

Rapid deep-seated slope failures in different paleoclimate: coseismic or rainfall induced? Insights from the Outer Western Carpathians

Ivo Baron^{1*}, Thanh-Tùng Nguyễn², Régis Braucher³, Rostislav Melichar⁴, Jia-Jyun Dong², Piotr Moska⁵, Tomasz Goslar⁶, Filip Hartvich¹, Jan Klimeš¹, Jia-Cian Gao^{7,8}, Cheng-Han⁹, Lin Martin Šutjak⁴, Lenka Kociánová⁴, Václav Dušek⁴, Chia-Han Tseng¹⁰, Černý Jan⁴

¹ *Institute of Rock Structure and Mechanics, the Czech Academy of Sciences, Department of Engineering Geology, Prague, Czechia*

² *Graduate Institute of Applied Geology, National Central University, Taoyuan, Taiwan*

³ *CNRS INRAE, CEREGE, Aix en Provence Cedex, France*

⁴ *Department of Geological Sciences, Masaryk University, Brno, Czechia*

⁵ *Institute of Physics, Silesian University, Gliwice, Poland*

⁶ *Adam Mickiewicz University, Faculty of Geographical and Geological Sciences, Krygowskiego 10, 61-680 Poznań, Poland*

⁷ *Earthquake Disaster & Risk Evaluation and Management Center, National Central University, Taoyuan, Taiwan*

⁸ *Graduate College of Sustainability and Green Energy, National Central University, Taoyuan, Taiwan*

⁹ *Department of Civil Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan*

¹⁰ *Department of Atmospheric and Geological Sciences, Chinese Culture University, Taipei City, Taiwan*

*Corresponding author: e-mail address: baron@irms.cas.cz

Keywords: *Keywords list.*

Abstract: Rapid deep-seated rockslides that transformed into rock avalanches and mudflows are one of the most dangerous features of mountainous regions. In the flysch belt of the Outer Western Carpathians along the border between the Czech Republic and Slovakia, high-resolution LiDAR digital terrain models revealed more than 2.5 thousand of clustered half-ellipsoidal scars of prehistoric depleted source zones belonging to such highly mobile deep-seated rockslides. These depleted source zones occur mostly in mudstone-dominated rock at generally gentle slopes ranging from 8 to 20° and they are up to forty meters deep and up to 500 m long. The released landslide masses travelled for a distance of up to 1-2 km, while being transformed to debris flows, mudflows and rock avalanches.

We conducted conventional radiometric techniques such as radiocarbon dating (¹⁴C) and optically stimulated luminescence (OSL) applied to datable sediments, and rock surface cosmogenic radionuclide exposure (CRE) Beryllium-10 dating at depleted source zones scars of those rockslides across the region. They grouped at discrete time periods of ~1.6-1.7 ka b2k, ~2.5-2.8 ka b2k, ~7.4 ka b2k, ~8.5 ka b2k, ~13.6-13.7 ka b2k, ~23 ka b2k, ~45 ka b2k and even ~90 ka b2k, corresponding mostly to the humid and warm climate of the Holocene, but also cold and dry periods of the Weichselian glacial period. Therefore, the climatic control seems not to be the only plausible factor of their origin.

In order to better infer their triggering mechanism, we implemented an integrated approach combining morphometric analysis, velocity-dependent friction laws (VDFL) from rotary shear experiments with Newmark Displacement Analysis (NDA), and numerical modeling to constrain possible earthquake parameters from a model case-study landslide characteristics. Firstly, we conducted a detailed structural analysis to characterize the failure surface and intersecting joints within an overturned anticline. Laboratory experiments of the host rock revealed that friction dropped dramatically during rapid slip, enabling catastrophic landslide acceleration under seismic loading of undrained saturated material. The undrained fully saturated conditions, however, could not lead to the failure alone. NDA incorporating VDFL identified a critical nearby earthquake magnitude threshold between Mw 7.1-7.3 necessary to trigger such a huge and hypermobile landslide. Additionally, discrete element modeling (PFC3D) successfully reproduced the long-runout distance and formation of a landslide dam in the flat valley floor known from the geological evidence.

For a coseismic triggering speaks also the local geological evidence of other sedimentary structures in the vicinity including injected sand and flame structures within fluviolacustrine sediments, or large angular boulders in riverbed fluvial sediments documented in a trench.

Besides, we also inferred the coseismic origin for a number of individual cases across the orogen. Based on their morphometric characteristics, their Index of Potential Dynamic Trigger - I_{PT} ranged between 0.32 and 0.75 providing another evidence for possible coseismic origin of those highly mobile slope failures. The convergence of complete source evacuation, extreme mobility, and structural controls demonstrate seismic rather than climatic triggering as well. These findings challenge existing views of seismic hazard in Central Europe and demonstrate that regions previously considered stable based on short historical catalogs may still face significant earthquake potential with millennial-scale recurrence intervals.

The research was supported by the international bi-lateral project “Earthquake-triggered landslides in recently active and stabilized accretionary wedges” of the Czech Science Foundation (GAČR 22-24206J) and the Taiwanese Ministry of Science and Technology (MOST 111-2923-M-008-006-MY3).