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Effect of Nonlinearity in Granular Layer on Critical Pavement Responses of Low Volume Roads

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Abstract: Low volume roads in India mainly comprise of unbound granular materials laid over subgrade with thin bituminous surfacing. Hence, properties of the granular materials play a significant role in the performance of these pavements, as the thin surfacing layer is considered to be a non-structural layer. Therefore, accurate modeling of the granular layers is essential in the evaluation of critical pavement responses. Under application of load, unbound materials exhibit stress dependent characteristics. Thus, consideration of non-linearity in these layers is necessary for accurate estimation of the pavement responses of a flexible pavement structure. The granular materials show stress hardening characteristics, which indicates that the resilient modulus of the material increases with an increase in bulk stress. Finite element codes can be suitably used to handle the nonlinearity of unbound granular layers. Using a three dimensional (3D) finite element (FE) model, this paper examines the effect of nonlinearity in granular layers of critical pavement responses of a low volume road.

Key words*: Finite element method; Granular pavement; Low volume road; Nonlinearity.*

Introduction

Low volume roads in India include district roads (ODR) and village roads (VR), which cover 80% of the total road network of the country. These roads are usually constructed as granular pavements with thin bituminous surfacing [1]. In such pavements, granular material comprises the main structural layer over the subgrade to carry the traffic load. Hence, accurate modeling of the granular layer during analysis is essential for the evaluation of critical pavement responses. Unbound materials behave nonlinearly under the application of load, and the resilient modulus is stress dependent. Thus, the stress hardening characteristic of the granular material needs to be considered in an accurate estimation of true pavement responses. The main objective of this paper is to examine the effect of nonlinearity in unbound materials on the critical responses of a granular pavement. Three dimensional finite element models have been developed for the analysis of typical granular pavements. The availability of high speed computing facilities and multipurpose finite element programs, such as ABAQUS, ANSYS and ADINA, encourage researchers to use the general purpose software to analyze the complex behavior of pavement structures. ANSYS has been used to model the nonlinearity of granular layer by developing a special macro program that assigns the moduli values to individual elements based on stress level until convergence. The subgrade layer was assumed to be linearly elastic in this study.

Finite Element Modeling

Though 3D finite element analysis requires more computational time and computer memory, researchers in the field still consider it better than the 2D analysis [2-3]. 3D models can better incorporate the complex behavior of the composite pavement materials under traffic loads of different configurations. They are also capable of simulating the actual tire imprint of the loaded wheel instead of the circular load shape as restricted by a 2D axisymmetric analysis or the infinite strip load as in a plane strain analysis, which is not realistic [4]. Gonzalez et al. [5] recommend the use of 3D FE analysis for thin pavement structures to avoid the calculation of nonexistent tensile stresses in the granular layers. Therefore, a 3D model has been adopted for analysis in the present study.

Modeling of Granular Pavement

An appropriate constitutive model representing the nonlinearity of a granular layer is necessary input to the finite element model of the pavement. For thin-surfaced pavements, this is more important, as the granular layer constitutes the main structural layer.

Model Geometry

Low volume rural roads in India are single lane roads of 3750*mm* in carriageway width with hard shoulders on both sides of the carriageway. The average shoulder width measures 1500*mm*. A 3D finite element model was developed using ANSYS [6] for the simulation of low volume road pavements. The model is a quarter model in which the load is symmetrical both in longitudinal and transverse directions, as shown in Figs. 1 and 2. A sensitivity analysis conducted to find the influence of the model geometry suggests that a subgrade depth of 2000*mm* is appropriate and hence was adopted by the present study. A length of 1800*mm* has been determined in the longitudinal direction. Half the single lane carriageway width and one shoulder width have been considered in the transverse direction. The 3D geometry of the model used for finite element analysis is shown in Fig. 3.

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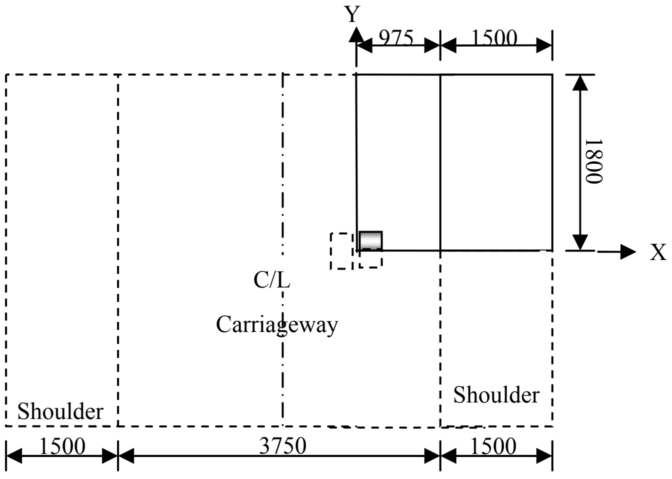

Note: All Dimensions are in *mm*

Fig. 1. Top View of Pavement Considered for FE Analysis.

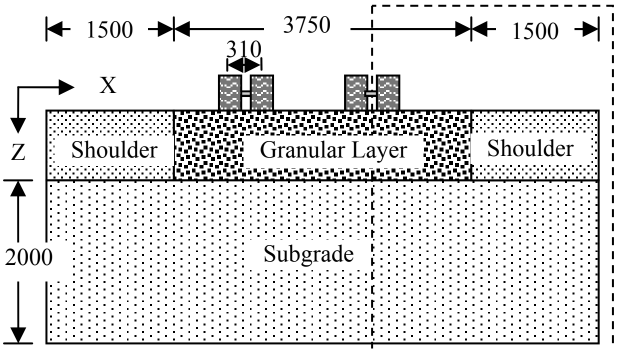

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Fig. 2. Sectional View of Pavement Considered for FE Analysis.

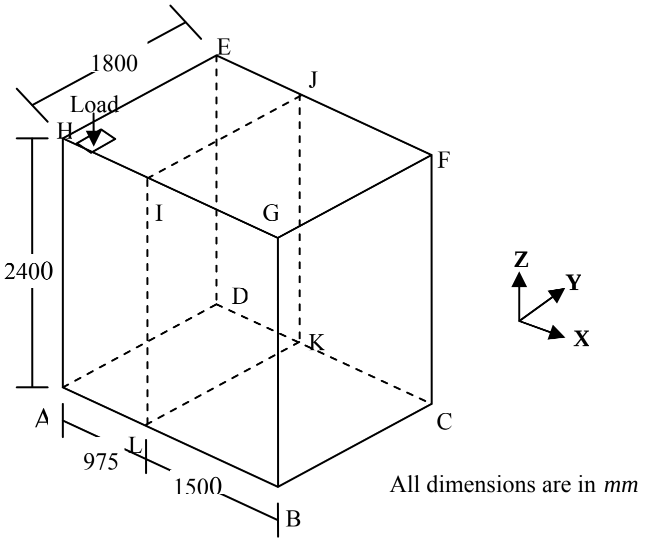


Fig. 3. Three Dimensional Model of Pavement Used for FE Analysis.

Element Type and Boundary Conditions

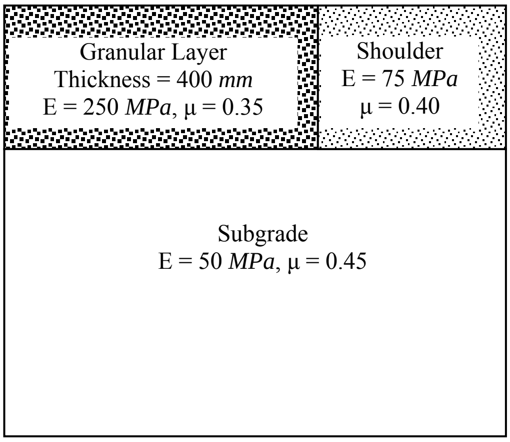


Fig. 4. Typical Two-Layer Pavement Considered for Sensitivity Analysis.

Solid-45 element was selected for developing the 3D FE model. The bottom of the pavement was constrained for all degrees of freedom. Lateral displacements u_x and u_y are restrained in X and Y directions, respectively, along the axis of symmetry ($u_x, u_y = 0$).

Loading

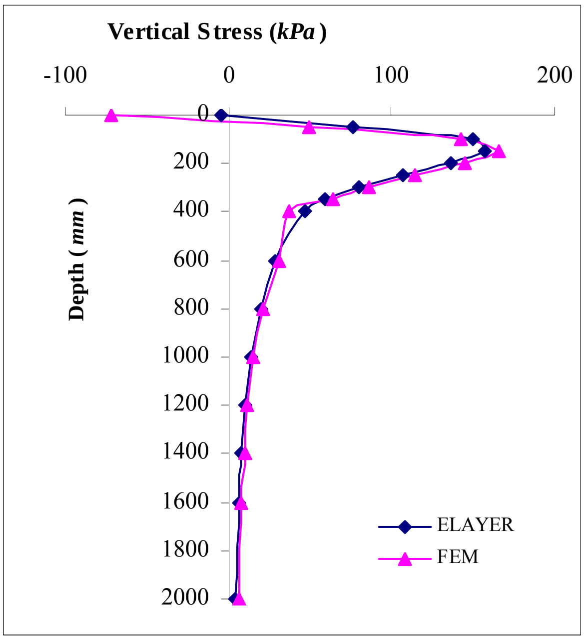
Sunkavalli [7] measured the dimensions of tire imprints for various combinations of load and tire pressure. He reported that the widths of imprints vary between 190 and 200*mm*. A wheel contact width of 200*mm* has been adopted in the FE model. To simulate the wheel load (20*kN*) of a standard axle with a tire pressure of 0.56*MPa*, the length of contact area has been taken as 180*mm*. Half of the single tire contact area has been considered in the quarter model, as shown in Fig. 1.

Validation of the FE Model

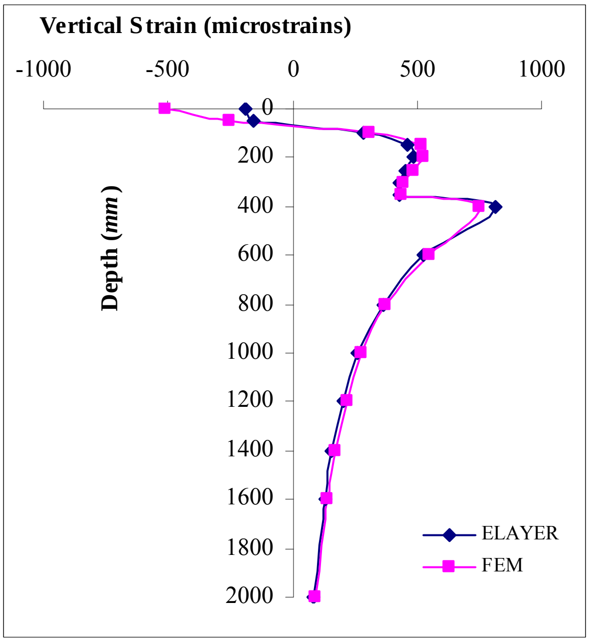
A typical two layer pavement system, as shown in Fig. 4, was analyzed using the FE model and demonstrated that both the layers are linearly elastic. For validation of the model, a similar pavement was analyzed using ELAYER, a linear elastic layered analysis program developed at IIT, Kharagpur [8]. Half of two wheel loads (dual) of 20*kN* each was considered for analysis. A contact pressure of 0.56*MPa* was used. While circular contact areas were considered for analysis using ELAYER, rectangular contact shapes with a dimension of 200*mm* × 180*mm* were used in the FE model. Granular layer thickness, elastic moduli and Poisson's ratio values were equivalent in both models. In the case of the FE model, the pavement had been considered along with the shoulder. Pavement layers are assumed to be infinite horizontally in a linear elastic layered analysis. A comparison of the results obtained using the FE model and ELAYER for a linear elastic system is shown in Fig. 5. As seen from the figure, the results match well in linear elastic analysis.

Modeling Nonlinearity in Granular Layer

Most of the analytical models used for the design of flexible pavements are based on linear elastic layered theory and hence consider the granular layer to be linearly elastic. This approach



(a) Vertical Stress



(b) Vertical Strain

Fig. 5. Comparison of Results Obtained using FE Model (linear) and ELAYER.

is simple and easy to use but does not reflect the nonlinear behavior of granular layers. Also, a linear elastic analysis of pavements with thick granular layers with no surfacing or with thin bituminous surfacing leads to nonexistent high tensile stresses within the granular layers [5].

The general purpose finite element software packages have the capability to model the non-linearity of granular material by considering the elasto-plastic behavior of the material. Many researchers [9-10] used the Drucker-Prager (DP) plasticity model to represent nonlinear behavior in granular materials.

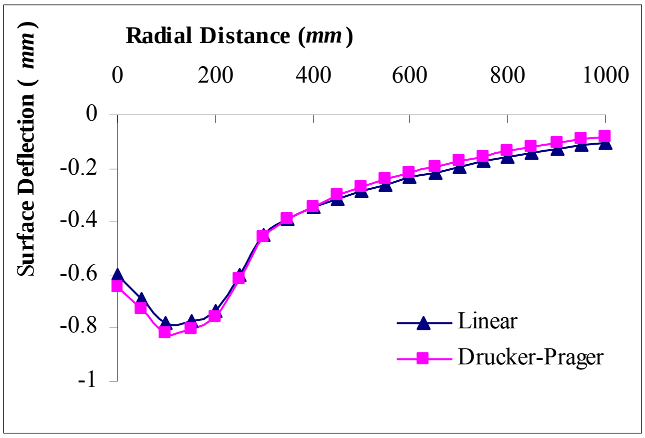


Fig. 6. Comparison of Deflection Responses from the Linear and DP Model.

To use the Drucker-Prager model in finite element analysis, the input parameters require the cohesion (c), angle of internal friction (φ) and the dilation angle (ψ), along with the linear elastic parameters (i.e. Elastic modulus and Poisson's ratio). The pavement system shown in Fig. 4 was analyzed using the FE model developed in this study, which considers granular layers to be (a) linear and (b) nonlinear. Nonlinearity was modeled using the DP model. The c, φ and ψ values obtained by Morgan [11] from tri-axial shear tests for good quality aggregates have been used in this analysis. These values are 38*kPa*, 53° and 0°, respectively.

Surface deflections computed at different radial distances using linear elastic analysis (ELAYER program) were compared with those obtained using nonlinear analysis (DP model). Nonlinear analysis resulted in an increase of about 7% in the central deflection value. The vertical strain over subgrade resulted in an increase of 9% compared to the values obtained using linear elastic analysis, which indicates that consideration of nonlinearity has some effect on the critical responses in the system. The comparison surface deflection is shown in Fig. 6. The maximum difference in the responses obtained using the two approaches range only from 7 to 9% and is not substantial.

Kim [12] also used DP and hypo-elastic models for granular material in a 3D FE model and compared the responses with those obtained using linear elastic analysis. He reported a difference of 10 to 15% in pavement responses of DP models and of 60% in the use of hypo-elastic models for thin asphalt surfaced pavement. However, he also stated the difficulty in selecting an appropriate set of hypo-elastic parameters and hence preferred the stress dependent modulus approach for handling the nonlinearity in unbound layers.

For realistic simulation of the granular materials, nonlinear stress-dependent constitutive models were developed by different researchers. Gonzalez et al [5] carried out a 3D FE analysis of a thin, sealed granular pavement using different nonlinear constitutive models and a linear elastic approach. The analytical responses were compared with the responses obtained from an instrumented test track. Results of the nonlinear analyses are in much better agreement with the measured responses compared to those obtained using linear analysis. They also found little differences between the responses obtained from different nonlinear models. As the $\bar{k}\theta$ model [13] is simple, with only two material constants required,

Table 1. Pavement Responses for Different Seed Moduli of Granular Layer.

Seed Modulus	Pavement Response		
(*MPa*)	Central Surface Deflection (*mm*)	Vertical Stress over Subgrade (*MPa*)	Vertical Strain over Subgrade
200	-0.82273	-4.93E-02	-9.98E-04
250	-0.82274	-4.93E-02	-9.98E-04
300	-0.82275	-4.93E-02	-9.98E-04
400	-0.82275	-4.93E-02	-9.98E-04

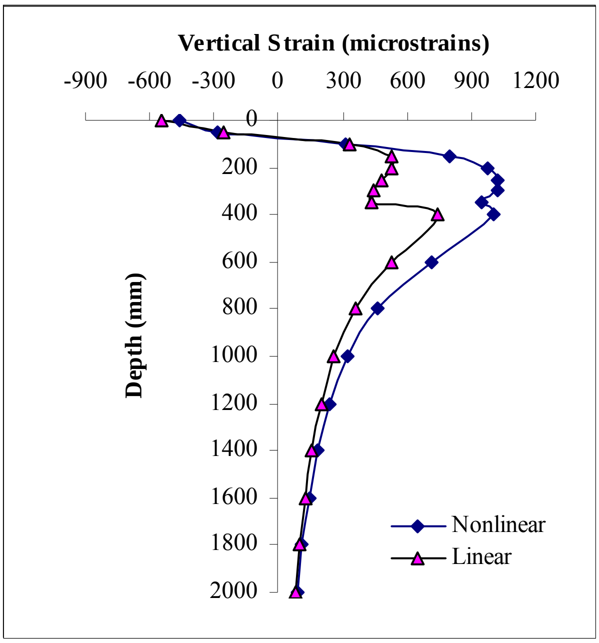


Fig. 7. Comparison of Vertical Strain.

the following relationship given by Eq. (1) and developed by Pandey and Naidu [14] has been adopted in the present study:

$$M_R = 3.47(\theta)^{0.7375} \qquad (1)$$

where M_R is in *MPa* and θ is in *kPa*.

Modeling Nonlinearity Using ANSYS

ANSYS [6] is a general purpose finite element package and does not include specific stress dependent nonlinear elastic models for granular materials. Macro programs were written to assign material properties for individual elements and compute the elastic modulus using Eq. (1) for each element in the granular layer depending on the stress condition. A seed modulus was initially assigned to all the elements of the layer to compute the bulk stresses on each element. Geostatic pressure due to self weight of the pavement layers was considered in the model for estimating the bulk stress. Since this is an iterative approach, the material properties change in each iteration according to the stress state of the element until the selected convergence criterion is met. The convergence criterion used in the present study is given as Eq. (2):

$$\frac{\sum_{i=1}^{N} abs(E_{new} - E_{old})}{\sum_{i=1}^{N} E_{old}} \times 100 \le 5 \qquad (2)$$

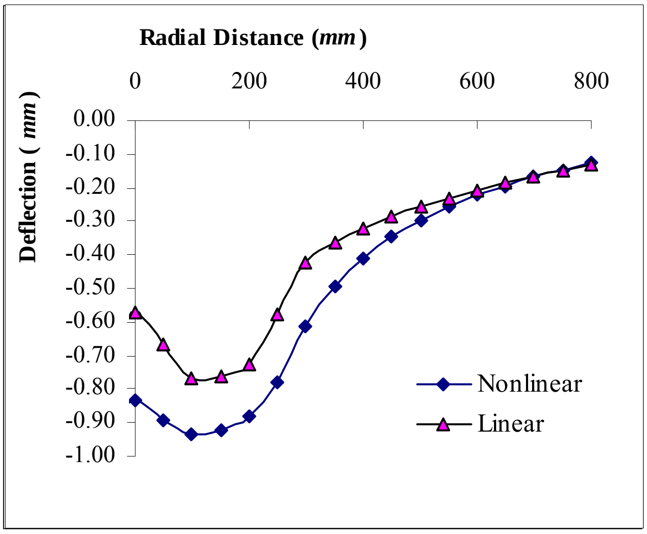


Fig. 8. Comparison of Surface Deflections.

where

N = Number of elements in the granular layer.

E_{new} = Elastic Modulus of i^{th} element for a given iteration.

E_{old} = Elastic Modulus of i^{th} element in the previous iteration.

No-Tension Material

Granular material does not possess any significant tensile strength. To model the material as a no-tension material, negative (i.e. tensile) minor principal stresses were set to zero. After nullifying the tensile stresses, if the computed modulus value is found to be smaller than a specified minimum modulus value, that particular element is assigned the minimum modulus value. Brown and Pappin [15] used a minimum value of 100*MPa* in the SENOL program for the elements experiencing tensile stresses. Bose [16] suggested a value of 80 to 140*MPa* as the minimum modulus value. He also reported an increase in the modulus value of the granular layer with increasing minimum modulus value. A value of 100*MPa* has been adopted in the present model as the minimum modulus value.

Seed Modulus

The effect of seed modulus on the pavement responses has been studied. The responses obtained from the FE model for different seed moduli are given in Table 1, which indicates that the results are not significantly influenced by the initial seed modulus values selected for the granular layer. The pavement attributes considered in this analysis are given in Fig. 4. The density value considered for granular material is 2250kg/m^3. For shoulder and subgrade layer,

Table 2. Variation in Vertical Strain over Subgrade.

Thickness of Granular Layer (*mm*)	Subgrade Modulus (*MPa*)				
	20	40	60	80	100
300	3.20E-03	2.02E-03	1.51E-03	1.22E-03	1.02E-03
400	2.36E-03	1.51E-03	1.13E-03	9.10E-04	7.66E-04
500	1.84E-03	1.16E-03	8.63E-04	6.97E-04	5.85E-04
600	1.46E-03	9.09E-04	6.80E-04	5.48E-04	4.59E-04

Table 3. Variation in Vertical Stress over Subgrade.

Thickness of Granular Layer (*mm*)	Subgrade Modulus (*MPa*)				
	20	40	60	80	100
300	5.96E-02	7.64E-02	8.73E-02	9.48E-02	1.01E-01
400	4.26E-02	5.53E-02	6.33E-02	6.91E-02	7.31E-02
500	3.31E-02	4.25E-02	4.84E-02	5.25E-02	5.53E-02
600	2.66E-02	3.38E-02	3.82E-02	4.12E-02	4.32E-02

Table 4. Variation in Maximum Surface Deflection (*mm*).

Thickness of Granular Layer (*mm*)	Subgrade Modulus (*MPa*)				
	20	40	60	80	100
300	2.34	1.55	1.24	1.06	0.94
400	2.07	1.45	1.20	1.05	0.94
500	1.99	1.43	1.20	1.06	0.94
600	1.97	1.44	1.22	1.07	0.95

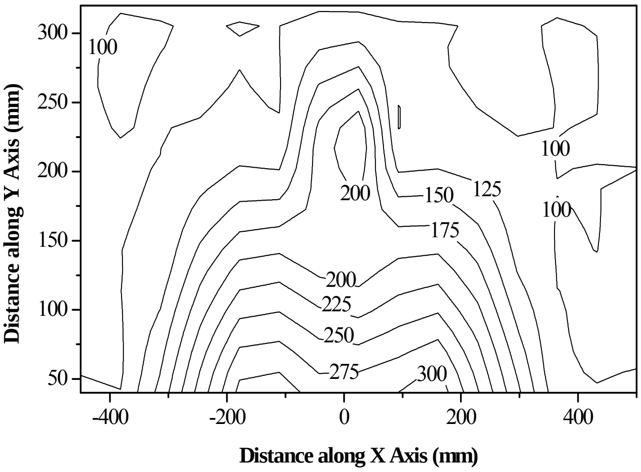


Fig. 9. Moduli Contours at 75*mm* below Pavement Surface.

the density was taken as 2000*kg/m*^{3}. A seed modulus of 250*MPa* is used for granular layer elements in the present study.

Effect of Nonlinearity in Granular Layer

To assess the effect of nonlinearity in granular layers on various pavement responses, the pavement model as shown in Fig. 4 was considered for analysis. The density values of different layers are the same as reported earlier. Comparison of the vertical strain over the top of the subgrade along the axis of symmetry of the dual wheel for pavements with linear and nonlinear granular layers is shown in Fig. 7. Comparison of the surface deflection values is shown in Fig. 8. Significant differences can be noted in the critical responses obtained from the two approaches. The maximum difference in the case of vertical strain is 35%, while it is up to 44% in the case of surface deflection.

Moduli Contours in Granular Layer

Fig. 9 shows the contours of granular layer modulus at a depth of 75*mm* from the surface of the pavement. The pavement system shown in Fig. 4 was used to generate the moduli contours. This plot was developed for a subgrade modulus of 50*MPa* and a granular layer thickness of 400*mm*. The coordinate 0 on the x-axis represents the centre of the dual wheel, and the plot shows results from half of the dual wheel load assembly.

Effect of Pavement Parameters on Critical Responses

The pavement system considered for the sensitivity analysis is the same as given in Fig. 4. Subgrade moduli and granular layer thicknesses were varied to assess their effect on critical pavement responses. As evidenced by Table 2, the vertical strain over the subgrade:

i. decreases with an increase in layer thickness
ii. decreases with an increase in subgrade modulus.

In Table 3, vertical stress over the subgrade:

i. increases with an increase in subgrade strength
ii. decreases with an increase in thickness of granular layer.

In Table 4, the surface deflection of pavement along the axis of symmetry of dual wheel load:

i. decreases with an increase in subgrade modulus
ii. decreases with an increase in the granular layer thickness for low subgrade strength while remaining nearly constant for stronger subgrades.

Conclusions

Consideration of nonlinearity in granular layers is necessary for the accurate modeling of a flexible pavement structure, especially in the case of pavements with thin bituminous surfacing. An analytical study was conducted in the present work to evaluate the effect of nonlinearity in granular material on critical pavement responses. Consideration of nonlinearity using the DP model showed a marginal difference of 7-9% in the critical pavement responses, which suggests that the model does not adequately reflect the sensitivity of the pavement responses to the nonlinearity of the granular layer. For typical granular pavements, consideration of nonlinearity using a stress dependent resilient modulus resulted in a 35% higher vertical strain over the subgrade, compared to the value obtained using linear elastic analysis. The increase is 44% in the case of surface deflection measured at the center of the dual tires. The present study concludes that linear elastic analysis may result in unsafe designs for low volume roads where granular material forms the only structural layer to carry the traffic load.

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