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models that are used to describe high-temperature superconductors.

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GEOPHYSICS

How River Beds Move

Philippe Frey[1] and Michael Church[2]

Insights into sediment transport at river beds can come from experiments in granular physics.

The transport of sediment through river channels has major consequences for public safety, management of water resources, and environmental sustainability. Most studies of sediment transport in rivers have focused on mass flux and its relation to water flow. Yet, after more than a century of work, there is no satisfactory theory for bedload, the component of the sediment load transported in contact with the stream bed. Bedload transport formulae often overpredict the actual rate by orders of magnitude (*1*). It is therefore difficult to predict, for example, the impact of disturbances such as extreme floods on the channel. Better insight may come from viewing bedload as a granular phenomenon.

Bedload transport can be divided into two stages (*2*): partial mobility of local bed surface material when part of the bed remains static but exposed grains may 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.

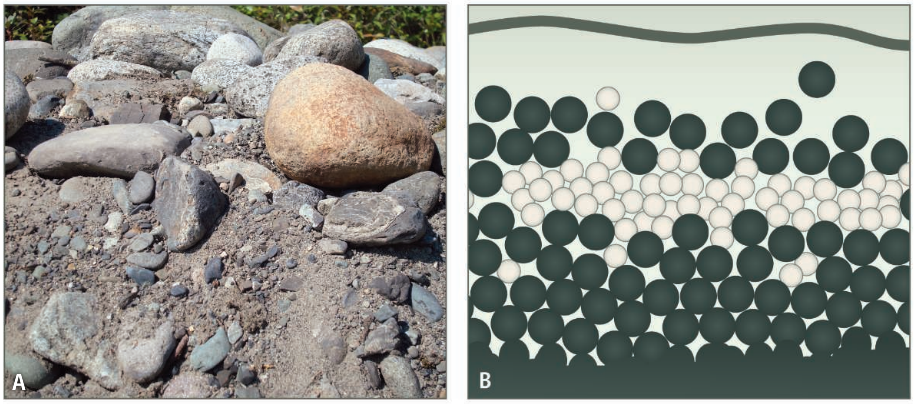
No single constitutive law reproduces the diversity of behaviors of cohesionless granular materials (*3*). Granular flows are often classified into three states: a gaseous state, in which flow is very rapid and dilute, and the particles interact by collision; an intermediate state, in which the material is dense but still flows like a liquid, the particles interacting both by collision and friction; and a dense, quasistatic 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 result is a downward flux of smaller particles and an upward flux of larger particles, resulting in the segregation observed in river deposits (see the figure, panel A) and in a substantial reduction in transport.

Velocity and concentration profiles provide insight into the rheology of the granular flow. Regardless of grain sizes, interstitial 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 permit computation of the granular "temperature" (the sum of streamwise and vertical variances of instantaneous velocity), a variable central to kinetic-theory modeling of low-density granular flows (*7*). In a study of size segregation (*8*), Hill and Zhang have shown that granular temperature profiles were particular to a size class, whereas mean velocity profiles were 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 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 usually observed in sands, but also occurs in gravels under sufficiently strong flows. Few studies have addressed particle velocity and concentration profiles in full-mobility bedload (*9*, *10*). The measured profiles have the same shape as their dry granular counterparts. Such results have been successfully compared with models of collisional grain flows based on kinetic theory or dense flow rheology (*3*, *11*). As to segregation, bedload studies usually investigate the spontaneous percolation of fine grains into immobile gravels (*12*). In an experimental study, smaller beads have been introduced



Segregation through motion. (**A**) This vertical profile in a gravel river bar (in Vedder River, British Columbia, Canada) shows size sorting with an armored surface and finer material below. (**B**) In a quasi–two-dimensional experiment (*13*), kinematic sieving leads to the formation of layers of smaller transparent beads under larger moving black beads. This panel was redrawn from a video snapshot.

CREDIT: (PANEL A) PHILIPPE FREY/CEMAGREF

[1]Cemagref, Unité de recherche Erosion Torrentielle, Neige et Avalanches, BP 76, 38402 Saint-Martin-d'Hères, France. E-mail: philippe.frey@cemagref.fr [2]Department of Geography, University of British Columbia, Vancouver, BC, V6T 1Z2, Canada.

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 the figure, panel B).

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—usually only marginally mobile—congregate into clusters, chains, and cell-like arrangements that dramatically increase the overall stability of the bed (*15*).

The second case is particularly interesting from the granular perspective, because 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 containing relatively large stones, stone lines become channel-spanning force chains, forming a distinctive step-and-pool morphology that maintains a stable channel in situations when any unconstrained stone would be swept away.

Heuristic models have been constructed for the development of surface structures, but 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 further, 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 steep channels, life-threatening debris flows result.

Granular physics provides a good basis for improving our understanding of bedload transport at relatively high rates. However, surface phenomena that would simulate partial bedload transport remain essentially uninvestigated in granular physics. While imparting insight into the bedload problem, experiments on these phenomena would also open a new perspective in granular physics.

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PHYSICS

The Super of Superradiance

Marlan O. Scully[1,2] and Anatoly A. Svidzinsky[1]

Cooperative single-photon emission from an atom ensemble will provide insights into quantum electrodynamics and applications in quantum communication.

In 1954, Robert Dicke introduced the concept of superradiance in describing the cooperative, spontaneous emission of photons from a collection of atoms. The concept of superradiance can be understood by picturing each atom as a tiny antenna emitting electromagnetic waves. Thermally excited atoms emit light randomly, and the emitted intensity is a function of the number of atoms, N. However, when the atomic "antennas" are coherently radiating in phase with each other, the net electromagnetic field is proportional to N, and therefore, the emitted intensity goes as N^2. As a result, the atoms radiate their energy N times faster than for incoherent emission. It is this anomalous radiance that Dicke dubbed "superradiance" (*1*–*3*).

[1]Texas A&M University, College Station, TX 77843, USA. [2]Princeton University, Princeton, NJ 08544, USA. E-mail: scully@tamu.edu

An even more interesting kind of radiation speedup can occur when a single photon is stored uniformly in a cloud of N atoms (see the figure, panel A). Suppose you have one atom that decays with a rate γ. Then suppose there are N such atoms close together in an atom cloud with only one of the atoms excited (but we don't know which one). Because there is only one atom excited, you might expect the decay rate to be γ. But if the atoms are symmetrically organized within the cloud, the decay rate is actually $N\gamma$ (*1*). This enhanced single-photon emission rate is "the greatest radiation anomaly" inherent in superradiance. Single-photon superradiance has become a subject of current interest (*4*–*12*), and promises to yield new tools for storing quantum information and deeper insight into the physics of virtual processes.

Dicke's point is that the N atoms act like one big atom and decay collectively. This is intuitive when the atoms are close together compared to the wavelength of radiation λ. When the same symmetric state is formed but the atomic cloud size is larger than λ, there is no longer constructive cooperation in radiation emission. The atoms will trap the light, decreasing the emission rate.

Nevertheless, it is possible to produce a state such that the large cloud also emits radiation with an enhanced rate proportional to $N\gamma$ (*4*, *5*). This is important because in quantum optics the sample is usually large compared to λ.

However, things are a bit trickier here. More subtle and interesting physics come into play, extending from quantum information and a new kind of cavity quantum electrodynamics (QED) (*13*), to new insights into quantum field theory (*9*–*12*).

The essential new physics is the transition from the coherent antenna array to the single-photon state in which cooperative emission is due to N entangled atoms (not N coherent

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