Three-Dimensional Finite Element Analysis of Soil-Geogrid Interaction under Pull-out Loading Condition

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ABSTRACT
Soil reinforcement has rapidly become one of the most common soil improvement techniques used in geotechnical engineering applications. Understanding the behaviour of a geogrid layer subjected to pullout condition is considered to be crucial to any successful design. In this paper, a 3D nonlinear finite element analysis is conducted using ABAQUS to investigate the role of different parameters that affect the soil-geogrid interaction. The 3D geometry of the geogrid material is explicitly modelled in the analysis to capture the different sources of interaction between the soil and the reinforcing layer. In addition, the effects of different numerical parameters that contribute to the soil-geogrid interaction, including the contact modeling technique, material model and the coefficient of friction are examined. Finally, conclusions are extracted to identify the most suitable and economic technique to numerically simulate the 3D features of the soil-geogrid interaction under pull-out loading condition.

RÉSUMÉ
Le renforcement des sols par géogrille est couramment une des méthodes d'amélioration des sols utilisés dans applications de géotechnique. Pour une meilleure conception, ceci nécessite une connaissance approfondie du comportement de la couche de géogrille sous l'effet d'arrachement. Dans cet article, une analyse 3D par éléments finis non linéaires est effectuée en utilisant ABAQUS pour étudier l'effet des différents paramètres qui contrôlent l'interaction sol-géogrille. La géometrie de la géogrille en 3D est modélisée en détails dans l'analyse afin d'évaluer les différentes sources de l'interaction entre le sol et la couche de renforcement. Aussi, les facteurs de différents paramètres numériques qui contribuent à l'interaction sol-géogrille, y compris la technique de contact de la modélisation, la modèle de matériau, et le coefficient de frottement sont examinés. Finalement, des conclusions sont tirées afin d'identifier la technique la plus appropriée et économique pour modéliser en 3D les caractéristiques de l'interaction sol-géogrille en cas de chargement d'arrachement.

1 INTRODUCTION

Reinforcement geosynthetics are used for different applications in geotechnical engineering such as reinforced earth fills, retaining walls, embankments, road pavement and foundations. The use of geosynthetics is known to improve soil performance, increase the safety factor while reducing the construction cost of the project. Geogrid is the generation of polymeric geosynthetics that is designed specifically to provide soil reinforcement. Their three-dimensional open structure, which interlocks with the surrounding soil, creates a cost effective earth structure (Koerner, 1994).

Finding the interaction mechanism between soil and geogrid is important in the design and analysis of geogrid-reinforced soil structures. Stresses in the reinforcing elements are transferred to the surrounding soil by the developed bonding between the soil and the reinforcement layer. This bond generally forms through i) friction, ii) passive soil resistance, or iii) a combination of both. To maintain equilibrium, the induced bond must resist the maximum tensile load carried by the reinforcing element (pull-out resistance).

In the past three decades extensive research has been conducted to investigate the role of different parameters that affect the interaction between a geogrid element and the surrounding soil using experimental (Palmeira and Milligan, 1989; Farrag et al., 1993; Bergado et al., 1994; Bakeer et al., 1998; Sugimoto et al., 2001; Moraci and Recalcati, 2006) as well as numerical analysis (Yuan and Chua, 1990; Wilson-Fahmy and Koerner, 1993; Shuwang et al., 1998; Perkins, 2003; Sugimoto and Alagiyawanna, 2003; Siriwardane, et al., 2008).

Numerical methods have been used along with laboratory data to develop a better understanding of the soil-geogrid interaction. Although the above studies explained several interesting features of the soil-geogrid interaction under different loading conditions, they are mostly based on simplifying assumptions related to either the details of the geogrid geometry or the constitutive model of the geogrid material. Modeling a geogrid inclusion as a continuous membrane sheet has proven to reasonably simulate the overall response of the soil-geogrid system; however, it does not explain the different sources of interaction between the geogrid layer and the surrounding soil.

In this paper, a three-dimensional finite element model of a laboratory size pull-out test is developed considering the non-continuous nature of the geogrid geometry. The model is then used to investigate the different sources of interaction between the soil and the reinforcing layer.

1.1 Theoretical Background

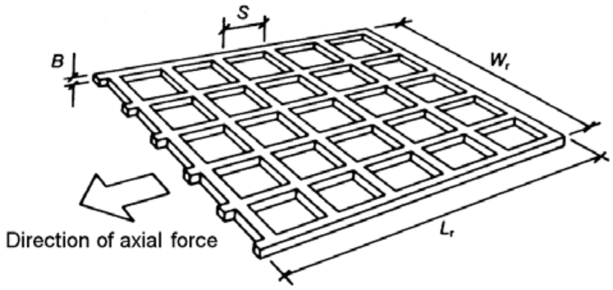
In the 1980's and 1990's, researchers developed an approach to describe the soil-reinforcement interaction. Jewell et al. (1984) and Milligan et al. (1987) classified the different mechanisms in which reinforcement interacts with soils into three main mechanisms:

a) skin friction along the reinforcement.
b) soil-soil friction.
c) passive (bearing) resistance on the transverse members of the reinforcement.

The general form of the interface shear strength can be defined as:

$$P = 2W_r.L_r.\sigma_n.f.\tan\phi \qquad [1]$$

where:
σ_n is the normal stress at the reinforcement level.
ϕ is the friction angle of the soil.
f is the soil-reinforcement interface coefficient ($0 < f < 1$).
W_r and L_r are defined in Figure (1).



$A_r = W_rL_r$ grid surface area
α_s fraction of grid surface area that is solid
α_b fraction of grid width available for bearing

Figure 1. Definition of reinforcement dimensions (After Jewell et al. 1984)

In Equation 1, the main challenge lies with the definition of (f). In fact (f) depends on the interaction mechanism mobilized along the soil reinforcement interface and on the relative movement that occurs along the same interface.

I) For planar sheet or strip, as with geotextiles, the mechanism mobilized is only skin friction. Hence, (f) is identical:

$$f = f_{ds} = f_b = \tan\delta/\tan\phi \qquad [2]$$

where:
δ is the skin friction angle between the soil and the reinforcement layer.
f_b is the interface (interaction) coefficient of bond (pull-out).
f_{ds} is the interface (interaction) coefficient of skin direct sliding.

II) In case of grid reinforcement as of geogrid, the shear strength of the soil-reinforcement interface is dependent on the mode of movement as below.

a) Geogrid with direct sliding resistance:
The direct sliding resistance between the reinforcement and the soil has two components: 1) the shear resistance between the soil and the reinforcement-plane surface area ($P_{s/r}$), and 2) the soil-to-soil shear resistance at the grid opening ($P_{s/s}$) (Jewell et al., 1984). The direct-shear (sliding) resistance, (P_{ds}), can be expressed as follows:

$$P = P_{ds} = P_{s/r} + P_{s/s} \qquad [3]$$
$$P_{s/r} = 2\alpha_s.W_r.L_r.\sigma_n.\tan\delta \qquad [4]$$
$$P_{s/s} = 2(1-\alpha_s).W_r.L_r.\sigma_n.\tan\phi \qquad [5]$$

Then:

$$P = P_{ds} = 2\alpha_s.W_r.L_r.\sigma_n.\tan\delta + 2(1-\alpha_s).W_r.L_r.\sigma_n.\tan\phi \qquad [6]$$

Using Equations 1 and 6:

$$P = 2W_r.L_r.\sigma_n.f.\tan\phi$$
$$= 2\alpha_s.W_r.L_r.\sigma_n.\tan\delta + 2(1-\alpha_s).W_r.L_r.\sigma_n.\tan\phi$$

The interface (interaction) coefficient of direct sliding (f_{ds}) mode is obtained as:

$$f = f_{ds} = \alpha_s (\tan\delta/\tan\phi) + (1-\alpha_s) \qquad [7]$$

Figure (2) shows different modes of direct sliding mechanisms between soils and three different types of reinforcement.

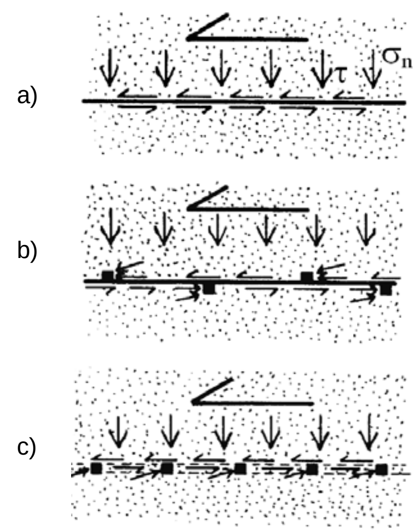


Figure 2. Interaction in direct sliding, a) sheet or strip reinforcement, b) ribbed strip reinforcement, and (c) grid reinforcement, (after Milligan et al., 1987)

b) Geogrid with bond (pull-out) resistance:
In case of pull-out movement, the contribution of a soil-soil ($P_{s/s}$) friction mechanism on soil-reinforcement interface resistance is almost nil as there is no relative movement of the soil on either side of the grid (Milligan et al., 1987 and Lopes, 2002). Generally, the pullout (bond), (P_b), resistance consists of two parts, namely: friction resistance ($P_{s/r}$) and passive bearing (P_{pb}) resistance on the bearing members.

$$P = P_b = P_{s/r} + P_{pb} \qquad [8]$$

where:
$P_{s/r}$ is expressed by Equation 4 while P_{pb} is given by:

$P_{pb} = (L_r/S).\alpha_b.W_r.B.\sigma_{pb}$ [9]

where:

L_r, S and B are the length of the reinforcement element, the distance between bearing (transverse) members and the thickness of the bearing members respectively and as illustrated in Figure (1).

L_r/S is the number of bearing surfaces.

Then:

$$P = P_b = P_{s/r} + P_{pb} = 2\alpha_s.W_r.L_r.\sigma_n.\tan\delta + (L_r/S).\alpha_b.W_r.B.\sigma_{pb} \quad [10]$$

Using Equations 1 and 10:

$$P = 2W_r.L_r.\sigma_n.f.\tan\phi = 2\alpha_s.W_r.L_r.\sigma_n.\tan\delta + (L_r/S).\alpha_b.W_r.B.\sigma_{pb}$$

The interface coefficient (coefficient of bond), (f_b) is obtained as:

$$f = f_b = \alpha_s (\tan\delta/\tan\phi) + (\sigma_{pb}/\sigma_n) (\alpha_b.B/S) (1/[2\tan\phi]) \quad [11]$$

If $\alpha_s = 1$ and $\alpha_b = 0$, Equation 11 will be equal to Equation 2, representing the coefficient of bond of a reinforcement where the only interaction mechanism mobilized is skin friction, as in geotextiles.

Figure (3) shows different modes of bond resistance mechanises between soils and three different types of reinforcement.

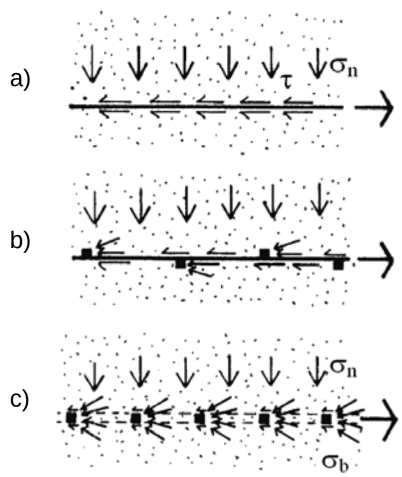


Figure 3. Interaction in bond resistance, a) sheet or strip reinforcement, b) ribbed strip reinforcement, and (c) grid reinforcement, (after Milligan et al., 1987)

1.2 Previous Numerical Work

Numerical methods have been used to interpret laboratory data and develop a better understanding of soil-geosynthetic interaction (Yogaarajah et al., 1994; Shuwang et al., 1998; Sugimoto et al., 2003; Perkins et al., 2003). It has been shown (Perkins, 2000) that the stress-strain behaviour of geosynthetic materials is complex and the 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.

Several studies have been conducted by researchers to simulate the pull-out test procedure using finite-element analysis. 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 behaviour 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 sheet 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 condition and the interaction between the soil and geogrid was modeled using non-linear springs. Perkins (2000) introduced a constitutive model for geosynthetics as 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. 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 as 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 assumed to extend 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.

2 CHARACTERIZATION OF THE SIMULATED PULL-OUT SETUP

In this study, an experimental pull-out test performed on a uniaxial geogrid type SR2 (Farrag, 1990; Farrag et al., 1993) is adopted and numerically modeled using the FEA. Details of the laboratory test are summarized as follows:

Figure (4) shows a side view of the examined 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. An air bag 5 cm in thickness was used to apply vertical pressure over the soil.

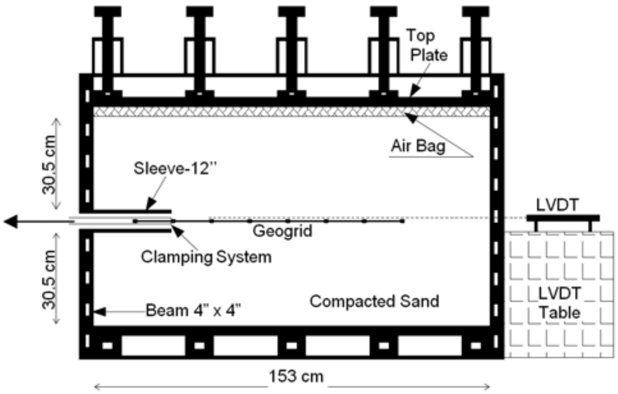


Figure 4. The pull-out box (adapted from Farrag, 1990)

Pull-out 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. Standard specimen of 30 cm width x 90 cm length, which comprises 13 longitudinal elements and 7 transverse elements, was tested as shown in Figure (5). The pull-out load was applied through a non-deformable clamp attached to the front end of the geogrid specimen. The properties of the soil and geogrid are summarized in Table (1).

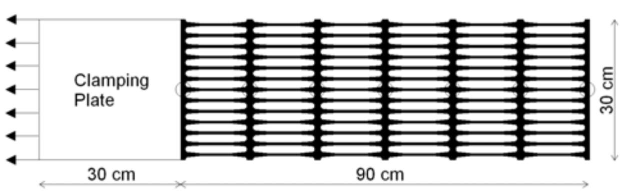


Figure 5. Standard geogrid specimen

3 FE-MODEL GENERATION

The numerical finite-element model has been developed using ABAQUS to simulate the described pull-out experiment. In order to analyze 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.

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

3.1 Geometrical Modeling

The lower half of the model is shown in Figure (6). The model was divided into three main domains; the top soil (above the geogrid), the bottom soil (below the geogrid) and the geogrid layer. It should be noted that the finite-element mesh was constructed using smaller elements near the geogrid location and larger elements further away.

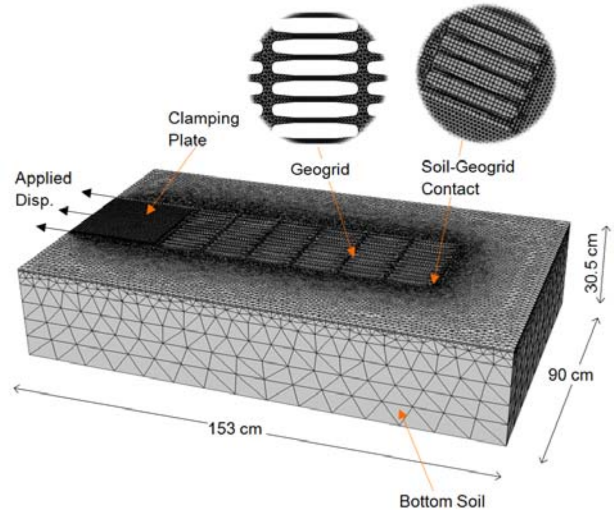


Figure 6. Finite-element mesh for the lower half of the box

Sand was discretized using 10-noded tetrahedron solid elements while the geogrid was modeled with 6-noded triangular membrane elements having negligible bending stiffness. The full geometry of the geogrid comprising over 17,000 triangular finite elements while soil mesh for both top and bottom domains contains more than 650,000 tetrahedral elements. The total number of nodes and elements generating the given mesh was 153,600 and 667,698 respectively.

The soil-geogrid interaction was established by creating two contact surface pairs above and below the geogrid layer. A parametric study was conducted to choose the most suitable contact modeling technique. Results indicated that using the surface to surface contact model with the traditional node to surface contact formulation is suitable to define such contact condition between the (soil) solid elements and the (geogrid) membrane elements. To keep the paper size manageable, the details of the above mentioned parametric study are not presented.

Boundary conditions were defined such that nodes along the vertical boundaries of the mesh may translate freely in the vertical direction but are fixed against displacements normal to the boundaries (smooth rigid). The nodes at the base are fixed against displacements in both directions (rough rigid). The overburden pressure was applied incrementally prior to applying the pull-out displacement. The finite element mesh used in the analysis is shown in Figure (7).

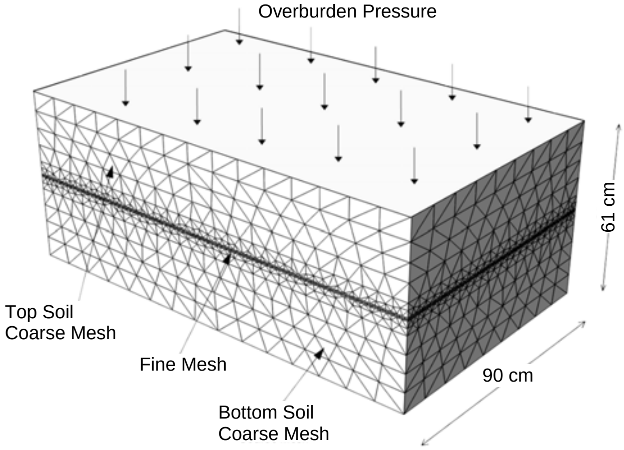


Figure 7. A complete finite-element mesh

It should be noted that the geogrid was explicitly modeled considering the details of the geometry including the aperture size and rib thickness. In addition, the interlocking between the geogrid and the surrounding soil was also modeled to accurately capture the different sources of interaction, as shown in the pattern given in Figure (8).

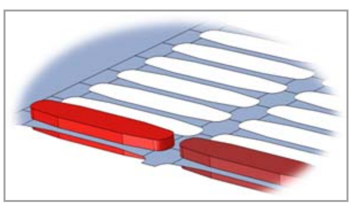


Figure 8. Soil-geogrid interlocking

3.2 Material Modeling

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.

For the geogrid, a non-linear elastic-plastic constitutive model, that separates the elastic and plastic strains, was developed to simulate the true behaviour of the polymer geogrid material. The properties of the generated model are determined by matching the experimental load-displacement curve obtained from the reported index tests performed under a displacement rate of 3 mm/min. The developed model allows for the non-linear elastic response of the geogrid to be captured such it agrees with the experimental data.

The behaviour of the soil-geogrid interface was simulated using the Coulomb friction model with two material parameters- a friction coefficient (μ), and a tolerance parameter (E_{slip}).

Table 2. Input parameters used in the finite element analysis (standard test)

Sand Material					
Density (kN/m^3)	E (MN/m^2)	ν	$\phi°$	$\psi°$	c (kN/m^2)
16.80	50	0.30	37	26	5

Geogrid Material			
Density (kN/m^3)	E (MN/m^2)	ν	Yield stress (MN/m^2)
85x10^{-5}	non-linear curve	0.30	non-linear curve

Soil-Geogrid Interface Parameters	
μ	E_{slip} tolerance
0.50	0.005

4 RESULTS AND DISCUSSIONS

4.1 Validation of the geogrid material model (in-air)

To measure the efficiency of the developed constitutive model for the geogrid material, the response of the geogrid layer under unconfined (in-air) tensile loading was first investigated and compared to the measured response as shown in Figure (9).

It can be seen that the calculated response of the developed model provided a better agreement with the measured results in both the elastic and the plastic regions. The model is capable of capturing the material nonlinearity in addition to the ultimate strength of the tested geogrid.

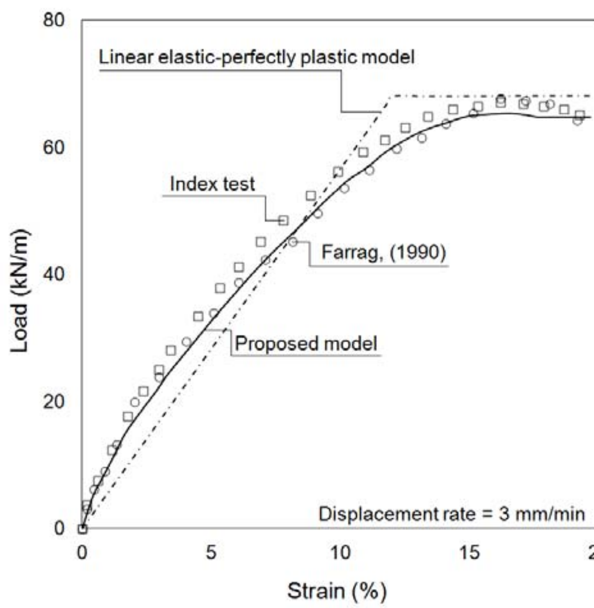


Figure 9. Unconfined (in-air) tensile test results on geogrid

4.2 Pull-out resistance (in-soil)

The relationship between the pull-out force and the frontal displacement for the embedded geogrid obtained from both the experimental and numerical models is shown in Figure (10).

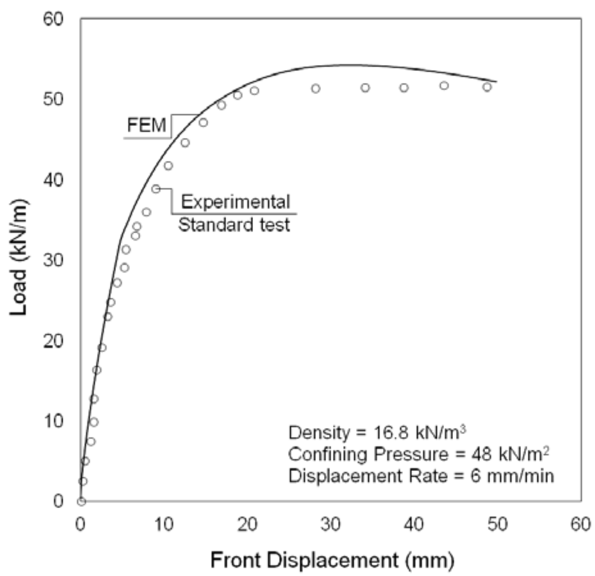


Figure 10. Pull-out response of the geogrid

From Figure (10), the numerical results, using the developed geogrid material model, captured the soil-geogrid response for the entire loading range with a maximum load of about 50 kN/m.

4.3 Components of pull-out resistance

Recalling Equation 8:

$$P = P_b = P_{s/r} + P_{pb} \quad [8]$$

The pull-out force comprises two components; the friction resistance ($P_{s/r}$) and passive bearing (P_{pb}) resistance. Each of these components contributes to the total pull-out resistance with various weights.

Contribution of each component to the total pull-out resistance is shown in Figure (11).

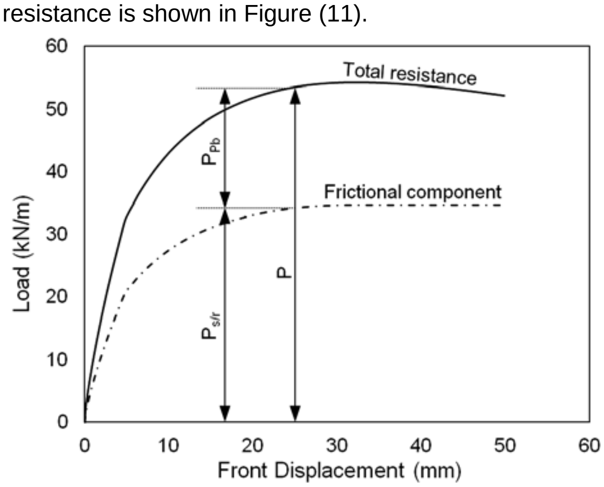


Figure 11. Components of the pull-out resistance

The total resistance was obtained by relating the pull-out load to the front displacement, whereas, the frictional resistance component was calculated by eliminating the contact force on the transverse members such that no bearing resistance exists.

From Figure (11), it can be seen that the difference between the total pull-out force and the frictional resistance is about 36% which reflects the contribution of the bearing resistance compared to the total pull-out resistance of the geogrid.

4.4 Soil friction angle and interaction coefficient

To study the effect of interaction coefficient on the pull-out resistance of geogrid, the model was solved with different angles of internal friction for the sandy soil that ranges from 30^o to 37^o. Figure (12) presents the influence of the change of interaction coefficient on the geogrid pull-out force.

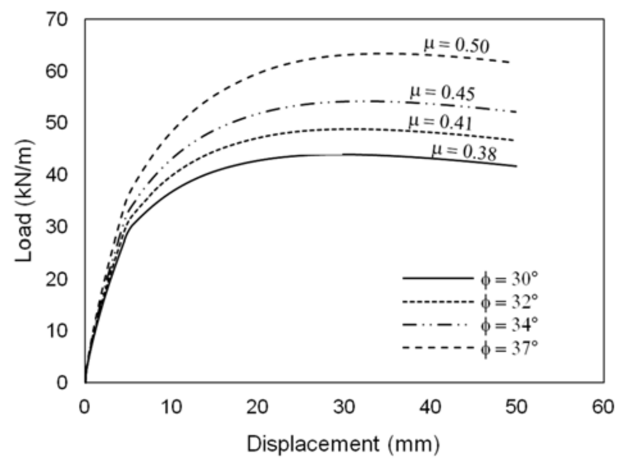


Figure 12. Effect of soil friction angle and interaction coefficient on geogrid pull-out load

Based on the results shown in Figure (12), increasing the soil friction angle from 30^o to 37^o (corresponding to an increase in interaction coefficient from 0.38 to 0.50), the pull-out resistance increased by about 45%.

5 SUMMARY AND CONCLUSIONS

In this paper, a three-dimensional finite element analysis was carried out to simulate the pull-out loading test of a uniaxial geogrid embedded in sandy soil. The geogrid was explicitly modeled considering the details of the geometry including the aperture size and rib thickness. A new constitutive model was proposed to model the geogrid material non-linearity. This model was first used to simulate an in-air tensile 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 response of geogrid layer embedded in soil under pull-out loading.

General agreement was found between the calculated and measured responses of the geogrid pull-out resistance. Results showed that the contribution of the bearing (transverse) members on the total pull-out resistance is about 36%. In addition, the presented results showed that the pull-out load has increased with the increase of the internal friction angle of the soil and the interaction coefficient.

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REFERENCES

Bakeer, R.M., Sayed, M.S., Cates, P. and Subramaniana, R., 1998 "Pullout and shear tests on geogrid reinforced lightweight aggregate", Geotextiles and Geomembranes, 16: 119-133.

Bergado, D.T. and Chai, J.C., 1994 "Pullout force/displacement relationship of extensible grid reinforcements", Geotextiles and Geomembranes, 13: 295-316.

Farrag, K., 1990 "Interaction properties of geogrids in reinforced soil walls- testing and analysis", Ph.D. Thesis, Louisiana State University, Baton Rouge, LA, USA.

Farrag, K., Acar, Y.B. and Juran, I., 1993 "Pullout resistance of geogrid reinforcements", Geotextiles and Geomembranes, 12: 133-159.

Jewell, R.A., Milligan, G.W.E., Sarsby, R.W. and Dubois, D., 1984 "Interaction between soil and geogrids", Proceedings of the Conference on Polymer Grid Reinforcement, Thomas Telford Publishing, London, 18-30.

Koerner, R.M., 1994 "Designing with geosynthetics", 3rd ed. Prentice Hall, Englewood Cliff, NJ, USA.

Lopes, M.L., 2002 "Soil-geosynthetic interaction", Geosynthetics and Their Applications, S.K. Shukla, ed., Thomas Telford, London.

Milligan, G.W.E. and Palmeira, E.P., 1987 "Prediction of bond between soil and reinforcement", Prediction and Performance in Geotechnical Engineering, Calgary.

Moraci, N. and Recalcati, P., 2006 "Factors affecting the pullout behaviour of extruded geogrids embedded in a compacted granular soil", Geotextiles and Geomembranes, 24: 220-242.

Palmeira, E.M., Milligan, G.W.E., 1989a "Scale and other factors affecting the results of pull-out tests of grids buried in sand". Geotechnique, 39(3): 511-524.

Perkins, S.W., 2000 "Constitutive modeling of geosynthetics", Geotextiles and Geomembranes, 18: 273-292.

Perkins, S.W. and Edens, M.Q., 2003 "Finite element modeling of a geosynthetic pullout test", Geotechnical and Geological Engineering, 21: 357-375.

Shuwang, Y., Shouzhong, F. and Barr, B., 1998 "Finite element modelling of soil-geogrid interaction dealing with the pullout behaviour of geogrids", ACTA Mechanica Sinica (English Series), Chinese Journal of Mechanics, 14(4): 371-382.

Siriwardane, H., Gondle, R., Kutuk, B. and Ingram, R., 2008 "Experimental investigation and numerical analysis of reinforced geologic media", The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), Goa, India, 4369-4379.

Sugimoto, M., Alagiyawanna, A. M. N., and Kadoguchi, K. 2001. Influence of rigid and flexible face on geogrid pullout tests, Geotextiles and Geomembranes, 19: 257-277.

Sugimoto M. and Alagiyawanna A.M.N., 2003 "Pullout behavior of geogrid by test and numerical analysis", Journal of Geotechnical and Geoenvironmental Engineering, 129(4): 361-371.

Wilson-Fahmy, R.F., Koerner, R.M., 1993 "Finite element modelling of soil–geogrid interaction with application to the behavior of geogrids in a pullout loading condition", Geotextiles and Geomembranes, 12: 479-501.

Yuan, Z. and Chua, K.M., 1990 "Numerical evaluation of the pullout box method for studying soil-reinforcement interaction", Transportation Research Record, Washington, DC, 1278: 116-124.

Yogaarajah, I., and Yeo, K.C., 1994 "Finite element modeling of pull-out tests with load and strain measurements", Geotextiles and Geomembranes, 13: 43-54.