Investigation of ancient mass movements by seismic noise analysis: application to the Romanian Carpathian Mountains

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INTRODUCTION

Assessing the geometry and volume of mass movements is essential for the appraisal of slope stability and for the understanding of slope failure trigger mechanisms. For the latter, we developed seismic ambient noise measurement techniques in order to better characterize the sub-surface of ancient **deep-seated landslides** in **seismic regions**, as in **Carpathian Mountains, Romania**.

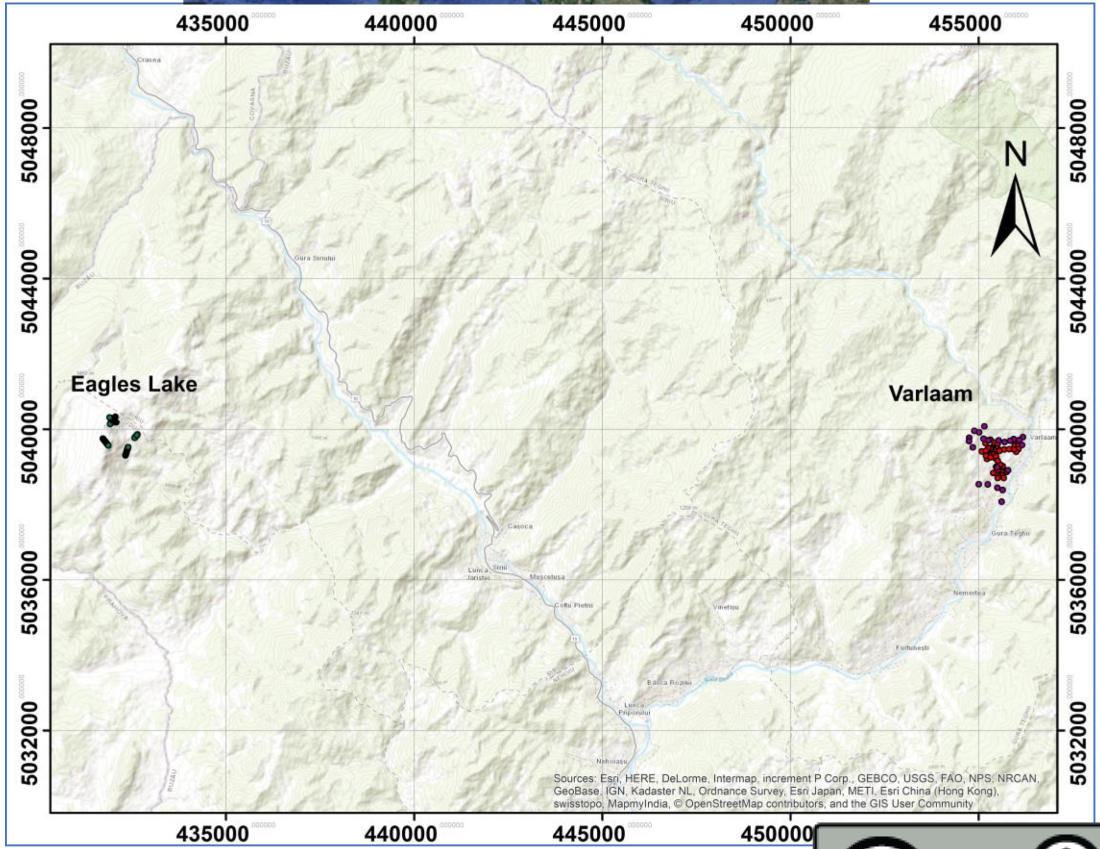
In particular, we conducted two thorough seismological and geophysical campaigns on the landslides **of Eagle's Lake and Varlaam**, in the Buzau region, Romania.

This region hosts very large and generally old (i.e. > 1000 years) mass movements with morphologies which might be due to seismically induced failure.

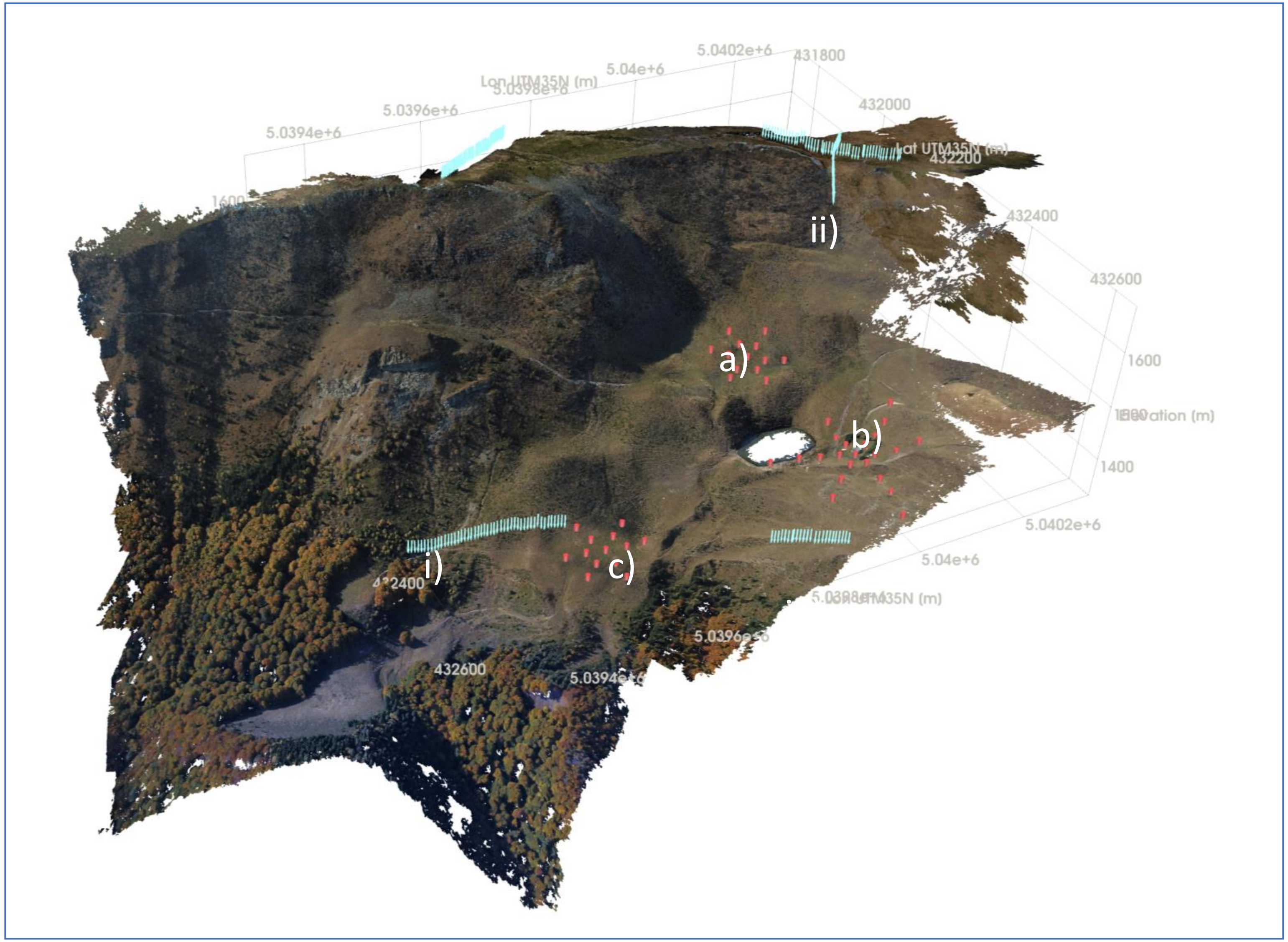
On both sites, we performed abundant horizontal-to-vertical noise spectral ratio (HVSR) measurements and installed several seismic arrays.

The **HVSR technique**, based on the analysis of three component seismic signals, is commonly used to identify the resonance frequency of a given site.

Through the installation of **seismic arrays**, we analyze the **dispersive properties of the surface waves**. By jointly inverting the information through a non-linear approach, we retrieve the shear-wave velocity profile beneath the arrays and identify velocity contrasts with depth.



Eagles Lake Rockslide



UAS based landscape photogrammetry: red cylinders indicate the installed seismic networks and the light blue arrows represent the performed SRT profiles

The Eagles Lake (Lacul Vulturilor) rockslide represents a massive slope failure in Flysch rocks spread out over a wide area, producing deposits with a maximum thickness of 50 m. This ancient rockslide involved the failure of the entire mountain top and formed in sub-horizontally layered sand- and mudstone rocks; a gravitational graben above the scarp indicates deep-seated brittle deformation.

This landslide is thought to be generated several thousands years ago.

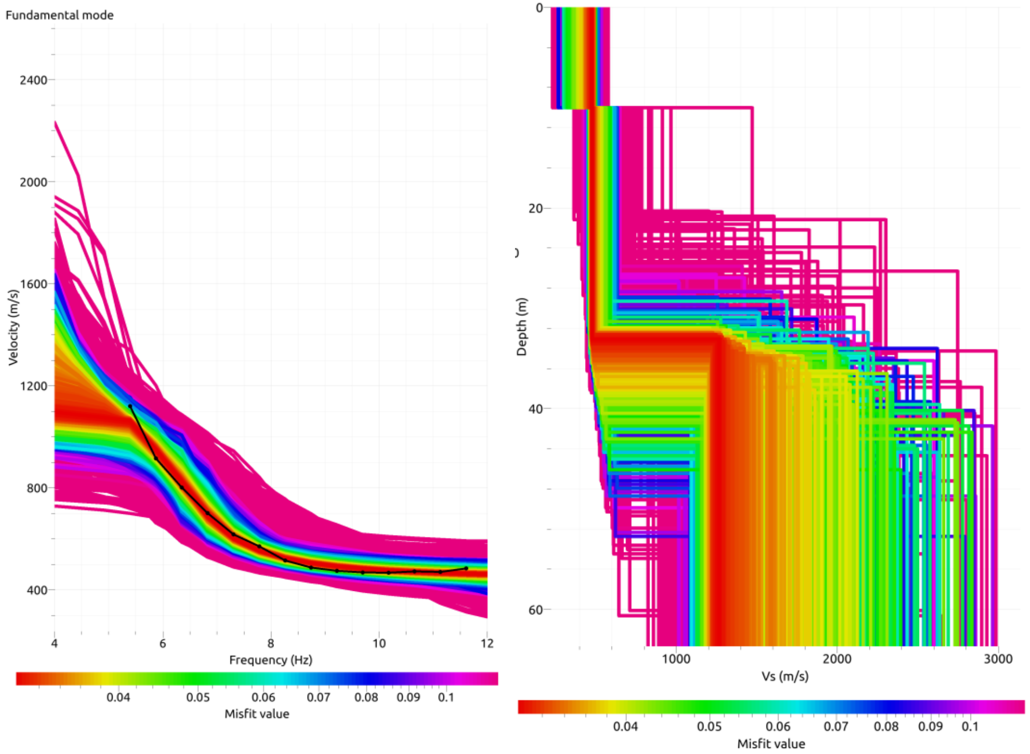
Surveys performed: seismic arrays + seismic refraction tomography profiles

Seismic ambient noise analysis

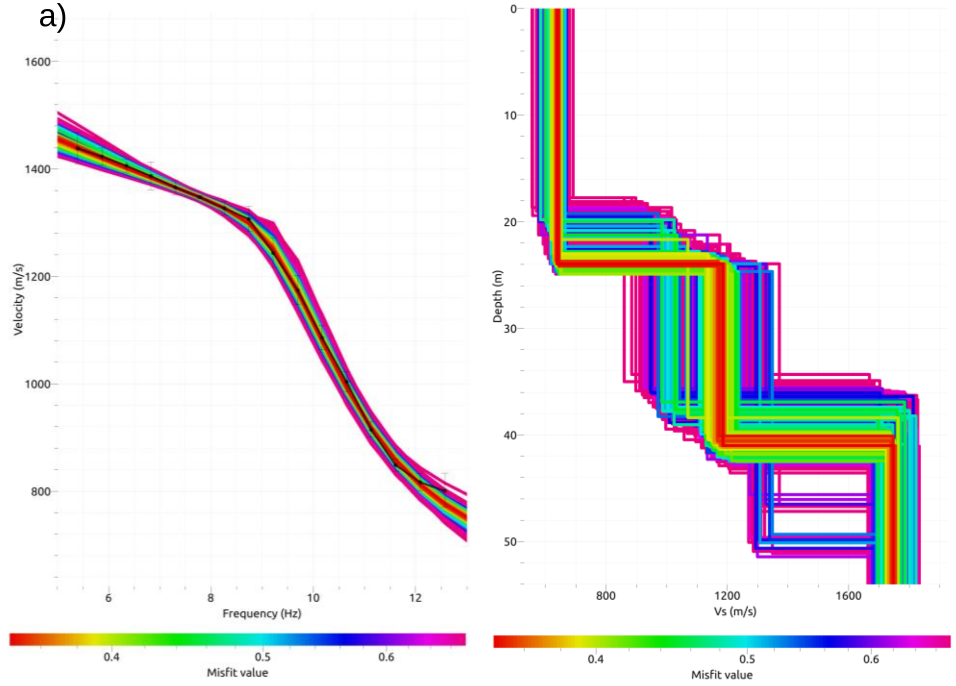
Shear wave velocity profiles are obtained from inversion of Rayleigh dispersion properties of **seismic ambient noise** for three seismic arrays installed on Eagles Lake landslide (labels a) b) c) on previous figure).

- The arrays are composed of 7 CMG-6TD sensors with hexagonal configurations and central point. Record durations between 3 and 9 hours for each configuration.
- The dispersion curves are obtained through high-resolution f-k analysis and inverted by using a neighborhood algorithm (Geopsy software, Wathelet et al., 2004).
- These profiles identify velocity contrasts at depth and the base of the landslide are estimated to approximately 42, 36, 50 m, respectively, under the 3 seismic arrays.

b)



a)



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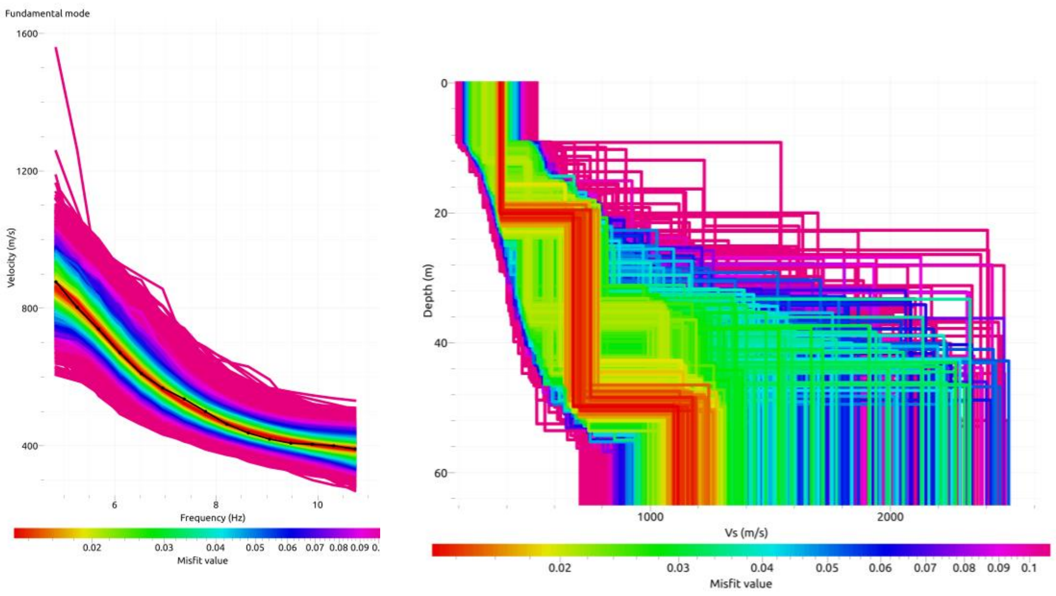
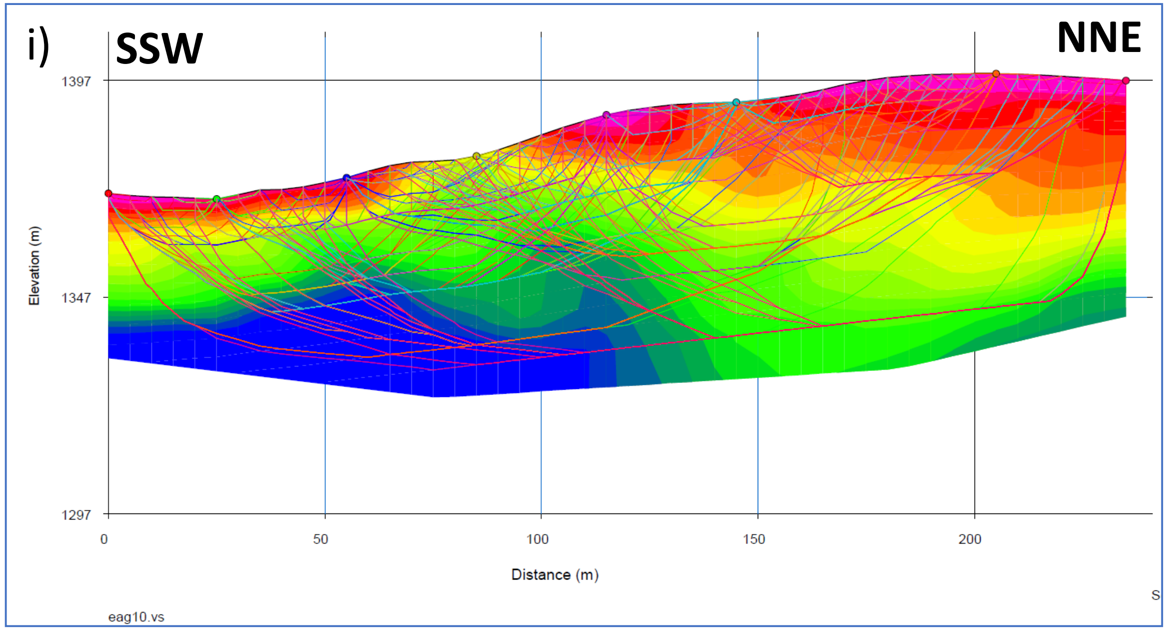
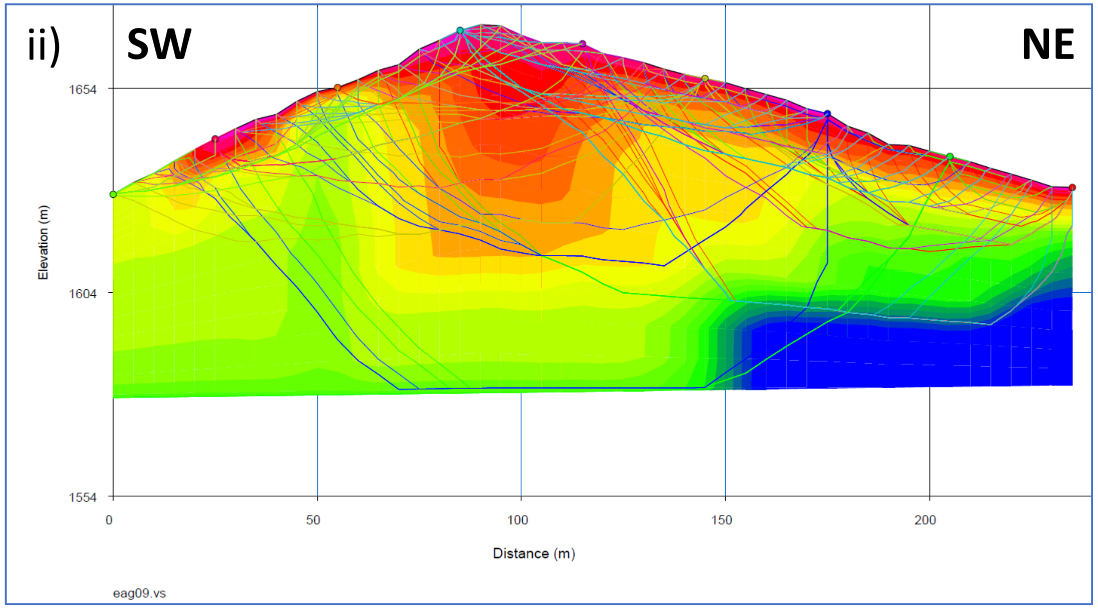
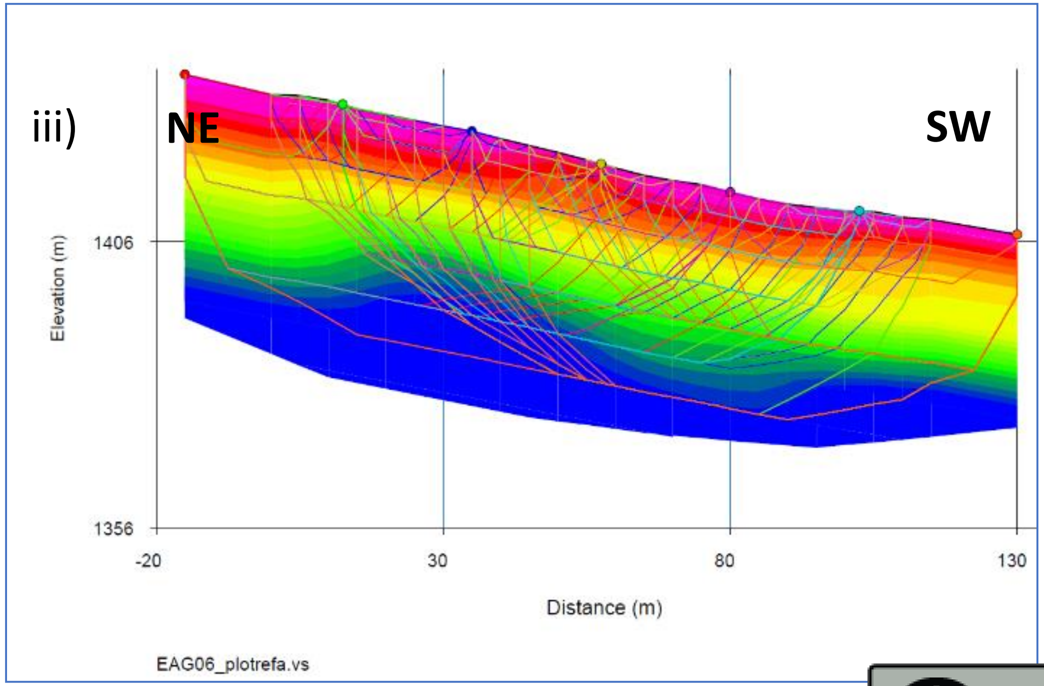


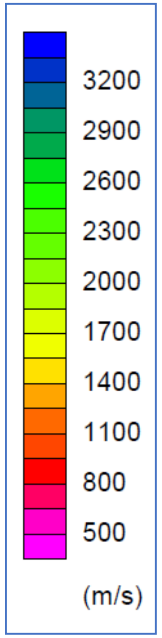
Seismic refraction tomography



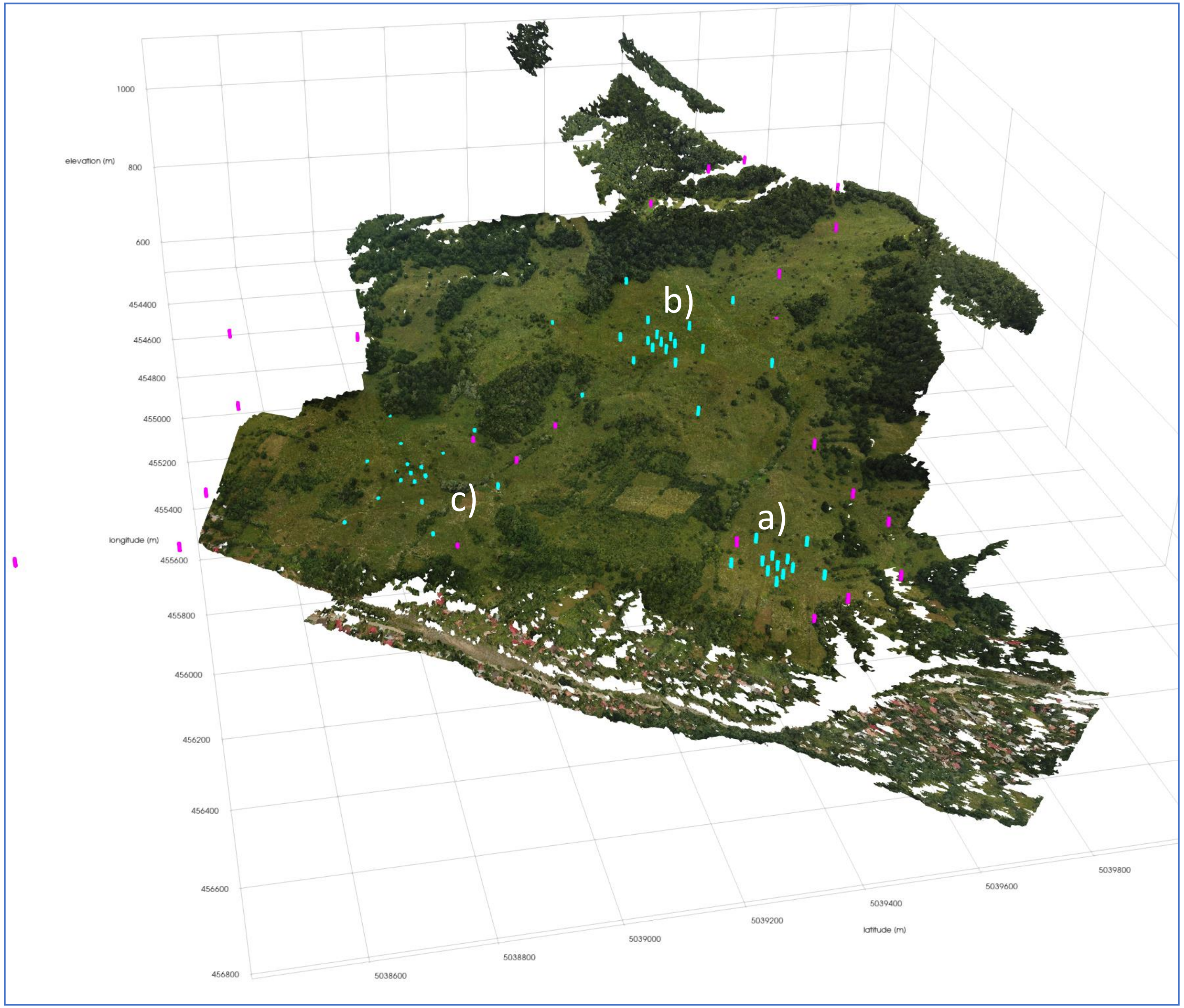
- P-wave velocity profiles are obtained respectively on the border of the landslide (i), on the top of the mountain (ii), and on the failed material (iii). Labels i) ii) and iii) are reported in slide 3.
- We used lines of 48 geophones (4.5 Hz; 5 m spacing). Active source: sledgehammer shots.
- Lateral variations in Vp are evidenced and the base of the landslide is likely inferred by the high contrasts measured in velocities.







Varlaam Landslide



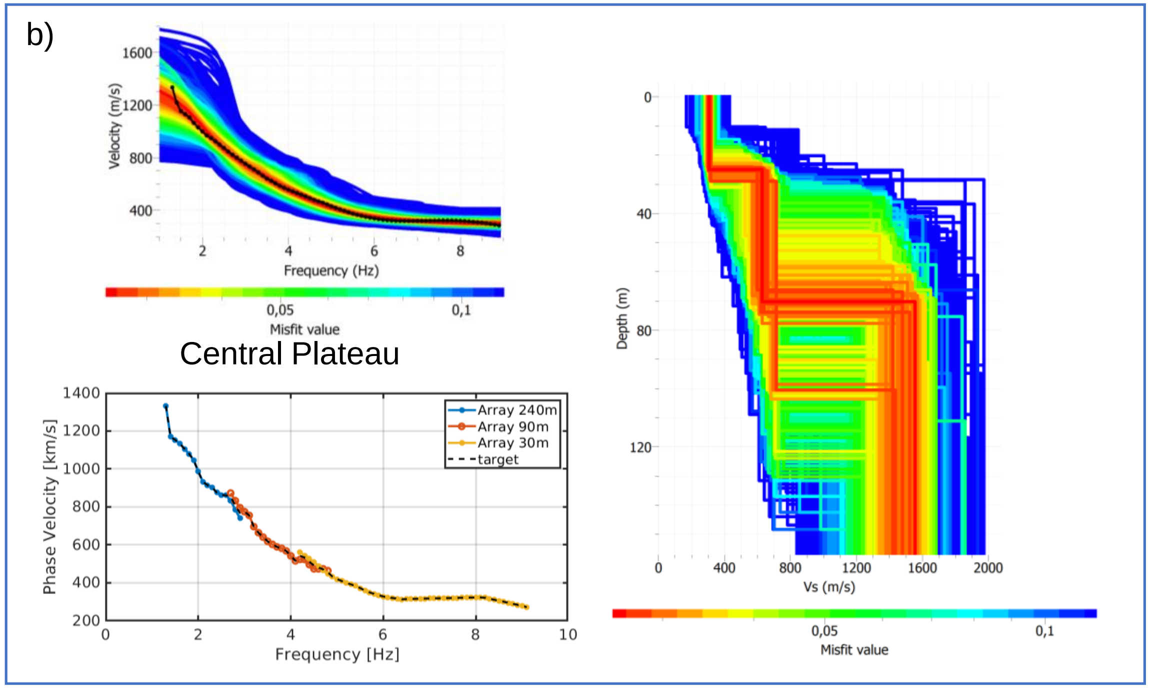
Varlaam is a massive slope landslide, reaching up to 2 km in length. It presents numerous shallow reactivation sectors across the body and is subject to river undercut along the toe, which is causing riparian reactivation.

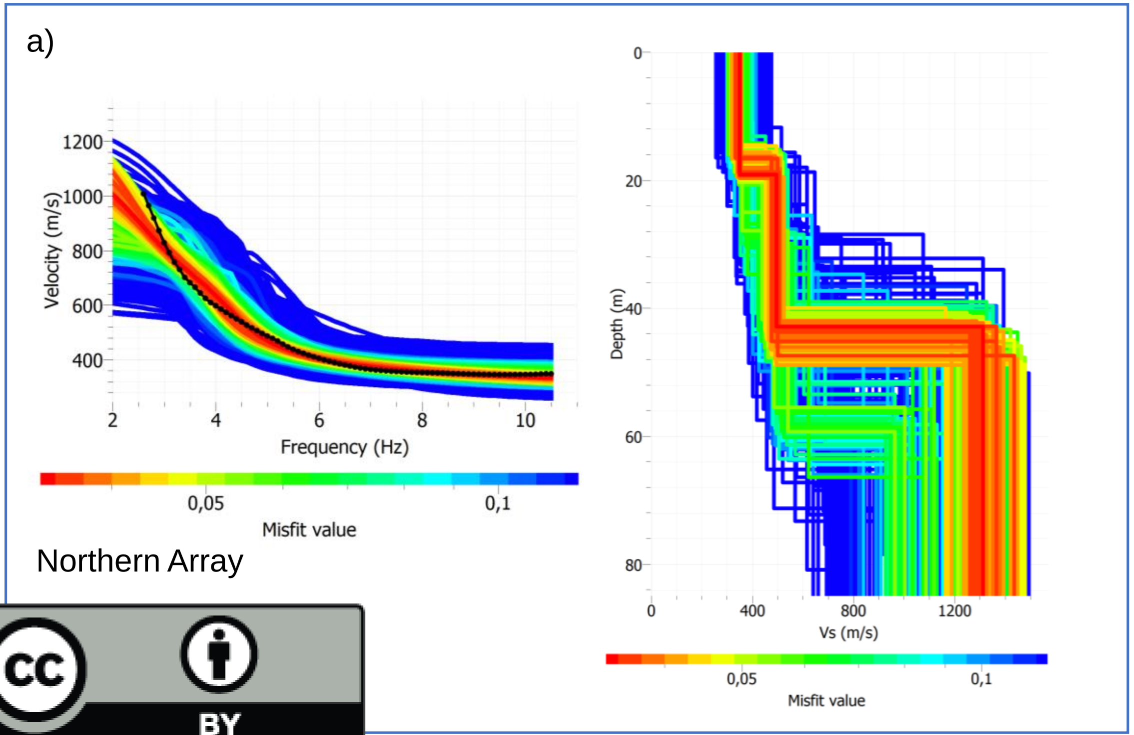
Surveys performed: seismic arrays + HV measurements.

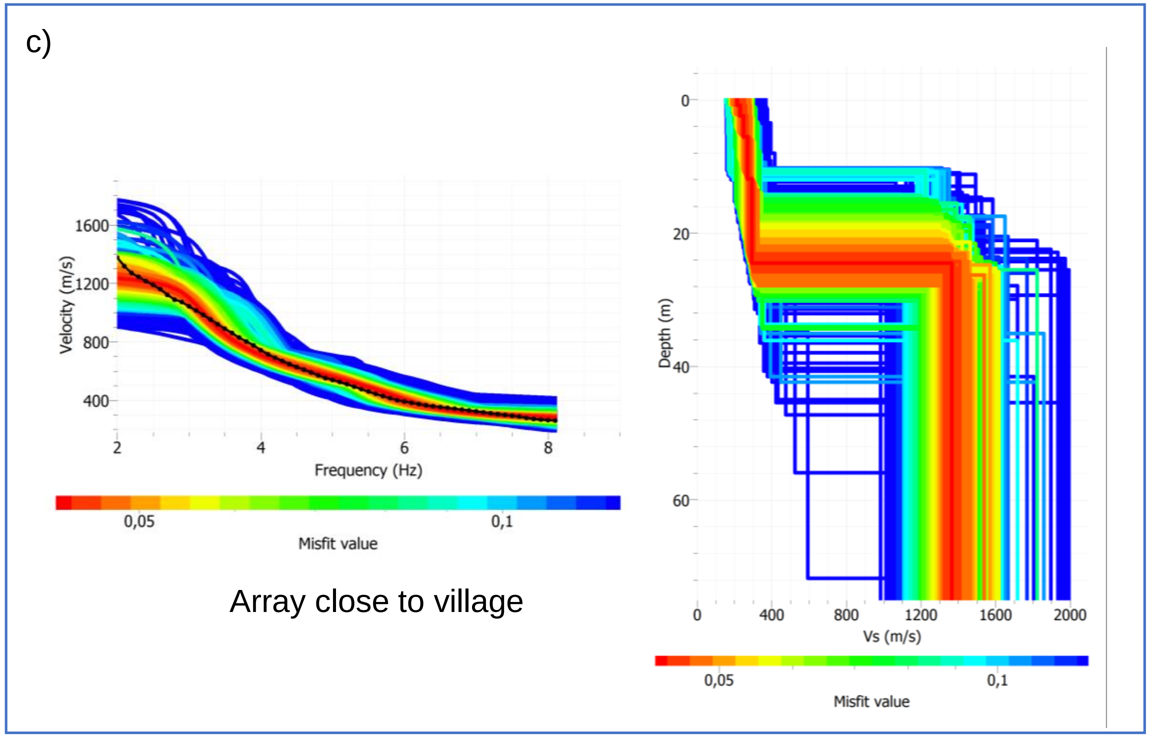
UAS based landscape photogrammetry: light blue cylinders indicate the installed seismic networks and the pink cylinders represent single H/V measurements.

Seismic ambient noise analysis

- Seismic arrays : hexagonal configurations + central station with 7 CMG-6TD broadband velocimeters.
- Rayleigh waves dispersion curves derived through f-k analysis of the network vertical recordings of seismic ambient noise and identification of the resonance frequency through H/V technique.
- The velocity model below each array is then retrieved from the non-linear joint inversion of the dispersion curve and the measured resonance frequency using the GEOPSY software suite (Neighborhood Algorithm, Wathelet et al., 2004).
- Results show contrast velocities at depth of 70, 44 and 24 m, for the 3 arrays, respectively, that are likely to be attributed to the base of the landslide.

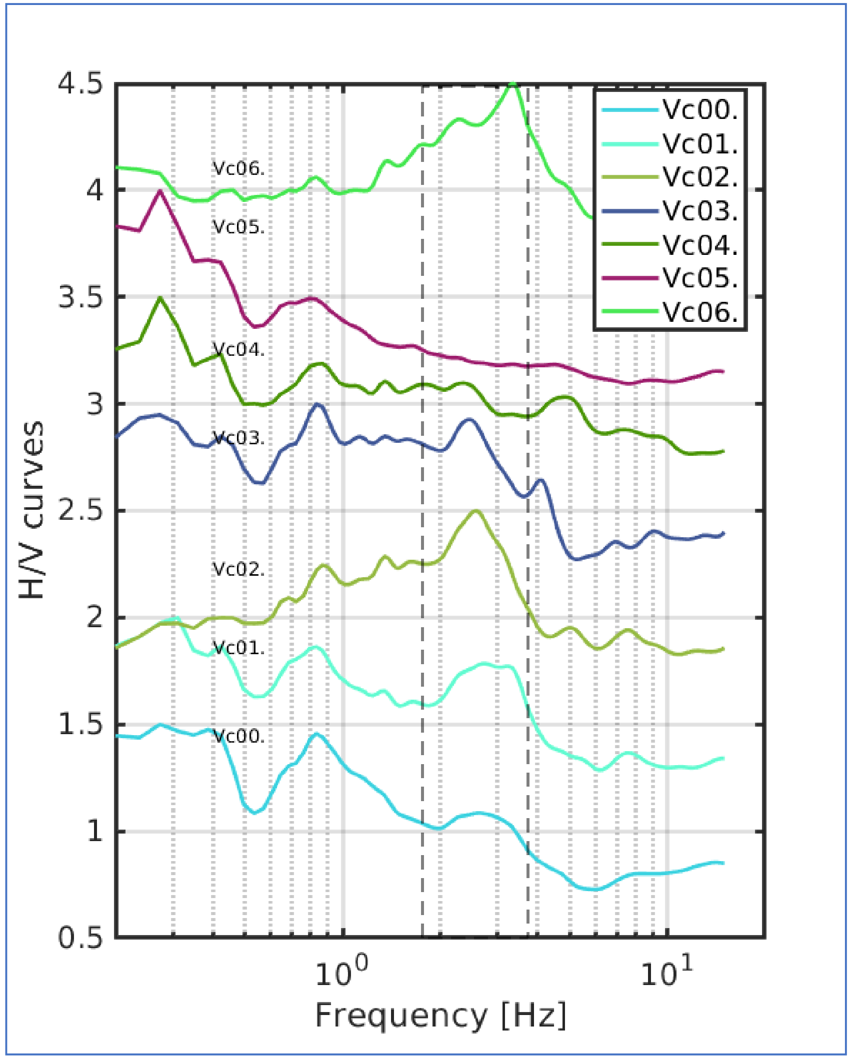




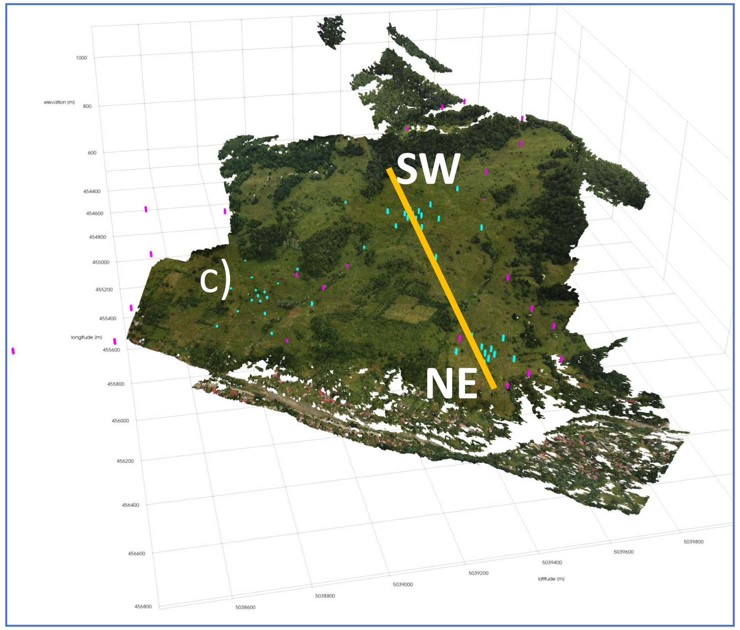


Seismic ambient noise analysis

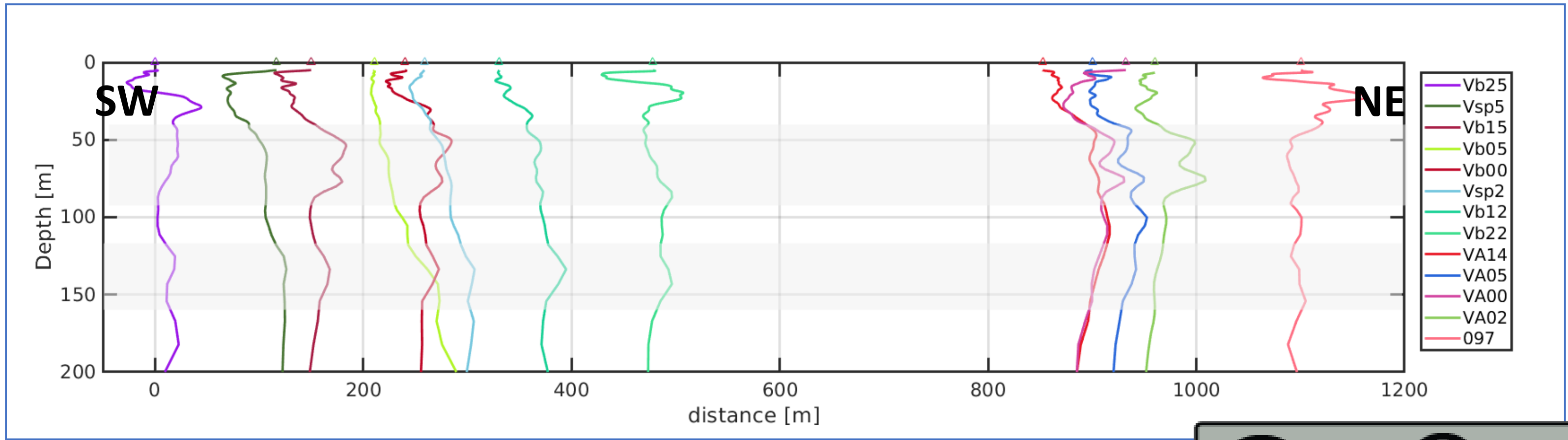
Example of HV measurements for stations at array c) expressed as a function of frequency



- Abundant H/V measurements were performed over the landslide body:
  29 measurements with Lennartz 3D 5s
  60 measurements with Guralp CMG-6TDs 30s (array points)
- At the individual arrays: the results show similar peaks at the different stations.
- By using the resonance frequency – thickness relationship: h=Vs/(4*fr) and Vs= 400 m/s, we estimated the depth of impedance contrasts (Example on a SW-NE profile crossing the landslide body). Depth is expressed in meters below the surface. Common peaks are visible at several measurement points in the gray bands.



H/V curves expressed as a function of depth below the surface



Conclusions

- ➢ Seismic ambient noise analysis (HV and Array analysis) allows us to characterize the landslides of Eagles Lake and Varlaam, Romania, with identification of impedance contrasts at depth, that are likely attributed to the bases.
- ➢ Several seismic array configurations with increasing interstation distances allowed us to reconstruct dispersion curves on a broad frequency band, therefore to increase the investigation depth.
- ➢ Integration with several geophysical methods permitted to characterize the landslide body: SRT leads to a good resolution of the elastic properties and evidenced lateral variations.
- This work, in the near perspectives, is aimed at reconstructing the geometry of the landslides and estimating their volume through 3D geo-modelling.
- In perspectives, this work aims at retrieving the conditions and the energy needed for triggering the landslides, in order to understand if any seismic component is involved in the failure process.

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