Influence of topographic stress on bedrock weathering and landslides

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1. Introduction

Landslides present one of the greatest geologic hazards that currently threaten human society and infrastructure. To better quantify landslide-derived sediment flux and mitigate landslide hazards, we need to better understand the controls on the landslide occurrences, timing, and characteristics. Theoretical studies have suggested that topographic perturbation of regional stress fields may impact bedrock fractures and rock strength and affect landslides (McTigue & Mei, 1981; Miller & Dunne, 1996; Moon et al., 2017; Savage & Swolfs, 1986; Savage et al., 1985). However, the influence of topographic stress on bedrock weathering and landslides has not been adequately quantified. For example, it is unclear how three-dimensional topography influences subsurface stress fields at depth, producing spatially varying fracture abundances and openness, hydromechanical properties of bedrock, and saturation and pore pressure development in the subsurface. Also, it is unclear whether these changes can influence the slope stability of shallow and deep-seated landslides in natural landscapes. To adequately assess the role of bedrock stress on landslides, an integrated approach that connects subsurface stress distribution, bedrock weathering and fracturing, subsurface hydrology, and landslides is needed. Here, we show theoretical and observational studies that explore the topographic stress influence on landslides in varying landscapes.

2. Methods

We first examine whether subsurface weathered zones induced by topographic stress affect the size of bedrock landslides at landscape scales (Li & Moon, 2021). To do this, we first map 861 earthquake- and 121 precipitation-induced bedrock landslides from high-resolution satellite images in a granitic terrain at the eastern margin of the Tibetan Plateau. Then, we use a three-dimensional topographic stress model to predict the spatial patterns of open fracture zone within bedrock (Moon et al., 2017; St Clair et al., 2015). Topographic stress is modeled as an elastic stress field beneath 3D topography, considering the influence of gravity and regional tectonics constraint by hydraulic fracturing at nearby sites (Meng et al., 2015). Then, we compare the sizes of mapped landslides with the modeled patterns of open-fracture zones.

Second, we examine how the varying weathered bedrock structures and rainfall history influence occurrences, locations, and sizes of shallow landslides (Higa et al., in prep.). We use an intensely-monitored catchment near Coos Bay, Oregon, as a benchmark. Previous studies provide extensive measurements of surface and subsurface material and hydrologic properties (e.g., Montgomery et al., 1997; Schmidt et al., 2001; Anderson et al., 2002; Ebel et al., 2007), an instrumental record of a rainfall-triggered shallow landslide (Montgomery et al., 2009), as well as an inventory of shallow landslides that occurred over a 10 year period in the surrounding area (Montgomery et al., 2000). We first construct the modeled weathered bedrock distributions, including the predictions from the topographic stress model. We calculate the degrees of saturation at the soil-weathered rock boundary for given rainfall records using the 3D transient hydrologic model GEOtop (Rigon et al., 2006; Endrizzi et al., 2014; Formetta & Capparelli, 2019). Then, we model occurrences and size distributions of shallow landslides using a multidimensional slope stability model coupled with a spectral search algorithm (Bellugi et al., 2015a; Bellugi et al., 2015b).

3. Results & Discussion

In our bedrock landslide study, we find strong positive correlations between the upper bound of bedrock landslide area and the maximum value of failure potential (FPmax, a proxy for shear failure) within the landslides induced by both the earthquake and precipitation from our site in eastern Tibet (Figure 1 from Li and Moon, 2021). Our work indicates that the increased extent of subsurface open-fracture zones, predicted by topographic stress, tends to produce larger areas of bedrock landslides in granitic terrain. These findings are consistent regardless of the landslides are climatically or seismically triggered. Our study highlights the potential importance of topographic stress-induced bedrock fracturing and weathering in determining the sizes of bedrock landslides.

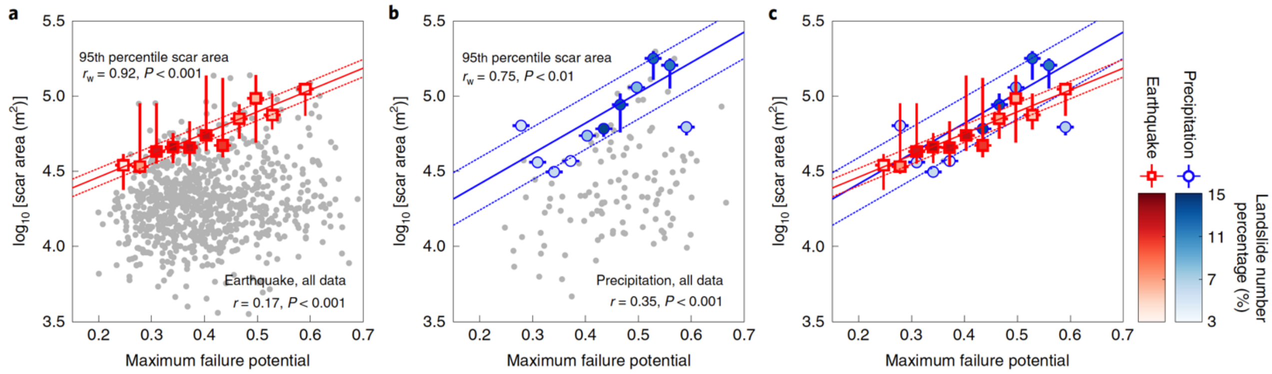

Figure 1. Comparison between bedrock landslide scar area and maximum failure potential (FPmax) for the earthquake-induced (a), precipitation-induced (b), and combined (c) bedrock landslides. Grey circles show all bedrock landslides. The bedrock landslides are grouped into 16 bins with equal FPmax intervals. Red squares (a,c) and blue circles (b,c) represent the 95th percentile of scar areas from the earthquake- and precipitation-induced landslides in each bin. The figure is from Li and Moon (2021).

The preliminary results from Oregon, USA, indicate measurable differences in soil saturation and shallow landslide distribution and characteristics depending on the subsurface structures of weathered bedrock and magnitudes of rainfall intensity. Our work implies that groundwater storage capacity in the subsurface modulates saturation in the soil-bedrock interface and potentially influences the response of shallow landslides to intense rainfall.

4. Conclusions

Our work shows that the topographic stress resulting from an interaction between tectonics and topography may influence subsurface bedrock weathering, subsurface hydrology, and shallow and deep-seated landslides in natural landscapes. Our work provides an improved understanding of the locations, timing, and magnitudes of hillslope failures and has potential implications in hazard mitigation and landscape evolution.

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