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Effect of particle shape on the response of geogrid-reinforced systems: Insights from 3D discrete element analysis[☆]

Ge Gao[a], M.A. Meguid[b,*]

[a] Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke St. W, Montreal, Quebec, H3A 0C3, Canada
[b] Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke St. W, Montreal, QC, H2A 0C3, Canada

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ABSTRACT

Understanding soil-geogrid interaction is essential for the analysis and design of reinforced soil systems. Modeling this interaction requires proper consideration for the geogrid geometry and the particulate nature of the backfill soil. This is particularly true when angular soil particles (e.g. crushed limestone) are used as a backfill material. In this study, a three-dimensional (3D) discrete element model that is capable of capturing the response of unconfined and soil-confined geogrid material is developed and used to study the response of crushed limestone reinforced with geogrid and subjected to surface loading. The 3D shape of the crushed limestone is modeled by tracing the surface areas of a typical particle and fitting a number of bonded spheres into the generated surface. Model calibration is performed using triaxial tests to determine the microparameters that allow for the stress-strain behaviour of the backfill material to be replicated. To demonstrate the role of particle shape on the soil-geogrid interaction, the analysis is also performed using spherical particles and the calculated response is compared with that obtained using modeled surfaces. The biaxial geogrid used in this study is also modeled using the discrete element method and the unconfined response is compared with the available index test results. This study suggests that modeling the 3D geogrid geometry is important to accurately capture the geogrid response under both confined and unconfined conditions. Accounting for the particle shape in the analysis can significantly enhance the predicted response of the geogrid-soil system. The modeling approach proposed in this study can be adapted for other reinforced soil applications.

1. Introduction

Geogrid has been successfully used for the reinforcement of different geotechnical structures (e.g. railway tracks, road embankments, foundations and retaining walls). The reinforcing effects generally develop via the interaction between the reinforcing material and the surrounding soil. This interaction can be very complex depending on the nature and properties of the reinforcement material and the interlocking effect that may develop due to the partial penetration of particles through the geogrid apertures.

A large number of laboratory tests and theoretical studies have been used over the past three decades to investigate the interaction mechanism between geogrid and the surrounding soil (e.g. Palmeira and Milligan, 1989; Moraci and Recalcati, 2006; Shin and Das, 2000; Sitharam and Sireesh, 2004; Demir et al., 2013; Lin et al., 2013; Ezzein and Bathurst, 2014; Bathurst and Ezzein, 2015, 2016; 2017; Cardile et al., 2017; Esmaeili et al., 2017; Mousavi et al., 2017; Saha Roy and Deb, 2017). Numerical analysis using finite element (FE) has been also used to predict the failure load as well as the displacements and strains developing in the reinforcement (Ling and Liu, 2009; Li et al., 2012; Kumar and Sahoo, 2013; Rowe and Liu, 2015; Hussein and Meguid, 2016; Zhuang and Wang, 2016). One inherent limitation of these methods is the difficulty in analyzing the soil-geogrid interaction at the particle level.

The discrete element method (DEM) (Cundall and Strack, 1979), has a particular advantage in capturing the kinematic behaviour of discontinuous media at the microscopic level (Stahl and Konietzky, 2011; Wang et al., 2016; Jiang et al., 2016; Shen et al., 2017; Gao and Meguid, 2018a; Lai and Chen, 2017). The method has also been used to investigate the interface behaviour of geogrid-soil system considering the discontinuous nature of granular particles. Ngo et al. (2017) studied the interface behaviour of geogrid-reinforced subballast through a series of large-scale direct shear tests and discrete element analysis. It was found that shear strength of the interface is governed by the geogrid characteristics, including geometry and opening size. Chen et al. (2014) evaluated the interlocking behaviour of geogrid-reinforced

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[*] Corresponding author.
E-mail addresses: ge.gao2@mail.mcgill.ca (G. Gao), mohamed.meguid@mcgill.ca (M.A. Meguid).

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railway ballast using discrete element method and found that modeling ballast particles as clumps holds much promise for investigating the interaction between geogrids and ballast material. Lai et al. (2014) investigated geogrid-reinforced pile-supported embankment using DEM and found that soil arching is a key factor in the load transfer mechanism from the embankment to the foundation system, which is strongly affected by the presence of the geogrid reinforcement. Chen et al. (2012) studied the cyclic loading of geogrid-reinforced ballast under confined and unconfined conditions, and concluded that geogrid reinforcement can significantly limit the lateral displacement in the reinforced zone. The above studies demonstrated that the stress-strain behaviour of a geogrid material embedded in backfill soil is complex, particularly for angular soil particles of irregular shapes as they interact with one or more geogrid layers.

The objective of this study is to propose a 3D particulate model that is able to capture the response of both unconfined and soil confined biaxial geogrid embedded in crushed rock material and subjected to surface loading. This is achieved in three phases as follows:

i) Modeling crushed limestone: The shape of a typical particle is simulated based on crushed limestone material used in laboratory experiments. The input parameters needed for the discrete element analysis are determined using triaxial and direct shear tests.
ii) Developing particle-based geogrid model: A 3D geogrid model is created using parallel bond between particles. The model is validated using tensile and flexural test results to ensure that the response of the geogrid material is properly captured under the applied loading.
iii) Analyzing a case study: Using the created backfill and geogrid models, a case study involving a square footing over geogrid-reinforced soil is analyzed and the results are compared with experimental data.

The analysis presented in this study has been performed using the particle flow code (PFC^{3D}), version 5.0 (Itasca, 2014).

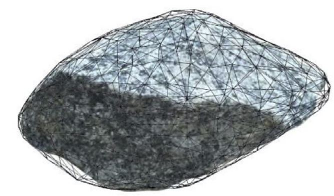
2. Modeling crushed limestone

Particle shape is known to influence the inter-particle friction, contact forces and coordination number. Researchers (e.g. Stahl and Konietzky, 2011; Chen et al., 2012; Stahl et al., 2014; Indraratna et al., 2014; Miao et al., 2017) have used clump logic in modeling complex-shaped particles in various applications. A clump is defined as a single rigid body of overlapping spherical pebbles of different sizes that acts as a single particle of a chosen or arbitrary shape (Gao and Meguid, 2018a; 2018b). In this study, an approach has been developed to create irregular shaped particles based on the construction of a triangular mesh that traces the actual geometry of a typical crushed limestone particle (Fig. 1). For the purpose of this investigation, crushed limestone material is selected based on the reported laboratory experiments performed by Chen et al. (2009). To demonstrate the effect of particle shape on the response of geogrid embedded in crushed limestone, the analysis is also performed using spherical particles and the response is compared with that obtained using irregular shaped clumps.

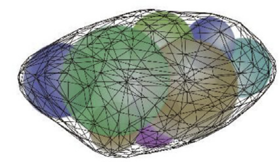
2.1. Triaxial compression tests

Several researchers used discrete element analysis to study soil-geogrid interaction (e.g. Lai et al., 2014; Wang et al., 2016; Miao et al., 2017; Ngo et al., 2017), however, only a limited number of these studies fully calibrated the set of microparameters that govern both the interface and interlocking effects, including the effective modulus, stiffness ratio (normal to shear stiffness ratio), peak and residual friction coefficients.

In this study, large-scale triaxial tests are used to determine the effective modulus of the contact that is needed for the discrete element



(a) Triangular mesh that traces the shape of a typical particle



(b) Fitting spheres inside the mesh to create particle-shaped clump

Fig. 1. Modeling crushed limestone particles: (a) Triangular mesh that traces the shape of a typical particle; (b) Fitting spheres inside the mesh to create particle-shaped clump.

analysis. The linear-based model depicted in Fig. 2 is used to represent the contacts between particles as well as between particles and rigid boundaries. A cylindrical sample 200 mm in diameter and 500 mm in height is modeled as shown in Fig. 3. A servo-mechanism is simulated and used to apply the confining pressures acting on the samples in both axial and radial directions. Careful consideration is usually given to particle size such that a reasonable balance between the computational cost and scaling effect is maintained (Tran et al., 2014b). In this study, spheres that represent particles of average diameter of 5.67 mm were initially generated using a scale factor of 3 (ratio of numerically generated to actual particle size), thus the diameter of the spherical particle is approximately 17 mm. The particle assembly is then cycled to equilibrium, which is considered to be reached when the ratio of unbalanced forces to the mean contact forces are smaller than a set tolerance value of 10^{-5} (Masson and Martinez, 2001). The modeled spheres were then replaced by the irregular shaped clumps that have been previously created to capture the geometry of a typical crushed limestone particle. The system is again cycled to equilibrium to reduce the excess contact forces resulting from the random placement of the clumps (Lu and Mcdowell, 2006; Chen and McDowell, 2013).

Stahl and Konietzky (2011) demonstrated that modeling the loading-unloading phase of the triaxial tests allows for the deformability of the system to be determined with a reasonable accuracy. Therefore, the response of the particles under loading-unloading condition is simulated in this study at an average confinement pressure of 50 kPa and axial strain of up to 0.05% as illustrated in Fig. 4. The effective contact modulus and stiffness ratio are determined such that the elastic modulus matches that measured in the laboratory experiments (about 120 MPa). The elastic modulus can be related to the effective contact modulus, E, and the normal-to-shear stiffness ratio, $k = k_n/k_s$, at the contact as follows (Itasca, 2014):

$$k_n := AE/L \tag{1}$$

$$k_s := k_n/k \tag{2}$$

with $A = \pi r^2$

$$r = \begin{Bmatrix} \min(R^{(A)}, R^{(B)}), & \text{ball–ball} \\ R^{(A)}, & \text{ball–wall} \end{Bmatrix} \tag{3}$$