SYMPOSIUM BB

The Granular State

April 24 – 27, 2000

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* Invited paper

SESSION BB1: GRANULAR STRUCTURE I
Chair: Eiichi Fukushima
Monday Morning, April 24, 2000
Franciscan I (Argent)

8:30 AM *BB1.1
JAMMING - GLASSES, FOAMS, AND GRANULAR MATTER. Corey S. O'Hern, UCLA and University of Chicago; Stephen A. Langer, NIST; Andrea J. Liu, UCLA; Sidney R. Nagel, University of Chicago, IL.

We study the properties of a variety of systems that become jammed due either to loading effects or to thermal quenching. We give plausibility arguments that there exists a generalized phase diagram that relates glass formation in supercooled liquids to jamming in granular materials and foams. As a particular example of the similarities that we may observe, we present data on the distributions of normal forces between adjacent particles in these different systems. We compare the data with the predictions of the q-model of Coppersmith et al. and with the predictions of a calculation based on liquid-state theory.

9:00 AM BB1.2
GRANULAR MATTER: A LIQUID? A FRAGILE SOLID? A NONLINEAR ELASTIC SOLID? Hernan Makse, David Johnson and Lawrence Schwartz, Schlumberger-Doll Research, Ridgefield, CT.

Granular materials are known to display a variety of fascinating properties, different from those of either conventional liquids or solids. In this talk I will review current work on these two aspects of granular materials: I will discuss the response of granular materials to external perturbations. Effective medium theories (EMT) are the usual tools used to describe this kind of problems. However, we show that EMT fails in granular materials, and we propose suitable modifications to the theory. Part of the problem with EMT is that granular materials at low confining pressures behave as a "fragile solid" supporting only loads compatible with the microstructure of the packing, and deform with severe rearrangements otherwise. As the pressure is increased, the packing shows a behavior reminiscent of conventional elastic solids. We show that friction generated forces play a crucial role for the stability of the system.

9:15 AM BB1.3
A LOW-FREQUENCY FORCED TORSION PENDULUM FOR THE MEASUREMENT OF THE FAILURE LIMIT OF A GRANULAR MEDIA. G. D'Anna, W. Benoit, IGA, EPFL, Lausanne, SWITZERLAND.

We present a forced torsion pendulum apparatus designed to measure the dynamic moduli of a granular medium. The apparatus works at low-frequency, typically 1Hz, and provides information about the quasi-static properties of the medium. In particular, a peak in the loss factor is ascribed to friction and adhesion between the grains, and a measure of the macroscopic failure limit can be obtained.

10:00 AM BB1.4
RANDOM PACKING OF SPHERICAL AND NON-SPHERICAL HARD PARTICLES. Frank B. van Swol, Sandia National Laboratories, Catalytic and Porous Materials Dept. and The University of New Mexico, Department of Chemical and Nuclear Engineering, Albuquerque, NM.

The random packing of mixtures of spherical particles and mixtures of nonspherical particles is a topic that is of great interest in a variety of areas, including ceramics, energetic materials and thermal management composites. It is not uncommon to encounter specific problems that revolve around the general question of how to determine the optimal particle size distribution for a given application. Experimentally, this is an enormous challenge as the number of variables (size ratios and molefraction) is very large. Recently, we have developed a new modeling approach that uses a limited number of moments of a size distribution to characterize mixtures. We performed new molecular dynamics and Monte Carlo simulations for both spherical hard particles that specifically test this distribution moments approach. For these simulations we present the detailed results which include random close packing fraction and the structural analysis in terms of Voronoi Polyhedra and orientational order parameters and discuss the applicability of the distribution moments. The generalization to nonspherical particles can be made in many ways. Here we will consider two kinds of novel models 1) deformable particles consisting of a collection of tethered spheres, and 2) parallelpipeds (or blocks). Tethered spheres can be studied using highly efficient molecular dynamics techniques, while blocks require Monte Carlo methods. We present new simulations for both these models.

10:15 AM BB1.5
GEOMETRY AND MECHANICS OF ELLIPSE GRANULATES. K. Nikolaj Berntsen and Ove Ditlevsen, Technical Univ of Denmark, Dept of Structural Engineering and Materials.

Molecular dynamics simulation of assemblies of a large number of small rigid or elasto-plastic particles is a promising method to study the mechanical behavior of granular materials. With the increase of computer power it has been possible to advance from the simulations of plane assemblies of circles as done by Cundall and Strack (1979) to simulation of plane assemblies of ellipses. Circles have the property that they tend to form crystalline or poly-crystalline packings. Such packings are very different from the disordered packings obtained for other particle shapes. The elliptical shape is a convenient generalisation of the circular shape by only requiring one extra parameter for its definition. By variation of this parameter the change of the properties of the particle assembly in dependence of particle shape can be studied ranging from the disk to the very narrow long particle. The paper reports about the geometric properties (coordination number, packing, distribution of normals, orientations etc.) and the mechanical properties (force networks, distributions of forces, relations between stress components) of granular ellipse assemblies formed by mass-drop (several particles dropped simultaneously) or by dripping one particle at a time. Knowledge about these properties is valuable in connection with formulation of continuum theories from first principles (as exemplified in e.g. Chang and Gao (1995)), or when seeking divine inspiration for suggesting continuum theories in the line of thought of Janssen (1895). A surprising observation from the simulations is that the crystallisation effect is stronger for almost circular ellipses than for circles. Another important observation is that the statistical distribution of the contact forces between the particles is invariably well modeled by a Gamma-distribution (i.e. a powerlaw distribution with an exponential tail), as also reported in the literature for simulations of disks and measured in experiments with spheres. The work is in a preliminary state.

10:30 AM BB1.6
INVESTIGATION OF PARTICULATE SYSTEMS USING OPTICAL PATH-LENGTH SPECTROSCOPY. Gabriel Popescu, Aristide Dogariu, School of Optics/CREOL, Univ. of Central Florida, Orlando, FL.

In many industrial applications involving granular media, knowledge about the structural transformations suffered during the industrial process is desirable. Optical techniques are noninvasive, fast, and versatile tools for monitoring such transformations. We have recently introduced optical path-length spectroscopy as a new technique for random media investigation. The principle of the method is to use a partially coherent source in a Michelson interferometer, where the fields from a reference mirror and the sample are combined to obtain an interference signal. When the system under investigation is a multiple-scattering medium, by tuning the optical length of the reference arm, the optical path-length probability density of light backscattered from the sample is obtained. This distribution carries information about the structural details medium. In the present paper, we apply the technique of optical path-length spectroscopy to investigate inhomogeneous distributions of particulate dielectrics such as ceramics and powders. The experiments are performed on suspensions of systems with different solid loads, as well as on powders and suspensions of particles with different sizes. We show that the methodology is highly sensitive to changes in volume concentration and particle size and, therefore, it can be successfully used for real-time monitoring. In addition, the technique is fiber optic-based and has all the advantages of versatility associated with it.

10:45 AM BB1.7
MIE SCATTERING IN GRANULAR MATERIALS - GLASSES AND SUPERCONDUCTORS. Tuck Choy, NCTS, Hsinchu, TAIWAN.

The theory of Mie scattering is important to granular materials such as polycrystalline silicon, glasses and granular superconductors. It has wide applications and in the regime of low fractional volume, many established results have been found to be in good agreement with experiments. For systems with larger fractional volumes however, multiple scattering corrections become significant and so far no good theory has been developed to account for these effects. We shall discuss an effective medium based approach and compare its agreement to experiments and numerical studies. Various technological applications and their associated problems will be presented.

11:00 AM BB1.8
MATERIALS CHARACTERIZATION OF SPRAY DRIED CERAMIC POWDERS. Chiaki Miyasaka, Bernhard R. Tittmann and Lili Jia Department of Engineering Science and Mechanincs, The Pennsylvania State University, University Park, PA.

Spray drying is a process used in the manufacturing of ceramic powders. Each granule of the ceramic powder has a structure comprising ceramics and organic binders. The binders are mostly segregated on the suface of the granule. This segregation is assumed to cause processing defects (e.g., pores). However, since the distribution behavior of the binders within the granule is hard to visualize by conventional microscopes such as optical microscopes (including laser scanning microscopes), scanning electron microscopes, and scanning acoustic microscopes, this assumption has not been proved with strongly supported science evedence. In this presentation, techniques are provided to visualize the distribution of spray dried granules using the ultrasonic-atomic force microscopy (U-AFM). The specimens were vibrated by ultrasonic waves, where the frequencies of the ultrasonic waves ranged up to 0.5 MHz. The topological image, the amplitude image, and the phase image were simultaneously obtained by scanning the surface of the specimen by a cantilever. Moreover, the contrast mechanisms are provided with a new modeling approach for the specimen, including boundary interfaces.
Finally, the distibution was confirmed by a nano-indentation technique.

SESSION BB2: GRANULAR FLOWS I

Chair: Sidney R. Nagel
Monday Afternoon, April 24, 2000
Franciscan I (Argent)

1:30 PM *BB2.1

NUCLEAR MAGNETIC RESONANCE STUDIES OF GRANULAR FLOWS - CURRENT STATUS. Stephen A. Altobelli, Arvind Caprihan, Eiichi Fukushima, Joseph D. Seymour, New Mexico Resonance, Albuquerque, NM.

Flow characteristics of granular materials are important because many industrial processes require that granular material be moved in an orderly (and inexpensive) fashion from one location to another. Nuclear magnetic resonance (NMR) is a non-intrusive method that can characterize not only the particulate density but also velocity and velocity fluctuation parameters. I will review the current status of the use of NMR to study granular flows. Following that, a new NMR scheme will be presented that yields spatial distributions of collisional correlation times for macroscopic particles undergoing granular flow. It is based on Pulsed-Gradient Spin-Echo strategy that is commonly used to measure molecular diffusion in liquids. The scheme will be demonstrated with an example from shear flow in a partially-filled horizontal cylinder.

2:00 PM BB2.2

BUBBLING AND LARGE-SCALE STRUCTURES IN AVALANCHE DYNAMICS. Vittorio Loreto, Supriya Krishnamurthy, P.M.M.H. Ecole Supérieure de Physique et Chimie Industrielles, Paris, FRANCE; Stéphane Roux, Unité Mixte de Recherche CNRS/Saint-Gobain, Aubervilliers Cedex, FRANCE.

Using a simple lattice model for granular media, we present a scenario of self-organization that we term self-organized structuring where the steady state has several unusual features: (1) large scale spatial and/or temporal inhomogeneities and (2) the occurrence of a non-trivial peaked distribution of large events which propagate like “bubbles” and have a well-defined frequency of occurrence. We discuss the applicability of such a scenario for other models introduced in the framework of self-organized criticality.

2:15 PM BB2.3

AVALANCHE DYNAMIC: INFLUENCE OF THE GRANULAR PACKING DIMENSIONS. Maria A. Aguirre, Nicolas Nerone, Adriana Calvo, Grupo de Medios Porosos, Facultad de Ingenieria, Universidad de Buenos Aires, Buenos Aires, ARGENTINA; Irene Ippolito, Daniel Bideau, Groupe Matiere Condensee et Materiaux, Université de Rennes 1, Rennes, FRANCE.

We report an experiment which studies different regimes on the surface flow and on the avalanche dynamic of a granular packing depending on its dimensions. A thin packing shows an avalanche process that behaves like a bouncing flow and a thick packing presents a creeping flow. Packing presenting both types of flows are found in the transition regime. Above a certain critical number of layers Nc, the avalanche characteristics are independent on the packing height. Nevertheless Nc strongly depends on the packing length. Experiments are done, for monosize glass beads packings of different sizes and number of layers. The influence of the granular packing dimensions and the roughness of the bottom bed on other avalanche parameter, such as its mass and the critical angles at which it begins and stops, are also studied.

3:00 PM BB2.4

THE DYNAMICS OF AVALANCHING BEAD CHAINS. Michael Bretz, Alberto Rojo, Dept of Physics, University of Michigan, Ann Arbor, MI.

Avalanche studies of granualar materials have traditionally used spherical grains, although the dynamics of misshapen sand grains, elongated rice grains, flat disks, etc. have also been explored. Here, we describe the 2D avalanching of flexible metal bead chains cut to various lengths, from 1 to 13 beads, and long bead chain polymers. We explore changes in avalanche profile, size distribution, the onset of caking with chain length and assess emergent behavior within the various bead beds (microcrystallinity, void formation, chain rolling and compaction issues).

3:15 PM BB2.5

SURFACE FLUCTUATIONS AND THE INERTIA EFFECT IN SANDPILE AVALANCHES. Nicolas Nerone, Alejandra Aguirre, Adriana Calvo, Dept. de Fisica, Fac. de Ingenieria, Univ. de Buenos Aires, ARGENTINA; Irene Ippolito, Daniel Bideau, GMCM, Univ. Rennes I, FRANCE.

We report an experiment on a granular packing: a box filled with a certain number of layers of glass beads is tilted very slowly up to the maximum angle of stability where a big avalanche is produced. The avalanche decreases the slope of the free surface of the packing until a second critical angle is reached: the angle of repose. During the build up period many rearrangements occur on the free surface of the packing. Digital imaging was used to study these rearrangements. The size of these rearrangements presents a noisy structure in time and the distribution function for the observed mass fluctuations follows a power-law behavior that last for almost two decades. However, this power-law description breaks down in the limit of big rearrangements where inertia effects are not negligible and an increase in the probability is observed. We reproduce these results within the framework provided by the sandpile cellular-automata model developed by Prado and Olami in which inertia effects are taken into account. It is the purpose of this work to study the transition between static and flowing states in a very slowly driven granular system. We will focus on the very rich behavior of the surface rearrangements leading up to an avalanche.

3:30 PM BB2.6

AVALANCHE STRATIFICATION - EXPERIMENTAL TESTS OF THE METASTABLE WEDGE AND CONTINUOUS FLOW MODELS. M.E. Swanson, M. Landreman, J. Michael and J. Kakalios, The University of Minnesota, School of Physics and Astronomy, Minneapolis, MN.

Recent experimental studies of size stratification of binary mixtures of granular media poured into a quasi two-dimensional vertical Hele-Shaw cell have led to the proposal of at least two distinct models to account for this phenomenon.[1-3] In the continuous flow (CF) model [1], stratification occurs due to differences of the local angles of repose of each granular species, leading to different thresholds for rolling and stopping along the free surface. [3] The metastable wedge (MW) model, on the other hand, assumes that stratification occurs only when the granular material contained in a previously stationary wedge, determined by the angle of repose and the larger maximum angle of stability, begins to avalanche down the free surface.[2] In this paper experimental results are described which indicate that the MW model provides a better explanation for the initiation of stratification, the CF model best describes the kinetics of layer growth and that both models are needed to account for the pairing of stratified layers [2] observed for certain flow rates and Hele-shaw cell plate separations. Supported by the University of Minnesota, U.R.O.P. and the NSF-R.E.U. program.

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[2] J.P. Koeppe, M. Enz and J. Kakalios, Phys. Rev. E, 58, R4104 (1998).
[3] T. Boutreaux and P.-G. deGennes, J. Phys. I (France) 6, 1295 (1996); T. Boutreaux, H.A. Makse and P.-G. deGennes, Eur. Phys. J. B 7 (in press).

3:45 PM *BB2.7

THICK SURFACE FLOWS OF GRANULAR MATERIALS. Achod Aradian, Elie Raphael, Pierre-Gilles de Gennes, Laboratoire de Physique de la Matiëre Condensee, College de France, Paris, FRANCE.

A few years ago, Bouchaud *et al.* introduced a phenomenological model to describe surface flows of granular materials. According to this model, one can distinguish between a static phase and a rolling phase that are able to exchange grains through an erosion/accretion mechanism. Boutreux *et al.* proposed a modification of the exchange term in order to describe thicker flows where saturation effects are present. However, these approaches assumed that the downhill

convection velocity of the grains is constant inside the rolling phase, a hypothesis that is not verified experimentally. In this presentation, we therefore modify the above models by introducing a velocity profile in the flow, and study the physical consequences of this modification in the simple situation of an avalanche in an open cell. We present a complete analytical description of the avalanche in the case of a linear velocity profile, and generalize the results for a power-law dependency. We show, in particular, that the amplitude of the avalanche is strongly affected by the velocity profile.
*Phys. Rev. E **58**, 4692 (1998).

4:15 PM BB2.8
SOLUTION OF SOME PROBLEMS OF SANDPILE EVOLUTION.
T. Elperin, A. Vikhansky, The Pearlstone Center for Aeronautical Engineering Studies, Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beer-Sheva, ISRAEL.

The study concerns with two problems of sandheap formation, namely, sandpile growth on an arbitrary rigid support surface due to an external source of granular material and flow of granular material in a three dimensional rotating container (see Refs. [1], [2]).
Generally the problem of sandpile evolution is formulated as follows. Let a cohesionless granular material with a constant bulk density ρ be poured down onto a rigid support surface with a profile $z = h_0(t,x,y)$ and forms a heap with a free boundary $z = h(t,x,y)$. The support surface can either be stationary or rotates as a solid body and produces flow of the granular material as it take place in tumbling mixers. The granular material has a constant angle of repose α, i.e., $(\nabla h)^2 \leq \tan^2(\alpha) = \gamma^2$.
The mass of the material which falls onto the surface area element dxdy during time interval dt is ρ w(t,x,y)dtdxdy, where ρ w(t,x,y) is the surface density of the external source of granular material. The problem is to determine the time dependence of the height of a granular pile h(t,x,y). Assume that flow of the granular material take place only in a thin boundary layer and that it occurs if and only if
$(\nabla h)^2 = \gamma^2$ (1)
Denote the horizontal projection of the mass flux density per unit area by $\rho\bar{q}$. In the present study we assumed that the flow is directed toward the steepest descent of the heap, i.e., $\bar{q} = k\nabla h$, where k(t,x,y) ≥ 0 is an unknown function. Since the bulk density of granular material is a constant, the mass conservation law can be written as follows:
$Dh/Dt + \bar{\nabla}\cdot\bar{q} = Dh/Dt - \bar{\nabla}\cdot(k\nabla h) = w$ (2)
where $D(\bullet)/Dt$ is a substantial derivative. Note, that the direct solution of the Eqs. (1), (2) with respect to the two unknowns k and h is a very complicated problem. In order to overcome this difficulty a more convenient variational form of the energy conservation law was proposed. The obtained system of variational inequalities was applied for the investigation of the pile growth on a number of rigid support surfaces, water transport and formation of lakes.
When the granular material is tumbled in an ellipsoidal container which is rotated around its nonprincipal axis the free surface of the granular material is flat and the Eqs. (1), (2) can be reduced to a system of two ordinary differential equations. In this case a three dimensional periodic flow field is developed in the container which produce an intensive material transport in the axial direction.
References
[1] T. Elperin and A. Vikhansky, Numerical Solution of the Variational Equations for Sandpile Evolution, *Physical Review* **E55**, 5785 (1997).
[2] Elperin T. and Vikhansky A., Granular Flow in a Three Dimensional Rotating Container, *Europhys. Lett.*, 1999 (submitted).

4:30 PM BB2.9
DRAG FORCE IN GRANULAR MEDIA.
Albert-László Barabási, I. Albert, R. Albert, M.A. Pfeifer, P. Tegzes, B. Kahng, J.G. Sample, T. Vicsek and P. Schiffer, University of Notre Dame, Department of Physics, Notre Dame, IN.

It is common to draw an analogy between granular media (e.g. sand) and liquids, since both conform to the shape of their containers and can be poured when their containers are tipped. A natural extension is to consider the analog of viscous drag in granular media, since objects moving through either a granular medium or a fluid will encounter a resistive drag force. Here we calculate analytically and investigate experimentally the resistive drag force on an object which moves horizontally through a static granular medium. We demonstrate that the drag force on a cylinder which extends from above into a granular medium is linearly dependent on the diameter of the cylinder, quadratically dependent on the length extending below the surface, and is independent of the velocity of the moving object. Furthermore, we show that the drag force exhibits stick-slip fluctuations with time, displaying a periodic pattern for small depths and an aperiodic pattern for large depths. We analyze the statistics of the fluctuations and discuss the origin of the transition from the periodic to the aperiodic regime.

SESSION BB3: NONLINEAR WAVES IN GRANULAR MEDIA
Chair: Harry L. Swinney
Tuesday Morning, April 25, 2000
Franciscan I (Argent)

8:30 AM *BB3.1
NEW WAVE DYNAMICS IN GRANULAR STATE.
Vitali F. Nesterenko, University of California, San Diego, Dept of Mechanical and Aerospace Engineering, La Jolla, CA.

Granular state is challenging us with the necessity to develop a qualitatively new wave dynamics. The unusual feature of this state is the negligible linear range of the interaction force between neighboring particles resulting in zero or very small sound speed in uncompressed or weakly compressed case (sonic vacuum). This makes weakly nonlinear continuum approach based on Korteveg de Vries equation invalid. The presentation will demonstrate the attempt to fill existing gap between weakly nonlinear continuum approximation and corresponding discrete system. Examples of materials with this unusual behavior include not only initially unstressed granular materials but also unstressed chains of particles or molecules in transverse motion, systems such as jointed rocks and other examples. Periodic waves, compression solitary and shock waves for these materials are qualitatively different from weakly nonlinear case. For example the spatial extent of compression solitons does not depend on amplitude, and initial sound speed does not determine the soliton parameters if strain in the wave is much greater than its initial value. The generalization of the results obtained for granular materials with Hertz interaction law as well as experimental results on wave propagation and wave interaction with contact of different granular materials will be presented. Special aspects of dynamic behavior of granular materials outside of continuum description will be emphasized.

9:00 AM BB3.2
SIGNAL PROPAGATION IN NONLINEAR GRANULAR CHAIN.
Jongbae Hong, Jeong-Pil Hwang, Seoul National Univ, Dept of Physics, Seoul, KOREA.

A soliton damps due to gravity when it is created in the vertical granular chain by impulse. We find that the type of damping is power-law in depth or time. We show that there are two types of propagating modes, such as quasisolitary and oscillatory according to the strength of impulse. The exponent of the power-law decreases as the strength of impulse increases in the quasisolitary regime. In the oscillatory regime in which the initial impulse is weak, however, the power-law exponent is independent of the strength of the initial impulse. We also show that the equation of motion of the oscillatory mode is nothing more than that of nonuniform transmission line. Some properties of the oscillatory mode can be treated analytically.

9:15 AM BB3.3
IMPULSE AND LOW FREQUENCY ACOUSTIC WAVE PROPAGATION IN GRANULAR BEDS.
Surajit Sen, Marian Manciu, Victoria Tehan, Dept of Physics, State University of New York at Buffalo, Buffalo, NY; Alan J. Hurd, Sandia National Laboratories, Albuquerque, NM.

The study of sound propagation in granular beds at frequencies exceeding a MHz has been a subject of study for many years. Much remains to be learnt about sound propagation at lower frequencies [1]. We shall present our studies on the problem of impulse propagation and of low frequency sound propagation in model granular beds using particle dynamical simulations and analytical methods [2]. The following results will be discussed. (i) Impulses propagating as solitary waves in 1-D granular chains with Hertz contacts in the absence of precompression [3-6]. (ii) The effects of uniform precompression and gravitational loading on wave propagation [7]. (ii) Impulse propagation in 2-D and 3-D granular beds, (iii) The effects of polydispersity and restitution. (iv) Dynamics of low frequency wave propagation in 3-D beds. The research presented shall highlight the intrinsically nonlinear nature of wave propagation in granular beds.
[1] A.J. Rogers and C.G. Don, Location of buried objects by an acoustic impulse technique, Acoust. Austral. 22, pp 5-9 (1994).
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related problems: I. Propagation, Physica A (to appear, 1999).
[7] J. Hong, J-Y. Ji and H. Kim, Power laws in nonlinear granular chain under gravity, Phys. Rev. Lett. 82, pp 3058-3061 (1999).

10:00 AM BB3.4
BACKSCATTERING OF NONLINEAR ACOUSTIC IMPULSES FROM BURIED INCLUSIONS IN GRANULAR BEDS.
Marian Manciu, Surajit Sen, Dept of Physics, State University of New York at Buffalo, Buffalo, NY; Alan J. Hurd, Sandia National Laboratories, Albuquerque, NM.

Nonlinear acoustic impulses travel as weakly dispersive bundles of energy through 3D dry granular assemblies. Such impulses can therefore be exploited to probe for buried objects in 3D granular beds and assemblies [1,2]. The systems are assumed to have polydisperse grains. Restitutional losses are taken into account in the analyses. In the presentation, we shall discuss the details of downward propagation of an impulse generated across a small area at the surface of a granular bed and its subsequent backscattering from buried inclusions in the bed for various degrees of polydispersity of the bed. The calculations will demonstrate that the backscattered data, as received at predetermined locations at the surface, can be used to reconstruct an approximate image of the buried inclusion as it is viewed from above. Comparison of the computer generated image of a buried inclusion with the actual inclusion reveals that nonlinear acoustic impulses may be useful in imaging buried objects.
[1] M.J. Naughton, R.S. Shelton, S. Sen and M. Manciu, in Detection of non-metallic landmines using shock impulses and MEMS sensors, Detection of Abandoned Land Mines, Inst. of Electrical Engineers Conference Publication No. 458, pp.249-252 (IEE, London, 1998).
[2] A.J. Rogers and C.G. Don, Location of buried objects by an acoustic impulse technique, Acoustics Australia 22, pp 5-9 (1994).

10:15 AM BB3.5
ULTRASOUND PROPAGATION IN DISORDERED GRANULAR MEDIA. Xiaoping Jia, Univ Paris 7, Groupe de Physique des Solides, Paris, FRANCE.

Sound propagation in a disordered granular medium is of fundamental interest (multiple scattering) and it also offers a very useful and sensitive probe for studying the structure and mechanical properties of granular materials. Recently we have identified two distinct types of sound transmission through a dry bead packing according to the ratio of the wavelength to the bead size* one corresponds to coherent ballistic waves (compressional and shear) in agreement with the effective medium description based on the Hertz-Mindlin model, the other to multiply scattered waves (acoustic speckles) due to the inhomogeneous stress distribution inside granular media. In this talk, we analyze the viscoelastic properties of dry granular materials via velocity and attenuation measurement of coherent ultrasonic waves. As to acoustic speckles very sensitive to the change of configuration, they are utilized to investigate irreversible rearrangements of the grains in a confined granular packing at rest or induced by cyclic loading-unloading. It is found in this compaction process that the correlation function of multiply scattered sound between successive runs increases when the packing fraction approaches the random close packed limit, indicating an evolution of irreversible behavior of granular media towards more reversible one in the response to external perturbation. Transport characteristics of strongly scattered acoustic waves in granular media will also be addressed.
*Jia, Caroli, Velicky, PRL 82, 1863 (1999).

10:30 AM BB3.6
THE PERFORMANCE OF GRANULAR FILTERS IN ATTENUATING WEAK SHOCK WAVES-SHOCK TUBE EXPERIMENTS AND NUMERICAL INVESTIGATIONS. A. Britan, G. Ben-Dor, O. Igra and H. Shapiro, Department of Mechanical Engineering, Pearlstone Center for Aeronautical Engineering Studies, Ben-Gurion University of the Negev, Beer-Sheva, ISRAEL.

When blast waves from high explosive weapons hit the ground in the vicinity of shelters, protective granular filters reduce their loading on more sensitive and expensive chemical filters and prevent their penetration in the ventilation duct. While these filters are well known as protectors against blast waves, almost no information about their performance can be found in the literature. Among the few papers on this subject the most relevants provide results related to the attenuation of shock waves inside sufficiently long ducts. In practice, when the external framework of the protected structure is close to the filter, any change in the length of the air gap between the filter and the structure can cause variations in the downstream flow pattern and pressure field. Bearing this in mind and owing to the very limited amount of published experimental data in this subject the main purpose of this study was to investigate the dependence of the granular filter performance on:
- the length of the filter - L,
- the length of the air gap downstream of the filter - Δ,
- the diameter of the beads composing the filter - d_p,
- the density of the beads composing the filter - P_ρ,
- the roughness of the side-walls of the filter

The experimental part of this study was conducted in a vertical shock tube. For the series of numerical calculations a well established and validated filtration model of the gas flow through the granular filter was employed. First the dynamics of the gas pressure upstream and inside the filter and behind the transmitted shock wave downstream of the filters were investigated. The filter length and composition were varied in a wide range. Then, the effects caused by the end-wall presence and the air gap length were checked. Thereafter the experiments and calculations were repeated to reveal new features that arise when this filter is placed directly at the end wall. The obtained data are aimed at providing the basis for the proper design of the protection of not only shelters and other high-priority military and civilian assets, but also for combustion suppressers, protective shields and munitions storage facilities.

10:45 AM BB3.7
LINEAR AND NONLINEAR ULTRASONIC PROPERTIES OF GRANULAR SOILS. B.P. Bonner, P.A. Berge, C.M. Aracne-Ruddle, H. Bertete-Aguirre, D. Wildenschild, C.N. Trombino and E.D. Hardy, Univ of California, Lawrence Livermore National Laboratory, Livermore, CA.

Wave propagation in natural granular media applies to a range of problems in near-surface geophysics and environmental engineering. The conventional ultrasonic pulse transmission method was adapted to measure compressional (P) and shear (S) wave velocities for highly attenuating quartz-clay and quartz-peat mixtures at ultrasonic frequencies (100-500 kHz). Velocities were determined as samples were loaded by small (up to 0.1 MPa) uniaxial stress to determine how stress at grain contacts, compaction, adhesion and capillarity affect wave amplitudes, velocities, and frequency content. Samples were fabricated from Ottawa sand mixed with either a swelling clay (Wyoming bentonite) or peat (natural cellulose). P velocities in these dry synthetic soil samples were low, ranging from about 230 to 430 m/s for pure sand, about 91 to 420 m/s for sand-peat mixtures, and about 230 to 470 m/s for dry sand-clay mixtures. S velocities were about half of the P velocity in most cases, about 130 to 250 m/s for pure sand, about 75-220 m/s for sand-peat mixtures, and about 88-220 m/s for dry sand-clay mixtures. These experiments demonstrate that P and S velocities are sensitive to the amount and type of admixed second phase, even at low concentrations. We found that dramatic increases in all velocities occur with small uniaxial loads, indicating strong nonlinearity of the acoustic properties. Adhesion, capillarity, and grain packing all contribute to the micromechanics at grain contacts and the nonlinear response at low stresses.
This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

11:00 AM BB3.8
RHEOLOGY OF A VERTICALLY PUSHED GRANULAR COLUMN. Evelyne Kolb, Guillaume Ovarlez, Eric Clement, Laboratoire des Milieux Desordonnes et Heterogenes, Universite Pierre et Marie Curie, Paris, FRANCE.

We study the rheology of a granular material confined in a vertical cylinder and pushed at a constant driving velocity. The resistance force encountered by the bottom piston is monitored while the piston is pushing the granular column upwards. Above a critical velocity, the motion is characterized by a steady sliding and by a force level increasing rather slowly with the pushing velocity. For driving velocities under this threshold, the system undergoes a dynamical instability and then, a stick-slip motion occurs. The amplitude of the slipping events, and thus, the elastic energy release, increase strongly as the velocity reaches values as small as the typical velocities of tectonic plates (cm/year). The onset of instability below a given driving velocity is reminiscent of solid-on-solid friction experiments and this regime was already observed in experiments done with beads confined in a 2 dimensional cell. The critical velocity depends on the stiffness of the driving system and on the height of the granular column. This transition can be shifted towards higher velocity values by increasing the friction at the walls of the cylinder. It is also very sensitive to the state of compaction of the grains. Moreover, the mean energy release during a stick-slip motion seems to increase as a power-law when the pushing velocity is decreased. We also show that the distribution of energy release is strongly dependent on the level of disorder in the grains (polydispersity, friction, etc.). We argue that this complex phenomenology characterizes confined granular packing in connection with arching and aging phenomena.

11:15 AM BB3.9
UNSTEADY HEAT CONDUCTION IN GRANULAR MATERIALS.
W.L. Vargas and J.J. McCarthy, University of Pittsburgh, Department of Chemical Engineering, Pittsburgh, PA.

Heat transfer in granular materials impacts a variety of industrial applications, such as calcination, drying kilns, packed bed and multiphase reactors, etc. and may yield insight into the thermal response of some porous materials (in combustion synthesis or sintering, for example). In a dense bed of granular material, conduction occurs almost exclusively through the particle-particle contacts over a wide range of conditions. The contact area – through which conduction occurs – is proportional to the normal force between the particles ($A \propto F_n^{1/3}$ for smooth, elastic particles; $A \propto F_n^{1.0}$ for rough contacts). For this reason, stress inhomogeneities and differences in bed microstructure (which affect the contact size and distribution) are expected to play an important role in granular heat conduction. We have developed a novel Thermal Particle Dynamics (TPD) Simulation technique which incorporates both contact mechanics and contact conductance theories in order to model the dynamics of flow and heat conduction in granular materials. This model is uniquely suited to studying the effects of microstructure and flow on the dynamics of heat conduction in particulate materials. In this paper, we present experimental as well as numerical results of transient heat conduction through a bed of spheres under conditions of varying load.

11:30 AM BB3.10
IMPULSE ACOUSTICS BASED EJECTION OF FERROFLUID GRAINS FROM A FERROFLUID: THE BLUEPRINT OF A CONCEPT FOR A NOZZLE-FREE INKJET PRINTER.
Felicia S. Manciu, Marian Manciu and Surajit Sen, Dept of Physics, State University of New York at Buffalo, Buffalo, NY.

We present numerical simulations to demonstrate that it may be possible to eject ferrofluid grains from a ferrofluid using non-linear acoustic impulses. The study considers a container with some dilute ferrofluid that is placed in a strong, vertical, homogeneous magnetic field. The field induces the formation of magnetic dipoles into vertical chains that connect the base and the surface of the container. We show that an impulse generated at the base of these chains, will typically travel as a weakly dispersive bundle of energy. When the impulse magnitudes are appropriate (typically about 60 m/s or more), the ferrofluid grain nearest to the surface of the liquid will be ejected by the impulse. Since all ferrofluid grains possess a coating of the liquid host, the ejected grain can be used as an ink-drop. The velocities of the ejecting grains can be controlled and hence the method, if experimentally feasible, may have wide ranging applications. One of these applications is likely to be in designing nozzle-free inkjet printers of unprecedented resolution.

SESSION BB4: GRANULAR FLOWS
Chair: Robert P. Behringer
Tuesday Afternoon, April 25, 2000
Franciscan I (Argent)

1:30 PM *BB4.1
MATERIAL INSTABILITY IN RAPID GRANULAR SHEAR FLOW.
J.D. Goddard, Department of Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, CA.

This is a survey of recent theoretical work on shear flow instabilities of dry granular medium in the Bagnold or grain-inertia régime. Attention is devoted to steady homogeneous unbounded simple shear, with the goal of identifying *material* or constitutive instabilities arising from the coupling of stress to granular concentration and temperature fields. Such instabilities, the dissipative analogs of thermodynamic phase transitions, are familiar in numerous branches of the mechanics of materials.
The current interest is motivated in part by the dissipative clustering found in various particle-dynamics (DEM) simulations of granular systems. Since particle clustering may invalidate standard gas kinetic theory, it is pertinent to ask whether hydrodynamic models based on such theories may themselves exhibit clustering instability.
The present talk is based largely on a recent review [1], which provides a unified linear-stability treatment for rapid granular flow, as well for slow flow of mobile particles suspended in viscous liquids. The analysis is based on a short-memory response of various fluxes to perturbations on steady uniform states, a feature characteristic of the most popular constitutive models for granular flow. In the absence of gravity, the theoretical analysis reveals transverse layering and spanwise corrugations as possible forms of material instability.
Based on current theoretical findings, further work is recommended, including the exploration of the effects of gravity and of stress relaxation, both of which are likely to be important in real granular flows.
[1] J.D. Goddard and M. Alam, 1999, Shear-Flow and Material Instabilities in Paticulate Suspensions and Granular Media. *Particulate Science and Technology*, **17**, 69-96.

*Work supported in part by NASA Grant NAG3-1888 and NSF Grant CTS-9510121.

2:00 PM BB4.2
CONSTITUTIVE EQUATIONS FOR DENSE GRANULAR FLOW.
Deniz Ertaş, Thomas C. Halsey, Exxon Research and Engineering, Annandale, NJ; Dov Levine, Technion, Haifa, ISRAEL; Gary S. Grest, Leo E. Silbert, Sandia National Laboratories, Albuquerque, NM.

The constitutive relation relating stress to strain rate for dense granular flow is constrained by rotational invariance, the lack of dimensional parameters in the Bagnold grain inertia regime, and the existence of a Mohr-Coulomb failure criterion for the initiation of flow. We find that in order to recover the phenomenology of such flows as seen, e.g., in numerical simulations, we must postulate implicit constitutive equations in which the stress tensor appears to higher than the first power. We calibrate these constitutive equations using simulations of spherical particles with realistic contact interactions in the chute geometry. We find that the continuum description works very well beyond 6 to 8 layers of grains from free surfaces or walls, and that local stresses are influenced by vorticity as well as by the symmetrized strain rate.

2:15 PM BB4.3
ANALYSIS OF SHEAR BANDS IN SLOW GRANULAR FLOWS USING A FRICTIONAL COSSERAT MODEL.
Prabhu R. Nott, L. Srinivasa Mohan, K. Kesava Rao, Indian Institute of Science, Dept of Chemical Engineering, Bangalore, INDIA.

The slow flow of granular materials is often marked by the existence of thin shear layers, adjacent to large regions that suffer little or no deformation. In flow through channels or tubes, for example, shearing occurs only in a thin layer adjacent to the walls while a large central core moves as a plug. This behaviour, in the regime where shear stress is generated primarily by the frictional interactions between grains, has eluded theoretical description. Most existing models based on the classical continuum do not predict the occurrence of shear layers, at variance with experimental observations. This feature has been attributed to the absence of a material length scale in their constitutive equations. In this paper, we present a rigid-plastic frictional Cosserat model that captures thin shear layers by incorporating a microscopic length scale. We treat the granular medium as a Cosserat continuum, which allows localised couple stresses and the possibility of an asymmetric stress tensor. We present results for flow in vertical channels, as well as for shear between two parallel plates with and without the presence of gravity. The velocity profile predicted by our model is in close agreement with available experimental data. The predicted dependence of the shear layer thickness on the width of the channel is also in reasonable agreement with data. Most significantly, classical rate-independent frictional models are unable to predict the velocity field in viscometric flows, while our model can.

3:00 PM *BB4.4
GRANULAR FLOWS: A SOMEWHAT PERSONAL PERSPECTIVE.
Charles S. Campbell, Univ of Southern California, Los Angeles, CA.

This talk will try and summarize 20 years of research into the flow behavior of granular materials. As such, it will try and follow the changing points of view on granular behavior, as reflected in the lecturer's own work. Most of the examples will come from discrete particle computer simulation studies. The early work will be centered in the area of rapid granular flow theory that blossomed in the 1980's. This theory is based on the kinetic theory of gases and treats individual particles as molecules that move randomly according to a granular temperature. Examples will include studies of heat, mass and momentum transfer as well as the definition of appropriate boundary conditions for rapid-flow problems. However, as time went on, it became clear that few granular applications can be modeled using rapid -flow theory. For the lecturer, this first became apparent in studying the phase change that occurs between fluid and solid-like behavior and became more apparent in further studies of landslides and hopper flows, non of which operate in the rapid-flow regime. The lecture will conclude with a presentation of some very recent investigations into the rheology of the quasistatic and transitional regime.

3:30 PM BB4.5
DISCHARGE FROM A LIQUID-FILLED HOURGLASS.
Benson Muite, Melany Hunt, California Institute of Technology, Div of Engineering and Applied Science, Pasadena, CA.

The current experiments investigate the effects of fluid and particle properties on the discharge of a granular material in an hourglass containing a Newtonian liquid. This study is applicable to two-phase flows with a relative velocity difference, such as occurs in mining and

oil production, and in slurry or debris flows. The experiments were performed with uniformed-sized glass beads in glycerin-water mixtures and with lead shot in silicon oil. The particle diameters ranged from 0.6mm to 4mm. The cylindrical hourglasses had a constant cross sectional area above the neck with a half-angle of 15, 30 or 90 degrees. As the hourglass discharged, position-time curves were recorded from digitized images of the interface between the pure liquid and particle bed. The experimental results indicated that the non-dimensional discharge speed is a function of Grashof number, which depends on the density of the two phases, the particle diameter, the fluid viscosity and gravity. In addition, the observed flow patterns may differ from that found in a discharging dry hourglass. Besides the Grashof number, these regimes depend on the hopper half angle and the ratio of orifice diameter to particle diameter.

3:45 PM BB4.6
EFFECT OF POLYDISPERSITY ON STRESSES AND CLUSTERING IN GRANULAR SHEAR FLOW. Meheboob Alam, University of Colorado at Boulder, Department of Chemical Engineering, Boulder, CO; Richard Clelland, University of Colorado at Boulder, Department of Mathematics, Boulder, CO; Christine M. Hrenya, University of Colorado at Boulder, Department of Chemical Engineering, Boulder, CO.

Over the past decade, gas-solid continuum models based on a kinetic-theory description of particle interactions have enjoyed widespread success. In particular, such models have been shown not only to predict the salient features associated with gas-solid flows (e.g., particle segregation toward wall in vertical flows, turbulence modulation due to the presence of particles), but have also compared well with available experimental data. To date, essentially all of the proposed models have been limited to monodisperse systems. However, the majority of practical applications involve a polydisperse particle phase. Although a distribution of particle sizes may simply be a property of the starting material, oftentimes a particular distribution is desired in order to improve flow behaviour. As part of an overall effort to determine the effects of polydispersity on gas-solid flows, the focus of the current work is to examine the effects of multiple particle sizes on a simpler system, namely a granular flow system. To accomplish this, molecular-dynamics simulations are performed for the simple shear flow of smooth, inelastic disks, focussing on the effect of polydispersity on the stresses and the clustering phenomena. Simulations are conducted for both a binary mixture and other polydisperse media. Lees-Edward boundary conditions are used in the transverse direction to attain the state of simple shear. It is known from similar studies on monodisperse granular flows[1,2] that such systems are prone to the formation of inhomogeneities (clusters) which, in turn, can significantly affect the mean-fields like stresses[3]. To isolate the effect of polydispersity on the mean fields, the presence of clusters is minimized by performing simulations at high values of the coefficient of restitution. For a binary mixture, the total volume fraction and the size ratios are varied, and the predicted stresses are compared with existing kinetic theory models[4,5]. Furthermore, the effect of polydispersity on "clustering" is ascertained by performing simulations at a lower value of e_p. Preliminary results (in the dilute regime) indicate the effect of different particle size distributions on the mean field stresses and the clustering phenomena.

[1]M.A. Hopkins and M.Y. Louge, 1991, Inelastic microstructure in rapid granular flows of smooth disks, *Phys. Fluids A* **3**, 47.
[2]I. Goldhirsch and G. Zanetti, 1993, Clustering instability in dissipative gases, *Phys. Rev. Lett.* **70**, 1619.
[3]E.D. Liss and B.J. Glasser, 1998, The effect of microstructure on stress in a sheared granular material. *AIChE Annual Meeting*, Miami.
[4]J.T. Jenkins and F. Mancini, 1987, Balance laws and constitutive relations for plane flows of a dense, binary mixture of smooth, nearly elastic, circular disks, *J. Appl. Mech.* **54**, 27.
[5]J.T. Willits, and B.O. Arnarson, 1999, Kinetic theory for a binary mixture of nearly elastic disks, *Phys. Fluids* **11**, 3116.

4:00 PM BB4.7
A NONEQUILIBRIUM APPROACH FOR SELF-DIFFUSION IN UNBOUNDED RAPID GRANULAR FLOWS. Payman Jalali, Piroz Zamankhan, Lappeenranta Univ. of Technology, Dept. of Energy Technology, Lappeenranta, FINLAND; William B. Polashenski, Lomic, Inc., PA.

A nonequilibrium simulation scheme is introduced to investigate the transverse diffusive motion in unbounded shear flows of smooth, monodisperse, inelastic spherical particles. A certain labeling algorithm is used in this scheme to extract a one-way particle mass flux which results a concentration gradient for the labeled particles. The self-diffusion coefficient can then be obtained from Fick's law. Using this scheme, one may find that the self-diffusion phenomenon across any layer inside the granular shear flow is analogous to the classic diffusion problem across a membrane. Under steady conditions, the current simulation results revealed that the particle diffusivity can be described by a linear law. This finding justifies the assumption of a linear law relationship in the kinetic theory type derivation of an expression for self-diffusivity. Moreover, it is shown that the results of self-diffusion coefficient obtained from the computer simulations are in agreement with the predictions of kinetic theory formulations in the range of solid volume fractions less than 0.5.

4:15 PM BB4.8
PARTICLE FLUCTUATION VELOCITY IN GAS FLUIDIZED BEDS: FUNDAMENTAL MODELS COMPARED TO RECENT EXPERIMENTAL DATA. George D. Cody, Rutgers Univ, Dept Mechanical and Aerospace Engineering, Piscataway, NJ.

The mean squared velocity fluctuation of particles or granular temperature T* in gas fluidized beds was only recently measured by: Acoustic Shot Noise (ASN) excitation of the wall of the fluidized bed by random particle impact[1], and Diffusing Wave Spectroscopy (DWS) of multiply scattered laser light[2]. The measurements differ in: (a) Technique: ASN employs structure borne sound - DWS, the scattering of laser light; (b) Localization: ASN measures T* at the wall as an average over the wall, - DWS measures T* at one location averaged over 7 particles, (c) Geometry: ASN experiment has a glass cylindrical structure - DWS, a rectangular structure. Both use monodispersed glass spheres. Remarkably, T* for both agrees within 10% in the Geldart B regime which bubbles at fluidization. Equally remarkable, the ASN T* data is about 7x larger than the DWS data in the Geldart A regime which fluidizes before bubbling. We compare these data with a theory due to Buyevich[3] which derives T* from a pseudo-turbulent Langevin model for steady state particle motion driven by random particle impacts. The agreement between this theory and both experiments in Geldart B suggests remarkable promise in capturing the physics of these complex systems with only one parameter, the collisional energy loss. In Geldart A, both the agreement between Buyevich and the DWS data and the disagreement of both with the ASN data, can be understood if we assume that random shear fluctuations contribute significantly to T* at small diameters. The sensitivity of shear fluctuations to circulation flow and hence bed geometry would then account for the difference found in the Geldart A. This conclusion, if validated by further research, will impact both theory and experiment of the steady state value of T* in the gas fluidized state of small diameter particles.
[1] G.D. Cody et al., Powder Technology 87, 211-232 (1996), Dynamics in Small Confining Systems-3, MRS Proc, 464, pp. 325-338 (1997).
[2] N. Menon, D.J. Durian, Phys. Rev. Lett. 79, 3407-3410 (1997).
[3] Y.A. Buyevich, Ind. Eng. Chem. Res. 38, 731-743 (1999), Int. J.

SESSION BB5: VIBRATED AND ROTATED GRANULAR MEDIA

Chair: Joe D. Goddard
Wednesday Morning, April 26, 2000
Franciscan I (Argent)

8:30 AM *BB5.1
DYNAMICS OF GRANULAR MEDIA IN EXPERIMENTS, PARTICLE SIMULATIONS, AND KINETIC THEORY. Harry L. Swinney, C. Bizon, M.D. Shattuck and J.B. Swift, Univ of Texas at Austin, Austin, TX.

Experiments on vertically oscillated granular layers reveal a variety of spatial patterns, including hexagons, stripes, and squares. These patterns are reproduced well by event-driven molecular dynamics simulations that simply assume that the particles are hard spheres that conserve momentum but dissipate energy in collisions [1]. The results from simulations are then used to test kinetic theory predictions for a dissipative hard sphere gas. The kinetic theory analysis assumes a Maxwell-Boltzmann velocity distribution and that the particle velocities are uncorrelated. The simulations yield a velocity distribution function close to a Maxwell-Boltzmann distribution over three orders of magnitude in velocity, but large velocity correlations are found to exist [2]. Despite the velocity correlations, the calculated transport coefficients compare well with the kinetic theory predictions. *Research supported by the Engineering Research Program of the Office of Basic Energy Sciences of the Department of Energy.
[1] C. Bizon, M.D. Shattuck, J.B. Swift, W.D. McCormick, and H.L. Swinney, Phys. Rev. Lett. 80, 57 (1998).
[2] C. Bizon, M.D. Shattuck, J.B. Swift, and H.L. Swinney, Transport coefficients for granular media from molecular dynamics simulations, http://xxx.lanl.gov/abs/cond-mat/9904132, Phys. Rev. E, to appear.

9:00 AM BB5.2
FROM PUDDLING TO HEAPING TO CRACKING - ORDERED AND DISORDERED RELIEFS IN VERTICALLY VIBRATED LIQUID-SATURATED GRANULAR MATERIAL. Johann M. Schleier-Smith[1], Howard A. Stone[2], Harvard University. [1]Department of Physics [2]Division of Engineering and Applied Sciences, Harvard Univ, Cambridge, MA.

Vertical vibrations are known to induce patterning instabilities in various fluid and fluid-like systems. Well known examples include the Faraday instability in viscous and nonviscous fluids and the patterned relief observed in dry granular systems. We study the vibrational instability in flat layers of granular material saturated with interstitial liquid and bounded above by an air interface. Increasing acceleration amplitude leads first to the accumulation of puddles of liquid on the surface, followed by a transition to a convecting heaping relief. This convective heaping phenomenon bears similarity to that observed in a granular system in a completely aqueous environment*. However, our system is quite different due to the air interface and because we study relatively thin layers of granular material, with a thickness of 20-50 diameters, rather than hundreds of diameters. While the heaping relief we observe is generally disordered, under some conditions heaps arrange themselves into a regular and robust pattern. At higher drive accelerations heaps show fissures and the hilly relief gives way to cracking and violent breakup. We report on the phase portrait in critical acceleration vs. frequency for the transitions to heaping and to cracking.

*V.G. Kozlov, A.A. Ivanova, and P. Evesque, Sand behavior in a cavity with incompressible liquid under vertical vibrations, *Europhysics Lett.*, 42(4):413-418, 1998.

9:15 AM BB5.3
PARTICLE NUMBER RATIO EFFECTS ON SIZE SEGREGATION IN GRANULAR BEDS SUBJECT TO VERTICAL VIBRATION.
C.R. Wassgren and D.N. Fernando, School of Mechanical Engineering, Purdue University, West Lafayette, IN.

Size segregation of particulates is of concern in a number of industries that handle materials such as chemicals, pharmaceuticals, fertilizers, and food products. Of particular interest in this paper is segregation resulting from externally applied vibration. In industrial applications this vibration may either be applied intentionally in devices such as vibrating conveyors or live wall hoppers, or unintentionally during material handling and transport. Previous studies concerning segregation in vibrated beds have investigated the effects of particle size ratio, vibration parameters, and boundary effects. These studies, however, have focused on the behavior of a single impurity within an otherwise mono-disperse system. This paper investigates how the particle number ratio in a binary mixture affects size segregation in granular beds subject to vertical vibration.

10:00 AM *BB5.4
FRICTION AND FLOW IN GRANULAR MATERIALS.
R.P. Behringer, L. Kondic, G. Metcalfe, D. Schaeffer and S. Tennakoon.

We focus on the transition to flow in granular materials. We use a novel shaking apparatus that allows us to vibrate a granular layer in the horizontal and vertical directions independently. Also, we can fluidize the layer by a stream of air injected from below. With this system, we have studied the transition from a static layer (in the shaker frame) to a sloshing layer. The relevant parameters include the accelerations in each direction. For pure horizontal shaking, the transition is hysteretic, and requires a model beyond the usual Coulomb model of static and dynamic friction to explain the hysteresis and the observed transition time scales. For mixed horizontal and vertical shaking, a static inclined layer precedes the sloshing state, as explained by Coulomb friction.

10:30 AM BB5.5
FLOW OF GRANULAR MATERIAL THROUGH ROTATING CYLINDERS: MODELLING TRANSIENTS.
Richard J. Spurling, John F. Davidson, David M. Scott, Univ of Cambridge, Dept of Chemical Engineering, Cambridge, UNITED KINGDOM.

Granular material, fed continuously into the top of a slowly rotating, slightly inclined cylinder, forms a moving bed. The bed rotates with the cylinder in solid body motion. When particles reach the bed's surface, they move rapidly down it, and are absorbed once more into the solid body motion. Such cylinders are used in calcining, pharmaceutical manufacture, and drying. A steady state transport model, applicable when the bed depth varies slowly along the cylinder, has existed for around 50 years. The bed surface is considered locally flat, and particles in it fall along the line of steepest descent, inclined to the horizontal at the angle of repose. There is reasonable agreement with experiment, but there are deviations for large and small inventories. We propose a quasi-steady state dynamical model, in which the steady state model is coupled with a volume balance across an axial element. The model takes the form of a nonlinear diffusion equation which was solved numerically. The parameters of the dynamic model are the dimensions of the cylinder and outlet dam, the inclination of the axis of the cylinder, its rotational speed, the angle of repose of the granular material and its feed volumetric flow rate: the dynamic model has no free parameters. Experiments were conducted using sand, mean particle size 500 microns, in a perspex tube of length 1 m, diameter 0.103 m, lined with sandpaper, with a feed end dam of height 0.029 m, and with no exit dam, or an exit dam of height 0.0105 m. With the system in steady state, step changes in feed flow rate or rotational speed have been imposed, and the resulting discharge flow rate and bed depth axial profile have been measured as a function of time. Excellent agreement is found between theoretical values and experimental results.

10:45 AM BB5.6
GRANULAR MIXING AND DIFFUSION IN A GALTON'S DEVICE.
Luciana Bruno, Adriana Calvo, Dept. of Physics, School of Engineering, Univ. of Buenos Aires, ARGENTINA; Irene Ippolito, Daniel Bideau, GMCM, Univ. Rennes I, Rennes, FRANCE.

Mixing of granular materials is difficult because commonly used mixing methods can lead to undesired segregation. However, granular mixing is a central feature of many processes in the food, pharmaceutical, paper, steel, and rubber industries. Diffusion is the mixing mechanism that takes place when two different fluids come into contact. In this case, the random movement of molecules due to collisions causes the mixing. Then, one question arises: can we understand granular mixing as analogous with diffusion in liquids or gasses? Diffusional mixing of a granular system differs from that of fluids systems in many important respects, being the most important, the lack of particulate motion equivalent to molecular diffusion; i.e. there is no relative movement of particles without an energy input. If we can design a mixer that gives the grains the necessary energy to flow and, at the same time, changes randomly their velocities, we will, in principle, simulate the diffusive movements of molecules in a liquid or a gas. Based on these ideas, we study experimentally the 2D flow of a granular material through a dispersive medium: a Galton's device. It consists in a regular array of obstacles that deflect the grains in random directions. The flow is gravity driven. Mixing and diffusive properties of this device are studied.

11:00 AM BB5.7
COEXISTENCE OF GRANULAR MIXTURE PHASES IN NEARLY-FILLED ROTATING CONTAINERS.
David T. Wu, Depts of Chemical Engineering & Chemistry, Colorado School of Mines, Golden, CO; Cunkui Huang & Masami Nakagawa, Particle Science & Technology Group, Div of Engineering, Colorado School of Mines, Golden, CO.

We have previously reported segregation in binary mixtures of large and small particles in nearly-filled rotating cylinders and disks. In these systems, there is very little room for surface-controlled segregation (for instance in a flowing surface layer), leaving open the possibility for other mechanisms that drive the system towards both radial and axial segregation. These experiments may also be relevant for understanding segregation in partially-filled systems where segregation can also occur in non-flowing regions (such as the cylindrical core in axial segregation). Here we present studies on nearly-2-dimensional rectangles (25cm $\times$ 6cm $\times$ 0.47cm) rotating about the long horizontal axis. The rectangle is 95% filled with approximately half 2mm and half 4mm balls. During the course of rotation, the pattern first flows axially, then enters a mixing phase, and finally settles into a relatively stable horizontally banded pattern, with the outer phase consisting of nearly 100% small particles, while the inner band consists of a mixture of large and small particles. Remarkably, the composition of the mixed phase appears to be a function of the particle diameters only, and not the initial amounts of large versus small balls. This observation is consistent with our previously reported idea that in these slowly-agitated (non-flow driven) systems, the particles undergo a slow but ergodic rearrangement. The final composition of the mixed phase then corresponds to a point where the entropic fluxes driving small particles into and out of the mixed region are balanced. Such a local condition then gives a mechanism consistent with a composition that depends only on the particle diameters. We present theoretical estimates of the steady-state composition, and compare with experiment.

11:15 AM BB5.8
PATTERN FORMATION IN IMPACTED LAYERS OF GRAINS: APPLICATION TO THE GRANULAR FARADAY INSTABILITY.
Eric Clement, Laurent Labous, Laboratoire des Milieux Desordonnes et Heterogenes, Universite Pierre et Marie Curie, Paris, FRANCE.

We study numerically the dynamical evolution of an impacted bidimensional layer of dissipative grains. We show that the dynamics can be decomposed into two phases. First, a collision wave regime consisting of a fast upwards compression followed by a downwards expansion, this regime is very dissipative. Thereafter, the next regime is a slow expansion in vacuum. We study the scaling behavior the density and the temperature profiles as well as the velocity gradients, as a function of the impact velocity, the layer height and the restitution coefficient. During the expansion phase, a pattern is selected corresponding to a density modulation with a characteristic wavelength. Moreover, we study in detail the selection mechanism occurring the so-called granular Faraday, instability produced by the vertical vibrations of a granular layer. We evidence two distinct regimes of wavelength selection. A first regime for which we propose a relationship between wavelength and frequency this regime is shown to cross over to a second saturation regime where the wavelength depends only on the number of layers. We relate the previous dissipative wavelength to the structure selected in the Faraday instability at saturation.

11:30 AM BB5.9
MIXING AND SEGREGATION PROCESSES IN TURBULA BLENDER. Nathalie Sommier, Université Paris Sud and Lab MSSM, Ecole Centrale Paris, Chatenay-Malabry, FRANCE; Patrice Porion, CRMD, Orléans, FRANCE; Pierre Evesque, Lab MSSMat, Ecole centrale de Paris, Chatenay-Malabry, FRANCE.

Magnetic Resonance Imaging (MRI) techniques have been used to study the mixing and segregation processes of granular materials in Turbula mixer using binary mixtures of sugar beads of different diameters d. When the ratio R of bead diameters is approximately $R = 1$ mixing process is observed, but segregation occurs as soon as $R \leq 0.9$ or $R \geq 1.1$. Furthermore, segregation develops faster than mixing and is induced by surface effect. We report in this paper, a qualitative and quantitative analysis of these phenomena; their dependences upon different parameters(beads diameter ratio, speed rotation, mixing time, concentration, filling ratio) have been determined. Flow properties have been investigated using Poincaré section technique. It is demonstrated that this device is an efficient separator of particles of slightly different size. A theory will be proposed to understand these features.

SESSION BB6: STRESS DISTRBUTIONS
Chair: Vitali F. Nesterenko
Wednesday Afternoon, April 26, 2000
Franciscan I (Argent)

1:30 PM *BB6.1
STATISTICAL MECHANICS OF STRESS TRANSMISSION IN STATIC ARRAYS OF RIGID GRAINS. Dmitri Grinev, Sam Edwards, University of Cambridge, Cavendish Laboratory, Cambridge, UNITED KINGDOM.

We develop the statistical-mechanical theory that delivers the fundamental equations of stress equilibrium for static arrays of rigid cohesionless grains. The random geometry of a static granular packing composed of rigid cohesionless particles can be visualized as a network of intergranular contacts. The contact network and external loading determine the network of intergranular forces. In general, the contact network can have an arbitrary coordination number varying within the system. It follows then that the network of intergranular forces is indeterminate i.e. the number of unknown forces is larger than the number of Newton's equations of balance. Thus, in order for the network of intergranular forces to be determined, the number of equations must equal the number of unknowns. This can be achieved by choosing the contact network with a certain fixed coordination number. The complete system of equations for the stress tensor is derived from the equations of intergranular force and torque balance, given the geometric specification of the packing. The stress-force equation is the analogue of the Euler-Cauchy relation. The granular material fabric gives rise to corrections which become significant at mesoscopic lengthscales. The stress-geometry equation establishes the relation between various components of the stress tensor, and depends on the topology of the granular array. The problem of incorporating the "no tensile forces" constraint into the formalism is considered. The inability of an intergranular contact to support tensile forces constrains the geometry and the stress state of the contact network. We establish a link between the structural component of the angle of repose and the packing fabric.

2:00 PM BB6.2
RESPONSE FUNCTIONS IN GRANULAR PILINGS. Eric Clement, Guillaume Reydellet, Guillaume Ovarlez, Loic Vanel, Evelyne Kolb, Laboratoire des Milieux Desordonnes et Heterogenes, Universite Pierre et Marie Curie, Paris, FRANCE.

We present the results of different experiments which aim is to investigate the response of a static granular assemblies to various local perturbations. A first series of experiments probe the response of a localized charge at the top of a granular piling. The piling is an horizontal 3D granular assembly confined in a box and the spatial distribution of loads at the bottom is monitored as a function of the average confining pressure and the amplitude of the localized surcharge. In addition, we present some results on a bidimensional model piling where we investigate, using image analysis techniques, the deformation of the piling in response to a localized deformations. This analysis defines some crucial experimental test to inform a currently debated issue on the mechanical status of static and quasi-static granular assemblies.

2:15 PM BB6.3
THEORY AND SIMULATION OF STRESS CORRELATIONS AND RESPONSE FUNCTIONS IN GRANULAR PILES. David T. Wu and Tawiwan Kangsadan, Dept of Chemical Engineering and Dept of Chemistry, Colorado School of Mines, Golden, CO.

There has been a growing focus on the distribution of forces in static granular media, and its relation to the particle spatial distributions, interactions, and polydispersity. Many of these approaches are based on underlying lattices, possibly decorated with random interactions. In real systems, the disorder is often linked to size polydispersity, especially in two dimensions, or geometric packing disorder. The disorder associated with packing of particles, however, involves the shape and sizes of the particles, which then affects the associated local ordering or texture–and hence the vectorial nature of the contact network. We present here simulation results on mono- and polydisperse nearly-hard disks in two-dimensions, in an effort to analyze the connection between particle packing geometry and force distributions. We consider here the case of particles without friction (which can qualitatively affect the resulting force networks), and focus on the effect of packing disorder. Our numerical results are analyzed in terms of a theory based on the stress response function (to a small perturbing force in the pile). In the limit of strong stiffness (hardness of the particle), the response function is shown to reflect a heirarchy of force dependencies (chains), and to depend on the boundary conditions. We present a vectorial theory for the stress response function whose input are the particle sizes, based on the idea of an averaged local vector repartitioning of the stress as controlled by the particle packing distribution, and compare the theory to our simulation results.

3:00 PM BB6.4
PERSISTENCE OF GRANULAR STRUCTURE DURING DIE COMPACTION OF CERAMIC POWDERS. William J. Walker, Jr. and James S. Reed, New York State College of Ceramics at Alfred University, Alfred, NY.

Die compaction of granulated powder is a common forming process used in the ceramics industry. Granulation of fine powders is necessary to produce the free flowing feed material required for die filling when high-speed presses are used. However, it is desirable to eliminate all artifacts of the granules during the compaction process in order to produce defect-free sintered components. Glass spheres were used as a model system to investigate granule failure during die compaction. Stresses within an assembly of spheres follow a network of pathways. When the spheres are of uniform composition, the magnitude of the stresses within a pair of contacting granules is a function of the locally transmitted stress and the diameter of the two spheres. Results obtained using glass spheres demonstrated the statistical nature of granule failure during compaction, with some granules failing at very low applied pressures while others persist at even the highest applied loads. Within a distribution of granule sizes, those granules with smaller diameter were seen to have a higher probability of failure at low pressure than were larger granules. These results are consistent with those observed in granulated powder systems.

3:15 PM *BB6.5
STRESS DISTRIBUTIONS IN GRANULAR MATERIALS; MEMORY FORMALISM AND ITS INTERPLAY WITH NONLINEARITY. V.M. Kenkre, Center for Advanced Studies and Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM.

Recent work in the theoretical analysis of stress distributions in granular materials undergoing packing, developed on the basis of the formalism of spatial memories [1], will be reviewed. The origin of spatially non-Markoffian equations will be discussed through generalization of constitutive relations as well as through stochastic arguments. Successful application to experiments [2] will be pointed out. Nonlinear wavefronts which can arise from the interplay of memory with nonlinearity and treated through exact solutions via piece-wise linear approximations [3] will be mentioned.
*Work done in collaboration with Alan Hurd, Marek Kus', Joe Scott, and Kiran Manne and with the partial support of the Sandia National Laboratories under Department of Energy Contract DE-AC04-94A85000.
[1] Non-local Analysis of Stress Distribution in Granular Materials: I. Theoretical Framework, V.M. Kenkre, J. Scott, E. Pease and A. Hurd, Phys. Rev. E 57, 5841-5849 (1998).
[2] Non-local Analysis of Stress Distribution in Granular Materials: II.

Comparison to Experiment, J. Scott, V.M. Kenkre and A. Hurd, Phys. Rev. E 57, 5850-5857 (1998).
[3] Nonlinear Waves in Reaction Diffusion Systems: the Effect of Transport Memory, K. Manne, A. Hurd and V.M. Kenkre, submitted to Phys. Rev. E.

3:45 PM BB6.6
A NEW SIMPLE NON LINEAR MODELLING OF THE QUASI STATICS OF GRANULAR MEDIA: PREDICTIONS, COMPARISONS WITH EXPERIMENTS. Pierre Evesque, Lab MSSMat, Ecole Centrale de Paris, Chatenay-Malabry, FRANCE.

In this paper a new simple non linear theoretical modelling of the mechanics of granular media is proposed, based on well known facts. It is used to demonstrate an old result: the value of the Jaky constant $k_{Jaky} = \sigma_3/\sigma_1$ of granular material stresses at rest. It predicts also new features which are observed experimentally indeed. So, in a first part, a simple hypoelastic incremental modelling is derived which fits classical results ; it is used to solve the oedometric-test case. It is found that the σ_3/σ_1 ratio evolves towards an asymptotic value k_o which depends on the friction angle ϕ only. It is shown that this asymptotic value k_o compares well with the experimental fit known as the Jaky constant i.e. $k_{Jaky} = 1 - \sin\phi$. In a second step the compression of granular media at constant volume is predicted from the previous modelling; it is found that the system undergoes a trans-bifurcation at some definite σ_3/σ_1 value; this is due to the non linear character of modelling. Experimental evidence of this bifurcation is demonstrated. The third part studies the topology of the trajectories in the phase space of soil mechanics, i.e. of (v, p', q) i.e. (specific volume, mean inter granular pressure, deviatoric stress) under simple triaxial tests. First, it is recalled that all trajectories under simple triaxial tests end up at a line of attracting point called the critical-state line. The surface of Roscoe (Hvorslev) is defined as the surface made of the last part of the set of trajectories ending to a given critical point and coming from all states of normally consolidated soils (from all states of over consolidated soils). It is demonstrated using dynamical system theory that Hvorslev surface and Roscoe surfaces are two parts of a regular surface. This is in agreement with the reported modelling and with experimental data.

4:00 PM BB6.7
A BALL IN A GROOVE. Thomas C. Halsey, Deniz Ertaş, Exxon Research and Engineering, Annandale, NJ.

We study the static equilibrium of an elastic sphere held in a rigid groove by gravity and frictional contacts, as determined by contact mechanics. As a function of the opening angle of the groove and the tilt of the groove with respect to the vertical, we identify two regimes of static equilibrium for the ball. In the first of these, at large opening angle or low tilt, the ball rolls at both contacts as it is loaded. This is an analog of the elastic regime in the mechanics of granular media. At smaller opening angles or larger tilts, the ball rolls at one contact and slides at the other as it is loaded, analogously with the plastic regime in the mechanics of granular media. In the elastic regime, the stress indeterminacy is resolved by the underlying kinetics of the ball response to loading.

4:15 PM BB6.8
SIMULATIONS OF GRANULAR SYSTEMS: STATICS AND DENSE FLOWS. L.E. Silbert and G.S. Grest, Sandia National Laboratories, Albuquerque, NM; D. Ertas and T.C. Halsey, Exxon Research and Engineering, Annandale, NJ; D. Levine, Technion, Haifa, ISRAEL.

Molecular Dynamics techniques are employed to study the statics and flows of dense granular systems in two and three dimensions. We focus on the effects of particle-scale properties, such as friction and coefficient of restitution, on the macroscopic behaviour of these systems. Relatively simple macroscopic theories can approximately account for our results on chute flows (or flows down inclined planes), which also show good agreement with experiment. We also explore the role of particle friction in determining properties of static particle packings, both with and without container walls; these latter results clarify some of the issues of current controversy.

4:30 PM BB6.9
GRAIN BOUNDARY KINETICS IN GRANULAR MEDIA. Jamie Turner, Mark T. Lusk, Masami Nakagawa, Colorado School of Mines, Golden, CO.

Disordered, two-dimensional assemblies of elastic spheres will order themselves into polycrystalline grains of hexagonal packing when subjected to external excitation. Under continued excitation, the associated grain boundaries will move in a manner reminiscent of coarsening phenomena in solid state systems. A primary goal of our investigation has been to describe the driving force and mobility associated with such grain boundary motion as functions of external excitation, particle constitution, grain misorientation, boundary orientation, and boundary height within the assembly. A series of shake table and discrete element experiments have been performed which help to elucidate the behavior of granular grain boundaries. We first present results showing the ordering and coarsening phenomena. This is followed by a presentation of experimental data associated with a series of bi-crystal experiments. Specifically, a circular internal grain is observed to shrink under external, periodic excitation, and the rate of shrinkage and rate of change of grain misorientation are recorded. The shake table component of this was accomplished using thin elastic molds to form the desired initial state. The shake table and simulation results are compared with the sort of behavior one would expect in a solid state system. This is used to make some initial conclusions about the physical underpinnings of grain boundary motion. An extension to three-dimensional assemblies will also be discussed.

SESSION BB7/GG3: JOINT SESSION:
FROM AVALANCHES TO SANDCASTLES
Thursday Morning, April 27, 2000
Franciscan I (Argent)

8:30 AM *BB7.1/GG3.1
STATISTICS OF AVALANCHES AS FAILURE PRECURSORS. Stéphane Roux, Unité Mixte de Recherche CNRS/Saint-Gobain, Aubervilliers, FRANCE.

We consider the development of damage in quasi-brittle heterogeneous materials, up to global failure. Various statistical models have been developed in this context, from one-dimensional or mean field models such as the fiber bundle model which can be solved analytically, to higher dimensionality models which can be studied numerically. Generically these models give rise to unstable breakdown events called "avalanches". The latters may display a statistical distribution which gives some information on the vicinity of the global failure of the system. In particular, avalanche sizes are power-law distributed with a universal exponent, up to a maximum avalanche size which diverges as the global failure point is approached. Such a behavior is formally reminiscent of critical phenomena where global failure plays the role of the critical point. This scenario is discussed in relation with the concept of self-organized criticality. Enlarging the scope of the models, such a statistics of avalanches can be applied to a wide variety of "depinning" phenomena, and traced back to the statistics of macroscopic driving force fluctuations. In this framework, two different features can account for the algebraic form of avalanches: one is the statistical distribution of the driving force itself, and the second is the time correlations which are present in the driving force signal. Extensions to crack propagation models are discussed. Other related models of thermally activated damage, which exhibits precursor signs to global failure, will also be discussed.

9:00 AM BB7.2/GG3.2
HUMIDITY-INDUCED COHESION EFFECTS IN GRANULAR MEDIA. Nathalie Fraysse, Luc Petit, Laboratoire de Physique de la Matière Condensée, Nice, FRANCE.

Despite the significance and the frequency of humidity effects on granular materials, the knowledge of these effects rests mainly on phenomenological and most of the time only qualitative observations. We have performed experiments under accurately-controlled humidity conditions in order to quantify such moisture-induced effects. We report the measurements of the maximal stability angle and the repose angle of a pile made of small glass beads, as a function of the relative vapor pressure, up to close to saturation. The influence of the wetting properties of the interstitial liquid on the grains was investigated; the comparison of the results obtained with water and heptane shows that the wetting properties have a strong influence on the cohesion of the non-saturated granular medium. In view of this, new experiments have been undertaken in order to obtain information on the liquid bridges that form between grains and give rise to cohesion of the granular medium. Our aim is to understand the close connection that exists, through interparticle forces, between microscopic properties such as wetting properties and surface roughness of the grains, and global-scale properties of the pile, as its stability and flowability.

9:15 AM BB7.3/GG3.3
EXPERIMENTAL STUDY OF INSTABILITY OF LARGE STRAIN FLOW IN DENSE GRANULAR MATERIAL. Vitali Nesterenko, Dept. of Mechanical and Aerospace Engineering, UC San Diego, CA; Richard Klopp, Donald Shockey, Donald Curran and Thomas Cooper, SRI International, CA.

Large strain flow of dense granular materials created by fracture (comminution) of initially solid ceramic is very important for ballistic performance of ceramic armor, penetration into dense rocks and concrete. There is a need for well characterized 2-D and 3-D experiments with dynamic flow of such materials to compare with existing theories and with the results of numerical modeling. Cavity expansion experiments (Klopp, Shockey et al., 1996) and collapse tube experiments - Thick Walled Cylinder (TWC) method (Nesterenko, Meyers et al., 1996) provide date with controlled low and large strain patterns under high dynamic pressures. They address initial and developed stages of penetration process correspondingly. This presentation is focused on the results obtained with the help of taped Thick Walled Cylinder method. In the experiments global hoop strains were in the range 0 - -0.12, and strain rates about 10-4 s-1. Shear localization was a primary mechanism accommodating large strains. Morphology of shear band was very different ranged from sharp crack-like to relatively broad area with large local shear strains accompanied by comminution. Number of localized shear bands does not depend strongly on overall hoop strain in experiments. Comparison of experimental results with results of numerical simulations based on FRAGBED model (Curran et al 1993, 1998) and the possibility to convert TWC approach into truly 3-D method by introducing a highly taped geometry of experiment with large angle of the central rod will be discussed.

9:30 AM BB7.4/GG3.4
DEM APPLICATION TO MIXING AND SEGREGATION MODEL IN INDUSTRIAL BLENDING SYSTEM. Kenji Yamane, Taiho Pharmaceutical Co, Ltd, Quality Control Dept, Tokushima, JAPAN.

To predict the motion of powders and grains is important in pharmaceutical industries. Many pharmaceutical engineers have studied granular flows related to powder mixing. In this study, DEM (Discrete Element Method) approach is presented as an industrial application to investigate the behavior of granular flows. The granular motion in a rotating cylinder was focused on the basic study of DEM for industrial application. Rotating cylinder is a fundamental system for commercial blenders widely used in many industrial processes. In addition, segregation of particles in a rotating cylinder is very interesting phenomena. Not only industrial engineers but also physicists study this segregation mechanism. DEM simulation showed radial segregation of two different size particles in a rotating cylinder. From the viewpoint of calculated granular temperature, radial segregation system was analyzed. Particle migration in axial direction, which is the source for axial segregation, was also shown by DEM simulation.

9:45 AM BB7.5/GG3.5
HOW SANDCASTLES FALL: THE CRITICAL ANGLE OF WET SANDPILES. Thomas G. Mason, Deniz Ertaş, Thomas C. Halsey, Exxon Research and Engineering, Annandale, NJ; Alex J. Levine, University of Pennsylvania, Dept. of Physics, Philadelphia, PA.

Capillary forces induced by small quantities of liquid significantly affect the stability of sandpiles, which makes possible the construction of sandcastles at the beach. We determine the maximum angle of stability of sandpiles as a function of liquid content, theoretically and experimentally. This angle becomes system size dependent in the presence of cohesive forces, as is well known in soil mechanics. The increase in the critical angle with increasing fluid content is controlled by the surface roughness of the particles, as well as by the surface tension of the added fluid, and exhibits three regimes as a function of the added-fluid volume. Theoretical results are in good agreement with experimental observations, which include confocal microscopy of the fluid-filled particle contact regions.

10:30 AM *BB7.6/GG3.6
NEW METHODS FOR SNOW AVALANCHE RISK MANAGEMENT AND FORECASTING. P. Bartelt, Swiss Federal Institute for Snow and Avalanche Research, SLF/ENA, Davos Dort, SWITZERLAND.

The Swiss Federal Institute for Snow and Avalanche Research is responsible for developing technical and organizational measures to prevent avalanche disasters. The institute is divided into two basic sections. The first is the operational avalanche warning service. This unit not only determines the avalanche danger on a day-to-day basis but is also responsible for developing information transfer tools that can be used by avalanche professionals at the local level. The second unit is a research group that studies physics of snow and avalanches. As part of this research, avalanche dynamics models have been developed that track the motion of flowing and powder snow avalanches. These risk management models are used by local communities to prepare hazard maps that delimit land into red (high danger), blue (medium danger) and white (no danger) zones. Numerical models have also been developed to track the development of the snowpack over time. In this presentation we will give a brief overview of the institute and talk about new methodologies (numerical models, forecasting models) that are being applied to prevent catastrophic avalanche disasters.

11:00 AM *BB7.7/GG3.7
WETTING-INDUCED EFFECTS IN GRANULAR MEDIA. P. Schiffer, R. Albert, A.-L. Barabasi, Dept. of Physics, University of Notre Dame, Notre Dame, IN; P. Tegzes, T. Vicsek, Department of Biological Physics, Eotvos University, HUNGARY.

While most studies of granular media focus on the properties of dry materials in which the intergrain forces are purely repulsive, the addition of a thin layer of a wetting fluid adds an attractive force to the system, and therefore a new dimension to the underlying physics. The physics of such a wet granular system is relatively unexplored, and there is no basic understanding of how interstitial liquid affects the granular properties. This problem is of great scientific interest and also practical importance since granular materials relevant to many industrial applications often contain significant liquid between the grains. We investigate the effect of interstitial liquid on the physical properties of granular media both theoretically and experimentally by measuring the angle of repose as a function of the liquid content in a spherical granular medium. We find that that large changes in the physical properties of granular materials can be induced by even a nanometer-scale layer of liquid on millimeter-size grains. The liquid-induced adhesive forces lead to three distinct regimes in the observed behavior as the liquid content is increased: a granular regime in which the grains move individually, a correlated regime in which the grains move in correlated clusters, and a plastic regime in which the grains flow coherently. The qualitative properties of the different regimes can be understood within the framework of two different proposed theories: the surface stability theory of Albert et al. and the bulk stability theory of Halsey and Levine.

11:30 AM BB7.8/GG3.8
TRANSPORT THROUGH PARTICULATE MATERIALS LIKE CONCRETE. Piet Stroeven, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, THE NETHERLANDS.

Cementitious composites are based on a particulate skeleton of a wide range of particle sizes, from the sub-millimeter into the decimeter range. Ideally, the open space between such particles is filled up by a cementitious binder, which is in the mixing stage a slurry of particles dispersed in water. Size of the (blended) cement particles can range from 1 to 100 μm, or more. Due to size seggregation of the binder particles at the aggregate surfaces at the initial (fresh) state, a so called interfacial transition zone (ITZ) is formed around the aggregate particles. Consequently, the grading of the cement particles (i.e., the particle size distribution function) is a function of the distance to the aggregate particle's surface. A relatively porous ITZ is resulting, a feature maintained in the hardened state. Ingress of harmful substances in hardened concrete (gas, fluid) is promoted by the relatively high porosity in the ITZ. i.e. the presence of dense aggregate particles increases the path length, but the low density makes this the favorable route. Presently, computer-simulation studies are underway to study the character (such as the contiguity) of the porosity in the interphase (as a function of water to cement ratio, cement fineness, etc). But even when technological measures are taken to improve the density (such as in high performance concrete), the substances have to circumvent the particles. This paper will therefore focus on the common problem in transport phenomena in a granular material like concrete, i.e. the *tortuosity* in the transport route. An analytical solution based on stereological notions will be presented. A similar solution could be used in aggregated matter of dense particles where the matrix is absent, like in sand, or sandy soils. It is interesting to note further, that the presented solution also describes the roughness of fracture surfaces in concrete, which are similarly governed by the relative weakness of the ITZ. Hence, this solution can be on the base of (fracture) mechanical estimates of strength properties.