Rate-independent transport processes in stirred granular medium

J. Alamia, G. Friedman, Electrical and Computer Engineering Department, Drexel University

I. INTRODUCTION

Hysteresis is distinguished from other irreversibe thermodynamic processes by the rate-indpendence property. Although not usually called hysteretic, rate-independent transport processes in fluids have been studied for some time. Locomotion of micro-organisms which do not rely on inertia is one important example that has been attracting attention over the past few decades. In this case, rate-independent, and therefore hysteretic, relationship is observed between relative displacement of micro-organism parts and the displacement of the micro-organism itself in the fluid [1].

Although locomotion of living creatures, such as desert lizards, through sand has been frequently observed, it has not been studied to the same extent. The question that we address in this work is: Can such locomotion and granular transport phenomena associated with it be rate-independent, similarly to the low Reynolds number transport in fluids?

In the existing literature on granular media objects that are larger than the surrounding grains are sometimes called intruders. Movement of intruders in vibrated granular medium has been of great interest in the past 2 decades in connection with the so-called Brazil Nut effect (BNE). It is often observed that intruders (of which larger Brazil Nuts are an example) often rise to the top of a vibrated container filled with granular medium, even if the intruder is more dense than the surrounding material. Convincing work in the past decade [2] suggested that the effect is caused by granular convection. It showed that BNE depends strongly on the rate and strength of vibration. Other work [3] suggested that rise of intruders can occur without convection and may be rate-independent. In this case, the effect called percolation, where the intruder exchanges positions with the grains falling around it, seems to be responsible.

Initial motivation for the present work came from our own observations that ants, when covered by sand, seem to float to the top after a while without making tunnels. We hypothesized that this occurs somehow due to stirring of the surrounding sand by the ants. Therefore, in this work we consider movements in granular medium caused by intruders that are stirred within it, not shaken. The intruders we employ are rotating rods and other elongated objects. Rods being considered here are magnetizable and rotate due to a rotating external uniform magnetic field. The rods are typically made of steel and are 2mm in diameter, while the surrounding glass grains are 0.5 mm in diameter.

II. RESULTS

As the external magnetic field rotates, we observe that rods buried at different depth, some starting at the very bottom of the container, others starting in the middle, always rise to the

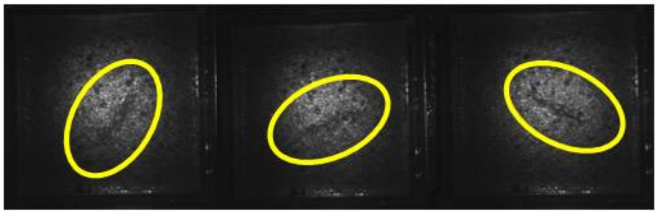

Fig.1. Rotation of steel rod buried in granular medium under action of rotating magnetic field. Observation is enabled by using optical index matching fluid.

top. The rods rise when positioned near the container walls or in the middle of it. They rise when the granular medium is soaked in water or with optical index matching fluid (glycerine) which helps to see the rod movements through the surrounding grains (see Fig. 1). Importantly, when we timed the rise of the rods from various depths while rotating them at various rates, it was found that the magnitude of their upward displacement depends only on the number of rotations, not on the rate. Therefore, we confirmed that rate-independent transport of the intruders that stir the granular medium is occurring.

By using layers of grains of different colors we confirmed that stirring of the rods is accompanied by convective motion of the granular medium. This convection is very different from one typically observed in fluids since displacement of the grains is independent of the stirring rate. We observed that similar convection occurs even if the rod is tethered to the bottom of the container, not being allowed to rise to the top.

As an explanation of the observed phenomena we propose that effective density of the granular medium is lowered around the intruder as the grains re-arrange their positions. This could be due to localized increase of granular temperature, for example. Thus, a bubble of lighter material effectively forms around the intruder as it is rotated. This is similar to convection created by a heater imbedded in fluid medium, except that heating usually cause rate-dependent effect (heating too slowly creates no convective effects). Some tests of this hypothesis will be described.

REFERENCES

[1] A. Shapere, F. Wilczek, Phys.Rev.Lett., 58, 2051-2054 (1987)

[2] M. Möbius, B.E. Lauderdale, S.R. Nagel and H.M. Jaeger, Nature (London) **414**, 270 (2001)

[3] J. Duran, J. Rajchenbach, E. Clément, Phys.Rev.Lett., **70**, 2431-2434 (1993)