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Himalayan sandpiles

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Himalayan avalanches are examined for agreement with power-law behavior between frequency of outfall and rock volume. The data support a scaling state beyond the size ranges in which corresponding sandpile experiments have suffered from finite-size effects. Large-scale data (12 orders of magnitude in rock volume) additionally suggest a possible role for the numerically predicted "snowball effects" of large rocks triggering more net dislodging events.

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As introduced by Bak, Tang, and Weisenfeld [1], the concept of self-organized criticality (SOC) puts forward a general model to describe many features observed in natural phenomena. Examples include the frequency and magnitude of earthquakes, avalanches, and volcanic emissions. SOC proposes that such activities propagate by branching as chain reactions. The most often cited SOC experiment which simulates the statistics of this behavior is grains of sand tumbling from a laboratory sandpile. In other contexts [2], the sandpile has been used widely to model such diverse physics as vortex motion in superconductors, behavior of spin glasses, and spread of forest fires.

As critical behavior is approached on a sandpile, flow depends on whether the sand's angle of repose exceeds its friction-limited slope. Fluctuations greater than a critical steepness induce avalanches, either by adding a single grain of sand or by slowly tilting a sandbox. In contrast to the otherwise ubiquitous exponential ("thermal") distribution, the size distributions for such avalanches give a characteristic power law. This scaling between frequency and magnitude is generally taken as the most striking signature of SOC. Many results found in numerical and analytical models have lent support to this SOC concept, but nevertheless experimental confirmation has shown some perplexing effects attributed to finite sample size [3,4].

To shed additional light on possible finite-size effects, data were examined from two road engineering projects in the Himalayas [5]. On two mountain roads with similar geology but different construction ages, avalanches resulting from natural landslides were cleared off overland bypasses. As shown in Fig. 1, landslide volumes spanned up to 12 orders of magnitude and covered a colossal range well beyond the sizes accessible in laboratory experiments and numerical simulations. Restricted power-law behavior can be seen to describe avalanches adequately across four orders in size. At one end, larger outfalls account for greater than the expected number of avalanches. At smaller sizes a second power-law region equally describes those avalanches which generate 10^4 times more volume than the smallest recorded outfall. For building an equivalent laboratory sandpile (grain size ~ 0.8 mm), the Himalayan data equates approximately to a sandpile experiment with single grains dropped onto a very large (10-m) pile.

Compared to laboratory sandpiles and simulations, the results for Himalayan landslides differ in two respects. First, the Himalayan hillroads start from an overly steep slope (supercritical), then relax back to their critical state (owing to fractures, slumping, and rock decomposition). This backward (from supercritical to critical) approach contrasts with the forward approach to criticality, which

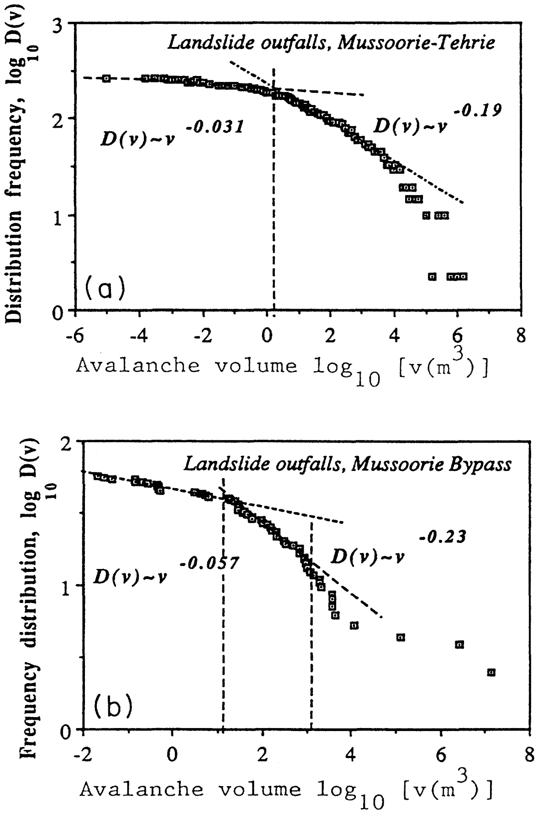

FIG. 1. Avalanche size distributions as reported from clearings of Himalayan hillroads. After 1978 field data [2] on mountain debris from (a) 6-km reach of Mussoorie-Tehrie road and (b) 2-km reach on recently completed (1987) Mussoorie Bypass.

either adds a single grain or slowly tilts a flat sandbox. In this way, the landslide data can be thought to more closely correspond to experiments which dry or vibrate an already overly steep pile. Less numerical work has addressed the directionality of the approach to the critical state and further work on this point may be warranted if SOC chain reactions propagate differently backward and forward. In general, the supercritical approach from an overly steep slope avoids some practical drawbacks of the forward, "pile-building" approach, namely, the kinetic energy imparted by dropping a single sand grain [4] is excluded from experiments which approach criticality from the backward direction.

A second difference between landslides and sandpiles is that Himalayan rock volume is not uniform like sieved sand, but itself shows a size and shape distribution. In fact, the irregular rock sizes of natural landslides more closely approximate the kind of random distributions in both applied stress and connectivity seen in other successful SOC models, such as earthquakes and volcanic emissions. For power-law behavior, it may be that an irregular driving force carries some physical significance.

Actual sandpile experiments [2,3] have succeeded in tracking big avalanches which cascade up to 100 grains of sand at a time. These have verified SOC to hold for small diameter (6-cm) piles but do not find power laws for (8-cm) piles. The larger piles do not yield power laws but instead relax by dumping a narrow range of avalanche sizes which cyclically build up on the larger piles. Contrary to SOC predictions for scale, an anomalous damping length appears whereby local avalanches propagate down the pile and hold up on the slope without any net loss of sand from the pile's rim. In this way, the pile releases its excess (gravitational) energy not across all sizes, but favoring a peaked region of sizes; the pile can be thought to relax by "ticking periodically" rather than "flowing smoothly in bursts." Similar holdup of rocks may equally distort landslide data for small-size (large-frequency) events [6].

It is worth emphasizing for landslides that a single power law cannot describe the full aspects of Himalayan avalanches (from Fig. 1, it clearly cannot describe their statistical dynamics for 12 orders of magnitude in rock volume). Rather, the significant point is that the outfall data extend well beyond where previous laboratory experiments have reported finite-size effects. In this connection, while the natural landslide data follow only a restricted range for power-law scaling, this result speaks more to the system's enormous size range rather than pointing to any particular dynamical explanation or pathology. For example, even the most restricted power-law behavior in Himalayan landslides extends an order of magnitude beyond the previously considered "excellent" agreement between SOC and the similar Gutenberg-Richter law for earthquakes [7].

It is well established that similar and restricted scaling regimes appear unavoidably whenever fractal dynamics play a constructive role in all real experimental systems [8]. In fact, all experimental systems are only locally fractal, or "all real fractals are not truly fractal." This observation contrasts with the broader and more comprehensive ranges in computer experiments. Although still not able to approach 12 orders in magnitude, these numerical results can span large observation windows. The appearance of a natural model with a characteristically long-tailed distribution and vast size differences may encourage further investigations into more closely matching sandpile experiments to actual avalanche conditions. Much akin to the present supercritical landslides one obvious laboratory model would be systematically drying or vibrating an overly steep pile of wet sand.

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