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Using earthquake-triggered landslides as a hillslope-scale shear strength test: Insights into rock strength properties at geomorphically relevant spatial scales in high-relief, tectonically active settings

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The material strength of rock is known to be a fundamental property in setting landscape form and geomorphic process rates as it acts to modulate feedbacks between earth surface processes, tectonics, and climate. Despite the long recognition of its importance in landscape evolution, a quantitative understanding of the role of rock strength in affecting geomorphic processes lags our knowledge of the influence of tectonics and climate. This gap stems largely from the fact that it remains challenging to quantify rock strength at the hillslope scale. Rock strength is strongly scale dependent because the number, size, spacing, and aperture of fractures sets the upper limit on rock strength, making it difficult to extrapolate laboratory measurements to landscape-scale interpretations. Here we present a method to determine near-surface rock strength at the hillslope-scale, relying on earthquake-triggered landslides as a regional-scale "shear strength" test. We define near-surface strength as the average strength of rock sample by the landslides, which is typically < 10 m. Based on a Newmark sliding block model, which approximates slope stability during an earthquake assuming a material with frictional and cohesive strength, we developed a coseismic landslide model that is capable of reproducing statistical characteristics of the distribution of earthquake-triggered landslides. We present results from two well-documented case-studies of earthquakes that caused widespread mass-wasting; the 2008 Mw 7.9 Wenchuan Earthquake, Sichuan Province, China and the 1994 Mw. 6.8 Northridge Earthquake, CA, USA. We show how this model can be used to determine near-surface rock strength and reproduce mapped landslide patterns provided the spatial distribution of local hillslope gradient, earthquake peak ground acceleration (PGA), and coseismic landsliding are well constrained. Results suggest that near-surface rock strength in these tectonically active settings is much lower than that obtained using typical laboratory shear strength measurements on intact rock samples. Furthermore, the near-surface material strength is similar between the study areas despite differences in tectonic, climatic, and lithologic conditions. Variations in near-surface strength within each setting appear to be more strongly associated with factors contributing to the weakening rock through chemical or physical weathering, such as mean annual precipitation and distance to active faults (a proxy for rock shattering intensity), rather than intrinsic lithologic properties. We hypothesize that the shattering of rock through long-term permanent strain accumulation and by repeated earthquakes is an important mechanism that can explain low rock strength values among the different study sites and the spatial pattern of rock strength within each location. These findings emphasize the potential role of factors other than lithology in controlling the spatial distribution of near-surface rock strength in high-relief, tectonically active settings, which has important implications for understanding the evolution of landscapes, interpreting tectonic and climatic signals from topography, critical zone processes, and natural hazard assessment.