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TITLE: JOTAIN LISÄÄ JOTTA SAADAAN MUUTAMALLE RIVILLE KAIKKI TÄMÄ MAHTUMAAN

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To all of you,
use freely

Yours, JR!

Contents

List of publications

Publication I
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Contribution...

Explain the author's contribution in each paper either here or after each paper title above. The list of papers may contain journal articles, conference articles and other suitable scientific publications. Apply same bibliography style, which has been used in the reference list. If the articles are not yet published, it must be mentioned in the comments as shown in the above examples. The contribution text may look like this:

Author Name is the principal author and investigator in papers I and III - V. In paper II, Dr. Firstwriter was the corresponding author and Author Name conducted the experiments and post processed the experimental data. In paper III, the literature data was assembled by Mr. Lastwriter.

Nomenclature

Latin alphabet

A	area	m^2
a	scale of a wavelet	
b	location of center of a wavelet	
$C(a,b)$	wavelet transform of a function	
d	diameter	m
E	error	
F	force	N
f	frequency	$1/\mathrm{s}$, Hz
f'	force fluctuation	N
f_c	center frequency	$1/\mathrm{s}$, Hz
G	parameter in layering model	
g	gravity	$\mathrm{m/s^2}$
h	height	m
$\bar{h}$	average height	m
k	stiffness of the spring	$\mathrm{N/m}$
L	layer number	
M	torque	Nm
m	mass	kg
N	number of particles	
r	radius	m
S	stress	$\mathrm{N/m^2}$
t	time	s
v	velocity	$\mathrm{m/s}$
w	width	m
x	x-coordinate	m
Z	number of particle chains	

Greek alphabet

β	packing angle	rad
Γ	evolution function	
γ	shear rate	$1/\mathrm{s}$
μ	friction coefficient	
ν	number ratio	
ω	rotation rate	$1/\mathrm{s}$,Hz
ϕ	solid volume fraction	
ϕ_{2D}	area fraction	
ψ	wavelet function	
ρ	density	$\mathrm{kg/m^3}$
σ'	stress fluctuation	$\mathrm{N/m^2}$

σ_0	overall compressive stress	$\mathrm{N/m^2}$
τ	sampling period	

Superscripts

p	partial layer
$*$	dimensionless

Subscripts

0	initial value
A	element A
B	element B
b	belt
d	dynamic
fluid	fluid-like shear region
hex	hexagonal lattice
max	maximum
min	minimum
m	mean value
n	normal
p	particle
q-s	quasi-static shear region
sqr	square lattice
s	shear
s-s	steady state
st	static
tot	total

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
CS	Completely sheared
CWT	Continuous wavelet transform
DAQ	Data acquisition
DEM	Discrete element method
DWT	Discrete wavelet transform
MD	Molecular dynamics
MRI	Magnetic resonance imaging
PDF	Probability density function
PS	Partially sheared
RCP	Random close packing
RLP	Random loose packing

STD	Standard deviation

1 Introduction

1.1 Granular material: definition and classification

Granular materials are collections of individual solid particles dispersed in a fluid or a gas or vacuum. Granular materials show multiple behaviors under different circumstances. In the presence or absence of external forces, the granular matter may behave like a solid, a fluid, or a solid-fluid mixture. Therefore, granular materials are well suited to the category of complex systems or complex fluids. The study of granular materials can improve our abilities in controlling almost every sector of industrial processes and natural incidents such as:

- The handling and conveying of core, ore, mineral concentrate, sand, powders, food products, or tablets.
- The mixing, segregation, drying and heating of granular materials.
- The applications of fluidized beds.
- Avalanches of snow, motion of ice sheets, slides of rock debris, and debris flows.
- Powder metallurgy and ceramic engineering.

In chemical industry more than 50% of products are formed as particles, and about 75% of raw materials exist as granules. The improper designs of hoppers, conveyors and reactors in industrial transport and chemical processes result in unnecessary expenses related to materials, energy, and facilities. The behaviors of dense granular flows are unique. For instance, a volume of granular material may be effectively sheared only within a few layers of particles, while a major portion of it remains still. This behavior may not be desirable in some industrial processes where homogenization is required.

In order to understand the cause of heterogeneity in granular media, stress fluctuations are measured globally and locally (Liu et al., 1995). Some measurements showed that the spatial distribution of force is highly inhomogeneous, which intermittently changes in any position with time (Miller et al., 1996). Some models have been developed which could satisfactorily match the statistics of stress fluctuations in granular material (De Gennes, 1991; Liu et al., 1995; Edwards and Grinev, 2003; Goldenberg and Goldhirsch, 2004; Edwards, 2005).

It is important to specify the circumstances which lead to fluid-like behavior of granular materials or their dual behavior. This thesis specifically concentrates on annular rapid shear flows of granular materials consisting of steel spheres used in commercial ball bearings. The diameters of the grains are 2 and 3 mm with fairly uniform distributions. Earlier experiments were performed by Savage and Sayed (1984) and Hanes and Inman (1985) in which very high shear rates were applied to glass beads. On the other hand, most of the recent investigations by Miller et al. (1996), Dalton and Corcoran (2001), Erikson et al.

(2002), Mueth (2003), Tsai (2004) and Daniels and Behringer (2005) have extensively studied the local and temporal features of stresses in static or slowly-deforming systems.

In many practical applications, medium or high rates of shear deformation (larger than 1 s^{-1}) are involved. Moreover, limited size of the apparatus is another issue that concerns scientists for the existence of large radial gradients in the flow as deformation rates are increased. In most experiments found in the literature, glass beads or some natural grains such as sand or seeds have been used. The design of our apparatus and corresponding experiments have addressed these issues. The size and capacity of our shear cell is considerably larger than previous ones, e.g. the apparatus used by Hanes and Inman (1985). This assures us that the resulting flow in the range of the shear rates used here (or even in larger rates) has a negligible radial gradient. Packing density is a key characteristic in shear granular flows. In this context, the larger capacity (loaded mass) of our system is crucial in approaching packing densities of infinitely large systems. Our experiments are presented for 2 and 3 mm steel spheres for which there are no extensive experimental results in the literature. Moreover, the design of our system provides a degree of freedom to vertical displacement of the lower support of the system, while a fixed rotating ring at the top shears the medium. Compressive and shear forces of the entire system are continuously measured as well as displacement of the lower support of the bed. A short introduction of the concepts of interest in this thesis are presented in Chapter **??**. In Chapter **??**, I introduce our experimental facility including the apparatus and measurement system as well as the experimental procedure. Results for transient and steady state behavior of the system are presented through Chapters **??** to **??** followed by some concluding remarks.

1.2 Motivation and objectives of the study

The objective of this work is to perform a series of experiments in rapid dense granular shear flows to obtain a deeper insight into corresponding physical and technological facts. Complexity of flow, deformation dynamics and stability of flow are some remarkable subjects that deserve precise investigations both experimentally and theoretically. This work was motivated by the need of the physics and engineering communities to understand the basics related to these subjects. As an outcome of this research, I will show in Chapter **??** how the formation of structures within a granular medium affects the stability of deformation and flow.

1.3 A short historical review

In the past, the physics of granular materials has received far less attention on the part of researchers than, say, hydrodynamics. Yet it is remarkable and, in a sense, admirable that a few notable scientists managed in those days to marvel at some fascinating aspects of the behavior of types of solids (Duran, 2000).

The first recorded mention of granular flows was made by Lucretius (ca. 98-55 B.C.), the famous poet and natural philosopher in ancient Rome. He wrote in 55 B.C.: “One can scoop up poppy seeds with a ladle as easily as if they were water and, when dipping the ladle, the seeds flow in a continuous stream.”

Scholars of the Renaissance had wide-ranging interests. Leonardo da Vinci (1452-1519) was the first to devise a simple and convincing experiment demonstrating the laws of dry friction. He and others were even able to make a few pertinent statements concerning piles of sand. It was not until the end of the eighteenth century, though, that Charles de Coulomb (1736-1806) wrote a definitive paper, which is still frequently cited, entitled “Essay on the rules of Maximis and Minimis applied to some problems of equilibrium related to architecture” (Coulomb, 1773). The paper in question, which is of interest in several respects, is based on a number of experimental observations on the equilibrium of earthen embankments, the stability of stone structures, and other edifices. It puts the physics of granular materials on a foundation that is difficult to contest even today. For instance, it ultimately led to the celebrated Coulomb laws of dry friction between solids, which in time would be extended to granular materials (Duran, 2000).

In the latter part of the nineteenth century, Osborne Reynolds had already distinguished himself in the field of hydrodynamics (Reynolds, 1885). He also made some fundamental contributions to the theory of granulars around the year 1885. Some concepts he developed, notably dilatancy and his analysis of slanted embankments remain high on the list of modern topics of investigation (Duran, 2000).

The number of scientists and engineers who have devoted their talents to this discipline has grown steadily during the twentieth century, particulary since the 1950s. One individual deserves to be singled out. His name is Ralph A. Bagnold. Between 1940 and 1970, he made many important observations (Bagnold, 1954, 1956) and wrote a book on desert sands that became a classic (Bagnold, 1941).

1.4 Review of former studies

1.4.1 Experimental studies

Early experiments were performed by Savage and Sayed (1984) and Hanes and Inman (1985) in which high shear rates were applied in annular Couette granular flows. Hanes and Inman concluded that the shear flow of granular-fluid materials demonstrate quadratic dependence of stresses on the mean shear rate. A schematic of the experimental device used by Hanes and Inman is presented in Figure 1.1(a). They also concluded that stresses are weakly dependent on the solid volume fraction of up to approximately 0.5. Above this solid volume fraction, the stresses were reported to be strongly dependent on the solid volume fraction.

The concept of force chains was materialized by Cundall and Strack (1979) and Liu et al. (1995) which was continued later by a number of experimental works (Miller et al., 1996; Howell et al., 1999b; Peters et al., 2005). Miller et al. observed large fluctuations in the normal stress signal. They reported that fluctuations can be over two orders of magnitude larger than the mean stress. Such large fluctuations have significant implications on the validity of continuum models commonly used in the study of granular materials. Miller et al. measured the distributions of stress time series, which have a general form resembling distributions derived from a microstructural model of idealized granular arrays known as the q-model. Howell et al. (1999a) performed a series of experiments in two dimensions to characterize force fluctuations in slowly sheared systems. Miller et al. concluded that force distributions measured from the three-dimensional (3D) stress time series are qualitatively consistent with exponential fall-off at large stresses. A schematic of the experimental device used by Miller et al. is presented in Figure 1.1(b).

Mueth et al. (2000) and Mueth (2003) used the Magnetic resonance imaging (MRI) technique to study particles in a sheared layer several grain diameters thick and determine the internal mass flow with sub-grain-size spatial resolution. Mueth et al. used a Couette cell consisting of two coaxial cylinders, where the inner cylinder was rotated at a constant angular velocity. Tardos et al. (2002) performed similar experiments for powders and found that both the grain velocity and the granular temperature or the magnitude of the strain-rate fluctuations decay exponentially from the moving wall.

Dalton and Corcoran (2001) and Dalton et al. (2005) examined the statistics of stick-slip motion in a slowly sheared granular medium, including the size, energy, and duration of events. Dalton and Corcoran demonstrated that the statistics are consistent with scale-invariant behavior over several decades, and suggest that their origin lies within a self-

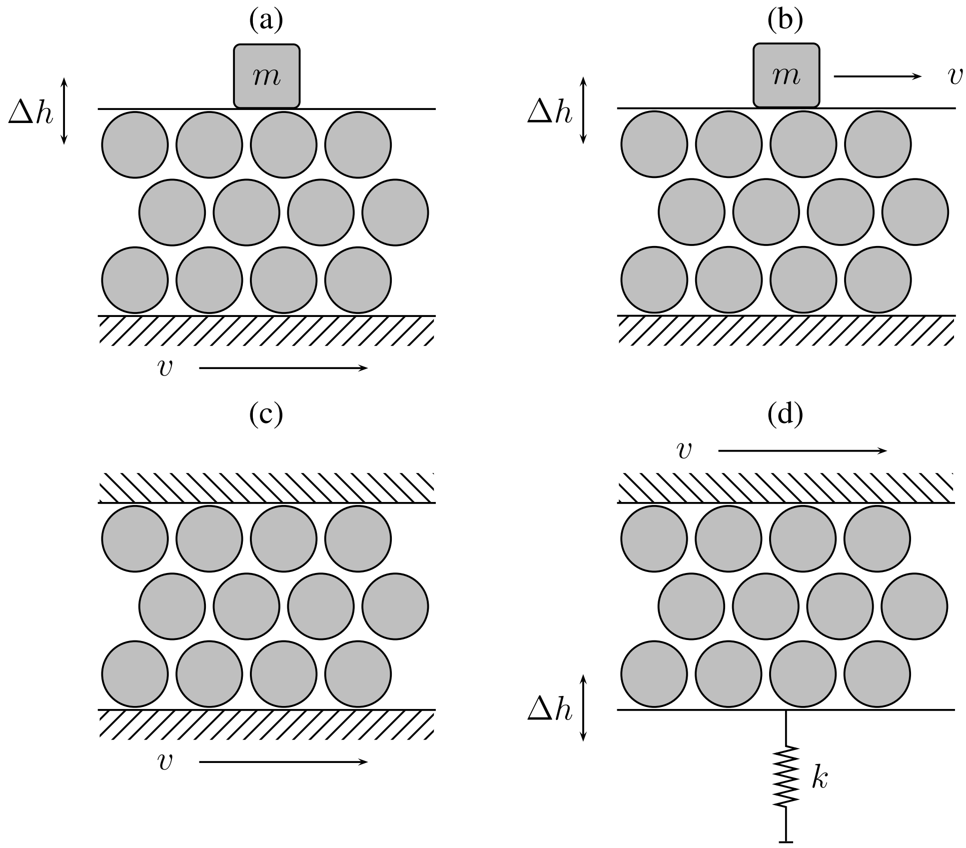

Figure 1.1: Schematics of different types of experimental devices used to study granular shear flow. (a) and (b) represent constant load devices, where compaction and dilation are allowed. The difference between (a) and (b) is whether the system is sheared at the top or from the bottom surface. (c) Constant volume shear cell. (d) The annular shear cell used in the present study. In the present experimental device the bottom surface is also allowed to tilt.

organized critical process. Their experiments were constant load experiments and the schematic of the type of the device is presented in Figure 1.1(b).

Tsai et al. (2003) investigated experimentally a quasi-static flow of glass beads packed and sheared in a 3D annular shear cell. These experiments were constant load experiments with a fluid in the pour space and the schematic of the type of the device is presented in Figure 1.1(b). Tsai (2004) utilized techniques of refractive-index-matched fluorescent imaging, particle tracking, and simultaneous measurements of volume and boundary shear force.

Hsiau and Yang (2004) studied the flow behavior of granular materials in a three-dimensional shear cell in constant volume fashion. An image processing technology and a particle tracking method were employed by Hsiau and Yang to measure fluctuation velocities and the self-diffusion coefficient. In addition, Hsiau and Yang measured normal and shear stresses along the upper boundary. The schematic of the type of the device is presented in Figure 1.1(c).

Although a number of investigations have been done for measuring overall conditions and stress fluctuations in static or slowly-sheared granular media (Losert and Kwon, 2001; Utter and Behringer, 2004), there is a limited number of works on rapid dense granular flows where higher shear rates are employed.

1.4.2 Computer simulations

Given the inherent limitations in performing reliable and exhaustive experiments, significant attention has been devoted in recent years to the simulation of granular flows in a variety of geometries and flow situations. Usually, such simulations are based on models derived from molecular dynamics (MD).

Campbell (1985) simulated a simple two-dimensional (2D) shear flow and compared the results with the constitutive models for the Couette flow. Later Schöllmann (1999) and Latzel et al. (2000) performed MD simulations for a 2D Couette shear cell with bidisperse material. They compared the simulation results and experimental results concluding that MD simulations are a suitable tool to reproduce the main features of granular shear flow in a Couette geometry. Aharonov and Sparks (2002) used a discrete element method (DEM) to simulate two-dimensional polydisperse granular shear flow. Aharonov and Sparks pointed out the distinct modes of deformation where the transition is controlled by confining pressure, shear velocity, and layer thickness. Aharonov and Sparks termed these modes as fluid-like and solid-like modes. Other notable computer simulations in Couette shear flow in two or three dimensions have been performed by Savage and Dai (1993), Louge (1994), Lun and Bent (1994), Jalali (2000), Jalali et al. (2003), and Baran and Kondic (2005).

References

Aharonov, E. and Sparks, D. (2002). Shear profiles and localization in simulations of granular materials. *Physical Review E*, 65, p. 051302.

Bagnold, R.A. (1941). *The physics of blown sand and desert dunes*. New York: William Morrow & Co.

Bagnold, R.A. (1954). Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluids under shear. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 225(1160), pp. 49–63.

Bagnold, R.A. (1956). The flow of cohesionless grains in fluids. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 249(964), pp. 235–297.

Baran, O. and Kondic, L. (2005). Velocity profiles, stresses, and Bagnold scaling of sheared granular system in zero gravity. *Physics of Fluids*, 17(7), p. 073304.

Campbell, C.S. (1985). Computer simulation of granular shear flows. *Journal of Fluid Mechanics*, 151, pp. 167–188.

Coulomb, C.A. (1773). Essay on the rules of Maximis and Minimis applied to some problems of equilibrium related to architecture. *Memoir de Mathématique et de Physique*, 70, p. 343.

Cundall, P.A. and Strack, O. (1979). A discrete numerical model for granular assemblies. *Géotechnique*, 29(1), pp. 47–65.

Dalton, F. and Corcoran, D. (2001). Self-organized criticality in a sheared granular stick-slip system. *Physical Review E*, 63(6), pp. 061312–061315.

Dalton, F., Petri, A., and Pontuale, G. (2005). Stress fluctuations and the solid/fluid transition in a sheared granular bed. In: García-Rojo, R., Herrmann, H., and McNamara, S., eds, *Powders and Grains*, pp. 353–355. Stuttgart, Germany, Jun. 18-22, 2005.

Daniels, K.E. and Behringer, R.P. (2005). Hysteresis and competition between disorder and crystallization in sheared and vibrated granular flow. *Physical Review Letters*, 94(16), p. 168001.

De Gennes, P. (1991). *Soft Matter*.

Duran, J. (2000). *Sands, Powders, and Grains: an introduction to the physics of granular materials*. New York: Springer-Verlag, Inc. ISBN 0-387-98656-1.

Edwards, S.F. and Grinev, D.V. (2003). Statistical mechanics of granular materials: stress propagation and distribution of contact forces. *Granular Matter*, 4(4), pp. 147–153.

Edwards, S. (2005). The full canonical ensemble of a granular system. *Physica A*, 353, pp. 114–118.

Erikson, J.M., Mueggenburg, N.W., Jaeger, H.M., and Nagel, S.R. (2002). Force distributions in three-dimensional compressible granular packs. *Physical Review E*, 66, p. 040301.

Goldenberg, C. and Goldhirsch, I. (2004). Small and large scale granular statics. *Granular Matter*, 6(2-3), pp. 87–96.

Hanes, D.M. and Inman, D.L. (1985). Observations of rapidly flowing granular-fluid materials. *Journal of Fluid Mechanics*, 150, pp. 357–380.

Howell, D., Behringer, R.P., and Veje, C. (1999a). Stress fluctuations in a 2D granular Couette experiment: A continuous transition. *Physical Review Letters*, 82(26), pp. 5241–5244.

Howell, D.W., Behringer, R.P., and Veje, C.T. (1999b). Fluctuations in granular media. *Chaos*, 9(3), pp. 559–572.

Hsiau, S.S. and Yang, W.L. (2004). Transport property measurements in shear granular flows. *Chemical Engineering Science*, 60, pp. 187–199.

Jalali, P., Li, M., Ritvanen, J., and Sarkomaa, P. (2003). Intermittency of energy in rapid granular shear flows. *Chaos*, 13, pp. 434–443.

Jalali, P. (2000). *Mass transfer and particle interactions in granular systems and suspension flows*. Ph.D. thesis. Lappeenranta University of Technology, Espoo, Finland.

Latzel, M., Luding, S., and Herrmann, H.J. (2000). Macroscopic material properties from quasi-static, microscopic simulations of a two-dimensional shear-cell. *Granular Matter*, 2(3), pp. 123–135.

Liu, C.H., et al. (1995). Force fluctuations in bead packs. *Science*, 269, pp. 513–515.

Losert, W. and Kwon, G. (2001). Transient and steady-state dynamics of granular shear flows. *Advances in Complex systems*, 4(4), pp. 369–377.

Louge, M.Y. (1994). Computer-Simulations Of Rapid Granular Flows Of Spheres Interacting With A Flat, Frictional Boundary. *Physics of Fluids*, 6(7), pp. 2253–2269.

Lun, C.K.K. and Bent, A.A. (1994). Numerical-Simulation Of Inelastic Frictional Spheres In Simple Shear-Flow. *Journal of Fluid Mechanics*, 258, pp. 335–353.

Miller, B., O'Hern, C., and Behringer, R.B. (1996). Stress Fluctuations for Continuously Sheared Granular Materials. *Physical Review Letters*, 77(15), pp. 3110–3113.

Mueth, D.M. (2003). Measurements of particle dynamics in slow, dense granular Couette flow. *Physical Review E*, 67, p. 011304.

Mueth, D.M., et al. (2000). Signatures of granular microstructure in dense shear flows. *Nature*, 406, pp. 385–389.

Peters, J.F., Muthuswamy, M., Wibowo, J., and Tordesillas, A. (2005). Characterization of force chains in granular material. *Physical Review E*, 72(4), p. 041307.

Reynolds, O. (1885). On the dilatancy of media composed of rigid particles in contact. *Philosophical Magazine*, 20, pp. 469–481.

Savage, S.B. and Dai, R. (1993). Studies Of Granular Shear Flowswall Slip Velocities, Layering And Self-Diffusion. *Mechanics of Materials*, 16(1-2), pp. 225–238.

Savage, S.B. and Sayed, M. (1984). Stresses developed by dry cohesionless granular material sheared in an annular shear cell. *Journal of Fluid Mechanics*, 142, pp. 391–430.

Schöllmann, S. (1999). Simulation of a two-dimansional shear cell. *Physical Review E*, 59, pp. 889–899.

Tardos, G.I., McNamara, S., and Talu, I. (2002). Slow and intermediate flow of a frictional bulk powder in a Couette geometry. *Powder Technology*, 131, pp. 23–39.

Tsai, J.C. (2004). *Evolution and internal dynamics of quasi-statically sheared granular flows*. Ph.D. thesis. University of Pennsylvania.

Tsai, J.C., Voth, G.A., and Collub, J.P. (2003). Internal granular dynamics, shear induced crystallization, and compaction steps. *Physical Review Letters*, 91(6), p. 064301.

Utter, B. and Behringer, R.P. (2004). Transients in sheared granular matter. *European Physical Journal E*, 14(4), pp. 373–380.