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The role of slope-material disintegration in controlling the geometry and size of landslides; Insights from Discrete Element Method computer simulations

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We carry out numerical simulations using the Discrete Element Method (DEM) to understand the conditions at slope failure and the resulting landslide sizes. Our modeled 2D slopes are constructed of numerous spheres simulating mechanically homogeneous material with friction and cohesion. This approach enables us to simulate Earth-like materials and their physical behavior, as discontinuities and heterogeneities can develop and propagate as the material undergoes yield and failure. Appealingly, the material properties and rheologies can evolve over time, and can be tracked in detail throughout the simulation of the slope-failure process.
We first examine in detail the mechanical causes of slope failure, while probing the stress field in a modeled slope throughout the initial failure process (slope height is fixed at 1050 m, and slope angle at 70 degrees). Failure initiates at the slope-foot, where slope material loses cohesion and disintegrates (interparticle bonds breakage). The failure surface propagates upwards with decreasing velocity (360-70 m/sec), forming a discrete sliding plane that separates the disintegrated and the intact slope-materials. The propagation of the failure surface is detected as a reduction in local mean stress as the landslide undergoes tensile failure and disintegration. This stress evolution is well-characterized by progressive changes in the normalized strength ratio (i.e., differential stress/mean stress) for the failing slope. Initial failure occurs at a high normalized strength, consistent with brittle failure, whereupon the normalized strength decreases toward the critical state line, consistent with post-failure weakening to reach residual strength of the rock. Significant downward slope movement occurs only after the failure surface and associated drop in the normalized strength ratio has reached the top of the slope.
We analyzed the evolution (stress, geometry, and size) of numerous simulated landslides. Our results demonstrate that landslide size and failure mode are strongly dependent upon the Factor of Safety (FS), defined as the ratio of resisting stresses to driving stresses. When material strength is low ($FS \ll 1$), landslides encompass the entire slope height. With increasing material strength (cohesion ranges from 0.5 to 3 MPa; friction is fixed at 31 degrees), the landslides encompass decreasing proportions of the lower slopes, until they vanish close to stabilization of the slope at FS=1. As natural landslides commonly encompass large portions of failing slopes, we argue that they occur under conditions of $FS< 1$, at least by the completion of the failure process, i.e. once the propagating sliding plane reaches the slope crest. Therefore in reality, slope failure occurs as a dynamic process in which failure initiates at the slope-foot, where $FS\sim 1$, but FS decreases as the slope material gradually disintegrates and loses its cohesion as the sliding plane propagates upslope, resulting in larger landslides than would be predicted for FS=1. Nevertheless, for a given slope angle, the landslide geometry, defined by the ratios of landslide thickness (t) to length (l), are independent of material strength. The values for this ratio calculated from the simulated landslides coincide with field-observed subareal landslides (t/l is 0.10, 0.15, and 0.17 for slopes of 30, 45 and 70 degrees, respectively).
Our approach demonstrates the utility of mapping out the evolving stress conditions to better predict the complex evolution of deforming slopes, thereby to obtain clearer insights into the mechanisms that constrain landslide failure modes, geometries, and resulting size distributions. The fact that landslide geometry (t/l) is independent of material strength coincides with the recently observed universal ratio of landslides volume and area.