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Geotechnical monitoring at the speed of light: New insights from distributed acoustic sensing

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ABSTRACT

Recent advances in distributed fibre optic sensing enable new opportunities in geotechnical monitoring and characterization. Distributed acoustic sensing (DAS) is a distributed fibre optic sensing technology relying on Rayleigh backscattering of light to detect and locate disturbances in near real-time along tens of kilometres of fibre optic cable. The dynamic strain sensing capabilities of DAS have prompted numerous research initiatives from the seismology community over the past decade. Although research on DAS for seismic applications is well established, studies on DAS for geotechnical monitoring applications are less common. Here, we present a summary of two recent case studies involving DAS for geotechnical monitoring. The first study considers a slow-moving landslide where DAS data were acquired over a three-day period of rainfall. The DAS aseismic strain and strain-rate data support the interpretation of the triggering and retrogression failure mechanism of the landslide. The second study considers an active mine site in northern Canada. Data were acquired from a cable installed ~1m below a tailings dam crest. Passive seismic interferometry was applied to DAS data to infer changes in seismic velocities in the uppermost several meters of the subsurface. These findings represent a first step towards advancing continuous monitoring techniques with fiber optic sensing technologies. However, further research is needed to improve our understanding of DAS performance for geotechnical monitoring applications over longer-term periods.

Keywords: distributed acoustic sensing, instrumentation, fibre optic sensing, geotechnical monitoring.

1. Introduction

This paper summarizes recent findings using an emerging fibre optic sensing technology (distributed acoustic sensing; DAS) for geotechnical monitoring applications. Distributed acoustic sensing (DAS) is a fibre-optic sensing technology capable of providing observations along extensive distances (e.g. up to ~100 km) with high spatial and temporal resolution. Furthermore, due to its broadband frequency response, DAS can be considered as an array of seismic sensors (Lindsey et al. 2020). These attributes make DAS an attractive technology to consider for monitoring critical infrastructure. This paper aims to provide a review of two emerging methods (passive seismic interferometry and LF-DAS for slope stability monitoring) using DAS technology.

Here, we present two case studies demonstrating complementary techniques harnessing different components of the DAS signal for geotechnical monitoring applications. At a slow-moving landslide observatory, we employ the low-frequency (<1 Hz) components of strain recordings that are due to aseismic deformation of the slope. These data are directly sensitive to the deformation in the vicinity of the cable and used to characterize a shallow slope failure, with high spatiotemporal resolution. At a tailings dam, we employ a geophysical technique based on seismic waves due to ambient noise. These signals are sensitive to the uppermost several meters of the subsurface. Here, we observe a decrease in seismic velocity indicative of a reduction in stiffness, correlating with the spring thaw and rainfall.

The first case study is located at the Hollin Hill Landslide Observatory. This is a slow-moving landslide observatory and has been monitored by the British Geological Survey since 2008. In 2020, ~925 m of fibre optic cable was installed at a depth of ~0.1 m below ground surface. Data were processed to obtain low frequency DAS (LF-DAS) strain and strain-rate data below 1 Hz. The results highlight changes in landslide processes, revealing the strain onset, landslide rupture zone development and subsequent retrogression with nanostrain-rate sensitivity.

The second case study is located at a tailings storage facility in northern Canada. In 2019, nearly six km of fibre optic cable were installed to a depth of 0.85 m below ground surface. DAS data were acquired from April to August 2021. Here, DAS data were processed with passive seismic interferometric methods to monitor changes in seismic velocities over the data acquisition period. Decreasing seismic velocities (dv/v) of up to ~1%

over the spring period align with expected ground thaw and a period of rainfall.

An overview of the resulting parameters and spatiotemporal resolution from the techniques implemented at each of these case studies is provided in Table 1.

Table 1. Case study overview

Description	Output	Temporal resolution	Spatial resolution
Landslide monitoring with LF-DAS	strain ε and strain-rate change (%)	1-minute (median filter)	4 meters
Tailings dam monitoring with passive seismic interferometry	Seismic velocity change dv/v (%)	one-day	~10 meters

These two case studies highlight different capabilities of DAS for geotechnical monitoring applications. LF-DAS provides information on strain and strain-rate at the location of the fibre optic cable, and geophysical techniques (such as the passive seismic interferometric method described here) can be used to infer changes in soil and rock properties at depth, below the location of the fibre optic cable. Although these case studies demonstrate advances in using DAS technology for slope stability monitoring applications, further research is still needed on appropriate techniques for geotechnical applications and measurement stability over longer-term periods.

1.1. Distributed acoustic sensing

DAS relies on Rayleigh backscattering of light that is injected into the fibre by a laser and is sensitive to axial strain and temperature perturbations in the fibre. The resulting output corresponds to an optical phase change $\Delta\varphi$. DAS does not provide an absolute measurement, but instead measures a relative change (Masoudi and Newson 2016). The DAS measurement, corresponding to a discrete point (channel) along the fibre, represents an average measurement over a length of fibre referred to as the gauge length (L_G). This signal can be converted to an equivalent strain change using the speed of light and known properties of the fibre. DAS is unique from other fibre optic sensing technologies in its ability to detect changes in strain and temperature as well as for seismic sensing. However, the former capabilities are poorly understood for geotechnical monitoring applications. Ouellet et al. (2023b) demonstrate the developing failure surface with nanostrain-rate sensitivity at a slow-moving landslide observatory over a three-day period of rainfall. Their findings illustrate the application of low frequency DAS for high-resolution slope stability monitoring. In addition, DAS data can be processed with seismic methods to glean information in the subsurface. Combining these two approaches provides complementary information on slope movement both at the location of the cable and at depth.

1.2. Landslide deformation monitoring with spatiotemporal strain changes

The Hollin Hill Landslide Observatory has been monitored by the British Geological Survey since 2008 (Chambers et al. 2022). A telecommunications fibre optic cable was installed at 0.1 m below ground surface, primarily parallel to the direction of slope movement over an area of ~135 m by 50 m (Fig. 1).

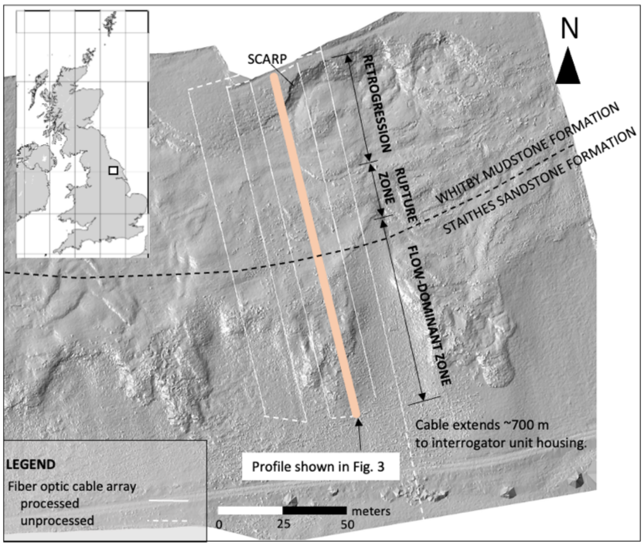

Figure 1. Overview of fibre optic cable array at the Hollin Hill Landslide Observatory. Strain and strain-rate data from highlighted cable segment in beige shown in Figure 3.

DAS data were acquired using an OptaSense ODH-F interrogator unit with a spatial sampling interval (i.e., channel) of 1 m and a spatial resolution (i.e., gauge length) of 4 m. The raw DAS data represent the optical phase change at a sampling rate of 500 Hz. By implementing a processing workflow to isolate the low frequency signal, DAS can be converted into an array of strain change sensors. Earlier work by others demonstrated how LF-DAS can provide information on longer-term changes in strain (Clarkson et al. 2022a; b). The following steps describe the data processing to obtain strain and strain-rate.

The optical phase data are first decimated to 50 Hz, followed by a subsequent decimation to 1 Hz. In both instances, a low-pass antialiasing filter is applied prior to decimation. The 1 Hz optical phase data are converted to a strain change $\Delta\varepsilon$

$$\Delta\varepsilon = \frac{\lambda\Delta\phi}{4\pi\zeta n L_G}, \quad (1)$$

where n corresponds to a refractive index, λ corresponds to the wavelength of the coherent laser pulse and ζ corresponds to a scalar multiplicative factor to account for changes in the index of refraction.

Relative strain measurements are obtained by subtracting subsequent samples from the initial sample for each DAS channel. Strain-rate data are obtained by computing the temporal derivative of strain using the central differences method between consecutive samples.

A 2D median filter is implemented on the strain-rate data, with a window size of 3 channels and 59 seconds.

The resulting strain and strain-rate dataset contains detailed information on the development of the rainfall-triggered failure surface. Fig. 2 shows the near-surface strain profile at discrete times over the rainfall period. The profile illustrates the development of negative strain (compression) and positive strain (tension) along the slope, indicative of a rotational failure surface with retrogression towards a head scarp. Terrestrial lidar acquired in November 2020 was used to provide elevation metadata to the as-built cable coordinates, allowing a 3D representation of the cable overlain with strain changes (Fig. 3).

The reader is referred to Ouellet et al. (2023b) for a complete interpretation of the slope failure processes.

1.3. Tailings dam monitoring with passive seismic interferometry

Passive seismic interferometry is a geophysical technique relying on ambient and anthropogenic noise signals (e.g. wind, waves, traffic) as a noise source. By cross-correlating the background noise signals between a pair of seismic sensors, relative changes in seismic velocities (dv/v, %) can be inferred. Coda waves represent scattered waves that have spent more time propagating in the medium due to heterogeneities. Changes in the travel times of the coda between two seismic sensors can be used to monitor velocity changes in the medium (Snieder 2002).

Shear wave velocities (V_s) are an important geotechnical parameter for soils (Andrus and Stokoe 2000). Industry standard methods for obtaining V_s for

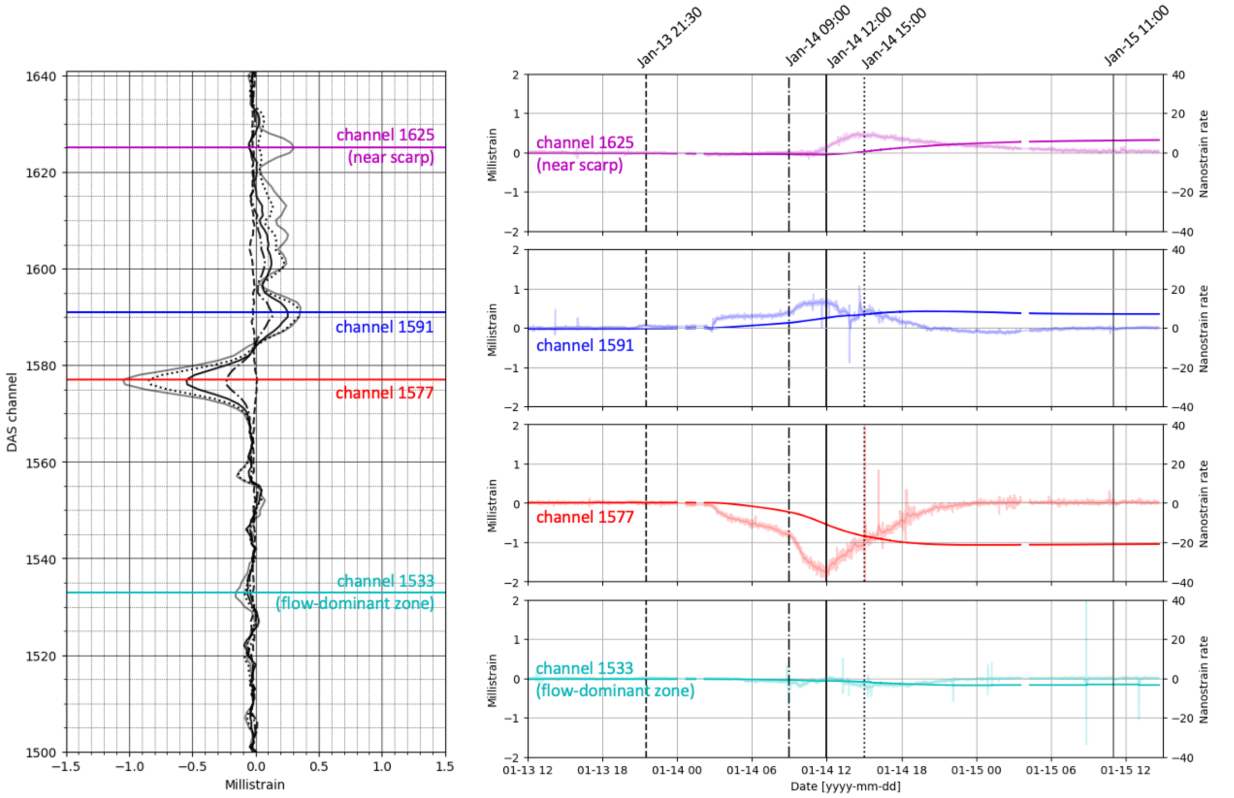

Figure 2. Left: DAS strain profile with location of strain profile shown in Figure 1. DAS channels 1500 and 1640 are located at the toe and crest of the slope, respectively.The different strain profiles correspond to the times highlighted on right figure as vertical lines. Right: Time-series of DAS strain (solid lines) and strain-rate (shaded lines) corresponding to the locations along the profile on left in same colour.

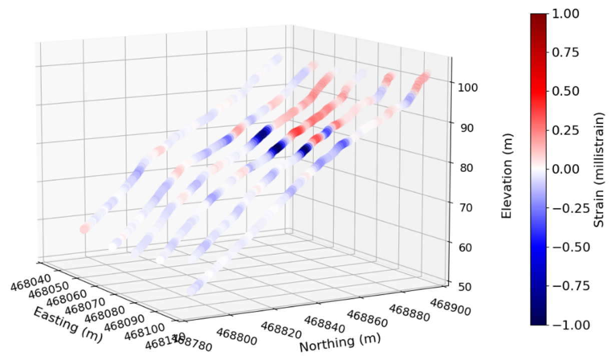

Figure 3. DAS georeferenced strain change data for strain change from 2021-01-12T11:38 to 2021-01-15T00:00

liquefaction assessments include in-situ measurements with seismic cone penetration testing (sCPT), geophysical field methods, and laboratory measurements using bender elements or resonant column tests (Hussien and Karray 2016). These methods are generally used to characterize site conditions at one point in space and time, as multiple acquisitions can be costly and time-consuming. Passive seismic interferometry can support geotechnical monitoring applications by improving understanding of how V_s may change over time, as coda waves are highly sensitive to V_s (Snieder 2002).

A telecommunications fibre optic cable was installed ~1m below surface along the crest of multiple active and inactive tailings dams in 2020 (Fig. 4; Forbes et al. 2021). This was connected to a DAS interrogator unit, with a

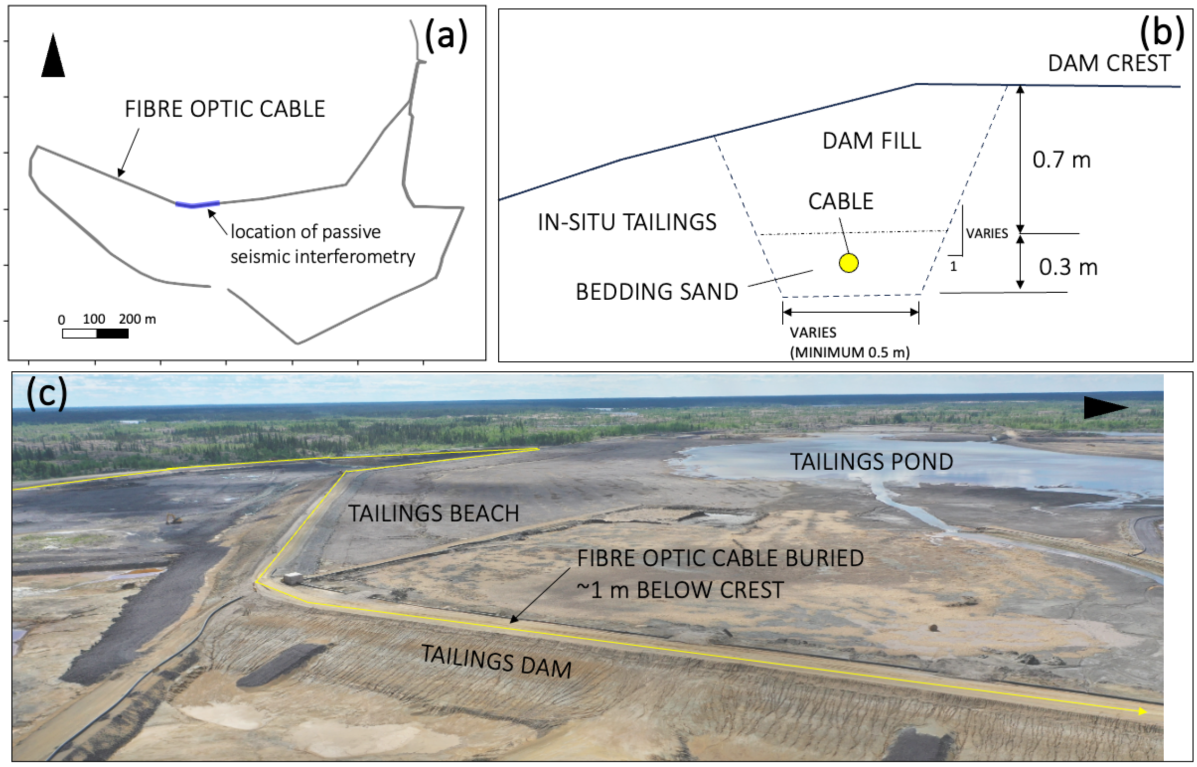

Figure 4. Overview of the fibre optic cable installation. (a) Layout of the fibre optic cable with highlighted section indicating section where passive seismic interferometry was implemented. (b) Simplified cross-section to highlight cable burial depth and backfilling material. (c) Drone aerial imagery of site in June 2020. Approximate location of buried fibre optic cable buried below dam crest shown in yellow.

spatial sampling interval of 2 m and a spatial resolution of 4 m. Data were acquired at 400Hz sampling from April to August 2021.

Data processing for passive seismic interferometry was carried out by selecting 12 DAS channels at 10 m spacing over a 110 m segment of buried cable (Ouellet et al. 2023). These data were decimated to 50 Hz by subsampling following the application of a low-pass antialiasing filter. Following this, data pre-processing steps included linear detrending, bandpass filtering from 5 Hz to 15 Hz, one-bit normalization and spectral whitening. One-bit normalization in the time domain reduces the effect of instrumental irregularities, earthquake signals and non-stationary noise sources. Spectral whitening broadens the frequency band of ambient noise and reduces the effect of monochromatic noise sources (Bensen et al. 2007).

Individual DAS channels were then cross correlated in twenty-second time windows over a twelve-hour period (18:00:00 to 06:00:00 local time). This period was chosen to minimize the effect of spurious noise sources from active traffic and construction occurring adjacent to the fibre during the day.

The easternmost DAS channel was selected as a virtual source and all other 11 DAS channels acted as virtual receivers. Cross-correlation waveforms were stacked over each day to obtain daily cross-correlation waveforms. A reference cross-correlation waveform (required for monitoring seismic velocity changes) was obtained by computing the mean of all daily cross-correlation waveforms over the data acquisition period (~90 days). To enhance the coherency of the daily cross-correlation waveforms, we implemented an adaptive frequency-wavenumber filter (Isken et al. 2022). Relative changes in seismic velocities using the reference and daily cross-correlation waveforms are obtained using the stretching method (Sens-Schönfelder and Wegler 2006). Seismic velocity changes with a correlation coefficient of less than 0.7 were removed as a quality control measure.

The resulting seismic velocity changes (dv/v) decrease to a minimum of ~ -0.3 % in early August (Fig. 5). This decrease is likely impacted by a combination of multiple coinciding conditions (i.e. rainfall, increasing pond levels, seasonal ground thaw). Surface temperatures fluctuate near freezing (0°C) from mid-April towards the later weeks of May. This coincides with the highest daily rainfall (35 mm) over the recording period occurring on May 24. Earlier work implementing passive seismic interferometry at the same site with a geophone array estimated a maximum depth sensitivity of dv/v ranging from 14 to 17 m (Ouellet et al. 2022). Furthermore, as there are still few published studies available using DAS-derived dv/v (Rodríguez Tribaldos and Ajo-Franklin 2021), additional effects relating to the DAS instrument response are less understood. Nonetheless, the advantages of combining passive seismic interferometry with the high spatiotemporal resolution of DAS are a motivating factor to continue advancing research in this area.

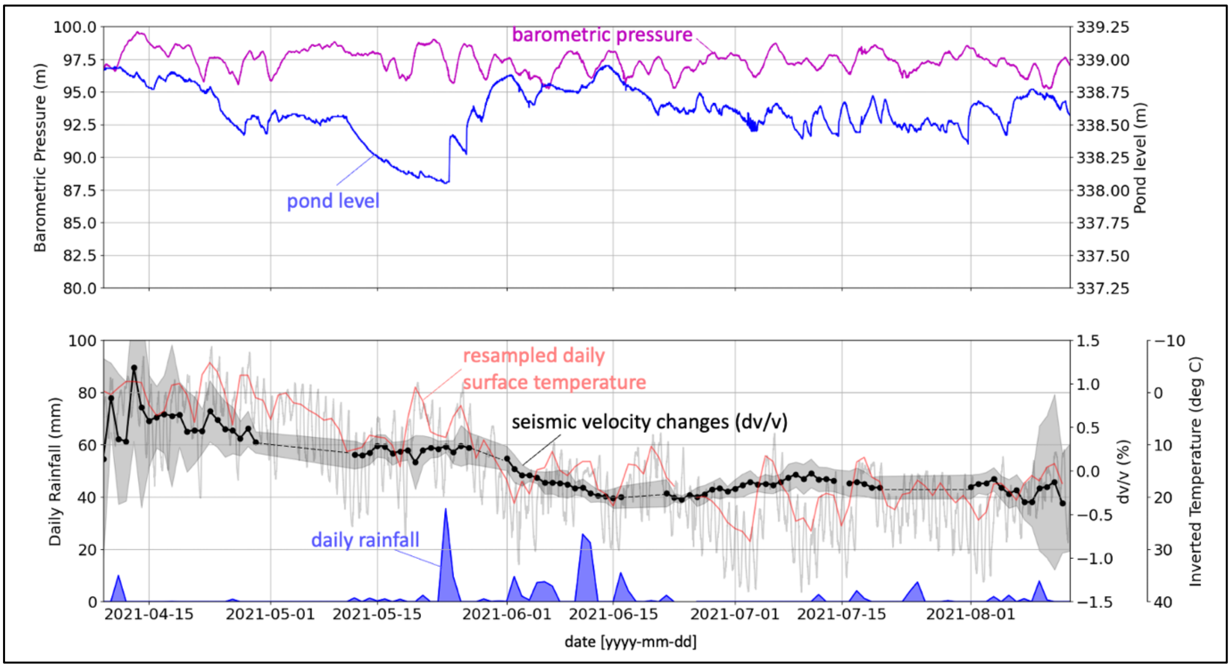

Figure 5. Results from applying seismic interferometry to the DAS dataset, shown as dv/v (%) alongside environmental site data. The upper plot shows tailings pond levels and barometric pressure. The lower plot shows the surface temperature (daily resampled temperature in red and hourly temperature data in light grey) and dv/v for comparison alongside daily rainfall. Dv/v data gaps shown as dashed line, due to interrogator malfunctioning. Shaded grey area along dv/v represents standard deviation from the mean dv/v over the twelve source-receiver cross-correlation pairs.

2. Discussion

The combined findings from the two case studies illustrate how DAS can support geotechnical monitoring applications. Important caveats and considerations for the two DAS methods we presented are discussed here.

Interpretation of the strain and strain-rate data at the Hollin Hill Landslide Observatory was supported by available site instrumentation and remote sensing data (Ouellet et al. 2023b). In this study, DAS provided high spatiotemporal measurements of strain and strain-rate changes parallel to the direction of slope movement. Collocated instrumentation permitted a comparison of inferred displacement. Further research on DAS for geotechnical monitoring applications should include collocated geotechnical instruments to improve understanding of technology limitations. A discussion on known caveats is provided herein.

Firstly, in the context of LF-DAS for strain changes, the measurement provided is a change from a reference versus an absolute strain or temperature measurement (unless measurements are calibrated with a collocated in-situ sensor). Therefore, continuous measurements are required, as disconnecting, and reconnecting the optical fibre to the DAS interrogator results in a new baseline measurement. This can prove challenging over longer monitoring periods if precautions are not taken (e.g. back-up power to prevent power outage of interrogator).

The application of LF-DAS for slope stability characterization at Hollin Hill covers a three-day period (Ouellet et al. 2023b). As such, the stability of DAS measurements over longer periods are less understood and further research with a longer-term data acquisition period is warranted to improve understanding of the sensitivity of the measurement over longer periods and the effect of potential instrumental errors (e.g. laser drift).

The measurement quality is reliant on the coupling between the cable and the surrounding formation. For example, a cable loosely covered and poorly compacted will be more susceptible to cable slippage. With increasing slippage, the measurements are decreasingly representative of ground deformation, although ground anchors may help mitigate this effect (Hauswirth et al. 2014).

Passive seismic interferometry with DAS data is a promising area of research. However, the resulting seismic velocity changes are affected by multiple environmental influences (e.g. temperature, rainfall infiltration, atmospheric pressure; Breton et al. 2021). Further research is warranted to better understand how to isolate these effects. Further, semi-subjective variations in selected parameters throughout the data processing steps leading to the resulting seismic velocity changes has been shown to lead to significant differences in the results (Fichtner et al. 2017). Practitioners should thus have a strong understanding of the effects of different processing variables to obtain meaningful indicators of changes in stability from the resulting seismic velocity changes.

Implementation of this method at a site requires a baseline monitoring period to better understand the ambient noise quality conditions at the site, as the temporal resolution of this method will depend on the noise conditions at the site. For example, a drilling program adjacent to the fibre optic cable may impede quality measurements for this method to be successfully implemented over a continuous period. It is misleading to claim real-time measurements with passive seismic interferometry, as stacking (e.g. obtaining the mean) over longer-duration periods, typically over a minimum period of one-hour but up to several days may be required. As noted previously, the temporal resolution will depend on the site noise conditions.

3. Conclusions

The two case studies presented separate applications to implement DAS for geotechnical monitoring applications. LF-DAS was shown to provide high spatiotemporal resolution of strain and strain-rate changes, which could be applied towards landslide early warning applications. Combining DAS with seismic techniques such as passive seismic interferometry provides complementary information by inferring changes in soil stiffness at depth. In addition to strain and seismic velocity changes, DAS can also be used as a distributed temperature gradient sensor (Sidenko et al. 2022). This capability could potentially be used to detect changes in seepage along levees or dams (Wagner et al. 2023). Further research on these aspects (strain, temperature, seismic) to support geotechnical monitoring could advance our understanding of soil behaviour by providing highly sensitive measurements at broad spatiotemporal scales, with far-reaching implications for the field of geotechnical engineering.

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