한국도로학회 논문집
第11券1號 2009年 3月
pp. 165 ~ 175

The Response Prediction of Flexible Pavements Considering Nonlinear Pavement Foundation Behavior

비선형 포장 하부 거동을 고려한 연성 포장의 해석

김 민 관*
Minkwan Kim

요 지

역학적 경험적 포장 설계법을 도입하려는 현재의 연구추세에 발 맞추어 정확한 응력, 변형률, 변형을 기초로 포장구조체를 해석하기 위한 역학적 접근방법이 필요한 시점이다. 기존의 실험결과에 따르면 연성포장 구조의 기층에 이용되는 자갈과 노상층에 이용되는 노상토등의 포장 하부재료는 반복하중 조건하에서 비선형 회복탄성계수의 특징을 따르는 것으로 나타났다. 이 비선형 거동은 재료의 현재 응력에 의한 회복탄성계수 모델로 나타나질 수 있으며 정확한 해를 구할 수 있는 역학적 방법중의 하나인 유한요소 해석 방법에 적용되어 질수 있다. 이 연구에서는 비선형 해석기법과 효과적인 해 수렴기법이 구현된 재료 모델 부 프로그램을 범용 유한요소 프로그램의 하나인 아바쿠스에 적용시켰다. 이 수치해석 방법에는 더 정확한 해를 찾기 위한 체눈분할에 의해 만들어진 유한요소 모델이 이용되었다. 이런 일련의 방법들에 의한 포장구조체의 해석결과, 2차원과 3차원 비선형 유한요소 해석의 결과가 큰 차이를 보이는 것으로 나타났다. 또한, 사용된 부 프로그램은 미연방 항공국 공항 시험포장에서 측정되어진 결과값에 의해 비교 검증되었다.

핵심용어 : 비선형 유한요소 해석, 연성포장, 포장기초, 회복탄성계수

Abstract

With the current move towards adopting mechanistic-empirical concepts in the design of pavement structures, state-of-the-art mechanistic analysis methodologies are needed to determine accurate pavement responses, such as stress, strain, and deformation. Previous laboratory studies of pavement foundation geomaterials, i.e., unbound granular materials used in base/subbase layers and fine-grained soils of a prepared subgrade, have shown that the resilient responses followed by nonlinear, stress-dependent behavior under repeated wheel loading. This nonlinear behavior is commonly characterized by stress-dependent resilient modulus material models that need to be incorporated into finite element (FE) based mechanistic pavement analysis methods to predict more realistically predict pavement responses for a mechanistic pavement analysis. Developed user material subroutine using aforementioned resilient model with nonlinear solution technique and convergence scheme with proven performance were successfully employed in general-purpose FE program, ABAQUS. This numerical analysis was investigated in predicted critical responses and domain selection with specific mesh generation was implemented to evaluate better prediction of pavement responses. Results obtained from both axisymmetric and three-dimensional (3D) nonlinear FE analyses were compared and remarkable findings were described for nonlinear FE analysis. The UMAT subroutine performance was also validated with the instrumented full scale pavement test section study results from the Federal Aviation Administration's National Airport Pavement Test Facility (FAA's NAPTF).

Keywords : nonlinear finite element analysis, flexible pavement, pavement geomaterials, resilient modulus

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* Member, Corresponding Author · Indiana Department of Transportation · Highway Engineer

1. INTRODUCTION

Flexible pavement is one of the most frequently used pavement structures and its demand is increasing in this era. As a large quantity of flexible pavement is needed and applied loading is heavier, it is significantly important to know the accurate behavior of each layered structure. The various layers of pavement structure have different behavior and this behavior is one of the most difficult problems to solve in pavement analysis. Previous laboratory studies have shown that resilient responses for granular materials used in base/subbase and soils used in subgrade layer following a nonlinear, stress-dependent behavior under repeated traffic loading (Brown and Pappin, 1981; Thompson and Elliot, 1985). As the demand for applied wheel loads and number of load applications increases, it becomes very important to properly characterize the behavior of unbound granular material and subgrade soil layers as the foundation of the layered pavement structure.

The finite element (FE) program that analyzes pavement structures needs to employ this kind of nonlinear resilient characterization to more realistically predict pavement response with mechanics approach. Many general-purpose FE programs, such as ABAQUS, ANSYS, and ADINA, have been used to analyze pavement structure under applied wheel loadings. However, the most of them already used built-in material models without proper consideration of material behavior and this kind of analyses was not appropriate to predict accurate material behaviors in flexible pavement. Thus, efforts to employ nonlinear resilient behaviors, which are well demonstrated material characteristics, are needed in FE modeling of flexible pavement foundation geomaterials.

Research investigated in this study focuses on employing nonlinear resilient behaviors of geomaterials to general-purpose FE modeling using ABAQUS (HKS, 2005) for a mechanistic pavement analysis. The properly developed resilient response model is programmed in a user material subroutine (UMAT) of ABAQUS program and computes the correct geomaterial modulus in each layer as a function of applied stress state. This study also describes the FE modeling research efforts focused on using the both axisymmetric and three-dimensional (3D) nonlinear FE analyses for flexible pavements. The mechanistic based analysis and design can primarily deal with critical responses and performances of flexible pavement system.

2. PREVIOUS STUDIES

Many general-purpose finite element programs, such as ABAQUS, ANSYS, ADINA, etc., allow use of built-in nonlinear constitutive models. These models, however, have not been readily applicable to nonlinear pavement structural analyses. This is because these constitutive models often define material behavior as a function of strain state, which is more applicable to incremental tangent or incremental secant stiffness type

Table 1. Summary of Previous Studies

Researcher	Dimension	FE Program	Analysis Method	Material Models used in FE analysis
Zaghloul et al. (1993)	3D	ABAQUS	Nonlinear	Base Materials: Drucker-Prager model Subgrade soils: Cam Clay model
Hjelmstad and Taciroglu (2000)	3D	ABAQUS	Nonlinear	Base Materials: Uzan model and K-θ model
Schwartz (2002)	2D and 3D	ABAQUS	Nonlinear	Base materials: K-θ model
Saad et al. (2005)	3D	ADINA	Nonlinear	Base materials: Drucker-Prager model Subgrade soils: Cam Clay model

nonlinear analyses. As of now, several researchers have investigated the nonlinear pavement responses using this kind of general-purpose FE programs shown in Table 1.

Although they proposed that both axisymmetric and 3D FE models yield suitable results for pavement responses, the research capable to predict the accurate pavement geomaterial behavior is needed under various loading conditions for different material characteristics.

3. NONLINEAR MATERIAL MODELS

After construction and shakedown of pavement geomaterials with initial traffic loading, the permanent deformation accumulation per each cycle decreases to a minimum. Under the repeated application of wheel loads, most of the pavement deformations are then recoverable and thus considered elastic. The resilient material properties are one of the essential input variables to evaluate pavement structures using mechanistic concepts. It has been customary to use resilient modulus for the elastic stiffness of the pavement materials. This stiffness associated with the resilient response is the resilient modulus (M_R) defined by

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

where M_R is resilient modulus, σ_d is deviator stress, and ε_r is recoverable strain.

Therefore, materials for base/subbase and subgrade layer in this study are considered as nonlinearity. A proper resilient modulus model considers the effects of stress-dependency and is also suitable to FE programming and practical design use. Especially, the Uzan model (1985) considers the effects of both confining and deviator stresses and therefore handles very well the modulus increase with increasing stresses in an unbound aggregate layer. The Uzan model used in this study is expressed as follows:

$$M_R = K_1\left(\frac{\theta}{P_0}\right)^{K_2}\left(\frac{\sigma_d}{P_0}\right)^{K_3} \qquad (2)$$

where M_R is resilient modulus, $\theta=\sigma_1+\sigma_2+\sigma_3=\sigma_1+2\sigma_3$ = bulk stress, $\sigma_d=\sigma_1-\sigma_3$ = deviator stress, P_0 is the unit pressure, and K_1, K_2, and K_3 are multiple regression constants obtained from repeated load triaxial test data on granular materials.

Later on, Witczak and Uzan (1988) proposed the use of universal model developed from the Uzan (1985) model by replacing the deviator stress term with the octahedral shear stress, τ_{oct}. Since the universal octahedral shear stress model considers material characteristics in all three directions, i.e., x, y, and z directions, this model is more suitable to 3D FE pavement analysis.

$$M_R = K_1 P_a\left(\frac{I_1}{P_a}\right)^{K_2}\left(\frac{\tau_{oct}}{P_a}\right)^{K_3} \qquad (3)$$

where first stress invariant $I_1=\theta=\sigma_1+\sigma_2+\sigma_3$, $\tau_{oct}=1/3\{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2\}^{1/2}$, P_a is atmospheric pressure, and K_1, K_2, and K_3 are multiple regression parameters.

For the subgrade layer, the nonlinear soil behavior is also considered. Likewise granular material, the resilient modulus of fine-grained subgrade soil is dependent upon the current stress state. Typically, soil modulus decreases in proportion to the increasing stress levels thus exhibiting stress-softening type behavior. The constitutive relationships are primarily established between the resilient modulus and the deviator stress for fine-grained subgrade soils. The bilinear model (Thompson and Robnett, 1979) is the most commonly used resilient modulus model for subgrade soils. The bilinear soil model used in the developed mechanistic model is given as follows:

$$M_R = K_1 + K_3 \times (K_2 - \sigma_d) \quad when \quad \sigma_d \le K_2$$
$$M_R = K_1 - K_4 \times (\sigma_d - K_2) \quad when \quad \sigma_d \ge K_2 \qquad (4)$$

where M_R is resilient modulus, K_1, K_2, K_3 and K_4 are material constants obtained from repeated load triaxial tests.

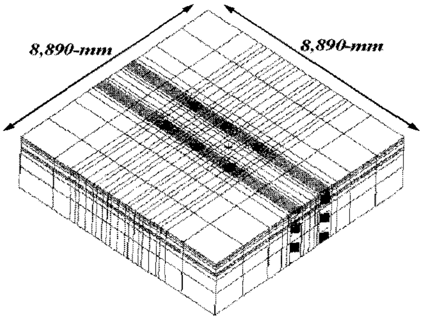
4. FIELD VALIDATION OF NONLINEAR FE ANALYSES

In a mechanistic-empirical flexible pavement analysis and design procedure, pavement structural responses have to be determined accurately from mechanistic structural models. Accordingly, the developed nonlinear geomaterial models employed in the ABAQUS FE program need to be validated for accurately predicting pavement responses. So, 3D ABAQUS FE analyses were performed to compute the pavement responses under aircraft gear loadings and to compare them with the measured section responses. Since 3D ABAQUS FE program is capable of considering multiple wheel loads and wheel load interaction effects, proper nonlinear pavement foundation models have to be used to predict responses of field pavement sections. For this purpose, the field measured responses of the National Airport Pavement Test Facility (NAPTF) flexible pavement test sections were utilized. 3D ABAQUS FE analyses were performed to compute the pavement responses under aircraft gear loadings and to compare them with the measured Construction Cycle 1 (CC1) section responses of NAPTF. The conventional section MFC (Medium strength subgrade Flexible Conventional pavement), chosen for validation herein, consisted of the P-401 plant mix bituminous pavement asphalt concrete (AC) surface, P-209 crushed stone granular base, and P-154 stone screening granular subbase layers over a medium strength subgrade. Table 2 lists the MFC section pavement layer thicknesses and material properties including the nonlinear resilient modulus model parameters of the unbound aggregates and subgrade materials used in the NAPTF MFC section (Gopalakrishnan, 2004). The AC surface layer was modeled as linear elastic.

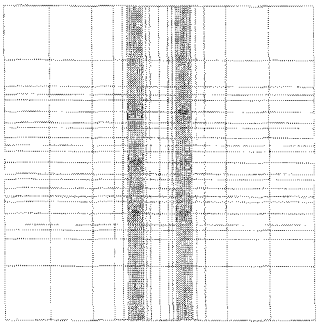
Table 2. Pavement Geometry and Material Properties Used in the Validation Study

Pavement Layer	Thickness (mm)	M_R (MPa)	ν	Material Properties			
Asphalt Concrete (AC)	127	8,268	0.35	Isotropic and Linear Elastic			
Base	203	Nonlinear	0.38	Nonlinear: Uzan model			
				K_1 (MPa)	K_2	K_3	
				10.3	0.40	0.0	
Subbase	305	Nonlinear	0.38	Nonlinear: Uzan model			
				K_1 (MPa)	K_2	K_3	
				6.9	0.64	0.0	
Subgrade	-	Nonlinear	0.40	Nonlinear: Bilinear model			
				$K_1 = E_{Ri}$ (MPa)	$K_2 = \sigma_{di}$ (MPa)	K_3	K_4
				62.8	0.042	420	570

Fig. 1 illustrates the modeled pavement 3D view and the FE mesh, which consisted of 20-noded hexahedron solid elements. A six-wheel dual-tridem type aircraft gear configuration, similar to that of Boeing 777 aircraft, applied individual wheel loads of 20 metric tonnes with 1372 mm wheel spacing and 1448 mm axle spacing. In order to model the circular wheel, fine meshes were used in the location applied to wheel loadings and the coarse meshes were used in the location far from the loadings. The bottom parts of the pavement section used fixed boundary conditions and the others used roller boundary conditions to allow vertical deformation. The single wheels were assumed in the analyses to apply uniform tire pressure of 1.3 MPa over a circular area.



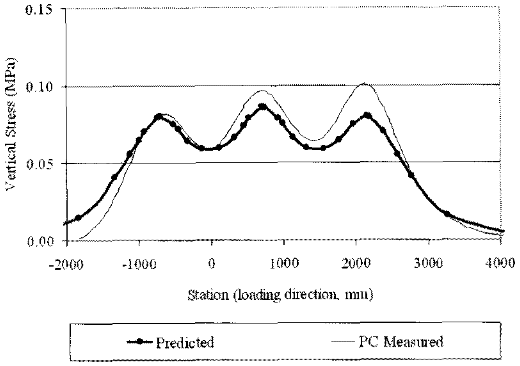
(a) 3D FE view



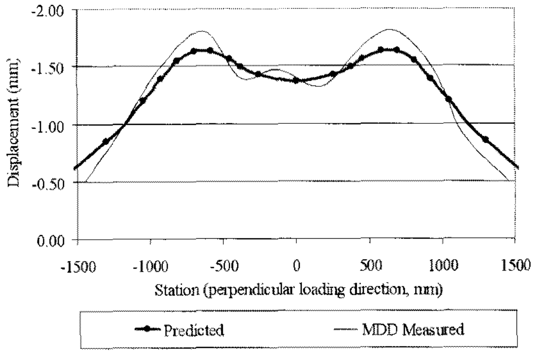
(b) Plan view of FE model

Fig. 1 Pavement Geometry & FE Mesh used to Analyze NAPTF MFC test section

Fig. 2 shows the measured and predicted pavement responses, i.e., vertical stresses on the top of subgrade and vertical displacements on the surface. The predicted subgrade stresses compare with the field installed pressure cell (PC) results and predicted surface displacements compare with the multi-depth deflectometer (MDD) for the MFC section. In general, considering the variability of the PC and MDD measurements, the nonlinear FE mechanistic model predictions were in reasonably good agreement with the measured responses of the NAPTF MFC test section. The tendency of somewhat high measured responses indicated in the actual tests is possibly because of localized PC and MDD depth and installation effects under wheel loads. Overall, the predicted responses are in the range of measured responses and validate the adequacy of the nonlinear UMAT characterizations in unbound aggregate base/subbase and subgrade layers.



(a) Pressure cell(PC) measured subgrade stresses



(b) Multi depth deflectomer(MDD) messured surface deflections

Fig. 2 Comparisons between Measured and Predicted Responses in the NAPTF MFC Pavement Test Section

5. DEVELOPING FE MODELS

5.1 FE Domain Selection Study

The pavement structures have an infinite domain in the horizontal and vertical direction. For this reason, it is important to choose a proper domain size that gives the most accurate pavement responses in FE analysis. According to Duncan *et al.* (1968), it was necessary to move the fixed boundary to a depth of 50-times radius of circular loading area (R) and move the roller boundary at the horizontal distance of 12-times R from center in the axisymmetric FE analysis in order to obtain the reasonable responses of FE analysis.

In this study, an axisymmetric FE model was generated to determine an appropriate domain size for predicting accurate pavement responses. This pavement section domain was modeled using axisymmetric finite elements truncated far away from the centerline of loading to get favorable results. To investigate the domain extents, the examined domain sizes were varied from 10- to 35-times the radius of loading area in the horizontal direction. The depth was fixed at 140-times the radius of loading area which showed good agreements in order to obtain accurate pavement responses from subgrade. All analyses were conducted using the various material properties and pavement geometries shown in Table 3.

Table 3. Inputs of Examined Pavement Domains using Axisymmetric Analyses

	Pavement Case 1		Pavement Case 2		Pavement Case 3	
Sections	Thickness (mm)	Modulus (MPa)	Thickness (mm)	Modulus (MPa)	Thickness (mm)	Modulus (MPa)
AC	76	2,759	102	2,069	76	2,759
Base	305	207	254	124	457	207
Subgrade	20,955	41	20,980	28	20,803	41

The load was applied as a uniform pressure of 0.55 MPa over a circular area of 152 mm radius. Fig. 3 shows the surface displacements to decrease as the domain extent increases. The complete analysis results show the differences in the predicted pavement responses.

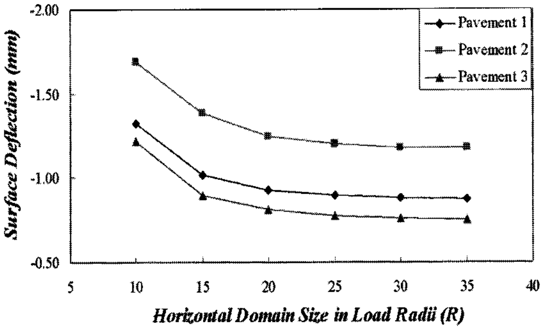


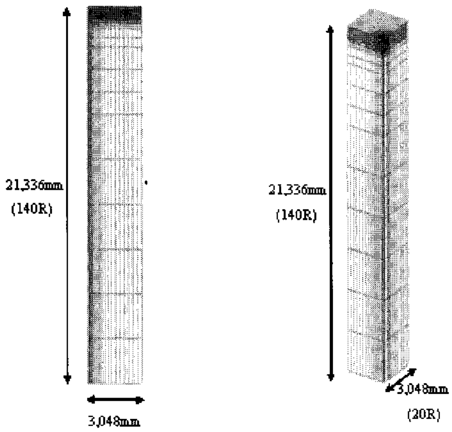
Fig. 3. Variations of Predicted Surface Deflections with Horizontal Domain Size

For the these pavement case studies, domain extent of 20-times the radius of loading area in the horizontal direction (H) and 140-times the radius of loading area in the vertical direction (V) with regular elements also showed that the influence of boundary truncation was negligible for domains larger than this finite element mesh domain. Since the variation of surface deflection was less than 0.025mm (1mil) with this domain, the difference was considered negligible. Using this mesh, the predicted pavement responses were also the most favorable with those of the elastic layered program (ELP), KENLAYER program (2004), as listed in Table 4. These comparisons are in general quite acceptable especially when considering all the assumptions made in the axisymmetric FE formulations and the circular shaped mesh discretization concerns for the wheel loading. Therefore, the developed mesh domain of pavement FE model was deemed accurate enough to study next the nonlinear pavement foundation modeling concepts in the FE analysis of flexible pavements.

Table 4. Comparison of 140R (V) by 20R (H) Domain Size for ELP and FE Analysis

	Linear Elastic Analysis	
Pavement responses	KENLAYER (ELP)	ABAQUS (FE)
$\delta_{.\ \text{surface}}$ (mm)	- 0.927	- 0.930
$\sigma_{\text{r bottom of AC}}$ (MPa)	0.777	0.773
$\sigma_{\text{v top of subgrade}}$ (MPa)	- 0.041	- 0.041
$\varepsilon_{\text{v top of subgrade}}$	- 936	- 933

Fig. 4 shows the constructed FE models in this study. Note that the three-dimensional model only considers one fourth of the problem to be solved due to symmetry. A good agreement of responses indicates in two different mesh constructions and this is related to modeling approximations being minimized the differences between the axisymmetric and 3D analyses to enable reliable comparisons.



(a) Axisymmetric FE model (b) 3D FE model

Fig. 4. Developed Axisymmetric and 3D FE Models

5.2 Nonlinear Pavement Analysis

From the previous mesh construction, a conventional flexible pavement was analyzed as an axisymmetric solid consisting of linear and nonlinear elastic layers in order to employ the nonlinear response models and evaluate the pavement responses in the ABAQUS FE programs. Table 5 lists pavement geometry and assigned material input properties. A uniform pressure of 828 kPa was applied over a circular area with a radius of 102-mm. To better validate ABAQUS UMAT nonlinear solutions in the base and subgrade layers, pavement responses were predicted separately for the following pavement layer material characterizations: (1) nonlinear base and linear subgrade, (2) linear base and nonlinear subgrade and (3) nonlinear base and nonlinear subgrade.

Table 5. Pavement Sections and Material Properties assigned in FE Analyses

<table>
<tr><th>Section</th><th>Element</th><th>Thickness (mm)</th><th>ν</th><th colspan="12">Material Properties</th></tr>
<tr><td>AC</td><td>8-noded solid,
20-noded solid</td><td>76
or
102</td><td>0.35</td><td colspan="12">Isotropic and Linear Elastic
(E = 2,759-MPa)</td></tr>
<tr><td rowspan="6">BASE</td><td rowspan="6">8-noded solid,
20-noded solid</td><td rowspan="6">305
or
254</td><td rowspan="6">0.40</td><td colspan="12">Nonlinear (Axisymmetric)
: Uzan model (Uzan, 1985)</td></tr>
<tr><td colspan="4">K_1 (kPa)</td><td colspan="4">K_2 (kPa)</td><td colspan="4">K_3 (kPa)</td></tr>
<tr><td colspan="4">4,100</td><td colspan="4">0.64</td><td colspan="4">0.065</td></tr>
<tr><td colspan="12">Nonlinear(Three-dimensional):
Universal Model with octahedral shear stress, τ_{oct} (Witczak and Uzan, 1988)</td></tr>
<tr><td colspan="4">K_1</td><td colspan="4">K_2</td><td colspan="4">K_3</td></tr>
<tr><td colspan="4">1,940</td><td colspan="4">0.64</td><td colspan="4">0.065</td></tr>
<tr><td rowspan="3">SUBG RADE</td><td rowspan="3">8-noded solid,
20-noded solid</td><td rowspan="3">20,955
or
20,980</td><td rowspan="3">0.45</td><td colspan="12">Nonlinear: Bilinear model
(Thompson and Robnett, 1979)</td></tr>
<tr><td colspan="3">E_{RI} (kPa)</td><td colspan="3">σ_{di} (kPa)</td><td colspan="3">K_3 (kPa/kPa)</td><td colspan="3">K_4 (kPa/kPa)</td></tr>
<tr><td colspan="3">41,400</td><td colspan="3">41</td><td colspan="3">1,000</td><td colspan="3">200</td></tr>
</table>

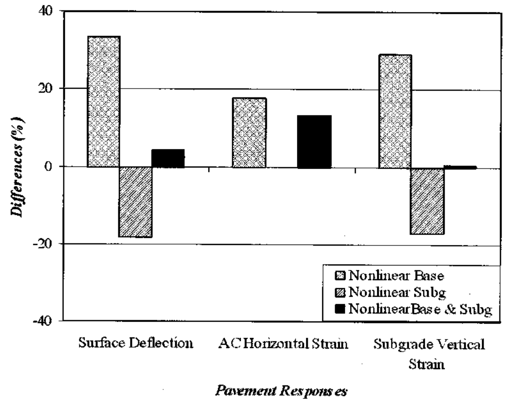
Table 6 presents the predicted critical pavement responses at the centerline of loading in the cases of 76mm AC and 305mm Base section and 102mm AC and 254mm Base section using the ABAQUS FE solution. Overall, according to nonlinear geomaterial models, the predictions are fairly different and this shows the importance of considering nonlinear geomaterial behavior in the pavement responses.

Table 6. Predicted Pavement Responses from Axisymmetric FE Analyses

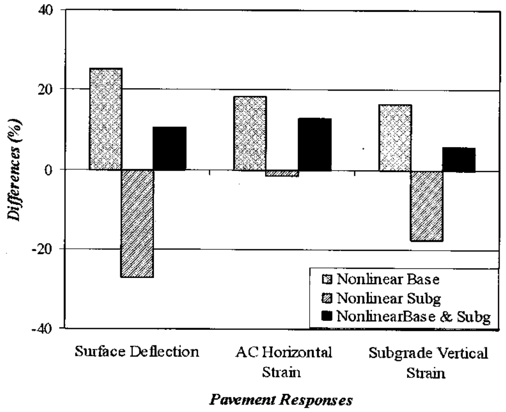
Pavement response	Linear base and linear subgrade	Nonlinear base and linear subgrade	Linear base and nonlinear subgrade	Nonlinear base and nonlinear subgrade
76mm AC and 305mm Base section				
$\delta_{surface}$(mm)	- 0.93	- 1.24	- 0.76	- 0.97
$\varepsilon_{r\ bottom\ of\ AC}$	227	267	227	257
$\varepsilon_{v\ top\ of\ subgrade}$	- 932	- 1,203	- 772	- 937
102mm AC and 254mm Base section				
$\delta_{surface}$(mm)	- 0.87	- 1.11	- 0.69	- 0.86
$\varepsilon_{r\ bottom\ of\ AC}$	240	310	234	292
$\varepsilon_{v\ top\ of\ subgrade}$	- 896	- 1090	- 730	- 837

* Negative is compression

The results in Fig. 5 show that the nonlinear base and subgrade have a considerable influence on the pavement responses. In the comparison with linear analysis results, the nonlinear characterization of the base layer mainly caused the increases in the predicted responses. The case of only nonlinear base material characterization has a remarkable effect on critical pavement responses, especially, tensile strain at the bottom of the AC and vertical strain on the top of subgrade. Nonlinear characterization of the base material caused a maximum increase of 33% in the tensile strain at the bottom of the AC, 18% in the vertical strain on the top of subgrade, and 29% in the surface deflection. Unlikely linear analysis, in the nonlinear analysis, the modulus distribution due to wheel loading was shown in base layer. The nonlinear modulus distribution followed by current material stress state was affected to pavement responses. From these differences, significantly diverse critical pavement responses, e.g., horizontal tensile strain at bottom of asphalt concrete (AC) related to fatigue cracking and vertical strain on top of subgrade linked to rutting, are able to be predicted. The nonlinearity of subgrade also affects the critical pavement responses. The nonlinear subgrade characteristics resulted in 27% decrease in the vertical subgrade strain and 18% decrease in the surface deflection. On the other hand, the nonlinearity of subgrade soils had a little impact on the tensile strain at the bottom of the AC. As listed in Table 6 and shown in Fig. 5, the combined nonlinear base and subgrade characterizations yield the most accurate pavement response predictions quite different from the linear elastic characterizations. Since these differences resulted from particular case studies analyzed in this research, these differences can vary on different modeling conditions.



(a) 76mm AC and 305mm base section

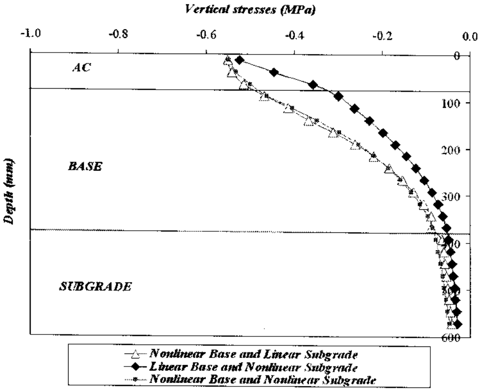


(b) 102mm AC and 254mm base section

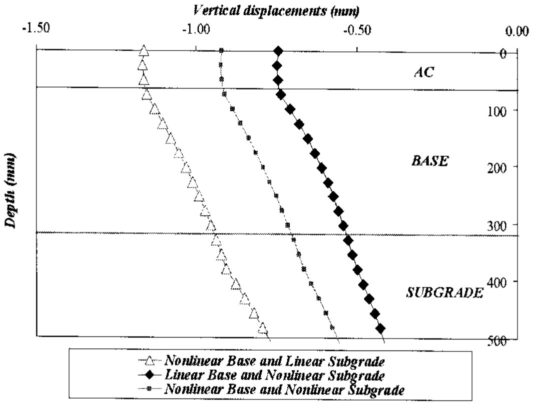
Fig. 5 Comparisons of Predicted Critical Pavement Responses from Axisymmetric Linear and Nonlinear FE Analyses

Fig. 6 shows the predicted vertical displacements on the surface and vertical stress predicted at the centerline of loading in the AC, base, and subgrade layers as obtained from the three different pavement layer material characterization cases of 76mm AC and 305mm Base section. This figure also shows that the predictions are fairly different according to nonlinear geomaterial behavior in the pavement responses. Applied wheel load shows different modulus distributions in pavement layers compared to linear analysis. The nonlinear characterization of the base layer mainly caused increases in predicted responses, but the nonlinearity of subgrade decreased in responses.

The 3D ABAQUS FE model was next used to analyze



(a) Predicted vertical stresses



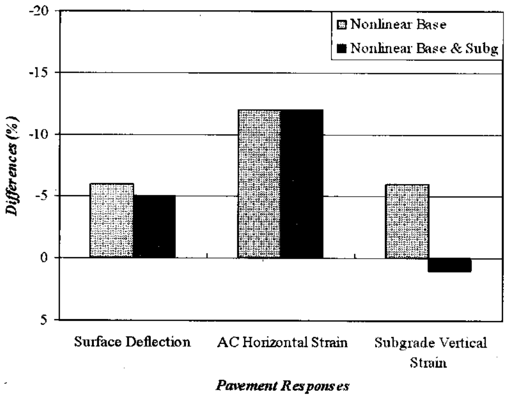
(b) Predicted vertical displacement

Fig. 6 Predicted Pavement Responses from Axisymmetric FE Analyses due to Various Material Characterizations

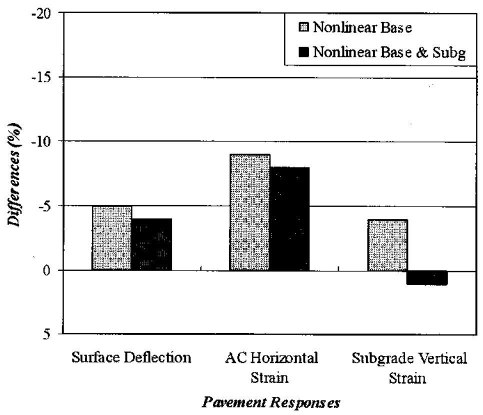
the pavement section selected for the domain study (see Fig. 4(b)) with nonlinear pavement geomaterial characterizations. Axisymmetric FE analysis has been known to be limited in its capacity especially for requiring 3D platform, such as multiple wheel/gear loading, which does not fit with the assumptions of axial symmetry. 3D FE analysis is viewed as the best approach to eliminate such limitations and shortcomings with the consideration all three-directional components, i.e., *x*, *y*, and *z*-directions. To do accurate FE analysis, neatly and well constructed meshes are necessary for proper 3D FE pavement analyses. Like in the axisymmetric analyses, a uniform pressure of 551 kPa (80 psi) was applied over the circular area of 152 mm (6 in.) radius.

To perform 3D nonlinear FE analysis, the Universal Model given in Eq. (2) was used for the unbound aggregate base while the bilinear model given in Eq. (3) was utilized in the fine-grained subgrade as the ABAQUS UMAT inputs. Although the Uzan aggregate base model was used earlier in all the axisymmetric FE analyses, this time the universal model with the octahedral shear stress (τ_{oct}) term had to be utilized in the 3D analyses since the 3D pavement FE model had the consideration for all three directional components including the intermediate principal stress (σ_2) now different than the minor principal stress (σ_3). This difference between the two aggregate base models inherently would be responsible for differences in predicted responses.

Fig. 7 gives detailed comparisons of the predicted critical pavement responses for two pavement geometry cases studied between the axisymmetric FE analysis results and the 3D FE analysis results. The differences in predicted pavement responses are quite large with the largest being for the horizontal strain on the bottom of AC more than 12%. From the comparisons of base characterized nonlinear only, surface deflections were somewhat different by up to 6%, tensile strains at the bottom of AC up to 12%, and vertical strains on top of subgrade by up to 6% in the largest differences. However, each response variable did not consistently increase or decrease between the two analyses. In general, for the combined nonlinear base and subgrade results, the predicted responses from the axisymmetric and the 3D FE analyses showed large differences at all with the largest being for tensile strain for up to 12%. Note that these differences, specific to the pavement geometries, layer material properties, and the loading



(a) 76mm AC and 305mm base section



(b) 102mm AC and 254mm base section

Fig. 7 Comparisons of Predicted Critical Pavement Responses from Axisymmetric and 3D Nonlinear FE Analyses

conditions studied here, were given as examples to demonstrate the important effects of nonlinear pavement foundation behavior. Therefore, the developed 3D pavement FE model was deemed accurate enough to study next the nonlinear pavement foundation modeling concepts in 3D FE analysis of flexible pavements. The future research should closely investigate whether the use of a nonlinear geomaterial model developed from proper material characterizations that can fully apply and simulate the 3D stress states in material modeling would bring any improvement in results from the 3D analyses of flexible pavements.

6. CONCLUSIONS

This study has focused on properly characterizing the resilient response of geomaterials, i.e., coarse-grained unbound aggregates and fine-grained subgrade soils. For this purpose, appropriate stress-dependent modulus characterization models were programmed in a user-defined material model subroutine (UMAT) in the general purpose ABAQUS finite element (FE) program. This way, stress-dependent characterization of the base/subbase and subgrade layers, was made part of the ABAQUS finite element nonlinear solutions. The conclusions of this study can be summarized as follows:

1) Compared to the linear elastic solutions that have one modulus assigned to the whole base and subgrade layers, considerable impact of critical pavement responses, e.g., horizontal tensile strain at the bottom of asphalt concrete (AC) linked to fatigue cracking and vertical strain on the top of subgrade linked to rutting, were predicted when nonlinear analyses were performed in the aggregate base and fine-grained subgrade soil layers.
2) The studies between the results of axisymmetric and 3D ABAQUS analyses using the developed material models for nonlinear solutions indicated large differences in the predicted pavement responses. Axisymmetric stress analysis has also been known to be limited in its capacity especially for modeling various geometries and loading conditions. The needed upgrade to the state-of-the-art 3D FE analyses of flexible pavements should properly implement the nonlinear, stress-dependent pavement foundation geomaterial behavior.
3) The validation of nonlinear stress-dependent

geomaterial model was conducted for multiple wheel loading of pavements as well. Computed 3D FE analysis predictions were validated by comparing the field measured responses of the National Airport Pavement Test Facility (NAPTF) pavement test sections installed and measured from Multi-Depth Deflectometers (MDD) and Pressure Cells (PC) for the NAPTF structure. In general, the nonlinear FE mechanistic predictions in this study were in reasonably good agreement with the obtained responses of the test sections. The predicted values of subgrade vertical stress and surface deflection compared reasonably well with the order of magnitudes of the measured responses in pavement sections.

Based on these findings, an appropriate stress-dependent modulus characterization model programmed in a user-defined material model subroutine in the general purpose ABAQUS FE program are the way to properly characterize the resilient response of geomaterials, i.e., coarse-grained unbound aggregates and fine-grained subgrade soils for flexible pavement response analysis.

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접 수 일 : 2008. 12. 17
심 사 일 : 2008. 12. 17
심사완료일 : 2009. 1. 8