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FORMATION OF SHEAR BAND IN A GRANULAR MATERIAL DURING TRIAXIAL COMPRESSION TEST*

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Abstract. Formation of shear band during triaxial compression test of a sample of granular material was investigated experimentally. A new method of displacement field fixation in the sample of granular material was proposed. The method allows to analyse of displacement distribution inside a sample of any course granular material. Thickness of the fully developed shear band obtained in the triaxial compression test of a mustard seed was found approximately 15 times bigger than the mean seed diameter.

Keywords: granular material, shear band, triaxial compression test

INTRODUCTION

Granular materials are deformed in several ways during technological operations. For a small strain deformation is usually uniform. For a larger strain deformation is localized in a narrow region of shearing strain. This region, called shear band, separates almost rigid blocks of a granular material. Triaxial and biaxial compression tests seem to be adequate for the investigations of the emergence of the strain localization within uniformly stressed granular materials.

An effective rupture zone called a boundary layer or shear zone is formed along the rough or corrugated wall in a bin with plug flow when friction between the wall and grain is higher than the internal grain friction [6]. There is always a shear zone of the width equal to a few particle diameters in which the velocity changes rapidly from that in the bulk to that at the wall. The thickness of the boundary layer was found to depend on the granular material. Zhang *et al.* [11] examined shear zones in wheat sliding against a corrugated steel surface. The lower boundary of the shear zone was estimated 4.5 mm below corrugation peaks and the upper boundary was 18.5 mm above the corrugation peaks. Dilation in the boundary layer resulting from shearing during discharge gives rise to an overpressure. The overpressure is independent of the silo scale causing a decrease in the relative overpressure with an increased silo size. It means that errors on a considerable scale can occur while comparing observations from similar tests performed on arbitrarily scaled dimensions of structures and granular solids that exhibit localized failures [8].

A shear zone in the granular material has recently attracted wider interest. Determination of thickness of the shear zone is important for the estimation of forces transferred from the granular material to the structure. The thickness of the shear zones depend on the wall roughness, grain diameter, specimen size and boundary value problem considered [10]. Relation between shear band thickness and grain size had profound implications on the investigations of

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progressive failures within granular solids. According to direct experimental observations by Roscoe, the width of the shear bands is about 10 times bigger than the average grain diameter [9]. Investigation on the shear band formation is mainly based on computer simulations or theoretical modelling [1,2,5,10]. Thickness of the fully developed shear band was found to be approximately 16 times bigger than the mean grain diameter. Only a few researchers investigated experimentally formation of the shear band in grain bulk [4,7,11].

The purpose of this study was to analyse experimentally formation of the shear bands during triaxial compression test of a seed bulk.

MATERIAL AND METHOD

Triaxial compression tests were performed to obtain information on the displacement distribution of particles inside the shear band. The rubber membrane of the triaxial compression sample provided homogeneous stresses with fixed principal stress directions. The sample was 30 cm high and 15 cm in diameter. Total volume of the sample was divided into 30 cylindrical regions using two different seed colours: stained and not stained mustard seed. Each region was of 3 cm high and 3 cm thick. In the vertical direction the sample was divided into three cylindrical coaxial regions by inserting two cylindrical moulds 3 and 9 cm in diameter into the sample mould. Layers of seed 3 cm high were poured into each of the three cylindrical regions of the sample. Ten layers of stained and not stained seed were poured into each column of the sample. After filling the entire sample, the moulds were removed gently from the sample. This method of sample preparation formed a chessboard of 50 squares in the vertical central cross-section of the sample: 10 squares in the vertical direction and 5 in the horizontal one: as indicated schematically in Fig. 1. Mesh deformation during the triaxial compression test was used to measure seed displacement across the sample [3]. A minor principal stress σ_3 was generated by means of underpressure created inside the sample voids. The experiments were curried out under a constant value of the minor principal stress σ_3 equal to 0.08 MPa. The major principal stress σ_1 was gradually increased by moving the rigid cylindrical platens of the sample closer to each other with a constant rate of displacement equal to 50 mm min^{-1}. To maintain the unchanged shape of the sample after a desired deformation was obtained, the underpressure was stabilised in the sample. A procedure of sample fixation was indicated schematically in Fig. 2. The shape of the sample (3) was fixed by immersing into liquid gypsum (2) in the container (1). After gypsum setting, the seed arrangement inside the sample was fixed by pouring resin into the sample voids (4). Underpressure remained in the sample (6) to assure full saturation of the sample with resin (5). After resin setting, the sample was cut into slices in the vertical direction perpendicular to the shear band.

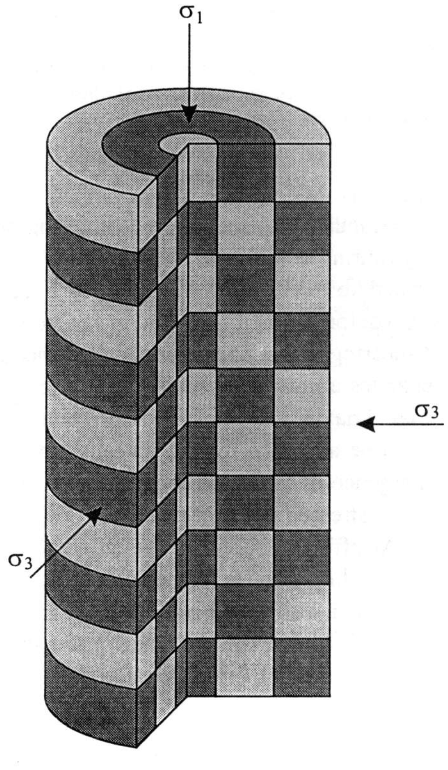

Fig. 1. Triaxial compression sample with a cylindrical mesh.

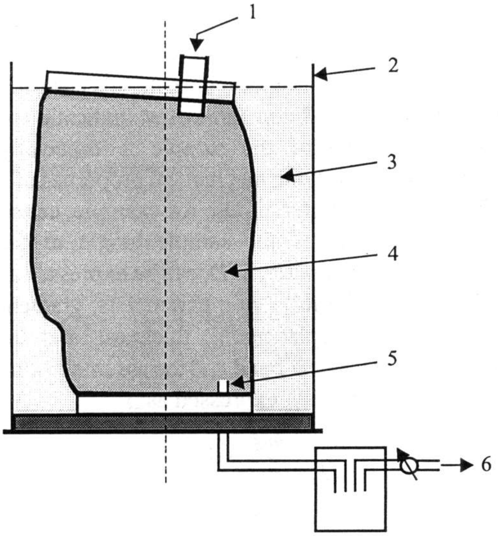

Fig. 2. Method of sample fixation; 1- resin inlet, 2 - container, 3 - gypsum, 4 - sample after deformation, 5- resin outlet, 6- underpressure pump.

Computer procedures of the image analysis were used to determine the displacement distribution across the shear band from the sample cross-sections. White mustard seed of the moisture content of 7% w.b. and the bulk density of 680 kg m^{-3} were chosen to represent spherical granules. The average seed diameter was 2.5 mm.

RESULTS AND DISCUSSION

In the first stage of the triaxial test (ε_1<0.05) the particle displacements generate a field of constant strain, i.e., horizontal and vertical components of the displacement, u_x and u_y, vary linearly with the x- and y-coordinates. With an increase in the axial strain (ε_1=0.1) deformation localizes gradually in the form of shear zone. The thickness of shear zone decreased with the axial strain increase. Thickness of the shear zone stabilizes when the major principal stress σ_1 reaches the maximum value. A typical plot of the stress σ_1 versus the axial strain ε_1 is shown in Fig. 3. Vertical cross-section of the sample at ε_1= 0.17 with the indicated initial and deformed meshes is shown in Fig. 4. Orientation angle of the shear zone α and its thickness were also indicated in Fig. 4. Shear zone was oriented at an angle of:

$$\alpha=\frac{\pi}{4}+\frac{\varphi}{2} \tag{1}$$

with the horizontal axis (direction of the minor principal stress σ_3) according to the Mohr-Coulomb theory, where φ is the angle of internal friction. The average value of the angle of

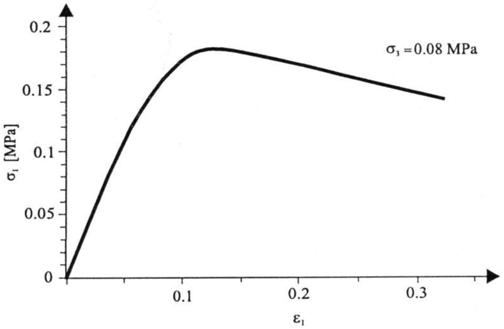

Fig. 3. Major principal stress σ_1 as a function of the axial strain ε_1.

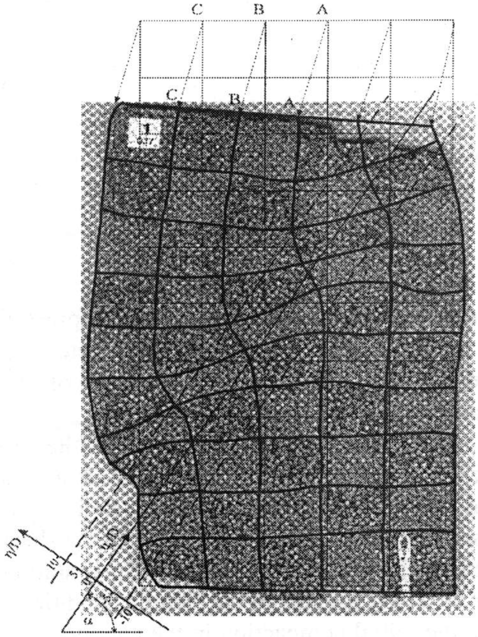

Fig. 4. Vertical cross-section of the sample (ε_1=0.17).

internal friction for the stained and not stained seed was 26°. Distribution of displacements across the shear band, at the axial strain ε_1 of 0.1 and 0.17, are shown in Figs 5 and 6. Vectors connecting the line of original and deformed mesh represent distribution of the displacement across the shear band. A vertical component of the vector represents the shear displacement, u_ξ, and the horizontal component represents the normal displacement, u_η. The thickness of the shear band was determined from the width of the ramp in the η-direction [1]. The thickness of the fully developed shear band was found to be 15 times bigger than the average grain diameter. For the stabilized thickness of the shear band, at ε_1=0.17, the gradient of the shear displacement across the shear band, $\frac{\partial u_\xi}{\partial \eta}$, was about 1. The gradient of the normal displacement, $\frac{\partial u_\eta}{\partial \eta}$, was negative at any point of the sample cross-section with the smallest value across the shear band. It means that the compaction of the granular material occurs in the entire sample and was the smallest across the shear band. The axial strain, ε_{1s}, associated with the shear displacement localized in the shear zone can be expressed as the product of the gradient of the shear displacement, the thickness of the shear band and its inclination angle with the horizontal axis can be expressed as:

$$\varepsilon_{1s} = \frac{\frac{\partial \xi}{\partial \eta} nD \sin \alpha}{H} \tag{2}$$

where: n - thickness of the shear band expressed as a number of the average grain diameter, D - average grain diameter, H - height of the sample.

The axial strain ε_{1s} is 0.106 for the experiment was performed at ε_1=0.17. It means that about 60% of the total axial strain ε_1 is associated directly with formation of the shear zone while 40% corresponds to the preparation for the shear process in the sample conditions, i.e., the initial compaction in the conditions of the constant strain.

The thickness of the shear band expressed as the constant number of the average grain diameter can be used to set the lower limit for the size of the sample of granular materials ensuring proper conditions for the failure test. Indication of the proper size of the sample is especially important for studying mechanical properties of a coarse-grained material, like for example, cereal grain. The ratio of the sample height to the average grain diameter, *H*/*D*, can be expressed as a function of the following parameters: gradient of the shear displacement, thickness and inclination of the shear band and the assumed value of the axial strain ε_{1s} expressed as:

$$\frac{H}{D} = \frac{\frac{\partial u_\xi}{\partial \eta} n \sin \alpha}{\varepsilon_{1s}}. \tag{3}$$

The shearing process in granular material involves two basic mechanisms: displacements and rotations of individual grains independently of grain size and origin of material [1,5,10]. Therefore, the experimental values used in the Eq. (3) for determining the *H*/*D* ratio should be similar for any granular material, and consequently the *H*/*D* ratio should be similar.

CONCLUSIONS

1. The proposed method of shape and internal structure fixation for a deformed sample provides an objective information on displacement distribution in granular material. The method can be applied for any course granular material.

2. Thickness of the fully developed shear band in mustard was found approximately 15 times higher than the average seed diameter.

3. Thickness of the shear band formed during the triaxial compression test under a constant minor principal stress σ_2=σ_3 stabilizes, when the major principal stress σ_1 reaches the maximum value, i.e., when the failure occurs in granular material. For the stabilized thickness of the shear band, the gradient of the component u_ξ of particle displacement in the η direction, $\frac{\partial u_\xi}{\partial \eta}$, is approaching 1.

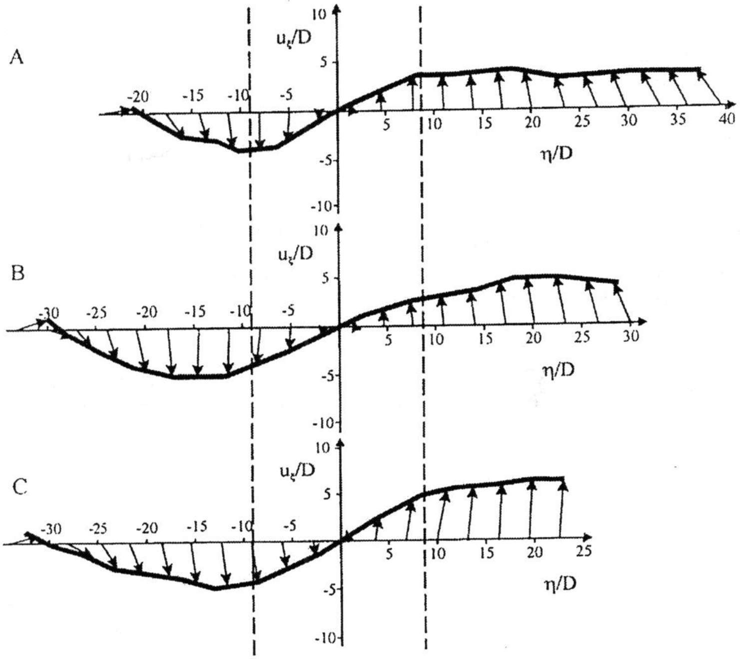

Fig. 5. Displacement distribution across the shear band (ε_1=0.1).

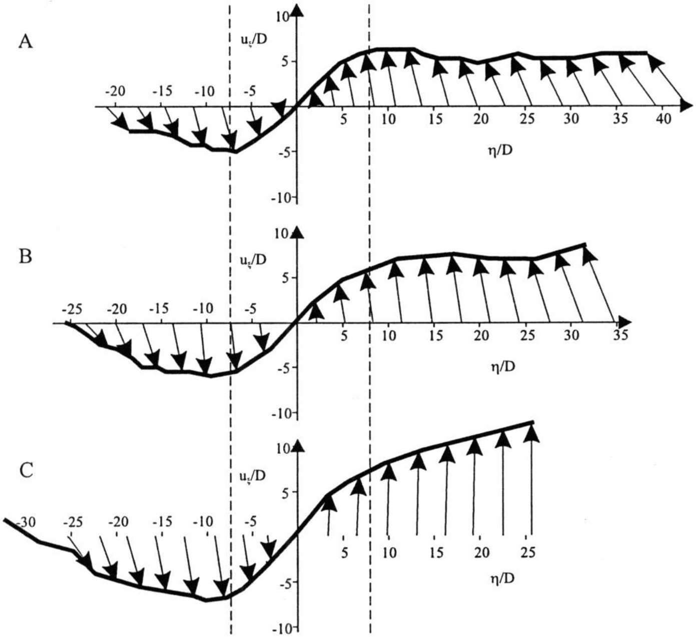

Fig. 6. Displacement distribution across the shear band (ε_1=0.17).

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