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Dynamic Jamming transition in granular media: approach from high-velocity drag friction
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We cannot explain the physical behaviors of granular materials by applying hydrodynamics or elastic theory with regarding granular systems as continuum media. The specific features such as inhomogeneously developed force chains or dynamics sometimes fluid-like but some other times solid-like are intertwined and understood only empirically and fragmentally. About 15 years ago, physicists noticed this important problem and since then they, in particular, soft matter physicists, have been working to understand physical properties of granular materials. Especially the " drag friction " acting on an obstacle in flow is one of the most basic and important problems of irreversible processes in non-equilibrium physics. In addition, a critical phenomenon called " jamming transition ", at which a finite stress starts to yield as in a solid when the packing fractions is increased, has recently been one of the central issues in granular physics in connection with glass transitions. After the jamming phase diagram was proposed in 1998 [1], remarkable progress has been made in understanding of the jamming transition, which includes proposal of theories based on scaling phenomenology or developed from glass theories and determinations of the critical exponents both from simulations and experiments. Accordingly, to connect the drag friction, which depends strongly on the applied shear and the packing fractions, to the jamming transition has been a topic of great interest in recent years.

In this paper, we approach this important issue from an extremely simple experiment. Recently, we proposed an experimental system which enabled us to directly measure the drag friction acting on a disk embedded in a granular media inside a closed two dimensional cell [2]. This setup has some original features which include: (i) there are many experiments on the drag frictions in granular media but mostly in low velocity regions $\sim$ a few 1 mm/s. However, our setup enables us to study higher velocity regions around a few 100 mm/s. (ii) Drag friction experiments in high-velocity region have been plagued with technical difficulties; the principal method of previous studies has been impact of an object onto a granular bed and in the impact experiments the force was indirectly calculated from the speed of the object inside the bed [3]. However, this method cannot eliminate the influence of unwanted factors such as gravity (unfortunately the effect of gravity acting on three dimensional granular media is not as simple as in water) and furthermore the speed inside the granular bed is changing throughout the impact. On the contrary, our setup allows high-velocity drags at a fixed speed under no influence of gravity and direct measurements of the frictions. (iii) This two-dimensional and horizontal system makes it possible to control the packing fraction of

granular media and to approach the jamming point for the first time [4].

Thanks to these original features of our setup, we obtained results which could be of great interest to many researchers. The main results are summarized as follows. (I) Proposal of Extension form of inertial term: in the previous works high- velocity drag friction was interpreted as the inertial term in the hydrodynamic equation both in experiments [3] and in simulation studies [5]. However, our experimental data cannot be explained as the simple inertial term for a general continuum media. Accordingly, we developed an original scaling theory, which involves an idea of a cluster which was created by multiple collisions between granular particles. As a result, we proposed a new concept to this field. Furthermore, we confirmed a correlation length which would be related to the cluster size. (II) Finding out a new critical phenomenon: the first experiment near the jamming point showed new critical behaviors. A number of physical quantities such as two components of forces and the fluctuation of the force tend to diverge as the packing fraction approaches the jamming point. Furthermore we succeeded in explaining the critical exponent in connection with the divergence of the above-mentioned cluster size. (III) Elucidation of the origin of friction by statistical analyses: Via statistical analysis of fluctuations, we calculated the characteristic time and the PDF to understand the physical origin of the frictions. The result shows that the statistical fluctuation in our case has an origin different from that in the case in which the force chain was dominant as often occurs in sheared systems near the jamming point [6]. These results support well our scaling theory (I) based on momentum transfer at multiple collisions.

As stated above, our results are expected to be an important step for constructing a constitutive equation for granular materials which has long been a target of the fiels.

[1] A. J. Liu and S. R. Nagel, *Nature* **396**, 21 (1998).

[2] Y. Takehara et. al, *EPL* **92**, 44003 (2010).

[3] H. Katsuragi and D. J. Durian, *Nature Phys.* **3**, 420 (2007).

[4] Y. Takehara and K. Okumura, *Phys. Rev. Lett.* **Accepted**, (2014).

[5] C. R. Wassgren, et. al, *Phys. Fluids* **15**, 3318 (2003).

[6] E. I. Corwin, et. al, *Nature* **435**, 1075 (2005)