Geocell-Reinforced Granular Fill under Static and Cyclic Loading: A Synthesis of Analysis

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ABSTRACT: Geocell is a three-dimensional geosynthetic that provides direct lateral confinement to the infill material. In recent years, the use of geocell-reinforced granular fill as a load supporting layer has received increased attention. In the past, lack of well-developed design methods that could quantify the benefit of geocell reinforcement limited the application. To fill the gap between the design and the application, fundamental, theoretical, and applied research projects have been carried out in several research institutes. This paper presents a synthesis of these studies on the analysis of geocell-reinforced granular fill. Due to the differences of soil behaviour under static and cyclic loading, theoretical and numerical analyses are summarized in this paper based on loading conditions. Experiments performed to facilitate the theoretical and numerical analyses are also reviewed. Recommendations are made for areas of future research.

KEYWORDS: Geocell, geosynthetic reinforcement, granular fill, static load, and dynamic load

1. INTRODUCTION

Geocell is a special type of geosynthetic product used primarily for soil confinement. It was originally developed by the US Army Corps of Engineers (USACE) in late 1970s for quick reinforcement of cohesionless soil to support military vehicles. The product developed in the USACE study was originally named the "sand-grid." Commercial geocell products made from polymeric materials became available in late 1980s. Today, geocell has been successfully applied for load support, earth retaining, and erosion control. Most modern geocell products have an expandable three-dimensional structure. During the construction, geocell is first stretched, placed and fixed on a leveled surface and the infill material is then poured into the pockets of the geocell as shown in Figure 1 and compacted to the desired density. The geocell and the infill soil form a reinforced mattress which can be used to support both static (from spread footings to embankments) and cyclic (from unpaved and paved roads to railways) loads.

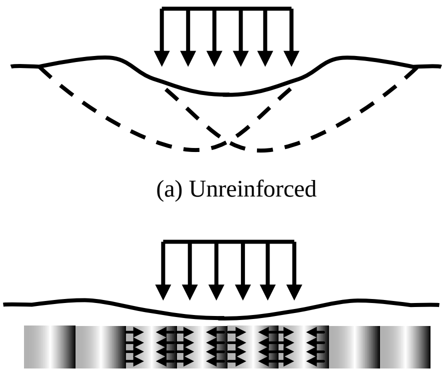
Figure 1 Filling of sand into geocell

Following the early USACE research (Webster, 1979a; 1979b), numerous laboratory and field experiments have been carried out to characterize the load responses of geocell-reinforced soils (e.g., Mitchell et al., 1979; Dash et al., 2003; Han et al., 2011; Yang et al., 2012; Thakur et al., 2012). In general, geocell reinforcement was demonstrated effective in (1) increasing the bearing capacity, (2) increasing the stiffness, and (3) reducing the settlement or permanent deformation of soils under static and cyclic vertical loads. The performance of the geocell-reinforced fill was affected by a number of factors such as the property of the infill soil, the geometry of the geocell, the stiffness of the geocell material, the level of compaction, and the thickness of soil covering the geocell (Mitchell et al., 1979; Bathurst, 1988; Pokharel et al., 2010). Findings from experimental studies greatly enhanced the product development and the application of geocell. However, there was still lack of quantitative design methods that could predict the bearing capacity/settlement of geocell-reinforced soils under a design load.

To fill the gap between the design and the application, theoretical and numerical analyses were carried out in several research institutes. This paper presents a synthesis of these studies on geocell-reinforced granular fill under static and cyclic loading. In the following section of this paper, the mechanism of geocell reinforcement is discussed in a qualitative sense. Next, a number of analytical models and design methods that help to quantify the behaviour of geocell-reinforced soils are presented. Experimental studies performed to facilitate the development of the analytical methods are also reviewed in this section. Last, numerical studies on geocell reinforcement are summarized with an emphasis on the selection of constitutive models.

2. MECHANISM OF GEOCELL REINFORCEMENT

Granular fill such as aggregate consists of particles without any bonding strength. Under a vertical load, the soil particles tend to move downward and laterally (Figure 2a). Geocell, a three-dimensional geosynthetic, can provide direct lateral confinement to the infill material. When a vertical load is applied on top of the reinforced mattress, the vertical wall of the geocell restricts the soil particles from lateral movement and prevents the formation of the shear failure surface (Figure 2b). Meanwhile, since the modulus of the granular material increases with the confining stress level (also called stress-dependency), the geocell-reinforced soil exhibits a higher stiffness than the unreinforced soil. The increased stiffness of the reinforced mattress helps distribute the vertical load to a wider area onto the underlying soil. Therefore, the settlement in the underlying soil can be minimized. This effect was also referred as a slab or beam effect by Han et al. (2011). Although the above mechanism of geocell reinforcement has been well recognized, there is need for a prediction tool to evaluate the benefit of geocell reinforcement at the design stage, which helps the decision maker to compare different design options.



(a) Unreinforced

(b) Geocell-reinforced

Figure 2 Mechanism of geocell reinforcement

3. THEORETICAL ANALYSIS OF GEOCELL-REINFORCED GRANULAR FILL

3.1 Bearing capacity and settlement under static loading

The early analytical work on the geocell-reinforced soil was performed by Mitchell et al. (1979), who identified seven possible failure modes when the geocell-reinforced sand overlying soft subgrade was subjected to a static vertical load. They are: (1) cell penetration into subgrade, (2) cell bursting, (3) cell wall buckling, (4) bearing capacity, (5) bending, (6) durability failure, and (7) excessive rutting. Although Mitchell and his colleagues did not address all the failure modes with analytical solutions, their study provided valuable understanding of the problems to later researchers. For example, they first noticed the difficulties in estimating the modulus of the geocell-reinforced layer because of "the stress-dependent nature of the sand stiffness and the three-dimensionality of the grid cell network" (Mitchell et al., 1979).

Triaxial shear test is commonly used in geotechnical research to characterize the fundamental behaviour of geomaterials. Bathurst and Karpurapu (1993) performed triaxial shear tests on a single-cell-reinforced granular soil sample. By analysing the Mohr circles and the Mohr-Coulomb failure envelopes of the unreinforced and reinforced samples, they proposed using the apparent cohesion c_r to account for the strength increase due to the geocell confinement. The apparent cohesion c_r resulted from the increased confining stress $\Delta\sigma_3$ provided by the geocell onto the infill soil:

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

where ϕ is the friction angle of the soil. The increased confining stress $\Delta\sigma_3$, as suggested by Bathurst and Karpurapu (1993), can be estimated by the Henkel and Gilbert (1952) equation:

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

where M is the tensile stiffness of the geocell material, D is the initial diameter of the geocell pocket, and ε_a is the axial strain of the soil in a triaxial shear test.

Rajagopal (1999) was one of the early researchers to perform triaxial shear tests on multi-cell reinforced soil samples. Due to the limited size of the triaxial test chamber, Rajagopal (1999) used laboratory-fabricated cellular confinement which had a much smaller pocket diameter than common geocell products. His test data supported Bathurst and Karpurapu's assumption that the geocell-reinforced sample has a friction angle almost the same as the unreinforced soil, but with an increased (or apparent) cohesion. Wesseloo (2004) performed unconfined compression tests on single-cell and multi-cell (2×2, 3×3, and 7×7 cells) reinforced soil. For the particular materials used in his study, he developed an elastoplastic constitutive model for the infill soil and rate-dependent non-linearly elastic membrane models for the geocell. Wesseloo (2004) analysed the stress-strain behaviour of the single cell-reinforced sand based on his models. He also raised the issue that the stress-strain behaviour measured from single cell-reinforced soil could not represent that of multi-cell-reinforced soil.

Calculation of the bearing capacity of the geocell-reinforced fill using the apparent cohesion was simple to implement. However, the axial strain ε_a in Equation (2) must be assumed. In reality, the axial strain of the reinforced soil may not be constant beneath and outside of the foundation footing (or embankment). In this sense, a limit equilibrium method or limit analysis may be more appropriate for estimating the bearing capacity. Zhang et al. (2010) developed an analytical solution to calculate the increased bearing capacity of the geocell-reinforced embankment foundation. It was assumed that the bearing capacity increment in the geocell-reinforced soil resulted from the "vertical stress dispersion effect" and the "membrane effect". The increased bearing capacity from each effect can be calculated separately (Zhang et al. 2010). Zhang et al. (2009) also proposed a semi-analytical method to estimate the settlement of an embankment on top of a geocell-reinforced fill.

3.2 Plastic deformation under cyclic loading

The geocell-reinforced layer is subjected to cyclic loading when used as a roadway base course or railway ballast. In these applications, cumulative plastic deformation is one of the main design considerations. Geocell can be used to reduce the plastic deformation of the granular material under cyclic loading. However, to develop an analytical method to predict the benefit of geocell in the plastic deformation is quite challenging.

Mengelt et al. (2000) and Pokharel (2010) both proposed empirical design methods for geocell-reinforced roadway base courses. Mengelt et al. (2000)'s design method was developed for flexible pavements based on laboratory cyclic triaxial tests on unreinforced and single-geocell-reinforced soils. Pokharel (2010)'s design method was calibrated against full-scale cyclic load tests and moving wheel tests on geocell-reinforced test sections. His design equations were modified from Giroud and Han (2004a, 2004b)'s design method for geogrid or geotextile-reinforced unpaved roads.

Due to the complex nature of soil behaviour under cyclic loading, it is difficult to describe the cyclic load response of soils based on a purely mechanistic analysis. To seek a balance between complexity and efficiency, the American Association of State Highway and Transportation Officials (AASHTO) adopted a mechanistic-empirical (M-E) methodology for pavement design (ARA, Inc. 2004). In the M-E design method, the plastic deformation of a layered system under a cyclic load was predicted by two steps. First, the resilient modulus M_r of each layer was used to calculate the resilient deformation under a static load using the mechanistic model. Then the calculated resilient deformation was transferred into the plastic deformation in the empirical damage model. In the current AASHTO M-E pavement design guide, the stress-dependent resilient modulus and the empirical transfer function can be expressed as:

$$M_r = k_1 p_a\left(\frac{\theta}{p_a}\right)^{k_2}\left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \tag{3}$$

$$\frac{\varepsilon_{1,p}}{\varepsilon_{1,r}} = \left(\varepsilon_0/\varepsilon_r\right)e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{4}$$

where M_r is the resilient modulus; k_1, k_2, and k_3 are the resilient modulus parameters of the material; p_a is the atmosphere pressure; θ and τ_{oct} are the bulk stress and the octahedral shear stress respectively. In the triaxial test condition ($\sigma_2 = \sigma_3$), θ and τ_{oct} can be calculated as $\theta = \sigma_1 + \sigma_3$ and $\tau_{oct} = \sqrt{2}(\sigma_1 - \sigma_3)/3$; $\varepsilon_{1,r}$ and $\varepsilon_{1,p}$ are the axial resilient and plastic strains respectively; $(\varepsilon_0 / \varepsilon_r)$, ρ , and β are the permanent deformation parameters.

Based on the AASHTO M-E design models (Equations (3) and (4)), Yang and Han (2013) proposed a unified analytical model to predict the resilient modulus and the plastic deformation of geosynthetic-reinforced cylindrical sample under a cyclic triaxial load condition. For a geocell-reinforced sample, it was assumed that the sample reaches a purely elastic (or resilient) state after a large number of load cycles. This assumption is consistent with the M-E design concept. After the resilient state is reached, the plastic deformation in the geocell induces an additional hoop stress $\Delta\sigma_3$ to the infill soil. $\Delta\sigma_3$ can be calculated by iterations using Equations (5) to (7):

$$\Delta\sigma_3 = \frac{M}{D}\left[-\frac{\Delta\sigma_3}{M_{r,1}} + \frac{\sigma_1 - (\sigma_3 + \Delta\sigma_3)}{M_{r,2}}\right](\varepsilon_0 / \varepsilon_r)e^{-\left(\frac{\rho}{N_{\text{limit}}}\right)^\beta}\left(\frac{1+\sin\psi}{1-\sin\psi}\right) \tag{5}$$

$$M_{r,1} = k_1 p_a \left(\frac{3\sigma_3 + 2\Delta\sigma_3}{p_a}\right)^{k_2}\left(\frac{\sqrt{2}\Delta\sigma_3}{3p_a} + 1\right)^{k_3} \tag{6}$$

$$M_{r,2} = k_1 p_a \left(\frac{\sigma_1 + 2(\sigma_3 + \Delta\sigma_3)}{p_a}\right)^{k_2}\left(\frac{\sqrt{2}[\sigma_1 - (\sigma_3 + \Delta\sigma_3)]}{3p_a} + 1\right)^{k_3} \tag{7}$$

In Equation (5), *M* is the tensile stiffness of the geocell material, *D* is the diameter of the geocell pocket, ψ is the dilation angle (can be set to zero for a conservative solution) of the infill material, and N_{limit} is the number of load cycles needed for the sample to reach the resilient state. For a typical granular material under a modest cyclic deviatoric stress, $N_{\text{limit}} = 10^5$ can be used. The calculated $\Delta\sigma_3$ as well as the stage resilient moduli $M_{r,1}$ and $M_{r,2}$ are substituted into Equations (8) and (9) to calculate the plastic strain $\varepsilon_{1,p}$ and the resilient modulus of the reinforced sample:

$$\varepsilon_{1,p} = \left[-\frac{\Delta\sigma_3}{M_{r,1}} + \frac{\sigma_1 - (\sigma_3 + \Delta\sigma_3)}{M_{r,2}}\right]\left(\frac{\varepsilon_0}{\varepsilon_r}\right)e^{-\left(\frac{\rho}{N_{\text{limit}}}\right)^\beta} \tag{8}$$

$$M_{r,\text{reinf}} = \frac{\sigma_1 - \sigma_3}{\left[\frac{\Delta\sigma_3}{M_{r,1}} + \frac{\sigma_1 - (\sigma_3 + \Delta\sigma_3)}{M_{r,2}}\right]} \tag{9}$$

Yang and Han (2013)'s analytical model is compatible with the current AASHTO M-E pavement design models. Only two additional properties of geocell are required, i.e., *M* and *D*. Further research is needed to fill the gap between a single-cell-reinforced sample in the laboratory and the multi-cell-reinforced fill in the field.

4. NUMERICAL ANALYSIS OF GEOCELL-REINFORCED GRANULAR FILL

Numerical analysis has been commonly employed to help understand experimental results and run parametric studies in geosynthetics research (e.g., Bergado et al. 1995, Bathurst and Knight 1998, Bergado and Teerawattanasuk 2008, Huang and Han 2009). A properly selected constitutive model for soil is crucial for a numerical analysis. Therefore, in this section, the past numerical studies on geocell-reinforced soils are reviewed with an emphasis on the constitutive models used. In general, more complicated constitutive models can capture more features of soil behaviour. However, the number of required material parameters and the efforts to determine them often increase with the complexity of the constitutive model. Therefore, a modeller needs to seek a balance between complexity and efficiency based on the problem of interest.

4.1 Numerical models for static loading

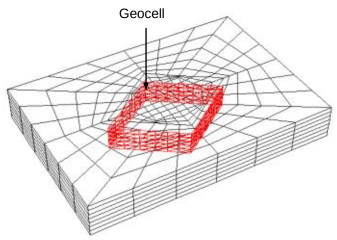
Several researchers have built numerical models to simulate the behaviour of geocell-reinforced granular fill under a static load from footings to embankments. These numerical models are summarized in Table 1. Among the literature reviewed, the Duncan-Chang model (Duncan et al., 1980) has been frequently used to simulate the stress-dependency of granular soils. Some researchers (Mhaiskar and Mandal, 1996; Madhavi Latha and Rajagopal, 2007; Madhavi Latha et al., 2009; Madhavi Latha and Somwanshi, 2009) modeled geocell-reinforced soil as a composite material with the equivalent parameters determined by Equations (1) and (2). Such simplification is helpful when analyzing a three-dimensional problem using two-dimensional numerical software. However, the equivalent composite model cannot accurately simulate the interaction between the infill soil and the geocell. One problem with this method is that the axial strain ε_a of the geocell-reinforced soil at failure has to be first estimated in order to calculate apparent cohesion c_r from Equations (1) and (2). In reality, the value of ε_a may vary from cell to cell, especially when the geocell reinforcement supports a load in a limited area (such as from a foundation footing). As Mitchell et al. (1979) pointed out, the confining stress in the cells beneath the loading area is much larger than that in the cells outside the loading area, which means the apparent cohesion and the modulus of the reinforced soil under the loading area should be larger than those outside the loading area.

Table 1 Numerical modelling studies reviewed on geocell-reinforced soil supporting static loads

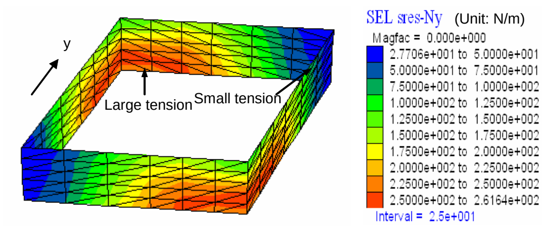
Reference	Load type	Program/ Dimension	Constitutive model: Soil	Constitutive model: Geocell
Evan 1994	Embankment	SSTIPG/2D	Duncan-Chang	Linear elastic
Mhaiskar and Mandal 1996	Rectangular footing	ANSYS/3D	Drucker-Prager[a]	--
Madhavi Latha and Rajagopal 2007	Embankment	GEOFEM/2D	Mohr-Coulomb[a]	--
Han et al. 2008	Rectangular footing	FLAC/3D	Mohr-Coulomb	Linear elastic
Madhavi Latha et al. 2009	Strip footing	GEOFEM/2D	Duncan-Chang[a]	--
Madhavi Latha and Somwanshi 2009	Square footing	FLAC/3D	Duncan-Chang[a]	--
Yang et al. 2010	Circular footing	FLAC/3D	Duncan-Chang	Linear elastic
Leshchinsky and Ling 2013a	Embankment	ABAQUS/3D	Drucker-Prager	Linear elastic

[a] Geocell and soil are modelled as a composite material

Han et al. (2008a) modelled soil and geocell separately in a three-dimensional numerical model as shown in Figure 3(a). They performed a laboratory model test on unreinforced and single cell-reinforced sand supporting a rectangular footing. In the numerical model created by FLAC3D, they used the Mohr-Coulomb model for the sand and the linearly elastic membrane model for the geocell. It was found that benefit of geocell on the bearing capacity shown in the test could not be simulated using this model because the Mohr-Coulomb model ignored the stress-dependency of soil. In order to match the test results, the modulus of the soil inside the geocell was increased by about 1.9 times. Figure 3(b) shows that the maximum tension in the geocell developed at the bottom and corner of the geocell. Han et al. (2008b) also modelled plate loading tests on multi-cell reinforced granular fill on soft subgrade in a test box as shown in Figure 4(a). The numerical results of vertical displacement versus applied pressure matched the measured results reasonably well (Figure 4(b)). To account for the stress dependency of the infill soil, Yang et al. (2010) developed an improved numerical model for single cell-reinforced sand supporting a circular footing. In this model, the soil was modelled using the stress-dependent Duncan-Chang model. In addition, the shape of the geocell and the boundary condition at the joint of the geocell were modelled in a more accurate way.

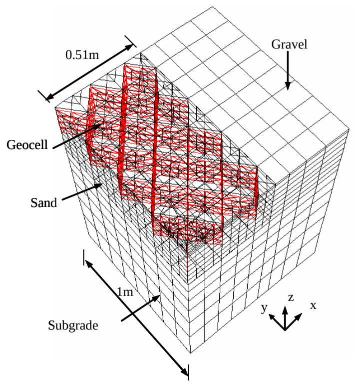


(a) Model

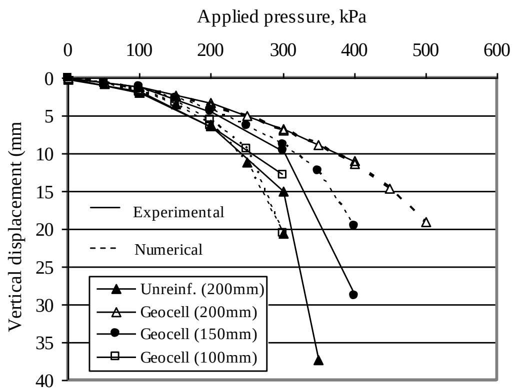


(b) Horizontal force

Figure 3 Numerical modelling of a single geocell in sand under vertical loading (Han et al., 2008a)



(a) Model



(b) Vertical displacement vs. applied pressure

Figure 4 Numerical modelling of multi-cell in soil under a loading plate (Han et al., 2008b)

4.2 Numerical models for cyclic loading

A linearly or non-linearly elastic-perfectly plastic model for soil may be adequate to simulate a geosynthetic-reinforced soil subjected to static loading. However, to model a cyclic load test, more complicated behaviour of soil needs to be considered. It is well known that granular soils develop some amount of plastic deformation in each loading-unloading cycle even when the stress level is below the yield strength of the soil. This is against the general assumption in the elastoplasticity theory that plastic deformation only occurs when the stress path touches the yield surface of the soil. To introduce progressive plastic deformation under cyclic loading, an advanced elastoplasticity theory (e.g., bounding surface plasticity) is generally required. However, the numerical implementation of advanced elastoplastic models is generally more difficult than to implement simple elastoplastic models. An alternative way to introduce progressive plastic deformation is to model the loading/unloading process as a dynamic load at certain frequency. In this case, the numerical analysis solves the problem as a dynamic one. Leshchinsky and Ling (2013b) modelled a laboratory cyclic load test on geocell-reinforced ballast using the ABAQUS/Explicit program. In their numerical model, the ballast was modelled using a simple elastoplastic model with a Drucker-Prager yield criterion and the vertical load (of 5-Hz frequency) was modelled as a dynamic load. The numerical model was able to reflect the general trend of the experimental results.

As mentioned previously, the cumulative plastic deformation of the granular soil under a cyclic load can be indirectly predicted using the M-E method. Similar to the static load models, the stress-dependency of the resilient modulus (Equation (2)) has to be considered in order to appreciate the benefit of the geocell reinforcement. However, Equation (2) cannot be used directly as a stress-dependent constitutive equation because the resilient modulus calculated by Equation (2) is a secant modulus (ARA, Inc. 2004). For a numerical analysis, the constitutive equation has to be in an incremental form, thus tangent modulus must be used. Under an axisymmetric stress condition, the tangent resilient modulus E_t can be calculated by:

$$E_t = \frac{M_r}{1-(\sigma_1-\sigma_3)\left[\dfrac{k_2}{\theta}+\dfrac{\sqrt{2}k_3}{3(\tau_{oct}+p_a)}\right]} \tag{11}$$

Equation (11) was implemented in the public review design software of the AASHTO M-E pavement design guide. However, the geometry of geocell can be accurately represented in a three-dimensional numerical model. In this case, Equation (11) must be re-derived based on a general three-dimensional stress condition. Yang et al. (2013) derived the three-dimensional tangent resilient modulus equation as Equation (12). Note that when $\sigma_2=\sigma_3$, Equation (12) can be simplified to Equation (11), which is reasonable because an axisymmetric condition is a special case of the general three-dimensional condition.

$$E_t = \begin{cases} \dfrac{M_r}{1-(\sigma_1-\sigma_3)\left[\dfrac{k_2}{\theta}+\dfrac{k_3(2\sigma_1-\sigma_2-\sigma_3)}{9\tau_{oct}(\tau_{oct}+p_a)}\right]-(\sigma_2-\sigma_3)\left[\dfrac{k_2}{\theta}+\dfrac{k_3(2\sigma_1-\sigma_2-\sigma_3)}{9\tau_{oct}(\tau_{oct}+p_a)}\right]}, & \tau_{oct}\neq 0 \\ M_r, & \tau_{oct}=0 \end{cases} \tag{12}$$

In addition to the three-dimensional tangent resilient modulus, Yang et al. (2013) suggested to consider the compaction-induced residual stress in the geocell-reinforced soil. This suggestion was based on the assumption that geocell-reinforced soils can lock in more horizontal stress than the unreinforced layer subjected to the same amount of compaction effort. A simple method to estimate the compaction-induced residual stress was proposed by modifying Duncan and Seed (1986)'s model. As shown in Figure 6, the stress path ABCD represents the virgin loading and unloading path suggested by Duncan and Seed (1986). The unloading curve of the unreinforced soil cannot pass through the passive earth pressure line (the K_1-line in Figure 5). In the geocell-reinforced layer, Yang et al. (2013) assumed that the residual stress in the soil can exceed the passive earth pressure because the geocell structure will stabilize the soil from the passive failure. With this modification, the stress path of the geocell-reinforced soil during compaction will follow the curve ABCE in Figure 6, and the lateral earth pressure σ_h' after removing the compaction pressure can be estimated by:

$$\sigma_h^{'} = k_0 \sigma_{v,0}^{'} \left(\frac{\sigma_{v,\max}^{'}}{\sigma_{v,0}^{'}} \right)^{0.018+0.974\sin\phi'} \tag{13}$$

where $\sigma_{v,\max}^{'}$ is the maximum vertical pressure induced by the compaction, K_0 is the lateral earth pressure coefficient at rest ($K_0 \approx 1-\sin\phi'$), and ϕ' is the friction angle of soil. Note that Equation (13) was obtained by simply rearranging the equations in Duncan and Seed (1986)'s model. The only modification was that the calculated lateral earth pressure $\sigma_h^{'}$ was not subjected to the upper bound value of passive earth pressure within the geocell-reinforced layer. The lateral earth pressure calculated using Equation (13) was applied to the numerical model as an initial stress condition by Yang et al. (2013). The calculated resilient strain along the centerline of the model was extracted and used to predict the permanent strain using the transfer function (Equation (4)) of the soil. The calculated permanent deformations of one geocell-reinforced sand section under moving wheel loading are compared with the measured results in Figure 6.

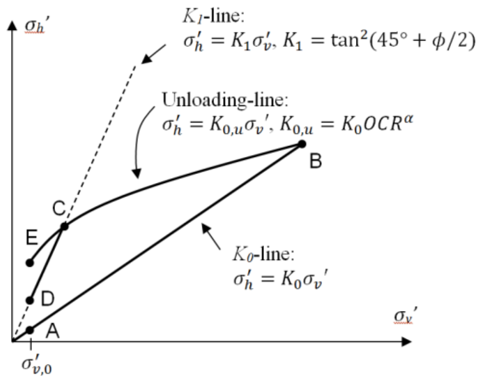


Figure 5 Stress paths of unreinforced and reinforced soils during compaction (modified from Duncan and Seed, 1980)

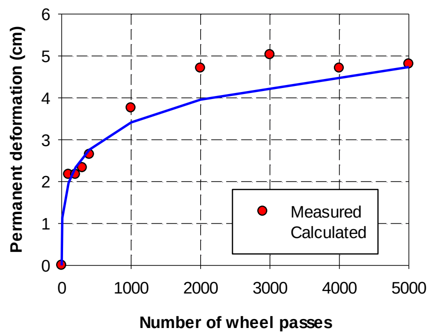


Figure 6 Measured versus calculated permanent deformations of geocell-reinforced sand under moving wheel loading using the M-E model (Yang et al., 2013)

The M-E method presented above is simple to implement. Only an elastic problem needs to be solved numerically. The main limitation of the M-E model is that it assumes the soil always reaches a resilient state after a large number of load cycles. This assumption may become invalid when the applied load is large enough to fail the soil. As a result, the M-E method may under-predict the plastic deformation of soil under large cyclic load levels. In order to model the complex cyclic behaviour of soil with or without reinforcement, advanced constitutive models have to be used. Researchers have applied bounding surface plasticity models in numerical analyses of geogrid-reinforced soils (e.g., Perkins, 2001; Ling et al., 2004), which may be extended to analyze geocell-reinforced soils as well.

Another group of constitutive models, namely hypoplasticity model, may also be used to simulate the cyclic response of soils. In contrast to elastoplasticity, hypoplasticity does not use any type of yield surface or flow rule in describing the stress-strain behaviour of materials. Thus hypoplastic constitutive equations are mathematically simpler than the advanced elastoplastic models (Kolymbas 1999). In addition, hypoplasticity is able to capture many aspects of soil behaviour such as stress dependency, critical state, dilatancy, and stress reversal. Yang and Annamraju (2013) recently explored the feasibility of using a hypoplastic model (developed by Weifner and Kolymbas (2007)) to simulate the behaviour of a single cell-reinforced soil under a triaxial load condition. The results from this numerical model seem promising. The hypoplastic model was able to capture the reduced plastic deformation of soil due to the geocell reinforcement (as shown in Figure 7). Furthermore, since Weifner and Kolymbas' hypoplastic model is able to account for the stress history effect, it may also be used to investigate the compaction-induced residual stress on geocell-reinforced fill. Further research is needed to implement the hypoplastic model to larger-scale numerical analyses of geocell-reinforced load-supporting structures.

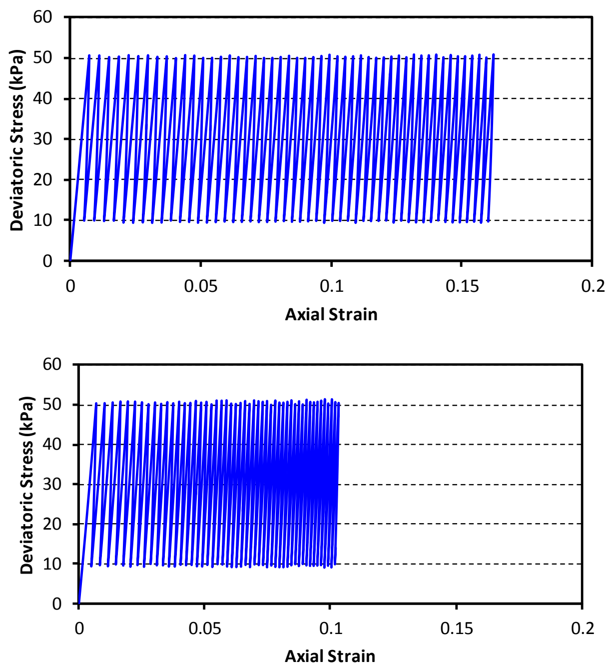


Figure 7 Modelling of cyclic triaxial shear tests on reinforced and unreinforced samples (Yang and Annamraju, 2013)

4.3 Constitutive model for geocell material

The thickness of the geocell wall is about a few millimetres, thus it is often modelled using plate or membrane elements in a numerical model. Geocell is typically made of polymeric materials such as the high-density polyethylene (HDPE). The behaviour of such materials is well known to be nonlinear and rate dependent. The nonlinearity of the geosynthetic material can be considered by applying a nonlinear tensile stiffness to the geocell elements (e.g., Ling et al., 2000). In roadway applications where the geocell is subjected to a low magnitude cyclic load, a properly constructed geocell may only develop less than 2 precents tensile strain (Yang et al., 2012). With such a small range of tensile strain, the geocell can be modelled as a linear elastic material for simplicity.

5. SUMMARY

This paper presents a synthesis of the theoretical and numerical analyses on geocell-reinforced granular fills under static and cyclic loading. Most of the studies reviewed in this paper were performed in the last two decades. In general, the theoretical research still lags behind the application of geocell reinforcement. A few analytical solutions have been developed in recent years to predict the behavior of geocell-reinforced soils under different load conditions. Validation and improvement are needed for these models to gain a wider acceptance.

As for the numerical modelling, it is generally recognized that the stress dependency of the granular soil should be considered in order to capture the confining effect from the geocell. The simulation of cumulative plastic deformation under a cyclic load is still challenging for numerical modelling. Plastic deformation may be determined indirectly using a three-dimensional mechanistic-empirical (M-E) model. However, the M-E model is unable to simulate the progressive failure of soil. Further research is needed regarding the implementation of advanced constitutive models such as the bounding surface plasticity and hypoplasticity models. Geocell can be modelled using interconnected plate or membrane elements in the numerical analysis. For roadway applications where a small deformation is involved, a linearly elastic model for the geocell material is adequate.

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