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Probabilistic and Mechanistic Approaches for Pavement Analysis

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ABSTRACT---- ***The pavement material properties have the variability during the construction process. and this realistic situation should be considered in the pavement analysis. In this study, the stochastic finite element is developed to investigate the effect of design parameters variability to pavement structural and performance analysis, and the mean and variance of pavement distress are computed. In order to verify the proposed method, the LTPP database developed by FHWA in the United State is used. The statistical parameters of material properties are backcalculated from FWD test data, and the LTPP database developed by FHWA in the United State were used to find the statistical parameters of pavement. Then, the average and the variance of the response parameters such as displacements and stresses are computed, and the statistical parameters of pavement distress under traffic loading are also calculated.***

Keywords--- Pavement Reliability Design, Stochastic Finite Element, Rutting, Fatigue cracking

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1. INTRODUCTION

The applicability of risk and reliability in engineering analysis, design, and planning has been accepted through out the world. Due to the variability of pavement materials in the pavement system, the probabilistic method had been considered in the pavement design methods (Kenis, 1977). However, these methods were based on mechanistic-empirical or statistical approaches. It is necessary to use more rational approach to consider the uncertainties of the materials properties in the pavement system based on mechanistic approach. The stochastic computation techniques are the better ways to deal these kinds of problems. There are different methodologies are adopted for the structural and pavement response uncertainties , and some stochastic finite elements had also been used in the pavement analysis . Among these methods, the Monte Carlo simulation (Astill et al., 1972) is the most simple approach to incorporate with the finite element method. In this study, the stochastic finite element method using the Monte Carlo Simulation is developed for the pavement analysis, and this approach had been verified with the perturbation finite element (Liu *et al*., 2010).

The statistical properties of pavement materials are obtained from the LTPP test pavement sections which are based on the Federal Highway Administration's Long-Term Pavement Performance program. In this program, a wealth of information has been collected which can benefit global highway researchers and organizations (LTPP, 2004). Since the LTPP data are of good quality and include complete information from the test pavement site, it can be used for model verification and performance analysis. The LTPP information is readily available for the researchers and highway design agencies via Data Pave at the FHWA website. In this study, the four test sites from the LTPP test sections are selected for the backcalculation which are based on the FWD test data for the different drop weights and locations, and the mean and variance of material properties for each pavement section are computed. Then the effect of the variation layer properties of pavement on the structural analysis are studied. Finally, the results of the stochastic finite element analysis are incorporated with the distress model to compute the mean and variance of the disstress of pavement under the traffic loading.

2. THE STOCHASTIC PAVEMENT ANALYSIS

A two-dimensional axisymmetric finite element program developed by Owen and Hinton(Owen et al., 1981) are incorporated with Monte Carlo simulation to form the stochastical pavement analysis program. This program includes the structural analysis and performance analysis procedures. The flow chart of the stochastic pavement analysis program is shown in Figure 1. At first, the statistical parameters of material properties are obtained from the backcalculation of FWD test. From the mean and variance of material properties, the Monte Carlo simulation are conducted to obtain N groups of layer material properties of pavement, then the pavement analysis program are conducted N times for structural and performance analysis. Finally, the expectation and coefficient of variation of displacement and rutting are evaluated. The results of these data can be used for the reliability analysis of pavement (Achintay et al., 2000).

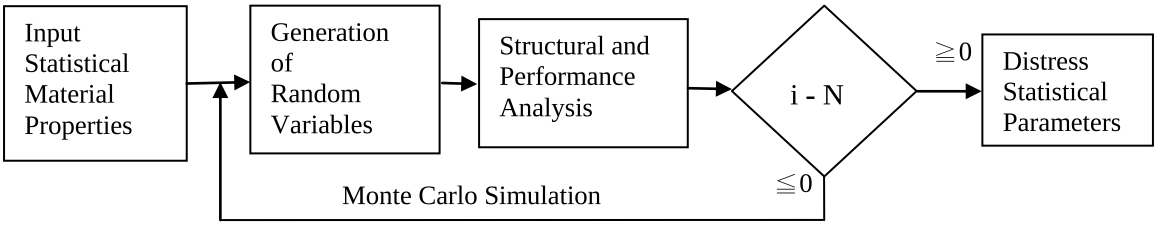


Figure 1. The flow chart of stochastic pavement analysis program

In the following, the models used in stochastic analysis of pavement are introduced for structural and performance analysis. The material properties model used in the finite element program is the two- parameter model which is the simplified from developed by Uzan (Uzan, 1999), and it can represent the behavior of the pavement material. The two-parameter model is expressed as:

$$E = (k_1 P_a)\left(\frac{I_1}{P_a}\right)^{k_2} \tag{1}$$

in which Pa is the atmospherical pressure, I_1 is the first invariant of stress tensor, and k_1 to k_2 are the material constants. The Poisson's ratio of material is assumed as constant. One of the most popular models to represent permanent deformation characteristic of the pavement materials under repeated loading is the linear relationship between the plastic strain and the number of repetitions on a log-log scale. This linear relationship can be defined by its intercept, μ at load cycle 1 and its slopes, and the plastic strain, ε^P, can be written as:

$$\log \varepsilon^P(N) = \log \mu + s \log N \tag{2}$$

In this equation, the μ and s are the material properties. However, it has been shown that μ is dependent on the state of stress (Behzadi et al., 1996), and the s is related to the state of stress. In this study, the Vermeer plasticity model (Vermer, 1982) is used to compute the plastic strain μ at the first cycle of loading of pavement material. The slope can be obtained from the repeated loading test such as dynamic creep test or dynamic triaxial test. Fatigue cracking is the phenomenon of repetitive load induced cracking. In this study, the number of load repetitions for fatigue cracking, N_f , is the sum of the number of load cycles to crack initiation, N_i , and crack propagation, N_p, and it can be expressed as:

$$N_f = N_i + N_p \tag{3}$$

The crack initiation is based on the microfracture model, and it had been used in the fatigue cracking in the LTPP test section. The crack propagation model is based on the Paris' crack growth law as shown in the following equation.

$$N_p = \frac{1}{A}\int_{c_0}^{h} \frac{dc}{\Delta K^n} \tag{4}$$

where, N_p is number of load repetitions to propagate a crack of initial length c_0 to the surface, h is the layer thickness.; c_0 is the initial crack length,; K is stress intensity factor, and A, n is the fractural mechanics material properties.

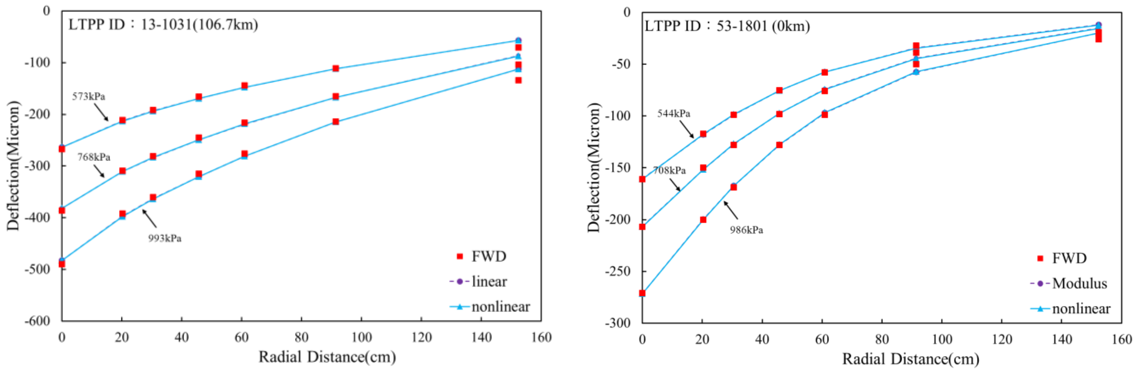
3. THE PROBABILISTIC PARAMETERS OF PAVEMENT MATERIALS

The field material properties for the proposed model were obtained from the FWD (Falling Weight Deflectometer) tests. The two test sites from the LTPP test sections are selected for the backcalculation, and those pavement sections structural information are shown in Table 1. The developed nonlinear finite element program is incorporated with the optimization scheme to backcalculate the nonlinear material properties of test pavement sections. The initial guess of the material properties is obtained first from the linear backcalculation program Modulus. It should be noted that the asphalt concrete material is assumed to be nonlinear model, and the rest of layers are linear model. In the following, the pavement material properties are obtained for the test pavement sections on which the FWD tests were conducted. For each pavement section, the Falling Weight Deflectometer tests were conducted on three different locations, and there are three different drop harmer weights. Table 2 show the material properties obtained from FWD tests for 2 LTPP test sections. The predicted deflections from the backcalculated properties are also compared with FWD test data and the results are shown in Figure 2. The results show the predictions are close to the measured test data for all these LTPP test sections, and the results from the nonlinear model are better than the results from the Modulus model. Since there are 9 groups of material properties for each test pavement section, the mean and coefficient of variation are computed for each test section as shown in the last two rows of Table 2. From these results, it can be seen that the coefficient of variation of the pavement material properties varies from 5.9% to 30.6%.

From above study, it shows that there is the variation of the material properties for each test pavement section, and their effects on the pavement structural and performance analysis will be investigated in the following section.

Table 1. Pavement information for two LTPP test sections

LTPP ID	AC(cm)	Base(cm)	Subgrade(cm)
13-1031	29.2	22.3	∞
53-1801	23.4	9.4	∞



(a) 13-1031 at 106.7km (b) 53-1801 at 0km

Figure 2. The backcalculation and FWD data for ID 13-1031 and ID 53-1801

Table 2. The material properties for pavement sections ID 13-1031 and ID 53-1801

13-1031						53-1801					
LOC	Load (kPa)	k_1	k_2	E_2 (MPa)	E_3 (MPa)	LOC	Load (kPa)	k_1	k_2	E_2 (MPa)	E_3 (MPa)
106.7 km	585	10570	0.21	554	71.1	0 km	544	15480	0.182	417	255
	756	10480	0.20	526.5	62.9		708	15295	0.189	417	258
	1036	11180	0.21	490.9	63.1		986	13860	0.238	331	279
114.3 km	589	10050	0.20	531.6	63.5	61 km	552	21735	0.285	315	153
	769	10230	0.20	492	55.7		709	20865	0.304	314	152
	1023	10700	0.21	511.3	56.7		990	21425	0.307	309	159
152.4 km	592	12340	0.23	579.5	58.2	114.3 km	553	17870	0.279	304	147
	759	12160	0.23	534.2	51.6		711	17005	0.295	297	142
	1036	11770	0.24	609.7	51		985	18090	0.286	302	146
Ave.		11053	0.21	537	59	Ave.		17958	0.263	334	188
CV (%)		7.7	5.9	7.3	10.2	CV (%)		16.0	18.3	14.4	30.6

Ave.: Average CV=Coefficient of Variation

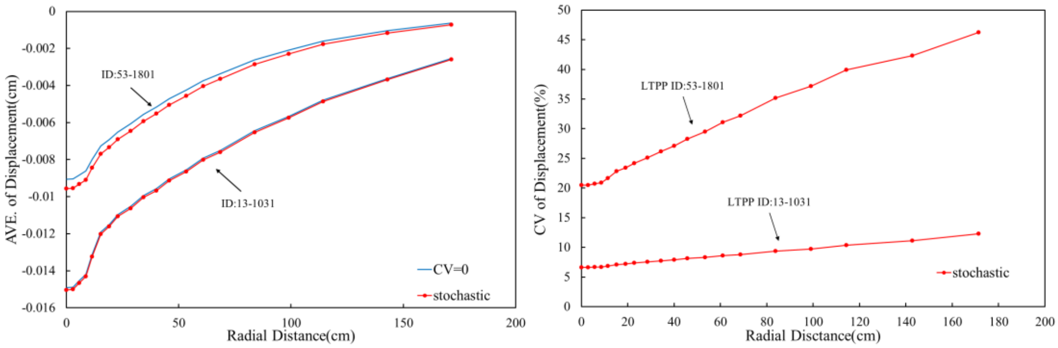
4.THE EFFECT OF MATERIAL VARIATION TO PAVEMENT PERFORMANCE

It’s important to investigate the effect of material variation to pavement response. The four pavement sections selected from LTPP database are analyzed. The loading information is based on dual wheel loads which the radius and tire pressure are 10.7cm and 483kPa for pavement analysis. The statistical parameters of material properties as shown in Tables 2 are used for the pavement structural and performance analysis. The number of Monte Carlo Simulation to generate the material properties should be determined before the pavement analysis. The Monte Carlo finite element solutions of pavement displacements were obtained using 100, 200, 400 and 1000 sets material properties which were generated based on normal distribution, From the convergent study the means and coefficient of variation of displacements are close when the number of simulation is greater than 400 sets. In the following study, the Monte Carlo solutions were obtained using 400 sets of material properties, and the average and coefficient of pavement response parameters are computed due to the variation of the material properties.

The effect of material variation to pavement structural and rutting analysis for four LTPP test sections are analyzed in the following. Figure 3(a) shows the expected values of surface vertical displacements on the radial direction for ID 13-1031 and ID 53-1801, and the results are compared with the displacements which the coefficient of variation is zero. The largest relative difference of percent are 1% and 5.5% with and without considering the material variation for ID 13-1031 and ID 53-1801. From Figure 3(b), the coefficient of variation of vertical surface displacement is 20% at the center of loading and it increases with the radial distance for ID 53-1801, and the coefficient of variation of vertical surface displacement is 15% at the center of loading, and the value is decreased with the radial distance.

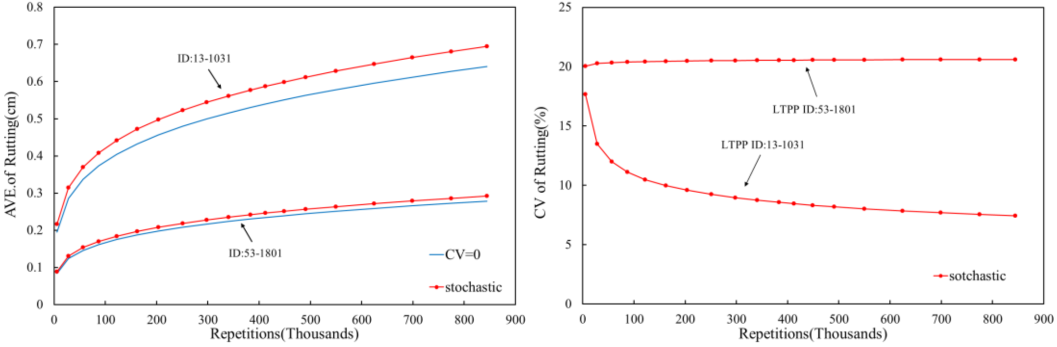
The stresses from the structural analysis are used for the rutting and fatigue cracking computation, and the expected values and the coefficient of variation of rutting with the number of traffic loading are calculated. Figure 4 is the effect of material properties to the rutting of pavement under the traffic loading for ID 13-1031 and ID 53-1801. It can be seen that the largest relative difference with and without considering the material variation is 5.38% for ID 53-1801, and the coefficients of variation are 17% and 20% for ID 13-1031 and ID 53-1801 at the center of loading. It also shows that there is a little effect for the coefficients of variation of rutting with the number of load repetition for ID 53-1801.

In the fatigue cracking analysis, the resilient modulus of pavement were backcalculated from FWD tests, and the fracture mechanics properties A and n were obtained from the repeated shear tests. The effect of material variation to the fatigue cracking for ID 13-1031 and ID 53-1801 is shown in Figure 5, and the cracked area of pavement with the material variation is greater than that without material variation about 12% for ID 13-1031, and the difference is small for ID 53-1801. It also shows that the number of crack initiation is small for considering the material variation.



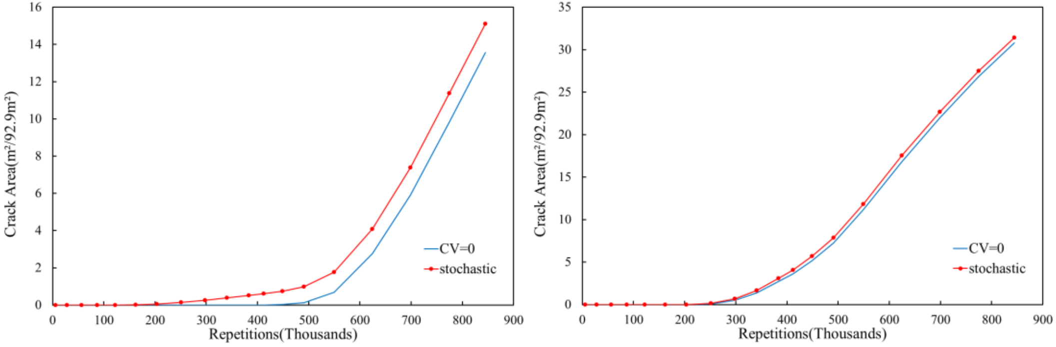
(a) average
(b) coefficient of variation

Figure 3. The effect of material variation to the vertical surface displacement



(a) average
(b) coefficient of variation

Figure 4. The effect of material variation to the rut depth for LTPP test sections



(a) ID13-1031
(b) ID 53-1801

Figure 5. The effect of material variation to the fatigue cracking for LTPP test sections

5. CONCLUSION

In this study, the stochastic finite element program is developed and applied to the reliability based pavement performance analysis. The important results from this study can be summarized:

1. From the backcalculation analysis of four LTPP test sections, the results show that the coefficient of variation of material properties varies from 8.7% to 30.6%, and these values should be considered in the pavement analysis.

2. In the structural analysis, the largest relative difference of expected value of displacement with and without considering material variation is 5.5%, and the maximum coefficient of variation of vertical surface displacement is 20% at the center of loading.
3. From the rutting analysis, the largest relative difference of expected value of rutting with and without considering material variation is 6%, however the coefficient of variation for rutting can reach to 53%. Based on the above results, it can be seen that the material variation has effect on the pavement response.
4. In the fatigue cracking, the fatigue cracking area is greater with the material variation than that of without material variation, and the number of crack initiation is smaller for considering the material variation.

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