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Numerical investigation of seismic source location using distributed acoustic sensing for rockfall monitoring

Y Duan *CSIRO Mineral Resources, Australia*

X Luo *CSIRO Mineral Resources, Australia*

M van de Werken *CSIRO Mineral Resources, Australia*

P Dean *CSIRO Mineral Resources, Australia*

M Elmouttie *CSIRO Mineral Resources, Australia*

Abstract

Accurate detection of rockfall trajectories in open pit mines is crucial for assessing the standoff designs and improving operational safety. In this research, we propose to apply seismic monitoring based on distributed acoustic sensing (DAS) to locate the impact points of rockfalls on the slope to determine the rockfall trajectories. A numerical simulation is conducted to investigate the accuracy of the location of rockfall impact points. Synthetic DAS signals are created to simulate the rockfall-induced impacts and arrival times of the signals are picked for impact point location. The results demonstrate that by enabling dense sensing points along fibre optic cables, DAS can achieve more accurate locations of rockfall impact points compared with those obtained with traditional geophone networks. The improvement in depicting the rockfall trajectories using DAS with fibre optic cable will be further validated in an upcoming field experiment.

Keywords: *distributed acoustic sensing, numerical simulation, seismic source location, rockfall monitoring*

1 Introduction

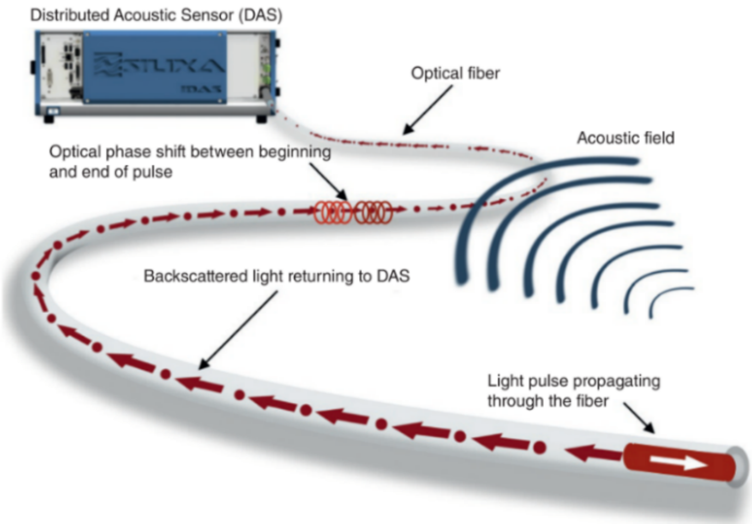
As rockfalls can induce impacts on the slope and ground which will generate a seismic signal, seismic monitoring systems can be used to detect rockfalls and locate the impact points to determine the trajectories of rockfalls (Deparis et al. 2008; Vilajosana et al. 2008). Guinau et al. (2019) adopted remote sensing technologies including LiDAR, photogrammetry and broadband seismometers to monitor rockfalls in Tarragona, Spain. They further characterised the trajectories and seismic energy of rockfalls with two temporary seismic stations installed close to the slope. However, traditional seismic monitoring networks consist of sparsely deployed geophones. The impact points of rockfalls may not be accurately located, especially when the monitoring scale is large. Feng et al. (2021) developed a framework to use microseismic monitoring to forecast slope failures at a limestone quarry in Italy. The location of impact points was carried out to determine the rockfall trajectories. The location errors of the impact points vary from 10 to 48 m. Additionally, as some events were only detected by less than three geophones, they cannot be accurately located and were only categorised as point or local events.

In this research, distributed acoustic sensing (DAS) with fibre optic cable is proposed as a component of a sensor fusion system for rockfall monitoring (Elmouttie et al. 2021). The advantage of this technology is that dense sensing points can be configured along a fibre optic cable for more sensitive and accurate detection of rockfalls in mines. This is the first time that DAS has been introduced for this application. A numerical simulation is conducted in this paper to investigate how the location accuracy of impact points can be improved using DAS compared with geophones.

2 Methods

2.1 Distributed acoustic sensing

Distributed acoustic sensing is an emerging technology which has been widely studied and applied in geophysics exploration, geotechnical engineering and civil engineering due to its large-scale monitoring range, continuous measurement and dense spatial resolution (Li et al. 2021). The principle of DAS is based on the phenomenon known as Rayleigh backscattering of light pulses injected into a fibre optic cable (Dakin 1989). As the vibrations induce strains in fibre optic cables, the intensity and phase of the backscattered light change (Figure 1a). By measuring the variations of the intensity and phases between two points separated by a distance called gauge length (Figure 1b), the strain rate changes in time and space domains can be obtained along the fibre cable (Posey et al. 2000). The intelligent distributed acoustic sensing (iDAS) system manufactured by Silixa is used for this project. The gauge length of the iDAS is 10 m and the channel spacing can be configured to 1 m. These parameters are incorporated in the numerical simulation.



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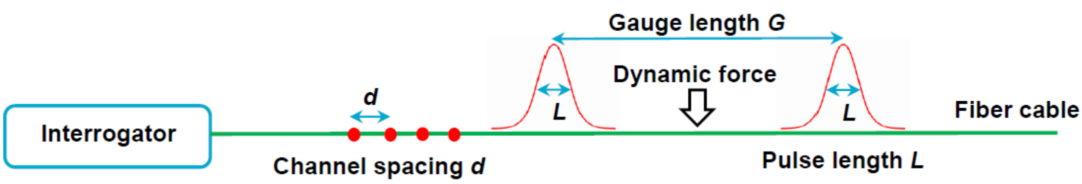


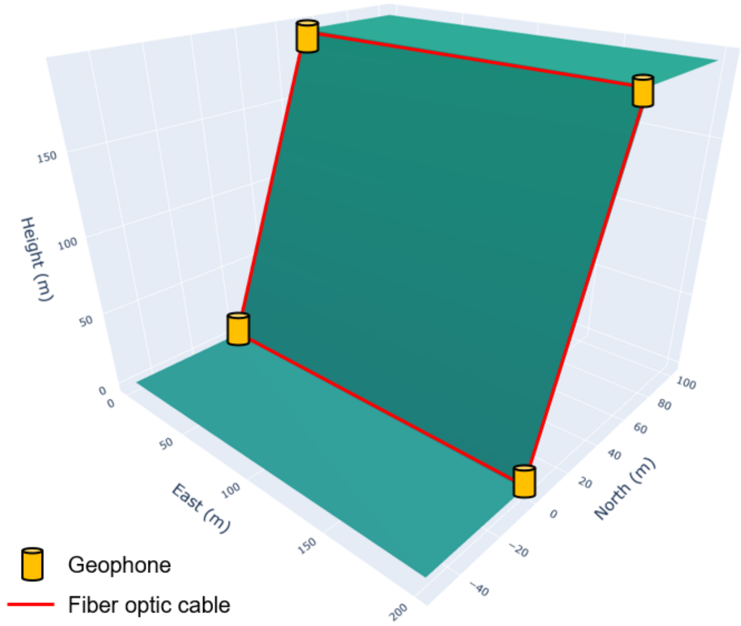
(b)

Figure 1 Illustration on the (a) principle of the DAS system (Shatalin et al. 2021); (b) gauge length and spatial resolution of DAS channels

2.2 Simulation of DAS response

2.2.1 Modelling configuration

A 2D homogeneous velocity model representing a slope with a dimension of 200 × 200 m is used for the numerical simulation. The P-wave velocity of this model is 3 km/s. There are 400 seismic sources with a spacing of 5 m assumed in this model. A fibre cable is deployed around the slope and receivers with 1 m spacing are configured along the fibre optic cable. The seismic waveforms recorded by receivers are simulated using the finite-difference method (Boore 1972) and a Ricker wavelet as the source time function. The axial strain rate measured by the DAS is then derived from the differential particle velocity following the tangential direction of the fibre cable (Bakku 2015; Baird et al. 2020). The strain rates of the channels in each gauge length are averaged as the measurements obtained at the centre point of the gauge length (Dean et al. 2017). As a result, the total number of DAS channels is 80 and the channel spacing is 10 m. No effect of cable transferring function and coupling are considered in this simulation. The cable is assumed to be well-coupled to the slope. A total of four geophones are used as the benchmark for the location accuracy comparison. The locations of seismic sources, DAS channels and geophones in the model are shown in Figure 2.



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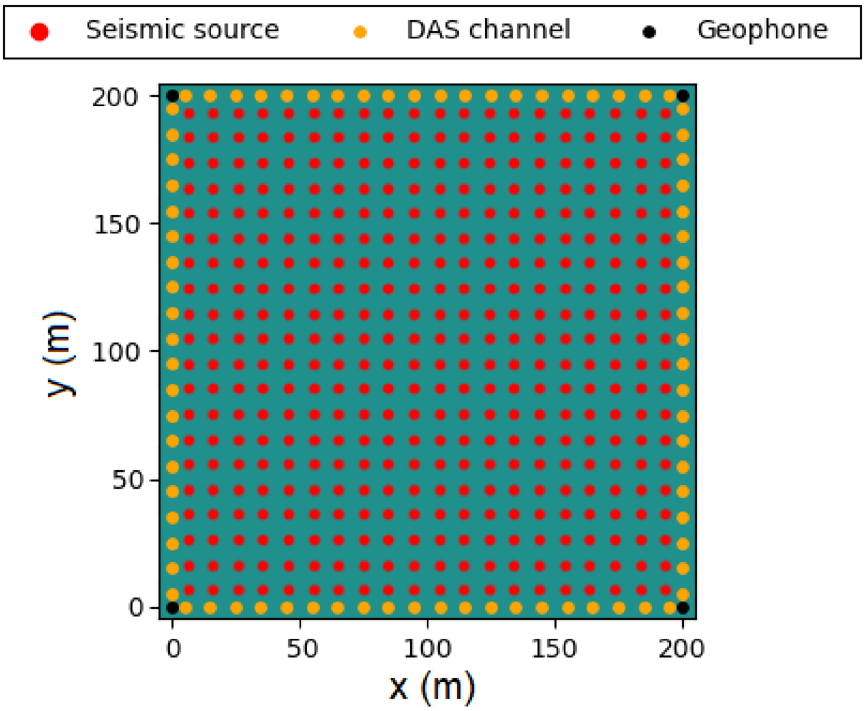

(b)

Figure 2 (a) Layout of a fibre optic cable and locations of geophones deployed on a slope; (b) Locations of synthetic seismic sources, DAS channels along the fibre optic cable and geophones on the slope projected as a 2D plane

2.2.2 *Synthetic seismic and DAS waveforms*

A representative seismic wavefield propagating from a seismic source is illustrated in Figure 3a. The simulated seismograms and DAS signals at the DAS channels are shown in Figures 3b and 3c, respectively, to demonstrate the differences between the seismic and DAS recordings. It can be found that the section of fibre cable which is perpendicular to the propagation direction of the seismic wave is insensitive to the disturbance. These channels are called broadside channels (Verdon et al. 2020). The signal-to-noise ratio (SNR) of seismic signal is greater than that of strain rate measurements. To simulate the real scenario, random noise following a normal distribution is generated to perturb the DAS signal. The noise is determined by a SNR of 5 dB with respect to the DAS channel which has the maximum amplitude signal. Different seeds are used to generate the random noise using the same SNR and reference signal for all DAS channels. An example of distribution of the noise and the perturbed DAS signals are shown in Figure 4. The seismic waveforms of four geophones are also obtained and perturbed following the same procedure.

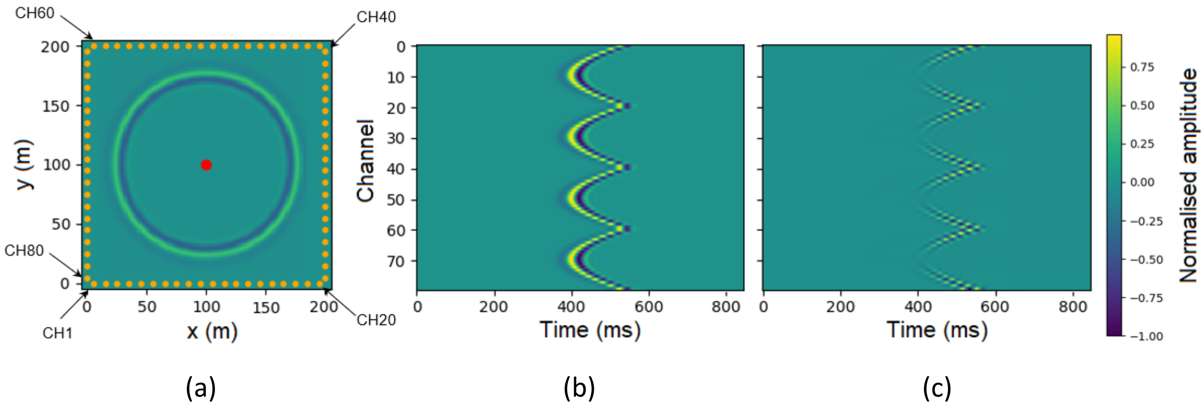

Figure 3 **(a) Seismic wavefield propagation from a source to DAS channels; (b) Simulated seismic signals; (c) DAS signals**

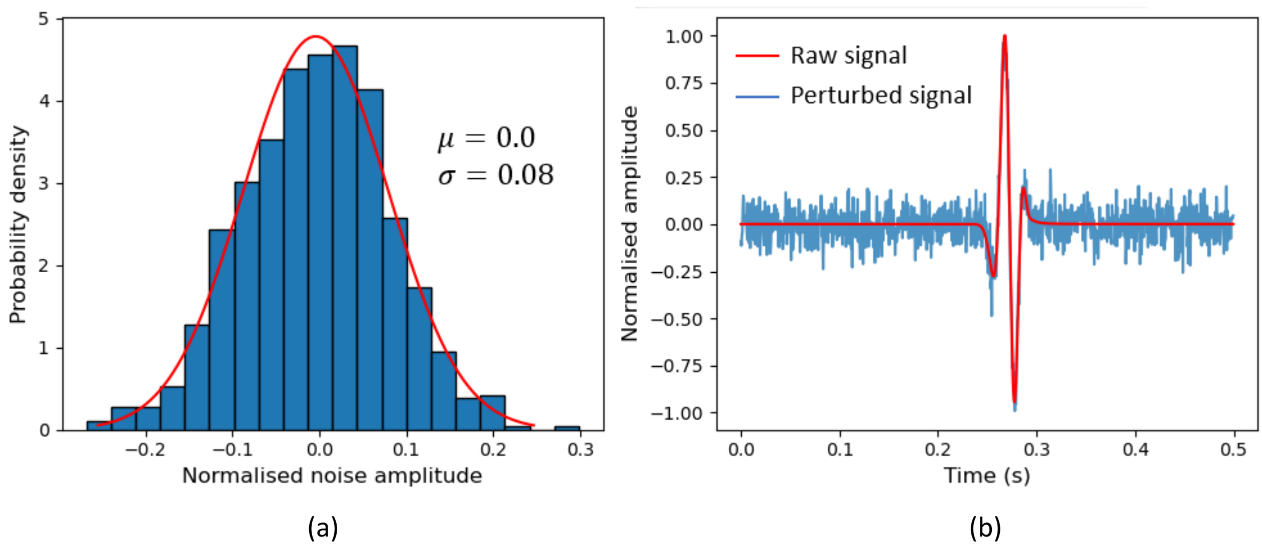

Figure 4 **(a) Distribution of noise superimposed on a DAS channel; (b) The raw and perturbed DAS signals**

3 Numerical modelling results

3.1 Arrival times

Arrival times of seismic waves are commonly used for source location in microseismic monitoring and the layout of the seismic network is crucial for achieving a stable solution (Pavlis 1986). The method can be expressed as minimising the residuals between the observed arrival times and theoretical travel times (Duan et al. 2021):

$$f = \sum_{i=1}^{n} \left| \left(t_i{}^{ob} - \overline{t^{obs}}\right) - \left(t_i{}^{cal} - \overline{t^{cal}}\right) \right|^m \tag{1}$$

where *n* denotes the number of sensors used for the source location, $t_i{}^{obs}$ and $t_i{}^{cal}$ represent the observed arrival time and calculated travel time from the source to sensor *i*, respectively. *m* indicates the norm which is generally 1 or 2 corresponding to the L1 or L2 norm solution. $\overline{t^{obs}}$ and $\overline{t^{cal}}$ are the average of observed arrival times and calculated travel times, respectively.

A 1 D convolutional neural network (CNN) is developed to pick the arrival times of the synthetic DAS and seismic signals (Duan et al. 2023) for source location. As the broadside channels cannot clearly register seismic waves, the signals of these channels are considered as noisy channels and no arrivals are labelled on these channels for training the CNN model. The test results show that the CNN model can achieve an average error which is less than 4 ms in arrival time picking on DAS signals. The CNN model is applied to pick arrival times of the synthetic DAS and seismic data for source location (Figure 5).

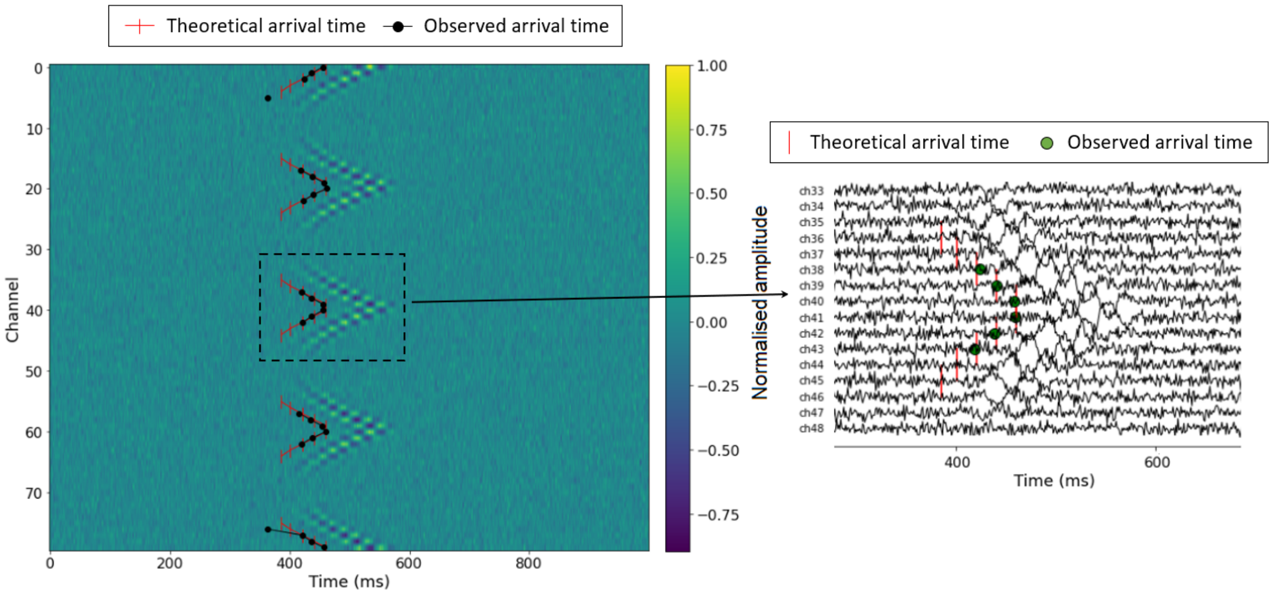

Figure 5 Comparison between the theoretical arrivals and observed arrivals picked by the CNN model

3.2 Location accuracy

The grid search method (Sambridge & Kennett 1986) with a spacing of 2.5 m is used to locate the seismic sources shown in Figure 2. To assess the location accuracy, as described in Section 2.2.2, the synthetic DAS and seismic data are perturbed with 1,000 noise signals generated using different random seeds. After the synthetic signals are perturbed, the CNN model is applied to pick the arrival times of the perturbed signals. The picked arrival times are then used for the source location. The average and standard deviation of location errors obtained by DAS and geophones are shown in Figure 6. The results show that for the impact points located in the centre of the model with an approximate dimension of 40 × 40 m, DAS and geophones can achieve comparable location accuracy within 1 m. As the impact events migrate outside of this area, the effect of errors in arrival time picking on source location cannot be effectively avoided by geophones, hence the location accuracy decreases. Compared with the geophones, because more DAS channels are used, it can provide better constraints for source location and reduce the location uncertainties of impact points assumed in this 2D model. Therefore, it is more likely for DAS to determine the rockfall trajectories.

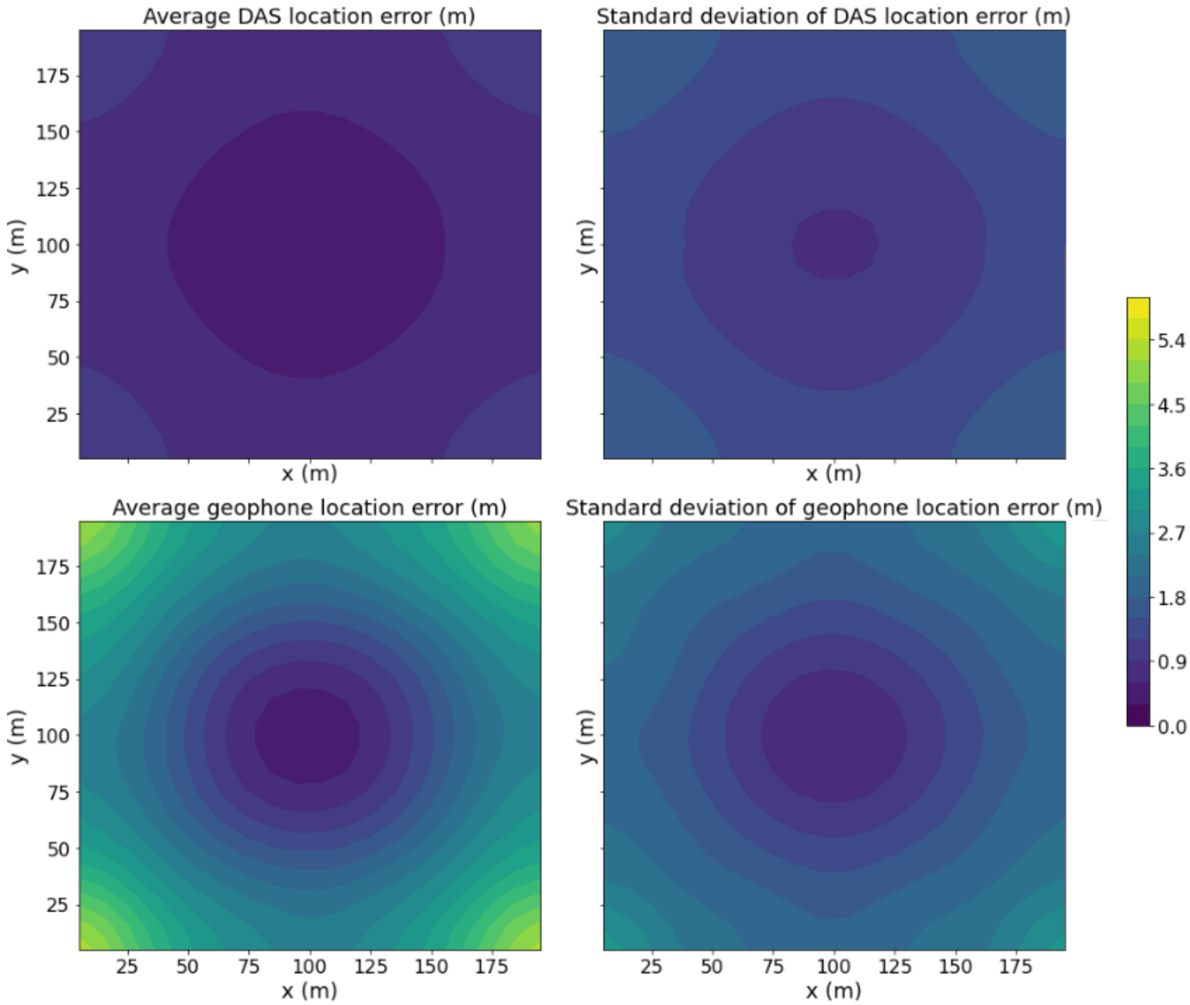

Figure 6 Mapping of the average and standard deviation of location errors obtained by DAS and geophones

4 Conclusion

For small-scale monitoring, geophones can effectively record and locate the impact points of rockfalls. However, for larger-scale monitoring with sparsely installed geophones, weak seismic events might only trigger nearby geophones and they cannot be accurately identified or located (Feng et al. 2021). The dense and continuous sensing features of DAS are in favour for such applications. As more sensing points can be employed along kilometres of fibre cable, DAS provides the potential to identify and locate moderate and weak seismic events (e.g. rockfalls) with better sensitivity and accuracy. The numerical modelling results in this paper show that a DAS network deployed around the slope boundary can achieve better location accuracy compared with four geophones installed at the four corners of the slope. More geophones can be added to the geophone monitoring network to improve the location accuracy. However, it will also increase cost, whereas fibre optic cable is a more cost-effective solution, especially when the monitoring needs to cover a much larger area.

Because of the nature of the DAS, broadside channels can pose challenges for arrival time picking. But as the DAS can provide an array of sensing points, the broadside channels can in turn be used to identify the source locations (Verdon et al. 2020; Luo & Duan 2021). One potential issue with this application is the deployment of the fibre optic cable around the slope. Unlike other DAS applications in which fibre optic cables can be installed in shallow trenches and boreholes (Zeng et al. 2021; du Toit et al. 2022; Rossi et al. 2022), great effort is required to couple the fibre optic cable along the slope to achieve satisfactory sensitivity for rockfall detection. The coupling practice also needs to be safe. If no access to the slope is allowed, the fibre optic cable can only be laid along the slope or buried close to the toe of the slope. Nevertheless, in addition to rockfall monitoring, considering fibre optic cable can be used for distributed acoustic and strain sensing to assess the rock fractures and slow deformation associated with the slope instability, it is beneficial to investigate the feasibility of using DAS for slope monitoring.

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