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THREE-DIMENSIONAL ANALYSIS OF GEOGRID REINFORCED FLEXIBLE PAVEMENT USING FINITE DIFFERENCE PROGRAM FLAC^{3D}

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ABSTRACT: India ranks second after the United States in terms of road infrastructure. In recent years, geosynthetics have created an impact on enhancing the life of the pavement. Numerous studies have been done on the application of geosynthetics on the flexible pavement to reduce rutting deformations and fatigue cracks. Laboratory and field studies have cost and time constraints. These limitations can be overcome by making use of numerical models. This research focuses on the numerical analysis of biaxial geogrids in flexible pavement. Proper knowledge of geogrid-pavement layer interaction is essential to obtain an understanding of strains, stresses, and deflections in pavement layers. In this study, a three-dimensional model of the geogrid reinforced unpaved road is developed using the finite difference program - FLAC^{3D}. Appropriate constitutive models are selected for the pavement layers. Geogrid is modeled using a linear elastic ‘geogrid’ element in FLAC^{3D}. The thickness of pavement layers in the analysis is taken as per the codal provisions of IRC: 37-2012. For pavements underlain by weak subgrade, the study shows that geogrid is more efficient in resisting the loads for settlement ratios higher than 2%. Based on the results from the numerical model, the optimal location of geogrid is proposed at one-third base thickness from the top of the surface of the pavement. This study is useful for construction sites where competent aggregates are not available and subgrade CBR is less than 5%.

Keywords: Geogrid, Numerical model, Static loading, FLAC^{3D}

1. INTRODUCTION

Geosynthetics have been successfully applied in various civil engineering problems, especially to enhance the long-term performance of the pavement. Major distress occurring in pavements is due to fatigue, rutting, reflective cracking, potholes, etc. At construction sites where competent aggregates are not readily available, geosynthetic reinforcement techniques can be a viable option. Three mechanisms mainly contribute to improvement in the pavement performance- (a) latj3eral restraint mechanism, (b) improved bearing capacity mechanism, and (c) tensile membrane effect of the reinforcement [1-4]. These mechanisms were based on the findings from the analysis of unpaved sections. In lateral restraint mechanism, geosynthetics prevents the lateral movement of base aggregates, which occurs under the application of traffic loading. This happens due to interfacial friction and interlocking between geosynthetic and aggregates. In the increased bearing capacity mechanism, geosynthetics shift the potential failure envelope to a stiffer layer. In the membrane support mechanism, geosynthetic will become concave in shape, and tension developed within will support the wheel load and decrease the vertical stress on the subgrade upon the application of load. Commonly used geosynthetics in pavement applications include geotextiles, geogrids, and geocells.

Researchers have examined the improvement in the structural performance of unpaved and paved sections using these reinforcement types via large-scale laboratory tests, full-scale field tests, and numerical modeling. Perkins [5] highlighted that geogrid when placed in the base layer improved the performance of pavements. It was found that stabilization of pavements using geosynthetic reinforcement has led to a reduction in granular base layer thickness [4-7], rutting and fatigue strains [3-4], and reflective cracking [8]; thereby increasing the service life of the pavement.

Laboratory and full-scale field tests [9-11] are often preferred but are subjected to cost and time constraints. With the development of advanced computational facilities, numerical modeling of pavement can aid in calculating strains, stresses, and deflections occurring in pavement layers and properly study the geogrid-pavement layer interaction under wheel load at a reasonable cost. Consequently, time-consuming laboratory and field tests can be avoided. There are several numerical methods used by researchers such as Multilayer elastic theory, Finite difference method (FDM), Finite element method (FEM), Boundary element method (BEM), Discrete element method (DEM), etc., to estimate stress, strain, and surface deformation in pavements.

Duncan [12] did pioneering work on the analysis of unreinforced flexible pavement using the FEM-based technique. He validated the model with elastic solutions and highlighted that this method is also capable of simulating the actual behavior of the pavement with inherent nonlinear material properties. Researchers have used FEM-based numerical software, such as ANSYS, ABAQUS, ADINA, PLAXIS, etc., for numerical modeling of pavement. Wathugala [13] modeled reinforced pavement using finite element software ABAQUS by placing geogrid at the interface of base-subgrade and found a significant reduction in rut depth. Perkins [3,5,9] conducted extensive experimental studies and field studies on reinforced pavement sections. They also conducted a three-dimensional analysis of geosynthetic modeling using ABAQUS [26]. Ling [14] used PLAXIS2D to perform the analysis of reinforced pavement subjected to static, cyclic, and dynamic loading. Barksdale [15] studied the behavior of unreinforced and geogrid-reinforced pavement sections subjected to cyclic loading via experimental studies. Leng [6] used ABAQUS to conduct an analysis of geogrid reinforced granular bases overlying soft subgrade. Leng [6], in his study, placed the geogrid at the interface of base and subgrade and studied the effect of thickness of a base layer on the reduction of surface deformation for geogrid reinforced sections. Saad [16] had used ADINA™ for three-dimensional finite element analysis of geosynthetic reinforced flexible pavement subjected to dynamic loads. It was recommended that geogrid should be kept at the lower one-third of the base layer thickness irrespective of subgrade strength. Moayedi [17] used PLAXIS2D axisymmetric analysis to study the effect of geogrid reinforcement in paved roads. Ahirwar [18] conducted an analysis of reinforced pavement using PLAXIS2D and Mohr-Coulomb model was used for various pavement layers. Geogrid with a triangular aperture shape was found to be more efficient in improving the behavior of pavements when compared with biaxial geogrid of similar stiffness [19-22]. Mousavi [8] conducted a finite element study of unpaved geogrid reinforced sections and evaluated the optimal location of reinforcement in pavement layers to study the maximum efficiency. Major parameters considering geogrid efficiency include the position of geogrid, stiffness of geogrid, and strength of subgrade. Pandey [23] concluded that the highest reduction in fatigue strain occurred when geogrid was placed at the base-asphaltic concrete interface and the highest reduction in vertical strain occurred when placed at the interface of base and subgrade.

This study considers a finite difference method for the analysis of unpaved roads subjected to wheel loading. Fast Lagrangian Analysis of Continua (FLAC3D), being an explicit FDM program, solves all equations of motion and has a variety of nonlinear constitutive models suitable for modeling nonlinear stress-strain characteristics of pavement materials. Goud [24] conducted a numerical analysis of reinforced unpaved roads using the two-dimensional finite-difference program $FLAC^{2D}$. The three-dimensional analysis provides a better understanding of the behavior of pavement under wheel loads of different configurations [16]. However, the present study focuses on the analysis of unreinforced and reinforced unpaved roads under stationary wheel loading. In this study, the explicit finite difference program $FLAC^{3D}$ is used to develop a three-dimensional comprehensive model of geogrid reinforced unpaved roads. This study uses a simple constitutive material model- the Mohr-Coulomb model -for modeling the nonlinearity of base and subgrade materials. The developed numerical model is subjected to static loading. The study also focuses on recommending the optimal position of geogrid based on the load improvement factor and the effect of axial stiffness on the efficiency of geogrid reinforcement. This study can be further used for analysis under various wheel configurations and moving wheel loads by considering more advanced material models for different pavement layers.

2. RESEARCH SIGNIFICANCE

The role of geosynthetics in providing long-term solutions for various engineering applications such as pavement foundations, retaining walls, and slopes are well known for the past few decades. The three-dimensional analysis is needed for accurate modeling of pavement subjected to multiple wheel loads. The development of advanced numerical models will help in analyzing and evaluating the reinforced flexible pavements at an affordable cost. Cancelli [21] showed that geogrid is more efficient when soft subgrade conditions exist. This research is useful for pavements with thicker granular bases overlying soft subgrades. It is essential to find the optimum location of geogrid reinforcement to know the maximum efficiency of reinforcement inclusion.

3. MATERIAL PROPERTIES

A typical unpaved road section consists of a granular base course layer and subgrade layer. One of the challenges in constructing unpaved roads is the nonavailability of competent aggregate for granular bases.

3.1 Aggregate Base Course and Subgrade

In this study, marginal aggregates with a typical elastic modulus of 50 MPa were considered. The thickness of the aggregate layer was chosen as 250 mm, as recommended by Indian Road Congress [25]. Geosynthetics have been found to have a dominant influence in improving pavements over poor subgrades [14, 26]. Therefore, relatively soft subgrades with an elastic modulus of 10 MPa with a thickness of 750mm were considered. The material properties of pavement layers and geogrid were chosen from a similar study [6]. Table 1 gives the properties of the pavement layers.

3.2 Geogrid and Geogrid Soil Interface Properties

The axial stiffness of geogrid is a major factor in finding the efficiency of geogrid application in pavement [18, 24]. Various geogrid axial stiffness used in the study were 300, 1200, and 2400 kN/m. Properties of various geogrid reinforcements used in the model were given in Table 2. Geogrid-soil interface properties were chosen based on Hedge [27] and Itasca [28]. Coulomb model was used as the interface model

Table 1 Properties of base course and subgrade

Property	Granular base	Subgrade
Material model	Mohr-Coulomb	Mohr-Coulomb
Mass density, ρ_d, (kg/m^3)	2100	1800
Elastic modulus, E, MPa	50	10
Poisson's ratio, ν	0.35	0.42
Cohesion, c, kPa	35	20
Friction angle, ϕdegrees	40	4.9
Dilation angle, ψdegrees	10	0

Table 2 Properties of various reinforcements

Properties	Reinfor-cement 1	Reinfor-cement 2	Reinfor-cement 3
Material model	Linear-elastic	Linear-elastic	Linear-elastic
Elastic modulus, E, MPa	1e8	4e8	8e8
Poisson's ratio, ν	0.35	0.35	0.35
Thickness, t, mm	3	3	3
Coupling spring cohesion, cs_coh, kPa	30	30	30
Coupling spring Friction angle, cs_fri, deg.	25	25	25

3.3 Loading

Standard equivalent axle load of 80 kN (18,000 lb) used in pavement (as per IRC 37:2012) corresponding to a tire pressure of 550 kPa with 150 mm radius of the loaded area was used in the study.

4. NUMERICAL MODELING

4.1 FLAC^{3D}

FLAC^{3D} is capable of modeling complex behavior of continuum models including non-linear material behavior considering large displacements and strains.

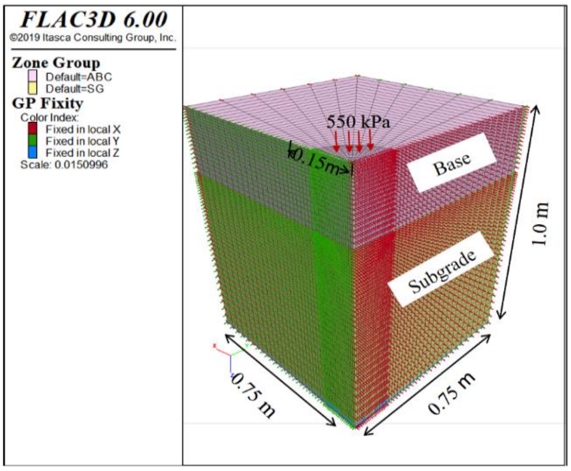

Fig.1 Numerical model in FlAC^{3D}

4.2 Modeling and Geometry

Considering the symmetry, one-fourth section of unpaved road was modeled. Boundary conditions were chosen so that fixed support was provided at the bottom and roller support at left and right boundaries. Lateral boundaries were kept at 0.75 m from the center and the bottom boundary is kept at 1.0m vertically down as in [6]. Fig. 1 shows the numerical model developed in FLAC^{3D}.

Granular base course and subgrade were modeled using the Mohr-Coulomb plasticity model. Modeling of biaxial geogrid was done using the linear elastic 'geogrid' element available in FLAC^{3D}. Geogrid is often modeled as an isotropic linear elastic element [29]. Uniform loading of 550 kPa was applied. The large-strain mode was activated to account for the significant plastic deformations by unpaved roads [30]. The convergence of the model in FLAC^{3D} was ensured by finer discretization of mesh and satisfying the criterion of reaching maximum unbalanced force ratio of 1e-6 for the equilibrium. In the analysis of reinforced pavement models, a refined mesh size around the interface equal to 0.8 times the mesh size of the surrounding region was used to study the effect of geogrid. Vertical displacement contours for unreinforced and reinforced models are shown in Figs. 2 and 3.

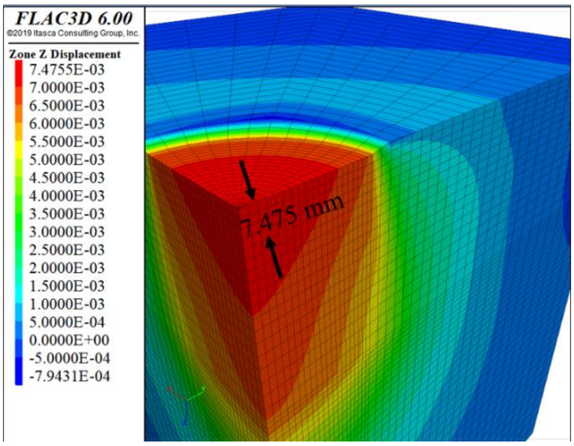

Fig. 2. Vertical displacement contours of the unreinforced unpaved section

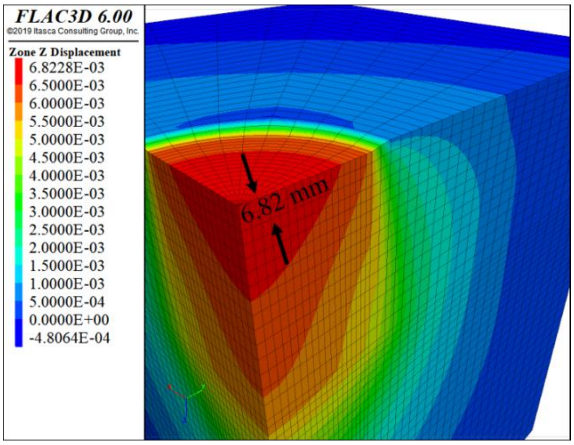

Fig. 3. Vertical displacement contours of the reinforced unpaved section

4.3 Validation

Unreinforced and reinforced pavement model developed was validated with available studies in the literature [6] by comparing the maximum surface displacements as given in Fig. 4. The base layer thickness was varied as 150, 200, and 250 mm. Leng [6] model showed a 13% reduction in surface deformation due to the presence of geogrid, whereas the present model showed 10% for a base thickness of 250 mm.

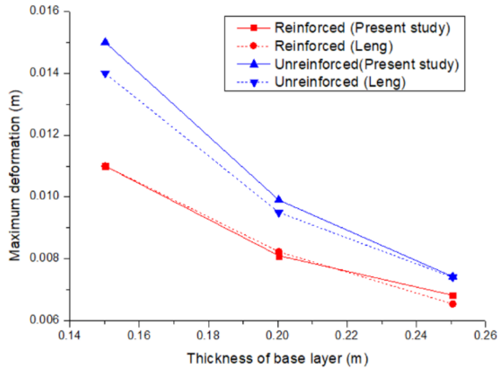

Fig. 4. Comparison of maximum surface displacement from this study with Leng [6].

Leng [6] has placed geogrid at the interface of the base and subgrade. Whereas the present study focused on placing the geogrid at various locations in the base layer to study the optimal location of geogrid to obtain the maximum efficiency of geogrid was observed. This study is beneficial for pavements with thicker granular bases overlying soft subgrades [31]. In addition, reinforcement stiffness was varied to study the effect of geogrid stiffness in reducing the settlement of the pavement.

5. RESULTS AND DISCUSSION

Analysis showed that geogrid reinforced unpaved sections undergo lesser deformation compared to unreinforced unpaved sections for given base layer thickness under the same loading. Fig. 5 shows the contour of vertical displacement of unreinforced and reinforced pavement section under 700 kPa.

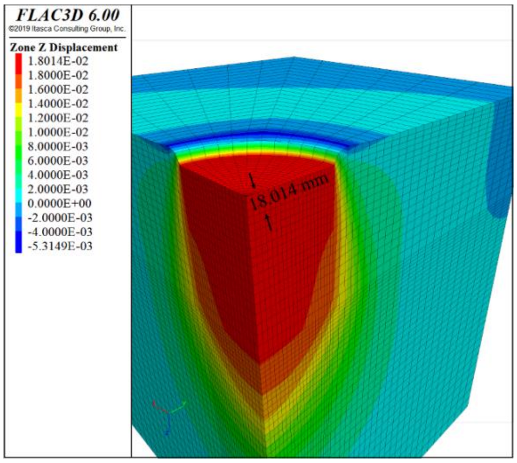

Fig. 5a Unreinforced section (subjected to loading of 700 kPa)

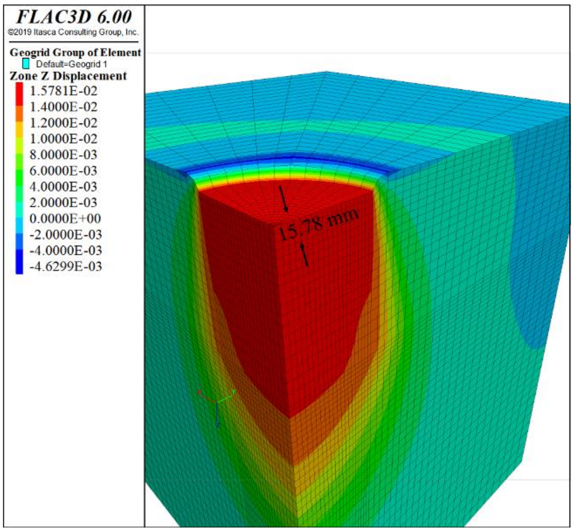

Fig. 5b Reinforced section (subjected to loading of 700 kPa)

It was found that the presence of geogrid has reduced maximum surface deformations by 12%. A parametric study on the optimal location of geogrid and the effect of axial stiffness was conducted.

5.1 Optimal Location of Geogrid

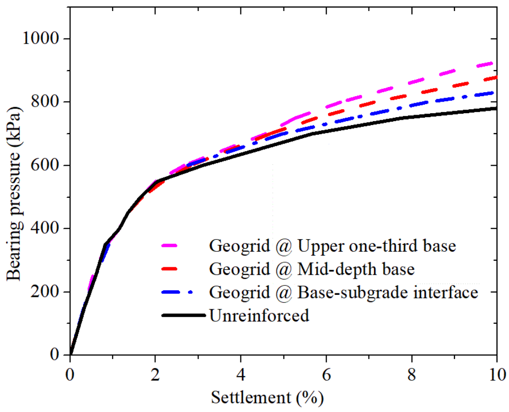

Fig. 6. Bearing pressure *vs.* settlement ratio of unreinforced and reinforced unpaved roads

Mousavi [31] reported that the addition of geogrid reduced the surface deformation for thinner granular base layers. They were also able to show that the location of geogrid plays an important role in reducing surface deformation. Fig. 6 shows the bearing pressure *vs.* settlement ratio at various locations of geogrid in the base layer. The inclusion of geogrid was found to reduce surface deformations. It was observed that as bearing pressure increases, the effect of geogrid was more significant. In addition, geogrid was more efficient at a higher settlement ratio (greater than 2%).

Geogrid was placed at three locations, viz., upper one-third base, mid-depth base, and at the interface of base and subgrade. This was shown to improve the load-settlement behavior. The optimal location of geogrid in the base layer is very important to assess the maximum benefit imparted by geogrid. In this study, placing the geogrid at the upper one-third resulted in the least deformations (Fig. 6).

5.2 Effect of Axial Stiffness of Geogrid

Reinforcement stiffness plays a major role in improving the performance of pavements. The axial stiffness of reinforcement was varied by keeping geogrid at the proposed location. As the axial stiffness of reinforcement increases, the load taken by the pavement for a given-settlement ratio was found to increase. Different geogrid stiffnesses, viz., 300, 1200, 2400 kN/m were used for the study. Fig. 7 shows load *vs.* settlement ratio for varied geogrid stiffness. Stiffness above 1200 kN/m showed a significant effect on the load-settlement curve.

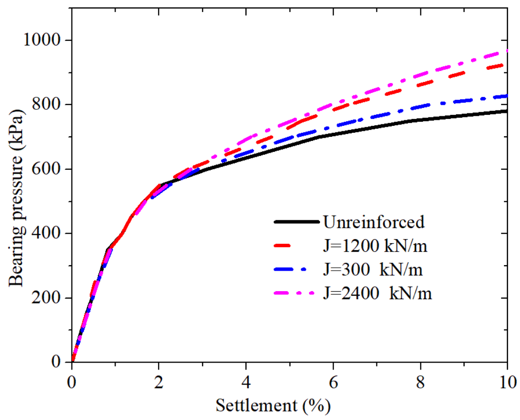

Fig. 7. Bearing pressure *vs.* settlement ratio of pavements reinforced with various geogrid axial stiffness

Load improvement factor is defined as the ratio between the bearing pressure under the footing of the reinforced section to that of the unreinforced section under the same settlement [32,33]. Table 3 shows the load improvement factor for various reinforcement axial stiffness. Load improvement factor was more significant for settlement ratio higher than 2% as reported in [30]. For axial stiffness equal to 300 kN/m, the load improvement factor ranged from 1.03-1.06%. Goud [24] observed a load improvement factor of 1.06 for settlement ratio equal to 8% for the case of reinforcement with axial stiffness of 292 kN/m, which matched with the present study. Whereas at higher stiffnesses of 1200 and 2400 kN/m, the load improvement factor varied from 1.05-1.19% and 1.11-1.25%, respectively. For unpaved roads, Goud [24] had reported load improvement factors ranging from 1.08 to1.28 for settlement ratios of 4-16% corresponding to geogrid axial stiffness ranging from 292-29,200 kN/m. Thus, a stiffness of 1200 kN/m gave better performance and is hence suitable for the pavement with marginal aggregates.

Table 3 Load improvement factor for various reinforcement stiffness

Sl. No	Settle-ment ratio (%)	Load improvement factor		
		Reinfor-cement 1	Reinfor-cement 2	Reinfor-cement 3
1	4	1.03	1.05	1.10
2	6	1.05	1.12	1.15
3	8	1.06	1.15	1.19
4	10	1.06	1.19	1.25

6. CONCLUSIONS

Three-dimensional analysis of the unreinforced and reinforced unpaved model was conducted using FLAC^{3D}. The reinforced unpaved section showed 12% lesser surface deformations in comparison with the unreinforced section corresponding to a settlement ratio equal to 5%. The optimal location of geogrid in the granular base layer is proposed as one-third depth from the surface. Another characteristic governing the reinforcement efficiency is choosing the appropriate axial stiffness of geogrid. As per the present study, reinforcement stiffness higher than 1200 kN/m was found to be more efficient than lower stiffness values. Judiciously choosing the optimal location and geogrid axial stiffness can save a huge amount of construction cost and time. This study is particularly relevant for construction sites where competent aggregate material is not readily available and for soil subgrade of low CBR ranging between 2 and 5%. Analysis using advanced constitutive materials models for various pavement materials subjected to multiple wheel loads is not within the scope of this study.

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