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Experimental and numerical investigation of the uplift capacity of plate anchors in geocell-reinforced sand

M. Rahimi[a], S.N. Moghaddas Tafreshi[a,*], B. Leshchinsky[b], A.R. Dawson[c]

[a] Department of Civil Engineering, K.N. Toosi University of Technology, Valiasr St., Mirdamad Cr., Tehran, Iran
[b] Forest Engineering, Resources and Management Department, College of Forestry, Oregon State University, 280 Peavy Hall, Corvallis, OR 97331, USA
[c] Nottingham Transportation Engineering Centre, University of Nottingham, Nottingham, UK

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ABSTRACT

Plate anchors are frequently used to provide resistance against uplift forces. This paper describes the reinforcing effects of a geocell-reinforced soil layer on uplift behavior of anchor plates. The uplift tests were conducted in a test pit at near full-scale on anchor plates with widths between 150 and 300 mm with embedment depths of 1.5–3 times the anchor width for both unreinforced and geocell-reinforced backfill. A single geocell layer with pocket size 110 mm × 110 mm and height 100 mm, fabricated from non-perforated and nonwoven geotextile, was used. The results show that the peak and residual uplift capacities of anchor models were highest when the geocell layer over the anchor was used, but with increasing anchor size and embedment depth, the benefit of the geocell reinforcement deceases. Peak loads between 130% and 155% of unreinforced conditions were observed when geocell reinforcement was present. Residual loading increased from 75% to 225% that of the unreinforced scenario. The reinforced anchor system could undergo larger upward displacements before peak loading occurred. These improvements may be attributed to the geocell reinforcement distributing stress to a wider area than the unreinforced case during uplift. The breakout factor increases with embedment depth and decreased with increasing anchor width for both unreinforced and reinforced conditions, the latter yielding larger breakout factors. Calibrated numerical modelling demonstrated favorable agreement with experimental observations, providing insight into detailed behavior of the system. For example, surface heave decreased by over 80% when geocell was present because of a much more efficient stress distribution imparted by the presence of the geocell layer.

1. Introduction

In recent years, geosynthetics have become increasingly common due to their cost-efficiency in reinforcement applications. Geosynthetics are commonly manufactured in planar form (geotextiles, geogrids, geonets, geomembranes, strips), but three-dimensional (3D) reinforcements, such as geocells, are increasingly being adopted for soil reinforcement applications (Koerner, 2012). Geocells have demonstrated particular utility for foundation support, embankment protection, subgrade stabilization and earth retention (Moghaddas Tafreshi et al., 2013; Hegde and Sitharam, 2015; Biabani et al., 2016) but there is limited research towards assessing the efficacy of geocells towards increasing uplift resistance of earth anchors (e.g. Choudhary and Dash, 2013; Moghaddas Tafreshi et al., 2014). There is promise in such an application, however, as geocells increase soil strength by confinement, reducing lateral displacement and causing the confined composite to act as a stiffer mattress-like composite (Zhang et al., 2010).

Various structures are subject to loading that require the uplift resistance of anchors, including free-standing towers, wind turbines, submerged pipelines, chimneys, suspension bridges, and roofs (Ilamparuthi et al., 2002). In these applications, anchors are commonly embedded within nearby soil to provide stability and transmit tensile forces to a competent medium (Krishnaswamy and Parashar, 1994; Ghosh and Bera, 2010; Rangari et al., 2013). Anchors are the typical means of resisting these loads, commonly found in the form of plate anchors, helical anchors, deadman anchors, pile anchors, and drag anchors (Sabatini et al., 1999). The uplift capacity of a buried anchor typically comprises of the weight of soil within the failure zone as well as frictional and/or cohesive resistance along the realized failure surface. The required uplift capacity of these systems can be enhanced by

* Corresponding author.
E-mail addresses: my.rahimi@mail.kntu.ac.ir (M. Rahimi), nas_moghaddas@kntu.ac.ir (S.N. Moghaddas Tafreshi), ben.leshchinsky@oregonstate.edu (B. Leshchinsky), andrew.dawson@nottingham.ac.uk (A.R. Dawson).

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increasing the size and embedment depth of the anchor or improving backfill strength and density (Choudhury and Subba Rao, 2005; Kumar and Bhoi, 2009; Song et al., 2009; Vishwas and Kumar, 2011; Liu et al., 2012; Bhattacharya and Kumar, 2014; 2015; Ganesh and Sahoo, 2016; Khan et al., 2017; Moayedi and Mosallanezhad, 2017; Shin et al., 2016).

Extensive research has been performed to improve assessment of anchor uplift behavior within unreinforced soil, comprising of experimental, analytical and numerical studies. Early research on anchor uplift capacity was performed under 1G conditions in the context of stabilizing transmission towers and was primarily limited to scaled laboratory experiments to demonstrate the effects of shape, embedment, soil conditions and soil types on anchor resistance (Meyerhof and Adams, 1968; Das and Seeley, 1975; Murray and Geddes, 1987; Frydman and Shaham, 1989; Ilamparuthi et al., 2002; Merifield and sloan, 2006; Sakai and Tanaka, 2007; Song et al., 2008; Kouzer and Kumar, 2009; Khatri and Kumar, 2009; Deskmukh et al., 2010; Horpibulsuk and Niramitkorburee, 2010; Honda et al., 2011; Tian et al., 2014; Wang and O'Loughlin, 2014; Dash and Choudhary, 2018). To better capture realistic, scaled gravitational conditions, centrifuge-based laboratory experiments have been employed in assessing uplift capacity (Dickin, 1988; Tagaya et al., 1988; Dickin and Leung, 1990). Theoretical uplift solutions have been developed by using cavity expansion theory (Vesic, 1971), limit equilibrium theory (Meyerhof and Adams, 1968; Murray and Geddes, 1987; Ghaly and Hanna, 1994; Sahoo and Khuntia, 2018), reverse hopper theory (Lee et al., 2014), and elasto-plastic continuum analyses (Rowe and Davis, 1982; Tagaya et al., 1988). However, there is very little research studying the effect of geosynthetic reinforcement in realizing uplift capacity. Extensive experimental research has been performed on assessing the mechanism and uplift capacity of plate anchors in dry, cohesionless sand. Dickin (1988) investigated the uplift behavior of square plate anchors through use of a centrifuge and 1G experiments, demonstrating that anchor geometry has a notable influence on the breakout factor and failure mechanism. In consideration of possibly non-conservative scale effects, Dickin (1988) proposed an alternative set of breakout factors derived from Meyerhof and Adams (1968) and Murray and Geddes (1987) for different plate sizes with similar embedment ratios. The solution demonstrates good agreement with the experiments, but overestimates the small scale centrifuge results for embedment ratios (i.e. depth of embedment, D, divided by anchor width, B) exceeding $D/B > 4$.

Employing large or deeply embedded anchors may not always be economical or practical means of obtaining the required anchor capacity. An alternative approach is to use smaller and/or less embedded anchors beneath geosynthetic reinforcements (Krishnaswamy and Parashar, 1994; Ilamparuthi and Dickin, 2001; Ghosh and Bera, 2010; Keskin, 2015). There is some insight into the load-bearing behavior of soil reinforced by geogrids and geotextiles (Binquet and Lee, 1975; Yetimoglu et al., 1994; Karpurapu and Bathurst, 1995; Dash et al., 2003; Moghaddas Tafreshi and Rahimi, 2012; Tran et al., 2013; Vahedifard et al., 2016; Ouria and Mahmoudi, 2018; Dawson and Lee, 1988; Jones et al., 1991). Three-dimensional cellular reinforcement has also been employed in this way (Yoon et al., 2008; Leshchinsky and Ling, 2013; Biswas et al., 2013; Song et al., 2014, 2017; Moghaddas Tafreshi et al., 2014, 2016; Hegde and Sitharam, 2015; Guo et al., 2015; Indraratna et al., 2015; Neto et al., 2015; Biabani et al., 2016; Trung Ngo et al., 2016; Oliaei and Kouzegaran, 2017, 2018; Satyal et al., 2018; Tavakoli Mehrjardi and Motarjemi, 2018). However, there is limited research improved anchor uplift capacity from geosynthetics - and that is almost entirely limited to the use of planar inclusions, such as geotextiles and geogrids, in dry sand. Krishnaswamy and Parashar (1994) investigated the uplift capacity of small-scale anchor plate embedded in dry sand with and without geosynthetics, finding that reinforcement can increase uplift capacity significantly. Ilamparuthi and Dickin (2001) investigated the behavior of small-scale belled piles embedded in sand, finding increased uplift resistance when reinforced with geogrids and geocells. Ghosh and Bera (2010) reported the results of experimental investigations on the effect of geotextile ties on uplift capacity of anchors embedded in sand.

Granular pile anchor foundations (GPAFs) are frequently used in expansive soils to resist the uplift forces mobilized due to the swelling behaviour of soils (Kumar and Rao, 2000; Kumar et al., 2004; Kumar, 2016). These comprise an anchor plate, placed at the bottom of a hole that is backfilled with granular soil, connected by cable or rod to foundation above. Kumar and Rao (2000) established that the pullout capacity of such GPAFs is increased when geosynthetics are used at the base, above the anchor plate, mainly owing to increased frictional resistance between the reinforcement and the confining medium. Kumar (2016) similarly reported that geogrid reinforcement increases the uplift capacity of granular pile-anchor in expansive clay beds.

Choudhary and Dash (2013) and Moghaddas Tafreshi et al. (2014) studied the effects of geocell reinforcement on enhancing the uplift capacity of anchors and belled piles, both demonstrating significant improvement when the reinforcement was present. However, there is limited analysis of anchor behavior in geocell-reinforced backfill and extrapolation to geometric configurations. Thus, this study expands on prior contributions by introducing the results of a comprehensive testing program on near full-scale anchors performed on a laboratory pit in unreinforced- and geocell-reinforced backfill.

2. Experimental series

A series of near full-scale tests (a total of 22 independent tests plus 28 repeated tests) on horizontal square plate anchor installed in unreinforced soil and geocell-reinforced soil was performed to:

a) evaluate the influence of geocell confinement above plate anchors subject to uplift loading,
b) investigate the influence of embedment depth and plate size on uplift capacity, and
c) calibrate numerical analyses that simulate the uplift response of the plate anchor and provide insight into internal behavior of both the geocell and backfill.

Only one type of geocell, one height (h) and pocket size (d) of geocell, and one type of soil were used in this study. Thus, d/B and h/B ratios adopted might not be the optimum values and a change in d/B and h/B might change the results. Other soils might change the benefit and/or the optimum geometrical arrangements. Nonetheless, the results still inform general trends that may be expected from use of geocell reinforcement in anchoring applications.

3. Test materials

3.1. Soil properties

The soil for both backfill and infill used in the experimental series was consistent throughout all of the physical experiments – well-graded sand (*SW* in the Unified Soil Classification System, ASTM D 2487-11, G_s = 2.66). There is a significant quantity of fine gravel (46%) and little fines (< 1%), as shown in the grain size distribution (**Fig. 1**). From modified proctor compaction testing (ASTM D 1557-12), the maximum dry unit weight of this soil was determined about 20.42 kN/m^3 with an optimum moisture content of approximately 5.1%. The angle of internal friction (ϕ) of the soil, obtained by consolidated undrained triaxial compression tests at a wet density of 19.74 kN/m^3 (92% relative compaction with moisture content of 5%, similar to the compacted density of the backfill soil layers - see Table 1) of specimens was 40.5°.

3.2. Geocell properties

The geocell used in the tests had a pocket size (d) and height (h) of