On the 3D Modelling of Soil-Geogrid Interaction

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ABSTRACT
Soil-geogrid interaction is a key issue in the design of geogrid-reinforced soil structures. Modeling a geogrid inclusion as a continuous membrane sheet has proven to reasonably simulate the overall response of the geogrid-soil system; however, it does not explain the different sources of interaction between the geogrid layer and the surrounding soil. This study presents the results of a three-dimensional finite-element analysis that has been conducted to simulate a laboratory size pull-out test considering the non-continuous nature of the geogrid material. The numerical results are compared with the measured forces and displacements along the geogrid as measured in the laboratory. The validity of the proposed numerical simulation and its advantages has been discussed.

RÉSUMÉ
L'interaction sol-géogrille représente une problématique majeure pour le dimensionnement des structures géotechniques renforcées par géogrille. L'utilisation d'une membrane continue pour modéliser l'intégration d'une géogrille simule de manière raisonnable l'ensemble du system géogrille-sol; cependant, ceci n'explique pas les différentes sources d'interaction entre la couche de géogrille et le sol avoisinant. Cette étude présente les résultats d'une analyse éléments finis en trois dimensions qui a été conduite pour simuler un essai d'arrachement en laboratoire considérant la nature discontinue d'une géogrille. Les résultats numériques ont été comparés avec les forces est les déplacements mesurés le long de la géogrille durant l'essai en laboratoire. La validité des résultats obtenus à travers la simulation numérique proposée ainsi que ces avantages sont discutés.

1 INTRODUCTION

Geogrid reinforcement has been shown to be an effective method to enhance the performance and service life of different earth structures (e.g. embankments, pavements, foundations and retaining walls). Extensive research has been conducted in the past two decades to study the role of different parameters that affect that interaction between a geogrid element and the surrounding soil using experimental (Palmeira and Meilligan, 1989; Bergado et al., 1993; Fannin and Raju, 1993; Farrag et al., 1993; Wilson-Fahmy, et al., 1994; Abramento and Whittle, 1995; Alfaro et al., 1995; Lopes and Ladeira, 1997; Bakeer et al., 1998; Hayashi et al., 1999; Sugimoto et al., 2001; Moraci and Recalcati, 2006) as well as numerical analysis (Yuan and Chua, 1990; Wilson-Fahmy and Koerner, 1993; Yogarajah and Yeo, 1994; Shuwang et al., 1998; Pal and Wathugala, 1999; Perkins, 2003; Sugimoto and Alagiyawanna, 2003; Siriwardane, et al., 2008). The improvement in the performance of the soil-geogrid system has been explained by the interlocking effect that leads to higher soil stiffness around the geogrid (Jewell et al., 1984; Lopes and Lopes, 1999).

To assess the design parameters related to the soil-geogrid interface, in-soil performance tests such as pull-out or shear box tests are commonly employed. Geosynthetics pull-out devices are used to assess soil-geosynthetics interaction for situation where the geosynthetics is pulled from a reinforced soil structure. Pull-out systems of different sizes and configurations have been proposed by several researchers to understand the pull-out behaviour of geosynthetic reinforced soils (Ingold, 1983; Farrag et al., 1993; Bergado et al., 1993; Collin and Berg, 1993). On the other hand, direct shear tests are commonly used to study the interface performance of soil-geosynthetic systems (Jewell and Wroth, 1987; Farrag, 1990; Alfaro et al., 1995; Bakeer et al., 1998; Nakamura et al., 1999).

Numerical methods have been used to interpret laboratory data and develop a better understanding of soil-geosynthetic interaction (Yogarajah and Yeo, 1994; Shuwang et al., 1998; Pal and Wathugala, 1999; Perkins and Edens, 2003; Sugimoto and Alagiyawanna, 2003).

It has been shown (Perkins, 2000) that the stress-strain behaviour of geosynthetic materials is complex and that a general purpose constitutive model must contain a number of components to describe this behaviour. Therefore, successful numerical simulation of reinforced earth structures depends on selecting proper constitutive models for the soil, geosynthetic and soil-geosynthetic interface (Pal and Wathugala, 1999).

The objective of this study is to investigate the three-dimensional response of a uniaxial geogrid embedded in granular material under pull-out loading condition. Emphasis is placed on the simulation of the true three-dimensional nature of the geogrid layer and the examination of the progressive changes in deformation during a typical pull-out experiment. To validate the proposed numerical model, the calculated response is compared with the measurements taken during pull-out test experiments.

2 PREVIOUS WORK

Several studies have been conducted by researchers to simulate the pull-out test procedure using finite-element analysis. Yuan and Chua (1990) presented a two-dimensional finite-element model where the soil and geosynthetic were modeled using hyperbolic relationships. Interface properties were derived from direct shear tests. Wilson-Fahmy and Koerner (1993) developed an incremental finite-element model to simulate the non-linear response of geogrids under pull-out loading. Polynomial and hyperbolic functions were used to describe the load-extension behavior of the geogrid and the soil-geogrid interaction. Yogarajah and Yeo (1994) used the finite-element program CRISP to simulate a pull-out experiment. A two-dimensional model was developed where the geosynthetic was simulated using bar elements. Joint elements were used to model the interface between the geosynthetic layer and the soil. Shuwang et al. (1998) proposed a two-dimensional finite-element model for the soil-geogrid interaction subject to pull-out loading. The geogrid was treated as a nonlinear-elastic plate with openings under plane stress-conditions and the interaction between the soil and geogrid was modeled using non-linear springs.

Perkins (2000) introduced a constitutive model for the geosynthetics as directional-dependent continuous layer with elasto-plastic material. Perkins and Edens (2003) conducted finite-element analysis of a pull-out test using the commercial finite-element program ABAQUS employing the constitutive model suggested by Perkins (2000) for the geogrid layer and the bounding surface plasticity model for the soil. The geogrid was modeled using 4-noded membrane elements. Shear interaction between the geogrid and the aggregate was established using two contact surface pairs employing Coulomb frictional model. The model parameters were adjusted to match the load-displacement relationships obtained from the laboratory tests. Results showed that the geosynthetic creep properties have a small effect on the load-displacement predictions. The results did, however, show that plasticity had a more significant effect on the load-displacement relationship as the geosynthetic approaches failure.

Sugimoto and Alagiyawanna (2003) performed 2D plane strain analysis of a pull-out test using DIANA program. The sand was modeled using eight-noded quadrilateral elements with elasto-plastic material obeying the Drucker-Prager yield criterion whereas the geogrid was modeled using three-noded truss elements. The study showed that when the geogrid stiffness increases and overburden pressure decreases the geogrid failure mode changes from elongation to slippage.

Siriwardane et al. (2008) conducted three-dimensional finite-element analysis to investigate the effect of the interface properties on the pull-out capacity of geogrid layers. The geogrid was treated as linear elastic material using membrane elements. To simplify the 3D model and avoid the termination of the geogrid inside the soil, the modeled geogrid layer was extended along the entire area of the box.

Although the above studies explained several interesting features of the geogrid-soil interaction under different loading conditions, they were mostly based on simplifying assumptions related to either the details of the geogrid geometry or the constitutive modeling of the geogrid material. To capture the non-continuous nature of the geogrid layers, discrete element analysis has been proposed by several researchers (e.g. McDowell et al. 2006). Results indicated reasonable performance in capturing the interface resistance and soil interlocking, however, the constitutive behaviour of the geogrid material had to be oversimplified.

3 DESCRIPTION OF THE ANALYZED PROBLEM

The pull-out test setup and experimental results used to validate the numerical model in this study are based on those reported by Farrag (1990). Figure (1) shows a side view of the analyzed pull-out box. The inside dimensions of the box are 153 cm long, 61 cm high, and 90 cm wide. The width of the box was chosen to keep a standard geogrid sample, of 30 cm wide, at a distance of 30 cm from each side of the box. The front wall contains a slot (5 cm in height) to allow for the clamping plates to be pulled out of the box. Five additional slots were located in the rear wall to facilitate the installation of measuring devices along the geogrid. An air bag 5 cm in thickness was used to apply vertical pressure over the soil. Sleeve plates were connected to the top and bottom of the front slot to transfer the pull-out load far behind the box rigid face. The sleeves also minimize the lateral stress transfer to the face during the pull-out process which would result in an apparent increase of the pull-out resistance.

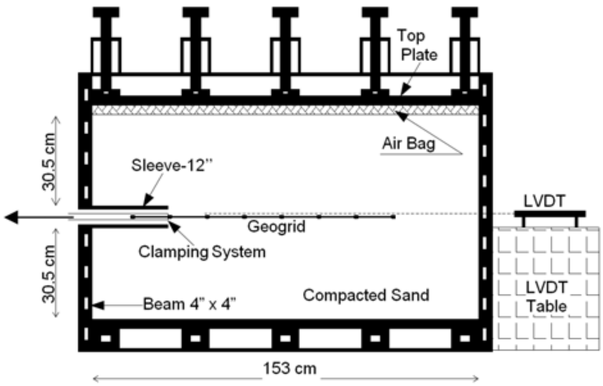

Figure 1. The pull-out box (Adapted from Farrag, 1990)

The instrumentation used to measure the geogrid response and the soil-geogrid interaction consisted mainly of, a load cell used to measure the pulling force applied from the hydraulic loading system, linear variable differential transformers (LVDT's) to measure the displacement at the pull-out application point, velocity transducers for measuring the front displacement rate of the reinforcement, pressure cells used to measure the internal earth pressure inside the box, and manometer gauge to measure the normal pressure applied from the air bag. LVDT's were placed at the back of the box to measure the displacements at different points along the reinforcement.

Several pull-out tests were conducted by Farrag (1990) to evaluate the performance of the testing facility and the effect of testing parameters. These tests include:

(1) Unconfined extension test: this in-air test was conducted on the geogrid specimens under constant extension-rate. This test was aimed to evaluate the equipment performance, the accuracy of the control system, and the material behaviour in the unconfined state. Results were compared with the index test data provided by the geogrid manufacturer.

(2) Pull-out tests: displacement controlled tests with a rate of 6 mm/min were conducted using a confining pressure of 48 kN/m^2.

The sand used in these experiments was uniform blasting sand. A uniaxial high density polyethylene (HDPE) geogrid 'Tensar SR2', commonly used in soil reinforcement, was tested. Standard specimen of 30 cm width x 90 cm length was tested. The properties of the soil and geogrid are described in Table (1).

Table 1. Sand and geogrid properties

Sand Material				
Density (kN/m^3)		ϕ°		E (MN/m^2)
16.80		37		50
Geogrid Material				
Weight (g/m^2)	Aperture size MD/XMD (mm)	Rib thickness (mm)	Junction thickness (mm)	Strength[1] (kN/m)
850	111/16.7	1.2	4.5/4.1	79

[1]Quality control strength at 10.5% strain

The displacement distribution along the confined geogrid was measured using five LVDT's placed at the numbered locations as shown in Figure (2). The LVDT's were connected to the transversal ribs of the geogrid through non-extensible wires.

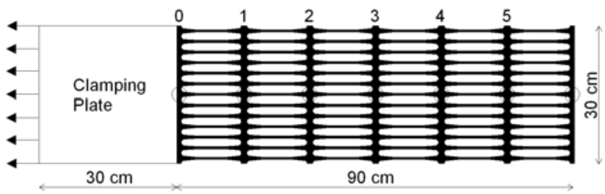

Figure 2. Instrumentation of the geogrid specimens

4 METHOD OF ANALYSIS

The three-dimensional finite-element model was developed using ABAQUS software (Hibbitt et al., 1998) to simulate the pull-out experiment described above. The lower half of the model is shown in Figure (3). The model was divided into three main parts; the top soil (above the geogrid), the bottom soil (below the geogrid) and the geogrid layer. The 3D finite element analysis was performed using six-nodded solid elements for the soil and 3-nodded triangular membrane elements for the geogrid. In order to simulate the actual configuration of the experiment, the dimensions and properties of different components (box, sleeve, geogrid, etc.) were chosen such that they represent those used in the actual test. It should be noted that the details of the grid apertures were taken into account in this study to capture the discontinuous nature of geogrid layer. Nodes along the vertical boundaries of the mesh may translate freely along the boundaries but are fixed against displacements normal to these boundaries. The nodes at the base are fixed against displacements in both directions. The finite-element mesh used in the analysis is shown in Figure 4.

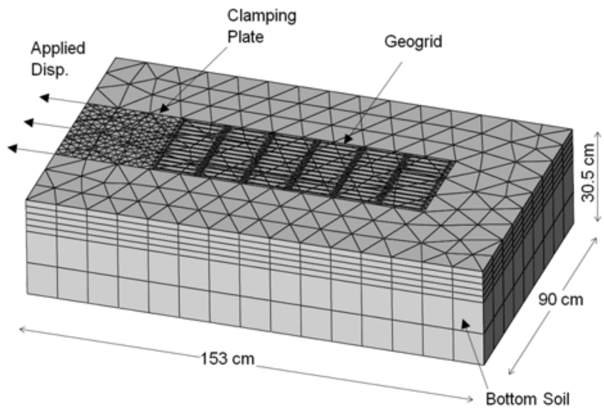

Figure 3. Model geometry showing the lower half of the box

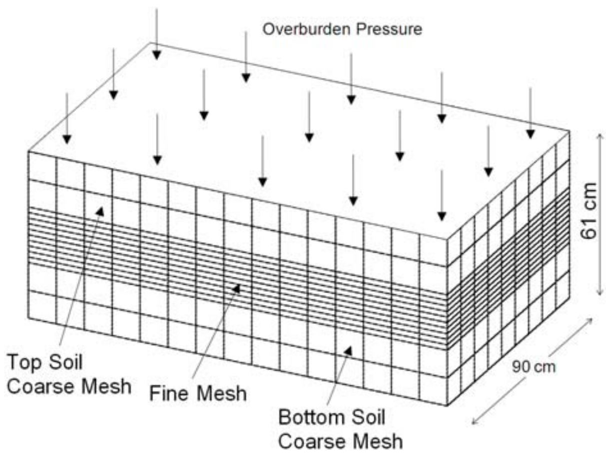

Figure 4. Finite-element mesh used in the 3D analysis

The elasto-plastic Mohr-Coulomb model implemented in ABAQUS was used for the sand material adopting a non-associated flow rule. This model involves five input parameters as listed in Table (2). A small cohesion value (5 kN/m^2) was used in this study to improve the stability of the analysis and avoid any singularity that may arise. The material model used for the geogrid was an isotropic-hardening elastic-perfectly plastic model. The model parameters are also listed in Table (2).

Shear interaction between the geogrid and the soil was established by creating two contact surface pairs above and below the geogrid. The model used to simulate this interaction was a Coulomb friction model with two material parameters- a friction coefficient (μ), and a tolerance parameter (E_{slip}).

5 RESULTS AND DISCUSSION

To examine the suitability of the chosen material model of the geogrid, the response of the geogrid layer under unconfined extension loading (in-air test) are first investigated as presented in Figure (5).

Table 2. Input parameters used in the finite element analysis

Sand Material					
Density (kN/m^3)	E (MN/m^2)	ν	φ°	ψ°	c (kN/m^2)
16.80	50	0.30	37	7	5
Geogrid Material					
Density (kN/m^3)	E (MN/m^2)	ν	Yield stress (MN/m^2)		
85x10^{-5}	472	0.30	56		
Soil-Geogrid Interface Parameters					
μ	E_{slip} tolerance				
0.50	0.005				

It can be seen that the measured response indicates a non-linear elastic behaviour up to failure (at an applied load of about 68 kN/m). The calculated response was in general agreement with the experimental results with a maximum difference of about 20% between the calculated and measured displacements in the elastic range. It should be noted that due to the elasto-plastic nature of the chosen material model, the calculated response was generally linear. The model, however, successfully predicted the maximum geogrid strength at failure.

The load-displacement behaviour of the embedded geogrid layer during the pull-out test is presented in Figure (6). In general, a stiffer geogrid response was noticed as compared to the in-air test with a maximum load of about 50 kN/m at failure. It can be seen that the numerical model captured the soil-geogrid interaction for the entire loading range.

Figure (7) shows the measured and calculated displacements at two selected locations along the geogrid, namely, at the face (node-0) and at a distance of 0.61 m (node-4) from the face. At any given time during the test, the loaded geogrid face experienced greater longitudinal displacements than other locations inside the soil. The numerical results generally agreed with the experimental measurements throughout the test with slightly smaller displacement values. It is believed that adopting nonlinear elasticity to simulate the behaviour of the geogrid in the elastic range would result in a better calculated response particularly at small displacements. This is presently being considered as part of the ongoing research program.

Figure (8) presents the displacement distribution along the entire length of the geogrid for applied displacements of 20 mm and 100 mm. Displacement values at the nodes are normalized with respect to the front displacement. It can be seen that for the two examined cases, node displacements decreased rapidly with distance from the loaded face and reached approximately zero when a small displacement (20 mm) was applied. For applied displacement of 100 mm, the displacement decreased by about 40% at node 5. Reasonable displacement magnitudes and overall trend were calculated using the developed numerical model for the investigated conditions.

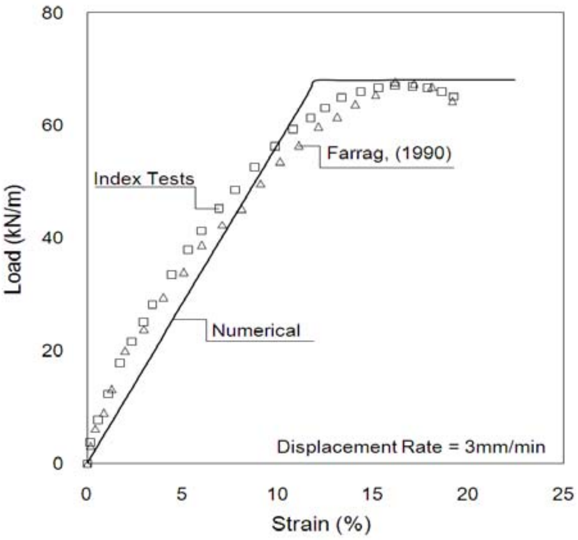

Figure 5. Unconfined (in-air) extension test results on geogrid

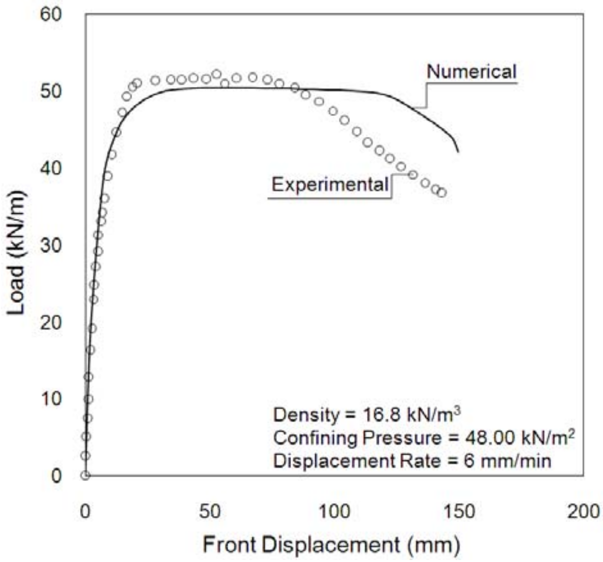

Figure 6. Pull-out test results on geogrid

Figure (9) shows the computed deformation pattern of the geogrid material during the pull-out loading. By inspecting the deformed shape of the geogrid, it can be seen that geogrid sheet extended more near the location of the applied load. The extension decreased with distance from the loaded boundary.

Figure (10) shows a comparison between the computed longitudinal and transverse displacements at a distance of 0.61 m (node-4) from the face. The inward movement was found to be insignificant with a maximum value of about 10 mm. This can be explained by the presence of the soil inside the aperture that is limiting the transversal displacement of the geogrid layer.

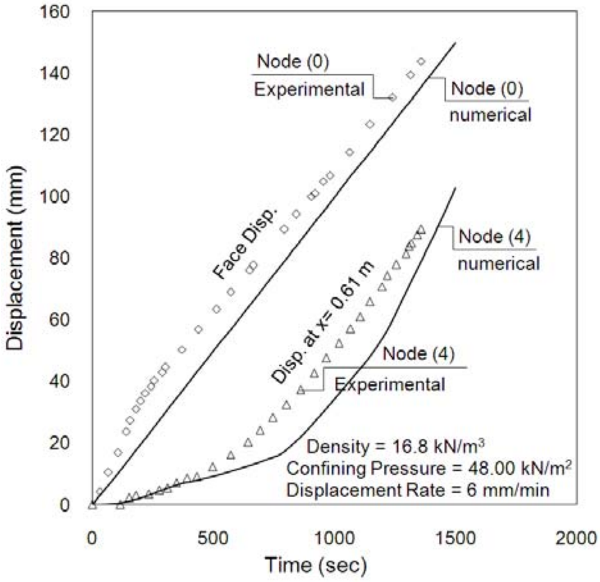

Figure 7. Longitudinal displacements at two locations

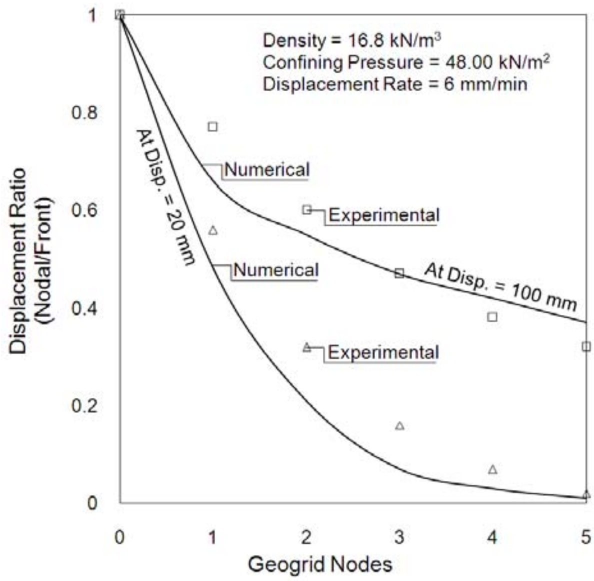

Figure 8. Distribution of displacement along the geogrid

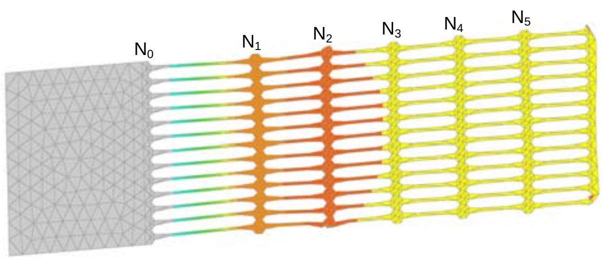

Figure 9. Deformation of geogrid during pull-out loading

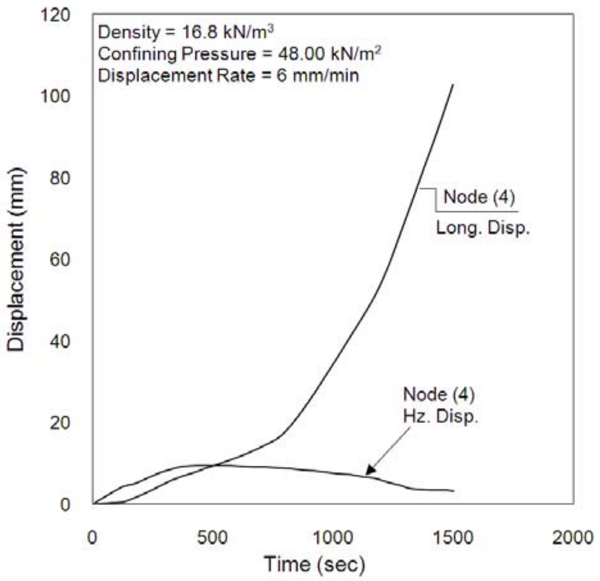

Figure 10. Comparison between longitudinal and transverse displacements at node (4)

6 CONCLUSIONS

A three-dimensional finite element model was developed and used to analyze the pull-out loading test of a uniaxial geogrid sheet embedded in granular material. The geogrid was explicitly modeled considering the details of the geometry including the aperture size and rib thickness. The geogrid was modeled as elasto-plastic material. The model was first used to simulate an in-air uniaxial extension test and the results were compared to laboratory measurements as well as to the index test results provided by the manufacturer. The model was then used to investigate the progressive changes in displacements at different locations along the embedded geogrid. General agreement was found between the calculated and measured response. Results showed that the proposed model is suitable for the analysis of geogrid-soil interaction. Further improvement to the material model of the geogrid is needed to capture the nonlinear response and correct stiffness as measured in the pull out experiment.

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