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## How river beds move

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## **Granular Bedload**

**Running title:** Fluvial bedload sediment transport is a granular phenomenon which can benefit from results in granular physics.

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The transport of sediment through river channels has major consequences for public safety, management of water resources, and environmental sustainability. The overwhelming majority of investigations of sediment transport in rivers has focused on mass flux and its relation to water flow. Yet after more than a century of work we have no satisfactory theory for bedload, the important component of the sediment load transported in contact with the stream bed. Transport formulae often overpredict the actual rate by orders of magnitude (1). Hence it is difficult to assess, for example, the impact on the channel of disturbances such as extreme sediment-laden floods causing casualties, loss of property and public infrastructure, and compromising water quality and aquatic habitat.

Bedload can also be viewed as a granular phenomenon. Much progress has been made recently in the study of dry granular flows, but the knowledge gained has not, in general, diffused into the river science community. Bedload transport can be divided into two stages (2): partial mobility of local bed surface material when, at any one time, part of the bed remains static but any exposed grain might eventually move; and full mobility, when all grains move to a depth of several grain diameters. Grain-grain interactions over short time and length scales bear importantly on the predictability of both stages.

No single constitutive law reproduces the diversity of behaviors observed in cohesionless granular materials (3). Granular flows are often classified into three different states: a gaseous

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state in which the flow is very rapid and dilute, and the particles interact by collision; an intermediate state in which the material is dense but still flows like a liquid, the particles interacting both by collision and friction; and a dense, quasi-static state in which the deformations are very slow and the particles interact by frictional contacts. All three states might be found in free surface flows and in bedload.

Probably the most important phenomenon relevant to bedload is size segregation by shearing in free surface flows. Two distinct size segregation phenomena occur. When the coarsest fractions of the bed do not move and the smallest fractions are sufficiently fine, spontaneous percolation occurs. But when the bed is moving kinematic sieving of the finer particles take place even if the size ratio is close to unity (4, 5). The usual net result is a downward flux of the smaller particles and an upward flux of larger particles, hence segregation, as observed in river deposits (see figure, panel A), and a significant reduction in transport.

Velocity and concentration profiles are important because they give access to the rheology of the granular flow. Indeed, the apparent viscosity is the ratio of the shear stress to the shear rate (or velocity gradient in simple shear). Whatever the grain sizes, fluid densities and viscosities, the mean granular velocity profile has a similar shape with a linear profile in the upper part and an exponential decay toward zero in the lower part (6). Velocity fluctuations are important too because they permit computation of the granular temperature (usually defined as the sum of streamwise and vertical variances of instantaneous velocity), a variable central in kinetic theory modelling of low density granular flows (7). Moreover, in a study of size segregation (8), it was shown that granular temperature profiles were particular to a size class, whereas the mean velocity profile was not.

Important differences between granular motion as usually studied, in both research and industrial contexts, and bedload transport in rivers include the very wide range of grain sizes and shapes normally present in fluvial sediments, the highly irregular geometry of river

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channels (itself a consequence of the movement and deposition of bed material), the highly variable forcing in rivers, both temporally and spatially, and the generally lower rates of flux.

Nevertheless, important analogies may be exploited.

In rivers, full mobility is customarily observed in sands, but also occurs in gravels under sufficiently strong flows. Only rare papers have addressed particle velocity and concentration profiles in full mobility bedload (9), some in very concentrated flows (10). Profiles agree with the shape of their dry granular counterpart. Such results have subsequently been used for comparison with models addressing collisional grain flows based on kinetic theory or dense flow rheology (3, 11). As to segregation, most studies in the bedload literature have concerned the spontaneous percolation of fine grains into immobile gravels (12). The motivations variously have been intrusion of fines into salmonid spawning beds, placer mineral concentration, and stratigraphical interpretation. In an experimental study, smaller beads have been introduced into a bedload flow initially formed only of larger moving beads (13). After a while a quasi-continuous layer of small particles developed beneath larger moving beads and above quasi-immobile larger beads (see figure, panel B). This kind of granular physics inspired experiment fosters advances in bedload science.

In the regime of partial mobility, processes are restricted to the surface of the bed and all particles experience long periods of rest. This condition is characteristic of gravel transport. The propensity for grains of similar size to block each other leads to accumulations of similar sized grains in restricted areas of the channel bed. Two phenomena command attention. Mobile materials collect in patches of similar size in the streambed, a phenomenon that mediates the overall sediment flux (14), while the largest stones in streambeds – characteristically only marginally mobile – congregate into clusters, chains and cell-like arrangements that dramatically increase the overall stability of the bed (15).

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The second case is particularly interesting from the granular perspective since the stone structures represent a natural case of force chains that have been studied in the laboratory for more than a decade (16). In the extreme case of steep mountain channels with relatively large stones in them, stone lines become channel-spanning force chains forming distinctive step-and-pool morphology that maintains a stable channel in situations when any unconstrained stone would be swept away.

While heuristic models have been constructed for the development of surface structures, the mechanisms that promote patch development and bed surface structures require additional experimental study before physically sound models may be developed. Stone lines and cells on the surface are relatively long-lived because, during most flows, their ultimate strength is not tested. This allows time for additional mechanisms to strengthen them beyond the state achieved by force chains in continuously deforming media. Hence, failure mechanisms are of particular interest. When extreme flows do break the stability of such channels, life-threatening debris flows result.

Altogether, it appears that a good basis exists in grain physics to improve our understanding of bedload transport at relatively high rates. However, surface phenomena that would simulate stage 1 bedload transport – that is, transport of individual grains over a rough surface composed of similar grains – remain essentially uninvestigated in granular physics. While imparting insight into the bedload problem, experiments on these phenomena would open a new perspective in the physics as well.

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**Figure.** A. Vertical profile in a gravel river bar showing size sorting with an armored surface and finer material below. B. Layers of smaller transparent beads under larger moving black beads as a result of kinematic sieving in a quasi two-dimensional experiment.

