ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Soils and Foundations xxx (2017) xxx–xxx

www.elsevier.com/locate/sandf

Anisotropic strength of large scale geogrid-reinforced sand: Experimental study

Alaa H.J. Al-Rkaby, A. Chegenizadeh *, H.R. Nikraz

Curtin University, Australia

Received 22 June 2016; received in revised form 27 February 2017; accepted 23 March 2017

Abstract

Although geogrid reinforced soil is widely used for reinforcement in geotechnical problems, the effect of principal stress direction on it has not yet been investigated. A large hollow cylinder apparatus (HCA-600) was employed to perform monotonic drained tests on large reinforced/unreinforced samples ($H = 600$ mm, $D_o = 300$ mm & $D_i = 150$ mm) to investigate the anisotropic response of geogrid reinforced sand to direction of principal stress ($\alpha = 0$–$90°$). Results revealed that stress-strain behavior strongly depends on the principal stress direction (α) providing clear evidence for the inherent anisotropy of the sand fabric. Thus, an increase in α resulted in a reduction in deviator stress, greater contraction and less dilation behavior where the maximum and minimum deviator stress occurred at $\alpha = 0°$ & $\alpha = 60°$ respectively, with a difference of about 22%. Reinforced sand showed a significant improvement in strength and effective restraint of dilation for all α due to the confinement resulting from the mobilization of tension in the geogrid, and this improvement was accompanied by a clear reduction in the variation of deviator stress due to anisotropy for $\alpha \leq 30°$. However, anisotropy for $\alpha \geq 60°$ was still pronounced for reinforced samples. This can be attributed to the approach of the maximum stress obliquity plane to the bedding plane, where the geogrid was placed horizontally, and also to the extension mode corresponding with the samples in this range of $\alpha \geq 60°$ where $\sigma_r > \sigma_z$, such that the geogrid did not provide the same resistance as for $\alpha \leq 30°$.

Keywords: Anisotropy; Principal stress direction; Reinforced sand; Geogrid; Hollow cylinder samples; Large sample

1. Introduction

The stress-strain characteristics of anisotropic materials possessing inherent anisotropy are directionally dependent. The majority of soils exhibit different levels of inherent anisotropy due to the directional preference with which the elongated particles tend to align horizontally. As a consequence, a soil's response to the direction of principal stress should be taken into account, especially in those geotechnical engineering problems where the direction of principal stress varies as shown in Fig. 1a (Jardine and Menkiti, 1999; Wrzesiński and Lechowicz, 2013; Razeghi and Romiani, 2015). Reinforcement is widely used in these structures, and this work studied the effect of anisotropy on such reinforced sand. Anisotropy is the reason for the significant differences between the calculated and experimentally-modeled bearing capacities that are often observed (Huang and Tatsuoka, 1990). Although pullout resistance is considered in the design of reinforced structures, it is limited to the representation of interface interaction resistance while other properties, such as deformation, are not considered in such tests. However, using triaxail tests, extensive studies have been conducted on reinforced soils to investigate many other parameters such as the number, position and arrangement of reinforcement layers, cyclic behavior, soil density, confining pressure, deformation,

Peer review under responsibility of The Japanese Geotechnical Society.
* Corresponding author.
E-mail address: amin.chegenizadeh@curtin.edu.au (A. Chegenizadeh).

http://dx.doi.org/10.1016/j.sandf.2017.03.008

Please cite this article in press as: Al-Rkaby, A.H.J. et al., Anisotropic strength of large scale geogrid-reinforced sand: Experimental study, Soils Found. (2017), http://dx.doi.org/10.1016/j.sandf.2017.03.008

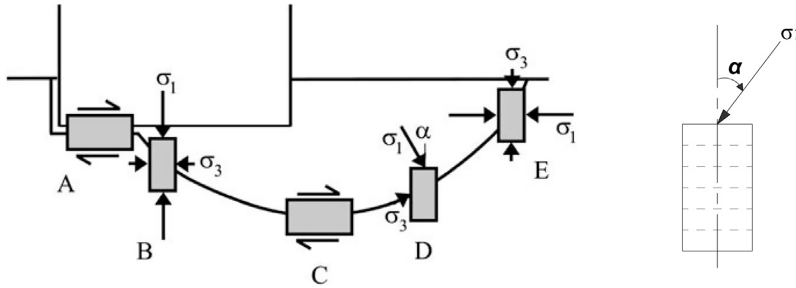

Fig. 1. (a) Variations of the principal stress direction in soil (O'Kelly and Naughton, 2009, permission was obtained from Elsevier); (b) definition of the angle of the principal stress direction (α).

and liquefaction, in addition to the anisotropy that is being investigated in the present study. For example, Kawamura et al. (2000) and Yasufuku et al. (2002) found that there is an additional reinforcing effect other than tensile force of reinforcement. This additional strength can be attributed to increase in the cohesion and angle of internal friction with increasing amount of reinforcement. Therefore, the present study, along with previous studies (on pure sand), can be considered as a basis for further efforts to investigate anisotropic effects in reinforced sand, which will likely result in design applications.

This awareness of anisotropic effects on the mechanical characteristics of soil and their relevance to geotechnical engineering applications is a consequence of extensive efforts to study this issue. However, most studies have investigated pure, and not reinforced, soil. Some studies were performed by applying a vertical stress on specimens with inclined bedding plane; whilst others (such as the present study) applying an inclined principal stress on specimens with a horizontal bedding plane. Thus, for both cases, the orientation (α) can be described as the angle between the principal stress/load and the axis of symmetry (normal to bedding plane) (Fig. 1b). For instance, a series of experimental studies have been performed on tilted samples prepared with an inclined bedding plane to produce different angles between the axis of symmetry of the samples and the vertical direction (major principal stress). These studies have found that the incline of the major principal stresses towards the bedding plane ($\alpha = 90°$) was associated with a clear decrease in strength (Arthur and Menzies, 1972; Oda, 1972; Oda et al., 1978; Azami et al., 2010). Similar effects were obtained recently using the true triaxial test (e.g. Rodriguez and Lade, 2013) and Guo (2008) has also reported similar trends using modified direct shear tests.

The hollow cylindrical apparatus (HCA) is an extremely valuable device employed in many investigations due to its capacity to impose a generalized stress path on specimens where the generated vertical stress (σ_z), radial stress (σ_r), circumferential stress (σ_θ) and shear stress ($\tau_{z\theta}$) can be independently adjusted under a combination of the vertical load (W), outer and inner cell pressure (p_o and p_i) and the torque (T) that applied to the hollow samples and controlled individually. The anisotropic behavior of sand has been widely investigated using this apparatus with small scale samples and it has been reported that the orientation (α) has a strong influence on soil strength. Range of, $\alpha = 60–75°$ produce minimum strength, and strength increase slightly thereafter at $\alpha = 90°$ (Miura et al., 1986; Lade et al., 2014). Similar results have also been found by Razeghi and Romiani (2015) for sand specimens that sheared under $\alpha = 0–60°$. Moreover, dilative behavior was dominant at $\alpha = 0°$ and decreased as α increased (Razeghi and Romiani, 2015). Some studies using HCA, however, have found a continuous decrease in the friction angle as the angle of principal stress direction (α) increased (e.g., Luan et al., 2007; Kumruzzaman and Yin, 2010, in sandy silt). This trend is in contrast to the one previously described where strength increased slightly after reaching the minimum value. Al-Rkaby et al. (2016) presented a comprehensive overview of this dependence of stress-strain characteristics of sand on different constant directions of principal stress (α), continuous rotation of (α) and inherent anisotropy.

Despite these experimental investigations, there are very limited studies on the effects of anisotropy and principal stress direction on stabilized soil, although such stabilized soil is widely used in geotechnical engineering problems. Soil reinforcement is one of the oldest known stabilization methods, dating back to more than 3000 years ago in Ziggurat of Ur (Iraq), with mats of reed laid horizontally in soil (Van, 2012). Modern reinforcement of soil using geosynthetics is a highly attractive technique and is used in various geotechnical applications such as roads, railways, buildings, retaining wall embankments and slopes to improve soil characteristics. It is desirable due to its easy construction techniques, low cost and reliability. A survey of the literature regarding geogrid-reinforced soil shows that no study has been reported about the effect of principal stress directions on reinforced soil, and the majority of studies were performed using either the compression triaxial test, direct shear test or loading test on a footing model. This point is also mentioned by Habibi et al. (2014) who investigated the strength of geotextile reinforcement of sand under triaxial compression, triaxial extension and torsional shear tests. The literature reveals that reinforcing results in the increased strength of reinforced soil (McGown et al., 1978; Latha and Murthy, 2006, 2007;