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# Influence of soil inherent anisotropy on behavior of crushed sand-steel interfaces

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**Abstract**

This paper presents the results of an extensive series of direct shear tests covering a broad spectrum of bedding plane inclination angles with respect to the shearing plane to study the outcome of inherent anisotropy on the mechanical behavior of sand-steel interfaces. As a part of the research, it is shown that the peak friction and the maximum dilation angles of the tested inherently anisotropic sand are highly influenced by the bedding plane inclination angle. However, for smooth, intermediate, rough, and very rough sand-steel interfaces, the test results indicate that the variation in peak friction angle with the bedding plane inclination angle is meaningfully less than that for the same sand. Moreover, it is observed that the extrema of peak friction and maximum dilation angles in sand-steel interface tests are attained at bedding plane inclination angles that are significantly different from those obtained from direct shear tests on sand samples.


*Keywords:* Sand; Anisotropy; Direct shear; Peak friction angle; Interface; Dilation; Normalized roughness

## 1. Introduction

Experimental studies have corroborated the substantial impact of inherent anisotropy on the stress-strain response of naturally deposited sand. For instance, Oda and Koishikawa (1979), Siddiquee et al. (2001), and Azami et al. (2010) showed that the bearing capacity of shallow foundations resting on inherently anisotropic sand decreases with the increase in the inclination of the bedding plane. Gutierrez et al. (1991), Nakata et al. (1998), Uthayakumar and Vaid (1998), Yoshimine et al. (1998), Lade and Kirkgard (2000), Chaudhary et al. (2002), Shibuya et al. (2003), Blanc et al. (2011), Sivathayalan et al. (2015), and Yang et al. (2016) conducted elaborate tests using hollow cylindrical apparatus and indicated a gradual loss in peak shear strength and a tendency towards contraction with the rotation of the major principal stress with respect to normal to the bedding plane. However, the limited accessibility and the high cost of the hollow cylindrical apparatus, as a sophisticated testing device, have led to the re-consideration of direct shear tests on specimens with inclined bedding angles as an inexpensive alternative to study the behavior of inherently anisotropic sand (e.g., Mahmood and Mitchell, 1974; Guo, 2008; Azami et al., 2010; Fu and Dafalias, 2011; Tong et al., 2014; Chen et al., 2014).

The load transfer in deep foundations, retaining structures, and reinforced soil systems is predominantly governed by the behavior of interfaces forming between soil and structure in the contact zone. Experimental and theoretical studies have revealed that several factors, including soil particle characteristics (mineralogy, mean size, and angularity), soil density, the degree of saturation, the stress level, the contact surface material, surface roughness, and the stress path have a great impact on the soil-structure

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**Nomenclature**

| | |
|---|---|
| $C_c$ | coefficient of curvature [–] |
| $C_u$ | coefficient of uniformity [–] |
| $d_{50}$ | mean particle size [mm] |
| $e_0$ | initial void ratio prior to shear [–] |
| $e_{\max}$ | maximum void ratio [–] |
| $e_{\min}$ | minimum void ratio [–] |
| $G_s$ | average specific gravity of sand particles [–] |
| $\overline{R}$ | average roundness of particles (*see* Appendix A) [–] |
| $R_{\max}$ | maximum peak-to-valley distance of surface asperities in sampling length equal to mean particle size [–] |
| $R_n$ | normalized roughness (Uesugi and Kishida, 1986) [–] |
| $\overline{S}$ | average sphericity of particles (*see* Appendix A) [–] |
| $u$ | shear displacement [mm] |
| $v$ | vertical displacement [mm] |
| $\theta$ | bedding plane inclination angle (*see* Fig. 5) [degrees] |
| $\sigma_n$ | normal stress [kPa] |
| $\tau$ | shear stress [kPa] |
| $\tau_p$ | peak shear strength [kPa] |
| $\tau_{cs}$ | critical state shear strength [kPa] |
| $\phi_p$ | peak friction angle [$=\tan^{-1}(\tau_p/\sigma_n)$] [degrees] |
| $\phi_p^*$ | the lowest value for $\phi_p$ within the range $0° \leqslant \theta < 180°$ [degrees] |
| $\phi_{cs}$ | critical state friction angle [$=\tan^{-1}(\tau_{cs}/\sigma_n)$] [degrees] |
| $\psi$ | dilation angle [$=\tan^{-1}(\delta v/\delta u)$] [degrees] |
| $\psi_{\max}$ | maximum dilation angle [$=\tan^{-1}(\delta v/\delta u)_{\max}$] [degrees] |
| $\psi_{\max}^*$ | the lowest value for $\psi_{\max}$ within the range $0° \leqslant \theta < 180°$ [degrees] |

interface response (e.g., Uesugi and Kishida, 1986; Evgin and Fakharian, 1996; Shahrour and Rezaie, 1997; Lee and Manjunath, 2000; Fioravante, 2002; Zeghal and Edil, 2002; DeJong et al., 2003; Lings and Dietz, 2005; Liu et al., 2006; Mortara et al., 2007; DeJong and Westgate, 2009; Hamid and Miller, 2009; Randolph, 2012; Chen et al., 2015; Lashkari, 2013; Lashkari and Kadivar, 2016; Lashkari and Torkanlou, 2016; Pra-ai and Boulon, 2016; Lashkari, 2012). The direct shear device has frequently been applied by researchers to investigate the behavior of interfaces (e.g., Lee and Manjunath, 2000; Fioravante, 2002; DeJong et al., 2003; Lings and Dietz, 2005; Mortara et al., 2007; DeJong and Westgate, 2009; Hamid and Miller, 2009; Chen et al., 2015; Afzali-Nejad et al., 2017). However, the outcome of the soil inherent anisotropy on the mechanical response of sand-structure interfaces is not yet understood.

Recent experimental investigations and numerical simulations have confirmed that a unique Critical State Line (CSL) is achieved in granular soils when they are subjected to extremely large (greater than 60%) shear strain. The unique CSL necessitates a unique eventual fabric (i.e., microstructure) that is independent of the initial ones (e.g., Fu and Dafalias, 2011; Huang et al., 2014; Li et al., 2009; Maeda et al., 2009; Muir Wood and Maeda, 2008; Peña et al., 2009; Wan and Guo, 2001; Zhao and Guo, 2013). However, the drained peak shear strength happens at considerably lower shear strain (usually less than 5%) for which the stress-induced anisotropy does not substantially erase the initial anisotropic microstructure. For this reason, the drained peak shear strength in triaxial and hollow cylindrical tests on soil samples subjected to the rotation of the principal stress axes, with respect to the bedding plane, has been selected by various researchers in order to characterize the impact of the initial (i.e., inherent) anisotropy on the mechanical behavior of granular soils (e.g., Arthur and Menzies, 1972; Gutierrez et al., 1991; Oda, 1972; Tong et al., 2014; Yang et al., 2016). Recently, the drained peak friction angle, obtained from inexpensive direct shear tests on sand samples with the inclined bedding angle, has been used to characterize the impact of the initial anisotropy on the mechanical behavior of sand (e.g., Azami et al., 2010; Chen et al., 2014; Guo, 2008; Fu and Dafalias, 2011; Oda, 1972; Tong et al., 2014).

Extended literature exists for different aspects of the inherently anisotropic behavior of sand; however, the outcome of soil anisotropy on the performance of sand-structure interfaces is not yet well known. The aim of this study is to better understand how soil inherent anisotropy affects the shear strength mobilization and the volume change behavior of the interfaces between sand and steel blocks with different surface roughness values. For this purpose, an extensive series of soil-steel interface tests is reported and analyzed here. Sand samples are prepared with a broad spectrum of bedding plane inclination angles, and very rough, rough, intermediate, and smooth steel blocks are used as the structural contact materials.

## 2. Test materials

An angular sand, obtained by crushing parent rocks with the physical properties summarized in Table 1, was used in this study. In accordance with the Unified Soil Classification System, the selected sand is categorized as poorly graded sand (SP). The particle-size distribution and a scanning microscope image of the particles are illus-

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