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Investigation of geogrid base reinforcement mechanisms considering residual stress and confinement effects

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ABSTRACT: Recent research at the University of Illinois focused on the development of a mechanistic model for the response analysis of geogrid reinforced flexible pavements. The model utilizesthe finite element approach and properly considers the nonlinear, stress dependent pavement foundation as well as the isotropic and anisotropic behavior of the granular base/subbase materials. Compaction and preloading induced base course residual stresses can also be considered in the mechanistic analysis. The inclusion of geogrids in the granular base caused development of a stiffer layer associated with aggregate interlock around the geogrid reinforcement. The primary focus was to study increased confinement effects on improved layer moduli and reduced critical subgrade vertical strains/stresses, which contribute to geogrid tensile reinforcement mechanisms. An increase in horizontal confinement due to residual stresses resulted in significant increases in the moduli of the base and subgrade layers in the vicinity of the geogrid reinforcement. The degree of structural benefit provided by geogrid reinforcement could be successfully quantified in response analysis to show the commonly observed technical benefit of geogrids in the field.

1 INTRODUCTION

Residual stresses develop in unbound aggregate layers as a result of the initial compaction and subsequent repeated traffic loading. These residual stresses should be properly quantified and taken into account for determining the initial stress state of the granular base and subbase layers in the mechanistic response analysis of a flexible pavement.

Among several geosynthetic products, geogrids are believed to enhance the structural performance of flexible pavements by providing reinforcement to the pavement structure through the base course aggregate interlock and improved confinement under wheel loading. The inclusion of the geogrid naturally causes development of a stiffer layer associated with the interlocking action that develops around geogrid reinforcement (Perkins et al. 2004, Konietzky et al. 2004 and 2005).

This paper primarily focuses on the investigation of geogrid confinement and interlock effects on pavement response by introducing residual stress distributions as initial stress states in the aggregate base. Using the recently developed mechanistic model at the University of Illinois, both unreinforced and geogrid reinforced pavement sections have been recently studied for identifying possible geogrid reinforcement mechanisms. Comparisons are made among various finite element solutions with and without residual stresses to highlight benefits of geogrid base reinforcement quantified in terms of reductions in predicted critical pavement responses.

2 BACKGROUND ON THE DEVELOPED MECHANISTIC MODEL

A mechanistic response model was recently developed based on the Finite Element (FE) methodology for the analysis of geosynthetic reinforced flexible pavements (Kwon et al. 2005). Continuum elements are used to model the asphalt concrete (AC), base, and subgrade layers using the 8-noded axisymmetric solid elements. In addition, 3-noded membrane elements and the neighboring 6-node interface elements are used to model the geosynthetic and the soil/aggregate-geosynthetic interfaces, respectively. The pavement system is then analyzed by assigning linear elastic and nonlinear elastic layer properties. Incremental loading is also considered in the nonlinear analysis for a proper characterization of stress dependency of the moduli and the optional inputs of unbound base residual stress distributions.

2.1 *Investigation of confinement effects using discrete element modeling*

Recent work by ITASCA researchers applied the Discrete or Distinct Element Modeling (DEM) technique by the use of a 3-dimensional (3D) particle flow code, PFC3D, for investigating soil/aggregate and geogrid interactions and modeling the confinement effects and the actual physical geometry of the aggregate-geogrid interlock (Konietzky et al. 2005). In this methodology, multiple interacting bodies undergoing large dynamic motions can be modeled by modeling the individual particles or elements and computing their motion, and the overall behavior of the assembly.

Konietzky et al. (2005) performed PFC3D pullout test simulations using a box with a footprint of 0.112 m by 0.1161 m and a height of 0.60 m filled with a uniformly graded CA-11 unbound aggregate material. A biaxial geogrid was placed horizontally in the middle of the aggregate column. Two to three different sized spherical elements glued together were used to establish the individual aggregate particle sizes and thereby achieve laboratory measured friction properties in model validations.

In the first stage, the consolidation process with 69 kPa surface load was performed for with and without geogrid cases. Next, the surface load was removed and the horizontal stresses near the geogrid were calculated. Then a complete pullout test was performed with the 69-kPa surface load. The complete data sets saved at intermediate stages were then used for computing the relaxation.

Figure 1 shows horizontal stresses near the location of geogrid computed after consolidation with and without geogrid (constant dashed and dashed-dotted lines, respectively) cases and the development of the horizontal stresses after relaxation during the pullout, each with removed surface load. S11 corresponds to the horizontal stress in the pullout direction while S22 is for the horizontal stress perpendicular to S11. What is remarkable is the significant difference between the horizontal residual stresses after consolidation with and without geogrid, in particular concerning the stresses above the geogrid (see Figure 1). While the stresses without geogrid are in the range of 2 to 2.5 kPa, with geogrid they go up to 4 kPa. Although stresses are small in magnitude, with and without geogrid stress ratio is in the order of 1.5 to 2. Below the geogrid, an increase in stresses with geogrid resulted in a similar ratio of nearly 1.5.

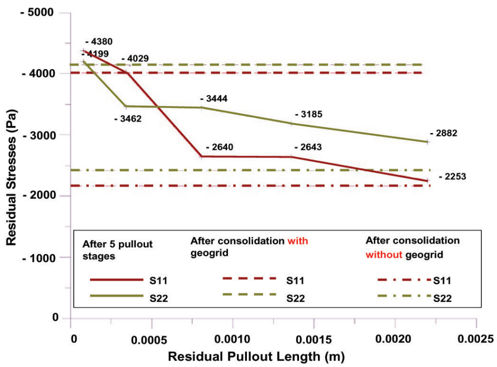

Figure 1. Development of S11 and S22 horizontal stresses above the geogrid.

This modeling simulation proved that small geogrid movements, for example, due to the compaction process during construction or later due to traffic load, can lead to permanent residual stresses locked-in around the geogrid, which may be directly linked to the increased confinement and interlock achieved through the use of geogrid base reinforcement in flexible pavement systems. Preliminary investigations by Konietzky et al. (2004) indicated that the zone of influence and consequently the area of locked-in permanent residual stresses is restricted to approximately 10 cm above and below the geogrid, depending on aggregate size and geogrid type.

3 GEOGRID REINFORCED PAVEMENTS

3.1 *CASE STUDY: finite element analysis of a low-volume road pavement*

Using the mechanistic FE response model, a typical low-volume road flexible pavement section was modeled to study the effects of initial residual stresses on the predicted pavement responses. The layer properties assigned to the unreinforced and geogrid-reinforced sections are given in Table 1.

Only isotropic analysis was considered in the base employing the Uzan (1985) model and the bilinear approximation by Thompson and Elliott (1985) as the nonlinear material models for the unbound aggregate base and subgrade layers, respectively (see Kwon et al. 2005). The geogrid and the interface elements were placed at the base-subgrade interface. Only one set of interface stiffness properties, k_s and k_n, were employed (see Table 1) for both the base-geogrid and geogrid-subgrade interfaces for simplicity although a more detailed study of the interface properties, currently ongoing at the University of Illinois, has indicated that typically higher shear stresses develop at the base-geogrid interface.

Figure 2 shows two different horizontal residual stress distributions considered in the response analyses of unreinforced and geogrid reinforced pavement sections. In Figure 2(a), a residual stress of 21 kPa was assumed to exist throughout the depth of the granular base in accordance with the field

Table 1. Material properties assigned in the nonlinear finite element analyses.

Materials	Thickness (mm)	E (MPa)	ν	Material Properties			
Asphalt Concrete	76	2,758	0.35	Isotropic and Linear Elastic			
Base	254	124	0.4	K_1 (kPa) 4,100	K_2 0.64	K_3 0.065	
Subgrade	–	41	0.45	K_1 or E_{RI} (kPa) 41,369	K_2 or σ_{di} (kPa) 200	K_3 1,000	K_4 200
Geogrid (placed at the base-subgrade interface)	1.27	552 or 5516	0.3	Isotropic and Linear Elastic			
Interfaces (above and below the geogrid)	0			Interface Spring Stiffnesses (kPa/m)			
		normal: k_n		$2{,}443*10^6$	shear: k_s	$4.1*10^6$	

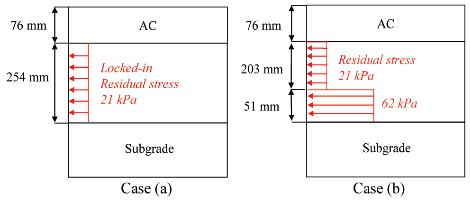

Figure 2. Pavement geometry and residual stresses assigned throughout the base layer.

measurements of Barksdale and Alba (1993). The nature and the distribution of the locked-in horizontal residual stresses in the base course around the geogrid reinforcement are still not known. After studying effects of different residual stress distributions on pavement responses, the distribution shown in Figure 2(b) with three times higher residual stresses was chosen to represent the stiffened zone in the base course directly above the geogrid for higher confinement and interlock.

Two different modeling approaches were taken to investigate geogrid reinforcement mechanisms with the locked-in residual stresses. In the first approach, a typically 10 times higher than normal geogrid modulus (5,516 MPa) was first assigned to the reinforced section to somewhat amplify the tensile reinforcement effects, as considered previously by Kwon et al. (2005). In this approach, a constant residual stress of 21 kPa [case (a) in Figure 2] was also assumed in the aggregate base. In the second approach, a normal geogrid modulus of 552 kPa was assigned to the reinforced sections to study the effect of increased residual stress distribution around the geogrid in the base-subgrade interface, case (b) in Figure 2, on the predicted pavement responses.

3.1.1 *Comparison of unreinforced and reinforced sections with high geogrid modulus*

Table 2 presents the critical pavement responses predicted at the centerline of loading from analyzing both the unreinforced and reinforced flexible pavement sections. Subgrade vertical strain, ε_v, has been the most commonly used critical pavement response to

Table 2. Predicted critical pavement responses

Pavement Response	Geogrid Modulus = 5,516 MPa (% Reduction from unreinforced pavement)				Geogrid Modulus = 552 MPa
	No residual stresses		Residual stress distribution		
			Case (a)		Case (b)
	UR*	Reinf	UR*	Reinf	Reinf
δ_v (mm) surface	1.08	1.05 (3.3%)	1.01	0.98 (3.3%)	0.99
ε_R (με) bottom of AC	–495	–482 (2.5%)	–466	–451 (3.2%)	–469
ε_v (με) top of subgrade	1,456	1047 (28.1%)	1351	993 (26.5%)	1089
σ_v (kPa) top of subgrade	57.7	55.7 (3.5%)	57.8	55.3 (4.4%)	56.0

*UR: unreinforced

correlate with subgrade rutting. This is also the pavement response that shows the most benefit of using geogrid tensile reinforcement in flexible pavements with its potential link to reduced subgrade permanent deformations through the use of transfer functions in the context of mechanistic-empirical pavement design.

The benefit of the geogrid reinforcement is expressed by the percent reduction in predicted responses of the unreinforced section in Table 2. The effects of using high modulus geogrid of 5,516 MPa are clearly shown for the predicted subgrade vertical strains for with and without residual stresses. In addition, Table 2 also lists the predicted responses when Figure 2 case (a) residual stresses were considered in both unreinforced and reinforced sections. In general, the presence of constant residual stresses distributed throughout the base does not really change much the degree of structural benefit provided by the geogrid reinforcement.

3.1.2 *Reinforced section with normal geogrid modulus*

The geogrid reinforced pavement section was analyzed in the second approach by assigning a typical biaxial geogrid modulus of 552 MPa. The residual stresses were also assumed to exist in this reinforced pavement section and the residual stress distributions were considered according to Figure 2(b). To numerically simulate stiffening around the geogrid in the second approach, much higher residual stresses in the order of 62 kPa were assigned in the 51 mm zone above the geogrid.

A very meaningful comparison can be made between the case (b) predictions and the results from the reinforced section with high geogrid modulus assignment of 5,516 MPa and no residual stresses. Considering these two cases what could be only achieved with really high geogrid modulus assignment can now be achieved with the typical geogrid modulus assignment and with the inclusion of case (b) residual stress distributions. This may be a very important finding to contribute to our present understanding of confinement affecting geogrid reinforcement mechanisms and also help to improve our continuum modeling in the FE analysis to potentially better simulate the observed geogrid benefits in pavement resilient response analysis.

Figure 3 shows as contour plots the predicted modulus distributions in the entire base and top of the subgrade layers in the reinforced sections with assigned 552 MPa geogrid modulus and Figure 2(b) residual stress distributions. The predicted modulus values are shown to increase very significantly especially around the geogrid to explain increased confinement indicated by the so-called stiffening effect above and below the geogrid reinforcement.

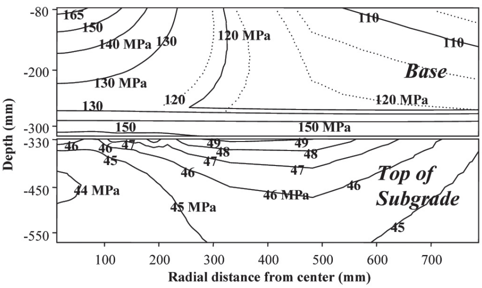

Figure 3. Predicted modulus distributions in the base and subgrade with assigned geogrid modulus of 552 MPa and 62-kPa residual stresses above the geogrid.

4 CONCLUSIONS

The results of the mechanistic pavement analyses indicated that the benefits of including geogrids in the granular base-subgrade interface could be successfully modeled by considering in response analysis up to 62 kPa residual stress concentrations assigned just above the geogrid reinforcement. Such residual stresses considerably increased the resilient moduli predicted in the base and subgrade of a pavement section modeled. Low subgrade vertical strains were also predicted to indicate a lower subgrade rutting potential when residual stress concentrations were assigned in the vicinity of the geogrid. The benefit achieved was equivalent to what could be achieved in previous studies only with a 10 times higher than normal geogrid stiffness assignment in the mechanistic response analysis.

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