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A simplified method for predicting the settlement of circular footings on multi-layered geocell-reinforced non-cohesive soils

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ABSTRACT

Multiple layers of geosynthetic reinforcement, placed below foundations or in the supporting layers of road pavements, can improve section performance through several mechanisms, leading to reduction in stresses and deformations. This paper aims to present a new analytical solution, based on the theory of multi-layered soil system to estimate the pressure–settlement response of a circular footing resting on such foundations, specifically those containing geocell layers. An analytical model that incorporates the elastic characteristics of soil and reinforcement is developed to predict strain and confining pressure propagated throughout an available multi-layer system, is proposed. A modified elastic method has been used to back-calculate the elastic modulus in terms of strain and confining pressure with materials data extracted from triaxial tests on unreinforced and geocell-reinforced soil samples. The proposed model has been validated by results of plate load tests on unreinforced and geocell-reinforced foundation beds. The comparisons between the results of the plate load tests and proposed analytical method reflected a satisfactory accuracy and consistency, especially at expected, practical, settlement ratios. Furthermore, to have a better assessment of geocell-reinforced foundations' behavior, a parametric sensitivity has been studied. The results of this study show that the higher bearing pressure and lower settlement were achieved when number of geocell layer, secant modulus of geocell and the modulus number of the soil were increased. These results are in-line with the experimental results of the previous researchers. The study also permits the limits of effective and efficient reinforcement to be determined.

1. Introduction

In the last decades, due to its cost savings, ease of construction and ability to improve the visual appearance, geosynthetic reinforced soil has been significantly exploited in geotechnical engineering applications such as road construction, railway embankments, lifeline provision, stabilization of slopes, and improvement of soft foundation beds (e.g., Collin et al., 1996; Raymond, 2002; Hufenus et al., 2006; Dash et al., 2007; Bathurst et al., 2009; Madhavi Latha and Somwanshi, 2009; Zhang et al., 2009; Ling et al., 2009; Palmeira and Andrade, 2010; Pokharel et al., 2010; Boushehrian et al., 2011; Lambert et al., 2011; Yang et al. 2012; Thakur et al., 2012; Tavakoli Mehrjardi et al., 2012; Leshchinsky and Ling, 2013a,b; Yang and Han, 2013; Tanyu et al., 2013; Chen et al., 2013a,b; Soudé et al., 2013; Avesani Neto et al., 2013; Kachi et al., 2013; Moghaddas Tafreshi et al., 2014; Indraratna et al., 2015). A desirable use of such reinforcements would be to improve the bearing capacity and settlement of footings. With this in mind, many researchers have investigated the beneficial ability of planar and cellular reinforcement (e.g. geocell) constructions and how best to arrange the inclusions so as to deliver effective reinforcement and to improve their bearing capacity and settlement response (Dash et al., 2007; Sitharam et al., 2007; Madhavi Latha and Rajagopal, 2007; Zhou and Wen, 2008; Chen and Chiu, 2008; Yoon et al., 2008; Sharma et al., 2009; Wesselo et al., 2009; Sireesh et al., 2009; Eid et al., 2009;

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Pokharel et al., 2010; Zhang et al., 2010a; Lambert et al., 2011; Yang et al., 2012; Kumar and Kaur, 2012; Tanyu et al., 2013; Tavakoli Mehrjardi et al., 2013; Dash and Chandra Bora, 2013; Chen et al., 2013a,b; Mehdipour et al., 2013; Biswas et al., 2013; Huang, 2014; Song et al., 2014; Hegde and Sitharam, 2015a,b).

Recently, two of the current authors have shown that geocell reinforcement can be significantly more effective than a planar reinforcement, in improving the behavior of foundation beds under static and repeated loads (Moghaddas Tafreshi and Dawson, 2010a,b). They attributed this to the superior confinement offered by the geocells in all directions, due to the frictional and passive resistance developed at the soil–geocell interfaces that increases the sand's bearing capacity and decreases the settlement of the foundation bed.

An analytical approach to the design of such footings and to explain their pressure–settlement behavior would be very useful. Although, there have been many experimental studies into the use of geocell reinforcement in civil engineering works, there are few analytical studies (e.g., Zhang et al. 2009, 2010a,b). Zhang et al. (2010a) presented a simple bearing capacity calculation method for a geocell-supported embankment on a soft subgrade based on the study of the reinforcement functions of a geocell layer beneath a road embankment. They indicated that their results were relatively close to the experimental results. Zhang et al. (2010b) idealized a geocell-reinforced mattress as a beam on a Winkler foundation in order to analyze its settlement response. Semi-analytic solutions were developed to assess the deformations of, and internal forces in, the foundation 'beam'. They reported that the interface resistance, related to the horizontal deformation of the composite beam (i.e., geocell–soil 'beam'), had a reduction effect on the embankment settlement.

2. Aim

A literature review, briefly reported above, indicated that there remains a lack of analytical study into the behavior of footings supported by a geocell-reinforced bed, particularly when that bed includes a multi-layered geocell. Therefore, this article seeks to redress this omission by providing a relatively simple analytical method, based on "*n*"-layered soil system theory (Hirai, 2008) and surface settlement of equivalent system (Vakili, 2008), for the evaluation of the pressure–settlement response of both unreinforced and multi-layered geocell-reinforced foundation beds. The results of this method have been compared with the results of plate load tests (Moghaddas Tafreshi et al., 2013) to investigate its validity. In addition, the effects of various parameters such as geocell and soil stiffness modulus, geocell layer height and diameter of plate load have been investigated so as to understand mechanisms for improving the pressure–settlements behavior of such footings. Note that, although, the settlement–stress behavior of plate loading tests is not elastic, yet the aforementioned analytical method simulated the behavior as a Multiple Linear Elastic (MLE) model (i.e., non-linear elastic) permitting calculation of the elastic modulus of each layer, for each loading step.

3. Problem statement

Geosynthetic inclusions are most effective if used in the zone significantly stressed by the footing. Since, a concentrated stress bowl occupies a zone equal to or twice the depth of the footing width/diameter (the "effective depth" being approximately 1.2–2 m for a typical footing width/diameter), and the heights of commercially produced geocells are usually less than 200 mm (available cell depths produced by two key manufacturers in Europe and USA), a single thick layer of geocell beneath the footing is not possible for field construction. Even if it were, such a thick geocell layer would likely make compaction of cell-fill extremely difficult (Thakur et al., 2012; Moghaddas Tafreshi et al., 2014), consequently decreasing the performance of a thick single layer of geocell. Hence, practically, if such a depth of soil needs to be reinforced by geocells, it necessitates designers to use 3–4 layers of geocell with thickness $\leq$ 200 mm.

Hence, the use of several layers of geocell (say, three or four) each with a thickness $\leq$ 200 mm and with vertical spacing between successive layers of geocell is a practical alternative and could be a beneficial means of reinforcing the soil beneath a footing. The schematic cross-section of the foundation bed containing geocell-reinforcement layers with the thicknesses of h_g, and of the footing, is shown in Fig. 1. In this figure, the first geocell layer is located at a depth of u beneath the footing and the next geocell layers are placed after an unreinforced soil thickness of h_s. It should be noted that, although there are three probable mechanisms by which geocell transfers stress through the depth of foundation bed ("lateral resistance effect", "vertical stress dispersion effect" and "membrane effect"), this study tried to simulate all these factors by considering soil–geocell layer as a composite material. Some simplification for a complicated problem like the current system is inevitable. Here, the characteristics of the composite material have been defined according to the soil and soil–geocell specimens in triaxial tests; and the simplifying assumptions made in the solution system mean that the behavior of the geocell layers are considered to be uniform layers that only deform vertically. Since the "*n*"-layered soil system theory by Hirai (2008) and surface settlement of equivalent system (Vakili, 2008) were employed for the evaluation of the pressure–settlement response of multi-layered geocell-reinforced foundation beds, a summary of these methods is presented in Sections 5 and 6.

4. Pressure–settlement variation of footing on unreinforced bed

For a semi-infinite soil medium of the elastic modulus E_n and Poisson's ratio ν_n, subjected to uniform pressure q on a circular

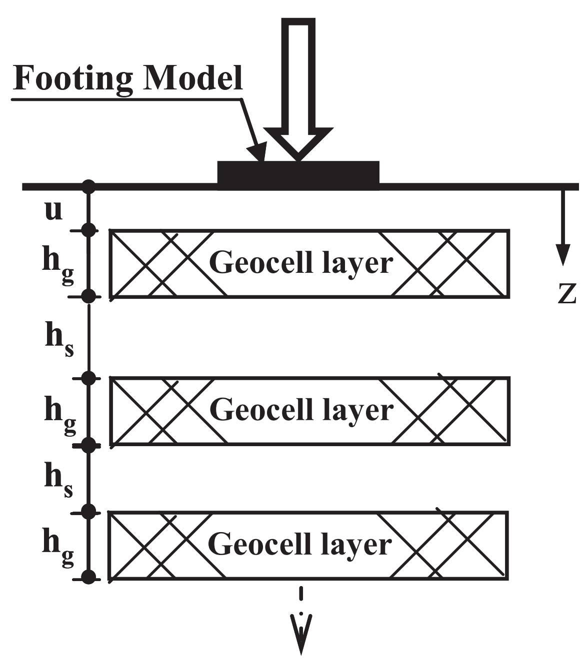

Fig. 1. Schematic of multi-layered geocell-reinforced foundation bed.