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Scaling of convective velocity in a vertically vibrated granular bed

Tomoya M. Yamada *, Hiroaki Katsuragi

Department of Earth and Environmental Sciences, Nagoya University, Furocho, Chikusa, Nagoya 464-8601, Japan

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ABSTRACT

We experimentally study the velocity scaling of granular convection which is a possible mechanism of the regolith migration on the surface of small asteroids. In order to evaluate the contribution of granular convection to the regolith migration, the velocity of granular convection under the microgravity condition has to be revealed. Although it is hard to control the gravitational acceleration in laboratory experiments, scaling relations involving the gravitational effect can be evaluated by systematic experiments. Therefore, we perform such a systematic experiment of the vibration-induced granular convection. From the experimental data, a scaling form for the granular convective velocity is obtained. The obtained scaling form implies that the granular convective velocity can be decomposed into two characteristic velocity components: vibrational and gravitational velocities. In addition, the system size dependence is also scaled. According to the scaling form, the granular convective velocity v depends on the gravitational acceleration g as $v \propto g^{0.97}$ when the normalized vibrational acceleration is fixed.

1. Introduction

In the solar system, there are many small bodies such as asteroids and comets. Since these small astronomical objects could keep the ancient information of the history of the solar system, a lot of efforts have been devoted to investigations of these objects so far (e.g., Bottke et al., 2002). For instance, the asteroid Itokawa was explored by the Japanese space craft *Hayabusa* from September 2005. The exploration uncovered the details of Itokawa's surface terrain. Itokawa is covered by various sizes of granular matters such as regolith, pebbles, and boulders (Fujiwara et al., 2006). Moreover, migrations and sorting of the regolith could occur on the surface of Itokawa (Miyamoto et al., 2007), although the surface gravity of Itokawa is extremely low. Impact craters located on the surface of Itokawa were very subtle, i.e., they show indistinct morphologies (Saito et al., 2006; Hirata et al., 2009). This is probably due to the erasure of the craters by seismic shaking (Michel et al., 2009). In addition, tiny samples returned from Itokawa allow us to analyze the detail of its history. Nagao et al. (2011) revealed that Itokawa's surface grains are relatively young in terms of cosmic-rays exposure. The estimated age is approximately eight million years. Besides, using X-ray microtomography, Tsuchiyama et al. (2011) found that some particles had rounded edges. All these facts suggest that the surface of Itokawa would be active and continue to be renewed until recently. One possible explanation of such young surface is the regolith convection caused by impact-induced seismic shaking.

Although the direct measurement of the seismic wave has not been achieved, Richardson et al. (2004) and Richardson Jr. et al. (2005) studied the possibility of global seismic shaking of asteroid Eros in order to explain its surface modification processes. They built a model of seismic shaking by considering the attenuating diffusion of the seismic wave. Miyamoto et al. (2007) partially applied the model to the asteroid Itokawa and showed that the global regolith convection might occur even by small-scale impacts. To unlock the regolith grains network supported by gravity, the maximum acceleration induced by the seismic shaking has to be greater than the gravitational acceleration. Miyamoto et al. (2007) revealed that this criterion can be satisfied by a small-scale impact since the gravity on the surface of Itokawa g_I is very small, $g_I \simeq 10^{-4}$ m/s^2 (Abe et al., 2006; Fujiwara et al., 2006). The value of g_I is about five orders of magnitude smaller than the Earth's gravitational acceleration, g_E=9.8 m/s^2. The evaluation is still qualitative since they only assessed the onset criterion of the regolith convection. While the quantitative assessment of the convective velocity is necessary to discuss the feasibility of the regolith convection, there have been very few such studies.

Granular convection can be generally observed in a granular matter under the mechanical vibration. When a granular matter is subjected to a steady vertical vibration, granular convection is readily induced. If the vibrated granular matter is polydisperse, the size segregation of grains occurs usually in the vertical direction. This vibration-induced size segregation is called the Brazil nut effect (BNE). The BNE can be caused by the granular convection

* Corresponding author. Tel.: +81 52 789 3014; fax: +81 52 789 3013.
E-mail address: yamada.tomoya@a.mbox.nagoya-u.ac.jp (T.M. Yamada).

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(Knight et al., 1993). This means that the grains can be migrated and sorted simultaneously by vibration. Although the regolith convection accompanied by migration and sorting seems to be a natural outcome of global seismic shaking, the scaling approach to the granular convective velocity is needed to discuss the consistency between regolith convection and observational data such as surface age of the asteroid. Therefore, we experimentally measure and scale the velocity of granular convection in this study, as a first-step approach to this problem.

The fundamental nature of granular convection itself is an intriguing problem. The granular convection has long been studied by both experiments (Faraday, 1831; Ehrichs et al., 1995; Knight et al., 1996; Pastor et al., 2007; Garcimartín et al., 2002) and numerical simulations (Taguchi, 1992; Luding et al., 1994; Tancredi et al., 2012). The onset of granular convection depends on the maximum acceleration of the applied vibration. If the maximum acceleration is less than the gravitational acceleration, any granular convection does not occur at all (e.g., Garcimartín et al., 2002). Thus the dimensionless parameter Γ, which represents the balance between the maximum vibrational acceleration and the gravitational acceleration g, has been used to characterize the behavior of granular convection. Γ is defined as

$$\Gamma = \frac{A_0(2\pi f)^2}{g}, \quad (1)$$

where A_0 is the vibration amplitude and f is the frequency.

In this study, the scaling method is applied to the analysis of granular convective velocity. We are interested in asteroidal-scale granular convection while the actual experiment is limited within the laboratory scale. In such a situation, the scaling is the only way to derive a meaningful quantitative relation. In the scaling analysis, dimensionless parameters such as Γ are useful since they do not depend on the system of unit. The weak point of the scaling analysis is its arbitrariness. Of course, Γ is one of the most important dimensionless parameters to discuss the vibrated granular matter. However, the choice of the important dimensionless parameter is not unique.

Specifically, another dimensionless parameter called shaking parameter S was first introduced by Pak and Behringer (1993) and recently used to describe the transitions among the granular Leidenfrost, bouncing bed, undulations, convection, and so on (Eshuis et al., 2005, 2007). Particularly, S is relevant to characterize a strongly shaken shallow granular convection (Eshuis et al., 2010). S is defined as

$$S = \Gamma \cdot \frac{A_0}{d} = \frac{(2\pi A_0 f)^2}{gd}, \quad (2)$$

where d is the constitutive grains diameter. S denotes the balance between the squared vibrational velocity and the squared gravitational velocity. Furthermore, S can be also obtained by the natural non-dimensionalization of the granular-hydrodynamic model for the strongly shaken granular convection (Eshuis et al., 2010). Using the aforementioned dimensionless parameters, we would like to find a useful scaling relation among granular convective velocity, the gravitational acceleration, and other parameters. Therefore, we carry out a systematic laboratory experiment of the vibration-induced granular convection.

This paper is constructed by following sections. In Section 2, we explain the experimental setup and how to measure the convective velocity. Section 3 shows the characterization of some convective-roll patterns and the result of the scaling. In Section 4, we discuss physical meaning and tentative implication of the scaling to the microgravity environment. Section 5 contains a conclusions.

2. Materials and methods

A schematic illustration of the experimental apparatus is shown in Fig. 1. The experimental setup consists of a cylinder made of plexiglass of its height 150 mm and inner radius R (R=16.5, 37.5, or 75 mm). Glass beads are poured in the cylindrical cell to make a granular bed of the height H=20, 50, 80, or 110 mm. The system is mounted on an electromechanical vibrator (EMIC 513-B/A) and shaken vertically. The vibration frequency f is varied from 10 to 300 Hz and Γ is varied from 2 to 6. The grains used in this study are glass beads. Most of the experiments are carried out with glass beads of diameter d=0.8 mm (AS-ONE corp. BZ08) and some of them are performed with glass beads of d=0.4 or 2 mm (AS-ONE corp. BZ04, BZ2). Size dispersion of glass beads is less than 25%, and the true density of glass beads is 2.5×10^3 kg/m^3.

To measure the granular convective velocity, the particle imaging velocimetry (PIV) method is utilized (Lueptow et al., 2000; Bokkers et al., 2004; Zeilstra et al., 2008). Motions of glass beads are filmed by a high-speed camera (Photoron SA-5) through a transparent side wall. To erase the memory effect of granular matter, one minute pre-vibration is applied before each experimental realization. This means that we measure the steady granular convection. While the actual impact-induced regolith convection might be transient, we have to concentrate on the steady convection to eliminate the memory effect. The frame rate is fixed at 1000 fps and the spatial resolution of the image ranges from 54 μm/pixel to 130 μm/pixel depending on the experimental conditions. The high-speed images are acquired for 5.5 s. Since each image consists of 1024×1024 pixels, the size of field of view ranges from 55×55 to 133×133 mm^2. Raw data images are shown in backgrounds of Figs. 2 and 3. Since it is hard to completely follow all the grains' motion, we use PIV method instead of the direct particle tracking. In the analyses of Figs. 2 and 3(a), each instantaneous image is divided into 16×16 boxes, i.e., each box consists of 64×64 pixels. Note that the number of image partitioning depends on the experimental condition. Then the velocity at each box is computed by detecting a peak of the cross-correlation between two different time snapshots. Obtained (time-averaged) examples of the velocity field are shown by colored vectors in Figs. 2 and 3. An interval time to compute the velocity (cross-correlation) is kept constant so that it corresponds to a multiple of the period of vibration, i.e., two cross-correlated images are kept in same phase. For instance, 0.01 s time interval is used for 100 Hz vibration. If we use a full temporal resolution to calculate the velocity field, the vibrational motion of individual grains can be captured just like Pastor et al. (2007) measurement. However, we are mainly interested in the global convective motion rather than such microscopic vibration. Therefore, we use phase-matching images to compute the velocity.

As shown in Fig. 2, convective-velocity vectors are decomposed into z (vertical) and x (horizontal) directions. They are averaged along the horizontal axis since we are mainly focusing on the

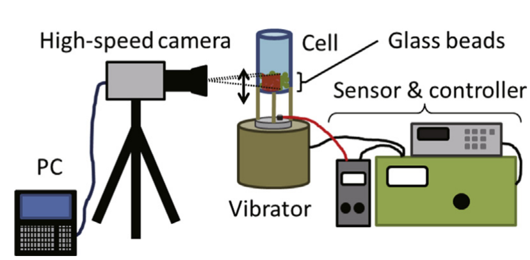

Fig. 1. A schematic diagram of the experimental setup. Glass beads are poured into a cylindrical cell and the cell is shaken by a vibrator. Glass beads motion on the side wall is captured by a high-speed camera and the convective velocity is measured by PIV method.