Ambient seismic noise monitoring in permafrost regions: a case study from the Matterhorn Hörnligrat (Valais, Switzerland)

V. Strallo[1]**, C. Colombero**[1]**, S. Weber**[2]

[1] *Politecnico di Torino, Department of Environmental, Land and Infrastructure Engineering (DIATI), Italy*
[2] *WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland*

Introduction

Permafrost degradation due to rising temperatures is a critical issue affecting slope stability and can trigger a wide range of natural hazards, such as an increase in rockfall activity (Haeberli et al., 2010; Hartmeyer & Otto, 2024; Hasler et al., 2012). Rockfalls and rock mass instabilities can seriously affect the Alpine region, especially in densely populated or highly frequented areas. Predicting these events is challenging due to the complex interactions between permafrost and rock masses. On the one hand, permafrost can act as a stabilizing force, keeping rock volumes compact by binding them together (Davies et al., 2003). On the other hand, frozen water in rock fractures can lead to increased frost wedging (Draebing et al., 2017; Gruber & Haeberli, 2007). As temperature rises and the ice melts, these fractured rocks may become more susceptible to instability, increasing the likelihood of rockfalls. Despite the increasing number of studies, the exact mechanisms influencing fracture formation in permafrost environments remain unclear.

Continuous passive seismic monitoring has proven to be extremely helpful in identifying potentially unstable rock masses and tracking their evolution in time. This technique allows for the extraction of the resonance frequencies and shear-wave velocity variations of the unstable formations (e.g., Colombero et al., 2021b; Del Gaudio et al., 2014). Monitoring these seismic parameters over time can reveal reversible variations in response to the environmental conditions, while long-term changes can indicate potentially irreversible accumulation of rock damage. Sudden drops in the parameters might also be detected while approaching the instability and provide early warnings for rockfalls (Bertello et al., 2018; Colombero et al., 2018; Fiolleau et al., 2020). However, despite the extensive use of this technique in various environments, its application to permafrost conditions in alpine regions remains limited, especially in relation to the seasonal variation of resonance frequencies linked to freezing and thawing cycles (Weber et al., 2018a).

In this context, we present some of the results obtained from ambient seismic noise analyses at a complex, unique monitoring site: the Matterhorn Hörnligrat in the Swiss Alps, located at an elevation of 3500 m. The analysis is focused on a continuous year of recordings at two passive seismic stations deployed on site. The site features steep, heavily fractured bedrock permafrost, with the ridge's north and south sides displaying contrasting permafrost conditions. The north side has widespread permafrost with a shallow active layer, while the south has a thick active layer with localized permafrost (Hasler et al., 2012; Weber et al., 2017; Weber et al., 2018b). Despite the challenging environment, the site provides a unique, excellent opportunity to study permafrost degradation and the potential hazards for mountaineers.

We focused on two passive seismic stations: MH36 and MH44, deployed on the south side of the ridge (Figure 1). Both stations are equipped with Lennartz Electronic low-noise seismometers (LE-3Dlite MKIIII and LE-3Dlite MKIII), with a sensitivity of 800 V/(m/s). MH36 has been operational since May 2015, while MH44 has been active since August 2018. For this study, we analyse data collected during 2022.

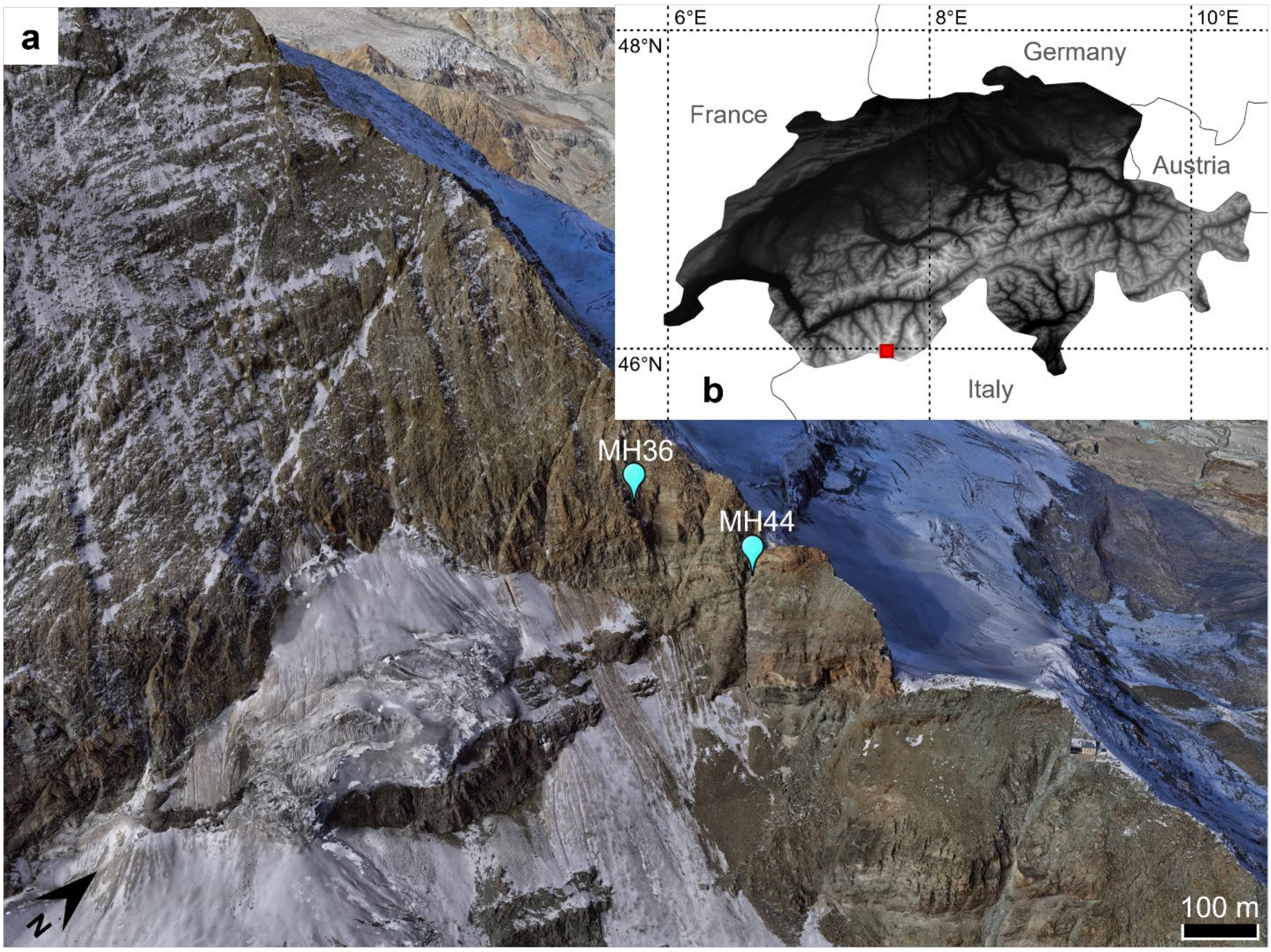

Fig. 1 – Matterhorn Hörnligrat study site, visualized via Google Earth (https://earth.google.com, last accessed on December 11, 2024). (a) Aerial view of seismometer stations MH36 and MH44. (b) Geographical location of the study site. DEM was obtained from SwissTopo (https://www.swisstopo.admin.ch, last accessed on December 11, 2024).

Methods

Spectral analysis and cross-correlation of ambient seismic noise were carried out to identify potential resonance frequencies and seismic velocity variations and follow their evolution throughout the year.

Single-station spectral ratios were computed in the 5-40 Hz frequency range for both stations. We computed the Fast Fourier Transform (FFT) of the three component recordings (East, North, Vertical) on 300-s windows within each hour of recording to optimize the computational time and efficiency. To smooth the spectra and reduce local fluctuations, we applied the Konno & Ohmachi (1998) smoothing method, with a bandwidth coefficient equal to 40. Finally, the Horizontal-to-Vertical Spectral Ratio (HVSR) was computed considering the total horizontal energy. For better visualization in time, the HVSRs were normalized by their maxima (Figure 2a).

The cross-correlation analysis was applied to the East components of the two stations filtered in the 2 to 20 Hz frequency band, following a standard pre-processing procedure involving time and frequency domain normalization (e.g., Bensen et al., 2007; Colombero et al., 2018; Colombero et al., 2021a; Fiolleau et al., 2020; Mainsant et al., 2012). Hourly correlograms between the two stations were then bandpass-filtered into narrower 2-Hz frequency bands. A reference correlogram was also computed, averaging the correlograms during the non-freezing period (May to September). For each narrow frequency band, we computed the hourly velocity change with respect to the reference correlogram through the stretching technique (stretching window ±1.5-2.5 s). The velocity variation dV/V (%) is selected as the one maximising the correlation coefficient (CC) between the hourly correlogram and the reference one.

The passive seismic results were compared with rock temperature measurements at 1-m depth to evaluate seasonal variations in response to the environmental forcings (Figure 2d). The temperature sensor is installed into a shallow borehole drilled next to MH36.

Results

Figure 2a shows the normalized HVSRs computed for station MH36. Several spectral peaks, with variable values and spectral amplitude, can be identified along the year. By contrast, the station MH44 showed no amplification in the considered frequency range. We interpreted the site's spectral peaks and resonance frequencies. Although they cannot be tracked throughout the entire period, two peaks appear in the frequency range of 20-30 Hz in January, becoming distinguishable only in the summer months. The presence of multiple resonance frequencies, along with their varying visibility throughout the year, highlights the complexity of the site and the thermo-mechanical processes controlling the permafrost distribution within fractures. The two frequencies show significant variation between freezing and non-freezing periods (Figure 2a-d). During the first freezing period (January to May), these frequency peaks show high values due to the increased stiffness of the rock-ice structure. During spring, when the uppermost layers in contact with the air (slightly above 0°C) begin to melt, the resonance frequencies slightly increase because of the contrast between the thawing surface layers and the still-frozen deeper layers. As summer advances, temperature rises above 0°C even at higher depths, causing deeper layers to melt. The frequency values decrease, reaching a minimum when the rock temperature drops below 0 °C, marking the start of the second freezing period (October-December).

Figure 2b-c show the seismic wave velocity variations and cross-correlation coefficients for the frequency band 4-6 Hz. During the non-freezing period, higher cross-correlation coefficient (CC) values are observed (Figure 2c), possibly due to higher ambient seismic noise levels at the site. In the winter, the presence of snow may attenuate energy sources, reducing the effectiveness of cross-correlation. Considering only values with CC higher than 0.7, seismic velocity variations follow a similar behaviour to HVSR. Rayleigh wave velocities decrease with increasing rock temperature, reflecting a reduction in the material's stiffness. This trend reverses once the temperature reaches its peak and begins to decrease.

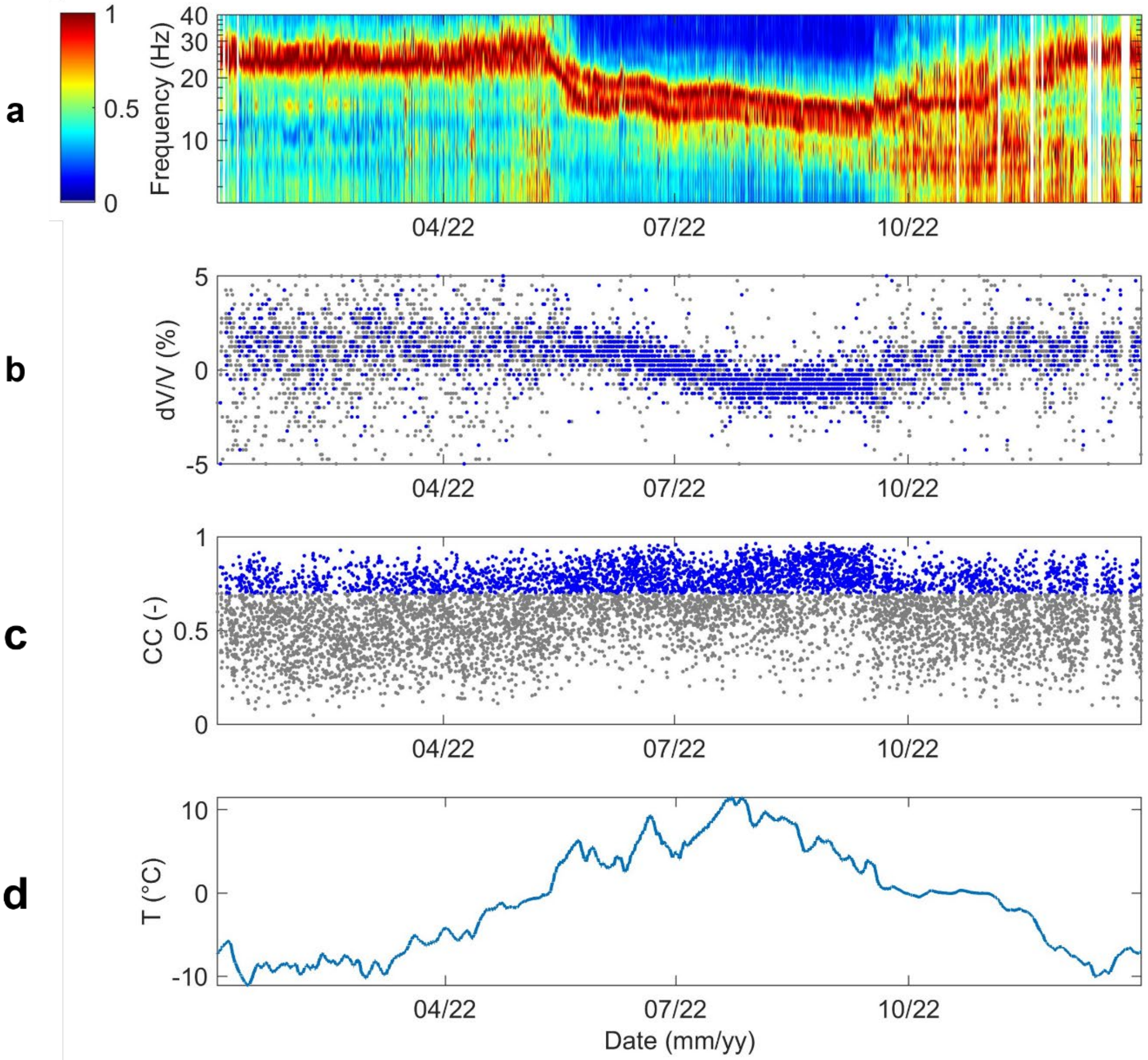

Fig. 2 – (a) Normalized single station HVSRs at station MH36. (b) Hourly velocity variations and (c) cross-correlation coefficients derived from the East components of stations MH36 and MH44 for the 4-6 Hz band; blue and grey colour represent values related to CC>0.7 and CC<0.7, respectively. (d) Rock temperature variations at 1 m depth in the proximity of MH36.

Conclusions

Substantial seasonal variations in resonance frequencies and seismic wave velocities, influenced by changes in rock temperature, were observed at one of the monitoring stations. The increase in resonance frequencies during the freezing period, and the decrease during thawing, reflect the behaviour of permafrost as a stabilizing force that can be compromised as temperatures rise with global warming. Additionally, the variations in seismic velocities further confirm the influence of temperature on the material rigidity and stability. However, due to the complex thermo-mechanical processes governing permafrost distribution within rock fractures, the interpretation of seismic data can be challenging. The surface layers, directly influenced by ambient temperatures, behave differently from the deeper, colder layers, which are less affected by environmental factors. These contrasting behaviours add complexity to the analysis and highlight the need for further investigation to understand these processes fully. Future perspectives of the work involve numerical modelling of the eigenfrequencies of the rock mass in the proximity of the potentially unstable station in order to fully understand the depicted frequency distribution and evolution over time. These findings emphasize the importance of long-term monitoring to capture reversible and irreversible changes in the rock-ice system, which could ultimately provide early warning indicators for potential rockfall events.

Acknowledgments

This work was supported by the PermaSense project (permasense.ch), which provided valuable resources. The authors would like to thank Jan Beutel for his significant contributions.

References

Bensen, G. D., Ritzwoller, M. H., Barmin, M. P., Levshin, A. L., Lin, F., Moschetti, M. P., Shapiro, N. M., & Yang, Y. (2007). Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. *Geophysical Journal International*, *169*(3), 1239–1260. https://doi.org/10.1111/j.1365-246X.2007.03374.x

Bertello, L., Berti, M., Castellaro, S., & Squarzoni, G. (2018). *Dynamics of an Active Earthflow Inferred From Surface Wave Monitoring*. https://doi.org/10.1029/2017JF004233

Colombero, C., Baillet, L., Comina, C., Jongmans, D., Larose, E., Valentin, J., & Vinciguerra, S. (2018). Integration of ambient seismic noise monitoring, displacement and meteorological measurements to infer the temperature-controlled long-term evolution of a complex prone-to-fall cliff. *Geophysical Journal International*, *213*(3), 1876–1897. https://doi.org/10.1093/gji/ggy090

Colombero, C., Godio, A., & Jongmans, D. (2021a). Ambient Seismic Noise and Microseismicity Monitoring of a Prone-To-Fall Quartzite Tower (Ormea, NW Italy). *Remote Sensing*, *13*(9), Article 9. https://doi.org/10.3390/rs13091664

Colombero, C., Jongmans, D., Fiolleau, S., Valentin, J., Baillet, L., & Bièvre, G. (2021b). Seismic Noise Parameters as Indicators of Reversible Modifications in Slope Stability: A Review. *Surveys in Geophysics*, *42*(2), 339–375. https://doi.org/10.1007/s10712-021-09632-w

Davies, M. C. R., Hamza, O., & Harris, C. (2003). *Physical modelling of permafrost warming in rock slopes*.

Del Gaudio, V., Muscillo, S., & Wasowski, J. (2014). What we can learn about slope response to earthquakes from ambient noise analysis: An overview. *Engineering Geology*, *182*, 182–200. https://doi.org/10.1016/j.enggeo.2014.05.010

Draebing, D., Krautblatter, M., & Hoffmann, T. (2017). Thermo-cryogenic controls of fracture kinematics in permafrost rockwalls. *Geophysical Research Letters*, *44*(8), 3535–3544. https://doi.org/10.1002/2016GL072050

Fiolleau, S., Jongmans, D., Bièvre, G., Chambon, G., Baillet, L., & Vial, B. (2020). Seismic characterization of a clay-block rupture in Harmalière landslide, French Western Alps. *Geophysical Journal International*, *221*(3), 1777–1788. https://doi.org/10.1093/gji/ggaa050

Gruber, S., & Haeberli, W. (2007). Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research: Earth Surface*, *112*(F2). https://doi.org/10.1029/2006JF000547

Haeberli, W., Noetzli, J., Arenson, L., Delaloye, R., Gärtner-Roer, I., Gruber, S., Isaksen, K., Kneisel, C., Krautblatter, M., & Phillips, M. (2010). Mountain permafrost: Development and challenges of a young research field. *Journal of Glaciology*, *56*(200), 1043–1058. https://doi.org/10.3189/002214311796406121

Hartmeyer, I., & Otto, J.-C. (2024). Rockfall, glacier recession, and permafrost degradation: Long-term monitoring of climate change impacts at the Open-Air-Lab Kitzsteinhorn, Hohe Tauern. *DEUQUA Special Publications*, *5*, 3–12. https://doi.org/10.5194/deuquasp-5-3-2024

Hasler, A., Gruber, S., & Beutel, J. (2012). Kinematics of steep bedrock permafrost. *Journal of Geophysical Research: Earth Surface*, *117*(F1). https://doi.org/10.1029/2011JF001981

Konno, K., & Ohmachi, T. (1998). Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. *Bulletin of the Seismological Society of America*, *88*(1), 228–241. https://doi.org/10.1785/BSSA0880010228

Mainsant, G., Larose, E., Brönnimann, C., Jongmans, D., Michoud, C., & Jaboyedoff, M. (2012). Ambient seismic noise monitoring of a clay landslide: Toward failure prediction. *Journal of Geophysical Research: Earth Surface*, *117*(F1). https://doi.org/10.1029/2011JF002159

Weber, S., Beutel, J., Faillettaz, J., Hasler, A., Krautblatter, M., & Vieli, A. (2017). Quantifying irreversible movement in steep, fractured bedrock permafrost on Matterhorn (CH). *The Cryosphere*, *11*(1), 567–583. https://doi.org/10.5194/tc-11-567-2017

Weber, S., Fäh, D., Beutel, J., Faillettaz, J., Gruber, S., & Vieli, A. (2018a). Ambient seismic vibrations in steep bedrock permafrost used to infer variations of ice-fill in fractures. *Earth and Planetary Science Letters*, *501*, 119–127. https://doi.org/10.1016/j.epsl.2018.08.042

Weber, S., Faillettaz, J., Meyer, M., Beutel, J., & Vieli, A. (2018b). Acoustic and Microseismic Characterization in Steep Bedrock Permafrost on Matterhorn (CH). *Journal of Geophysical Research: Earth Surface*, *123*(6), 1363–1385. https://doi.org/10.1029/2018JF004615

Corresponding author:
Valeria Strallo
valeria.strallo@polito.it