Construction and Building Materials 122 (2016) 214–230

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Numerical modeling of geogrid-reinforced flexible pavement and corresponding validation using large-scale tank test

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HIGHLIGHTS

- Geogrid-reinforced pavement structure is modeled using the finite element software ABAQUS.
- An analytical model is developed to predict the cross-anisotropic resilient modulus of geogrid-reinforced granular material.
- A user-defined material subroutine is programmed to simulate the nonlinear cross-anisotropic behavior of geogrid-reinforced granular material.
- The influence of geogrid on pavement performance is quantified using the finite element results.
- A comprehensive large-scale tank test program is designed to validate the developed geogrid-reinforced pavement model.

ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 7 June 2016
Accepted 14 June 2016

Keywords:
Geogrid-reinforced flexible pavement
Finite element model
Cross-anisotropy
Large-scale tank test

ABSTRACT

This study aimed to develop a finite element model to simulate the geogrid-reinforced flexible pavement structure by taking into account the lateral confinement effect of geogrid layer, the interaction between geogrid and aggregate/soil, and the nonlinear cross-anisotropy of geogrid-reinforced unbound granular material (UGM). First, an analytical model was proposed to quantify the effect of the lateral confinement of geogrid layer on the resilient modulus of UGM. By comparing to the laboratory triaxial test results, the developed analytical model was proven to accurately predict the resilient modulus of geogrid-reinforced UGM. Second, the Goodman interface element model was used to characterize the contact behavior of geogrid-aggregate/soil interface. In order to simulate the nonlinear cross-anisotropic behavior of geogrid-reinforced UGM, a user-defined material (UMAT) subroutine was programmed using the secant modulus approach. The accuracy of the developed UMAT was verified by comparing the numerical simulation results to the analytical solutions in a virtual triaxial test.

Two pairs of geogrid-reinforced and unreinforced pavement models were analyzed in this study. It was found that the geogrid reinforcement is effective in mitigating the rutting damage of base course and subgrade, but cannot significantly extend the fatigue life of flexible pavement. The geogrid reinforced in the middle of the base course is better at reducing the rutting damage of base course than that placed at the base/subgrade interface. However, the geogrid reinforcement is much more effective in reducing the rutting damage of the subgrade when it is placed at the bottom of the base course. A comprehensive large-scale tank (LST) testing program was designed to record the critical pavement responses, including the surface deflection, the tensile strain at the bottom of the asphalt concrete, and the vertical stresses in base course and subgrade. The developed geogrid-reinforced and unreinforced finite element models were finally validated by comparing the model predictions with those measurements from the LST test.

1. Introduction

Geogrids are commonly used in unbound aggregates as a means of enhancing the performance of flexible base layer or the railroad ballast layer [1,2]. Many studies introduced tests performed on

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http://dx.doi.org/10.1016/j.conbuildmat.2016.06.081
0950-0618/

large-scale or in-service geogrid-reinforced pavement sections [3,4]. The test results indicated that geogrids are effective in improving the stiffness and stability of the reinforced pavement structures and reducing the accumulated permanent deformation. Beneficial effects of the geogrid layer have been identified on the responses of pavements under the traffic loading through two major mechanisms [5]:

a) Lateral confinement, which is produced by the interface frictional interaction and interlocking between the base course aggregates and the geogrid layer. Significant tensile stress is generated in the geogrid layer when a spreading motion is created by the traffic loading, which in turn reduces the vertical stress and shear stress dramatically due to the increased base course stiffness.
b) Vertical membrane effect. The inward shear stress caused by the membrane deformation reduces the outward shear stress generated by the repetitive wheel loading. As a result, the vertical stress is reduced and distributed widely around the geogrid layer.

To extend the use of geogrid in flexible pavement structures, there is a need to incorporate the geogrid material into the pavement design. The efficient laboratory characterization of geogrid-reinforced unbound granular material (UGM) is the first step for including the geogrid material in the pavement design, which has been completed recently by Gu et al. [6]. The repeated load triaxial tests were used to quantify the characteristics of geogrid reinforcement in terms of the cross-anisotropic resilient moduli and permanent deformation of the geogrid-reinforced UGM. It was found that the geogrid reinforcement effectively increases both the horizontal and vertical moduli of the UGM, meanwhile significantly reduces the accumulated permanent deformation of the UGM. The development of a numerical model to accurately simulate the geogrid-reinforced flexible pavement structure is the next step to quantify the influence of a geogrid on flexible pavement performance, and further to guide the geogrid-reinforced flexible pavement design.

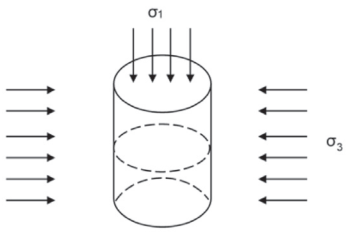
The numerical modeling of geogrid-reinforced pavement structure mainly focuses on the constitutive models of paving materials, the geogrid-aggregate/soil interface model, and the lateral confinement effect of the geogrid. The existing studies have shown that modeling the nonlinear cross-anisotropy nature of UGM is crucial to the accurate performance prediction of flexible pavement [7–10]. However, limited studies have been found on modeling the cross-anisotropic behavior of UGM for the geogrid-reinforced flexible pavement. Gu et al. [6] evaluated the effect of geogrid on the cross-anisotropy of UGM in the laboratory, which provided a sound basis for modeling the geogrid-reinforced pavement structure. In the numerical modeling of geogrid-reinforced pavement, the interaction between geogrid and aggregate/soil interface is another important aspect. When surfaces of geogrid and aggregate/soil are in contact, they usually transmit shear and normal stresses across their interface. The Goodman model has been widely used to characterize such interface contact, which is shown in Eq. (1) [11].

$$\begin{bmatrix} d\tau \\ d\sigma_n \end{bmatrix} = \begin{bmatrix} k_s & 0 \\ 0 & k_n \end{bmatrix} \begin{bmatrix} du_r \\ dv_r \end{bmatrix} \tag{1}$$

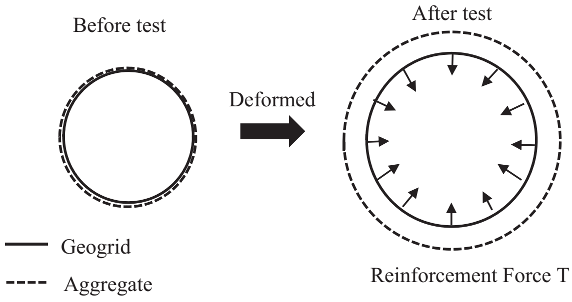
where τ is the shear stress; σ_n is the normal stress; u_r is the relative shear displacement; v_r is the relative normal displacement; k_s is the shear stiffness; and k_n is the normal stiffness. The interface slippage condition is quantified by the shear stiffness k_s. If the geogrid-aggregate/soil interface is fully bonded, the shear stiffness k_s will be assigned a large value, for example $k_s = 2.7 \times 10^8$ kPa/m [12]. If the slippage occurs at the geogrid-aggregate/soil interface, the shear stiffness k_s will be determined by Eq. (2) using the pullout test data.

$$k_s = \frac{\Delta P}{2l \cdot \Delta u_r} \tag{2}$$

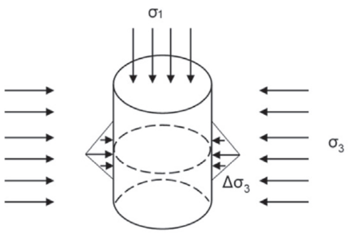
where ΔP is the incremental applied pullout force, l is the embedded length of geogrid, and Δu_r is the incremental relative displacement. To simulate the lateral confinement effect, Kwon et al. [13] developed a geogrid-reinforced pavement model by empirically assigning the additional confining stresses around the geogrid layer. This approach was found to effectively capture the resilient modulus of geogrid-reinforced base layer. Yang and Han [14] provided an analytical model to predict the resilient modulus of geogrid-reinforced UGM. One assumption made in developing the analytical model is that the additional confining stresses are uniformly distributed in the base course. This assumption, however, ignores the phenomenon that the influence of the geogrid reinforcement decreases with the distance of the aggregates from the geogrid, and the geogrid reinforcement is negligible when the material is distant from the geogrid. Therefore, it is desirable to improve the analytical model by using a more realistic additional confining stress distribution, and further to incorporate the improved analytical model into the numerical modeling of geogrid-reinforced pavement structure.



(a) Displacement Pattern of UGM Restraint by Geogrid



(b) Difference in Radial Movement of Geogrid and Aggregate



(c) Equivalence of Reinforcement Force to Additional Stress Δσ3

Fig. 1. Schematic Plot of Geogrid Reinforcement on UGM Specimen.