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Time-lapse velocity changes during an open-pit mine slope failure

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Summary

Landslides are widespread geological events that directly impact thousands of people every year and cause significant loss of life. Landslides are often triggered by extreme weather events or earthquakes. Melting permafrost in mountainous areas and increased extreme weather events are expected due to climate change, which will likely lead to greater occurrence of landslides.

While most slope monitoring approaches focus on surface deformation (e.g. using radar), there is evidence that by the time changes manifest at surface, it can be too late to provide adequate early warning. Seismic ambient noise correlation has been successfully applied in landslide monitoring (for example, for a recent review, see Le Breton et al., 2021). This approach measures time-lapse seismic velocity changes in the subsurface of a slope. Several cases of precursory changes have been shown using seismic ambient noise correlation and shows promise in providing early warning of failure.

We present a case study from a dense borehole geophone array installed beneath a well-monitored slope of an open-pit mine in Australia (Figure 1). We applied seismic ambient noise correlation across a period of slope failure and measured a decrease in seismic velocity approximately two weeks prior to the initiation of the slope failure. We investigated this change and its relationship to seismicity, rainfall and surface deformation recorded during this period.

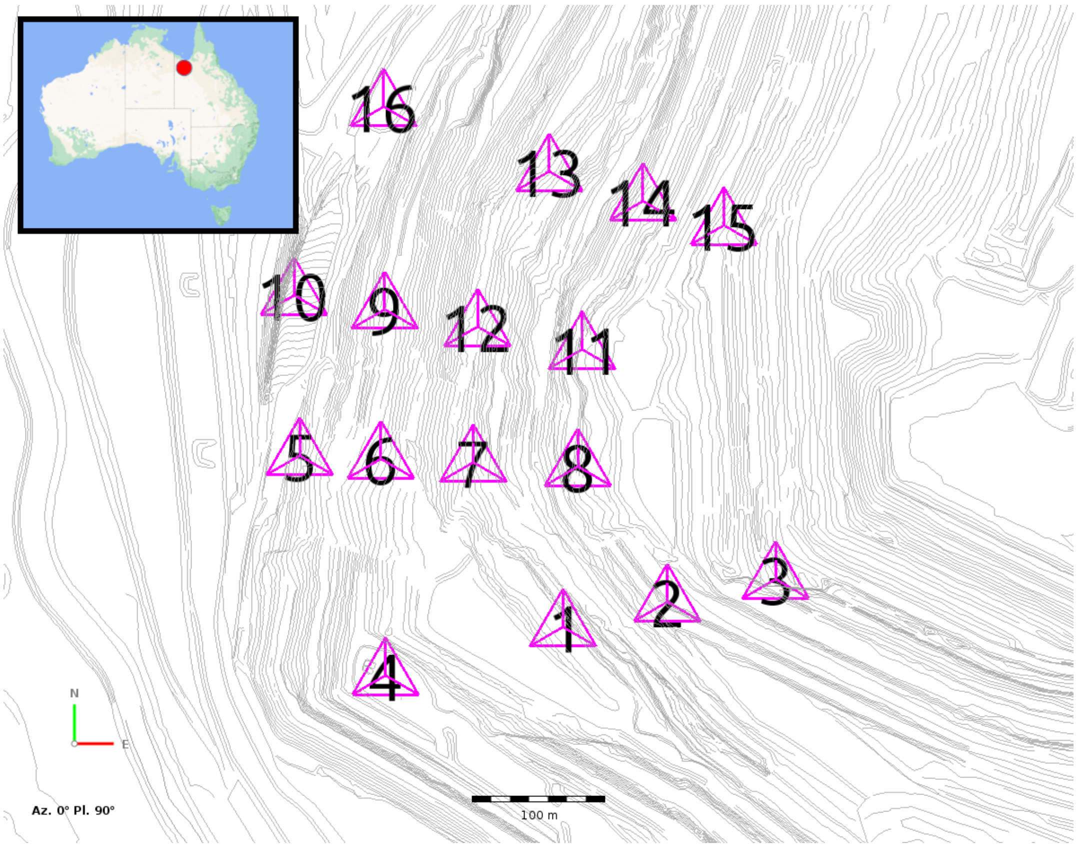

Figure 1: Plan view of locations of the geophones in the seismic array (magenta triangles) installed below the western slope of the open-pit mine. The location of the mine within Australia (inset).

Theory / Method / Workflow

Continuous seismic data from geophones spread across a tailings dam wall are generally recorded at 6,000 samples per second (sps). Ambient noise seismic interferometry is applied to this data to try measure velocity changes in the medium. For each sensor, continuous data for each component is sliced into 10 second detrended and decimated traces (500 sps), with amplitude normalization (one-bit normalization) and spectral whitening (between 6 and 30 Hz) pre-processing steps applied (as suggested in Bensen et al., 2007). For each unique sensor pair and each 10 second trace, the pre-processed data were cross-correlated with a maximum lag time of 2 seconds (2001 samples).

By stacking these cross-correlations, we effectively turn one of the seismic sensors in to a virtual source (Campillo and Paul, 2003). Although accurate reconstruction of the direct arrivals of these virtual source signals rely on a homogeneous distribution and large quantity of noise sources, the tail (or coda) is more dependent on the distribution of scatterers in the medium. As a result, we can make robust measurements of velocity changes even with imperfect virtual source (or Green's function) reconstruction by measuring changes in the coda (Hadziioannou et al., 2009).

Although the cross-correlations are relatively stable over time, they have some temporal variation. This is likely due to slight changes to the noisefield between subsequent 10 second periods. In order to make robust measurements of velocity change, we use a moving window average, or "stack", of each of the cross-correlations in a 2-day window. Note, this does apply a smoothing to temporal measurements of velocity changes, but the tradeoff is that the measurements made are more robust.

Although body wave arrivals appear clear in this case, it is the coda portion of these correlations that we are interested in. We therefore focus on lag times after the direct S-wave arrival and before 2s (at which the decay of the coda mostly disappears and above which is dominated the auto-correlation of the source). Since coda is mostly comprised of shear waves (Aki and Chouet, 1975), we are most sensitive to changes in S-wave velocity.

For making velocity change measurements between correlation stacks, the Moving Window Cross Spectral (MWCS) method was used. For in-depth details on the method, a detailed description can be found in (Clarke et al., 2011). As a brief summary, the method uses a moving window between lag times of interest to measure a time perturbation (Δt) for each window between a current and reference cross-correlation stack. A linear regression (weighted least squares fit) is made to these Δt, with coherence providing the weighting factor, the slope of which can be directly related to a change in velocity by: $\Delta t/t = -\Delta v/v$

Considering the choice of frequency range of 6 to 30 Hz, a window length of 0.17s was chosen so as to contain a full period at the lowest frequency of interest. This frequency range corresponds to S-waves with wavelengths of about 60m to 330m (using a S-wave velocity of 2000 m/s, as estimated during a velocity calibration from known blasts). Measurement windows were strided by 0.017s (90% overlap) to increase the number of measurements and reduce the uncertainty in the linear regression.

In making temporal measurements of velocity change, the final aspect that needs to be considered is a choice of reference stack. Here we use a moving window approach with a second moving window that follows behind the current window stack as a reference stack. It is worth noting that this approach measures differential velocity changes, so measurements need to be integrated to view total velocity changes as a function of time, whereas when using a fixed reference approach (e.g. average of all cross-correlations in the time period of interest), absolute velocity changes are measured. The fixed window approach has the advantage that uncertainties in measurements are independent, whereas using a moving window approach, the uncertainties are small due to the high coherence of the cross-correlation functions, but the drawback is that uncertainties in measurements are perpetuated in time.

Results, Observations, Conclusions

Figure 2 shows time-lapse velocity change measurements for a single sensor component pair (1X and 3Z) between the 25th of December 2013 and 31st of March 2014. A decrease in seismic velocity is first detected approximately 10 days prior to the start of the slope failure (indicated by the dashed black line). Other sensor component pairs show a similar trend, albeit of varying magnitude of velocity decrease. This study investigates this precursory change (and that of all other sensor component pairs) and its relationship to seismicity, rainfall and surface deformation recorded during this period.

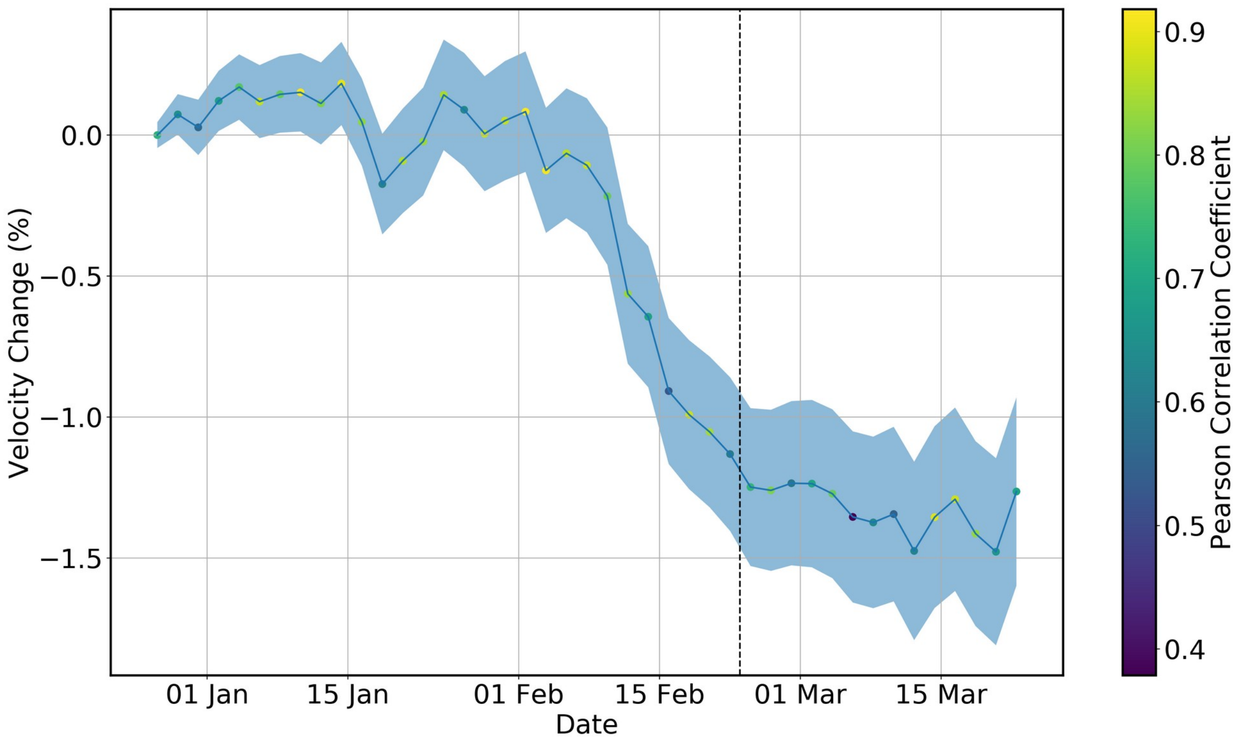

Figure 2: Time-lapse velocity changes for sensor component pair 1X and 3Z between the 25th of December 2013 and 31st of March 2014. Uncertainties in these measurements are indicated by the shaded region. The black dashed line indicates when the slope first began to fail.

Novel/Additive Information

Following the ground-breaking results from Mainsant et al. (2012) detecting precursory velocity changes leading up to a landslide failure in the Swiss Alps, such a result has never been shown (to the authors knowledge), for a slope failure in an open-mine, making this a novel case study.

Acknowledgements

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