How does anisotropy control rock slope deformation? A discrete element modeling investigation

Marius Huber[1*^], Luc Scholtès[2], Jérôme Lavé[1]

[1] Centre de Recherches Pétrographiques et Géochimiques (CRPG), Université de Lorraine & CNRS, Nancy, France
[2] Laboratoire Magmas et Volcans (LMV), Université Clermont Auvergne & CNRS & IRD & OPGC, Clermont-Ferrand, France

* Corresponding author information: marius.huber@univ-lorraine.fr
^ Presenting author

Abstract

Deep-seated failures of rock slopes, both in the form of rapid rockslides (e.g., Clastonbury and Fell, 2010) or slow-moving landslides (e.g. Crosta et al., 2013), are partly controlled by structural, lithological and topographical factors. Among other structural factors, layering, schistosity and foliation in rock material, which could be described as inherent material anisotropy, affect the initiation and evolution of deep-seated slope deformation in sedimentary and metamorphic rocks. However, there is currently no quantitative or even conceptual framework that clearly defines the parametric role of anisotropy on the occurrence and type of landslides. Numerical modeling approaches are widely used to link the impact of mountain-slope-scale rock-mechanical parameters and slope geometry on the stability and failure behavior of rocky slopes (e.g. Katz et al., 2014; Spreafico et al. 2021), but very few have explored the influence of material anisotropy on slope stability. In order to address this important issue, we carry out a parametric study using a discrete element model implemented in the open source YADE DEM platform (Šmilauer et al., 2021).

After a validation test performed with an isotropic material, where we compare our numerical approach to an analytical slope stability solution (Leshchinsky et al.,1985), we introduce anisotropy (transverse isotropy) in our model by inserting preferentially oriented and weakened bonds be-tween discrete elements (a weakness plane) as proposed by Dinç and Scholtès (2018).

The introduction of these oriented and weakened bonds allows us to adequately reproduce in numerical triaxial tests the variations of strength of anisotropic rocks (shales, gneisses,…) as a function of the orientation of the weakness plane with respect to the maximum stress. In order to explore the stability of mountain slopes, we make the hypothesis that the transposition of this behavior on a large scale can be done essentially by degrading the material strength without modifying the formalism to introduce numerically the anisotropy. Working on simple geometries (1000m high slope-step, ridge or valley), we then explore the influence of the weakness plane's orientation on failure occurrence and volume. Using a strength reduction technique where the interparticle strength components are progressively reduced up to failure (Bonilla-Sierra et al., 2015) (Figure 1, A), we estimate for each studied case the required material strength that causes failure.

We show that certain orientations of the weakness plane relative to the topographic slope favor deep-seated deformation. We also observe significant disparities in material strength at failure, failure surface localization, and mobilized volume depending on the weakness plane orientation. For instance, the largest mobilized volumes are observed when the weakness plane rises 10° to 30° less than the slope angle and with an interparticle strength reduced less than for the other weakness plane orientations (Figure 1, A). These instabilities are associated with well-localized deformation at depth which produces morphological features (see for instance the double-crested ridge observed on the collapsing topography on Figure 1, B) that are commonly described along mountain ridges in association with slow-moving and deep-seated rock slope failures (Pánek and Klimeš, 2016).

Our results might help explain the appearance or absence of deep-seated failures in mountainous areas depending on the respective orientation relationship between the topography and the layering/foliation, and allow to better assess slope failure hazard induced by anisotropic rock strength.

Figure

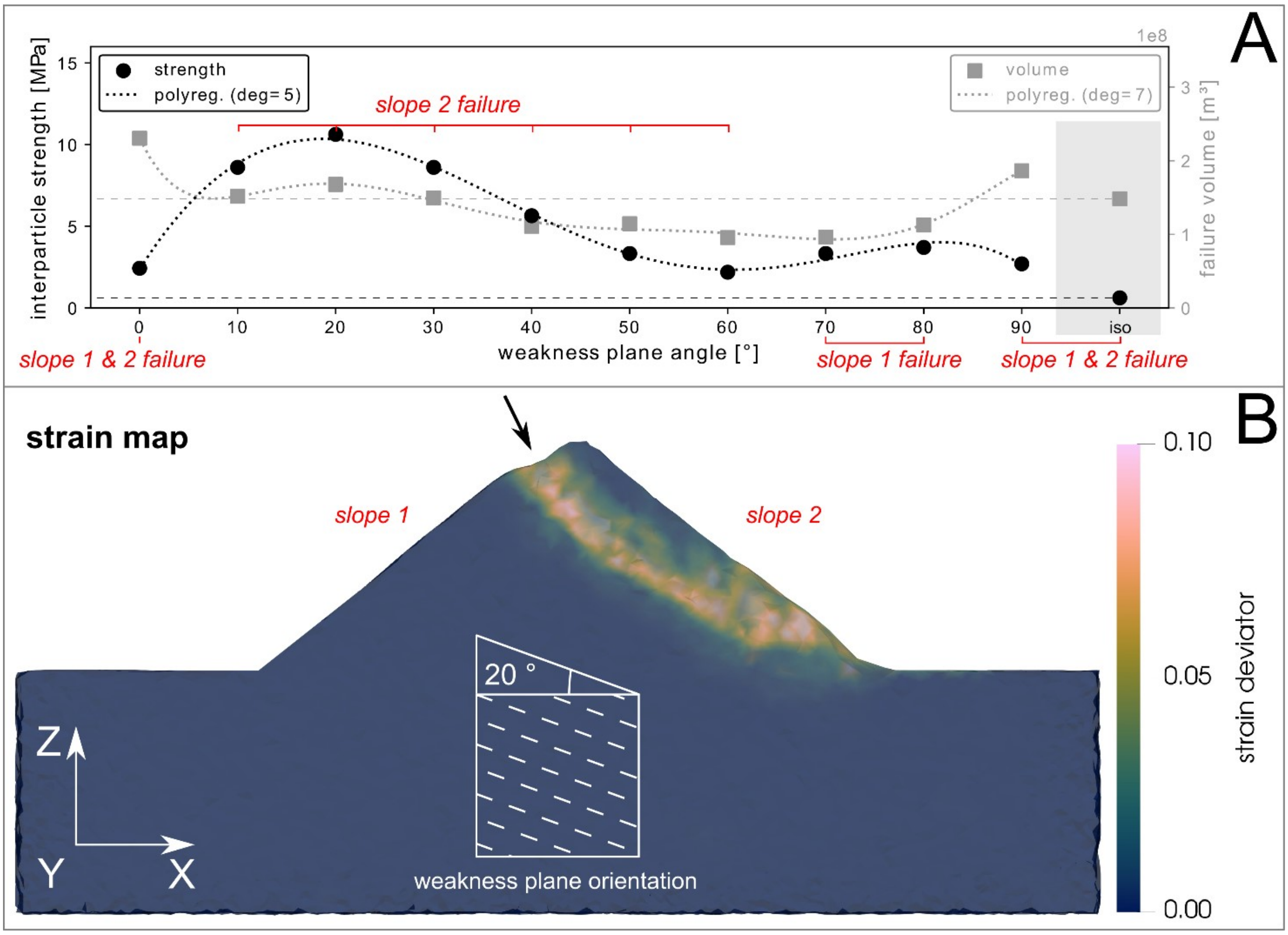

Figure 1. Numerical model (discrete element method) results obtained for a 40°-ridge-geometry. A: Interparticle strength at failure and estimated failure volume for different anisotropy angles and the isotropic case (no weakness plane introduced). Strength reduction starts from 20 MPa. What slopes fail depends also on the weakness plane orientation. B: deviatoric strain map calculated for an anisotropy angle of 20°. Failure surface is forming within the slope and a "double crest"-morphology is emerging on the opposite slope (indicated by the arrow).

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Reference list

Bonilla-Sierra, V., Scholtès, L., Donzé, F.V., and Elmouttie, M.K., 2015, Rock slope stability analysis using photogrammetric data and DFN–DEM modelling: Acta Geotechnica, v. 10, p. 497–511, doi:10.1007/s11440-015-0374-z.

Crosta, G.B., Frattini, P., and Agliardi, F., 2013, Deep seated gravitational slope deformations in the European Alps: Tectonophysics, v. 605, p. 13–33, doi:10.1016/j.tecto.2013.04.028.

Dinç, Ö., and Scholtès, L., 2018, Discrete analysis of damage and shear banding in argillaceous rocks: Rock Mechanics and Rock Engineering, v. 51, p. 1521–1538.

Glastonbury, J., and Fell, R., 2010, Geotechnical characteristics of large rapid rock slides: Canadian Geotechnical Journal, v. 47, p. 116–132, doi:10.1139/T09-080.

Katz, O., Morgan, J.K., Aharonov, E., and Dugan, B., 2014, Controls on the size and geometry of landslides: Insights from discrete element numerical simulations: Geomorphology, v. 220, p. 104–113, doi:10.1016/j.geomorph.2014.05.021.

Leshchinsky, D., Baker, R., and Silver, M.L., 1985, Three dimensional analysis of slope stability: International Journal for Numerical and Analytical Methods in Geomechanics, v. 9, p. 199–223, doi:10.1002/nag.1610090302.

Pánek, T., and Klimeš, J., 2016, Temporal behavior of deep-seated gravitational slope deformations: A review: Earth-Science Reviews, v. 156, p. 14–38, doi:10.1016/j.earscirev.2016.02.007.

Smilauer, V. et al., 2021, Yade documentation: The Yade Project, doi:10.5281/zenodo.5705394.

Spreafico, M.C., Sternai, P., and Agliardi, F., 2021, Paraglacial rock-slope deformations: sudden or delayed response? Insights from an integrated numerical modelling approach: Landslides, v. 18, p. 1311–1326.