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Efficiency of cellular geosynthetics for foundation reinforcement

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ABSTRACT

A numerical simulation of geocell-reinforced foundation beds is reported. The three-dimensional geocells and soil are simulated separately using $FLAC^{3D}$ Finite Difference software. A single geocell-reinforced soil is modeled and the results compared with those from a laboratory test in the literature. The model is extended to geocell foundation beds. The placement conditions in which the geocell layers have the highest efficiency (highest bearing capacity with the lowest cost) are determined. Also, a comparison is made between the performance of cellular geosynthetic reinforcement and a planar form with the same mass of used material (as two reinforcing systems with similar materials but different behavior mechanisms) to identify the system with the greatest efficiency. The analyses are performed for both sandy and clay beds and their results are compared.

1. Introduction

Geocells are a form of geosynthetic reinforcement system used for soil improvement. Geocells are polymeric, honeycomb-like cells connected to each other by joints that form a network of cells to provide confinement for infilled soil. They were developed and first used by the US Army Corps of Engineers for the quick stabilization of sand in the military field (Webster, 1979).

Like other geosynthetic products, geocells are usually made from polymeric materials (e.g., high density polyethylene (HDPE)). However, the mechanisms of geocells and planar geosynthetics are completely different. Because of their three-dimensional, unique geometry, geocells can provide noticeable confinement for their infilled soil and can improve its strength and stiffness parameters (Yuu et al., 2008).

Most past research has focused on planar reinforcements and has developed design methods for these products (i.e., Allen and Bathurst, 2015; Ambauen et al., 2016; Esmaili et al., 2014; Ferreira et al., 2016; Giroud and Han, 2004; Giroud and Noiray, 1981; Hatami and Bathurst, 2000; Hinchberger and Rowe, 2003; Huang, 2016; Huckert et al., 2016; Khosrojerdi et al., 2016; Khoury et al., 2011; Lenart et al., 2016; Leng and Gabr, 2006; Miao et al., 2014; Mirmoradi and Ehrlich, 2015; Mosallanezhad et al., 2016a,b,c; Naeini and Gholampoor, 2014; Rowe and Li, 2005; Rowe and Liu, 2015; Rowe and Skinner, 2001; Skinner and Rowe, 2003, 2005; Sukmak et al., 2016; Tang et al., 2016; Tatsuoka et al., 2016; Yang et al., 2016; Zheng and Fox, 2016; Zhang et al., 2014; Zhuang and Wang, 2015). Investigations in the field of three-dimensional reinforcements showed that, despite of the effectiveness of the geocell system in soil improvement, its usage is limited due to the considerable gap that exists between the applications and theories of geocell-reinforcement systems in their different applications (Han et al., 2008; Pokharel et al., 2009; Yuu et al., 2008).

Field applications (Al-Qadi and Hughes, 2000; Cowland and Wong, 1993; Guo et al., 2015; Jiang et al., 2016) have shown the benefits of using geocell-reinforcing systems. Several laboratory tests were also carried out to investigate the benefits of geocell reinforcement and different influencing factors (i.e., Bathurst and Jarrett, 1988; Biswas et al., 2013; Chang et al., 2007; Chen et al., 2013a; Dash et al., 2008; Dutta and Mandal, 2016; Indraratna et al., 2014; Latha and Murthy, 2007; Mehrjardi et al., 2013; Mengelt et al., 2006; Moghaddas Tafreshi and Dawson, 2010; Moghaddas Tafreshi et al., 2014; Song et al., 2014; Suku et al., 2016; Tanyu et al., 2013; Yu et al., 2016). In an experimental study, Pokharel et al. (2010) investigated the factors influencing the behavior of bases reinforced by a single geocell. These factors are shape, type, embedment, the height of the geocell and the quality of infilled materials.

Despite the relatively comprehensive experimental studies in this field, because of its complexity, numerical modeling of geocell reinforcement, which is essential for investigating its behavior, has

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rarely been performed. Many of the numerical and analytical studies are based on an equivalent composite model for representing the strength and stiffness of geocell-confined soil (i.e., Aboobacker et al., 2015; Chen et al., 2013b; Latha and Somwanshi, 2009; Moghaddas Tafreshi et al., 2015; Neto et al., 2015). Also, several researchers modeled geocell-reinforced soil separately through numerical analysis i.e., Biabani et al., 2016a,b; Han et al., 2008; Hegde and Sitharam, 2015a,b,c; Leshchinsky and Ling, 2012, 2013; Yang, 2010; Yang et al., 2010).

In the composite model, the geocell-reinforced soil is replaced with a soil with higher parameters. These parameters are selected based on test results performed on the geocell-reinforced soil (Bathurst and Karpurapu, 1993; Chen et al., 2013a). For example, after analyzing the Mohr-Circles (at failure) of the granular soil with and without geocell confinement, Bathurst and Karpurapu (1993) suggested the use of apparent cohesion c_r to account for the increased strength of the geocell-soil composite. They approximate the value of the apparent cohesion with the following equation (Bathurst and Karpurapu, 1993):

$$c_r = \frac{\Delta\sigma_3}{2}\tan\left(\frac{\pi}{4}+\frac{\phi}{2}\right) \tag{1}$$

where ϕ is the friction angle of the infilled soil and $\Delta\sigma_3$ is the increased confining pressure.

They also compared the measured cohesion and the predicted values using Equation (1) and concluded that the predicted values differed from the measured values by 5%–18%.

To estimate the increased confining pressure ($\Delta\sigma_3$) due to the membrane stresses in the geocell wall, they used the membrane correction theory proposed by Henkel and Gilbert (1952):

$$\Delta\sigma_3 = \frac{2M}{d}\left(\frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}\right) \tag{2}$$

where d is the initial diameter of the geocell pocket; ε_a is the axial strain of the geocell-soil composite, assuming the geocell and the soil deform together as a right cylinder; and M is the secant modulus of the geocell material corresponding to the axial strain ε_a.

To determine the increased stiffness of the geocell-reinforced soil, Madhavi Latha (2000) proposed the following empirical equation:

$$K_r = K_e + 200M^{0.16} \tag{3}$$

where M has the same meaning as in Equation (2). K_r and K_e are the dimensionless modulus numbers of the geocell-soil composite and the unreinforced soil, respectively. The modulus number K is a parameter of the hyperbolic constitutive model for soil (also known as the Duncan-Chang model) developed by Duncan and Chang (1970). Latha and Somwanshi (2009) used the composite method to simulate the geocell-reinforced soil layer numerically using the above equations for composite soil parameters.

In the composite method, the increased soil parameters are determined based on equations resulting from some limited experimental tests; hence, generalizing them for other kinds of soils could cause more errors. Moreover, as mentioned, the geocell reinforcing system has various complicated mechanisms that cannot be considered thoroughly in such models. Jamnejad et al. (1986) compared existing theoretical methods for a soil-geocell composite and concluded that they are not satisfactory in predicting its performance.

To achieve an accurate model that can represent the three-dimensional nature of geocells, soil and geocells should be modeled separately. In doing this, the key behavior mechanisms of the geocell reinforcing system can be simulated accurately, such as the all-round confinement effect provided by the geocell for the infilled soil (as the most important mechanism), vertical stress reduction etc.

Thus, in the current research, to simulate the geocell reinforcing system accurately and to generalize it to real conditions, a three-dimensional finite difference modeling was conducted. To increase the accuracy of this model, geocells and soil were modeled separately. This simulation method leads to a model that can eliminate the composite method errors and also simulate the key features of geocells.

The first step of this research was to verify the model. An experimental test performed on single geocell-reinforced bases by Pokharel et al. (2010) was simulated numerically and the numerical and experimental results were compared.

Since in addition to soil improvement, cost reduction is also an aim of using geocell reinforcing systems, determining the optimum placement of reinforcing layers (e.g., the optimum height, width and embedment depth) is a significant issue. Therefore, in the next step of this research, to achieve these parameters the model was extended to geocell-reinforced foundation beds and several analyses were conducted for both sandy and clay soils.

3D and planar geosynthetic reinforcements can be considered two reinforcing systems of similar materials but with different behavior mechanisms. Thus, it is important to determine which system has a higher efficiency in reinforcing the foundation beds. Therefore, in the last part of this research, to compare the performance of geocell and planar geosynthetics the planar geosynthetic-reinforced foundation beds for both sand and clay were also modeled and the results of geocells were compared for the same geosynthetic mass used in both systems.

2. Numerical model

In the present study, FLAC^{3D} (employing FDM) was used. This software contains several built-in material models and structural elements to model the two different reinforcement systems and their interfaces with adjacent materials.

To perform an accurate study of geocell-reinforced soil and eliminate composite method errors, the soil and geocells were modeled separately. The elastic perfectly plastic Mohr Coulomb model was used to simulate the infilled soil; to simulate the geocell (and planar reinforcement), the geogrid structural element (one of the planar structural elements available in the software) was used. In this model, the geogrid element behaves as an isotropic, linear elastic material. A shear-directed frictional interaction occurs between the geogrid and grids. The stresses on the geogrid are shown in Fig. 1. These stresses (consisting of an effective confining stress σ_m and a total shear stress τ) are balanced by the membrane stresses that develop within the geogrid itself.

The interface behavior is represented numerically at each

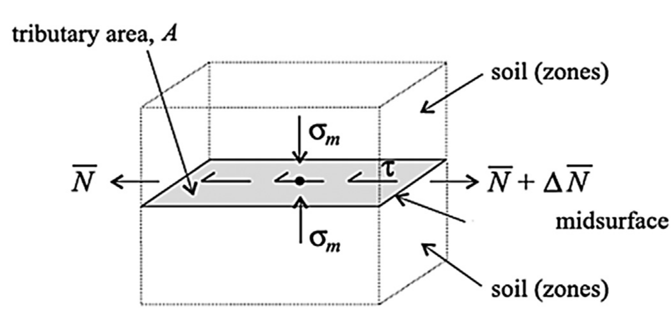

Fig. 1. Stresses acting on the geogrid structural elements (Itasca, 2005).