

1 **Title:**

2 Stability and failure modes of slopes with anisotropic strength: Insights from discrete element models

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16 **Abstract**

17 This paper investigates the relationships between hillslope stability and fabric anisotropy of brittle rock
18 materials and the implications for landscape shaping. We use discrete element models to study the
19 stability and failure modes of slopes made of transverse isotropic rock materials, focusing more
20 particularly on the influence of the material orientation relative to the topographic slope. After validating
21 the numerical approach with a limit equilibrium analytical solution in the case of an isotropic material,
22 we modify our numerical slope models to simulate the rheological features of anisotropic gneissic rocks.
23 Systematic exploration of the transverse isotropy plane's orientation in two dimensions (dip angle)
24 reveals that slope collapse requires strength values that are highly dependent on the orientation of the
25 material relative to the slope. For a 1000 m high escarpment, the stability of a slope with a fixed gradient
26 requires strength that is one order of magnitude greater in a configuration where the isotropy plane is
27 slightly less inclined than the topographic slope (i.e., cataclinal overdip configuration) than in a
28 configuration where the isotropy plane is perpendicular to the slope (i.e., anaclinal configuration).
29 Mirroring this highly variable stability according to the relative orientation of the material, four modes of
30 deformation or gravitational instability are observed: in order of appearance, when the transverse
31 isotropy plane orientation goes from 0 to 180° with respect to the horizontal (going from cataclinal to

32 anaclinal configurations), the slope collapses respectively by sliding, buckling, toppling and crumbling.
33 The crumbling mode corresponds to a very stable configuration for which the preferred ground
34 movements will be rock falls from the cliff compared to the structurally controlled, deep-seated
35 deformation modes leading to sliding and toppling. Despite the simplifications inherent to the numerical
36 approach, our study highlights the essential characteristics of landslides occurring along slopes cut in
37 transverse isotropic materials and reproduces the various instability modes observed in natural slopes.
38 It also enables assessing their respective kinetics as well as the volumes of material they mobilize.
39 Finally, by comparing our findings on the azimuthal variations in hillslope gradients observed along the
40 central Himalaya (Nepal), in an area characterized by the relatively uniform orientation of the anisotropy
41 in gneissic and mica-schist formations, we show that, even though multiple environmental factors come
42 into play, landscape shaping is indeed strongly controlled by material anisotropy.

43

44 **Keywords**

45 Slope stability, landslides, failure modes, rock, anisotropy, numerical modeling, discrete element
46 method

47

48 1. Introduction

49 Landslides are known to play a key role in shaping landscapes ([Densmore and Hovius, 2000](#); [Korup et al., 2010](#)) and are a major hazard for millions of people and infrastructure globally ([Glade et al., 2005](#);
50 [Davies, 2021](#)), especially evident nowadays in mountainous regions in times of global warming (e.g.,
51 [Huggel et al., 2012](#)). The study of their dynamics and the control by factors like climate, lithology, and
52 tectonics on predisposing and triggering slope failures is fundamental for improving of natural disaster
53 preparedness and better understanding of the Earth's surface evolution over time.

54 Among the factors governing slope deformation, geological structures, with their different forms related
55 to nature and scale, are probably the most critical ([Jaboyedoff et al., 2011](#); [Stead and Wolter, 2015](#)).
56 Apart from large discrete structures such as folds, faults, and unconformities, intrinsic textural anisotropy
57 is commonly present in many rocks near Earth's surface through the lithology itself in the form of layering
58 and/or foliation. This homogeneously distributed matrix anisotropy, that predominantly corresponds to
59 transverse isotropy (TI), is not necessarily localized by bedding planes or joints, and usually concerns
60 the entire rock mass. The ability of TI rock materials to deform and withstand stresses varies according
61 to the orientation of stresses relative to their isotropy plane ([Hoek, 1964](#); [Barton and Quadros, 2014](#)).
62 Therefore, the orientation of a slope with respect to the plane of isotropy significantly affects its overall
63 stability, particularly the rupture localization and the associated failure mode. Slope failures related to
64 bedding planes, schistosity, or joint sets have been described and studied for either natural (e.g., [Stead
65 and Wolters, 2015](#)) or engineered slopes (e.g., [Read and Stacey, 2009](#); [Cheng and Lau, 2014](#)). For
66 natural slopes, such failure characteristics should play a key role in shaping the landscape.
67

68 Indeed, topography associated with underlying inclined bedrock of layered or foliated rocks commonly
69 features landforms described by geomorphologists as dip slopes, escarpments or homoclinal ridges
70 (e.g., [Cotton, 1949](#)). [Cruden and Hu \(1999\)](#) and [Cruden \(2000\)](#), based on a theory that links bedding
71 orientations to slope angles in sedimentary sequences of the Canadian Rocky Mountains, identified two
72 major failure modes, sliding and toppling, respectively, and observed that slope angles decrease when
73 the bedding is oriented parallel to the slope. [Chigira \(1992\)](#) identified different deformation patterns
74 governed by the preferential orientation of structures relative to the slope morphology from analyses of
75 slow-moving landslides in Japan. [Chigira \(2000\)](#) built upon these observations to define four distinct
76 failure modes controlled by the relative orientation of the slope with respect to the bedding (or foliation),
77 i.e., sliding, toppling, buckling, and a dragging mode for slopes that are principally stable but nonetheless
78 subjected to a deep-seated deformation process with a rupture zone cross-cutting the bedding planes

79 at depth. [Grelle et al. \(2011\)](#) also identified in southern Italy certain conditions strongly related to the
80 bedding orientation with respect to the slope, susceptible to promoting landslides in a bedrock composed
81 of an interlayering of clayey and stony sediments. Besides, studying landslides triggered by the 1933
82 Diexi earthquake in China, [Cui et al. \(2022\)](#) found variability in failure mode, frequency, and landslide-
83 affected area as a function of lithology and bedding orientation relative to the slope. All these studies
84 show that the mode of failure and the susceptibility of a slope to failure is strongly dependent on the
85 orientation of material anisotropy, i.e., bedding, schistosity, or regular jointing.

86
87 Many rock-mechanical lab-scale tests have been performed on a variety of TI rocks worldwide to assess
88 their direction-dependent properties (see e.g., [Donath, 1961](#); [Hoek, 1964](#); [McLamore and Gray, 1967](#);
89 [Niandou et al., 1997](#); [Nasseri et al., 2003](#); [Bonnelye et al., 2017](#)). All these tests show that strength
90 properties and failure modes are highly direction-dependent in such rock materials. For instance, [Tien](#)
91 [et al. \(2006\)](#) used compression tests on an analog rock material to illustrate how the failure mode and
92 strength change depending on the isotropy plane inclination with respect to the principal stress.
93 Transferring results from laboratory tests to the slope-scale requires scaling considerations (e.g.,
94 [Brideau et al., 2009](#); [Marinos and Carter, 2018](#)) which makes assessing and characterizing the
95 mechanical failure behavior of anisotropic rock media at the slope scale difficult. Existing studies with
96 analog models can provide valuable insight into the behavior of slopes made up of regular pervasive
97 joints: see, for instance, the centrifuge experiments that replicate flexural toppling ([Adhikari et al., 1997](#))
98 and sliding ([Li et al., 2014](#)), or the experiments with rigid blocks by [Aydan et al. \(1989\)](#). However, these
99 studies remain descriptive, are performed only for a few joint orientations, lack scaling considerations
100 for larger slope dimensions, and are technically challenging. It is, therefore, a logical step for scientists
101 to resort to numerical methods to study anisotropic rock slopes, given their capacity to reproduce results
102 systematically and to conduct comprehensive parametric studies, as well as the possibility they offer to
103 set up geometries and loading procedures that could not otherwise be realized by analog experiments.
104 Numerical studies of slope stability considering transverse isotropy are not so common in the literature.
105 Some studies based on continuum approaches, included anisotropic rock strength in their model
106 formulation for specific case studies ([Agliardi et al., 2012](#); [Roy et al., 2015](#); [Wang et al., 2018](#)) because
107 it is unavoidable to take into account the direction-dependent strength of layered or foliated rock slopes.
108 [Azami et al. \(2012\)](#) used the finite element method (FEM) to investigate the stability of a simple step-
109 like geometry considering the full 180° range of angles possible in a slope made up of a TI material in

110 two dimensional plane strain configuration. They determined the factor of safety for 22 different angular
111 configurations and found two stability minima and two stability maxima when plotting their results against
112 the full angle range. However, they did not use their methodology to track the temporal evolution or
113 mode of failure in their simulations. Discontinuum approaches, thanks to their capability to explicitly
114 describe discrete structures in materials, have been widely used for slope stability analysis and landslide
115 research (see, e.g., the review by [Stead and Wolter, 2015](#)). These approaches, which apply either the
116 discrete element method (DEM) ([Cundall and Strack, 1979](#)) or a hybrid method that combines the latter
117 with the FEM (FDEM, [Munjiza 2004](#)) can describe large deformation typical of rock slope failures as well
118 as their progressive failure ([Wang et al., 2003](#); [Utili and Crosta, 2011](#); [Scholtès and Donzé 2012](#); [Katz
119 et al., 2014](#)). They have been successfully used to investigate and reproduce complex failure
120 mechanisms of historic landslides in anisotropic rock formations (see, e.g., case studies from [Benko
121 and Stead, 1998](#) and [Zou et al., 2017](#)), or to mimic and theoretically study step path failures of mono-
122 or multi-modal pervasive joint sets inside rock slopes ([Scholtès and Donzé, 2015](#); [Zheng et al., 2018](#);
123 [Zheng et al., 2021](#); [Sun et al., 2022](#)). Nonetheless, despite their intrinsic capabilities and strengths over
124 continuum methods, discontinuum methods have not yet been used to perform a valuable,
125 comprehensive study covering the full range of possible rock strength anisotropy to slope face angles
126 within rock slopes.

127 Here, we propose such an investigation to gain better insight into how anisotropy quantitatively affects
128 slope stability and governs deformation characteristics and failure modes, aiming to shed light on how
129 the Tl rock orientation potentially modulates the Earth's surface topography and hazards in mountainous
130 regions. First, we present our modeling approach and justify its relevance for simulating rock slopes and
131 Tl materials. Then, after comparing our model's predictions to an analytical limit equilibrium solution that
132 describes failure in isotropic slopes, we present a comprehensive study of Tl rock slope stability that
133 covers the full range of isotropy plane vs. slope orientation in two dimensions for two different slope
134 gradients. The stability and failure modes observed over the entire range of orientations are then
135 discussed, and a comparison is finally made with a satellite data extraction of the Annapurna Massif of
136 Nepal to compare our findings in a natural setting.

137

138 2. Methods

139

140 2.1 The DEM model:

141 To study rock slope stability, we used the discrete element method (DEM) implemented in the open-
142 source software Yade Open DEM ([Šmilauer et al., 2021](#)). The rock material was simulated by spherical
143 discrete elements (DE) bonded to one another through elastic-cohesive-frictional interaction laws
144 governed by a modified Mohr-Coulomb criterion, as defined in the bonded particle model (BPM) of
145 [Scholtès and Donzé \(2013\)](#) (see also Figure S1). In the present study, we built upon previous works
146 dedicated to investigating slope stability using the same BPM ([Scholtès and Donzé, 2012, 2015](#); [Bonilla](#)
147 [et al., 2015, 2017](#)). The mechanical properties of the interparticle bonds dictate the overall emergent
148 behavior of the DE assembly. The bonds can break to give place to purely frictional inter-particle
149 interactions. Every time a bond breaks, a “crack” is defined at the former bond location. Cracks can be
150 either of tensile nature (mode I) or of shear nature (mode II), depending on the local stress field. As
151 classically done in the DEM, the simulations were calculated in iteration steps where the positions of the
152 particles are updated based on an explicit time integration of Newton’s second law of motion. In addition,
153 a non-viscous type damping was introduced to dissipate kinetic energy and favor the quasi-static nature
154 of the simulated behavior. We used a damping coefficient of 0.5 for all the models presented hereafter
155 (for details of the implementation, please refer to previously cited works and to [Šmilauer et al., 2021](#)).

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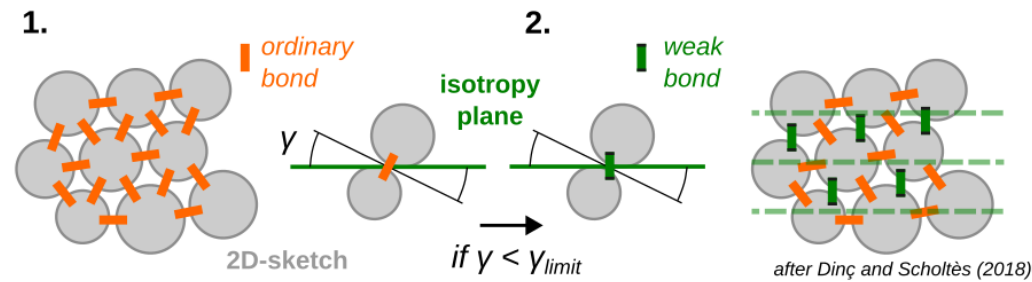
157 2.2 Modelling anisotropic rock materials

158 The BPM implemented in Yade has been recently enhanced to simulate TI rocks thanks to the
159 introduction of isotropy planes at the scale of particle contacts ([Dinç and Scholtès, 2018](#)). Here, we
160 make use of the same methodology to account for TI in our slope models (Figure 1a). Using the smooth
161 contact logic proposed by [Scholtès and Donzé \(2012\)](#), preferentially oriented discrete weak bonds are
162 introduced homogeneously within the particle assembly so that the overall emergent behavior presents
163 the typical features of transverse isotropic materials, i.e., direction-dependent properties or anisotropic
164 strength. As shown in [Dinç and Scholtes \(2018\)](#), the amount of these weak bonds and their mechanical
165 properties have to be chosen carefully to ensure the simulated behavior is representative of the target
166 rock material. In this study, we chose to simulate slopes made of a metamorphic rock. Following the
167 procedure proposed by [Dinç and Scholtes \(2018\)](#), we thus calibrated our BPM to mimic the laboratory
168 scale behavior of a gneissic rock presented in [Saroglou et al. \(2004\)](#). To do so, we performed a series

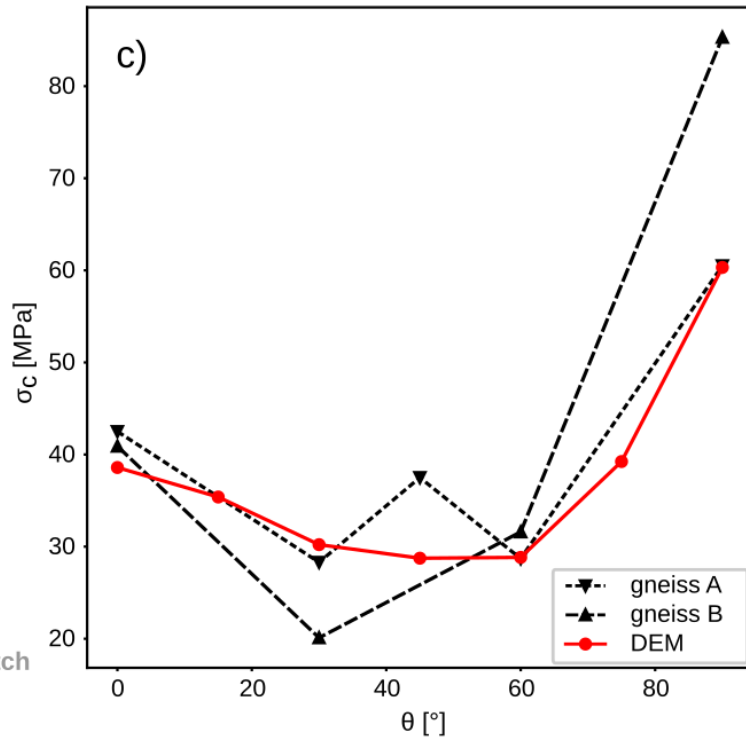
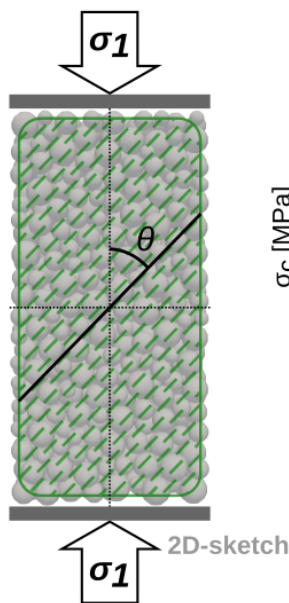
169 of uniaxial test simulations (Figure 1b) and adjusted the BPM parameters to match the experimental
170 behaviors described by Saroglou et al. (2004) with emphasis put on the direction-dependent strength
171 properties characteristic of such rock type. As shown in Figure 1c, the calibrated BPM can reproduce
172 the experimental observations: the uniaxial compressive strength evolves as a function of the angle θ
173 between the principal stress direction and the isotropy plane with a typical asymmetric U-shape, the
174 maximum strength corresponding to $\theta = 90^\circ$ (loading perpendicular to the foliation), and the minimum
175 strengths corresponding to $\theta \in [30^\circ, 60^\circ]$ (see the model properties in Table S1). Similarly, the Young
176 modulus E_{lab} of the simulated material varies with θ , E_{lab} being minimum for $\theta = 90^\circ$, and maximum for
177 $\theta = 0^\circ$ such as $E_{lab}^{0^\circ}/E_{lab}^{90^\circ} \approx 1.5$, with $E_{lab}^{0^\circ} \approx 55$ GPa. Of course, given our objective to simulate large
178 rock slopes, we used a specific strategy to upscale these properties for our slope models (see Section
179 2.3.2).

180

a) anisotropy introduction



b) uniaxial test



181

182 Figure 1: a) Selection (1) and reorientation (2) of ordinary bonds to preferentially oriented weak bonds

183 in a DEM assembly to produce an emergent transverse isotropic behavior (after Dinç and Scholtès,

184 2018). γ is the angle used to detect contacts subparallel to the isotropy plane and to change the

185 corresponding ordinary bonds to weak bonds. b) Uniaxial testing simulation used to calibrate the DEM

186 model. θ is the angle between the isotropy plane and the major principal stress direction (axis of

187 compression here). c) Comparison of the model prediction with the experimental observations by

188 Saroglou et al. (2004): change in the uniaxial compressive strength as a function of θ .

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191 2.3 Model set-up

192

193 2.3.1 Geometry, boundary conditions and preconditioning

194 Our slope failure experiments are performed on slope slices with a height of 1,000 m and a slope angle
195 β that can be varied (Figure 2a-b). To avoid numerical artifacts caused by regular packings, the slope
196 models were made up of particles presenting a polydisperse size distribution (with variation up to 1/3 of
197 the predefined mean particle radius). The packings were generated through the progressive growth of
198 particles initially randomly placed within a predefined closed volume (i.e., as a cloud of polydisperse
199 particles). The growth was stopped when the porosity of the packing reached 30%, and the packing was
200 mechanically stable. The mean particle radius was set to 20 m. The thicknesses of our slope slices are
201 designed so that approximately 10 particles were present in the out-of-plane direction, a resolution that
202 proved to give mesh objective results (see Section 3). Lateral boundary conditions were defined by
203 blocking the translation in the direction normal to the boundary for the outermost particles (those whose
204 centers are located within a zone of 3 times the mean particle radius from the boundary). At the bottom
205 of the model, translations and rotations were blocked in all three directions for an equally defined layer
206 of particles (Figure 2b).

207 To initialize stresses within our slope models, we adapted the loading procedure proposed by [Katz et](#)
208 [al. \(2014\)](#), as illustrated in Figure S2. First, we applied gravity to a square packing of particles whose
209 density ρ_p was adjusted to ensure that the gravity-induced stress within the model corresponds to the
210 stress found in a slope made up of a material with density $\rho = 2500 \text{ kg/m}^3$ (i.e., $\rho_p = \rho \cdot V/V_p$, with V the
211 volume of the model and V_p the volume occupied by the particles). This gravity loading was performed
212 considering 200 m of overburden above the final height of the slope. Then, after cutting of the
213 overburden by eliminating particles from the simulation, the slope geometry was defined in a similar way
214 by removing particles located above the final topography (Figure S2). This process was chosen to mimic
215 the natural genesis of mountains where the subsurface is under the influence of the overlaying rock
216 mass, and the topography only develops later through erosion, as observed for valleys forming through
217 fluvial or glacial erosion in mountainous environments. The strength of all the interparticle bonds was
218 set to a very high value during this preconditioning stage to ensure an elastic response of the model
219 (i.e., no internal damage was induced up to the end of the preconditioning stage) (step 4 in Figure S2;
220 Table 1).

221 2.3.2 Upscaled mechanical behavior

222 To define the properties of our slope models, we followed a procedure classically used in rock
223 engineering where lab-scale properties are upscaled based on rock mass classification and associated
224 empirical scaling indexes. For instance, the elastic properties of the slope models were defined following
225 the approach by [Hoek and Diederichs \(2006\)](#), who proposed an empirical relation that relates the lab-
226 scale Young's modulus of the rock material E_{lab} to the rock mass deformation modulus E as a function
227 of the Geological Strength Index (GSI):

$$228 \quad E = E_{lab} \times \left(0.02 + \frac{1-D/2}{1+e^{((60+15D-GSI)/11)}} \right) \quad (1)$$

229 where D is a disturbance factor related to the excavation method (we considered $D = 0$ here). The GSI
230 is a rock mass classification index that relies on the description of rock structures and block surface
231 condition, which can vary between 0 and 100 depending on the quality of the rock mass ([Hoek et al.,
232 2002](#)). Originally built upon a large data set of field measurements, the GSI approach has been used
233 successfully by geotechnical engineers for decades to upscale the mechanical properties of rock
234 masses from lab-scale measurements. We used Equation (1) to define the elastic bond properties of
235 our slope models based on the lab-scale values measured by [Saroglou et al. \(2004\)](#) and a GSI value
236 ranging between 15 and 30 (see Table 1 for values). This GSI value would correspond to a moderately
237 to severely damaged rock and could be assumed realistic for natural slopes affected by weathering and
238 tectonism ([Marinos and Hoek, 2000](#); [Marinos and Carter, 2018](#)).

239 In addition, we also altered the intrinsic strength of our slope models by adjusting the $intR$ parameter of
240 the BPM which is an explicit representation of the degree of particle interlocking ([Scholtès and Donzé,
241 2013](#)). At the lab scale, $intR$ can be adjusted to simulate the behavior of more or less porous rocks,
242 which would respectively present typical linear Mohr-Coulomb failure envelopes for $intR = 1$ or non-
243 linear Hoek and Brown failure envelopes for $intR > 1$. Considering the scale of our slope models, the
244 degree of particle interlocking can be seen as an indicator of the fracturing degree of the rock mass, and
245 we thus made the choice to define $intR = 1$ in our simulations in order to take into account the role of
246 defects of all sorts coexisting within the medium (faults, fractures, joints, etc.). Given the method that
247 we used in our simulations, we don't have to define upscaled values for the strength parameters (see
248 the following section).

249 2.3.3 Strength reduction method

250 Once the slope model is stabilized under gravity and the slope topography is cut, all bond strengths are
251 initialized at the predefined values (see Table 1) and the actual simulation starts (Figure S2, step 4).
252 The intrinsic model time is set to zero at this exact moment. The simulation consists of a strength
253 reduction (SR) method that involves the progressive decrease of the interparticle bond strength, as
254 proposed by [Bonilla-Sierra et al. \(2015\)](#). The tensile strength T_p and the cohesion C_p of the bonds
255 (ordinary bonds only, since the weak bonds do not have any strength, as shown in Table 1) are reduced
256 simultaneously to promote failure of the slope. The SR method enables to reach failure without having
257 to predefine an upscaled strength for the rock material. Also, it provides critical strength reduction values
258 at failure, which are case-dependent and thus enables assessing the proneness of different slope
259 models to fail by comparing the amount of strength reduction needed to reach failure.

260 Practically, T_p and C_p decreased stepwise by 10% up to failure, the strength reduction factor (redFac)
261 defining the cumulative reduction applied (see Figure S1 and Table 1). In this study, we combined
262 different criteria to check if the slope models were stable and if further SR was needed (see Figure 2c-
263 d). Practically, SR is applied if the three following conditions are met:

- 264 • the overall kinetic energy (E_k) remains below a threshold,
- 265 • a moving average of E_k , namely \bar{E}_k , remains below a threshold
- 266 • no cracks were generated since the previous checkpoint.

267 The redFac plotted over the iterations of a simulation allows us to determine the critical inter-particle
268 strength needed for stability for each simulation (Figure 2c). For more information on the SR method,
269 please refer to the Supplement (S1).

270

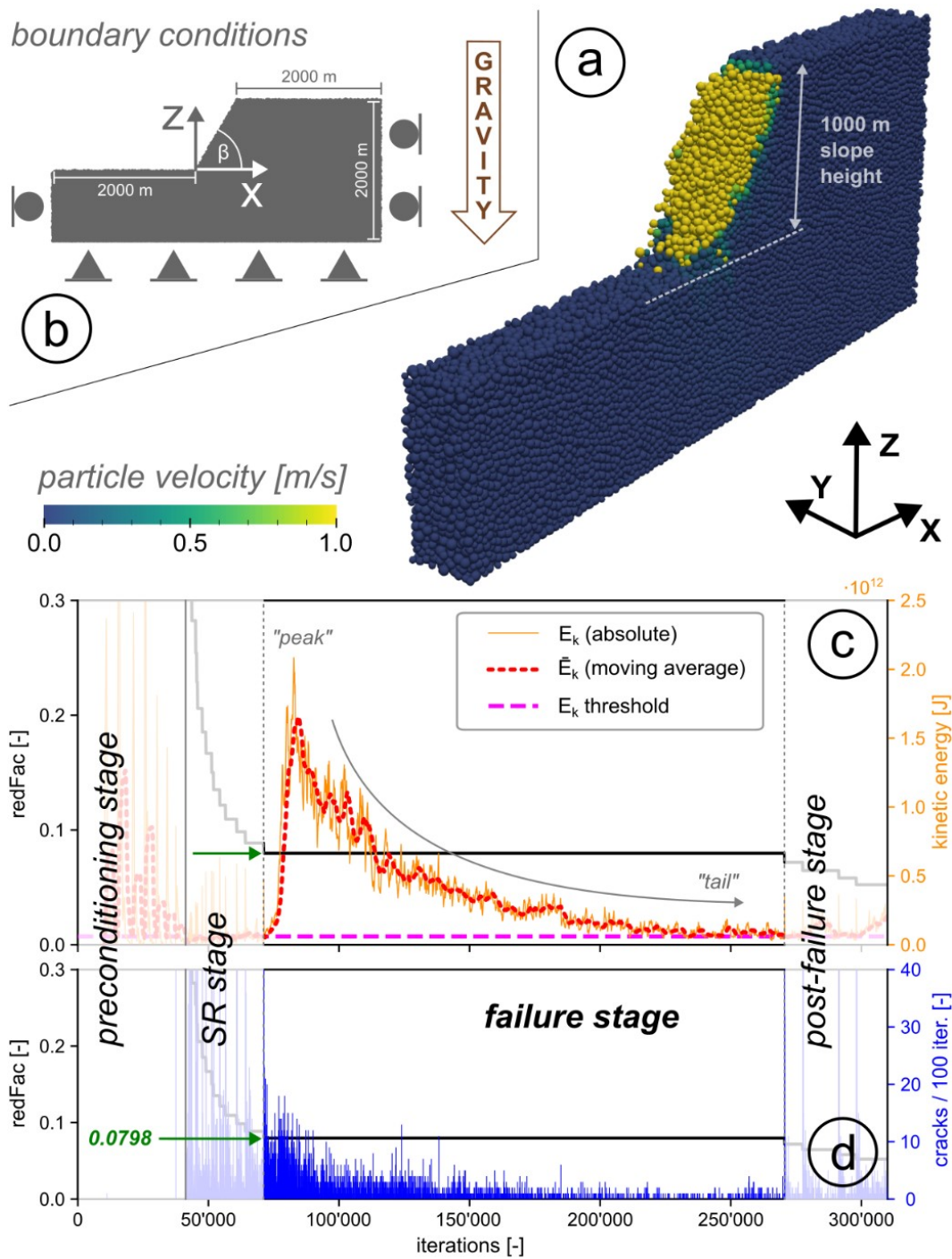
271 Table 1: Inter-particle bond properties of the slope models before SR is applied

272

Parameter	ordinary bonds	anisotropy bonds
Interaction radius intR [-]	1.0	-
Elastic modulus Y [GPa]	10	1
Stiffness ratio P [-]	0.1	0.1
Tensile strength T_p [MPa]	100	0
Cohesion C_p [MPa]	100	0
Friction angle ϕ_p [°]	10	0
Dilation angle ψ [°]	-	0
Angle range γ_{limit} [°]	-	55

273

274



275

276 Figure 2: a) 3D view of a slope model at failure; b) boundary conditions; recordings from a simulation

277 (anisotropy angle $\alpha = 70^\circ$ and slope angle $\beta = 60^\circ$) that has been brought to failure by strength reduction

278 (SR): c) reduction factor (redFac) and kinetic energy indices (absolute value E_k and moving average \bar{E}_k),

279 and d) crack frequency plotted over iterations.

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281 3. Relevance of the discrete element approach for investigating slope stability

282

283 Assessing the capability of numerical models to simulate slope failure in anisotropic materials is not
284 straightforward. A recent study ([Stockton et al., 2019](#)) explores, using a semi-analytical procedure, the
285 stability of slopes in the presence of frictional or cohesive anisotropy. However, the proposed definition
286 of anisotropic cohesion as a $\sin^2(\cdot)$ function of the angle between the isotropy plane and the principal
287 stress direction is not consistent with our emergent TI behavior nor with uniaxial laboratory results for
288 gneisses (Figure 1), so a direct comparison was not possible. We, therefore, preferred to assess the
289 relevance of our numerical models by comparing their predictions with an analytical solution derived
290 from stability analysis in the case of an isotropic material. We performed such a comparison considering
291 the same geometry, loading procedure, SR method, and inter-particle bond properties as the ones
292 presented in Table 1, except that no weak bonds were introduced into the model (see Section 2.2 and
293 Figures 2 and S2). We compared our model results to the analytical solution derived by [Leshchinsky et](#)
294 [al. \(1985\)](#) based on the limit equilibrium theory and a variational calculation scheme. The solution
295 consists of a log-spiral failure geometry associated with a factor of safety (FoS) obtained for a slope
296 step with a certain slope angle (β), made of a homogeneous Mohr-Coulomb (MC) type material with
297 given cohesion (C) and friction angle (φ). It is thus possible to determine the critical MC strength
298 properties (C , φ) of a slope and its rupture surface by considering $\text{FoS} = 1$.

299 The comparison exercise was also an opportunity to test the objectivity of the numerical model when
300 varying some of its parameters, such as the number and size of its constitutive elements, their spatial
301 arrangement, or the criteria used for the SR method. To this end, we carried out a total of 48 slope
302 simulations on eight different packings built up with two different mean particle radii ($R = 20$ m and $R =$
303 15 m) and cut at two different slope angles β (40° and 60°). This parametric study showed that the
304 results obtained are generally insensitive to the choice of particle radius or spatial arrangement,
305 indicating that they are overall robust (see Supplement S2 for further details).

306 Table 2 summarizes the critical interparticle bond strength values (C_p and T_p) and the corresponding
307 emergent MC parameters at failure (C_e and φ_e) obtained for the 48 slope simulations (see in Supplement
308 S2 and S3 how these properties were obtained based on results of dedicated bi-axial tests, Figure S3).
309 They are compared to the MC parameters predicted by the 2D solution of [Leshchinsky et al. \(1985\)](#). For
310 both slope angles tested here, φ_e ranges around 32° . For such a value of the friction angle φ , the
311 analytical 2D solution predicts critical cohesion values C that are slightly different from the C_e of the

312 numerical material. Agreement on the cohesion values can be reached, however, by considering a
313 slightly lower (around -2° offset) or higher (around 3° offset) friction angles for the 40° and 60° slopes,
314 respectively. These minor deviations are nonetheless acceptable, taking into account the dispersion of
315 the original T_p and C_p values (see Table S2) and the procedure used to obtain the emergent MC
316 parameters (fitting a Mohr-Coulomb criterion to discrete values). Regarding the geometry of the failure
317 plane, the numerical and analytical rupture surfaces are in close agreement for the $\beta = 60^\circ$ slope
318 simulations (Figure 3). For $\beta = 40^\circ$, the analytical solution shows a slightly more pronounced curvature
319 than the numerical solution (Figure S5). Overall, our numerical results compare relatively well with the
320 analytical solution for both the MC strength parameters at failure and the geometry of the failure surface.
321 We did not increment the slope height in our simulations because, according to limit-equilibrium
322 description of slope stability problems (e.g., [Leshchinsky et al., 1985](#)), changing the slope height (e.g.
323 to 100 m or 500 m) does not significantly change the geometry of the failure plane, but only changes
324 the strength at failure by a proportionally inverse amount. For instance, for a slope height $H = 100$ m,
325 we would simply get much higher C_p and T_p values at failure (see Figure 4) than for $H = 1000$ m with a
326 similar rupture plane geometry, as predicted by the non-dimensional parameter $N = C/\rho g H$ ([Leshchinsky](#)
327 [et al., 1985](#)), with material density ρ and gravitational acceleration g .

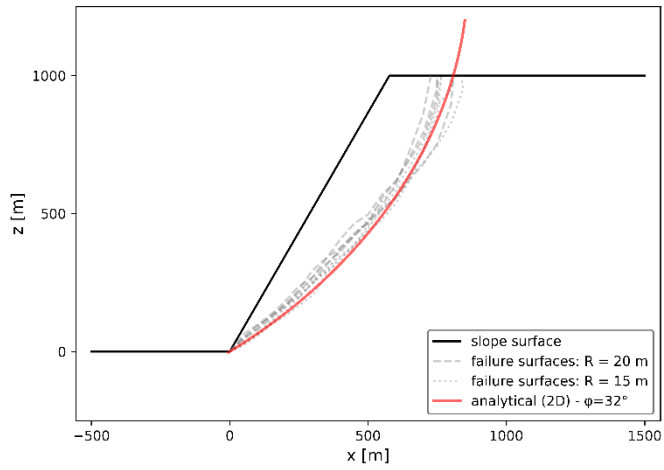
328 Table 2: Comparison of DEM results and analytical solution after [Leshchinsky et al. \(1985\)](#). The DEM
 329 interparticle properties at failure correspond to means calculated over 4 different slope models run with
 330 different packings (see Table S2 in Supplement). The emergent MC parameters were obtained from
 331 back analyses of biaxial test simulations (see Table S2 in Supplement). The MC parameters at failure
 332 were obtained based on the 2D analytic solution ([Leshchinsky et al., 1985](#)) (values of interest in bold).

333

	Topographic slope $\beta = 40^\circ$		Topographic slope $\beta = 60^\circ$	
DEM	Interparticle strengths at failure			
	φ_p [°]	C_p & T_p [MPa]	φ_p [°]	C_p & T_p [MPa]
	10	0.42 ± 0.13	10	2.86 ± 0.16
	Emergent Mohr-Coulomb parameters			
	φ_e [°]	C_e [MPa]	φ_e [°]	C_e [MPa]
	32	0.33 ± 0.03	32	1.14 ± 0.07
analytical solution	Mohr-Coulomb parameters at failure			
	φ [°]	C [MPa]	φ [°]	C [MPa]
	30	0.37	30	1.47
	31	0.31	31	1.40
	32	0.26	32	1.32
	33	0.21	33	1.25
	34	0.17	34	1.18
	35	0.13	35	1.11

334

335



336

337 Figure 3: The $\beta = 60^\circ$ slope results obtained for 2 resolutions (mean particle radius $R = 20$ m and $R =$
 338 15 m respectively) compared to [Leshchinsky et al. \(1985\)](#)'s 2D analytical slope stability solution for $\phi =$
 339 32° (red curve).

340 Color in print, one column width

341 4. Results

342

343 SR simulations were conducted on two different particle arrangements, referred to in the following as
344 packings P1 and P2, each with an identical mean particle radius of 20 m and the same overall
345 geometrical properties but created from two different initial clouds of particles (see Section 2.3). We
346 explored slope stability in two dimensions considering the full range of possible orientations of the
347 isotropy plane relative to the horizontal (dip both towards and away from the slope, hereafter designated
348 as the anisotropy angle $\alpha \in [0^\circ, 180^\circ]$, Figure 4) by running simulations every 10° increments considering
349 two different slope angles ($\beta = 40^\circ$ and 60°) for each packing.

350

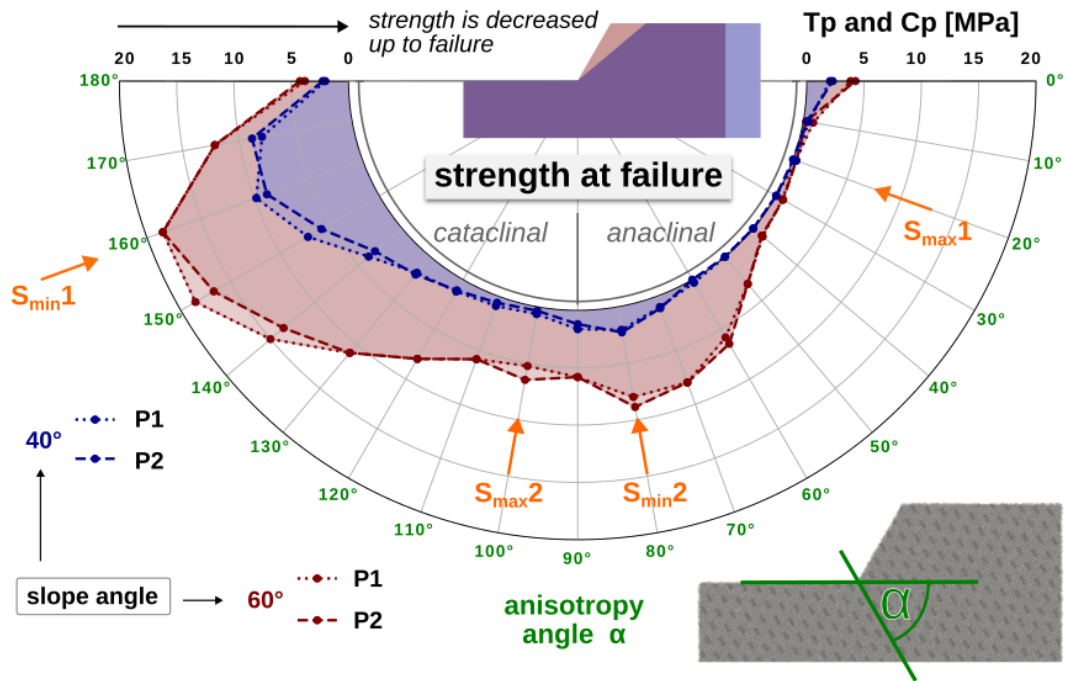
351

352 4.1 Slope stability over the 180° range

353 Overall, the T_p and C_p values at failure show similar trends for both the $\beta = 40^\circ$ and 60° slopes, as well
354 as strong variations depending on the angle α (Figure 4). As expected, 40° slopes fail for considerably
355 lower inter-particle strengths, whatever the configuration (40° slopes are intrinsically more stable than
356 60° slopes). Slope models with an isotropy plane that rises less than the slopes themselves ($\alpha \in [130^\circ,$
357 $170^\circ]$), classified as cataclinal overdip slopes by [Cruden and Hu \(1996\)](#), fail with the highest T_p and C_p
358 values, meaning that they correspond to the least stable slopes. The stability minimum $S_{\min 1}$
359 corresponds to $\alpha \approx 160^\circ$. Slope models with isotropy planes dipping sub-vertically towards the slope (α
360 $\in [60^\circ, 90^\circ]$), defined as anaclinal slopes with steepened escarpment by [Cruden and Hu \(1996\)](#), fail for
361 lower T_p and C_p values than $S_{\min 1}$ and show another stability minimum, $S_{\min 2}$, at $\alpha = 80^\circ$. Slopes with
362 isotropy planes dipping at low angles into the slope ($\alpha \in [10^\circ, 50^\circ]$), classified as anaclinal slopes with
363 subdued escarpment by [Cruden and Hu \(1996\)](#), fail for the lowest recorded inter-particle strengths,
364 which means they correspond to the most stable slopes (for $\beta = 40^\circ$, interparticle strength values drop
365 down to zero for some cases). For $\beta = 60^\circ$, the stability maximum $S_{\max 1}$ is at $\alpha = 20^\circ$. Another stability
366 maximum $S_{\max 2}$ can be identified around $\alpha = 100^\circ$, a configuration that corresponds to cataclinal
367 underdip slopes according to [Cruden and Hu \(1996\)](#).

368 By looking at the stability minima and maxima over the entire range of possible anisotropy angles, we
369 observe an apparent symmetry over the $\alpha = 90^\circ$ plane for both slope angles, with both minima and
370 maxima lying 80° apart from each other.

371



372

373 Figure 4: Stability curves over the full range of possible orientation (α) of the isotropy plane with respect

374 to the horizontal: interparticle strength at failure (T_p and C_p) obtained from DEM simulations performed

375 on slopes with distinct angles ($\beta = 40^\circ$ and 60°). P1 and P2 are two different particle packings. Stability

376 minima and maxima are indicated (S_{min} and S_{max}).

377 Color in print, 1.5 column width

378 *4.2 Stability extrema: overall kinetics*

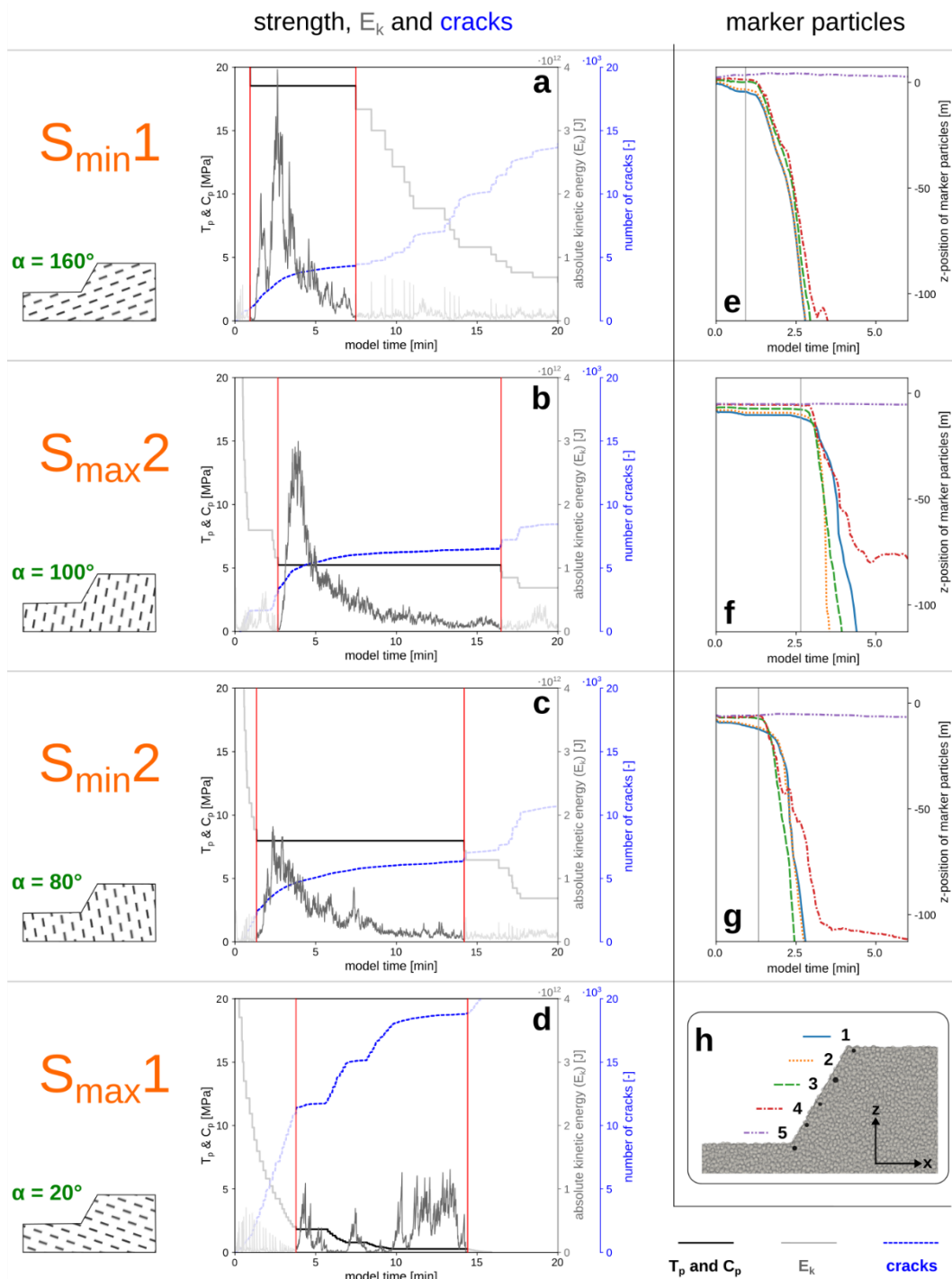
379 Our simulation results can be further explored by comparing failure index parameters evolving (like in
380 Figure 2, Section 2.3). Here, we only investigate the $\beta = 60^\circ$ slope angle simulations (packing P1)
381 corresponding to the four stability extrema. In Figure 5, we plot out their respective critical strength
382 values, T_p and C_p , their overall kinetic energy E_k , and their accumulated total number of cracks over the
383 simulation time. Only cracks occurring near the slope surface are accounted for in the analysis (see
384 Figure S6). The plots reveal significant disparities in failure evolution for the four cases (the respective
385 start and end of the failure stage are marked with vertical red lines in Figure 5a-d).

386 First, the more stable configurations ($\alpha = 20^\circ$ and 100°) need more time/iterations to fail since they need
387 more SR. For $\alpha = 100^\circ$, a minor instability is responsible for a small pre-failure plateau in the SR-curve
388 (Figure 6c). E_k does not rise high during this stage compared with the failure stage observed afterward,
389 and we thus considered that this pre-failure stage was irrelevant when assessing the critical state
390 parameters. This pre-failure stage resulted from the detachment of a few individual particles along the
391 slope face that had to settle at the base of the slope before the SR could resume. For $\alpha = 20^\circ$, E_k shows
392 several peaks of low and similar magnitude, which were separated by periods of additional SR (see
393 Figure 6d). The principal slope failure was assigned over all three SR plateaus as a multi-step failure (in
394 Figure 4, T_p and C_p at failure were plotted for the lowest plateau in simulations where multi-stage failure
395 occurred). The other three configurations display pronounced individual peaks of E_k that differ in shape
396 and magnitude (Figure 5a-c). The $\alpha = 160^\circ$ configuration shows the highest rise in magnitude, but the
397 peak has a short tail. The failure duration correlates directly with the length of the E_k -peak's tail. The $\alpha =$
398 100° and $\alpha = 80^\circ$ configurations need more time to stabilize after failure initiates compared to the $\alpha =$
399 160° configuration. The latter configuration exhibits the smallest amount of cracks accumulated before
400 and at the end of failure among all simulations. The $\alpha = 20^\circ$ case already has a very high number of
401 total cracks before its first failure and a low gradient of the cracks-curve during the failure plateaus (see
402 Figure 5d). This can be explained similarly to the $\alpha = 100^\circ$ pre-failure plateau by the detachment and
403 subsequent fall-down of isolated particles. In contrast, the other simulations reveal much more
404 intensified cracking during failure (Figure 5: steeper gradient of cracks-curve reflects intensified cracking
405 within the slope).

406 The slope failure evolution is additionally tracked by making use of marker particle recordings shown in
407 Figure 5e-h and Figure S7. They indicate fundamental differences in the way deformation takes place
408 within the slope. For $\alpha = 160^\circ$ they show a coherent translation of the elements along the slope surface

409 far into the failure process (Figure 5e and Figure S7a). In contrast to the lower marker particles, the
410 upper two marker particles have already subsided by several meters before the main failure sets in
411 (Figure 5e). The marker particles of the $\alpha = 100^\circ$ case (Figure 5f and Figure S7b) reveal that the mid-
412 slope section (marker particles no. 2 and 3) drops down earlier than the lower part of the slope (marker
413 particle no. 4). The lower two marker particles of the $\alpha = 80^\circ$ case start to move a bit later but more
414 suddenly and then faster than the upper two (Figure 5g and Figure S7c). For all simulations shown in
415 Figure 5e-g, marker particle no. 4 (red line), which is located at the base of the slope, does not fall down
416 consistently like the other marker particles located further upslope. For simulations with sub-vertically
417 dipping isotropy planes ($\alpha = 80^\circ$ and $\alpha = 100^\circ$), the drop of marker particle no. 4 slows down significantly.
418 Overall, the marker particles of $\alpha = 80^\circ$ and $\alpha = 100^\circ$ (Figure 5e-f) move less uniformly than the ones of
419 the $\alpha = 160^\circ$ case (Figure 5g; see also Figure S7).

420



421

422 Figure 5: Failure characteristics of the four stability extrema observed for the $\beta = 60^\circ$ slope (packing P1).

423 a - d: interparticle T_p and C_p reduced by SR method, absolute kinetic energy E_k , and cumulative number

424 of cracks. Start and end of the main failure stage are indicated with red vertical lines. e - g: time records

425 of the marker particles vertical position relative to their initial position; the vertical grey line indicates the

426 start of failure; h: initial locations of marker particles on the slope.

427 Color in print, double column (full width)

428 4.3 Stability extrema: failure behavior

429 The deformation processes of the four anisotropy angles that yield extreme T_p and C_p values at failure
430 for $\beta = 60^\circ$ are illustrated in Figure 6. The deviatoric strain maps (Supplement S3; [Catalano et al., 2014](#))
431 are plotted for 2 states within the failure stage to examine the onset of failure and its progression
432 throughout the slope. As an additional indicator of the deformation, the cracks (broken bonds) that have
433 accumulated up until the respective deformation stages are also shown. In addition, we present so-
434 called layer cake visualizations in which the particles are alternately colored according to the orientation
435 of the isotropy plane to better illustrate the different failure behaviors at more advanced points of the
436 simulation. Finally, we extracted videos using the layer cake visualizations of Figure 6 from the beginning
437 to the end of the failure stage for some configurations (Failure videos in Supplement) and also displayed
438 the final stage of the failure process, representing the displacement and the damage index of each
439 particle (Figure S8).

440 The failure of the stability minimum $S_{\min 1}$ ($\alpha = 160^\circ$) initiates in the lower half of the slope and progresses
441 further up along a rupture zone that eventually reaches the top of the slope (Figure 6a-b). Cracks appear
442 mostly in the zone of high deviatoric strain that predefines the post-failure rupture surface (thin white
443 line). A quasi-translational failure is observed with a well-defined primary block that slides along the
444 failure surface and a secondary block slightly tilted on the upper end of the mobilized volume (Figure
445 6c). Cracks (i.e., damage) are mainly localized along the failure surface, corroborating the formation of
446 a blocky structure that slides down the slope. The sliding mass retains most of its original shape,
447 including a large undeformed chunk in its upper part (Figure S8, a and e), and collapses with only a
448 minimal rotation during failure. The dip of the rupture surface is slightly steeper than the dip of the
449 isotropy plane; thus, the rupture cuts across the isotropy plane.

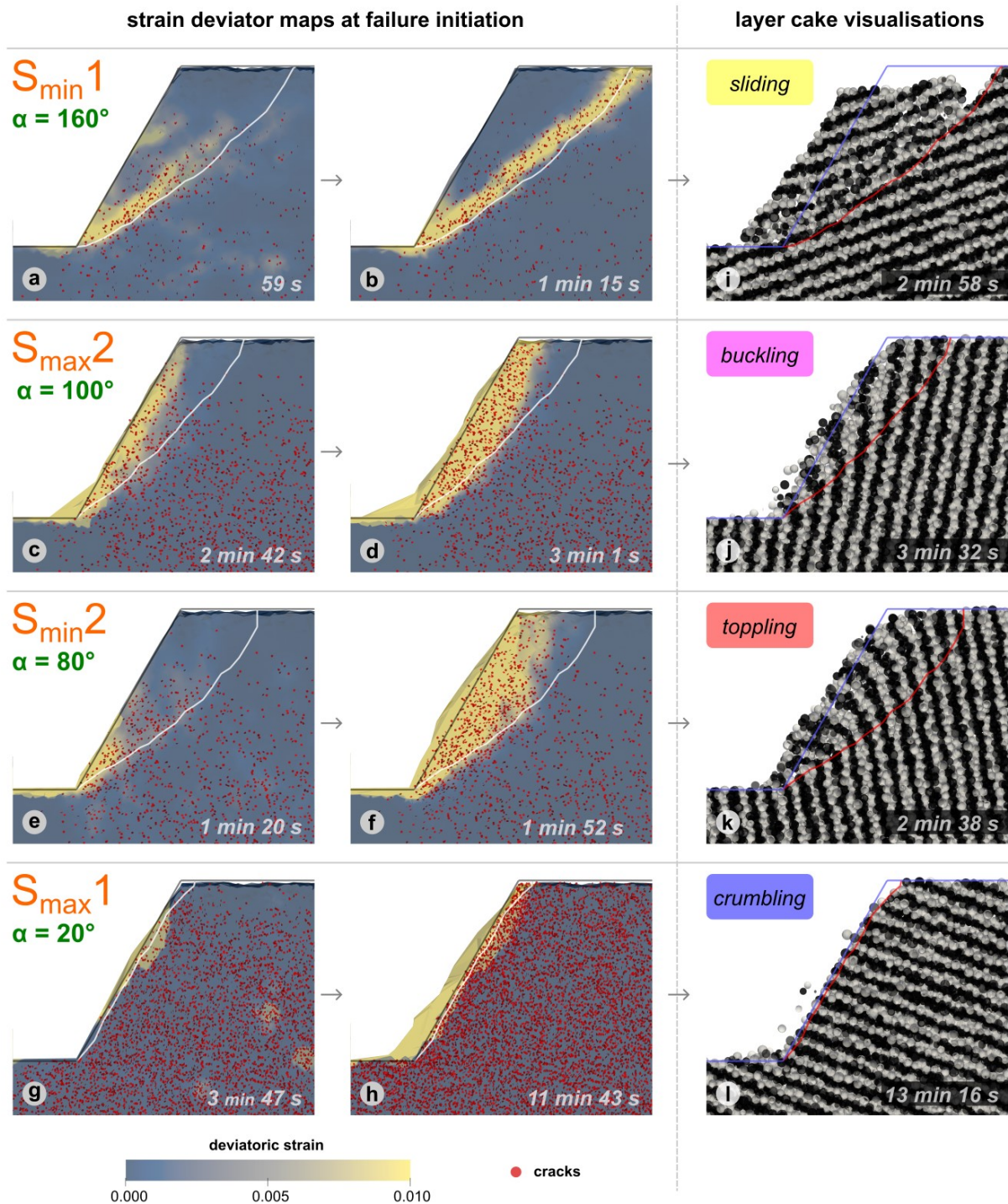
450 The mode of failure observed for $\alpha \in [130^\circ, 170^\circ]$ is sliding. The Failure videos show that the internal
451 deformation at the early stages of failure is much higher for $\alpha = 130^\circ$ and gets lower with the shallower
452 dipping angle at $\alpha = 160^\circ$ where big parts of the sliding mass remain coherent, and deformation localizes
453 mostly on the rupture surfaces. For $\alpha \in [150^\circ, 170^\circ]$, failures involve high mobilized volumes and the
454 lowest amount of cracks among all the cases (Figure S9).

455 Figure 6 reveals that failures observed for $\alpha = 80^\circ$ and $\alpha = 100^\circ$ develop clearly differently than for the
456 sliding case ($\alpha = 160^\circ$): both of these simulations with subvertical isotropy planes show similarities as
457 shown in the strain deviator maps. However, deviatoric strains and cracks observed for $\alpha = 80^\circ$ tend to
458 initiate only at the base of the slope, while for $\alpha = 100^\circ$ they appear on almost the entire slope from the

459 beginning (Figure 6c+e). For both cases, deformation is moving retrogressively towards the top and into
460 the slope, soon affecting the entire slope and eventually defining the final rupture surfaces (Figure 6d+f).
461 Many more cracks in the deeper subsurface formed for $\alpha = 80^\circ$ and $\alpha = 100^\circ$ compared to $\alpha = 160^\circ$
462 since the SR at failure is more advanced (see Figure 4). The layer cake visualization for $\alpha = 80^\circ$ shows
463 a clear bending or toppling of the material in the vicinity of the slope face (Figure 6k), whereas the slope
464 material appears to buckle with more particles detaching from the slope surface for $\alpha = 100^\circ$ (Figure 6j).
465 For both configurations, the entirety of the slope is strongly affected by deformation, as corroborated by
466 the high density of cracks within the slope. The fact that almost the entirety of the failed material is
467 severely damaged after the main failure in these cases (Figure S8f+g) indicates that failure occurs more
468 diffusely compared to the blocky movement observed for $\alpha = 160^\circ$ (sliding). However, the toe of the
469 collapsed mass is located at a similar distance for the three configurations (Figure S8, a-c and e-g),
470 likely controlled by the residual friction angle of the loose elements (see also [Katz et al., 2014](#)).
471 All simulations with $\alpha \in [60^\circ, 80^\circ]$ fail in toppling or bending mode. At the onset of failure, a large portion
472 of the slope tilts and rotates towards the toe of the slope before the material subsequently disintegrates.
473 The failure mode obtained for $\alpha = 90^\circ$ is not that clear, and it can be considered transitional between the
474 toppling and buckling failure modes. Despite a slight buckling movement that can be spotted in the lower
475 half of the failing slope, the rotational movement ultimately prevails, and we classified this failure as
476 toppling (see Failure video $\alpha = 90^\circ$ in Supplement). Buckling is the mode of failure observed for all
477 simulations with $\alpha \in [100^\circ, 120^\circ]$. For all these cases, the material is bulging towards the surface in the
478 lower half of the slope, followed by a rotational movement and severe break-up (hereafter referred to as
479 buckling).
480 The shallow dipping, most stable configuration with $\alpha = 20^\circ$ indicates a high amount of cracks even
481 before the SR stops for the first time (see Figure 6g and compare with Figure 5d). The failure stage
482 initiates with some superficial deformation detected in the upper part of the slope that likely corresponds
483 to a few particles detaching. At a later point, the deviatoric strain is high along most parts of the slope
484 surface, but, as shown in Figure 6h, failure does not propagate further within the slope. The deviatoric
485 strain at the surface of the slope (Figure 6h) results from the detachment of a thin layer of particles which
486 fall down the slope face, as illustrated in the layer cake visualization (Figure 6l), and tend to accumulate
487 at its toe (see also Figure S8d+h). Interestingly, although no clear overall failure could be observed,
488 extensive damage developed and spread over the entire slope, as evidenced by the high density of
489 cracks within the medium. This extensive and deeply distributed damage was much more pronounced

490 than in the other three extreme configurations, and the slope remains stable overall. Marker particles of
491 the $\alpha = 20^\circ$ case do not indicate relevant movements and were not presented.

492 The subdued anaclinal slopes with $\alpha \in [0^\circ, 50^\circ]$ fail in a mode that is best designated as “crumbling”
493 (see Figure 6l and Failure video for $\alpha = 20^\circ$ in Supplement). The transition from crumbling to toppling
494 mode is unambiguous (compare Failure videos $\alpha = 50^\circ$ and 60° in Supplement). This failure type
495 observed in the most stable slope configurations is characterized by the detachment of individual
496 particles on the slope face and, in the case of $\alpha = 50^\circ$ and $\alpha \in [0^\circ, 10^\circ]$, by an advancing front of material
497 disintegration from the slope face into the slope. Neither large-scale deformation before complete
498 disintegration nor deformation acting deeper within the slope are visible for all the subdued anaclinal
499 slopes. In Figure S9, we observe that some of the crumbling failures produced for $\alpha = 20^\circ, 30^\circ$ and 40°
500 involve very low mobilized volumes: basically, only the surface layer of particles crumbles down the
501 slope. However, of all the simulations, the crumbling failures show the highest number of cracks in the
502 vicinity of the slope face (Figure S9).



503

504 Figure 6: a - h: strain deviator maps (Supplement S3) with cracks at two early recording steps for the
 505 four stability extrema cases ($\beta = 60^\circ$, packing P1). Black lines show original slope surface, white lines
 506 show rupture surfaces (Supplement S3). c - l: layer cake visualizations where layers are oriented
 507 according to the isotropy plane, final rupture surfaces here in red.

508 Color in print, double column (full width)

509 5. Discussion

510

511 Our modeling results correlate relatively well with findings from former studies that have investigated a
512 partial (Sun et al., 2022) or the full (Aydan et al., 1989; Azami et al., 2012) range of possible strength
513 anisotropy orientations relative to the slope. In comparison to these studies also covering the full range
514 of possible anisotropy angles, our DEM approach enables us to record the failure initiation and
515 progression for the first time in great detail. We confirm the previous results of Azami et al. (2012)
516 concerning stability variations according to the relative orientation of anisotropy, and go further by
517 describing four distinct failure modes with respect to deformation characteristics, estimates of mobilized
518 volumes and damage potential (number of cracks), as well as analyses of the kinetics of failure in both
519 space and time (please refer to Figures 4, 5, 6, S7, S8, S9). Overall, the configurations affected by
520 sliding and toppling are the less stable ones, and the stability of each particular configuration is related
521 to its failure mode (Aydan et al., 1989; Sun et al., 2022).

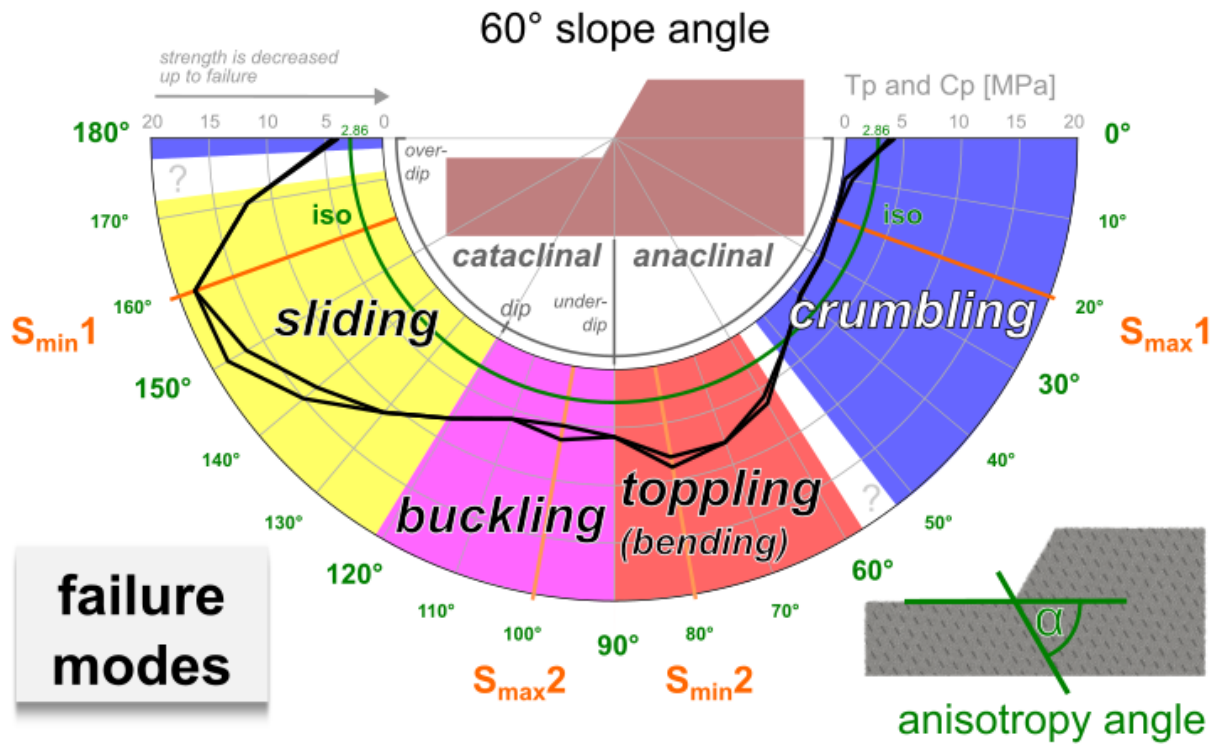
522

523 5.1 Modes of failure

524 The stability extrema generated by our numerical approach correspond to four different modes of failure
525 that can be differentiated by initiation, localization, type, and progression of deformation within the slope
526 (Figures 5, 6, and S9): sliding ($\alpha = 160^\circ$), toppling ($\alpha = 80^\circ$), buckling ($\alpha = 100^\circ$) and a type of crumbling
527 failure ($\alpha = 20^\circ$). Exploring the TI orientation for the entire 180° α -range (see also Failure videos in
528 Supplement), it further appears that the failure mode can always be described by one of these four end-
529 members (Figure 7). These anisotropy-induced failure modes are different from the circular failure mode
530 observed in isotropic slopes (Figure S10 and compared with Figure 3).

531 The sliding and toppling modes observed for the least stable configurations are very well known and
532 described in natural and engineered slopes with cataclinal overdip configuration or anaclinal slopes with
533 steeply dipping layering, foliation or, joint sets (steepened escarpment), respectively (Hungre et al., 2014;
534 Stead and Wolter, 2015). Buckling failure has been described in previous works for cataclinal slopes
535 (e.g., Yang et al. 2020) but appears less frequently observed than the other two failure modes. Cruden
536 (2000) also observed these three distinct failure processes (sliding, toppling, and buckling) on slopes in
537 sedimentary rock masses in the Canadian Rockies, with buckling associated only with cataclinal dip
538 slopes.

539 The crumbling mode, observed in our modeling for the highly stable shallow-dipping anacinal
540 configurations (subdued escarpment), has not been described as such in previous studies. However,
541 [Chigira \(1992\)](#) described four modes of failure for slow-moving rock structures made up of different rock-
542 types in Japan that are largely controlled by their host rock bedding or foliation angle. Besides the three
543 modes of sliding, buckling, and toppling that match very well with our findings, he observed that anacinal
544 slopes with shallow-dipping TI angles are either stable or fail in a “dragging” mode. This dragging mode
545 of failure is a localized, deep-seated, ductile, and slow-moving deformation that cross-cuts the bedding
546 or foliation at a wide angle. According to [Cruden \(2000\)](#), when the bedding plane angle is favorable for
547 neither sliding nor toppling, which corresponds roughly to $\alpha \in [0^\circ, 50^\circ]$ (for $\beta = 60^\circ$), failures tend to
548 follow or be guided by structural joints or fractures oriented orthogonally to the bedding plane. This
549 switch to a secondary preferential structural plane of failure cannot be reproduced by our current model
550 set-up, where only one isotropy plane exists, and localized deep-seated failures with a discrete fracture
551 plane or rupture zone that cross-cuts the isotropy plane at a wider angle do not form. Instead, the
552 corresponding slope models remain stable, implying the possibility for such configurations to present
553 very high slope angles. In certain mountainous regions, such as the Canadian Rockies ([Cruden, 2003](#)),
554 the angle of slope can indeed reach 65° in low cohesion rock masses for gently dipping bedding and
555 anacinal slope configurations, i.e., slope values well above the values of $35\text{-}40^\circ$ usually observed in
556 mountain ranges (e.g., [Schmidt and Montgomery, 1995](#)). In addition, at the bottom of such steep cliffs,
557 it is quite common to observe talus deposition, produced by the accumulation of numerous rock falls,
558 similar to the accumulation of detached particles observed in our modeling for the crumbling mode.
559



560

561 Figure 7: Failure modes observed for the $\beta = 60^\circ$ slope models depending on the orientation (α) of the

562 isotropy plane with respect to the horizontal. See Figure 6 for layer cake visualizations of extreme

563 stability configurations ($S_{\min 1}$, $S_{\min 2}$, $S_{\max 1}$, $S_{\max 2}$) and the associated Failure videos in Supplement.

564 Color in print, double column (full width)

565 *5.2 Mechanical interpretation*

566 The DEM set up enables us to extract the magnitudes and orientations of stresses acting on the particles
567 that make up the slope (see [Catalano et al. \(2014\)](#) for details of the calculations). The magnitude of the
568 differential stress ($\sigma_1 - \sigma_3$) and the orientation of the principal stress (σ_1) for all particles in the vicinity of
569 the slope face are plotted together for both the stability extrema and the isotropic case in Figure 8 just
570 before their respective main failure initiates. They can be directly related to the dimensionless failure
571 potential Φ , a measure of the potential for shear failure to occur adapted from [Moon et al. \(2017\)](#) and
572 defined ([Iverson and Reid, 1992](#)):

573
$$\Phi = \left| \frac{(\sigma_1 - \sigma_3)}{(\sigma_1 + \sigma_3)} \right| \quad . \quad (2)$$

574 Looking at the stresses within the isotropic slope model (Figure 8), it is evident that failure occurs in the
575 region where $\Phi > 1$. This is much less evident for the anisotropic slopes because of the varying relation
576 between stress orientation vs. isotropy plane orientation, and the direction-dependent shear strength
577 ([Fu and Dafalias, 2011](#)).

578 In the overdip configuration failing in the sliding mode of S_{min1} ($\alpha = 160^\circ$), the isotropy plane is oriented
579 favorably for the development of a shear zone oriented subparallel to it, as evidenced by the distribution
580 of Φ within the slope (Figure 8). Moreover, the principal stress tends to be slightly tilted toward the
581 direction of the isotropy plane, thus favoring stress concentration along this direction.

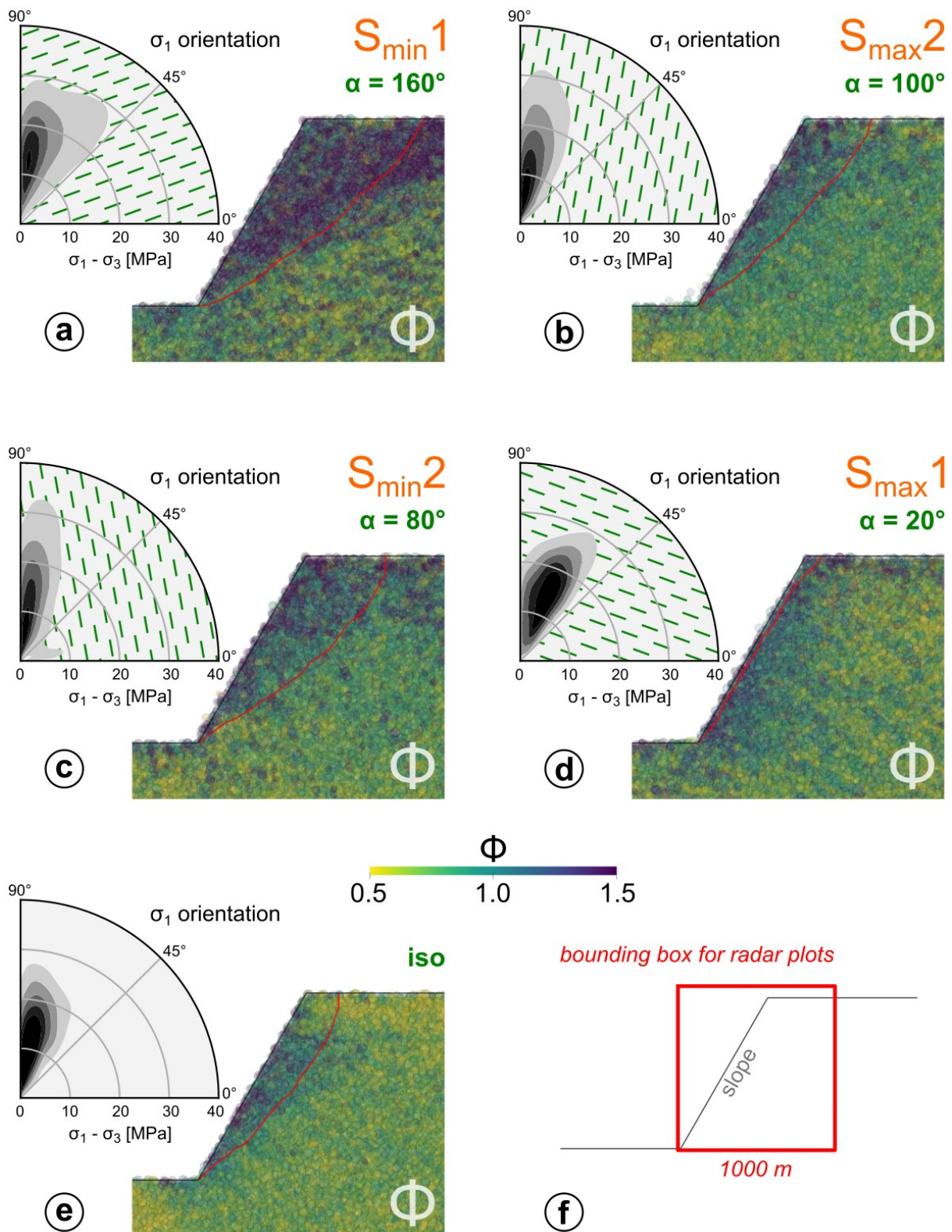
582 When the isotropy plane dips deeper than the slope face, the material cannot fail anymore through
583 sliding along the isotropy plane, and slope stability increases substantially (Figures 4 and 7). For $\alpha =$
584 100° (S_{max2}), $\Phi < 1$ in most parts of the slope except along the slope face, and the principal stress is
585 subparallel to the isotropy plane. This stress distribution favors transverse buckling, which initiates at
586 the base of the slope, where the compressive stress is higher, and progresses upward as a result of the
587 progressive material excavation (Figure 6).

588 For toppling failures occurring in anacinal slopes with steepened escarpments ($\alpha \in [60^\circ, 90^\circ]$), our
589 results tend to verify the criterion proposed by [Goodman and Bray \(1976\)](#), assuming an emergent friction
590 angle of $\varphi \leq \sim 30^\circ$, which seems realistic in consideration of our analysis of the emergent mechanical
591 properties of the DEM models (Section 2.3.2, Figure 7). In these configurations, toppling initiates as a
592 result of shearing/sliding along the isotropy planes at the bottom half of the slope, as illustrated in Figure
593 8c for $\alpha = 80^\circ$ (S_{min2}). There, contrasting Φ -values seem to be localized preferentially along the isotropy

594 planes. As for the sliding mode, the mobilized volume is bigger than for the isotropic case and
595 corresponds to the area where $\Phi > 1$.

596 Unlike the sliding, buckling, and toppling failure modes, the crumbling failure mode corresponds to cases
597 that are mostly more stable than the isotropic case (Figure 7). Why are the anacinal subdued slopes so
598 stable despite reducing the inter-particle strength substantially up to zero? According to [Goodman and](#)
599 [Bray's \(1976\)](#) criterion, shearing/sliding cannot develop along the isotropy plane, and toppling cannot
600 occur. Additionally, either circular or translational sliding failures would need shear zones to cross-cut
601 the isotropy plane at a wide angle. Interestingly, the major principal stress (σ_1) of $S_{\max 1}$ ($\alpha = 20^\circ$) does
602 deviate more from the vertical than in the other extreme configurations, with σ_1 oriented almost
603 orthogonally to the isotropy plane (Figure 8d), a configuration that would correspond to the highest
604 strength configuration for TI materials (Figure 1). The slope finds itself in a "locking state" that promotes
605 some sort of hardening of the material against failure (Figure 8d). One can notice that bands of higher
606 Φ values are localized along the isotropy plane: given the orientation of these bands with respect to the
607 slope geometry and, given the boundary condition on the right side of the model, the overall slope failure
608 toward the left is impeded and only superficial material disintegration occurs along the slope face (i.e.,
609 crumbling). Even if we might question the role of bond reorientation (intrinsically linked to the introduction
610 of anisotropy into our model, Figure 1a) in this hardening phenomenon, we note that this increase in
611 shear resistance for certain isotropy plane orientations relative to the principal stress direction is known
612 both from numerical and analog shear tests ([Fu and Dafalias, 2011](#); [Tong et al. 2014](#)).

613



614

615 Figure 8: Stress distributions within the most representative slope models before failure: density plots

616 show differential stress ($\sigma_1 - \sigma_3$) plotted against principal stress orientation (σ_1) and slope visualizations

617 show the dimensionless failure potential Φ . a-d: stability extrema with strength anisotropy, e: isotropic

618 simulation, f: only particles in red box are used for the density plots.

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620 5.3 Comparison with natural settings

621

622 5.3.1. How representative is our DEM approach?

623 To remain practical, a model designed to represent real-world phenomena must adopt simplifications to
624 reduce the complexity of a natural environment. Natural slopes do generally comprise a lot of
625 heterogeneities in the form of different lithological layers and discrete structures like joints, faults, and
626 folds. Additionally, rock texture and strength may vary towards the surface and along discontinuities due
627 to progressive fatigue and weathering processes (e.g., [Brantut et al., 2013](#); [Viles, 2013](#)), and natural
628 slopes often present complex topography that evolves gradually over time. All these ingredients that
629 make every natural slope unique have a great impact on their mechanical behavior and, subsequently,
630 on their failure process and mode. Our slope models do not account for geometrical and mechanical
631 complexity. They are based on a simple step like geometry to be as general as possible and consider a
632 diffuse material anisotropy rather than discrete structures in order to ease the consideration of scale
633 effect and to avoid the explicit influence of only a few critical structures on the overall behavior. Despite
634 their simplicity, our numerical simulations are capable to reproduce fairly accurate failure modes
635 observed in natural settings that are controlled by rock strength anisotropy as shown, for instance, in
636 studies focusing on landslides in Japan ([Chigira 1992, 2000](#)) or in the Canadian Rocky Mountains
637 ([Cruden and Hu 1996, 1999](#); [Cruden 2000, 2003](#)). Strikingly, in their analysis of landslides triggered by
638 the 1933 Diexi earthquake in China, [Cui et al. \(2022\)](#) found no rock topples but mostly rock slides on
639 cataclinal slopes, and no rock slides but mostly rock topples on anaclinal slopes, which coincides well
640 with our modeling results.

641 Furthermore, the presence of groundwater is known to be one of the most influential driving and
642 triggering factors of slope failure due to the effect of pore pressure on the effective stress ([Jaeger et al.,](#)
643 [2007](#); [Glastonbury and Fell, 2010](#); [LaCroix et al., 2020](#)). We do not account for groundwater in our
644 modeling, and thus only consider total stress analysis under dry conditions, although it is well known
645 that slope deformations are often related to short-term variations of pore pressures ([Agliardi et al., 2020](#)).
646 The scaling we applied to derive realistic slope-scale mechanical properties based on the GSI approach
647 was not initially designed for anisotropic rock masses ([Marinos and Carter, 2018](#)) and we are also aware
648 that estimating GSI-values for large natural slopes is a complex undertaking ([Brideau et al., 2009](#)).

649 Another important aspect that distinguishes our simulations from natural slopes is the strength reduction
650 method we applied. In our simulations, slopes are brought to failure by a homogeneous incremental

651 decrease of strength up to a point where a small disturbance expands to a larger failure. Topography is
652 already cut when SR sets in which does not correspond to the gradual evolution of slopes in natural
653 settings. In nature, strength degradation does happen over time due to progressive weathering of
654 bedrock, deepening of the front of alteration (e.g., [Anderson et al., 2019](#)), or stress fatigue induced by
655 repeated seismic shaking ([Gischig et al., 2016](#)) or/and pore pressure increase ([Petley et al., 2005](#);
656 [Agliardi et al., 2020](#)). However, strength reduction within slopes is certainly not homogeneously
657 distributed -either in space or in time as it is prescribed in our models. For this reason, it is difficult to
658 transfer the temporal evolution of our simulated slope failures to natural slopes. Nevertheless, we
659 observe some relative differences for failure duration between different configurations over the full range
660 of possible isotropy plane orientations (α -angle) which might be of interest for field studies (see Figure
661 S9c).

662 In our model results, the failure duration is minimal for the sliding mode, and double for the steeply
663 dipping isotropy planes affected by buckling or toppling modes of deformation. It is difficult to assess the
664 duration of failure of natural landslides. However, it may be asked whether anisotropic configurations
665 and failure duration have an influence on the kinetic energy of the rock mass and on the mobility of the
666 landslides. Similarly, could the differences observed between failure modes in the manner and speed at
667 which failure propagates from bottom to top indicate differences in the type of instability? A reduced
668 catalogue of DSGSDs in the Italian Alps ([Ambrosi and Crosta, 2006](#)) seems to indicate that these deep,
669 progressive deformations develop more when the foliation of the rocks is relatively steep, i.e., when
670 buckling or toppling are favored. At this stage, more exhaustive studies would be necessary, but the
671 results of our study suggest a potential influence of the relative orientation of anisotropy on the overall
672 dynamics of gravitational instabilities.

673 In concomitance with time scaling considerations, the transposition of our results to natural cases may
674 require the addition of debris erosion in our modeling procedure. Indeed, as the collapse progresses,
675 erosion of the debris base, particularly by a river, will modify the geometry of the debris apron and could
676 promote the mobility of the collapsing slope. Future models dedicated to monitoring the temporal
677 evolution of slope failure should consider erosion processes.

678 5.3.2 Rock anisotropy and hillslope angle at erosional steady state

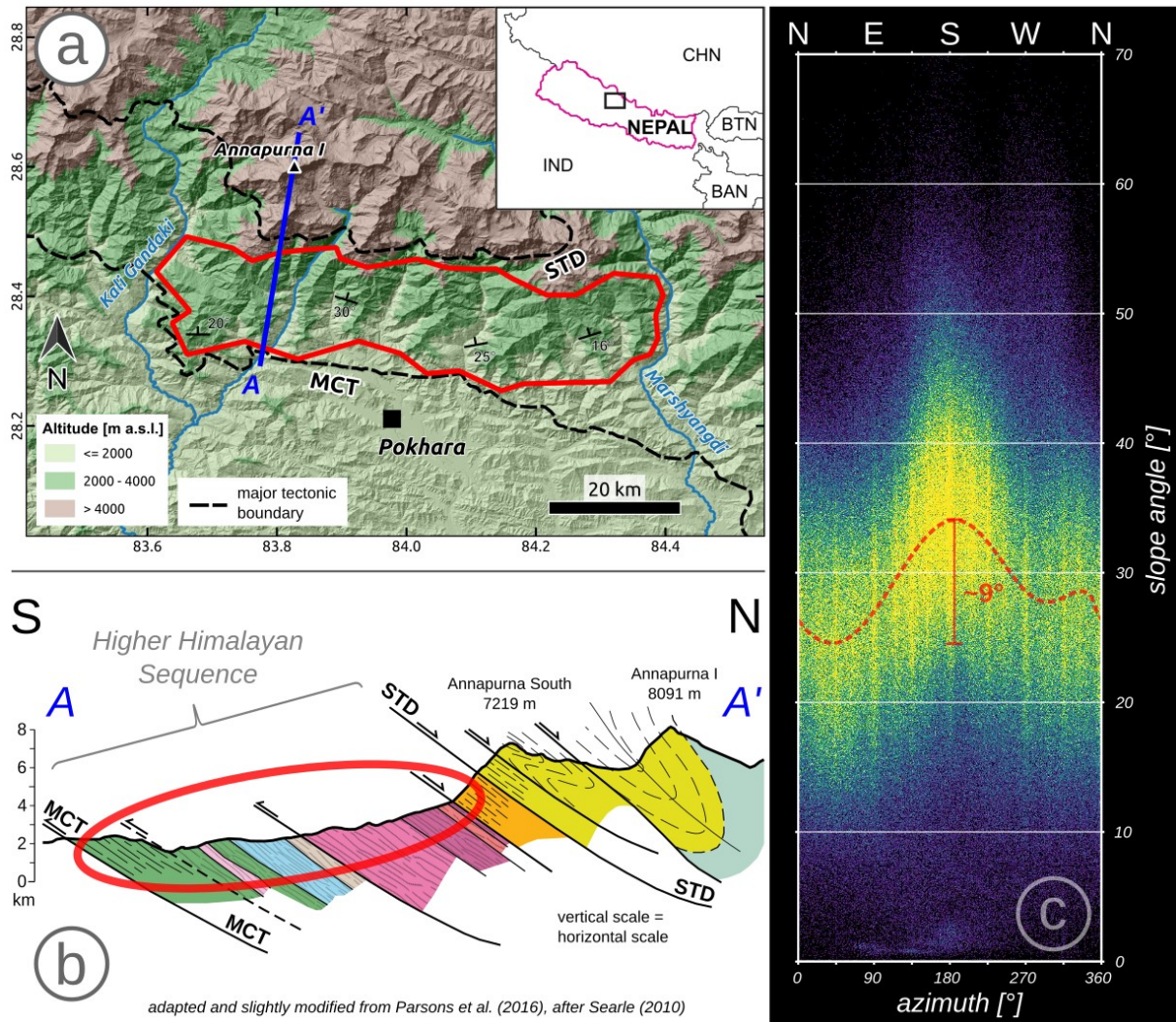
679 In mountainous environments, as for any natural setting, strength reduction within slopes due to
680 progressive weathering and fatigue of rock mass lead to a decrease of the resisting forces and therefore
681 to hillslope instability. However, landslide triggering also is first of all driven by an increase of the tractive
682 forces, i.e., the progressive increase of slope angle and relief. As tectonic processes uplift the land
683 mass, rivers respond by incising their channel, thus lowering the local base level of the hillslopes: this
684 leads to slope steepening and hillslope height increase until mechanical instability is reached. As
685 denudation exhumes bedrock over time, the slope angles are therefore presumed to episodically adjust
686 through landsliding, with an average angle that depends on the local bedrock strength (Townsend et al.,
687 2020; Lavé et al., 2023). In the case of bedrock presenting TI characteristics (most sedimentary and
688 metamorphic rocks), we expect the stability of slopes and average slope angles to vary significantly with
689 slope orientations or slope aspects, as simulated by our study. In particular, anaclinal slopes should fail
690 at higher slope angles than cataclinal slopes, as shown, for example, in Figure 4 for $T_p = C_p = 5$ MPa:
691 for these fixed inter-particle bond properties, 60° sloping scarps developed in an anaclinal configuration
692 are still stable, whereas the 40° sloping scarps developed in the overdip cataclinal setting have already
693 failed. This expected result was indeed observed in the Rocky Mountains (Cruden, 2000). Although
694 various earlier studies have looked at the relationship between the direction of anisotropy and slope
695 orientation, they have mainly focused on the modes of failure (Cruden and Hu, 1996, 1999; Cruden
696 2000, 2003; Chigira, 1992, 2000; Teshebaeva et al., 2019; Cui et al., 2022) or on variations in landslide
697 activity and frequency (Cruden and Eaton, 1987; Cui et al., 2022), but have paid, to our knowledge, little
698 attention to the influence of this relative orientation on slope steepness.

699 To confirm that the anisotropy of the rock's resistance ultimately contributes to control the average slope
700 angles in natural settings, we need to find a region where anisotropic structures are uniform at a scale
701 larger than the typical hillslope length. Often, bedrock anisotropy is variable in an area due to folds,
702 faults, and lithological changes, but in some places, the tectonic setting can result in large terrains of
703 uniformly dipping unfolded rocks. Despite some minor secondary folding, this is the case for the south-
704 facing slopes of the Annapurna Massif in central Nepal, where overthrusting due to continental collision
705 is responsible for gneisses dipping consistently 10° - 40° towards NW - NE in between two major tectonic
706 structures, the Main Central Thrust (MCT) and the South Tibetan Detachment (STD): see Figure 9a-b
707 and refer to geological maps of Colchen et al. (1986) and Parsons et al. (2016). There, we performed a
708 simple raster data analysis on a 30 m digital terrain model (Hawker and Neal, 2021) for an area high

709 2000 - 4000 m a.s.l. (red polygon in Figure 9a) actively eroding but devoid of any geomorphological
710 evidence of hillslope glacial erosion and well below the permanently frozen areas where slope and rock
711 mass cohesion are observed to be distinctively higher (Lavé et al., 2023). For the selected area, slope
712 angle distributions appear to vary with slope orientation (Figure 9c): south-facing slopes are, on average,
713 up to 9° steeper than slopes facing east, north, and west. Anacinal slopes are, therefore, steeper than
714 cataclinal slopes, as proven by our analysis (compare Figures 4 and 9). This finding agrees well with
715 the observations of Uhler and Schramm (1997) for central Himalayan slopes in a near-identical geological
716 setting: constant dip of bedrock schistosity towards the north coincides with south-facing-slopes
717 significantly steeper than north-facing slopes. The slope-aspect diagram in Figure 9c is qualitatively
718 aligned with our modeling expectations if the variation in slope angle as a function of slope orientation
719 is considered to be the cause of varying slope stability. However, a quantitative analysis of slope-scale
720 mechanical conditions is difficult to perform at this stage, as it would be necessary to characterize the
721 strength anisotropy of Himalayan gneisses, particularly at the scale of the hillslope (see Section 2.3). It
722 would also be necessary to characterize slope stability when the azimuth of the isotropy plane is different
723 from that of the topographic slope, i.e., we would need to numerically explore not only the dip angle of
724 the isotropy plane in two dimensions but also its azimuth between 0 and 180° relative to the azimuth of
725 the topographic slope in three dimensions. Additionally, the role of other factors, such as the distribution
726 and orientation of fractures or the hydrology of groundwater, which is certainly influenced by stratified
727 or foliated rocks (e.g., Dong et al., 2012), should be addressed.

728 As an additional corollary to this southern Annapurna slopes setting, we would expect, according to our
729 modeling, differences in failure modes depending on the orientation of the slopes. Failure modes are
730 difficult to assess by conventionally available satellite imagery due to rapid re-vegetation of landslide
731 scars and the sparsity of large failures (>1 km² landslides only occur every ~500 years following Marc
732 et al. (2019)). Capturing a statistically representative frequency of the different failure modes for different
733 slope orientations would require an exceptional number of slope failure events due to, for example, a
734 very large earthquake (as in Cui et al. (2022) for the eastern margin of the Tibetan plateau), and/or the
735 availability of a high-resolution digital terrain model (e.g., airborne Lidar). Despite the absence of such
736 a quantitative approach, observations along the southern flank of the Himalayas (see Figure S11) are
737 at least qualitatively in line with our model predictions. For instance, in the Ankhu Khola region (80 km
738 to the east of the southern flank of the Annapurna Massif, in a near-identical setting), in conjunction with
739 slope angle variability, slope failure modes are particularly contrasted between north-facing (cataclinal)

740 and south-facing (anaclinal) slopes: low-volume rock falls, rock topples, and small rockslides appear to
741 be more frequently observed on south-facing slopes, whereas numerous voluminous translational
742 rockslides detach sub-parallel to the schistosity planes along north-facing slopes ([Thouret, 1983](#); [Uhlir](#)
743 [and Schramm, 1997](#)).



744

745 Figure 9: a: Topographic map of the Annapurna massif with location of area selected for raster data
 746 extraction (red polygon): country borders in white box (top left) serve as orientation, MCT and STD were
 747 extracted from the geological map of Parsons et al. (2016); b: tectonic profile modified after Searle
 748 (2010) (see location of blue line in a), red ellipse indicates terrain extracted for raster analysis; c) scatter
 749 plot showing azimuth - slope angle relationship colored by density (linear), red dashed line indicates the
 750 maximum density along azimuth.

751 Color in print, double column (full width)

752 **6. Conclusion**

753

754 Understanding the factors influencing the deformation and failure of rock slopes is fundamental to
755 assessing slope failure hazard better and understanding landscape evolution. Using parametric
756 numerical modeling, we explored the influence of rock anisotropy on slope stability, focusing more
757 specifically on slopes made of transverse isotropic materials and investigating their stability potential
758 and deformation modes. Our study enables us to identify distinct failure behaviors caused by different
759 orientations of the isotropy plane with respect to the slope face, as regularly observed on natural and
760 artificial slopes: sliding in overdip cataclinal slopes, toppling (bending) in anacinal slopes with steepened
761 escarpment, and buckling in underdip cataclinal slopes. One can also note that the crumbling failure
762 mode does resemble rockfalls on anacinal subdued slopes. Moreover, our approach enables us to
763 relate the stability of slopes to these deformation modes. It suggests, for instance, that anacinal slopes
764 are generally more stable than cataclinal ones, with subdued escarpments showing the highest stability
765 potential and overdip cataclinal slopes showing the lowest stability potential. Obviously, natural slopes
766 exceed the bounds suggested by our modeling exercise due to their inherent complexity. Nonetheless,
767 our results comprehensively describe all the first-order mechanisms that govern landscape evolution in
768 mountainous areas where stability potential drives the topography. To go further into the analysis, one
769 would need to include the contribution of additional factors to slope deformation, like pore pressure built-
770 up or seismic shaking, that could greatly impact the prevailing failure mode and other failure
771 characteristics. Nevertheless, our study, like that of [Chigira \(2000\)](#) on natural objects, indicates a whole
772 typology of deformation modes that seem to depend directly on the presence of anisotropic rocks and
773 on the relative anisotropy orientation with respect to the topography. It is difficult to know whether other
774 factors may also lead to the emergence of the four identified end-members or whether the orientation
775 of the anisotropy is the sole source of this typology. In any case, slope stability analyses should consider
776 this parameter more systematically so that the various possible deformation modes and associated
777 hazards can be clearly identified.

778

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786

787

788 **Competing Interests**

789

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792

793

794 **Declaration of generative AI and AI-assisted technologies in the writing process**

795

796 During the preparation of this work the authors used the online AI-translator DeepL in order to improve
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799

800 **References**

- 801 Adhikary, D.P., Dyskin, A.V., Jewell, R.J., Stewart, D.P., 1997. A study of the mechanism of flexural
802 toppling failure of rock slopes. *Rock Mech Rock Engng* 30, 75–93.
803 <https://doi.org/10.1007/BF01020126>
- 804 Agliardi, F., Crosta, G.B., Frattini, P., 2012. Slow rock-slope deformation, in: Clague, J.J., Stead, D.
805 (Eds.), *Landslides*. Cambridge University Press, Cambridge, pp. 207–221.
806 <https://doi.org/10.1017/CBO9780511740367.019>
- 807 Agliardi, F., Scuderi, M.M., Fusi, N., Collettini, C., 2020. Slow-to-fast transition of giant creeping
808 rockslides modulated by undrained loading in basal shear zones. *Nat Commun* 11, 1352.
809 <https://doi.org/10.1038/s41467-020-15093-3>
- 810 Ambrosi, C., Crosta, G.B., 2006. Large sackung along major tectonic features in the Central Italian
811 Alps. *Engineering Geology* 83, 183–200. <https://doi.org/10.1016/j.enggeo.2005.06.031>
- 812 Anderson, R.S., Rajaram, H., Anderson, S.P., 2019. Climate driven coevolution of weathering profiles
813 and hillslope topography generates dramatic differences in critical zone architecture.
814 *Hydrological Processes* 33, 4–19. <https://doi.org/10.1002/hyp.13307>
- 815 Aydan, Ö., Shimizu, Y., Ichikawa, Y., 1989. The effective failure modes and stability of slopes in rock
816 mass with two discontinuity sets. *Rock Mech Rock Engng* 22, 163–188.
817 <https://doi.org/10.1007/BF01470985>
- 818 Azami, A., Yacoub, T., Curran, J., 2012. Effects of strength anisotropy on the stability of slopes.
819 Presented at the 65th Canadian Geotechnical Conference, CGS Geo-Manitoba.
- 820 Barton, N., Quadros, E., 2015. Anisotropy is Everywhere, to See, to Measure, and to Model. *Rock*
821 *Mech Rock Eng* 48, 1323–1339. <https://doi.org/10.1007/s00603-014-0632-7>
- 822 Benko, B., Stead, D., 1998. The Frank slide: a reexamination of the failure mechanism. *Canadian*
823 *Geotechnical Journal* 35, 299–311. Bonilla-Sierra, V., Elmouttie, M., Donzé, F.-V., Scholtès, L.,
824 2017. Composite wedge failure using photogrammetric measurements and DFN-DEM modelling.
825 *Journal of Rock Mechanics and Geotechnical Engineering* 9, 41–53.
826 <https://doi.org/10.1016/j.jrmge.2016.08.005>
- 827 Bonilla-Sierra, V., Scholtès, L., Donzé, F.V., Elmouttie, M.K., 2015. Rock slope stability analysis using
828 photogrammetric data and DFN-DEM modelling. *Acta Geotech.* 10, 497–511.
829 <https://doi.org/10.1007/s11440-015-0374-z>
- 830 Bonnelye, A., Schubnel, A., David, C., Henry, P., Guglielmi, Y., Gout, C., Fauchille, A.-L., Dick, P.,
831 2017. Strength anisotropy of shales deformed under uppermost crustal conditions. *Journal of*
832 *Geophysical Research: Solid Earth* 122, 110–129. <https://doi.org/10.1002/2016JB013040>
- 833 Brantut, N., Heap, M.J., Meredith, P.G., Baud, P., 2013. Time-dependent cracking and brittle creep in
834 crustal rocks: A review. *Journal of Structural Geology* 52, 17–43.
835 <https://doi.org/10.1016/j.jsg.2013.03.007>
- 836 Brideau, M.-A., Yan, M., Stead, D., 2009. The role of tectonic damage and brittle rock fracture in the
837 development of large rock slope failures. *Geomorphology* 103, 30–49.
838 <https://doi.org/10.1016/j.geomorph.2008.04.010>
- 839 Cui, S., Wu, H., Pei, X., Yang, Q., Huang, R., Guo, B., 2022. Characterizing the spatial distribution,
840 frequency, geomorphological and geological controls on landslides triggered by the 1933 Mw 7.3
841 Diexi Earthquake, Sichuan, China. *Geomorphology* 403, 108177.
842 <https://doi.org/10.1016/j.geomorph.2022.108177>

- 843 Catalano, E., Chareyre, B., Barthélemy, E., 2014. Pore-scale modeling of fluid-particles interaction and
844 emerging poromechanical effects. *International Journal for Numerical and Analytical Methods in*
845 *Geomechanics* 38, 51–71. <https://doi.org/10.1002/nag.2198>
- 846 Cheng, Y.M., Lau, C.K., 2014. *Slope stability analysis and stabilization: new methods and insight,*
847 *Second edition.* ed. CRC Press, Taylor & Francis Group, Boca Raton.
- 848 Chigira, M., 2000. Geological structures of large landslides in Japan. *Journal of Nepal Geological*
849 *Society* 22, 497–504. <https://doi.org/10.3126/jngs.v22i0.32423>
- 850 Chigira, M., 1992. Long-term gravitational deformation of rocks by mass rock creep. *Engineering*
851 *Geology* 32, 157–184. Colchen, M., Le Fort, P., Pêcher, A., 1986. Annapurna–Manaslu–Ganesh
852 Himal. *Centre National de la Recherche Scientifique, Paris* 75–136.
- 853 Cotton, C.A., 1949. *Geomorphology: an introduction to the study of landforms.* John Wiley & sons,
854 New York.
- 855 Cruden, D., Hu, X.Q., 1996. Hazardous Modes of Rock Slope Movement in the Canadian Rockies.
856 *Environmental and Engineering Geoscience* 2, 507–516.
857 <https://doi.org/10.2113/gseegeosci.11.4.507>
- 858 Cruden, D.M., 2003. The shapes of cold, high mountains in sedimentary rocks. *Geomorphology* 55,
859 249–261. [https://doi.org/10.1016/S0169-555X\(03\)00143-0](https://doi.org/10.1016/S0169-555X(03)00143-0)
- 860 Cruden, D.M., 2000. Some forms of mountain peaks in the Canadian Rockies controlled by their rock
861 structure. *Quaternary International* 68–71, 59–65. [https://doi.org/10.1016/S1040-6182\(00\)00032-](https://doi.org/10.1016/S1040-6182(00)00032-X)
862 [X](https://doi.org/10.1016/S1040-6182(00)00032-X)
- 863 Cruden, D.M., Eaton, T.M., 1987. Reconnaissance of rockslide hazards in Kananaskis Country,
864 Alberta. *Can. Geotech. J.* 24, 414–429. <https://doi.org/10.1139/t87-052>
- 865 Cruden, D.M., Hu, X.-Q., 1999. The shapes of some mountain peaks in the Canadian Rockies. *Earth*
866 *Surface Processes and Landforms* 24, 1229–1241. [https://doi.org/10.1002/\(SICI\)1096-](https://doi.org/10.1002/(SICI)1096-9837(199912)24:13<1229::AID-ESP42>3.0.CO;2-1)
867 [9837\(199912\)24:13<1229::AID-ESP42>3.0.CO;2-1](https://doi.org/10.1002/(SICI)1096-9837(199912)24:13<1229::AID-ESP42>3.0.CO;2-1)
- 868 Cundall, P.A., Strack, O.D.L., 1979. A discrete numerical model for granular assemblies.
869 *Géotechnique* 29, 47–65. <https://doi.org/10.1680/geot.1979.29.1.47>
- 870 Davies, T., 2022. Reducing landslide disaster impacts, in: *Landslide Hazards, Risks, and Disasters.*
871 Elsevier, pp. 623–639.
- 872 Densmore, A.L., Hovius, N., 2000. Topographic fingerprints of bedrock landslides. *Geology* 28, 371–
873 374.
- 874 Dinç, Ö., Scholtès, L., 2018. Discrete Analysis of Damage and Shear Banding in Argillaceous Rocks.
875 *Rock Mech Rock Eng* 51, 1521–1538. <https://doi.org/10.1007/s00603-017-1397-6>
- 876 Donath, F.A., 1961. Experimental Study of Shear Failure in Anisotropic Rocks. *Geol Soc America Bull*
877 72, 985. [https://doi.org/10.1130/0016-7606\(1961\)72\[985:ESOSFI\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1961)72[985:ESOSFI]2.0.CO;2)
- 878 Dong, J.-J., Tu, C.-H., Lee, W.-R., Jheng, Y.-J., 2012. Effects of hydraulic conductivity/strength
879 anisotropy on the stability of stratified, poorly cemented rock slopes. *Computers and*
880 *Geotechnics* 40, 147–159. <https://doi.org/10.1016/j.compgeo.2011.11.001>
- 881 Fu, P., Dafalias, Y.F., 2011. Study of anisotropic shear strength of granular materials using DEM
882 simulation. *Int. J. Numer. Anal. Meth. Geomech.* 35, 1098–1126. <https://doi.org/10.1002/nag.945>
- 883 Gischig, V., Preisig, G., Eberhardt, E., 2016. Numerical Investigation of Seismically Induced Rock
884 Mass Fatigue as a Mechanism Contributing to the Progressive Failure of Deep-Seated
885 Landslides. *Rock Mech Rock Eng* 49, 2457–2478. <https://doi.org/10.1007/s00603-015-0821-z>

- 886 Glade, T., Anderson, M.G., Crozier, M.J., 2005. Landslide hazard and risk. Wiley Online Library.
- 887 Glastonbury, J., Fell, R., 2010. Geotechnical characteristics of large rapid rock slides. *Can. Geotech.*
888 J. 47, 116–132. <https://doi.org/10.1139/T09-080>
- 889 Goodman, R.E., Bray, J.W., 1976. Toppling of rock slopes. Presented at the Proc. Specialty Conf. on
890 Rock Engineering for Foundations and Slopes, Amer. Soc. Civil Eng., pp. 201–234.
- 891 Grelle, G., Revellino, P., Donnarumma, A., Guadagno, F.M., 2011. Bedding control on landslides: a
892 methodological approach for computer-aided mapping analysis. *Nat. Hazards Earth Syst. Sci.*
893 11, 1395–1409. <https://doi.org/10.5194/nhess-11-1395-2011>
- 894 Hawker, L., Neal, J., 2021. FABDEM V1-0. <https://doi.org/10.5523/bris.25wfy0f9ukoge2gs7a5mqpq2j7>
- 895 Hoek, E., 1964. Fracture of anisotropic rock. *Journal of the Southern African Institute of Mining and*
896 *Metallurgy* 64, 501–518.
- 897 Hoek, E., Carranza-Torres, C., Corkum, B., 2002. Hoek-Brown failure criterion-2002 edition.
898 *Proceedings of NARMS-Tac* 1, 267–273.
- 899 Hoek, E., Diederichs, M.S., 2006. Empirical estimation of rock mass modulus. *International Journal of*
900 *Rock Mechanics and Mining Sciences* 43, 203–215. <https://doi.org/10.1016/j.ijrmms.2005.06.005>
- 901 Huggel, C., Clague, J.J., Korup, O., 2012. Is climate change responsible for changing landslide activity
902 in high mountains? *Earth Surface Processes and Landforms* 37, 77–91.
903 <https://doi.org/10.1002/esp.2223>
- 904 Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update.
905 *Landslides* 11, 167–194. <https://doi.org/10.1007/s10346-013-0436-y>
- 906 Iverson, R.M., Reid, M.E., 1992. Gravity-driven groundwater flow and slope failure potential: 1. Elastic
907 Effective-Stress Model. *Water Resour. Res.* 28, 925–938. <https://doi.org/10.1029/91WR02694>
- 908 Jaboyedoff, M., Crosta, G.B., Stead, D., 2011. Slope tectonics: a short introduction. SP 351, 1–10.
909 <https://doi.org/10.1144/SP351.1>
- 910 Jaeger, J.C., Cook, N.G.W., Zimmerman, R.W., 2007. *Fundamentals of rock mechanics*, 4th ed. ed.
911 Blackwell Pub, Malden, MA.
- 912 Katz, O., Morgan, J.K., Aharonov, E., Dugan, B., 2014. Controls on the size and geometry of
913 landslides: Insights from discrete element numerical simulations. *Geomorphology* 220, 104–113.
914 <https://doi.org/10.1016/j.geomorph.2014.05.021>
- 915 Korup, O., Densmore, A.L., Schlunegger, F., 2010. The role of landslides in mountain range evolution.
916 *Geomorphology* 120, 77–90. <https://doi.org/10.1016/j.geomorph.2009.09.017>
- 917 Lacroix, P., Handwerker, A.L., Bièvre, G., 2020. Life and death of slow-moving landslides. *Nat Rev*
918 *Earth Environ* 1, 404–419. <https://doi.org/10.1038/s43017-020-0072-8>
- 919 Lavé, J., Guérin, C., Valla, P.G., Guillou, V., Rigaudier, T., Benedetti, L., France-Lanord, C., Gajurel,
920 A.P., Morin, G., Dumoulin, J.P., Moreau, C., Galy, V., 2023. Medieval demise of a Himalayan
921 giant summit induced by mega-landslide. *Nature* 619, 94–101. [https://doi.org/10.1038/s41586-](https://doi.org/10.1038/s41586-023-06040-5)
922 [023-06040-5](https://doi.org/10.1038/s41586-023-06040-5)
- 923 Leshchinsky, D., Baker, R., Silver, M.L., 1985. Three dimensional analysis of slope stability. *Int. J.*
924 *Numer. Anal. Methods Geomech.* 9, 199–223. <https://doi.org/10.1002/nag.1610090302>
- 925 Li, X., Wartman, J., Tang, H., Yan, J., Luo, H., Hu, W., 2014. Dynamic Centrifuge Modelling Tests for
926 Sliding Rock Slopes, in: Sassa, K., Canuti, P., Yin, Y. (Eds.), *Landslide Science for a Safer*
927 *Geoenvironment*. Springer International Publishing, Cham, pp. 75–79.
928 https://doi.org/10.1007/978-3-319-05050-8_13

- 929 Marc, O., Behling, R., Andermann, C., Turowski, J.M., Illien, L., Roessner, S., Hovius, N., 2019. Long-
930 term erosion of the Nepal Himalayas by bedrock landsliding: the role of monsoons, earthquakes
931 and giant landslides. *Earth Surface Dynamics* 7, 107–128. [https://doi.org/10.5194/esurf-7-107-](https://doi.org/10.5194/esurf-7-107-2019)
932 [2019](https://doi.org/10.5194/esurf-7-107-2019)
- 933 Marinos, P., Hoek, E., 2000. GSI: a geologically friendly tool for rock mass strength estimation.
934 Presented at the ISRM international symposium, ISRM, p. ISRM-IS.
- 935 Marinos, Vassilis., Carter, Trevor.G., 2018. Maintaining geological reality in application of GSI for
936 design of engineering structures in rock. *Engineering Geology* 239, 282–297.
937 <https://doi.org/10.1016/j.enggeo.2018.03.022>
- 938 McLamore, R., Gray, K.E., 1967. The Mechanical Behavior of Anisotropic Sedimentary Rocks. *Journal*
939 *of Engineering for Industry* 89, 62–73. <https://doi.org/10.1115/1.3610013>
- 940 Moon, S., Perron, J.T., Martel, S.J., Holbrook, W.S., St. Clair, J., 2017. A model of three-dimensional
941 topographic stresses with implications for bedrock fractures, surface processes, and landscape
942 evolution: Three-Dimensional Topographic Stress. *J. Geophys. Res. Earth Surf.* 122, 823–846.
943 <https://doi.org/10.1002/2016JF004155>
- 944 Munjiza, A.A., 2004. The combined finite-discrete element method. John Wiley & Sons.
- 945 Nasser, M.H.B., Rao, K.S., Ramamurthy, T., 2003. Anisotropic strength and deformational behavior of
946 Himalayan schists. *International Journal of Rock Mechanics and Mining Sciences* 40, 3–23.
947 [https://doi.org/10.1016/S1365-1609\(02\)00103-X](https://doi.org/10.1016/S1365-1609(02)00103-X)
- 948 Niandou', H., Shao, J.F., HENRYf, J.P., Fourmaintraux, D., 1997. Laboratory Investigation of the
949 Behaviour of Tournemire Shale. *Int. J. Rock Mech. Min. Sci.* 34, 3–16.
- 950 Parsons, A.J., Law, R.D., Searle, M.P., Phillips, R.J., Lloyd, G.E., 2016. Geology of the Dhaulagiri-
951 Annapurna-Manaslu Himalaya, Western Region, Nepal. 1:200,000. *Journal of Maps* 12, 100–
952 110. <https://doi.org/10.1080/17445647.2014.984784>
- 953 Petley, D.N., Higuchi, T., Petley, D.J., Bulmer, M.H., Carey, J., 2005. Development of progressive
954 landslide failure in cohesive materials. *Geol* 33, 201. <https://doi.org/10.1130/G21147.1>
- 955 Read, J., Stacey, P. (Eds.), 2009. Guidelines for open pit slope design, Reprint. with corr. ed. CSIRO
956 Publ. [u.a.], Collingwood, Vic.
- 957 Roy, S., Baruah, A., Misra, S., Mandal, N., 2015. Effects of bedrock anisotropy on hillslope failure in
958 the Darjeeling-Sikkim Himalaya: an insight from physical and numerical models. *Landslides* 12,
959 927–941. <https://doi.org/10.1007/s10346-014-0513-x>
- 960 Saroglou, H., Marinos, P., Tsiambaos, G., 2004. The anisotropic nature of selected metamorphic rocks
961 from Greece. *Journal of the Southern African Institute of Mining and Metallurgy* 104, 217–222.
962 https://doi.org/10.10520/AJA0038223X_2825
- 963 Schmidt, K.M., Montgomery, D.R., 1995. Limits to Relief. *Science* 270, 617–620.
964 <https://doi.org/10.1126/science.270.5236.617>
- 965 Scholtès, L., Donzé, F.V., 2015. A DEM analysis of step-path failure in jointed rock slopes. *Comptes*
966 *Rendus Mécanique* 343, 155–165. <https://doi.org/10.1016/j.crme.2014.11.002>
- 967 Scholtès, L., Donzé, F.-V., 2013. A DEM model for soft and hard rocks: Role of grain interlocking on
968 strength. *Journal of the Mechanics and Physics of Solids* 61, 352–369.
969 <https://doi.org/10.1016/j.jmps.2012.10.005>
- 970 Scholtès, L., Donzé, F.-V., 2012. Modelling progressive failure in fractured rock masses using a 3D
971 discrete element method. *International Journal of Rock Mechanics and Mining Sciences* 52, 18–
972 30. <https://doi.org/10.1016/j.ijrmms.2012.02.009>

- 973 Searle, M.P., 2010. Low-angle normal faults in the compressional Himalayan orogen; Evidence from
974 the Annapurna–Dhaulagiri Himalaya, Nepal. *Geosphere* 6, 296–315.
975 <https://doi.org/10.1130/GES00549.1>
- 976 Šmilauer, V., Angelidakis, V., Catalano, E., Caulk, R., Chareyre, B., Chèvremont, W., Dorofeenko, S.,
977 Duriez, J., Dyck, N., Elias, J., Er, B., Eulitz, A., Gladky, A., Guo, N., Jakob, C., Kneib, F., Kozicki,
978 J., Marzougui, D., Maurin, R., Modenese, C., Pekmezi, G., Scholtès, L., Sibille, L., Stransky, J.,
979 Sweijen, T., Thoeni, K., Yuan, C., 2021. Yade documentation. The Yade Project.
980 <https://doi.org/10.5281/zenodo.5705394>
- 981 Stead, D., Wolter, A., 2015. A critical review of rock slope failure mechanisms: The importance of
982 structural geology. *Journal of Structural Geology* 74, 1–23.
983 <https://doi.org/10.1016/j.jsg.2015.02.002>
- 984 Stockton, E., Leshchinsky, B.A., Olsen, M.J., Evans, T.M., 2019. Influence of both anisotropic friction
985 and cohesion on the formation of tension cracks and stability of slopes. *Engineering Geology*
986 249, 31–44. <https://doi.org/10.1016/j.enggeo.2018.12.016>
- 987 Sun, L., Grasselli, G., Liu, Q., Tang, X., Abdelaziz, A., 2022. The role of discontinuities in rock slope
988 stability: Insights from a combined finite-discrete element simulation. *Computers and*
989 *Geotechnics* 147, 104788. <https://doi.org/10.1016/j.compgeo.2022.104788>
- 990 Teshebaeva, K., Echtler, H., Bookhagen, B., Strecker, M., 2019. Deep-seated gravitational slope
991 deformation (DSGSD) and slow-moving landslides in the southern Tien Shan Mountains: new
992 insights from InSAR, tectonic and geomorphic analysis. *Earth Surf. Process. Landforms* 44,
993 2333–2348. <https://doi.org/10.1002/esp.4648>
- 994 Thouret, J.-C., 1983. Géodynamique des grands versants de l'Ankhu Khola, Népal central. Editions du
995 Centre national de la recherche scientifique.
- 996 Tien, Y.M., Kuo, M.C., Juang, C.H., 2006. An experimental investigation of the failure mechanism of
997 simulated transversely isotropic rocks. *International Journal of Rock Mechanics and Mining*
998 *Sciences* 43, 1163–1181. <https://doi.org/10.1016/j.ijrmms.2006.03.011>
- 999 Tong, Z., Fu, P., Zhou, S., Dafalias, Y.F., 2014. Experimental investigation of shear strength of sands
1000 with inherent fabric anisotropy. *Acta Geotech.* 9, 257–275. <https://doi.org/10.1007/s11440-014-0303-6>
1001
- 1002 Townsend, K.F., Gallen, S.F., Clark, M.K., 2020. Quantifying Near-Surface Rock Strength on a
1003 Regional Scale From Hillslope Stability Models. *Journal of Geophysical Research: Earth Surface*
1004 125, e2020JF005665. <https://doi.org/10.1029/2020JF005665>
- 1005 Uhlir, C., Schramm, J.-M., 1997. Weathering and erosional processes within the landslide deposit of
1006 Jarlang (Ganesh Himal, central Nepal). *Journal of Nepal Geological Society* 53–65.
- 1007 Utili, S., Crosta, G.B., 2011. Modeling the evolution of natural cliffs subject to weathering: 2. Discrete
1008 element approach. *J. Geophys. Res.* 116, n/a-n/a. <https://doi.org/10.1029/2009JF001559>
- 1009 Viles, H.A., 2013. Linking weathering and rock slope instability: non-linear perspectives: Linking
1010 weathering and rock slope instability. *Earth Surf. Process. Landforms* 38, 62–70.
1011 <https://doi.org/10.1002/esp.3294> Wang, C., Tannant, D.D., Lilly, P.A., 2003. Numerical analysis of
1012 the stability of heavily jointed rock slopes using PFC2D. *International Journal of Rock Mechanics*
1013 *and Mining Sciences* 40, 415–424. [https://doi.org/10.1016/S1365-1609\(03\)00004-2](https://doi.org/10.1016/S1365-1609(03)00004-2)
- 1014 Wang, P., Yang, T., Zhou, J., 2018. Slope failure analysis considering anisotropic characteristics of
1015 foliated rock masses. *Arab J Geosci* 11, 222. <https://doi.org/10.1007/s12517-018-3583-6>
- 1016 Yang, C.-M., Kang, K.-H., Yang, S.-H., Li, K.-W., Wang, H.-J., Lee, Y.-T., Lin, K.-K., Pan, Y.-W., Liao,
1017 J.-J., 2020. Large paleo-rockslide induced by buckling failure at Jiasian in Southern Taiwan.
1018 *Landslides* 17, 1319–1335. <https://doi.org/10.1007/s10346-020-01360-3>

- 1019 Zheng, Y., Chen, C., Liu, T., Zhang, H., Xia, K., Liu, F., 2018. Study on the mechanisms of flexural
1020 toppling failure in anti-inclined rock slopes using numerical and limit equilibrium models.
1021 Engineering Geology 237, 116–128. <https://doi.org/10.1016/j.enggeo.2018.02.006>
- 1022 Zheng, Y., Wang, R., Chen, C., Meng, F., 2021. Analysis of Flexural Toppling Failure in Rock Slopes
1023 Using Discrete Element Method. Front. Earth Sci. 9, 773088.
1024 <https://doi.org/10.3389/feart.2021.773088>
- 1025 Zou, Z., Tang, H., Xiong, C., Su, A., Criss, R.E., 2017. Kinetic characteristics of debris flows as
1026 exemplified by field investigations and discrete element simulation of the catastrophic Jiweishan
1027 rockslide, China. Geomorphology 295, 1–15. <https://doi.org/10.1016/j.geomorph.2017.06.012>