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Study on couple stress and shear band development in granular media based on numerical simulation analyses

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Abstract

From the reasonable accordance between the simulation and laboratory tests, it is concluded that the simulation test using the distinct element method can provide a powerful tool to simulate the micro- as well as macro-behavior of granular media. This is true, in particular, when the rotational resistance is introduced into the conventional one. Based on both the simulation and laboratory tests, we reached the following conclusions: One of the most important changes in microstructure, which takes place during a strain hardening process, is the formation of column-like structure growing parallel to the major principal stress direction. After failure, the column-like structure is reconstructed during a strain softening process by means of rolling, not sliding, at contact points so that a high gradient of particle rotation is generated, changing from negative to positive in a relatively narrow shear zone. Large voids appear in the shear band, and the resulting local void ratio can exceed the corresponding maximum one determined by a standard method. This fact strongly suggests that unique stress condition, which leads to such special microstructure, may develop in the shear band. In fact, couple stresses exist in a shear band in a manner consistent with the change of the particle rotation gradient from negative to positive. In spite of the presence of the couple stress, the stress tensor is nearly symmetric, indicating that the couple stress is very small in magnitude. The presence of the small couple stress still plays an important role in the development of microstructure in shear bands.

Keywords: Couple stress; Granular materials; Microstructure; Simulation analysis; Shear band

1. Introduction

Granular media are widely distributed in nature and are frequently dealt with in industry. Their related topics have therefore been discussed in various fields of science and engineering for the

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past two decades [1–7]. Sand, a typical granular medium in nature, is composed of hard, almost rigid, particles. When it is subjected to change of stress, arrangement of particles is easily altered during plastic strain because of discrete nature among them. The discrete nature leads to some marked mechanical properties such as large volume expansion under drained shear (known as dilatancy) and liquefaction under undrained cyclic loading.

A particle moves against neighboring particles, in general, by sliding and rolling at contact points. Frictional sliding played a dominant role in classical theories for the strength and dilatancy [8–10]. A sliding model by Newland and Allely [8], among others, is of particular importance since it had a great influence on the following research works. The model basically relies on the assumption that failure occurs in a similar manner to frictional sliding between two rigid blocks. The only difference is that sliding in a granular medium does not occur on a single plane, but on many contact surfaces whose sliding directions vary locally and therefore deviate, even on the average, from the macroscopic sliding direction. Accepting this model, Newland and Allely could interpret beautifully how the deviation of local (microscopic) sliding directions from a macroscopic sliding direction causes dilatancy during shear, and how the dilatancy is related to the frictional resistance. It seems to the present writers, however, that such a conventional model laid too much emphasis on sliding to interpret the dilatancy and failure of granular media. In fact, some observations in laboratories have strongly suggested that rolling, rather than sliding, is a dominant micro-mechanism of deformation [11]. In addition, Oda [12] and Oda and Kazama [13] pointed out that particles rotate so extensively during a shear banding process that a high gradient of particle rotation appears in a shear band. If the particle rotation gradient should be considered as an independent kinematic measure, an additional stress-like quantity (called couple stress) might also be required to formulate a complete set of the governing equations.

Oshima [14,15] probably first recognized the importance of couple stress in the formulation of governing equations for granular media. Since then, several authors have also suggested that granular media might successfully be founded on a polar continuum theory [16–21]. Mühlhaus and Vardoulakis [19] have shown that a bifurcation analysis, if it is based on a micropolar theory, makes it possible to predict the thickness of a shear band, as well as the shear band direction, in good agreement with experimental observations. Bardet and Proubet [22] conducted a numerical simulation test on an idealized assembly of particles and supported the micropolar theory on which the results could be successfully interpreted. However, no direct experimental evidence for the reality of the couple stress has been reported so far in spite of such theoretical advancement [23]. Brown and Evans [24] criticized the applicability of the couple stress theory to granular media by suggesting that the couple stress must be extremely small.

Our present objectives are:

1. to show a realistic micro-mechanical model for deformation of granular media;
2. to demonstrate a fundamental role of the micropolar effects (gradient of particle rotation and couple stress) on the development of shear bands.

Nobody has succeeded in detecting couple stress in a granular medium yet. This might be partially because the couple stress is, if it exists, very small in magnitude and it only appears in a very narrow limited zone. So, we did not seek a possibility of detecting the couple stress in a real test, but rather took a slightly different approach using a numerical simulation technique.

A numerical simulation method (called distinct element method or DEM) has been used as a new tool for fundamental research into the micro-mechanics of granular media [25–27] since the