Stripe patterns of granules induced by slow deformation of a container

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ABSTRACT: We report experimental results for stripe patterns appearing on the surface of granular matters under gravity. They are induced by slow deformation of a container. As the average size of granular particles is larger, stripes become more obscure with keeping roughly the spaces. We found that under these stripes, some faults appear in parallel to one another.

1 INTRODUCTION

Dry granular matters, such as sand, display very different behaviors from many particle systems which can be understood by using statistical physics (Jaeger et al. 1996). They are caused from the properties that thermodynamic fluctuations are negligible for particles with large mass, that dry granules have no attractive interaction, and that fictions between contacting particles dissipate energy. In particular, static states under gravity make a solid phase peculiar to granular matters.

Differences between solid states of granules and elastic materials are observed distinctly on stress distributions. All particles in a sample are stationary due to static frictions and particles on which stronger forces concentrate than on the surrounding ones forms a network which is called a stress chain. In a macroscopic viewpoint, dry granular media in a static state experiences compressive stresses anywhere because no cohesive interaction acts among particles. It is well known from experiments of sandpiles that the spatial distributions of stresses depend strongly on the history of the formation of a sample (Mueth et al. 1998; de Gennes 1998; Vanel et al. 1999).

Granules in a sold state start to move typically with arising either a fracture or a surface flow. As stresses increase slowly, a granular media cracks to form a slip plane. It is called a shear band, which has the thickness of the order of 5-10 grain diameters. An empirical law for cracking of granular matters is known as the Mohr-Coulomb criterion (Åström et al. 2000). In the case that a container is inclined, for example, granules flow on the surface. The granules in the container are divided into a fluid phase and a solid phase. In mixtures of some kinds of granules, stripes are induced by segregation in surface flows (Makse et al. 1998).

In this paper, we report experiments for stripe patterns of one kind of granules, which are caused by some fractures than by surface flows. The experiments started from the accidental finding by Kurumatani, one of authors, that stripe patterns appeared on the surface of sands when she put a bag containing fine sands down on a table. Although the phenomena can be reproduced easily both in many kinds of sands and in glass beads, we couldn't find a report related to it in the past literatures. The stripe patterns are observed only when we deform a container of granules slowly, and it seems that no sand flows on the stripes. We present here the results of well-controlled experiments and discuss about stress distributions formed in the granular media.

2 EXPERIMENTAL SETUP

We used spherical glass beads in most of all the experiments described below. They are made of soda-lime silicaed glass of which density is $2.5 \pm 0.1 g/cm^3$. We prepared three kinds of glass beads with average diameter $R = 40, 100$ and $200 \mu m$, which we refer GB40, GB100 and GB200, respectively. They are nearly mono-disperse, $80-90\%$ particles of which have diameters from $0.9R$ to $1.1R$. (They were bought from the association of powder process industry and engineering (APPIE) and Union Inc. in Japan.)

Only in the experiments where we made colored layers, we employed less uniform glass beads with about $0.1 mm$ diameter, which are sold for using in crushers. We stained them with a water-soluble ink. We confirmed that stripe patterns can be also reproduced similarly in these glass beads, whether they are stained or not. We refer them as GB-01.

We show the experimental setup schematically in

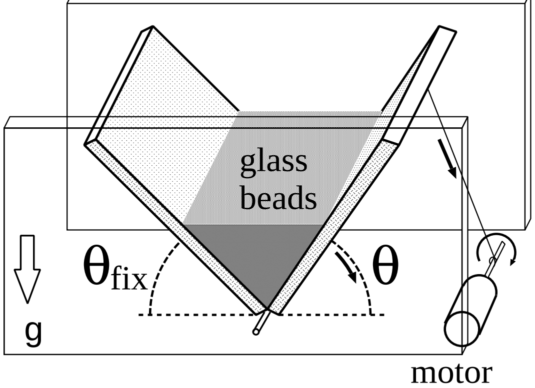

Figure 1: The experimental setup

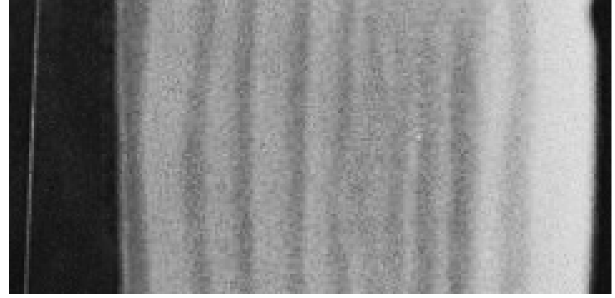

Figure 2: A snapshot of a stripe pattern
GB100, $\theta_{fix} = 50°$, $\theta_0 = 60°$, $\theta = 30°$, $M = 400g$.

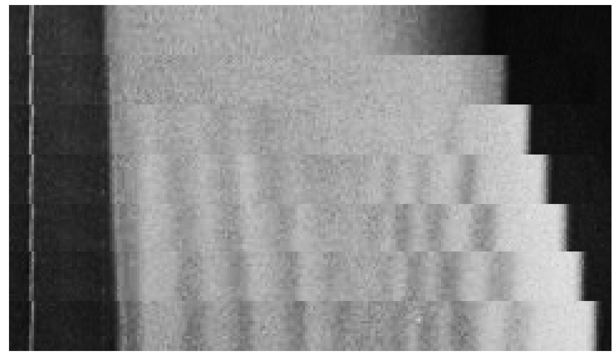

Figure 3: A process of the formation of stripes
GB100, $\theta_{fix} = 50°$, $\theta_0 = 60°$, $M = 400g$.

Figure 1. A container of glass beads is composed of two rectangular acrylic plates which join in a V-shape. The slopes of each plate are variable. We covered the surfaces of the two plates with thin rubber sheets because it is easy for acrylic to be scratched. On their lateral sides, we sticked pieces of felt in order to move smoothly with keeping grains in the container. Then the V-shaped plates were held between parallel acrylic plates. The formation of stripe patterns is not considered to depend strongly on boundary conditions of the bottoms because the patterns have little changed when we used plastic sheets in the place of the rubber ones.

At the beginning of experiments, we fixed one of the V-shaped plates at an angle of inclination $\theta = \theta_0$ and the other at θ_{fix}. We poured glass beads with weight Mg into the container and tapped it a few times to level the surface horizontally. The density of grains, including airs, is $1.5 \pm 0.1 g/cm^3$. Then we decreased the slope of the one plate θ very slowly while the other was fixed at θ_{fix}. We used a motor connected to a power supply with a constant voltage to pull the plate at a line. The angular velocity $\dot{\theta}$ keeps almost constant during an experiment and $\dot{\theta} = 0.60 \pm 0.05°/s$ in the following experiments. The way of pouring grains at the beginning doesn't seem to affect stripe patterns although it isn't the same exactly in each experiment.

We put the above experimental setup in an airtight container with desiccants in which the relative humidity of the air was $5 - 15\%$. Before we used glass beads in experiments, we had dried out them in the container some days until the weight had finished to decrease with desiccation. Although we employed this procedure to keep granules dried, we confirmed that the phenomena reproduce both in the air with higher humidity of a room and in a nitrogen gas with little humidity.

We photographed the top views of granules by using a digital video recorder, where we lighted up the surface obliquely. Figure 2 is a photograph of a typical stripe pattern. The width of the image corresponds to length 11.1 cm on the surface. The vertical axis is pararell to the rotation axis of the plate, and the fixed plate is placed in the left side. The grey scale represents the shape of the surface because glass beads composed of small grains are paractically opaque. We took statistical data from 5 experiments for each condition to investigate the spaces of stripes.

3 RESULTS

In Figure 3, we cut out the horizontal zones in the center of snapshots from $\theta = \theta_0 = 60°$ to $\theta = 30°$ every $5°$ in an experiment and arranged them from the top to the bottom. Stripes are formed early at $\theta = 0 \sim 10°$ and they make clears with the growth of the amplitude during the following rotaion.

The surface near the moving boundary inclines nearly at the repose angle ϕ_c because granules flow here. This region is shown in the rightest light part of the images. In contrast, no pattern appears near the fixed plate in the case of $\theta_{fix} \lesssim 50°$ and the surface in the area remains horizontally. The stripe patterns appears on the surface between these two regions at the angle of slope $0 \sim \phi_c$.

The spaces of stripes is typically $3 \sim 10mm$, which tend to become large away from the horizontal center. The spaces are independent on the weight of granules in the container. Although we compared the results of GB40, GB100 and GB200, the spaces doesn't depend distinctively on the size of grains, while stripes become more obscure as the size is larger.

We can observe displacements of grains on the lateral boundary through the acryle wall. Although the

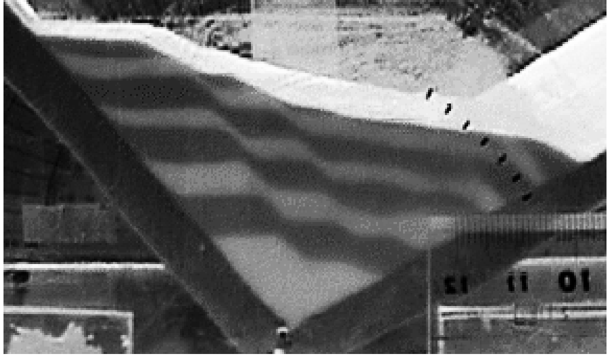

Figure 4: A lateral view of the experiment where horizontal colored layers are prepeared initially. GB-01, $\theta_{fix} = 50°$, $\theta_0 = 60°$, $\theta = 30°$, $M = 400g$.

stripe patterns are disturbed by the boundary, we can guess movements of granules inside a sample. Figure 4 shows a snapshot of the experiment where horizontal layers of stained glass beads were formed before the rotaion of the plate. We know that some faults develope in pararell one another and appear on the surface as stripe patterns. It seems that there are also a few faults nearly pararell to the moving plate. Some clear faults near the fixed plate incline at $61 \pm 2°$ against the horizontal plane in the case of glass beads GB-01.

4 CONCLUSIONS AND DISCUSSIONS

We investigated the characters and the cause of the stripe patterns induced by slow deformation of a container. The patterns appear on the surface of dry granular matters, such as sands or glass beads. From the observaions of colored layers prepared in granules, we found that some slip planes develope in parallel under the surface.

We used a V-shaped container in the experiments, where stripes arise in pararell to the rotation axis of the bondary. The spaces of the stripes tend to become small near the center of the surface and they are independent on the total amount of granules. As the size of grains is larger, stripes make unclear with keeping roughly the spaces.

What a stress distribution is formed in the granules? If we assume the critial stress condition where the Mohr-Coulomb criterion is satisfied anywhere in the region containing the slip planes, we can calculate that the incline of the slip planes is $45° + \phi_c/2$ against the horizontal plane. Because the glass beads GB-01 used in the experiments have a repose angle $\phi_c = 29.5 \pm 0.7°$, the angle $45° + \phi_c/2 = 60.1 \pm 0.4°$ agrees well with the measured data. It represents that the stress distribution on these slip planes is nearly at the critical stress states.

The mechanism of the formation of the slip planes is a future problem, although we are studying it with a theoretical model. The details of experimental data and the theoretical investigations will be reported elsewhere.

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