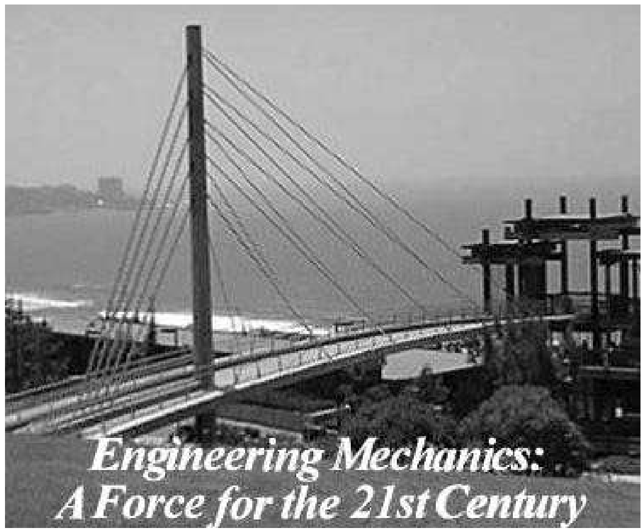
Engineering Mechanics:A Force for the 21st Century
Proceedings of the 12th Engineering Mechanics Conference
La Jolla, California, May 17-20, 1998
H. Murakami and J. E. Luco (Editors)
@ASCE, Reston, VA, 1998



Slip Deformation Structures in Granular Materials

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pp. 1736-1739

SLIP DEFORMATION STRUCTURES IN GRANULAR MATERIALS

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Abstract

The paper presents a method for using the Discrete Element Method to investigate deformation at the level of individual void cells within a two-dimensional granular material. Of interest are local deformation patterns that deviate from the average deformation of the assembly. Numerical experiments repeatedly reveal thin "microbands" of significant slip deformation that occur at low strain levels during biaxial compression tests.

Introduction

Deformation of a granular material results in the local movements of its individual particles. These movements deform the void spaces between them, and deformation of the entire material can be largely attributed to these local void deformations. In this paper, we observe deformation at the level of individual voids in a two-dimensional assembly of densely packed disks. We are interested in local deformation patterns that deviate from the average deformation of the assembly, and particularly in patterns that could suggest a long-range organization of nonhomogeneous deformation. One such pattern, thin "microbands" of slip deformation, has been repeatedly observed during numerical simulations and is documented herein.

Methods

Numerical experiments were performed on an assembly of 4008 circular disks by using the Discrete Element Method (Fig. 1a). The densely packed square assembly had an initial isotropic fabric and was surrounded by periodic boundaries. The assembly was compressed in the vertical, x_2, direction, while the side

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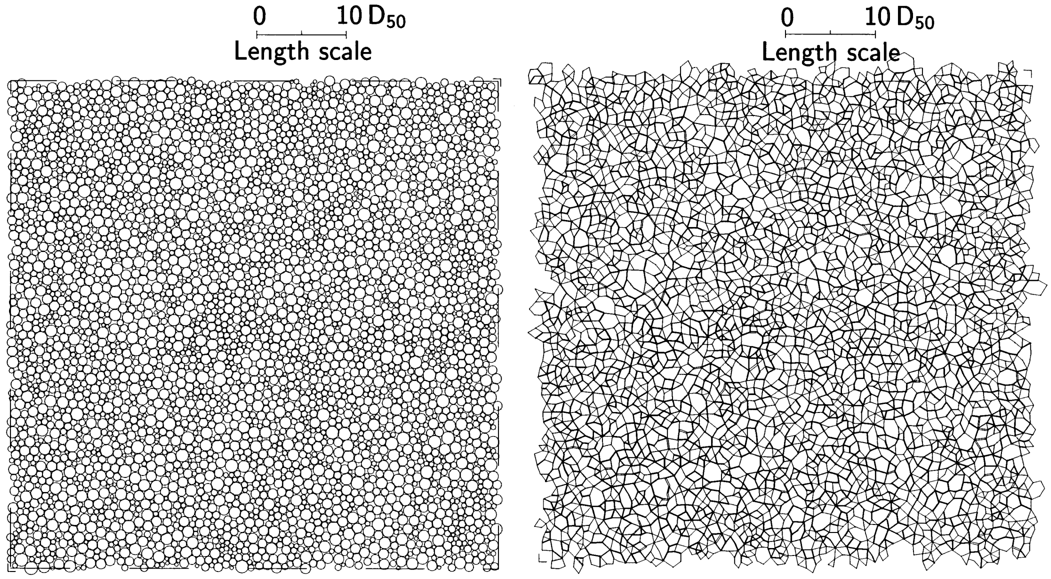
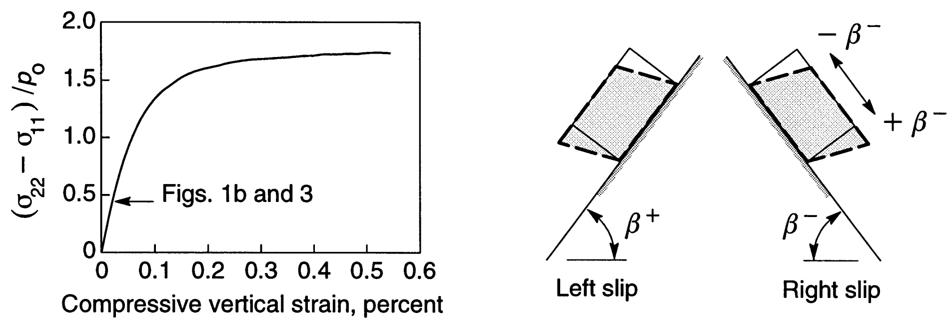


(a) Particles (b) Particle graph

Figure 1. Assembly of 4008 particles

boundaries were continuously adjusted to maintain a constant average horizontal stress $\bar{\sigma}_{11}$. The dimensionless deviator stress $(\bar{\sigma}_{22} - \bar{\sigma}_{11})/p_o$ is plotted as a function of the compressive strain in Fig. 2a, where p_o is the initial mean stress.

A particle graph, Fig. 1b, was constructed at each stage of loading so that deformations could be computed within individual void cells. The concept of a particle graph has been presented by Satake (1992). The graph's nodes represent particle centers; its edges (lines) represent contacts (branch vectors) between neighboring particles; and faces (polygons) represent the void cells formed by circuits of contacting particles. An algorithm for constructing these planar particle graphs was given by Kuhn (1997), and it assures that the graph includes only load-bearing particles. Results will later be present for a vertical strain of 0.02%. At this stage of loading, the particle graph contained 3777 load-bearing



(a) (b)

Figure 2. Stress-strain results and slip deformation patterns

particles, 7646 branch vectors, and 3869 void cells (Fig. 1b).

Deformations within individual void cells were computed with a method suggested by Bagi (1996) for triangular cells and extended to polygonal cells by Kuhn (1997). The deformation rate within the i-th void cell is expressed by its velocity gradient $\bar{\mathbf{L}}^i$, where the overbar signifies a spatial average within the void cell that is computed by integrating velocities along its surrounding branch vectors. We are primarily interested in local deviations from the mean deformation of the entire assembly, denoted by $\bar{\mathbf{L}}$ and computed as

$$\bar{\mathbf{L}} = \frac{1}{A} \sum_{i} A^i \, \bar{\mathbf{L}}^i \, , \tag{1}$$

where A^i is the area of the i-th void cell and A is the area of the entire assembly. The local deviations are computed as $\bar{\mathbf{L}}^i - \bar{\mathbf{L}}$, each of which has the four Cartesian components $\bar{L}^i_{pq} - \bar{L}_{pq}, \ p, q \in \{1, 2\}$.

Results

A difficulty in studying the spatial distribution of these local deviations lies in representing a four-component tensor on a flat and monochrome media. A somewhat satisfactory, but cumbersome, means is to use a gray scale to represent the magnitudes of each component in separate plots. We instead "filter" a selected deformation mode by computing the inner product of the local void cell deformations with respect to the selected four-component deformation pattern $\mathbf{\Phi}$. This yields a scalar measure of the local aligned magnitudes of the selected pattern:

$$\frac{(\bar{\mathbf{L}}^i - \bar{\mathbf{L}}) \cdot \mathbf{\Phi}}{|\bar{\mathbf{L}}| \, |\mathbf{\Phi}|} \, , \tag{2}$$

where the result has been normalized with respect to the norms of the average and pattern deformations.

Of particular interest are the slip deformations at orientation angle β (Fig. 2b), which have the deformation patterns

$$\mathbf{\Phi}^{\beta \pm} = \begin{bmatrix} \cos\beta \sin\beta & \mp \cos^2 \beta \\ \pm \sin^2 \beta & \cos\beta \sin\beta \end{bmatrix} \, , \tag{3}$$

where β^+ and β^- correspond to left and right slip deformations. Figures 3a and 3b show the spatial distribution of right slip deformations among the 3869 void cells, where a β^- of 52° has been selected. With a monochrome gray scale, two figures are necessary to display both the positive and negative values of these local deviations from the mean (expression 2). The figures show a pattern of thin "microbands" of right slip deformation that trend obliquely through the material. These figures were captured at a small vertical compressive strain of 0.02% (see Fig. 2a) and at a low level of stress for which the mechanical response

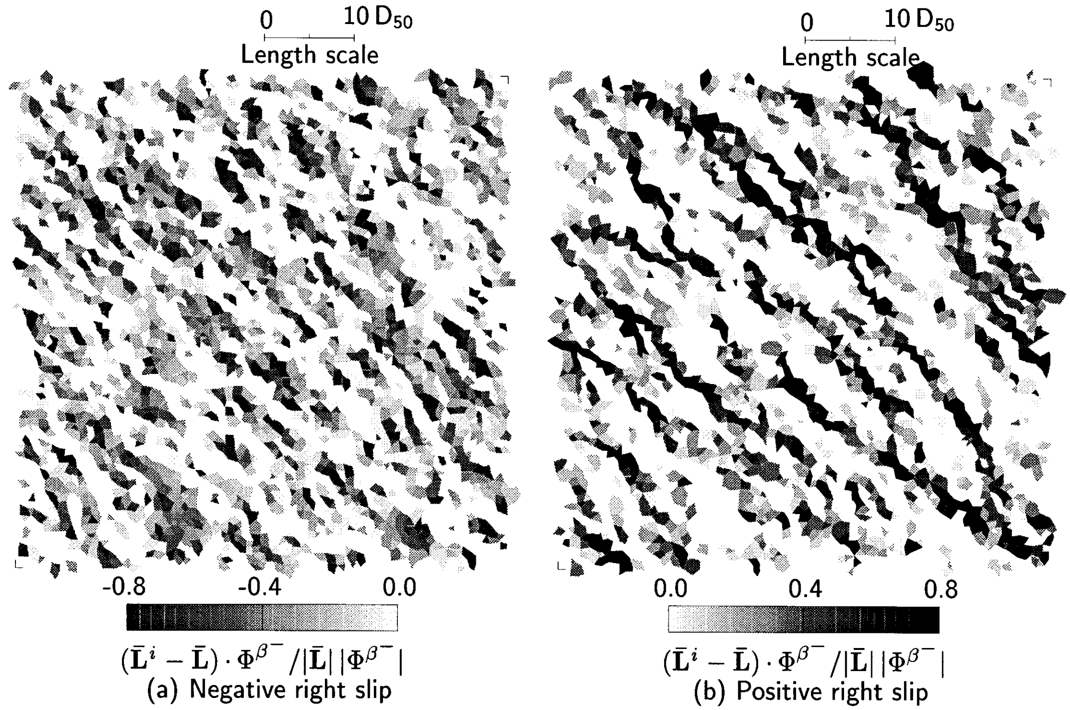


Figure 3. Local right slip deviations at $\epsilon_{22} = 0.02\%$, for $\beta^- = 52°$

is primarily elastic. The intensity of the slip deformations is significant, as the darkest void cells represent slip deformations that exceed 80% of the average deformation magnitude $|\bar{\mathbf{L}}|$. The microbands are quite thin, with thicknesses of between one and four particle diameters D_{50}, and some bands extend through the entire assembly. The formation of these slip deformation microbands likely plays an important role in the mechanical behavior of granular materials.

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