Particles, contacts, bulk-behavior

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Granular matter consists of *discrete “particles”*. These can be separate sand-grains, agglomerates (made of many primary particles), or solid materials like rock, composites, or metal-alloys—all with particulate inhomogeneous, possibly anisotropic micro-structure. Particles can be as small as nano-meters (atomic clusters, domains, and aerosols), micro-meters (fine powders like TiO_2 , flour, starch, and cement) or millimetres (grains like coffee, food-powders, corn, sand, gravel, pills). Generally, we may distinguish between granular ($d > 100 \mu\text{m}$), fine ($d < 100 \mu\text{m}$), ultrafine ($d < 10 \mu\text{m}$) and nanosized particles ($d < 0.1 \mu\text{m}$).

Particle systems as bulk show a different behavior as one could expect from single particles. They, collectively, can either *flow like a fluid* or rest *static like a solid*. In the former case granular materials are collisional or inertia-dominated and compressible nearly like a gas, in the latter case particles can form a conical heap that does not move for long time. Their most special property is the dissipative, frictional nature of the interactions between the discrete particles, where dissipation means that kinetic energy is irrecoverably lost in plastic deformations or emitted, for example, as heat or sound. The transition from fluid to solid is caused by dissipation, which tends to stop motion. The transition from solid to fluid (start of flow) is due to failure and instability, when dissipation is not strong enough to avoid flow.

Particulate systems (granular materials) consist of discrete particles with a peculiar mechanics and physics of the contacts between the particles and of particles with walls. They show a broad range of not yet understood phenomena like segregation, structure-formation, or failure of structures due to (granular) flow. Generations of scientists and engineers have developed a basic, practical understanding and have provided applicable “recipes” for the solution of material-transport and processing issues. Since about 20 years, also theoretical physics and computer simulations significantly contribute by explaining many not well understood topics in particulate granular matter. However, especially when quantitative predictions of the behaviour of complicated systems of particles in contact are desired, many open fundamental and practical problems of these—or say it in mechanical categories—multibody systems remain to be solved.

Besides experiments, the methods used to explore the behavior of particle systems involve numerical simulations and micro-macro transition methods as well as new particle-contact experiments. Application of particle simulations to really large-scale systems fails due to the large numbers of particles involved, so that continuum theory based numerics is the only available industrial design tool. The particulate nature and the contact mechanics and their influence on the bulk behavior, however, is not included in many of those approaches and has to be better understood to provide predictive tools for particulate flow predictions. A way out are coarse-grained meso-scale particle methods or continuum models based on micro-mechanical insights from the particle- and contact-level.

As *example*, in particle processing and product handling, a comprehensive list of well-known flow problems of dry cohesive powders has to be considered in process apparatuses or storage and transportation containers. This includes e.g. bridging, channelling, widely spread resi-

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dence time distribution associated with time consolidation or caking effects, chemical conversions and deterioration of bioparticles. Avalanching effects and oscillating mass flow rates in conveyors lead to feeding and dosing problems. Finally, insufficient apparatus and system reliability of powder processing plants are also related to these flow problems. Thus, it is very essential to understand the fundamentals of microscopic particle mechanics on the one hand, say the problem “diagnosis”. But to be able to ensure excellent product quality and process performance in particle technology, on the other hand, suitable and efficient solutions for these problems have to be elaborated, the technological “therapy”.

The papers in this thematic issue on *particles, contacts and bulk behaviour* are sorted according to the theme from particles (simple, spherical [1,2] to complex, non-spherical [3,4]), via their contacts (from simple, linear to non-linear, frictional, elasto-plastic, cohesive [2]) towards rapid impact [5,6], and the bulk behaviour [7–10]. For particles and their contacts, the state-of-the-art in constitutive modelling of elastic, elastic-adhesion, elastic-dissipative, plastic-adhesion and plastic-dissipative contact deformation response of a single particle is discussed in most papers in this special issue [1–10]; furthermore, on all levels from particles, their contacts and on the macroscopic bulk-flow level, models are shown but also experimentally validated.

The particle-contact includes the constitutive models of the four contact stressing modes, namely by normal compression and detachment (tension), sliding, rolling and torsion, which completely describe the elastic–plastic force–displacement and moment–angle behaviour of adhesive and frictional contacts. The consequences of elastic–dissipative, elastic–plastic, frictional unloading and reloading paths of normal and tangential forces, rolling and torsional moments are discussed, and novel test techniques on single particle contact level are shown [1,3,6,7,9].

By modelling the particle contact behaviour by suitable micro-macro interaction rules, constitutive equations can be derived [6–10] to describe the pre-consolidation dependent, mechanical behaviour of ultrafine cohesive powders and to simulate the dynamics of packed particle beds in powder processing, i.e. at agglomeration, disintegration, size reduction, powder storage and flow. At present, with this advanced knowledge on improved apparatus design (process chambers, feed hoppers, silos and conveyors) is accomplished for industrial clients in, e.g., the process industries. Other fields of

application of the novel state of the art involve mechanical and chemical engineering, pharmacy, civil engineering and geophysics as well as remote fields as astrophysics when dust on interstellar objects is concerned.

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