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The granular origin of the relation between slope and sediment flux in soil mantled hillslopes

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Hillslopes occupy most of the Earth's surface area, and are the main source of sediments to the fluvial routing system. Since the slope of soil mantled hillslopes normally lies below the angle of repose, it has been suggested that sediment mobilization across and from hillslopes is facilitated by climatic, biologic, and tectonic environmental disturbances. Previous empirical studies have shown that sediment flux out of hillslopes depends non-linearly on the slope. However, the functional dependency between the slope and the flux that aspires to span a range of processes from slow creep to rapid landsliding generally lacks a mechanistic explanation. The absence of a physical understanding of the slope-flux relation hinders our ability to assess hillslope evolution in different settings and evaluate the effect of changing environmental conditions on the flux.

Due to the particulate nature of the material composing the upper layer of soil mantled hillslopes, sediment transport on and from hillslopes has discrete granular characteristics. Entrainment of grains, grain travel distance, velocity and acceleration, all depend on the dynamics of the sediment particles and their interactions. It is therefore likely that the spatial and temporal evolution of the sediment flux in response to a given slope and disturbance characteristics should inherently depend on the inter-particle dynamics. For this reason, the current work investigates the relations between flux, slope, and disturbance characteristics at the granular scale. This has the advantage of using first order mechanical principles without the need to assume a priori empirical relations.

We construct a two-dimensional model representing a long hillslope, and we model granular interactions and their response to environmental disturbances using a soft disc granular dynamics algorithm. Environmental disturbances are simulated by applying temporally and spatially variable 'external' forces to individual grains following a random scheme that is characterized by a maximum magnitude and pseudo-wavelength. We perform many simulations that vary in the layer thickness, the slope, and the disturbances magnitude and wavelength.

Our simulation results reveal a rich meso-scale dynamic behavior with a relatively abrupt transition between two end members. Creep motion that rapidly decays with depth occurs at low and intermediate slope angles, while landsliding with kinematics that follows Bagnold's rheology dominates higher angles, albeit, still below the angle of repose. Disturbances thus effectively reduce the angle of repose as they allow for landslides to develop below the angle of repose of disturbance-free slopes. Our results further demonstrate a positive correlation between disturbance magnitude and pseudo-wavelength to sediment flux, which is consistent with previous theoretical predictions. Non-linearity between the slope and the flux is shown to emerge both from the creep dynamics and from the transition between creep motion to landsliding. The simulations further allow a unique view into the micro-mechanics of granular motion down hillslopes.