Deformation of granular material flow in converging channels

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Abstract. The authors study deformations of a granular material flow from a converging channel using the method of Particle Image Velocimetry (PIV). It is experimentally proved that shears localize along two orthogonal families of slip lines. During material flow, shears periodically “switch” between the families. Furthermore, the flowing material is split into blocks of different densities, and the maximum rates of density variation are concentrated along the slip lines of one of the families. The results of numerical modeling by the discrete element method and the laboratory-scale experiments qualitatively agree.

1. Introduction
In mining, many processes are studied experimentally using physical models. Such studies, first of all, include rock pressure phenomena, explosion load on rock mass, processes of ore and coal discharge from stopes and bunkers, haulage, etc. Adequate modeling involves the analysis of similarity criteria, manufacture of models using equivalent materials and experimentation aimed to register kinematics of deformation failure and to measure stresses.

A convenient object for modeling processes in mining is granular materials and equivalent geomaterials made of them with addition of binders.

Granular materials possess two fundamental properties intrinsic to all types of rocks, namely, internal friction and dilatancy. At the same time, cohesive forces between particles are very low, and granular materials are incapable to resist tensile stresses. For this reason, it is very difficult to measure deformation of granular materials on lab-scale and, moreover, full-scale models.

The best suitable techniques for such studies are non-contact measurements one of which is the method of Particle Image Velocimetry (PIV). This method consists in comparison of successive images of deformation process and determination of velocities in the target area. As a result, it is possible to determine field of strains in a specimen [1, 2].

2. Flow of granular materials in converging channels (laboratory modeling)
The general view of the test slot-type bunker with the flat converging side walls 1 and the flap-gate discharge 2 is given in figure 1. On the inside of the transparent front wall 2, a thin pipe filled with a colored granular material was attached. As the main flow was let out of the bunker, the colored particles were entrained in it and visualized the flow trajectory.

Regarding granular materials, it is known that their mechanical properties differ in different packings. The cause is the filling conditions, first of all. For instance, rain-like fill process generates a dense packing of particles while stream-like fill results in a loose packing. It is possible to improve
structure and stabilize mechanical parameters of a packing by subjecting it to alternating small-amplitude shearing [3, 4].

In this study, for stabilization of experimental results, the granular material was in stationary conditions. To that end, the material was continuously added while being discharged so that the bunker was always filled. Additional filling was carried out using a continuous batcher (not shown in figure 1). Fixed weight of the fill material ensured steady average pressure on the side walls of the bunker and constant discharge velocity.

The experiments showed that quartz sand flow velocity was constant with the continuous additional fill, while without the fill, during the period of complete discharge of the material from the bunker, the flow velocity was higher with the higher column of the material. To check adherence to the condition of time invariance, the discharge hole and the batcher were closed simultaneously, and the material in the bunker was weighed. The average weight of seven specimens was 2059 g at the deviation from the mean was no more than 6 %.

Thus, the adjustable continuous batcher provides stationary condition of the medium in the bunker in operation. The average density of the packing was 1.4 g/cm$^3$ and porosity was 45 %.

The flow process allows observing localization of deformations, clustering, initiation of new flows and their re-routing [5]. By way of illustration, figure 2 demonstrates the view of the marker belt during local flow. The images are taken at an interval of 20 s. It is seen that at a distance of 120 mm from the bunker top, the marker belt begins to crook and stretch. The flow path varies with time. The average flow velocity of the belt was 1.7 mm/s, standard deviation made 3 %, and maximum deviation totaled 6.5 %.

In this manner, the experiment shows that despite the stationary external conditions, the flow does not reach steady state.

**Figure 1.** Slot-type bunker, general view: 1 – converging walls; 2 – flap-gate discharge; 3 – transparent front wall; 4 – nozzle of marker flow source. Bunker height $H = 310$ mm, width $D = 52$ mm, top length $L = 182$ mm.

**Figure 2.** Marker belt deformation at different times of flow.
For the more detailed studies of kinematics, the flow process was continuously filmed on a digital camera at a speed of 25 frames per second. Each 12th frame was selected from the video file. The resultant series of images was processed in MatLab by the PIV method. Finally, fields of velocities (displacements) were obtained for the process of discharge at a step of 0.5 s; later on, they were additionally treated to calculate rates of shearing velocities and density variations.

Figure 3 demonstrates contour lines of shearing rates during gravity flow. The figures are the numbers of frames. It is seen that the maximum shear rates gradually localize in certain areas of the converging channel. Slip lines split the material into blocks. Splitting starts nearby the discharge hole and propagates upward as the material is discharged. Slip line progressively reach the top of the channel, which is clearly visible on frame 0181. Later on, the lines move downward and are slowly “healed”. During this process, orthogonal families of slip lines are formed, and shearing “switches” from one family to the other. Successive switching of orthogonal families of localized slip lines proceeds during the whole experiment. For example, frames 0613–0733 show the sequence of slip lines, starting 25 s after discharge onset. Apparently, switch of sliding from one family to the other takes place every 4 s.
Now, let us discuss contour lines of maximum rates of density variations in the granular material (volumetric strains) in figure 4. In this figure, the darker shades show higher rates of compaction. It is seen that the flowing material is divided into areas of different density. Along the localized deformation lines, the material experiences higher rate compaction. Furthermore, regardless the existence of two slip line families and their successive switching, the highest rates of compaction concentrate along one family, except for the onset of the flow process (frame 0121). This fact points at a certain asymmetry in the directions of shearing localization, the cause of which will be the object of the further research.

3. Flow of granular materials in converging channels (numerical modeling)
In the numerical investigations of kinematics of deformation in granular media, different variants of flow simulation models are very popular [6, 7]. In such models, a cell is set, and a material vanishes from it (leaves the study domain). Then, certain probabilities of the vacant cell filling by the material from the neighbor cells are defined. As a result, based on very simple rules, it is possible to obtain sufficiently complex flow patterns which simulate real processes. On the other hand, this approach fails to solve the problem of stresses. In order to calculate forces between particles, it is required to take closed models including stresses. It is the most convenient to carry out simulation using discrete element models [8–10]. Being the basic alternative to classical methods founded on the traditional continuum mechanics, the discrete element method currently finds wide application in studies of different modes of granular material flow.
Figure 4. Contour lines of density variation rates in the flow of quartz sand in the converging channel.

Figure 5 demonstrates the result of 3D DEM-based calculation in the form of successive kinematic patterns of flow deformation at fixed times.

(a)  (b)  (c)  (d)

Figure 5. Successive kinematic patterns of granular material deformation calculated by DEM
The calculations show that deformations localize along separate slip lines which divide the flowing material into blocks. Then, deformation takes place as relative slip of these blocks (on each other and on the channel walls) as rigid integer bodies. After a certain time, these slip lines are “healed”, and a new system of slip lines appears orthogonally to the previous one. On the whole, the experimental kinematics of flow and the DEM-calculated patterns correlate.

The numerically obtained stresses demonstrate quasi-periodic behavior also correlated with the sliding switches between the orthogonal families of slip lines.

Thus, the numerical modeling data agree qualitatively well with the experimental results.

4. Conclusions
1. Under stationary external action, gravity flow of granular materials in converging channels is steady-state. Shearing is localized along two orthogonal families of slip lines which function successively, one after the other.
2. The granular material flow is split into zones having different densities, and maximum compaction rates concentrate along one of the families of slip lines.
3. The data of the numerical modeling using the discrete element method agree qualitatively well with the laboratory-scale experiment on localized mode of granular material flow in converging channels.

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