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Structural Geology of Rockslide Scarps Analyzed in Virtual Modelling Environments

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Abstract: Geological structures, such as bedding, faults, folds, joints and fractures often contribute to decreased stability of rock slopes according to their strike and dip with respect to the general orientation of the main slope. Additionally, a rock slope may undergo many forms of gravitational displacement-induced (e.g. toppling), erosional (e.g. river undercutting) and/or weathering-induced destabilization. A variety of deep-seated very large (with a volume of > 10^7 m^3) rock slope failures have been analyzed according to their structural characteristics. Studies include field surveys with structural geology measurements and image collection with Unmanned Aerial Vehicles (UAVs). The latter were then used to construct digital twins of the rockslide sites. Structural elements were analyzed by using stereo plot tools that can also produce 3D outputs of the studied planes. In a few cases additional geophysical data were collected in the field (both on the rockslide deposits and on bedrock around the scarps). All those data were then combined within 3D geomodels of the studied sites and related 3D representations were integrated in immersive virtual environments. To some of the models also numerical analyses have been applied.

Keywords: ***UAV, Geomodels, Rock structures, VR.***

Introduction

One first practical objective of the use of 3D constructions from UAV imagery within Virtual Reality (VR) is to investigate sites that are barely accessible in the field, such as the rock outcrops within high and very steep rockslide scarps. Second, 3D geomodels help reconstruct the subsurface domain and allow viewing the geological structures from all sides to understand better the spatial relationships between different structural elements (including different joint families, and toppling-related folding and fracturing).

For a few cases, also numerical models have been developed to study the influence of structural and geomechanical elements on (potentially seismically induced) rock slope failure. The main goal is to identify features that would allow us to distinguish seismic trigger modes from climatic ones, notably on the basis of the source zone rock structures. For instance, anti-dip slope bedding orientation may hint at a seismic origin, but we also consider a series of mixed structural types, which are more difficult to interpret as markers for a seismic or of climatic rock slope failure origin.

Most of our studied rockslide sites are located in seismically active mountain ranges (southeastern Carpathians, Caucasus, Tien Shan, Longmenshan). However, outcomes of this study could also help identify rockslides with a partly seismic origin in less seismically active mountain regions, such as the northern and western Carpathians and the Alps. In the Alps, sites previously studied include the Fernpass, Tamins rockslides and avalanches. Related results had been published in Lemaire et al. (2020).

Methodology and results

Structural geology data have been collected both in the field (see examples Figure 1 and Figure 2 with, respectively, plots of 3D strike-and-dip symbols and of related planes in a 3D geomodel environment, here using the Leapfrog® software) and in immersive virtual environments. The latter have been built by using UAV imagery data collected on the site (for some sites also geophysical and geomechanical properties were studied); constructed models can also be inserted in Cesium® to ensure a more extensive virtual environment (but with limited on-site resolution).

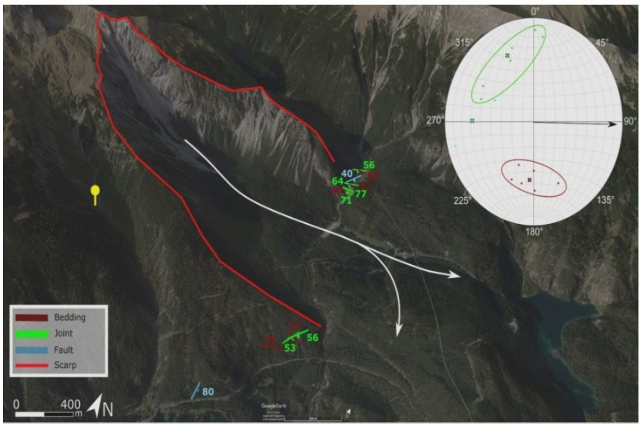

Figure 1, Structural elements measured in the field on the Fernpass rock avalanche site, Austria (from Lemaire et al., 2020); two views shown.

The sites of the Karasuu rock avalanches located along the Talas-Fergana Fault in the Tien Shan demonstrate the usefulness of the analysis in VR, as most of the rock outcrops in the scarp area are barely accessible in the field, as located within the very high and nearly vertical scarp. In summer 2024, UAV data collected for those sites and a series of other rockslides in the Tien Shan. A screenshot of the structural measurements simulated in the immersive virtual environment is shown in Figure 3.

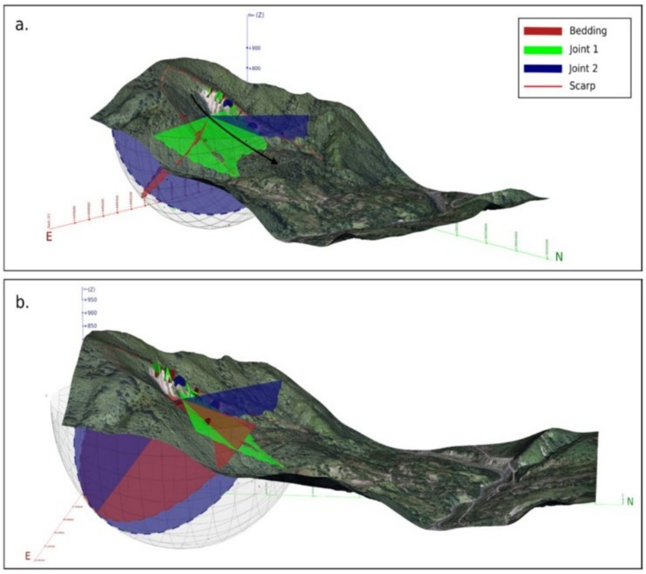

Figure 2, Structural elements measured in the field on the Fernpass rock avalanche site, Austria (from Lemaire et al., 2020); two views shown.

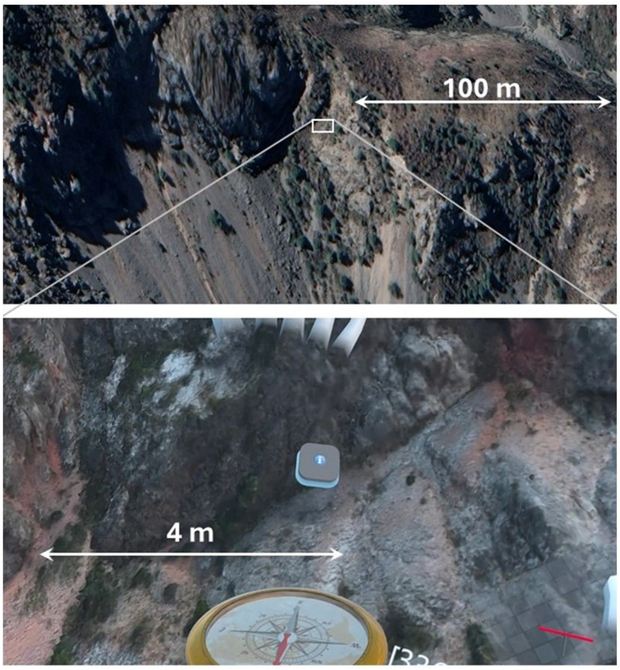

Figure 3, Structural measurement (see strike-and-dip symbol and virtual compass in lower part, with location within the Google Earth® view above) of joint planes in the lower Karasuu rockslide scarp, within an immersive virtual environment

Conclusion

For a series of sites, like for the Tamins rockslide in the Alps, structural analysis both in the field and in a geomodel environment helped conclude that a seismic trigger was not needed to trigger the massive rock slope failure. However, the same analysis, supported also by numerical modelling lead to the conclusion that e.g. the Balta rockslide the Carpathians (see structural numerical model shown in Figure 4), has most probably a seismic origin. One of the main structural elements hinting at a seismic origin is the anti-dip slope situation with layering or main joint planes dipping into the slope, which basically stabilizes the slope and requires a strong trigger event to produce a massive failure.

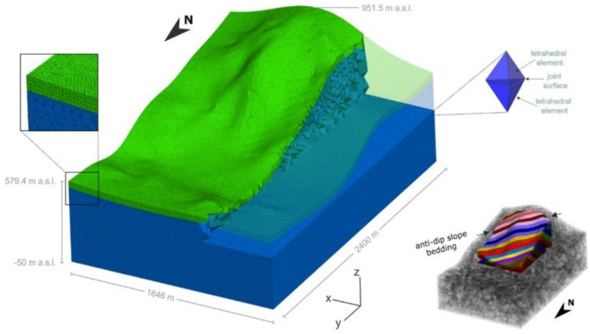

Figure 4, Structural 3D model of the Balta rockslide site used for the dynamic numerical analysis (with 3DEC, by Itasca®) completed by Mreyen et al., (2022).

For the Fernpass rock avalanche, we concluded that it might at least partially have been triggered or prepared by seismic shaking. For other Alpine rockslides (e.g. for the Oeschinensee slide in the Swiss Alps), paleo-studies (see, e.g., by Köpfli et al., 2018) concluded the same – for those a detailed dynamic numerical back-analysis is needed like the one we did for the Balta site.

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