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A three-dimensional finite element approach for modeling biaxial geogrid with application to geogrid-reinforced soils

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A B S T R A C T

Understanding soil-geogrid interaction is essential for the analysis and design of geogrid-reinforced soil structures. A first step towards accurate modeling of this interaction is choosing a suitable material model for the geogrid that is capable of simulating tensile test results. The model must be able to capture the three-dimensional response of the geogrid considering its exact geometry. Modeling geogrid inclusion as a continuous sheet has proven to reasonably simulate the overall response of soil-geogrid systems; however, it does not explain the different sources of interaction between the geogrid layer and the surrounding soil. To understand the three-dimensional aspects of this complex interaction problem, a two-phase numerical investigation is developed in this study. The first phase focuses on the three-dimensional modeling of unconfined biaxial geogrid subjected to tensile loading. Applicability of the geogrid model in solving soil-structure interaction problems is then demonstrated, in the second phase, by investigating the response of a reinforced subgrade subjected to a square shaped surface loading. It is concluded that modeling the three-dimensional geogrid geometry is important to accurately capture the true response of geogrid under both confined and unconfined conditions. The modeling approach proposed in this study for the analysis of unconfined and soil-confined geogrid can be adapted for other reinforced soil applications.

1. Introduction

Geogrid reinforcement is known to be an effective method to enhance the performance and service life of different earth structures (e.g. embankments, pavements, foundations and retaining walls). Reinforced soil structures are usually designed using limit equilibrium methods. These methods do not generally provide sufficient information on the failure load and the displacements and strains developing in the reinforcement (Rowe and Mylleville, 1994; Sugimoto and Alagiyawanna, 2003). On the other hand, finite element (FE) methods have become powerful tools to efficiently predict the pre-failure displacements, and stresses generated in the reinforcement material.

Several studies that employ finite and discrete element methods to analyze geogrid-reinforced structures have been reported in the literature (Yogarajah and Yeo, 1994; Perkins and Edens, 2003; McDowell et al., 2006; Hussein and Meguid, 2013; Tran et al., 2013a,b; Mosallanezhad et al., 2016; Wang et al., 2016). Most of these studies focused on the overall response of the reinforced structure while adopting simplifying assumptions related to either the details of the geogrid geometry or the constitutive model of the geogrid material.

The nonlinear stress-strain response of geogrid polymeric material is recognized as an important characteristic that needs to be captured in both analytical and numerical modeling of reinforced-soil applications (Bathurst and Kaliakin, 2005; Kongkitkul et al., 2014; Ezzein et al., 2015). It is therefore, necessary to develop and incorporate a nonlinear constitutive model for the geogrid material to improve the accuracy of the numerical analysis. This model should contain sufficient components to characterize the unconfined response and captures the important geometric features of the geogrid before it interacts with the backfill material. In addition, the model has to be relatively simple, with respect to the number of required parameters, to facilitate implementation into existing numerical codes. A limited number of dedicated studies have been reported, to date, focusing on geosynthetic modeling in three-

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dimensional (3D) space. Most notably, the work of Perkins and his coworkers between 2000 and 2003.

Perkins (2000, 2001) presented an elastic–plastic model for geosynthetics that accounts for the creep behavior and direction dependency of the material. The model required a total of 24 input parameters to capture the material response under axial loading. The model, treated the geogrid as a planer sheet and, therefore, did not account for the discontinuous nature of the geogrid geometry. It has been demonstrated (Perkins and Edens, 2003) that the creep components have a small effect on the calculated load–displacement response of the geosynthetic material. The results did, however, show that plasticity had a significant effect on the load–displacement relationship, particularly, as the geosynthetic material approaches failure.

Another important factor to be considered in modeling geogrid is the 3D geometry of the network structure. Modelling geogrid using planer sheet does not allow for essential features to be captured, including: i) the unique deformation characteristics of each member during unconfined tensile loading condition, and ii) the effect of bearing resistance on confined geogrid ribs.

The objective of this study is to propose a 3D modeling approach to capture the details of biaxial geogrid under both unconfined and soil-confined conditions. This is achieved in two phases as follows:

i) A 3D nonlinear FE analysis has been performed to simulate the behavior of unconfined geogrid under tensile loading. The ABAQUS-based constitutive model used in the FE analysis is capable of capturing the ranges of elastic and plastic regions of the stress–strain relationship in the short-term under monotonic tensile loading. The geogrid geometry is modeled explicitly with its detailed features including the rib and junction thicknesses and the geogrid apertures.
ii) Using the geogrid model developed in the first phase, a 3D analysis of soil-confined geogrid is then performed to examine the validity of the geogrid model. An example that involves a square footing over geogrid-reinforced soil is presented and the results are compared with experimental data.

The 3D FE models presented throughout this study have been performed using the general finite element software ABAQUS/Standard, version 6.13 (ABAQUS, 2013).

2. Modelling unconfined geogrid

The details of the experiments and the 3D FE modeling of unconfined geogrid, covered in the first phase of this study, are discussed in this section.

2.1. Tensile tests

A series of index tests involving uniaxial-tensile loading was performed to measure the load–displacement response of the biaxial geogrid samples. The geogrid properties as provided by the manufacturer are summarized in Table 1. The tests are conducted according to the ASTM standard D6637-11 (2011) on multi-rib geogrid specimens in both the machine (MD) and the cross machine (XMD) directions. The geogrid sample comprises three longitudinal ribs and six transverse bars as shown in Fig. 1. In these index tests, one of the clamps is usually fixed while the other is allowed to move and pull the geogrid specimen. A 5 kN MTS machine with constant strain rate of 10% strain/minute was used to test five identical geogrid specimens in each direction. An extensometer with a gauge length of 25 mm was mounted at the center of the specimen to measure the elongation during the test whereas the applied load was recorded using a load cell integrated into the MTS machine. It should be noted that this test procedure allows for the overall geogrid response to be measured considering homogenized characteristics of the geogrid geometry. To take into account the solid material characteristics, the load carried by each rib is obtained by dividing the applied machine load by the number of ribs in the loading direction. The directional (axial) load-strain response of the solid material is presented in Fig. 2. The mean values of the measurements obtained from the five index tests are shown with one standard deviation range bars. For both the MD and XMD, the measured values are tightly clustered around the mean which indicates that the test results in both directions are repeatable and the material properties are uniform for the tested specimens.

From Fig. 2, the geogrid response is found to be mostly nonlinear with significant plastic deformations developing as failure is approached. The maximum strength was found to be 12.8 kN/m and 20.5 kN/m for MD and XMD, respectively. These results are consistent with the values reported by the manufacturer (given in Table 1). It is noted that although the response shown in Fig. 2 represents the specific biaxial geogrid used in this study, similar approach can be used for other types of geogrid by considering the number of ribs per meter in a given direction.

2.2. Model development

Three-dimensional FE analyses are conducted to simulate the index tests considering the geometric features of the geogrid, including the different element thicknesses and the opening dimensions as per the geogrid specimen. An elastic–plastic constitutive model is used to explicitly simulate the measured nonlinear behavior of the geogrid. The numerical model is first validated with the test results and then used to investigate the detailed response of the geogrid under tensile loading. Sensitivity analyses are also performed to examine the effect of the finite element size, type, shape, and interpolation function on the calculated geogrid response. The modeling details and the findings of the sensitivity analyses are discussed below.

2.2.1. Model components

Two main components are required for the successful development of the unconfined geogrid model: i) constitutive behavior, and ii) geometry and boundary conditions. These components are discussed in this section.

Constitutive behavior: Experimental results (Fig. 2) show that the biaxial geogrid sample behaves as a nonlinear elasto-plastic

Table 1
Index properties of the biaxial geogrid.

Direction	Aperture size (mm)	Specimen size (mm)		No. of members		Ult. strength (kN/m)	Mass/unit area (g/m^2)	Stiffness @ 2% strain (kN/m)
		L	W	Long.	Trans.			
MD	29	149	78	3	6	12	215	204
XMD	37	185	58			20		292

Note: The above values are reported by the manufacturer.