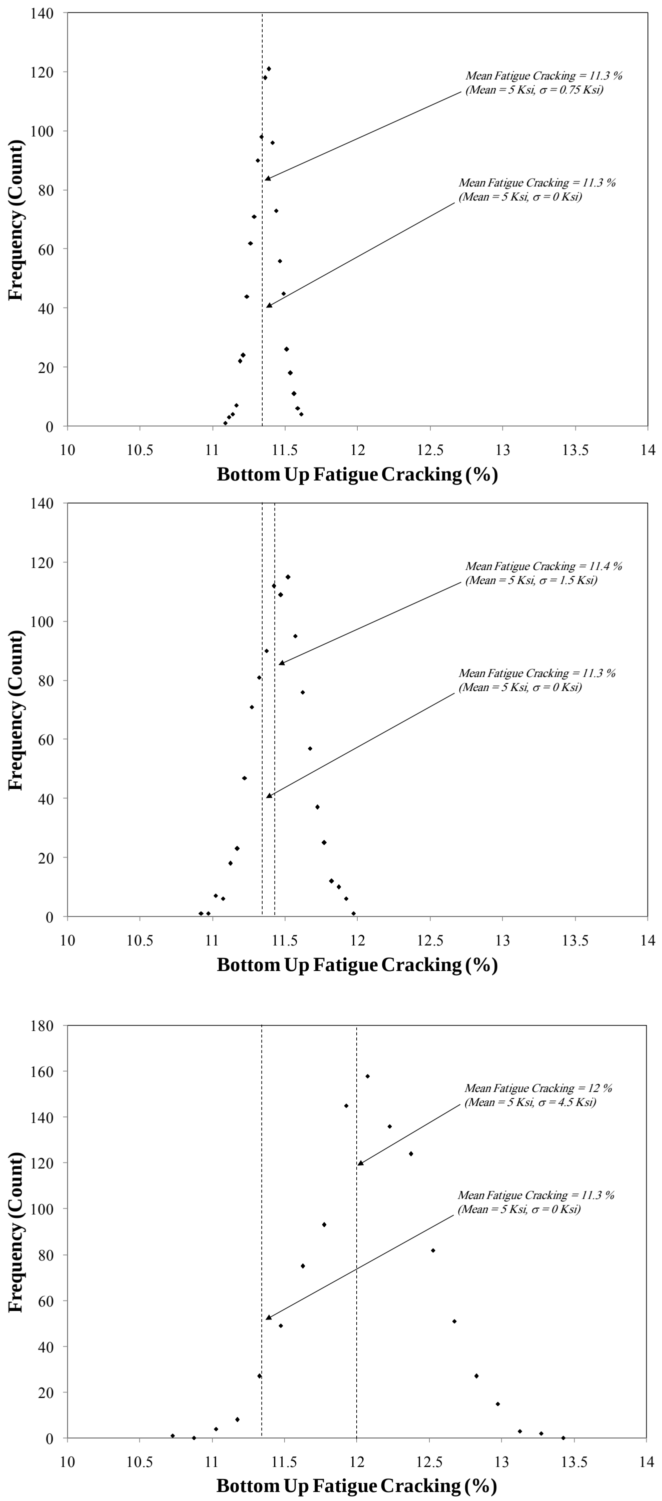


Fig. 4. Distributions of MEPDG Predicted Bottom-Up Fatigue Cracking.

and fatigue cracking predicted using the MEPDG procedure discussed previously. It can be seen from these figures that the higher the variability in the subgrade stiffness values, the higher the variability in the predicted performance values. Furthermore, Figs. 3 and 4 show that the variability in the permanent deformation is higher than that in fatigue cracking. This is expected since the subgrade stiffness was varied while the asphalt and base layers were kept constant. Another observation that these figures show is that although a lognormal distribution was used to generate the used stiffness values at all standard deviations considered, the distribution of the predicted fatigue cracking was closer to a normal distribution.

Summary and Conclusions

This paper presented an approach to examine the effect of the spatial variability in subgrade stiffness on the performance of flexible pavements. Three-dimensional finite element models were utilized to simulate the behavior of the layered pavement structure, and to account for the stiffness variability within the subgrade layer. The finite element models were used to determine certain tensile and compressive strains. The corresponding permanent deformation and fatigue were then estimated using the Mechanistic-Empirical Pavement Design Guide (MEPDG) models.

The following conclusions were drawn from the analysis results:

- The higher the variability is in the subgrade stiffness, the higher the variability is in the pavement response.
- The effect of the spatial variability in subgrade stiffness is more pronounced on the rutting life than on the fatigue life of flexible pavements, as predicted using the MEPDG models.

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