



Structural and Dynamic Numerical Models of Rockslides in the Carpathians and the Alps

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Abstract

The stability of rock slopes is often guided by the structural geology of the rocks composing the slope. In this work, we analyse the influence of structural characteristics, and of their seismic response, on large and deep-seated rock slope failure development. The study is focused on the Tamins and Fernpass rockslides in the Alps and on the Balta and Eagles Lake rockslides in the southeastern Carpathians. These case studies are compared with catastrophic rock slope failures with ascertained or very likely seismic origin in the Tien Shan Mountains. The main goal is to identify features allowing to identify seismically induced deformation modes based on the source zone rock structures. We will present examples of classical anti-dip slope and along-strike rock structures that hint at a possible/partial seismic origin, but we will also consider a series of mixed structural types, which are more difficult to be interpreted. This morpho-structural study is supported by distinct element numerical modelling results showing that seismic shaking typically induces deeper seated deformation in initially ‘stable’ rock slopes. In addition, for failures partially triggered by dynamic shaking, these studies can help identify the contribution of the seismic factor to slope movements. The identification of the partial seismic origin on the basis of the dynamic response of rock structures can be particularly interesting for case histories in less seismically active mountain regions (in comparison with the Andes, Tien Shan, Pamirs), such as in the Alps and the Carpathian Mountains.

Keywords

Deep-seated failure • Bedding and joint orientation • Seismic deformation • Structural analysis • Discrete element modelling

Introduction

Hazards related to massive rockslides affect most mountain regions of the World, especially those in tectonically active areas. However, the origin of the pre-historic failures is often unclear, as they are often the result of processes acting over longer terms (preparatory factors: e.g., slope oversteepening, weathering, glacier retreat and debuttressing) and of those acting over the short term (single or multiple triggers: e.g. single or multiple earthquakes, climatic events). In addition, several preconditioning factors influence the stability of rock slopes, such as the type of local lithology and the orientation of geological structures. Indeed, geological structures, such as bedding, ductile folds, discontinuities, brittle faults and fractures are known factors decreasing the stability of rock slopes according to their orientation and the (seismo-)tectonic deformation history (Stead and Wolter 2015). In this paper we will shortly review structural features that would allow distinguishing seismic trigger modes based on the source zone rock structures. Therefore, especially deep-seated and very large failures (with a volume of $>10^7$ m³) will be analysed with regard to their structural characteristics. We will focus on the SE Carpathians and the Alps that have been exposed to numerous rockslide hazards, but for which the seismic contribution to rockslide hazards is not well defined (examples analysed include the ‘Balta’ and ‘Eagles Lake’ rockslides located in the SE Carpathians and the ‘Tamins’ and ‘Fernpass’ rockslides, respectively, in the Swiss and Austrian Alps—Fig. 1). The main goal of this work is to define the general influence of the rock structure,

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Fig. 1 Location of studied rockslides

and, more specifically, of its seismic response, on the stability of a slope.

Seismotectonic Context of Studied Rockslides

SE Carpathians

The SE bend of the Carpathian Mountains belt, Romania, shows possibly the highest sub-crustal earthquake activity in Central Europe. Even though the region presents a comparatively smooth relief, it is prone to slope instabilities due to intense precipitation and floods, but also seismic events (Balteanu et al. 2010). Especially the here studied Vrancea-Buzau region is known to be seismogenic and numerous intermediate-depth events were registered in the last three centuries. Magnitudes of these events vary between M_w 7.4–7.9. Historic reports of most $M > 7$ earthquakes (in 1802, 1838, 1940, 1977) also document geohazards such as groundwater rises, floods, liquefaction, cracks and landslides (see e.g. Georgescu and Pomonis 2012).

Here, we focus on the case studies of the Balta and Eagles Lake rockslides, both deep-seated failures located in the Flysch Carpathians, of unknown age, but marked by geomorphic and structural indices of potential co-seismic failures. Balta rockslide developed in a Paleogene schistose sandstone flysch marked by thick sandstone layers (general view shown in Fig. 3). The Eagles Lake rockslide was triggered from a crest made of Cretaceous sandstone flysch. These mass movements are marked by profound head scarps, and anti-dip slope bedding ($40\text{--}50^\circ$ for Balta, 20° for Eagles Lake). For both, a major part of the crushed mass accumulated in the middle part of the slope. For the Balta rockslide, the landslide toe spreads into the valley and most likely had dammed the river in previous times (Mreyen et al. 2017).

The pronounced morphology of the rockslide distinguishes itself from the vast number of superficial debris flows typical for the region. Views of this rockslide together with structural data are presented in the next section, in Figs. 3 and 4.

The Alps

Earthquakes in the Alps take place at different depths and have the potential of reaching seismic magnitudes above 6 (e.g. Friuli 1976 and Basle 1356) and can therefore trigger landslides up to 50 km away from the epicentre (Lenhardt 2007).

There is a long record of landslide disasters in historical and recent times in the Alps, but there only a few documented cases of larger rockslides triggered by earthquakes. For instance, in 1348, six landslides were triggered from the Dobratsch Mountain by an earthquake in the Friuli region (northern Italy).

In the Eastern Swiss Alps (Grisons region), the ancient Tamins rockslide with a volume exceeding 1 km^3 has an unknown origin but presents some characteristics of a mass movement with at least partial seismic origin—such as the deep scarp morphology that was also highlighted above for the Balta rockslide in Romania. This rockslide collapsed from the Sennenstein Mountain and blocked the Rhine Valley. The Tamins rockslide is a very large mass movement, but it was far less studied than the neighbouring Flims slide. It is assumed that the Tamins event influenced the Flims slide through the formation of the dam on Rhine River and the related impounding of a lake (Krietsch and Wolter 2016). Pollet et al. (2011) have dated the Flims event between 8000 and 9000 14C years BP and other dating measurements suggest that Tamins is about the same age as Flims (Poschinger et al. 2006).

In the western Austrian Alps, the Fernpass rock avalanche made of about 10^9 m^3 of rock material (Fig. 1) is also marked by a deeply incised scarp, cut into thick layers of dolomites, limestones and marls (Ostermann and Prager 2016). Rock materials of the massive slope failure split into two separate arms and were transported 12 km towards the North and 15.5 km towards the South. Prager (2010) mentioned that the particular shape of the scarp suggests that this along-strike wedge failure depends not only on the existing rheology and bedding conditions, but mostly due to convoluted intersections of fracture and uncemented fault systems. The Alps Gmbh mentioned the possibility of a local earthquake in the area but the trigger process of the Fernpass rockslide is still debated. The age of the Fernpass event has

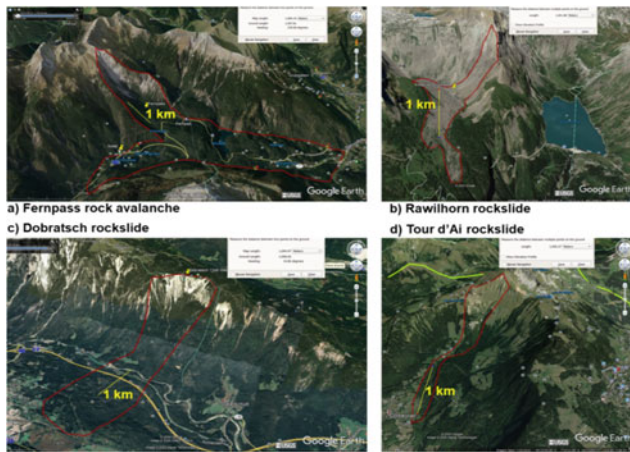


Fig. 2 Google Earth® views of the **a** Fernpass rock avalanche, Austria; **b** Rawilhorn rockslide triggered by the 1946 Sierre earthquake (Switzerland); **c** Dobratsch rockslide triggered near Villach (Austria) in 1348; **d** Tour d'Ai rockslide triggered by the 1584 Aigle (Switzerland) earthquake (with uncertain outline)

been fixed at about 4.2 ka (Ostermann and Prager 2016). Google Earth® views of the Fernpass rock avalanche and the main rockslide that fell in 1348 from Dobratsch Mountain, both located in the Austrian Alps, are shown, respectively, in Figs. 2a, c. Figures 2b, d present two other proved seismically triggered mass movements, located in the Swiss Alps, the 1946 Rawilhorn and 1584 Tour d'Ai rockslides

Geomodels of Studied Rockslides

Inputs

3D geomodels were created for the Tamins and Balta rockslides with surface data and structural features. The Leapfrog Geological Modelling software, developed by Seequent, was used in order to display several types of structural data within a 3D model. For the development of these 3D models, surface data were extracted from the 11 m resolution TanDem-X digital elevation model (UTM 35 N) for the Balta site and from the Swiss ALTI3D digital elevation model for the Tamins site (Swisstopo). The aim of the model is to better outline the spatial relationship between the structural and morphological features of the site. The structural data were collected during field trips and were imported in the software using the Dip and Dip-azimuth data format. These structural data are displayed as disks oriented and inclined according the strike and dip and within a stereographic projection. A stereographic projection, also called stereonet, allows us to represent the 3-dimensional geometry of lines and planes and to display and assess complex structural data (Davis and Reynolds 1996).

The Balta and Tamins Structural Geomodels

The Balta rockslide is a typical anti-dip slope case. The field measurements compiled into Google Earth® images (Fig. 3) and the stereographic projection (Fig. 4) are composed of three main structural features: the bedding planes and two families of joints. The bedding planes are mainly dipping S-SE, with a $N48^{\circ} E/40^{\circ} S$ Fisher mean plane. Indeed, the figures below clearly highlight the anti-dip character of the bedding. The first family of joints (green), with the mean Fisher plane oriented $N241^{\circ} E/56^{\circ} NW$, favours instability, as dipping in the direction of the sliding. The second family of joints (blue), has a Fisher mean plane oriented $N133^{\circ} E/74^{\circ} SW$ and displays patterns favouring detachment.

The structural data of the Tamins rockslide collected on the field and reported on Google Earth® images with strike and dip symbols (Fig. 5) and on a stereographic projection (Fig. 6) display bedding planes with a $N171^{\circ} E/46^{\circ} W$ oriented Fisher mean plane (red dashed line), however, some planes are more oriented northwards or southwards. Indeed, the bedding planes measured on the eastern flank are dipping westwards, while near the top of the scarp the bedding is dipping southwards, and on the western flank it is dipping towards the north-west. Figures 5 and 6 outline the different orientations of the bedding planes. The Fisher mean planes of the bedding were calculated with a $N179^{\circ} E/57^{\circ} W$ orientation for the eastern flank, $N82^{\circ} E/45^{\circ} S$ orientation for the top of the scarp and $N230^{\circ} E/50^{\circ} NW$ orientation for the western flank (see all results in Fig. 5). The bedding planes of the eastern and western flanks do not have a favourable dip orientation for sliding (towards the south), while the bedding planes observed on the top the scarp are dipping in the same direction as the main sliding movement. During the field work, it was noticed that the top of the western flank shows some destabilisation. Indeed, recent rock falls were observed and confirm the favourable trend of the upper part of the mountain for instabilities.

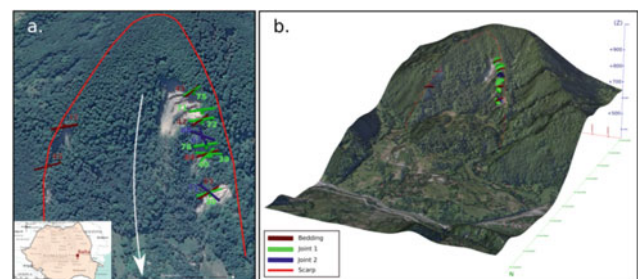


Fig. 3 3D geomodel of the Balta rockslide with a 3D stereonet **a** view towards the South, **b** view towards the SW and **c** view towards the W. The coloured planes are the Fisher mean planes and the disks mark the local strike and dip orientation

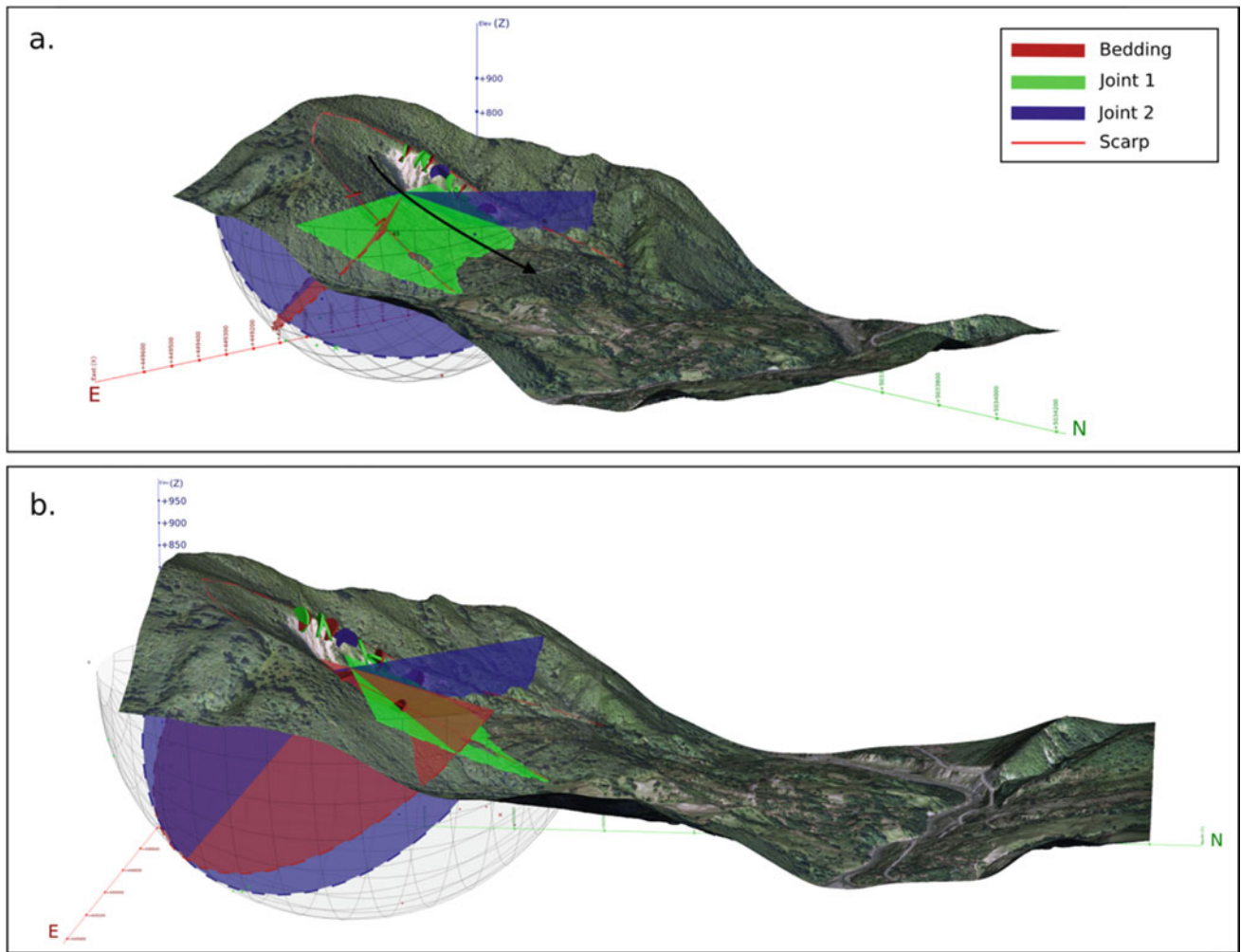


Fig. 4 3D geomodel of the Balta rockslide with a 3D stereonet **a** view towards the South, **b** view towards the SW and **c** view towards the W. The coloured planes are the Fisher mean planes and the disks mark the local strike and dip orientation

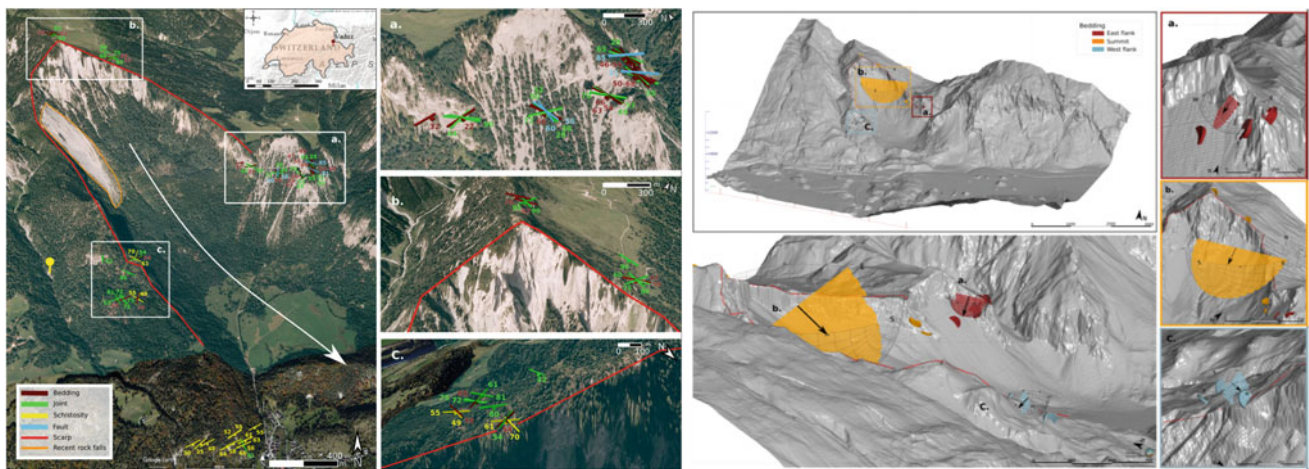


Fig. 5 Left: Google Earth® views with the strike-dip symbols of the measurement made on the Tamins rockslide; the numbers near the strike-dip symbols are the value of the dip and the white arrow displays the direction of the slide. The red icon on the Swiss map show the location of the rockslide. Right: Five different views of the 3D model of the Tamins rockslide; the upper left panel gives a global view of the rockslide, the lower left panel if a zoom on the three stereonet representing **a** the bedding of the east flank, **b** the bedding of the summit and **c** the bedding of the west flank. The colour planes are the Fisher mean planes, the black arrows show the plunge of these planes and the red line outline the scarp of the rockslide.

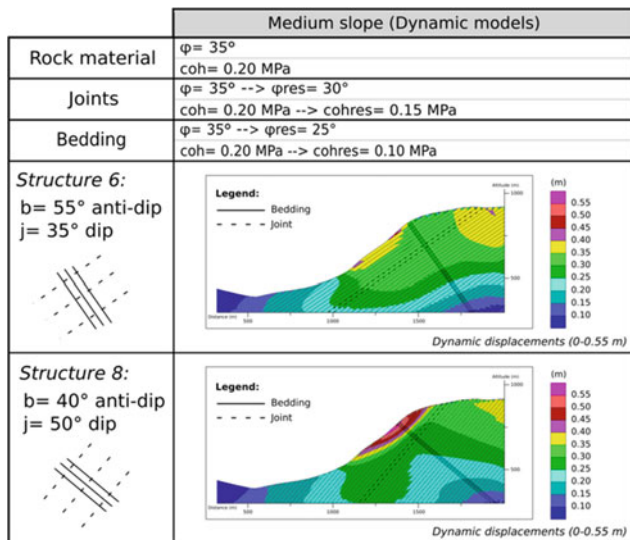


Fig. 6 Dynamic modelling results (in terms of displacements) for the rock slope conditions closest to the Balta case, with anti-dip slope bedding structure

In the following section, some influence of bedding and joint orientation on static and dynamic deformation will be discussed on the basis of 2D numerical modelling results.

2D Numerical Modelling of Static and Dynamic Deformation

Discrete Element Modelling

For the modelling we used the UDEC (Universal Distinct Element Code) 2D numerical code developed by Itasca® for discontinuous problems. The software allows to quantify the effects of loads and external stresses applied to jointed rock material by combining two numeric approaches: the distinct element method (DEM) and the finite-difference method (FDM). Here, we present the application of UDEC to estimate the initial slope stability conditions of the Balta rock-slide and of two other variants of the initial slope (only for comparison, as those do not represent slope morphologies of the studied area – a smooth and a very steep slope). In

addition to the observed 35–55° anti-dip slope bedding and associated orthogonal dip-slope joint orientation also four other structural models were tested. Those tests were completed both by applying static and dynamic loading (about 4 m/s² as peak acceleration), i.e. gravitational force and a synthetic Ricker wavelet, respectively.

For those models the geomechanical properties are summarized in Table 1 (considering that this is mainly a parametric study, average properties of sandstone rocks were used, applying lower values for the more gentle slope and larger shear resistance properties for the steeper slopes). For all models a volumetric weight ρ of 2400 kg/m³ and a bulk modulus K of 10⁷ kPa and a shear modulus G of 4 × 10⁶ kPa were applied.

A possible slope surface prior to failure at the Balta site was created, based on analyses of the failed rock volume. The reconstructed slope morphology is designated as “medium slope” and supposedly represents the most realistic scenario. The two additional surface morphologies were created by decreasing (“gentle slope”) and increasing (“steep slope”) the slope angle, respectively, of the medium slope case. For those three slope cases, as indicated above, various rock structures have been designed. Structural parameters are summarized in Table 2.

By varying the slope angle and bedding-joint structure parameters as indicated in Table 2, fourteen static and corresponding dynamic modelled displacement sections were obtained. Here, we show (Fig. 6) only the displacement sections produced by dynamic modelling for the two cases closest to the Balta morphology and structure, with a medium slope and 40° to 55° anti-dip bedding structure. Those results indicate that some minor displacements occurred after simulated shaking, while the static conditions are totally stable. Actually, only the steep-slope case with 80° anti-dip slope bedding structure produced significant displacements (0.3 m) after gravitational loading. Indeed, the same bedding structure revealed to be the most unstable one, as 0.5 m displacements could be simulated for all slope morphologies, even the gentle one, after seismic inputs. Interestingly, the 80° dip slope bedding structure did not produce any significant (>0.3 m) displacement after shaking, for any slope morphology or structure. We associate this surprising

Table 1 Geomechanical properties: friction angle ϕ and cohesion for the bulk material; both are also used as peak values for the bedding and joint planes; corresponding residual values for the bedding are bfricr and bcohr and for the joints, jfricr and jcohr

Slope	Φ bfricr/jfricr (°)	Cohesion bcohr/jcohr (kPa)
Gentle ~ 15°	30 20/25	100 0/50
Medium = Balta ~ 35°	35 25/30	200 100/150
Steep ~ 70°	45 35/40	1000 300/500

Table 2 Structural parameters, considering the ‘-’ means ‘anti-dip’ (into the slope) and ‘+’ means ‘dip’ (out of the slope)

Slope	Bedding dip (°) variants	Joint dip (°) variants
Gentle ~ 15°	10/–80	–80/10
Medium = Balta ~ 35°	10/–10/80/–80/ 35/–40/50/–55	–80/80/–10/10 –55/50/–40/35
Steep ~ 70°	10/–10/80/–80	–80/80/–10/10

output to the toppling and detachment process that can affect the 80 anti-dip slope structure (also under static conditions, strongly accentuated by shaking). This process finally leads to the collapse of the whole upper part (above mid-slope position) of the steep and medium slope. For the latter the deformation can be very deep (more than 100 m deep) while only some 0.5 m deformation occurs near the surface over the convex curved part of the more gentle slope.

Conclusions

In this paper we presented some structural geology information for several rockslide cases. Actually, some rock structures can have a strong influence on slope stability and may be more or less susceptible to seismically induced failures. The Balta rockslide in Romania, is the prime example of ancient massive slope failure, which origin is unknown but for which a seismic origin is very likely: that slope is made of an initially stable bedding structure, dipping into the slope with 35° to 50°, locally including very thick (>5 m) sandstone beds. A similar conclusion can be determined for the Eagles Lake rockslide. For the Tamins rockslide source zone, a mixed situation was found, as rocks outcropping in the lateral parts of the scarp are not really favouring massive slope failure, while the central zone is marked by a bedding dipping in the same direction as the sliding movement (towards the South). Now, as the Tamins rockslide is likely to be the oldest one analysed here (even though we do not know the ages of the Romanian rockslides), so with an origin that is the closest to the glacier retreat and related debuitressing effects, a possible seismic influence cannot be easily proved for this mass movement. The much younger Fernpass rock avalanche, however, presents an untypical type of along-strike failure. The possible/partial seismic contribution to it cannot be excluded and is thus worth to be studied more in detail.

Static and dynamic numerical 2D models confirm that the medium slope case with anti-dip slope bedding structure (closest to the ‘Balta model’) is stable after gravitational loading and only minor deformation occurs for the applied seismic load (~0.4 g). The most unstable rock structure surprisingly appeared to be the one with an 80° anti-dip slope

bedding orientation. This structure likely supports toppling and detachment, both in static and dynamic conditions. The possible/partial seismic origin of the aforementioned case of the Fernpass rock avalanche could, however, not be analysed here as the along-strike failure requires a back-analysis based on a 3D numerical modelling approach.

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References

- Balteaun D, Chendes V, Sima M, Enciu P (2010) A country-wide spatial assessment of landslide susceptibility in Romania. *Geomorphology* 124:102–112
- Davis GH, Reynolds S (1996) *Structural geology of rocks and regions*. 2nd edn, JohnWiley Sons, p 776
- Georgescu ES, Pomonis A (2012) Building damage vs. territorial casualty patterns during the Vrancea (Romania) earthquakes of 1940 and 1977. 15th world conference on earthquake engineering, 24–28
- Krietsch H, Wolter A (2016) Preliminary forensic investigation of the structural and geomorphological controls on the prehistoric Tamins rockslide in Grisons, Switzerland. In *Landslides and Engineered Slopes. Experience, Theory and Practice*; CRC Press, 2016, 1205–1210
- Lenhardt W (2007) Earthquake-triggered landslides in Austria – Dobratsch revisited. *Jahrb Geol Bundesanst* 147:193–199
- Mreyen AS, Micu M, Onaca A, Cerfontaine P, Havenith HB (2017) Integrated geological-geophysical models of unstable slopes in seismic areas. In *Advancing Culture of Living with Landslides*; Springer International Publishing, 269–279
- Ostermann M, Prager C (2016) Field Trip 12 - Large-scale catastrophic rock slope failures in the Ötz-Inn-Loisach Valley region. *Geo Alp* 13:2257–276
- Pollet N, Cojean R, Couture R, Schneider JL, Strom A, Voirin C, Wassmer P (2011) A slab-on-slab model for the Flims rockslide (Swiss Alps). *Can Geotech J* 42:587–600
- Poschinger AV, Wassmer P, Maisch M (2006) The flims rockslide: history of interpretation and new insights. *Landslides from massive rock slope failure*. In: Evans SG, Mugnozsa GS, Strom A, Hermanns RL (eds) Springer Netherlands: Dordrecht, pp 329–356
- Prager C (2010) *Geologie, Alter und Struktur des Fernpass Bergsturzes und tiefgründige Massenbewegungen seiner Umgebung* (Tirol, Österreich). PhD thesis
- Stead D, Wolter A (2015) A critical review of rock slope failure mechanisms: The importance of structural geology. *J Struct Geol* 74:1–23