Geotextiles and Geomembranes 46 (2018) 869–881

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Role of soil inherent anisotropy in peak friction and maximum dilation angles of four sand-geosynthetic interfaces

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ARTICLE INFO

Keywords:
Geosynthetics
Sand
Inherent anisotropy
Interface
Direct shear
Friction
Dilation

ABSTRACT

Using a modified direct shear apparatus, an extensive experimental investigation is conducted into the influence of the inherent anisotropy of sand on the mobilization of the peak and critical state friction angles as well as the maximum dilation angle of the interfaces between an inherently anisotropic crushed sand and two woven geotextiles, one nonwoven geotextile, and one geomembrane. Experimental findings confirm that both peak and maximum dilation angles of sand-geosynthetic interfaces are affected from soil inherent anisotropy depending on the bedding plane inclination with respect to the shear plane. However, a unique critical state (residual) friction angle is attained for each interface type irrespective of the bedding plane inclination angle. Compiling results of a total of 141 tests, it is shown that a unique rule describes stress-dilation relationship of four different dense crushed sand-geosynthetic interfaces. The experimental data indicate that the ϕ_p vs. θ and ψ_{max} vs. θ curves are symmetrical with respect to $\theta = 90^{\circ}$ for the sand-woven geotextile and sand-geomembrane interfaces. Finally, it is shown that a constitutive equation by Pietruszczak and Mroz (2001) can predict the variation of ϕ_p with θ for the sand-woven geotextile and sand-geomembrane interfaces.

1. Introduction

Polymeric geotextiles and geomembranes have been applied extensively in practice as civil engineering materials for geotechnical, geoenvironmental, and pavement engineering purposes in the recent years. The design and performance of geosynthetic reinforced earth structures depend strongly on the mechanical behavior of the thin interfaces transmitting forces between soil and geosynthetics at their contact area. Experimental studies have indicated that the mobilization of friction and dilation at the interfaces between nonplastic granular soils and geosynthetics largely depend on the average soil particle shape characteristics, soil relative density, normal stress, degree of saturation, and soil cementation on one hand, and the geosynthetics polymer category, surface texture, tensile strength, and surface roughness on the other (e.g., Giroud et al., 1985; Negussey et al., 1989; Athanasopoulos, 1993; Lee and Manjunath, 2000; Anubhav and Basudhar, 2010; Khoury et al., 2011; Frost et al., 2012; Esmaili et al., 2014; Anubhav and Wu, 2015; Ferreira et al., 2015; Hatami and Esmaili, 2015; Martinez et al., 2015; Vieira et al., 2015; Choudhary and Krishna, 2016; Lashkari and Kadivar, 2016; Liu et al., 2016; Vangla and Gali, 2016a, 2016b; Vieira and Pereira, 2016; Afzali-Nejad et al., 2017; Fowmes et al., 2017; Martinez and Frost, 2017; Punetha et al., 2017).

The mechanical behaviors of natural and man-made deposits of granular soils are usually considered anisotropic because such soils behave differently with rotation of the principal stress axes with respect to their bedding plane. The anisotropic behavior of granular soils from a micromechanical view is attributed to the preferred orientation of particles and contact forces between them (Oda, 1993; Guo and Zhao, 2013; Jiang et al., 2017). The inherent (say initial) anisotropy is instituted through soil sedimentation and each sedimentation process possesses its own initial fabric (*see* Papadimitriou et al., 2005). Consequently, inherent anisotropy may play a central role in the initial stiffness, drained peak friction and maximum dilation angles. Testing with true triaxial and hollow cylindrical torsional shear apparatuses can offer a broad perspective of different impacts of inherent anisotropy on the mechanical behaviors of granular soils (e.g., Nakata et al., 1998; Yoshimine et al., 1998; Rodriguez and Lade, 2013; Xiong et al., 2016; Al-Rkaby et al., 2017; Xiao et al., 2014, 2017). However, the true triaxial and hollow cylindrical torsional shear apparatuses are still in relatively limited use owing to their high operation costs. Therefore,

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https://doi.org/10.1016/j.geotexmem.2018.08.003
Received 21 January 2018; Received in revised form 28 July 2018; Accepted 2 August 2018
0266-1144/

Nomenclature

a_1, a_2	parameters of Eqs. (3) and (5)
A, B, C, D	constants of the third order polynomial function given in Eq. (6)
C_c	coefficient of curvature
C_u	coefficient of uniformity
d_{50}	mean particle size
d_{85}	particle size at which 85% of the soil is finer by weight
d_{max}	maximum particle size
e_0	initial void ratio prior to shear
e_{max}	maximum void ratio
e_{min}	minimum void ratio
G_s	average specific gravity of sand particles
n_i	*i*th component of the unit vector normal to the shear plane
$\overline{R}$	average roundness of particles
$\overline{S}$	average sphericity of particles
u	shear displacement
v	vertical displacement
X	$X = 1 - 3\cos^2\theta$ (*see* Eq. 6)
θ	bedding plane inclination angle (*see* Figs. 4 and 5)
σ_n	normal stress in direct shear test
τ	shear stress in direct shear test
τ_p	peak shear strength in direct shear test
τ_{cs}	critical state shear strength
ϕ_p	peak friction angle [$= \tan^{-1}(\tau_p/\sigma_n)$]
$\phi_p(\theta = 0°)$	the peak internal friction angle for $\theta = 0°$
ϕ_p^*	the lowest value of ϕ_p within the range $0° \le \theta < 180°$
ϕ_{cs}	critical state friction angle [$= \tan^{-1}(\tau_{cs}/\sigma_n)$]
ψ	dilation angle [$= \tan^{-1}(\delta v/\delta u)$]
ψ_{max}	maximum dilation angle [$= \tan^{-1}(\delta v/\delta u)_{max}$]
ψ_{max}^*	the lowest value of ψ_{max} within the range $0° \le \theta < 180°$
$\mathbf{\Omega}$ (= Ω_{ij})	second-order tensor describing the bias in the spatial distribution of ϕ_p
Ω_1, Ω_2, Ω_3	principal values of $\mathbf{\Omega}$ for naturally deposited transversely isotropic soils

direct shear testing on inherently anisotropic soils has been reconsidered as an economic means in recent years (e.g., Guo, 2008; Azami et al., 2010; Tong et al., 2014; Oboudi et al., 2016; Farhadi and Lashkari, 2017). Moreover, direct shear testing is also a suitable tool to study the behavior of interfaces between soils and civil engineering materials such as steel, concrete, geotextiles and geomembranes (e.g., Evgin and Fakharian, 1996; Lee and Manjunath, 2000; Lings and Dietz, 2005; DeJong and Westgate, 2009; Anubhav and Basudhar, 2010; Khoury et al., 2011; Frost et al., 2012; Hatami and Esmaili, 2015; Vieira et al., 2015; Choudhary and Krishna, 2016; Liu et al., 2016; Vangla and Gali, 2016a, 2016b; Wang et al., 2016; Vieira and Pereira, 2016; Afzali-Nejad et al., 2017; Farhadi and Lashkari, 2017; Fowmes et al., 2017).

Experimental studies reported by Oda and Koishikawa (1979), Siddiquee et al. (2001), Azami et al. (2010), Li et al. (2010), and Qin et al. (2016) have confirmed that inherent anisotropy has a remarkable influence on the bearing capacity of shallow foundations resting on anisotropic sands and retaining walls with anisotropic backfills. The mechanical behavior of geosynthetic reinforced earth structures strongly depends on the mobilization of shear strength at the interfaces between the soil and reinforcement. However, the impact of soil inherent anisotropy on the mechanical behavior of soil-structure interfaces is a rather young subject of research. Recently, Farhadi and Lashkari (2017) studied the mechanical behavior of sand-steel interfaces of different normalized roughness values. They reported the combined impact of contact surface asperities and sand inherent anisotropy on mobilization of shear stress and dilation in rough sand-steel interfaces. Al-Rkaby et al. (2017) studied the mechanical behavior of geogrid reinforced anisotropic sand specimens using a large hollow cylinder torsional shear apparatus. Depending on the angle of principal stress rotation with respect to the bedding plane, Al-Rkaby et al. (2017) reported that a significant improvement of strength in geogrid reinforced sand specimens may be attained as a consequence of confinement resulting from the tension in geogrid layers.

In order to investigate the outcome of sand inherent anisotropy on the behavior of sand-geosynthetic interfaces, an extensive series of direct shear tests on the interfaces between an inherently anisotropic crushed sand and two woven geotextiles, one nonwoven geotextile, and one geomembrane is reported here. The testing program covers a wide spectrum of bedding plane inclination angles in order to realize the detailed impact of inherent anisotropy on the peak friction and maximum dilation angles of sand-geosynthetic interfaces. Analyses of 141 sand-geosynthetic interface and 42 sand alone direct shear tests have indicated that soil inherent anisotropy may affect the peak internal friction and the maximum dilation angles of sand and sand-geosynthetic interfaces.

2. Test materials

2.1. Crushed sand

An artificially graded quarry-run sand obtained through industrial crushing, milling, and washing processes of parent rocks was used in this study. The particle size distribution of the sand is demonstrated in Fig. 1 and accordingly, the uniformly graded sand can be classified as SP based on the Unified Soil Classification System (ASTM D2487). Table 1 lists the primary physical properties of the tested crushed sand, and a Scanning Electron Microscope (SEM) image of the typical sand particles is shown in Fig. 2.

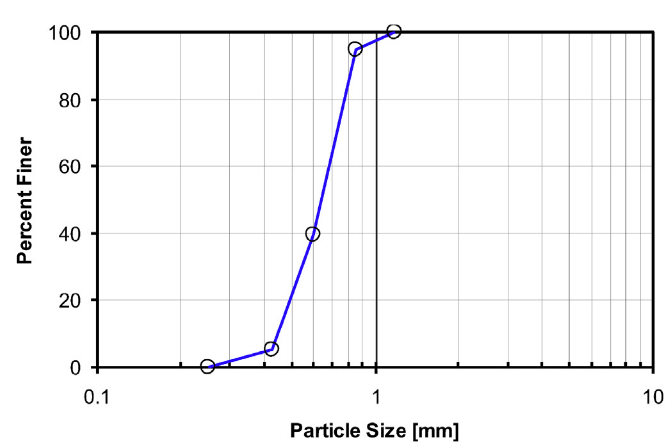

Fig. 1. Particle size distribution of the tested sand.