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Discrete element modeling of shear band in granular materials

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ABSTRACT

Numerical biaxial tests using discrete element method (DEM) were carried out to study the shear band formation in granular materials and the microstructures of the specimen at different strain levels were carefully examined. The effect of initial density and confining pressure on the characteristics of shear band were investigated. It was found that the progressive formation of the shear band was successfully captured by the DEM simulation with flexible lateral boundaries. During the shearing, several potential shear bands are formed at the peak deviatoric shear stress. With further shearing, the potential shear bands enlarge and softening behavior happens. Finally, a persistent shear band forms and other potential shear bands deteriorate. Generally, loose state and high confining pressure "delay" the onset of shear banding. The simulation also showed that the shear band thickness decreases with increasing confining pressure and density. Meanwhile, the inclination angle of shear band in dense specimen is generally higher than that in loose specimen. The void ratio of shear band is significantly larger than other parts of the specimen. At microscopic level, the overall coordination number of the specimen decreases significantly. The coordination number in the shear band is significantly lower than that outside the shear band, which is consistent with the large porosity in the shear band. The formation of shear band is due to the bulking of lateral confining force chains and the shear band is characterized by large void ratio, low coordination number, and high particle sliding and rotation compared with other part of the specimen.

1. Introduction

It is well recognized that many geotechnical failures are attributed to the localized failure of soils which is characterized by the appearance of shear band. Generally, the soil behaviors within the shear band control the strength and deformation properties of the earth structures [9], suggesting the importance of accurately predicting the shear band formation in geotechnical problem. In the past decades, tremendous theoretical, experimental and numerical studies have been carried out to predict the occurrence and explore the fundamental mechanism of localized failure (i.e. shear band), especially in granular soil.

Theoretically, the formation of localized failure can be regarded as a type of instability resulted from the bifurcation of uniformly deformed soil [30]. Therefore, the initiation of shear band strongly depends on the constitutive description of the prelocalization homogeneous deformation. The shear band is treated as a "thin" layer along which two rigid blocks move at inconsistent velocity (or strain rate). Mathematically, the initiation of the shear band is equivalent to the happening of non-uniqueness of equilibrium equations for a given constitutive model. Such theories have successfully predicted the occurrence of shear band based on conventional elasto-plastic constitutive models [30,36,37,15,26,27] and Cosserat continuum theory [38]. Nevertheless, the theoretical method is only applicable to solve simple boundary-value problems, rather than complex problems [18]. Meanwhile, it is generally unable to properly predict the thickness and inclination of the shear band as well as the mechanical behavior after the occurrence of shear band. For example, Han and Drescher [15] predicted that the inclination angle increases with confining pressure using bifurcation theory, which is opposite to the observation in their laboratory tests.

Besides the theoretical study, numerous laboratory tests have performed to investigate the shear band of granular soils (e.g., [3,8,33,15,5,20,39,1]. These experimental works have revealed that the shear band formation and its characteristics are influenced by a number of factors, including the density, the confining pressure, inherent and stress-induced anisotropy of the material, and the particle size and shape of the material. With the help of advanced technologies, extensive laboratory experiments have also been performed to look insight into the shear band formation and

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evolution. These technologies include X-ray Computed Tomography [14], stereophotogrammetry [8,9], photoelasticity [25], and particle image velocimetry (PIV) [42]. For example, Desrues et al. [8] used stereophotogrammetry to study the shear band in dry sand. The results indicated that the initiation of shear band took place before the peak in the overall stress–strain curve. Meanwhile, the shear band initiated at certain points and progressively propagated to a final persistent shear band. Han and Drescher [15] performed drained biaxial tests on poorly-graded Ottawa sand and found that the shear strain at shear banding increases with increasing confining pressure. Meanwhile, the shear band thickness and the shear band inclination angle with respect to the minor principle stress direction decrease as the confining pressure increases. Tatsuoka et al. [32] also indicated that the thickness of shear band decreases as confining pressure and initial density increases. Desrues and Viggiani [9] summarized the experimental results of strain localization in sand performed in Grenoble and the influence of soil initial state (i.e. confining pressure and density), specimen size and slenderness, grain size and particle size distribution are discussed. However, these experimental methods are extremely difficult, tedious and generally impossible to continuously provide all the important aspects of shear band that concerned (e.g. void ratio, contact force and particle rotation). Most importantly, the fundamental mechanism related to the shear band formation and how the influencing factors affect the characteristics of shear band is not well understood.

From the viewpoint of micromechanics, the granular soil is an assemblage of discrete particles and the soil behavior depends on the particle interactions through contacts that bear and transfer the loads. Therefore, the contact-based microstructure of the granular soil, such as the contact number, contact force and their distributions, is expected to play an important role in determining the macroscopic behavior. The discrete element method (DEM) proposed by Cundall and Strack [6] provides a powerful tool for simulating macroscopic behaviors and analyzing the microstructure of granular soil. DEM captures the particulate nature of granular soil and it has been extensively used to investigate the macroscopic behavior at micromechanical (or particulate) level, including small strain stiffness [7,40,10,11], monotonic shear behaviors [34,12], soil liquefaction [31], and critical state soil mechanics [13,12]. It also has been employed by several researchers to investigate the strain localization or shear band in granular materials [4,17,41,18,21]. For example, Bardet and Proubet [4] performed DEM simulation to investigate the structure of shear band and found that the thickness of shear band decreases with axial strain

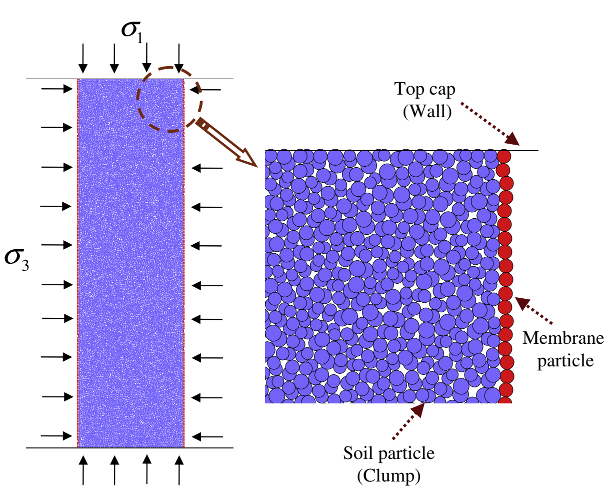

Fig. 1. Specimen in the DEM simulation.

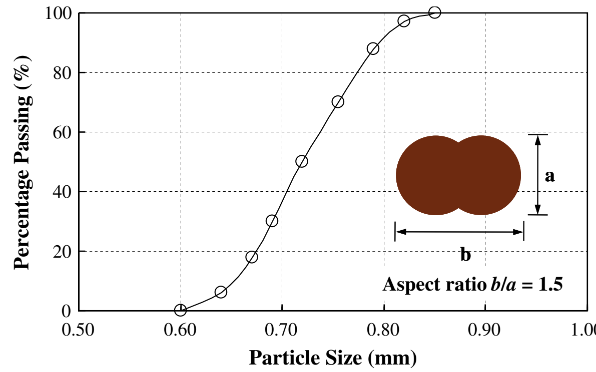

Fig. 2. Particle size distributions of soil in DEM simulation.

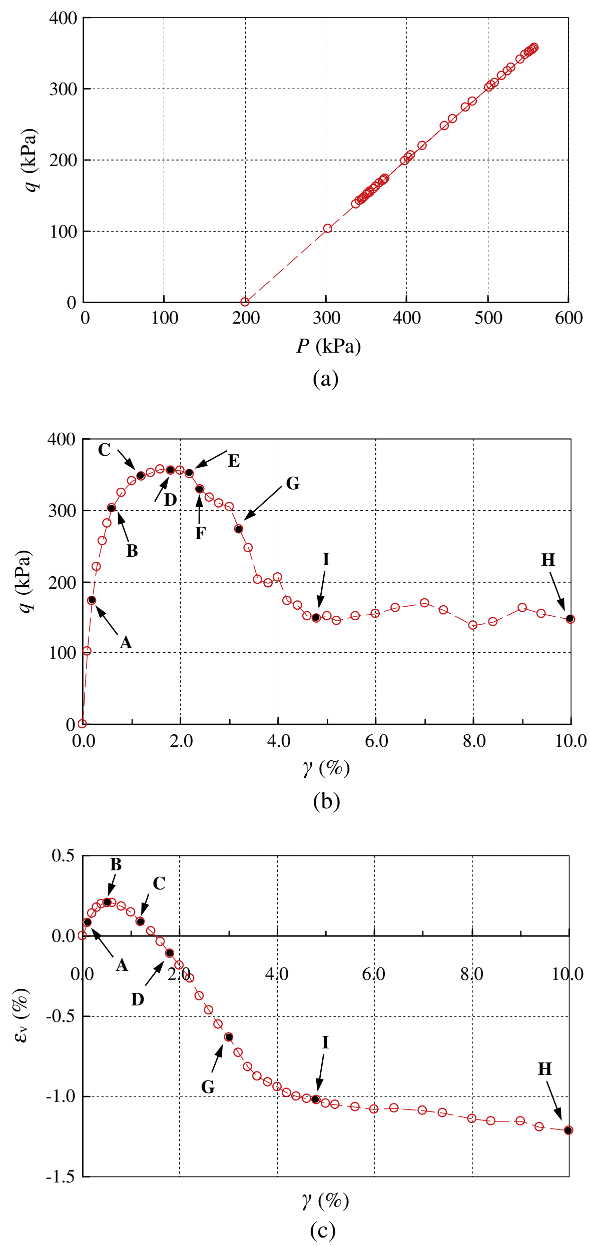

Fig. 3. Macroscopic behaviors of the dense specimen with porosity $n_0 = 0.112$ at $p_0 = 200$ kPa: (a) stress path; (b) deviatoric stress; (c) volumetric strain;