A NUMERICAL STUDY OF STRUCTURAL EVOLUTION INSIDE THE SHEAR BAND IN QUASI-STATIC SIMPLE SHEAR TESTS

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Summary The response of a polydisperse granular assembly to quasi-static simple shear under constant confining pressure was investigated using 2D Discrete Element Method (DEM) simulations. Simulation results show that within the shear band the deformation field displays a vortex-like structure. Analysis of the history of force chains inside the localized shear zone reveals that the formation of vortex structures is related to the buildup and buckling of the force chains

INTRODUCTION

Shear banding is a ubiquitous phenomenon occurring in many geological and industrial situations. Numerous experimental and numerical researches on shear banding have been aimed at understanding the mechanism of shear banding and predicting the formation of shear band. For granular materials, once a shear band is formed, the further deformation is then mainly accommodated by the material within the shear band. Thus, it is critical to understand the nature of granular material behaviour within the shear band so as to accurately characterize the physical behaviour for large deformation. It has been well recognized that inside shear band the deformation is non-uniform, characterized by the production of extremely large pores[1]. Recently, several research works have revealed that such non-uniform deformation is accompanied by the occurrence of vortex-like structure inside shear band [2-5]. While the formation of such vortex-like structure is generally assumed to be attributed to the buckling of force chains inside shear band[3-5], detailed experimental characterization of the evolution of force chains within shear bands poses challenges, due to the thin characteristics of shear bands. In this work, Discrete Element Method (DEM) simulations were performed to model two-dimensional, densely packed, cohesionless, polydisperse granular assemblies under simple shear. The objective of this study is to investigate, under quasi-static loading conditions, the deformation structures within shear bands, with particular attention paid on the possible linkage between the formation of vortex-like structure and the evolution of force chains.

NUMERICAL METHODS AND SAMPLE PREPARATION

Two-dimensional granular assemblies were modelled using the so-called modified discrete element method (MDEM) proposed by Iwashita and Oda[6]. The key difference between MDEM and the classical DEM lies in the contact law: MDEM incorporates a moment transfer to account for rolling resistance, thus allowing the modeller to achieve more realistic particle rotations. To prepare densely packed samples as required in our study, gases made of approximately 6000 non-overlapping discs with size uniformly distributed between 0.5mm and 1.0mm were generated. The particle gases were bounded by periodic condition in horizontal (*x*-) direction and by two rigid plates in vertical (*y*-) direction. The samples were then densified by applying a pressure P to the upper and lower plates and also on the sides. The gravity was set to zero in all the simulations reported here. Densification ceases once stress components in both *x*- and *y*-directions have reached the desired values. After packing, the typical sample size was approximately 60mm (*x*-)*50mm (*y*-). The compacted samples were then subjected to horizontal shear by slowly moving the upper and lower plates horizontally in opposite directions. During shear, the vertical stress was kept constant (P) while the horizontal normal stress was free to adjust to the ambient kinematic conditions

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Fig.1 presents the typical particle displacement field in the residual state. Although the dilation of the whole sample was marginal in the residual state (data not shown), Fig.1a indicates that particles inside the shear band display significant vertical movements. A pattern with alternating upward and downward particle movement can be observed. Combined with the horizontal displacement, such a pattern represents a vortex-like structure inside the localization zone, as illustrated in Fig.1b. The vortices rotate clockwise, consistent with the orientation of the shear angle. In between neighbouring vortices, intense vertical shear happens, which hints at the formation of microbands.

To explore the mechanism of the formation of such vortex-like structure, we examined the evolution of force chains within shear band. Fig.2 gives a close-up of the evolutions of the vertical particle displacement field and of a force chain across the shear band. Snapshots were generated in shear strain interval 0.385~0.421 with a shear strain increment of 0.006. The black particles constituted a force chain at a shear strain of approximately 0.385. The thickness of the green

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lines connecting these black particles indicates the magnitude of the normal contact force between black particles. As this force chain was sheared along the band, the normal forces at the contacts between black particles increase, as indicated by the changing thickness of the green line shown in Fig. 2a~c. With the constant vertical confining pressure condition, the increasing normal forces induced vertical lengthening in which particles at the upper part of the force chain moved upward and those at the bottom part moved downward, as shown in Fig.2a~c. Such vertical lengthening is accompanied by the buckling of the force chain. Buckling concentrated in the middle of the force chain, as indicated by the curving three-particle segment highlighted by a red oval in Fig.2c. Further shear was then mainly accommodated by the development of the bending of the force chain until the whole force chain collapses at a shear strain of approximately 0.421. In this process, particles in the end parts of the force chain moved inwards towards the force chain center (see Fig.2d~f), resulting in vertical displacement patterns different from those shown in Fig. 2a~c. Note that as the force chain buckling proceeded, a large void was produced behind the three-particle segment which had undergone a significant change in curvature (highlighted region in Fig. 2f). Such a phenomenon supports the hypothesis that very large voids observed in laboratory shear tests are resulted from the buckling of force chains [1].

In the vicinity of the black particle column there were also some short and branched force chains. Detailed examination suggested that it was the black particle column which dominated the deformation of this local section (figures not shown here). Such domination was also reflected in the displacement field where particles adjacent to the black column almost always follow the motion of their closest neighbours within the black column (see the upper left regions in Fig.2a and b and also the bottom right regions in Fig.2 e and f). Such phenomenon supports the hypothesis proposed by Rechenmacher et at [5] that collective particle vertical movements are due to the formation of force chains.

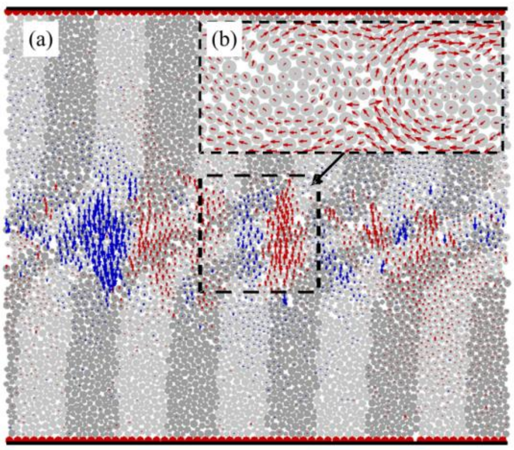

Fig.1 particle vertical displacement field at a shear strain interval 0.437-0.453.

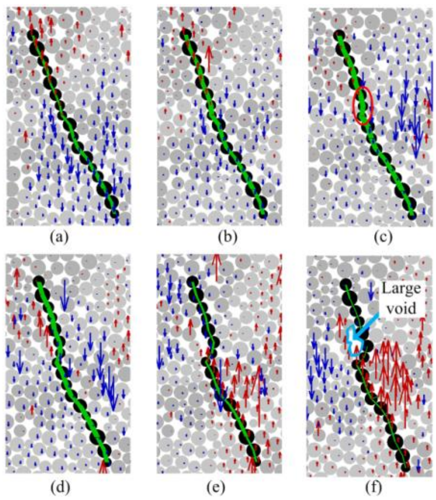

Fig.2 Snapshots of temporal evolution of the particle displacement field and force chain (black column).

CONCLUSIONS

Discrete element simulations were carried out to model the microstructure developed inside shear bands in densely packed granular materials undergoing simple shear. It was observed that inside the localized zone, a spatially distinct pattern with alternating upward and downward particle movements was found, in agreement with the previous experimental finding[4,5]. Combined with horizontal displacement, such a pattern represents a spatial vortex structure inside the shear band. A detailed analysis showed that the appearance of vortices was tied to the vertical lengthening and the buckling of force chains. The buckling of force chains also leaded to the formation of large voids that have been experimentally observed in natural soils [1].

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