Hillslope evolution by nonlinear creep and landsliding: An experimental study: Comment and Reply

COMMENT

B.Ph. van Milligen
Asociación Euratom-CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), Avenida Complutense 22, 28040 Madrid, Spain
P.D. Bons
Tektonophysik, Institut für Geowissenschaften, Universität Mainz, D-55099 Mainz, Germany

Roering et al. (2001) describe very careful and interesting experiments that beautifully illustrate the transition from steady downhill creep at low gradients to highly dynamic transport on steep slopes. They interpret this behavior in terms of a single nonlinear diffusion coefficient, suggesting that transport on steep and gentle slopes is governed by common underlying physics. However, Figure 2A of Roering et al. (2001) shows that there is a transition from a state of mostly continuous flux on gentle slopes, to strongly pulsed behavior with avalanches on steep slopes. It does not seem adequate to describe transport on steep slopes by a larger effective diffusion constant, because the nature of this transport is fundamentally nondiffusive. Such a treatment does not lead to a proper understanding of the complexity of the processes involved.

Basically, in a diffusive system any particle (or grain) describes a random walk (Brownian motion), and its total distance grows as the square root of the traveling time. However, avalanches travel at constant velocity (Hwa and Kardar, 1992; Carreras et al., 1996), as can be verified experimentally using tracer grains. This constitutes a new element in the transport of particles that cannot be described correctly using a diffusive equation, unless the diffusion ''constant'' is chosen to be a nonlinear function in order to cancel out the square-root behavior. However, there is no justification for this when the propagation can simply be described using a constant velocity. Moreover, avalanches seen in sandpile models show finite-size scaling behavior (Christensen, 1996), i.e., behavior dependent on the system size, implying that the effective diffusion derived for one system is not valid in another larger or smaller system. This annuls the predictive power of the effective diffusion coefficient for any system other than the one for which it was derived.

So, while at gentle slopes transport is diffusive, at steep slopes ''ballistic'' transport with avalanches takes over. Here, the flux self-organizes (adjusts its value) in order to maintain the slope below the critical value. It is natural that the flux should increase sharply when approaching the critical, highly unstable slope. At high values of the slope (near the critical gradient), the flux is mainly determined by the sediment supply rates, rather than by the slope itself. Naturally, there is a smooth transition between the two regimes.

The transport flux might be described by a formula of the following type (cf. Sánchez et al., 2001):

$$q = \mathrm{K}\, S + \alpha\, v\, \Theta(S - S_c), \qquad (1)$$

where q is the mass flux, S the slope or gradient, K the diffusion coefficient, α a fit parameter, v the ballistic velocity, S_c the critical slope, and $\Theta(x)$ a sharply (i.e., nonlinearly) growing function of x when $x > 0$, and small when $x \leq 0$ (as a first approximation, the Heaviside function may be used). Equation (1) describes the local transport flux, which increases strongly when the critical gradient is exceeded locally. Then, the increased flux steepens the slope further down the hill, leading to an increase of flux there, thus generating a propagating avalanche.

The spectra shown by Roering et al. (2001) are also indicative of the suggested transport regime transition. The logarithmic spectral slope increases from near 0 in the diffusive case (white noise, random walk) to near 1 in the critical case ($S \approx 0.42$). For higher supply rates the spectral slope is seen to increase further, related to the quasi-periodic behavior also seen in Figure 2A. At the highest supply rates ($S = 0.48$–0.52), the large flux that is imposed by the external supply rate forces all avalanches to be large, so that the small avalanches cease to exist. One can test this idea experimentally by determining the distribution of avalanche sizes or flux amplitudes, which should be power-law in the critical case ($S \approx 0.42$) and be peaked at large sizes when $S > 0.42$. Thus, it would seem that at moderate values of the supply rate ($S \approx 0.42$) the system is in a self-organized critical state, free of any characteristic lengths and time scales (Bak et al., 1987, 1988), reminiscent of the behavior of numerical sandpiles described in the ample literature on self-organized critical state (Bak et al., 1988; Hwa and Kardar, 1992).

It is interesting to note that the external noise source, applied in the form of a speaker, may be a crucial ingredient to resolve the intermediate critical region adequately (cf. Rosendahl, 1994, where noise was absent). To further investigate the possible correspondence between experiment and models, we would suggest that the experiment data be subjected to the relevant analyses: detection of self-similarity (Hurst, 1951; Mandelbrot and Wallis, 1968); estimation of the probability distribution functions of the transport events and the flux (Bak et al., 1988; Frette at al., 1996); and the transport of tracer grains to distinguish between diffusive and ballistic behavior (Christensen et al., 1996).

In conclusion, while the nonlinear diffusion model of Roering et al. (2001) may adequately predict an average hillslope profile in the given experimental situation, we believe, based on the arguments given, that it does not allow extrapolation to other situations. Correct recognition of self-organized critical transport is crucial to understanding, modeling, and predicting the flux in all its highly dynamic aspects, and to be able to make adequate risk assessments and perform hazard mitigation in real-life situations.

REFERENCES CITED

Bak, P., Tang, C., and Wiesenfeld, K., 1987, Self-organized criticality: An explanation of 1/f noise: Physical Review Letters, v. 59, p. 381–384.

Bak, P., Tang, C., and Wiesenfeld, K., 1988, Self-organized criticality: Physical Review A, v. 38, p. 364–374.

Carreras, B.A., Newman, D., Lynch, V.E., and Diamond, P.H., 1996, A model realization of self-organized criticality for plasma confinement: Physics of Plasmas, v. 3, p. 2903–2911.

Christensen, K., Corral, Á., Frette, V., Feder, J., and Jøssang, T., 1996, Tracer dispersion in a self-organized critical system: Physical Review Letters, v. 77, p. 107–110.

Frette, V., Christensen, K., Malthe-Sørenssen, A., Feder, J., Jøssang, T., and Meakin, P., 1996, Avalanche dynamics in a pile of rice: Nature, v. 379, p. 49–52.

Hurst, H.E., 1951, Long-term storage capacity of reservoirs: Transactions of the American Society of Civil Engineers, v. 116, p. 770–799.

Hwa, T., and Kardar, M., 1992, Avalanches, hydrodynamics, and discharge events in models of sandpiles: Physical Review A, v. 45, p. 7002–7023.

Mandelbrot, B.B., and Wallis, J.R., 1968, Computer experiments with fractional Gaussian noises: 2. Rescaled ranges and spectra: Water Resources Research, v. 5, p. 242–259.

Roering, J.J., Kirchner, J.W., Sklar, L.S., and Dietrich, W.E., 2001, Hillslope

evolution by nonlinear creep and landsliding: An experimental study: Geology, v. 29, p. 143–146.
Rosendahl, J., Vekic, M., and Rutledge, J.E., 1994, Predictability of large avalanches on a sand pile: Physical Review Letters, v. 73, p. 537–540.
Sánchez, R., Newman, D.E., and Carreras, B.A., 2001, Mixed SOC diffusive dynamics as a paradigm for transport in fusion devices: Nuclear Fusion, v. 41, p. 247–256.