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Long-term Passive Seismic Monitoring of Permafrost Dynamics at the Matterhorn Hörnligrat (Valais, Switzerland)

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Permafrost degradation in alpine regions driven by climate warming is increasing the likelihood of rock slope destabilization. However, the mechanical response of fractured rock-ice systems to repeated freeze-thaw cycles and long-term warming remains poorly monitored and understood. Using a decade of continuous passive seismic data recorded at different stations, this study investigates how seasonal and long-term environmental forcings affect the mechanical properties of a steep bedrock permafrost site at the Matterhorn Hörnligrat ridge (Valais, Switzerland). We applied spectral analysis (single-station and site-reference spectral ratios), auto- and cross-correlation of ambient seismic noise combined with microseismic event detection and analysis to track the long-term temporal variations and evolution in resonance frequencies and seismic wave velocity within the rock mass, and in the spectral characteristics of microfracturing events. We observed strong, reversible seasonal variations of mechanical parameters linked to freeze-thaw cycles, characterized by reduced stiffness in summer and increased stiffness in winter. Long-term observations showed a continuous decrease in resonance frequencies, wave velocities, and peak frequencies of the microseismic events, indicating progressive and irreversible mechanical weakening of the rock-ice system.

These results demonstrate that passive seismic monitoring enables the detection of both reversible and irreversible mechanical changes in alpine permafrost slopes, providing early indicators of progressive destabilization under ongoing climate warming.