DEPENDENCE OF THE PHASE TRANSFORMATION STATE ON FABRIC ANISOTROPY IN UNDRAINED BEHAVIOUR OF GRANULAR SOIL

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Summary This paper presents a fundamental study of the shear behaviour of granular soil with inherent fabric anisotropy by means of a grain-scale modelling technique, focusing on the so-called phase transformation state. The essential mechanisms underlying the complex behaviour are clarified by examining the link between the macro-scale and micro-scale properties.

INTRODUCTION

Phase transformation (PT) is tacitly referred to as a state with the minimum mean effective stress in the undrained shear responses of geomaterials (Vaid et al. 1990). In the q – p plane, PT state divides a typical undrained shear process into two parts: softening part and hardening part (see Fig. 1a). Due to the particulate nature (see Fig. 1b), in situ granular soil has an inherent anisotropic fabric which is formed in the process of natural deposition of soil particles under gravity forces. The inherent fabric anisotropy leads to such complex behaviors at PT state that there remain a number of controversial issues. For instance, it was believed by Vaid et al. (1990) that the friction angle mobilized at PT state ϕ_{pt} cannot be differentiated from the friction angle mobilized at critical state or steady state ϕ_{ss}; that is, the friction angle ϕ_{pt}, which is equivalent to the friction angle ϕ_{ss}, does not depend on stress path, void ratio, confining pressure and fabric anisotropy, and is regarded as a constant for a granular soil. However, Ishihara (1993) found that the friction angle ϕ_{pt} is independent of initial fabric but differs from the critical state (steady state) friction angle ϕ_{ss}. Moreover, Nakata et al. (1998) revealed that the friction angle ϕ_{pt} relies on the rotation of principal stress direction, meaning that the response of the same soil mass at PT state may vary as the stress tensor rotates with reference to the orientation of the soil fabric.

The complex behavior at PT state in fact originates from the discrete nature of granular soil. That is, the observed macroscopic behavior at PT state in laboratory may not be only reliant on the microscopic properties of individual particles but also on their spatial arrangements and interactions. Nevertheless, the traditional pathway to study the behavior at PT state is to treat granular soil as a continuum material, and the constitutive theories are established in the framework of continuum mechanics. The conventional studies have ignored the most basic attribute of granular soil — the discrete nature, so the fundamental mechanism underlying the complex behavior of granular soil at PT state remains unclear. This paper aims to clarify the existing contradictory issues and to explore the essential mechanism behind the fabric anisotropy effect on the behavior of granular soil at PT state by utilizing a numerical modeling technique at grain scale to treat it directly as a discrete medium.

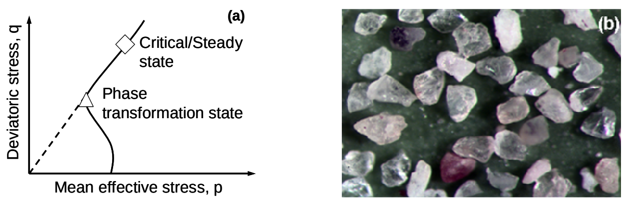

FIG. 1 (a) PT DEFINITION; (b) MICROSCOPIC VIEW OF SAND

MODELING GRANULAR SOIL

The numerical modeling technique, referred to as the discrete/distinct element method (DEM) (Cundall & Strack 1979), is established upon contact models and the Newton's Second Law, solving a system of finite difference equations with explicit time-stepping numerical scheme to trace the motions and positions of particles and their interactions. In the present study, a DEM program PFC^{2D} developed from the above principles is adopted. All particles in a granular

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assembly are clumped discs with equivalent diameters varying from 0.26 to 0.66 mm. A linear elastic contact model and the Coulomb friction law are employed to describe the contact behavior between particles. The modeling parameters are given as: normal and tangential stiffness = 10^9 N/m, mass density = 2.65 g/cm^3, and inter-particle coefficient = 0.5. To mimic the inherent anisotropic fabric formed in the natural deposition process, the gravitational deposition method is used to produce numerical specimens. As shown in Fig. 2, the case of β = 0° means that particles are deposited to the bedding plane parallel with the x_2 axis whereas the case of β = 90° means that particles are deposited to the bedding plane normal to the x_2 axis. In total, five deposition directions are considered: 0º, 30º, 45º, 60º, and 90º. After deposition, each sample with the size of 25 × 25 mm^2 is consolidated to 1000kPa at a void ratio 0.217. The undrained shearing is implemented by moving the two loading walls (top and bottom walls) inward and the two lateral walls (left and right walls) outward simultaneously with a constant volume.

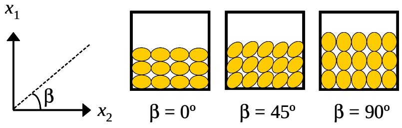

FIG. 2 SAMPLE PREPARAION

RESULTS AND DISCUSSIONS

Fig. 3a presents the macroscopic responses of the concerned specimens in the q – p plane. The deviatoric stress q is noted as the difference of the principal stresses σ_1 and σ_2 respectively in x_1 and x_2 directions, and the mean effective stress p is given as the average of σ_1 and σ_2. The results are similar to those observed in the laboratory (Nakata et al. 1998). It is seen that contractiveness increases with increasing the orientation angle of bedding plane, indicating a significant influence of fabric anisotropy. The least contractive specimen β = 0° seems not to exhibit a PT state since no substantial decrease occurred in the mean effective stress, whereas the most contractive one β = 90° suffered from a loss in the deviatoric stress at PT state, and this special PT state is also known as the quasi-steady state (Yang and Dai 2011). Fig. 3b indicates that the mean effective stress at PT state decreases with the orientation angle of bedding plane, and the friction angle ϕ_{pt} shows a slight increasing trend. These findings reveal an essential role of fabric anisotropy in the behaviour at PT state.

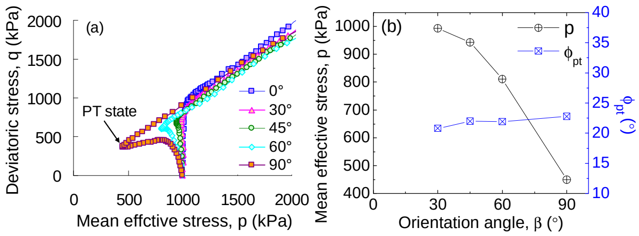

FIG. 3 MACROSCOPIC OBSERVATION

To explore the fundamentals, the microscopic responses are given in Fig. 4. It is noted in Fig. 4a that coordination numbers have experienced interim decreases at PT state, which suggests the loss of contacts at PT state. Particularly, the contact loss at PT state is aggravated with the increase of the bedding plane orientation angle. The loss of contacts corresponds to the decrease of mean effective stresses at PT state. The former is the typical microscopic response and the latter is the typical macroscopic response. Fig. 4b compares the angular distribution probability density of contact orientations for the case β = 45°. At the initial state, the principal direction of fabric anisotropy is orientated around 135°, while at PT state, the principal direction of fabric anisotropy has rotated by a certain degree toward the loading direction ─ 90° with reference to initial state.

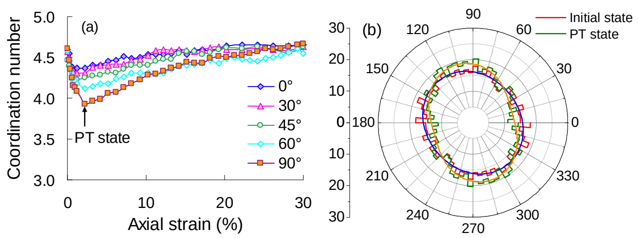

FIG. 4 MICROSCOPIC OBSERVATION

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