

EGU21-3276

<https://doi.org/10.5194/egusphere-egu21-3276>

EGU General Assembly 2021

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Inferring hillslope response under seismic loading and rainfall: A case study from the SE Carpathian, Romania

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Seismic stability evaluation plays a crucial role in landslide disaster risk reduction. Related modeling also has to consider the potential influences of the rainfall on the hillslopes. This study aims at understanding the relative influence of the seismic loading and extreme cumulative rainfall on a massive active landslide in the seismically active Vrancea-Buzau region of the Romanian Carpathians (45° 30' 23" N, 26° 25' 05" E). This region has been subjected to more than 700 earthquakes ($M > 4$) events with the highest magnitude of 7.2 (M_w) during the year 1960-2019. Rainfall data of the year 2000-2019 revealed the occurrence of relatively intense rainfall events, especially during the last ten years. The landslide has an aerial dimension of ~9.1 million m². It hosts the small village of Varlaam at the toe along the Bisca River. The slope (with an average gradient of 15-20°) is covered by shrubs and scattered trees near its borders and is relatively barren in the central part. Shales with some intercalated sandstone layers belonging to the Miocene thrust belt constitute the rocks of the slope.

A first survey involving the multi-station array and related Horizontal-to-Vertical noise Spectral Ratio (HVSR) measurements was completed in summer 2019. The findings of the HVSR were processed using the inversion process to infer the shear wave velocity distribution with depth and to detect the sliding surface of the landslide. These velocities were further used to estimate the geotechnical properties of the subsurface using the empirical equations. The HVSR based depth profiles and the Unmanned Air Vehicle based topographic information were used to take four 2D slope sections. These sections were considered for 2D discrete element modeling based stability evaluation under static and dynamic condition along with sensitivity analysis. Static simulation was used to determine the Factor of Safety (FS) using the shear strength reduction approach. Ricker wavelet was used as input seismic load in the dynamic simulation. Potential run-out and flow characteristics of the slope material were explored using the Voellmy rheology based RAMMS software. The relationship between rainfall, surface runoff, and soil moisture was also explored to understand the hydrogeological influence on slope stability.

Though the slope reveals meta-stability ($1.0 < FS < 2.0$) condition under static loading, displacement in the soil reaches up to 1.5 m that further increases to 2.8 m under dynamic loading. According to the topographic characteristics of the slope and to the presence of landslide material or intact

bedrock near the surface, acceleration along the slope reaches a Peak Ground Acceleration in the range of 0.6 to 1.3g. Eight extreme rainfall events (>50mm/24 hours) during the year 2000-2019 are noted to temporally coincide with enhanced surface runoff and increased soil moisture in the region. Debris flow runout modeling indicated that the slope material may attain a maximum flow height and flow velocity of 13 ± 0.8 m and 5 ± 0.5 m/sec, respectively, along the river channel.

Keywords: Landslide; Earthquake; Slope stability; Runout; SE Carpathian