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Application of the two-layer system theory to calculate the settlements and vertical stress propagation in soil reinforcement with geocell

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ABSTRACT

This paper presents a methodology for determining the surface settlements of the geocell-reinforced soil layer and the vertical stresses propagated to the foundation subgrade at the layers interface, on the subgrade. Based on the theory of equivalent thicknesses, which is an approximation of the theory of elasticity for layered systems, a generalized equation for determining settlements was proposed in a two-layer system composed of geocell-reinforced soil layer over the subgrade. The equation obtained is dependent only on the relations between the elastic parameters of these two layers, such as the deformation moduli and Poisson's ratio, and geometric parameters, such as geocell layer thickness and loading width,. The proposed equation generated very close results with rigorous solutions of the two-layer system from the theory of elasticity. It was applied, together with rigorous methods, in an instrumented field Plate load test allowing the determination of the geocell-reinforced soil layer modulus of deformation by retro analysis and the vertical stresses propagated to the subgrade. The results showed that the two-layer system theory from theories of elasticity and equivalent thicknesses can be used in a simple and efficient way for determining settlements and the propagation of vertical stresses. The proposed methodology also satisfactorily calculated these results when compared with the rigorous methods and with the values obtained in the field test.

1. Introduction

Geocell is a geosynthetic of great versatility and is increasingly used in several areas of Engineering, especially for improving bearing capacity in foundations, embankments, paved and unpaved roads, railways and heavy duty traffic areas and storage yards; retaining walls; erosion control in water channels and slopes; and structure protection, such as buried pipelines (Bush et al., 1990; Cowland and Wong, 1993, Moghaddas Tafreshi and Khalaj, 2008, Tavakoli Mehrjardi et al., 2012, 2013; Sitharam and Hegde, 2013; Hegde and Sitharam, 2015a; Song et al., 2017; Rahimi et al., 2018).

Studies in several areas were conducted for better understanding of the behavior and performance of the geocell in its applications. In the case of soil reinforcement and improvement of bearing capacity, the initial researches were based on laboratory tests evaluating the different geometric, physical and mechanical properties of the geocell in the reinforcement performance (Mandal and Gupta, 1994; Mhaiskar and Mandal, 1996; Dash et al., 2001; Wesseloo et al., 2009; Chen et al., 2013; Han et al., 2008; Pokharel et al. 2010, 2017; Sireesh et al., 2009; Hegde and Sitharam, 2015b; Dash and Choudhary, 2018). Subsequently, the numerical analysis allowed executed simulations enhancing the understanding of the behavior of the geocell in soil reinforcement. The geocell mattress was formerly simulated as a 2D layer with equivalent parameters (Bathurst and Knight, 1998, Madhavi Latha and Rajagopal, 2007; Hegde and Sitharam, 2015b). However, with the advent of new computational tools coupled with their improved processing, 3D simulations with the ability to create more complex geometries allowed sculpting the individual cells in different formats, which allowed deeper and more realistic analyses (Mhaiskar and Mandal, 1996, Han et al., 2008, Sireesh et al., 2009, Leshchinsky and Ling, 2013, Mehdipour et al., 2013, Hegde and Sitharam, 2015c, 2015d and 2017). Finally, with an increased use of the geocell in large works, large-scale and even field tests have been conducted in recent years to verify the effectiveness and performance of the reinforcement under more real conditions (Bathurst and Jarrett, 1988; Indraratna et al., 2015; Biabani et al., 2016; Guo et al., 2015; Han et al., 2011; Rajagopal et al., 2014; Thakur et al., 2012; Yang et al., 2012; Saride, 2013; Saride et al., 2016, Tavakoli Mehrjardi et al., 2013; Ngo et al., 2018; Satyal et al., 2018).

In the conceptual area, the first mathematical treatment for determining the improvement due to the geocell reinforcement was made by Bathurst and Karpurapu (1993). Using the Mohr-Coulomb rupture theory and the Henkel and Gilbert (1952) membrane theory to determine the increase of confinement in the fill material due to the

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presence of the geocell, the authors used the concept of induced apparent cohesion to express the improvement in the geocell-reinforced soil layer (Bathurst and Karpurapu, 1993; Rajagopal et al., 1999). The model was later extended to reinforcement on an embankment (Madhavi Latha et al., 2006) and for the cyclic loading condition (Yang and Han, 2013; Indraratna et al., 2015). Subsequently, several analytical methods for calculating the bearing capacity improvement due to the geocell reinforcement were proposed based on the mechanisms of geocell reinforcement, such as lateral resistance and confinement effects, vertical stress dispersion and membrane effect, with equations using limit equilibrium and semi-empiric concepts (Koerner, 1994, Presto, 2008, Zhang et al., 2010a, Sitharam and Hegde, 2013, Avesani Neto et al., 2013 and 2015).

Some researchers have generated equations and methodologies in an attempt to mathematically translate the stress and strain effects that occur in the geocell-reinforced layer and in its interface with the subgrade. Madhavi Latha (2000) proposed an equation for determining the geocell mattress modulus of deformation, also called Young's modulus, elastic modulus or even layer's stiffness, for pavement engineers, as a function of the moduli of filling soil and cell wall material. Zhang et al. (2009 and 2010a) transformed the geocell-reinforced soil layer into an equivalent Winkler foundation beam, obtaining semi-analytical solutions to assess the deformations of, and internal forces in, the foundation 'beam'. Moghaddas Tafreshi et al. (2015) presented an analytical solution based on the theory of elasticity for multiple layers of soil intercalated with layers of geocell capable of calculating their stress and strain behavior.

Regardless of this recent advance in the development of equations capable of calculating the improvement, besides the stress and strain behavior in the geocell-reinforcement system, there remains a lack of a methodology to more realistically determine the settlements and stresses in the geocell-reinforced layer (Hegde, 2017).

The present article thus proposes a new, simple and effective generalized methodology for interpretation and analyzing the geocell-reinforced system under the theory of elasticity allowing calculating settlements on the surface and the vertical stresses propagated to the subgrade.

2. Layered system

The study of layered systems started in the 1930s with rigorous solutions for a finite layer underlain by a rigid base – layer of soil over a bedrock (Marguerre, 1931; Biot, 1935; Pickett, 1938). For an elastic two-layer system, as soil over soil, and circular loads, Burmister (1943) derived rigorous solutions for stresses and settlements on the surface, presenting a numerical solution in chart form for the deflections in the specific case of Poisson's ratio equal to 0.5 and total friction at the interface between the layers (Fig. 1, equation (9b)). Subsequently, the researcher expanded the equations for the without friction situation at the interface between the layers and for a three-layer system (Burmister, 1945a, 1945b; 1945c).

Later, several authors made significant contributions to the study and application of the layered system: Fox (1948) performed integrations in the system of equations proposed by Burmister (1945a, 1945b and 1945c) and obtained numerical solutions of the vertical, radial, tangential and shear stresses at the interface, for the special case of Poisson's ratios equal to 0.5 in both layers. Burmister (1956) developed the system of equations for rectangular loads. Schiffman (1957) and Jones (1962) presented solutions in chart forms for the three-layer system. Burmister (1962) reported a solution for settlement and vertical and shear stresses at the interface considering Poisson's ratio equal to 0.2 and 0.4, respectively, for the upper and lower layers. de Barros (1966a) satisfactorily verified the application of the multilayer theory to interpret several Plate load tests carried out on soil-cement pavements in airports in Brazil. de Barros (1966b) suggested a methodology to reduce a three-layer system to a two equivalent layer system simplifying the calculations and also presented solutions for the deflection of the system of two and three layers considering Poisson's ratios equal to 0.35. Ueshita and Meyerhof (1967) evaluated the rigorous two-layer theory using laboratory tests in sandy and clayey soils and reported a good approximation between the calculated and tests results.

Approximate solutions using the theory of equivalent thicknesses were proposed by Palmer and Barber (1940) - even before Burmister's rigorous, and later Odemark's (1949) methods. The theory of equivalent thicknesses proposes the transformation of the multiple layers of the soil into an equivalent thickness with properties equal to those of the underlying layer, such as the subgrade, allowing treating a multilayer problem by the theory of elasticity of semi-infinite homogeneous mass with the Boussinesq's solution. The methods of Palmer and Barber (1940) and Odemark (1949) (Fig. 1, equations (10b) and (11b)) adopt a structural equivalence between the layers using a relation between their thicknesses and their elastic parameters, such as deformation/Young's modulus, E and Poisson's ratio, ν. More recently, Freeman and Harr (2004) proposed another method based on the theory of equivalent thicknesses using a probabilistic distribution of stresses in the subsoil and a transformation of the layers using a soil parameter similar to the lateral earth pressure coefficient. Ueshita and Meyerhof (1967) and Ullidtz (1998) evaluated the theory of equivalent thicknesses with laboratory tests verifying a good approximation between experimental and theoretical results. In fact, Ullidtz (1998) reported that the differences between the deflections calculated by this theory with the rigorous solution are less than 5% in most soil applications cases: relation between the moduli of deformation of upper, E_1, and lower, E_2, layers - E_1/E_2 ranging from 2 to 200; and relation between the thickness of the geocell layer, h, and the load radius, r - h/r from 0.25 to 2. According to the author, this difference is mostly due to the precision in the determination of the deflection factor using the chart from rigorous solution.

Fig. 1 shows a summary of the equations and solutions described above for a continuous medium and a two-layer system that will be used throughout this paper.

There are also approximate semi-empirical solutions for determining stresses and deflections in the layered system. Steinbrenner (1934) suggested a method for calculating the deflections at the top of a soil layer underlying a rigid base. Egorov (1939) and Vesic (1963) extended the Steinbrenner (1934) solution to the vertical stress and deflection for that situation. Nascimento et al. (1961) proposed to approximate the curved shape of the Burmister (1943) solutions by straight lines and obtained simplified solutions for determining vertical stresses and deflections in multi-layer systems. Lister and Jones (1967) developed approximate equations for calculating vertical and radial stresses in the layers interface and for the surface deflection for two and three-layer systems. Ueshita and Meyerhof (1968) proposed a method for determining deflection for a two-layer system under the condition that the lower one is stiffer than the upper one. Mitchell and Gardner (1971) used results from a Plate load test and finite element analysis (FEA) to fit the equation proposed by Lister and Jones (1967) for clay deposits under a sand layer. Milović (1992) carried out an extensive FEA to determine analytical formulations for determining deflections and vertical stresses in the layered system.

Some of the solutions mentioned here can be easily found in Poulos and Davis (1974).

Finally, with the increase of the computational capacity, FEA began to be used for accurately determining the stresses and strains in a layered soil system. However, the success of these simulations lies in the appropriate choice of layers constitutive models and their respective input parameters, the construction of models with adequate refinement level to investigate the problem and in the consumption of the time necessary to carry out computational calculations. For most practical cases, these aspects employ FEA replaced by using conventional analytical methods that have greater feasibility and simplicity of