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Evolution of fabric under the rotation of the principal stress axes in the simple shear test

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ABSTRACT

A mathematical relation is presented for predicting the value of the contact normal plane distribution or the anisotropy parameter "α" (the ratio of the second invariant to the trace of fabric tensor) for granular materials under shearing loads. The changes of the contact normal planes are attributed to the mobilized stress ratio, internal friction angle, fabric principal direction and non-coaxiality between the major principal directions of stress and fabric. A new relationship between "α" and the main factors is derived by focusing on two particles across a potential sliding plane and the peanut-shaped function for the distribution of the contact normals. This formulation is obtained by combining the contact normal distribution function and mobilized stress ratio for sliding planes in a micro-level analysis. The dependence of "α" on the internal mobilized friction angle and the shear to normal stress ratio are the main characteristics of this relationship. The degree of anisotropy is easily obtained by applying this equation. The variation of the inter-particle mobilized friction angle in micro-level and double-shearing is briefly discussed. The variation of "α" with shear strain is similar to the variation of the shear to normal stress ratio with shear strain. The inter-particle mobilized friction angle with shearing approaches the mobilized stress ratio on the spatial mobilized plane. A comparison with experimental tests demonstrates the validity of this formula for the evolution of anisotropy.

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1. Introduction

Anisotropy is one of the main parameters that affects the behavior of soils (Oda, 1972b; Matsuoka, 1974; Nemat-Nasser, 1980, 2000; Matsuoka and Geka, 1983; Li and Dafalias, 2002, 2004). The micro-structural arrangement and intrinsic features of granular material under gravitational force and/or shear loads within a representative volume of the material is called the fabric (Oda, 1972a; Chang, 1993; Pietruszczak and Mroz, 2000). Anisotropy influences the stress–strain characteristics of granular materials via the contact normal surface (induced anisotropy) and the orientation and shape of particles (inherent anisotropy). When a granular mass undergoes shear deformation, contact planes deform, new contacts form, and some existing contacts may disappear.

Oda (1972b) performed triaxial compression tests on natural sands to study and model their deformation mechanisms. He found that the contact normals tend to concentrate toward the direction of the major principal stress and form column-like rows whose elongation axes are oriented in the major principal stress direction (Oda, 1972b, 1993). Oda (1972b) also found that non-spherical particles tend to be rotated in the direction perpendicular to the major principal stress (maximum compression). Arthur et al. (1986) investigated the principal stress direction and effects of strain-induced anisotropy in sand that was initially isotropic in the plane of strain. They showed that induced anisotropy depends on the changes in the contact normal distribution and related these changes to the strain. In

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Nomenclature

α	the second invariant of fabric tensor
F_{ij}	second-rank fabric tensor
F_1, F_2	the principal values of fabric tensor
$E(n)$	the spatial distribution of contact normals
n_i, n_j	are the components of a unit vector
$\dot{\varepsilon}^p_{ij}$	increment of the plastic strains
$\dot{\eta}_{ij}$	increment of the stress ratio
z	a constant used in the strain approach
$\hat{F}$	the saturated state for fabric
F_2	the deviatoric part of the fabric
ds_{ij}	variation of the stress tensor
θ_1	non-coaxiality between stress and fabric in Oda formulation (1993)
$\bar{\theta}_s$	the average value of the contact normals
θ_i	angle of the contact normal
θ_f	major direction of the fabric tensor
θ_σ	major direction of the stress tensor
f_i	internal contact force
τ	shear stress on potential sliding plane
p	normal stress on potential sliding plane
ϕ	inter-particle friction angle
$\phi_{\mu mob}$	inter-particle mobilized friction angle
ϕ_{mob}	mobilized friction angle
σ_1, σ_3	major and minor principal stresses
$d\varepsilon^*_n, d\gamma^*$	normal and shear strain increments respectively
λ, x	material constants
$\varepsilon_v, \varepsilon_q$	volumetric and deviatoric strains, respectively
φ	the angle of dilation
v	the angle of dilatancy
Λ	material function

addition, they showed that changes in major principal stress directions lead to considerable contraction in the shearing process. In the presence of the rotation of the principal axes, the fabric changes such that it accords with the principal stress axis (Matsuoka, 1974; Oda and Konishi, 1974b; Subhash et al., 1991).

Based on the micromechanical analysis of the stress tensor, Oda (1972a), Rothenburg and Bathurst (1989), Nemat-Nasser (2000), Guo and Stolle (2005), and Radjaï and Azema (2009) showed that anisotropy is the one of the most important factors, if not the most important factor, in the shear strength of granular materials. Nemat-Nasser (2000) attributed the shear resistance on a critical failure plane to a Coulomb-type inter-particle friction (isotropic state) and fabric anisotropy. He included the effect of a fabric by a second-order tensor that describes the distribution density function of contact normals. The second invariant of the fabric tensor is a main parameter required to determine the shear resistance of the fabric anisotropy. Pietruszczak and Mroz (2001) incorporated a distribution of strength parameters that depends on orientation. In a micro-level analysis, Guo and Stolle (2005) showed that the stress tensor may be divided into three components. This decomposition allows the specification of anisotropic strength due to the spatial distribution of contact normals. Radjai et al. (2004) and Radjai and Azema (2009) improved the equation developed by Rothenburg and Bathurst (1989) by incorporating the non-coaxiality between the stress and fabric components. They showed that the two microscopic sources of the shear strength in granular media are as follows: (1) fabric anisotropy, represented by the parameter “α”, and (2) force anisotropy. In order to enhance the capabilities of the geomaterials models, it is essential to include fabric and its evolution during shearing in the models. Nemat-Nasser (2000) proposed relationship between the evolution of fabric and the variation of strain. Wan and Guo (2001a,b) attributed the evolution of fabric to the variation of shear stress ratio $\dot{\eta} = \dot{q}/\dot{p}$. They used the ratio of the principal values of fabric tensor for the variation of anisotropy. Li and Dafalias (2012) expressed the evolution of fabric by a corotational rate in association with spin ω. They also attributed the evolution of fabric to the plastic multiplier which is a function of stress or strain and internal variables, for example, initial value of fabric.

Kuhn (2010) used discrete element method (DEM) simulations to show that the evolution of fabric is due to two components, the “material effect” and a term is called an “en masse”, which imply the changes of contacts and forces from one orientation to another. He attributed the hardening process to the material effect and softening to the “en masse” effect. Kruyt (2012) also investigated the evolution of the fabric tensor using DEM simulation. He studied invariants of the fabric tensor, namely, the coordination number and the fabric anisotropy. The evolution of fabric was described as a function of a volumetric as well as deviatoric strains. In the critical state or at large strains, both the coordination number and the fabric anisotropy tend to be constant (Kuhn, 2010; Kruyt, 2012).

The magnitude of anisotropy is also an important parameter in evaluation of shear strength of granular materials (e.g. Rothenburg and Bathurst, 1989; Nemat-Nasser, 2000; Guo and Stolle, 2005). Evolution of this parameter (or the contact normals) has been related to stress and strain (e.g. Arthur et al., 1986; Nemat-Nasser, 2000; Wan and Guo, 2001a; Li and Dafalias, 2012), while experimental data showed that there are other factors such as non-coaxiality between stress and fabric, inter-particle mobilized friction angle, dilatancy and current state of fabric have dominant effects (Oda, 1993). The assessment and evaluation of the α parameter and the factors that influence its magnitude are discussed and formulated in this paper. The known formulation is extended to include the effect of non-coaxiality between stress and fabric. The concept of the mobilized inter-particle friction angle is examined from two aspects: micro-level and double-shearing. Finally, these equations are verified using experimental data from Oda and Konishi (1974a,b).

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