Numerical modeling of geogrid reinforced granular bases in unpaved and paved roads under wheel loading

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ABSTRACT

Geosynthetics have been used commonly in the past three decades to stabilize and to improve the service life of pavements. Various researchers have conducted large-scale model studies, accelerated pavement testing, and numerical model simulations to evaluate the benefits of reinforcement in pavements. Conventional method for design of pavements is based on layered elastic theory and ensuring that the stresses under wheel load are within allowable stresses of each pavement layer. In order to model the critical response of pavement accurately, it is essential to consider the non-linear behavior of pavement. This study focuses on three-dimensional numerical modeling of unreinforced and reinforced flexible pavements using explicit finite difference program - FLAC^{3D}. This study also uses various constitutive models to evaluate the mechanistic behavior of pavement section. The improvement in reinforcing base layer is presented in terms of load-settlement curves and the maximum settlements at the surface are presented. This research is relevant at places where reinforcing the aggregate base layers is essential to improve the performance of pavement system and to reduce the quantity of aggregate material needed for their construction.

Keywords: Geogrid, pavements, non-linear analysis, FLAC^{3D}

1. INTRODUCTION

The role of geosynthetics in pavements over the last three decades is significant. Use of geosynthetics, viz., geotextiles, geogrids and geocells, have been proven to improve the performance of pavements. Two critical responses of pavement affecting pavement performance are (a) fatigue strain (horizontal tensile strain) at the bottom of the bituminous layer, and (b) rutting strain (vertical strain) at the top of the subgrade. Geosynthetics improve pavement performance via three mechanisms: (1) lateral confinement (2) increased bearing capacity, and (3) tensile membrane support (Zornberg and Gupta 2010). Lateral flow of granular materials are restrained by geosynthetics on the application of loading. This increases the lateral confinement within the soil, thereby increasing the modulus of the granular base material. Increased stiffness of base layer leads to the decrease in vertical strain (rutting strain) at top of the subgrade. In addition, the tension mobilised in the geosynthetic due to its membrane action will support the wheel load and thereby reduces the vertical stress on the subgrade. Geogrids often used in improving pavement performance are made from synthetic polymers (polypropylene, polyester, and polyethylene). Routinely used type of geogrids include uniaxial and biaxial geogrids. Perkins (1999) reported that geogrid when placed in base layer improved performance of pavements. Al-Qadi et al. (2012) recommended the optimal position of geogrid as upper one-third depth of base layer for thicker base, and at the interface of the granular base and subgrade layer for thinner base layer.

Pioneering work by Duncan et al. (1968) paved the way to finite element analysis of flexible pavements. Duncan has compared displacements and stresses within the pavement system computed by FEM technique based on Boussinesq’s solution. The study also indicated that it was possible to conduct non-linear analysis of pavement. Ling and Liu (2003) validated numerical model of geogrid reinforced pavement section developed using PLAXIS with experimental results and highlighted that geogrids were more effective on weaker subgrade. Pandey et al. (2012) used PLAXIS for numerical analysis of modeling critical response of pavement layers assuming linear elastic model. It was found that when geogrid positioned at the base-bituminous concrete interface reduced fatigue strain, and reinforcement when placed at the interface of base and sub grade layer caused maximum reduction in rutting strain. Saad et al. (2005) conducted dynamic FEM analysis of reinforced flexible pavement using ADINA.

Since 1990’s, Fast Lagrange continuous analysis (FLAC) has been widely used for solving large-strain geotechnical deformation problems. Benmebarek et al (2013) and Goud et al. (2018) conducted numerical analysis of reinforced unpaved road using two-dimensional finite difference program FLAC^{2D}. Present study focuses on analysis of reinforced paved section and reinforced equivalent unpaved section under static loading using FLAC^{3D}. The results obtained using linear elastic model was validated by comparing the results from KENLAYER. Additionally, the Mohr-Coulomb material model was also used to model non-linear behavior of pavement layers. The study mainly focusses on the effect of geogrid reinforcement on unpaved and paved sections.

2. OBJECTIVES

- To compare the performance of unpaved and paved roads under wheel loading
- To compare the maximum settlements of unpaved and paved roads using various constitutive models
- To compare the reduction in the maximum settlement of geogrid-reinforced unpaved and paved sections
- To obtain load-settlement curves for unpaved and paved sections

3. APPROACH

A typical paved section was chosen and static load was applied by assuming pavement layers as linear elastic. Widely used elastic layered pavement analysis program, KENPAVE, was used to evaluate deflection, stress and strain in pavement layers. Numerical modeling of paved section was done using FLAC^{3D} and resulting maximum surface settlements, compressive, and fatigue strains were compared with KENPAVE. An equivalent unpaved road section was chosen by matching the compressive strain at the top of subgrade to that of paved section as in Fig 1. According to the literature, base layer and subgrade layer exhibit non-linear behaviour. Mohr-Coulomb model was used for base and subgrade to conduct non-linear analysis. The mechanism by which the reinforcement improves the behavior of the unpaved and paved roads under the effect of static load was examined. For unpaved section, geogrid is placed at the upper third of base layer as proposed by Al-Qadi et al (2012). Geogrid was kept at the same position for paved section and performance were compared.

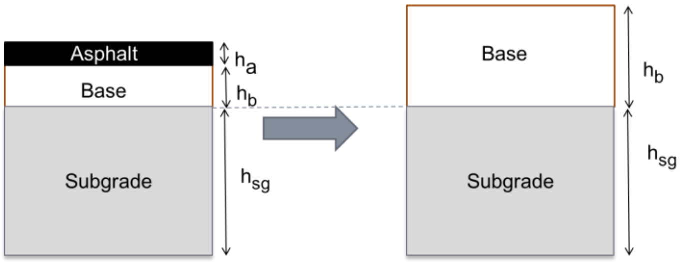


Figure 1. Equivalent unpaved section corresponding to a paved section

4. MATERIAL PROPERTIES

Material properties of various pavement layers, such as asphalt, base course and the subgrade soil, were chosen from Correia et al. 2018. A typical weak subgrade and marginal aggregate were chosen to study the effect of geogrid on the performance of the pavement. Tables 1 and 2 give the properties of the materials and reinforcement.

Table 1. Properties of pavement layers

Properties	Asphalt	GSB	Subgrade
Material model	Linear Elastic	Mohr-Coulomb	Mohr-Coulomb
Mass density	25	22	18
Elastic modulus (MPa)	2500	100	10
Poisson's ratio	0.35	0.3	0.4
Thickness (mm)	110	200	1000
Cohesion (kPa)	-	20	46
Friction (deg)	-	35	1
Dilatancy (deg)	-	5	0

Table 2. Properties of reinforcement considered in FLAC^{3D} model

Properties	Reinforcement
Material model	Linear elastic
Elastic modulus, *E*, MPa	8.5e8
Poisson's ratio, ν	0.33
Thickness, *t*, mm	3
Coupling spring cohesion, *cs_coh*, kPa	7
Coupling spring Friction angle, *cs_fri,* deg	24
Coupling shear stiffness, *cs_sk*, kPa	2.7e9

5. NUMERICAL MODELING

Explicit finite difference program FLAC^{3D} was used for modeling of unreinforced and reinforced flexible pavement sections. Pavement material properties for the analysis were chosen from the existing literature. Because of symmetry, one-fourth section of paved section was chosen for modeling. Duncan et al. (1968) modeled flexible pavement as 2D axisymmetric problem using FEM technique by radially constraining nodes at 12 times radii from centre and 18 times radii in vertical direction. Mousavi et al. (2005) used five times radii from centre and six times radii in vertical direction to fix the boundaries in lateral and vertical directions. Goud et al. (2018) modeled a plain-strain pavement section using 20B and 17B in horizontal and vertical directions to ensure sufficient accuracy. In this study, nodes were radially constrained at 12 and 35 times radii in horizontal and bottom boundaries. Linear elastic models were validated with KENPAVE. Static loading equal to 550 kPa was applied over 15 cm radius. Fig. 2 shows the model developed using FLAC^{3D}.

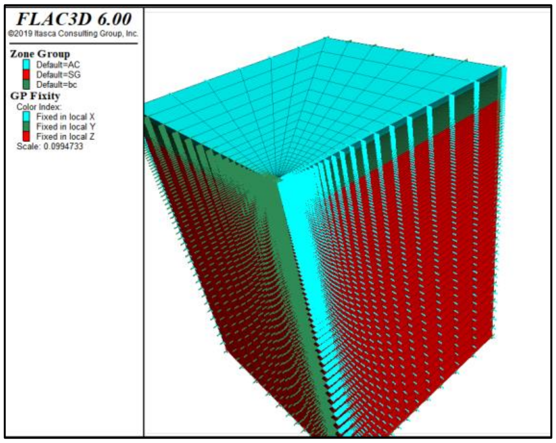


Figure 2. FLAC^{3D} model with boundary conditions assigned

Table 3 gives the comparison of maximum surface deformation, compressive strain, and horizontal strain with numerical model. An equivalent unpaved section with granular base of thickness 490 mm was chosen corresponding to 200 mm granular base in paved section exhibiting similar compressive strain at top of subgrade. Further, granular base course and subgrade were modelled using the Mohr-Coulomb model to model the non-linear behavior of pavement. 'Geogrid' element with linear elastic behaviour was used for modeling of biaxial geogrid in FLAC^{3D}. For this study geogrid with axial stiffness of 2500 kN/m was used. Large strain was activated to accurately model the deformations occurring in model.

Table 3. Comparison of KENLAYER and FLAC^{3D}

Program	Maximum settlement(mm)	Maximum Tensile strain (at bottom of asphalt)	Maximum Compressive strain (at top of subgrade)
KENLAYER	2.40	-5.319e-4	1.00e-3
FLAC^{3D}	2.39	-5.27e-4	1.06e-3

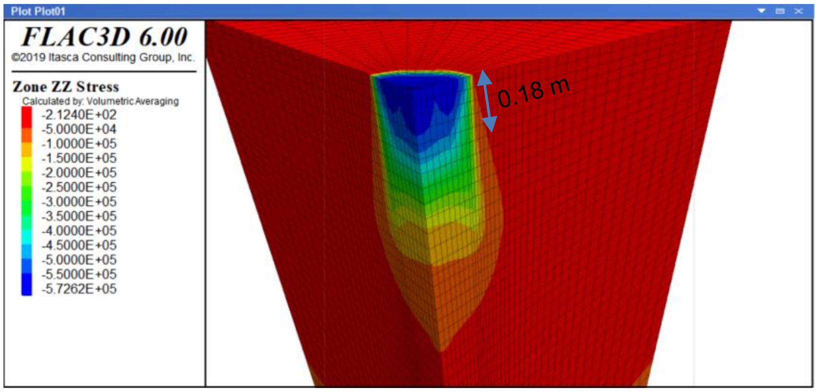
6. RESULTS AND DISCUSSION

Modeling of unpaved and paved sections were done using FLAC3D. Linear elastic analysis matched well with output of KENLAYER program. Non-linear analysis was done by modeling base course and the subgrade soil using Mohr-Coulomb model. Table 4 shows the comparison between linear and non-linear analysis. Surface deformations for unpaved and paved sections considering M-C model were found to be higher than that of linear elastic method.

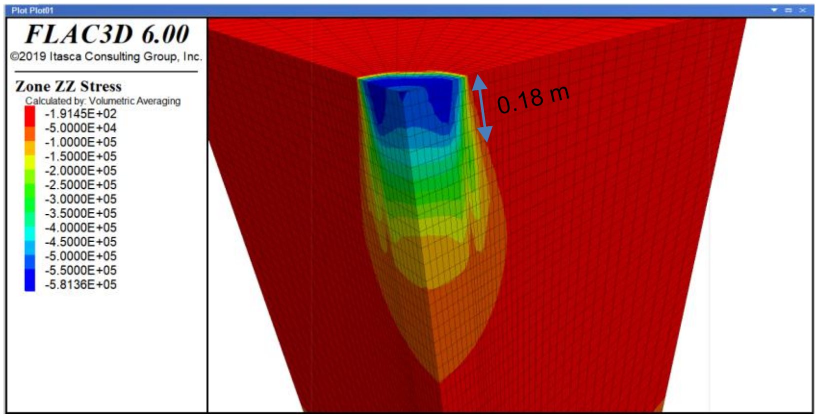
Table 4. Comparison of linear and non-linear analysis of granular base and subgrade

	Maximum surface deformations (mm)	
Analysis Type	Unpaved	Paved
Linear Elastic	3.3	2.4
Mohr-Coulomb	10.3	2.9

Fig. 3 shows the vertical stress contours for unreinforced and reinforced unpaved section for applied loading of 550 kPa. Presence of reinforcement reduces the vertical stresses and can be clearly seen from the pressure bulb. Vertical stress at a depth 0.18m for unreinforced unpaved section was 470 kPa and for reinforced section was 389 kPa (a reduction of 17.23%).



a) Unreinforced paved section



b) Reinforced paved section

Figure 3. Vertical stress contours

Fig. 4 & Fig. 5 show the bearing pressure vs. settlement ratio for unpaved and paved sections. For unpaved section, presence of geogrid reduced the maximum surface deformations. As the load increases, the effect of geogrid was found to be more significant especially for higher settlement ratio (greater than 5%). For settlement ratio of 8%, it can be noted that there was 5% increase in load bearing pressure of reinforced case compared to unreinforced case. For this study, load improvement factor (defined as ratio of the bearing pressure under footing of reinforced section to unreinforced section under for the equivalent settlement) was found to vary from 1.01 to 1.10 for settlement ratios from 4% to 16%, and was found to match well with Goud et al. (2018). For paved section, there was no variation in load-settlement curves indicating that the geogrid in base layer of paved roads is not very effective under static loading. The effect of geogrid on paved section may be more significant for dynamic loading compared to static loading.

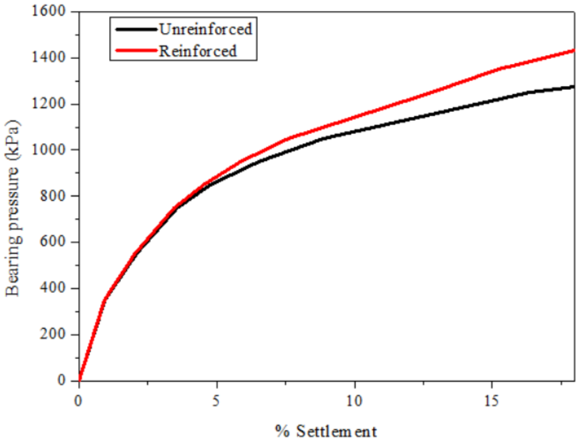


Figure 4. Load-settlement curve for unreinforced and reinforced unpaved sections

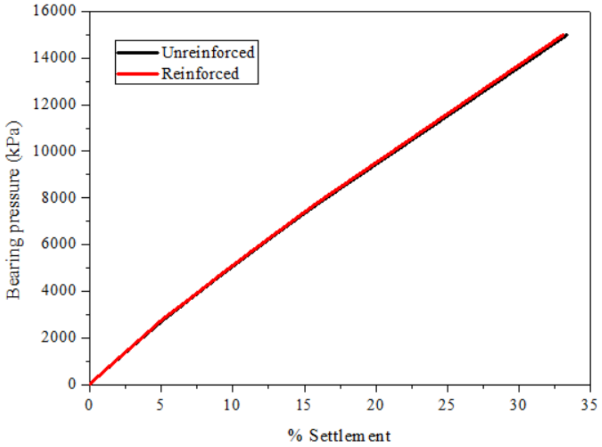


Figure 5. Load-settlement curve for unreinforced and reinforced paved sections

7. CONCLUSIONS

Based on the analysis carried out using FLAC^{3D} for flexible pavements, we can conclude that

- Surface deformations for unpaved and paved sections considering Mohr-Coulomb model were found to be higher than those compared to linear elastic model. Hence, it is necessary to conduct non-linear analysis of flexible pavements.
- Effect of geogrid was found to be significant in unpaved section for settlement ratio greater than 5%.
- Load improvement factor, a governing parameter comparing the behavior of unreinforced section and reinforced sections, from this study was found to range from 1.01 to 1.10 for settlement ratios varying from 4% to 16%.
- The load bearing pressure of reinforced case was observed to be 5% higher than unreinforced case corresponding to a settlement ratio equal to 8%.
- Effect of geogrid in base layer of paved roads was not very significant for static loads.

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