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# 3D modeling of topographic stress in alpine landscapes: the competition between relief formation and destruction

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The geometry of alpine landscapes is shaped by multiple stress-dependent factors. Relief formation through valley incision increases topographic stress toward a critical state, where rock failure occurs, which in turn reduces topographic stress due to relief-destroying landslides. Rock strength is a superior control in the delicate balance between the construction and destruction of the rock relief. By computing topographic stresses across entire mountain massifs, we can identify stress maxima in steep landforms prone to landsliding. This allows us to determine the maximum rock strength at the mountain scale, delineate potential surfaces of rock failure, and explain the contrasting geometries of alpine landscapes based on prevailing rock types.
Traditional 2D methods oversimplify complex stress patterns, particularly at converging valleys or around ridges and peaks. Although 3D finite element methods (FEM) provide detailed insights, they are computationally expensive for entire mountain massifs at the required high spatial resolution.
Our study addresses these challenges by combining several state-of-the-art 3D numerical methods into the numerical framework ViktorFCM. We utilize the Marching Volume Polytopes Algorithm for mesh generation, incorporating an octree-like structure and advancing-front meshing techniques to create accurate tetrahedral meshes. The Finite Cell Method (FCM), a fictitious domain approach, serves as an efficient alternative to FEM, transforming the problem of generating a suitable grid for complex geometries into specifying an adequate integration scheme for finite cells, thus saving degrees of freedom and computational resources. This computational efficiency is especially advantageous for equidistant grids such as digital elevation models, which serve as input data.
Benchmarking against other FEM programs showed that our method delivers comparable accuracy with the added benefits of FCM. Verification and validation confirm the algorithm's reliability and robustness.
In our initial study, we computed 3D topographic stress distributions for the three Austrian UNESCO Global Geoparks, characterized by steep valley flanks and high landslide activity. Results indicate high shear stress maxima predominantly in over-deepened glacial valleys, with shear stresses peaking at valley flanks and at or slightly below valley floors. Unexpected stress patterns emerged in areas with complex geometries, such as converging valleys or intersecting ridge lines. Lithological contrasts led to varying stress patterns, with carbonate-dominated units exhibiting the highest shear stress maxima.
Our model provides a new tool for combining local topographic metrics, spatial distribution of observed landslides, and rock types and eventually for assessing landslide potential over large areas (mountain scale). In the field of landscape evolution, before-and-after studies of stress distribution pre- and post-landslides support the hypothesis that landslides reduce topographic stress. Our findings provide new insights into the evolution of alpine landscapes, where, by calculating the topographic stresses, we can shed new light on the cycle of relief-forming (i.e., stress increase) and relief-reducing (i.e., stress decrease) processes towards a topographic equilibrium.

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