Introduction to Granular Flows

Figure 1: Left: Avalanche. Right: Coal tip flow.

Dense fluid-particle flows in which the direct particle-particle interactions are a dominant feature encompass a diverse range of industrial and geophysical contexts (Jaeger *et al.* 1996) including, for example, slurry pipelines (Shook and Roco 1991), fluidized beds (Davidson and Harrison 1971), mining and milling operations, ploughing (Weighardt 1975), abrasive water jet machining, food processing, debris flows (Iverson 1997), avalanches (Hutter 1993), landslides, sediment transport and earthquake-induced soil liquefaction (Housner (1985)). In many of these applications, stress is transmitted both by shear stresses in the fluid and by momentum exchange during direct particle-particle interactions. Many of the other multiphase sections analyse flow in which the particle concentration is sufficiently low that the particle-particle momentum exchange is negligible. In these sections we address those circumstances, usually at high particle concentrations, in which the direct particle-particle interactions play an important role in determining the flow properties. When those interactions dominate the mechanics, the motions are called *granular flows* and the flow patterns can be quite different from those of conventional fluids. An example is included as figure 2 which shows the downward flow of sand around a circular cylinder. Note the *upstream wake* of stagnant material in front of the cylinder and the empty cavity behind it.

Within the domain of granular flows, there are, as we shall see, several very different types of flow distinguished by the fraction of time for which particles are in contact. For most slow flows, the particles are in contact most of the time. Then large transient structures or assemblages of particles known as *force chains* dominate the rheology and the inertial effects of the random motions of individual particles play little role. Force chains are ephemeral, quasi-linear sequences of particles with large normal forces at their contact points. They momentarily carry much of the stress until they buckle or are superceded by other

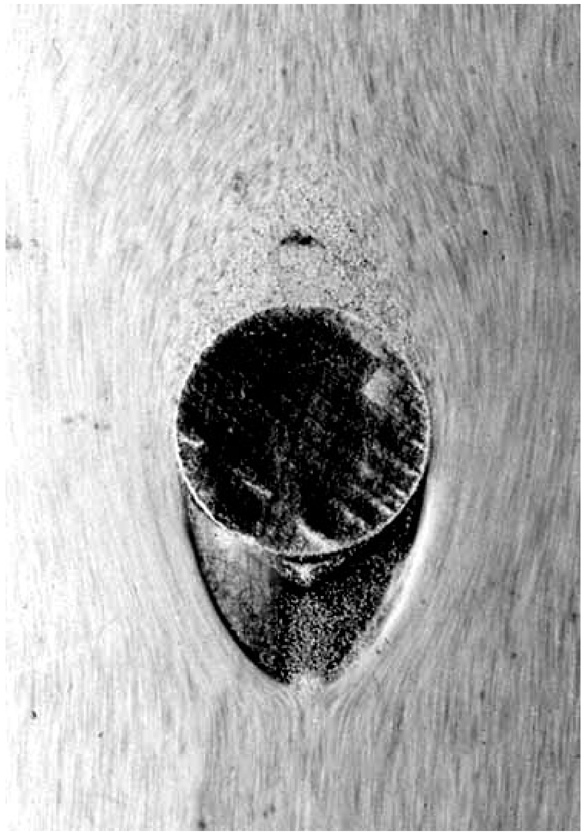

Figure 2: Long exposure photograph of the downward flow of sand around a circular cylinder. Reproduced with the permission of R.H.Sabersky.

chains. Force chains were first observed experimentally by Drescher and De Josselin de Jong (1972) and, in computer simulations, by Cundall and Strack (1979). They can be visualized using photoelastic particles in two-dimensional experimental granular flows as shown by the examples in Figure 3. Their dynamics have also been studied using computer simulations.

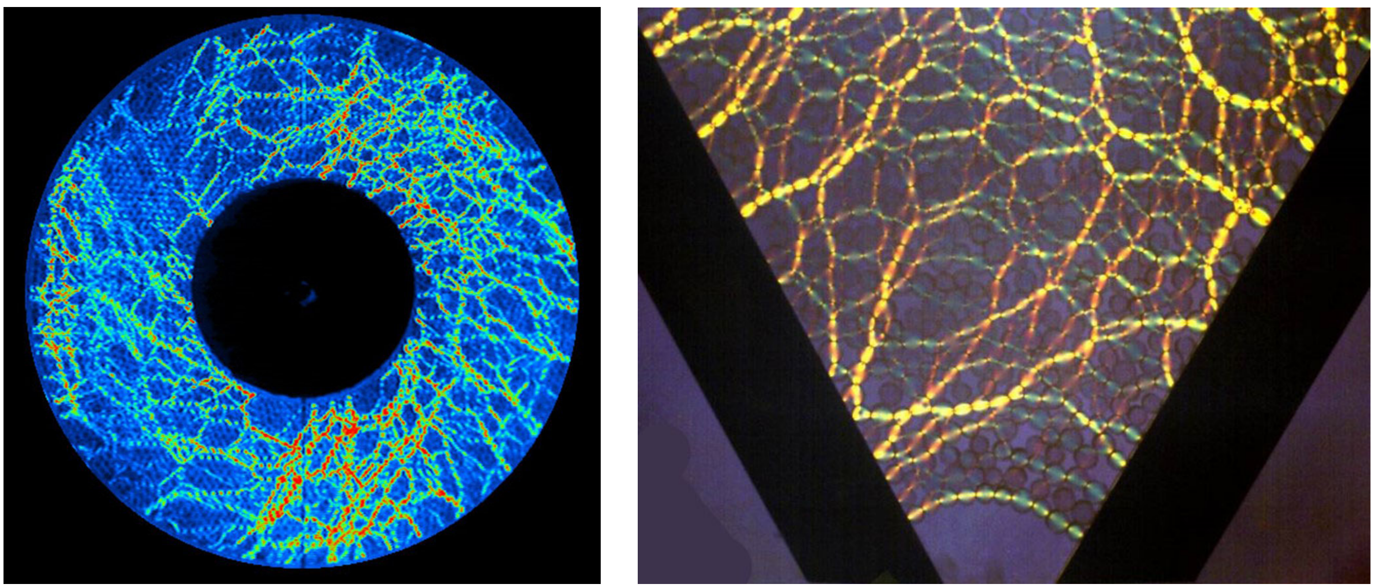

Figure 3: Left: Force chain visualization in two-dimensional shear flow (Howell *et al.*(1999)). Right: Force chain visualization in two-dimensional hopper flow (Tang and Behringer (2016)).