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# Controls on shallow landslide initiation: Diverse hydrologic pathways, 3D failure geometries, and unsaturated soil suctions

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Shallow landslides and ensuing debris flows are a common hazard worldwide, yet forecasting their initiation at a specific site is challenging. These challenges arise, in part, from diverse near-surface hydrologic pathways under different wetting conditions, 3D failure geometries, and the effects of suction in partially saturated soils. Simplistic hydrologic models typically used for regional hazard assessment disregard these complexities. As an alterative to field studies where the effects of these governing factors can be difficult to isolate, we used the USGS debris-flow flume to conduct controlled, field-scale landslide initiation experiments. Using overhead sprinklers or groundwater injectors on the flume bed, we triggered failures using three different wetting conditions: groundwater inflow from below, prolonged moderate-intensity precipitation, and bursts of high-intensity precipitation. Failures occurred in 6 $m^3$ (0.65-m thick and 2-m wide) prisms of loamy sand on a 31º slope; these field-scale failures enabled realistic incorporation of nonlinear scale-dependent effects such as soil suction. During the experiments, we monitored soil deformation, variably saturated pore pressures, and moisture changes using ∼50 sensors sampling at 20 Hz. From ancillary laboratory tests, we determined shear strength, saturated hydraulic conductivities, and unsaturated moisture retention characteristics.

The three different wetting conditions noted above led to different hydrologic pathways and influenced instrumental responses and failure timing. During groundwater injection, pore-water pressures increased from the bed of the flume upwards into the sediment, whereas prolonged moderate infiltration wet the sediment from the ground surface downward. In both cases, pore pressures acting on the impending failure surface slowly rose until abrupt failure. In contrast, a burst of intense sprinkling caused rapid failure without precursory development of widespread positive pore pressures. Using coupled 2D variably saturated groundwater flow modeling and 3D limit-equilibrium analyses, we simulated the observed hydrologic behaviors and the time evolution of changes in factors of safety. Our measured parameters successfully reproduced pore pressure observations without calibration. We also quantified the mechanical effects of 3D geometry and unsaturated soil suction on stability. Although suction effects appreciably increased the stability of drier sediment, they were dampened (to <10% increase) in wetted sediment. 3D geometry effects from the lateral margins consistently increased factors of safety by >20% in wet or dry sediment. Importantly, both 3D and suction effects enabled more accurate simulation of failure times. Without these effects, failure timing and/or back-calculated shear strengths would be markedly incorrect. Our results indicate that simplistic models could not consistently predict the timing of slope failure given diverse hydrologic pathways. Moreover, high frequency monitoring (with sampling periods < ∼60 s) would be required to measure and interpret the effects of rapid hydrologic triggers, such as intense rain bursts.