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Effect of Fabric on the Strength of Granular Materials in Biaxial Compression

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Abstract. An equation is presented to unify the strength of granular materials in the presence of inherent and induced anisotropy. By applying a Fourier series that was developed to model fabric, direct incorporation of the fabric in the strength of granular materials is done. Based on the experimental data, in the presence of the same density, fabric is a main parameter to determine the shear strength of the granular materials. The difference between $(\sigma_1/\sigma_2)_f$ for the specimens have a same density (or void ratio), is attributed to this equation. Applying this equation the different trends between the samples with different bedding angles can be simulated. Verifying with the experimental data reveals the validity of this formulation.

Key words: fabric, inherent anisotropy, induced anisotropy, shear strength at failure

PACS: 45.70.-n

INTRODUCTION

To connect the microscopic measure of the granular materials with the overall macroscopic anisotropy, various quantities have been introduced; for example, the anisotropy of fabric is defined by the distribution of the unit contact normal [1-3]. Mehrabadi et al. [4] introduced another fabric measurement and connected their relations to the overall stress and other mechanical characteristics of granular materials. Backer & Desai [5] proposed the so-called joint isotropic invariants of stress and appropriate anisotropic tensorial entities. By using this method a constitutive model was proposed to account fabric anisotropy. Direct incorporation the effect of fabric in the constitutive equations starts with the work of Wan and Guo [6]. They used the ratio of the components of the fabric tensor as an affective parameter to show the effect of fabric and its evolution during shearing mechanism. Li & Dafalias [7, 8] included fabric anisotropy in their constitutive model. They used the method which was originally proposed by Tobita [9] and Tobita and Yanagiwasa [10]. In this method the stresses were modified according to the fabric tensor components. The stresses deviate from their normal value to accommodate with the inherent fabric anisotropy.

In this paper the effect of inherent and induced anisotropy is included in the ratio $(\sigma_1/\sigma_2)_f$ which is used as a strength parameter for the biaxial case. The effect of inherent anisotropy that is due to the particle shape and apparent long axes in its deposition is discussed and formulated. Induced anisotropy is accounted by the parameters that were proposed by Rothenburg and Bathurst [11]. These two factors are combined to show and models the effect of inherent and induced anisotropy in the failure strength of the granular materials. Finally, this formulation will be verified and simulated with the experimental tests which were conducted by Konishi et al. [12].

DEFINITION OF INHERENT ANISOTROPY

Inherent anisotropy is attributed to the deposition and orientation of the long axes of particles [1, 3, 13, 14] and Yoshimine et al. [15] have shown that the drained and undrained response of sand and approaching to the critical state failure were actually affected by the direction of the principal stresses relative to the orientation of the soil sample. Wan and Guo [6] accounted the effect of inherent anisotropy in micro-level analysis by the ratio of projection of major to minor principal values of the fabric tensor along the direction of the principal stresses. Li & Dafalias [7, 8] incorporate this effect by the fabric tensor which was proposed by Oda and Nakayama [16]. These two methods used a same basic approach; they used the principal values of the fabric tensor in their formulations. However, micromechanical studies [13, 16] have shown that in the shearing process, the preferred orientation of the particles in a granular mass may undergo only small changes. Its value may well endure after the

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onset of the critical state; hence, the fabric anisotropy renders the locus of the critical state line. In this paper cos2(β_i- β_o) is used to model the effect of inherent anisotropy. β_i shows the variation of the contact normals with respect to the major principal stress; β_o is the angle of deposition with respect to the major principal stress. Hence:

$$(\sigma_1/\sigma_2)_f \propto \cos 2(\beta_i - \beta_\circ) \tag{1}$$

DEFINITION OF STRESS-INDUCED ANISOTROPY

With increasing shear loads the contact normals tends to the concentrate in the direction of the major compressive stress. Contacts generated in compressive direction and disrupted in the tensile direction. These disruption and generation of the contact normals are the main cause of the induced anisotropy in the granular materials [13]. To include the fabric evolution (or induced anisotropy) a function in which changes of the contact normals is included must be defined. Wan and Guo [6] used the following equation:

$$\dot{F}_{ij} = x\,\dot{\eta}_{ij} \tag{2}$$

, where $\dot{F}_{ij}$ shows the evolution of fabric anisotropy, x is a constant, and $\dot{\eta}_{ij}$ is the ratio of the shear stress to the confining pressure, or $\eta = (q/p)$. Li and Dafalias [7] did not include the effect of fabric evolution in their constitutive equations.

By using Fourier series Rothenburg and Bathurst [11] show that the distribution of the contact normals distribution, *E(n)*, can be presented as follows:

$$E(n) = (1/2\pi)(1 + \alpha \cos 2(\theta - \theta_f)) \tag{3}$$

, where α is the magnitude of anisotropy, and θ_f is the major principal direction of the fabric tensor. The variations of the parameters α and θ_f show the evolution of anisotropy in the granular mass. Experimental data shows that the shear strength of the granular material is a function of the magnitude of α and θ_f [1, 12, 14]. The following equation is used to consider the effect of the induced anisotropy:

$$(\sigma_1/\sigma_2)_f \propto (1 + (1/2)\alpha \cos 2(\theta - \theta_f)) \tag{4}$$

As mentioned before, the shear strength in the granular medium is a function of inherent and induced anisotropy. The equation can predict the difference between samples due to the fabric which is a combination of the inherent and induced anisotropy as follows:

$$(\sigma_1/\sigma_2)_f \propto [(1 + (1/2)\alpha \cos 2(\theta - \theta_f)) \\ \cos 2(\beta_i - \beta_\circ)] \tag{5}$$

Another parameter that must be added to the above relation is the rolling strength of the granular material. It was shown that the rolling strength of the particles is important, especially in 2D case. This effect incorporated in the following form:

$$(\sigma_1/\sigma_2)_f \propto [(1 + (1/2)\alpha \cos 2(\theta - \theta_f)) \\ \cos 2(\beta_i - \beta_\circ) m \exp(\cos 2(\beta_i - \beta_\circ))] \tag{6}$$

,where m is a constant that depends on the inter-particle friction angle, ϕ_μ and the shape of the particles. When the samples are subjected to the shear loads have a same density their difference in the shear strength due to the fabric can be attributed to the equation (6).

VERIFICATION WITH THE EXPERIMENTAL DATA

To show the ability of the equation (6) to represents the effect of the fabric on the shear strength, this equation is verified with the experimental tests have done by Konishi et al. [12]. They conducted an experimental study on biaxial deformation of two dimensional assemblies of rod-shaped photoelastic particle with oval cross section. The samples were confined laterally by a constant force 0.45 kgf and it was compressed vertically by incremental displacement. Two types of particle shape were used, one was r_1/r_2=1.1 and another was r_1/r_2 =1.4, in which r_1 and r_2 are the longer and the shorter axes of cross section respectively. To consider the influence of friction, two sets of experiments were performed on these two particle shapes, one with non-lubricated particles of average friction angle of 52°, the other with particles which had been lubricated in an average friction angle of 26°. The distributions of the contact normals of the assemblies for different samples were presented by Konishi et al. [12] could not be shown here because of the limit space. The magnitude of the degree of anisotropy, α and the major direction of the fabric, θ_f are calculated by the following equations:

$$A = \int_0^{2\pi} E(\theta) \sin 2\theta d\theta \tag{7}$$

$$B = \int_0^{2\pi} E(\theta) \cos 2\theta d\theta \tag{8}$$

$$\theta_f = (1/2) arc\tan(A/B) \tag{9}$$

To represent the ability of equation (6) in Fig.1 the proportion of fabric with the shear strength variations are shown. The differences in the shear strength ratio at failure for different bedding angles are attributed to the differences in the developed anisotropic parameters. In other words, the combination of anisotropic parameters (for inherent and induced anisotropy) as the proposed form in Eq. (6), is proportion with the shear strength. The variation of right side of Eq. (6) is proportion with the variation of shear strength ratio for different bedding angles. The right side of Eq.(6) is shown by fabric anisotropy in Fig. 1. The effect of bedding angle on stress ratio at failure for the different inter-particle friction angle ϕ_μ is shown in Fig.2. By applying equation (6) differences between the stresses ratio at failure will be same for all the assemblies.

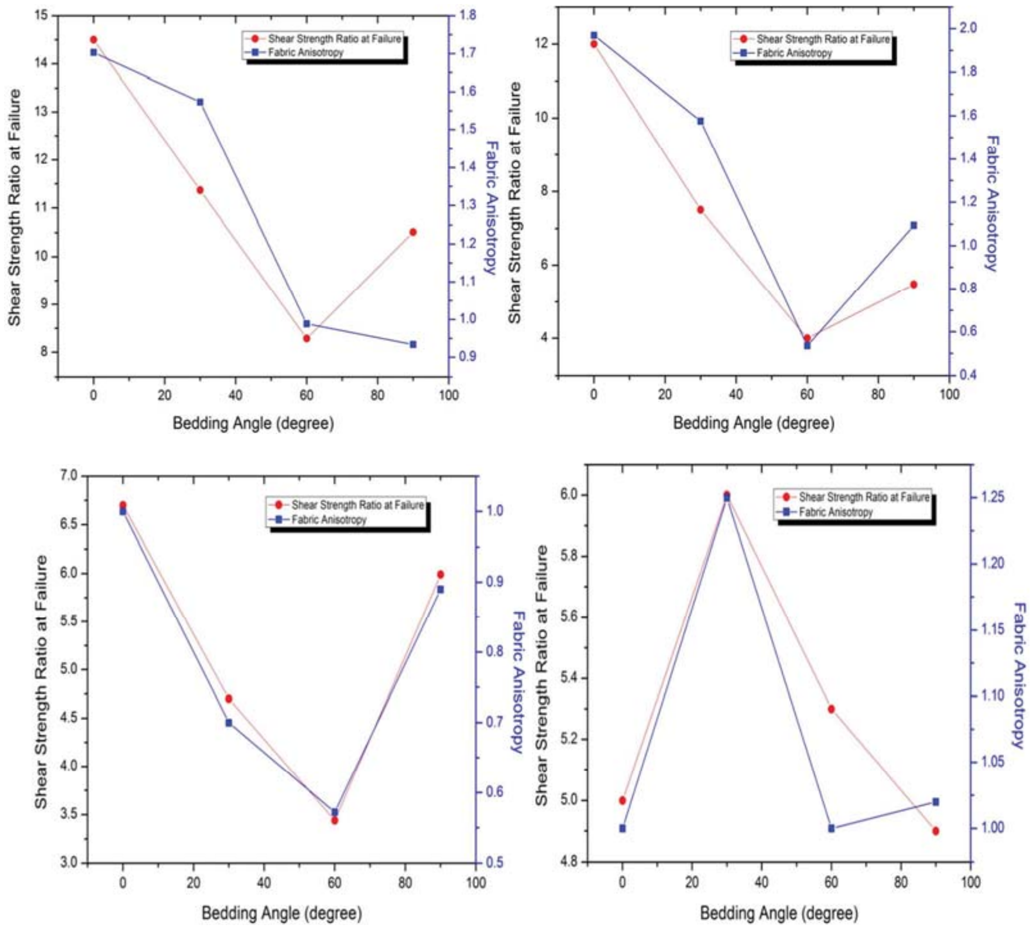

FIGURE 1. Samples with ϕ_μ = 52^o and r_1/r_2=1.1 (right-top), ϕ_μ = 26^o and r_1/r_2=1.1 (left-top), ϕ_μ = 52^o and r_1/r_2=1.4 (right-bottom), ϕ_μ = 26^o and r_1/r_2=1.4 (left-bottom)

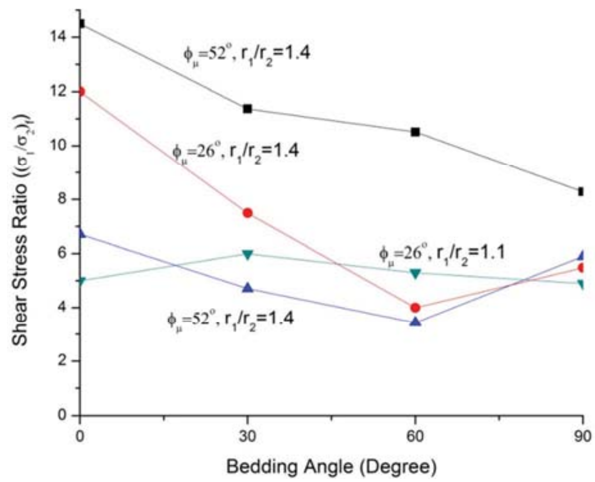

FIGURE 2. Effect of bedding angle on stress ratio at failure for the model assembly (data form Konishi et al. [12])

CONCLUSION

An equation was proposed to include the effect of inherent and induced anisotropy. This relation obtained by combining the effect of inherent and induced anisotropy. Rolling resistance, also, included in this equation. The differences between the samples due to inherent and induced anisotropy captured well by applying equation (6).Verifying with the experimental data show that this equation can predict the ratio of the shear strength at failure of granular materials in the presence of inherent anisotropy as good as possible.

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