

Distributed Acoustic Sensing and Portable Active Seismic Sources: A Framework for Groundwater Monitoring

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ABSTRACT: Groundwater monitoring is a vital aspect of geotechnical engineering, especially in the context of embankment dams, levees, and other critical infrastructure. This paper presents a novel framework that integrates Distributed Acoustic Sensing (DAS) with a Portable Active Seismic Source (PASS) to enable high-resolution and time-lapse monitoring of subsurface hydrological processes. The paper focuses on the technologies and processing methodologies employed. DAS converts standard fibre optic cables into dense seismic arrays, while the PASS device provides a repeatable and mobile seismic source. The combined system allows for monitoring of the dynamic groundwater level. The study describes the acquisition strategies and signal processing techniques designed for active-source datasets, emphasizing the importance of repeatability and spatial coverage.

KEYWORDS: Distributed Acoustic Sensing, Groundwater Monitoring, Active Seismic Source, Signal Processing

1 INTRODUCTION

Groundwater level monitoring is essential for assessing aquifer recharge, predicting drought impacts, managing water resources, and ensuring the structural integrity of earthworks (Monir et al., 2024). Groundwater levels are dynamic and can vary spatially and temporally due to seasonal recharge, anthropogenic extraction, or structural deterioration. Detecting and monitoring these variations in near-real-time remains a challenge for traditional methods such as piezometers, electrical resistivity tomography (ERT), and observation wells. These instruments provide only discrete point measurements and often require many installation points, limiting their spatial coverage and long-term practicality (Binley et al., 2015).

To address these limitations, fibre optic sensing technologies have gained traction in recent years. DAS in particular has emerged as a promising tool for distributed seismic and vibration monitoring over large distances with high spatial resolution (Hartog, 2017). DAS systems repurpose standard single-mode optical fibre cables into dense arrays of virtual sensors, capable of capturing dynamic strain responses to seismic signals (Jousset et al, 2018). Prior studies have demonstrated the use of DAS for various applications such as traffic noise interferometry (Dou et al., 2017), earthquake detection (Sladen et al., 2019), and active seismic reservoir monitoring (Daley et al., 2013).

Despite these advancements, much of the existing DAS research has relied on either ambient noise or large-scale permanent sources such as vibroseis or airguns. Ambient noise interferometry has shown potential for passive monitoring (Rodríguez Tribaldos and Ajo-Franklin, 2021), but it lacks temporal control and may be affected by variability in noise source distribution, complicating interpretation in hydrological settings. This paper diverges from ambient noise approaches and instead focuses exclusively on active-source DAS using PASS. PASS provides a controlled and repeatable energy input, ideal for time-lapse seismic imaging and dynamic monitoring of subsurface processes.

The combined DAS-PASS system enables a dense seismic dataset along an installed fibre optic cable. Its high repeatability ensures that temporal changes in recorded signals reflect physical changes in the subsurface. This active monitoring strategy offers a non-invasive, scalable, and high-resolution alternative for detecting groundwater level fluctuations.

In this paper, the study describes the architecture, data acquisition strategy, and signal processing techniques tailored for DAS with PASS, aimed at advancing active seismic monitoring for the dynamics of groundwater level. No field results are presented; instead, the focus is on methodology and technical readiness to support future deployment. Several recent studies have shown DAS sensitivity to hydrological changes, including variations in saturation and pore pressure, due to the associated changes in elastic wave velocities (Ajo-Franklin et al., 2019; Tribaldos et al., 2021). However, most existing DAS applications in hydro geophysics rely on passive sources, which may not offer the repeatability or spatial control needed for high-resolution data interpretation.

2 TECHNOLOGY

2.1 Distributed Acoustic Sensing (DAS)

DAS is a technique that converts a standard single-mode optical fibre into a distributed array of vibration sensors by measuring the strain-induced phase shifts in Rayleigh backscattered light (Figure 1). A DAS interrogator sends a coherent laser pulse down the optical fibre and measures the Rayleigh backscattered signal. Variations in the dynamic phase of the backscattered light are analyzed to detect strain or strain rate changes along the fibre, which are induced by acoustic or seismic events (Hartog, 2017). This method enables sensing at intervals of one to several meters, offering thousands of channels along a single fibre.

In geotechnical and hydrogeological applications, Distributed Acoustic Sensing (DAS) offers distinct advantages over conventional point-sensor methods due to its ability to transform standard fibre-optic cables into dense arrays of seismic sensors. This enables high-resolution, continuous spatial coverage over tens of kilometres without the need for installing discrete geophones, accelerometers, or downhole instrumentation (Zhan, 2020). For groundwater-level monitoring, DAS can detect subtle changes in seismic wave velocities that occur due to variations in pore-water saturation and effective stress within the subsurface (Ajo-Franklin et al., 2019). These velocity changes influence the travel times of surface and body waves, allowing for indirect inference of hydrological processes such as recharge, infiltration, or depletion. The real-time data acquisition capabilities of DAS, combined with its suitability for remote and long-term

monitoring, make it especially valuable for continuous surveillance of critical infrastructure.

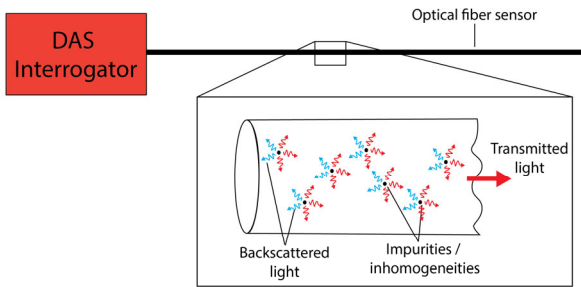


Figure 1. Rayleigh Backscattered.

2.2 Portable Active Seismic Source (PASS)

The Portable Active Seismic Source (PASS), shown in Figure 2, is a lightweight, cost-effective device designed for repeatable and multi-deployment seismic energy generation in near-surface investigations (Tsuji et al., 2022). It employs a piezoelectric-driven mechanism capable of generating both vertical and horizontal impact components, thereby enhancing the excitation of multiple seismic wave modes, including both P-waves and S-waves, as illustrated in Figure 3. The piezo actuator provides precise control over impact amplitude and timing, which is essential for high-resolution imaging and time-lapse seismic monitoring.

Unlike conventional drop-weight systems, the piezo-driven PASS provides improved coupling with the ground and allows fine-tuned frequency targeting within the operational bandwidth. One of the major advantages of PASS is its repeatability; each actuation delivers nearly identical source characteristics (as shown in Figure 4), essential for monitoring dynamic changes in the subsurface. The system is powered by a portable battery and can be operated manually or remotely, making it suitable for temporary field installations or semi-permanent monitoring sites.

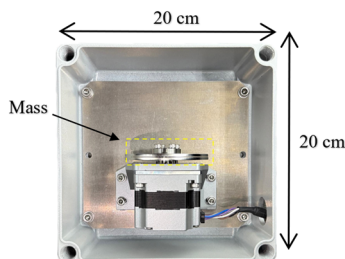


Figure 2. Top view of PASS.

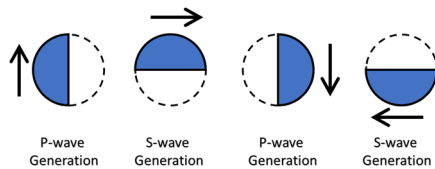


Figure 3. One complete weight mass rotation.

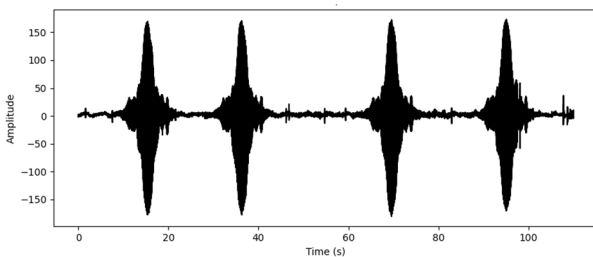


Figure 4. Example of the repeatable shot.

PASS generates broadband chirp signals with user-defined frequency ranges and time durations, enabling flexible tuning to the subsurface conditions of specific target regions. This configurability is essential for optimising seismic wave penetration, resolution, and signal-to-noise ratio (SNR) in diverse geotechnical environments. By adjusting the chirp parameters such as sweeping from low to high frequencies over a controlled time window, the system can effectively illuminate both shallow and moderately deep structures, making it particularly well-suited for applications involving DAS-based monitoring.

As illustrated in Figure 5, the PASS system is capable of generating low-frequency signals in the range of 10 to 50 Hz. The configuration of the chirp signal, specifically its frequency range and sweep duration, is a critical parameter for optimizing seismic data quality in geotechnical and hydrogeophysical monitoring. These parameters are typically selected based on site-specific subsurface conditions and the depth of the target features. Lower frequency bands are preferred for deeper targets and highly attenuating soils due to their greater penetration capability, although this comes at the cost of reduced spatial resolution.

The sweep duration, typically ranging from 0.2 to 5 seconds, influences the energy content of the transmitted signal. Longer sweeps generate greater energy and are better suited for environments with high ambient noise or poor coupling. In DAS monitoring, where signal repeatability and SNR are crucial, longer-duration and broadband chirps are often favoured to ensure consistent and detectable seismic responses over time (Piana et al., 2022). Therefore, site-specific testing and iterative calibration are recommended to determine the optimal chirp parameters for each deployment scenario (Isaenkov et al., 2022).

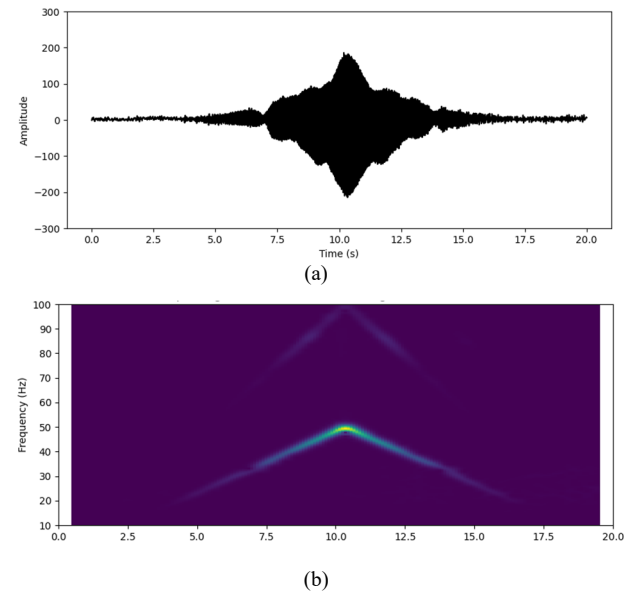


Figure 5. One-shot of (a) waveforms and (b) spectra from the PASS

3 DATA ACQUISITION STRATEGY

3.1 Data Acquisition Setup

The DAS-PASS monitoring framework involves systematic data acquisition using an installed fibre-optic cable in the ground and strategically positioned shot points. To ensure optimal fibre-soil coupling, which is critical for effective seismic wave transmission and detection, the cable is typically installed in shallow trenches at 5 to 30 cm deep and backfilled with native soil or fine sand. This shallow burial approach

enhances mechanical coupling by maximising contact between the fibre and the surrounding material, thereby improving the sensitivity and fidelity of the recorded seismic signals.

Seismic energy is introduced into the ground using the PASS device, which is strategically positioned at predetermined shot points along or adjacent to the fibre path, as shown in Figure 6. The selection of shot locations, estimated 5-10 meters from first sensing point to avoid the highly non-linear near-field zone (Daley et al., 2016; Zhan, 2020) and it also suggested to install 1 km between two seismic source. By systematically relocating the PASS to these shot positions and activating it in a controlled manner, a series of active seismic records can be generated.

It is important to note that the seismic signal generated by the PASS originates from a rotating eccentric mass, which effectively acts as a single-mass actuator. This introduces variability in the amplitude and directionality of the emitted seismic energy. Specifically, the radiation pattern is not uniform in all directions, as shown in Figure 7, leading to signal amplitude variations as a function of azimuthal angle from the source. This anisotropic energy radiation, commonly referred to as source directivity, can significantly influence the quality and consistency of the recorded signal along the fibre-optic cable.

To maximise signal strength and improve the coherence of the recorded wavefield, the orientation of the PASS device relative to the fibre is critical. Laboratory experiments from this study suggest that the fibre should be positioned perpendicular to the plane of the eccentric mass rotation. This alignment ensures that the dominant component of the source couples effectively with the strain-sensitive direction of the fibre.

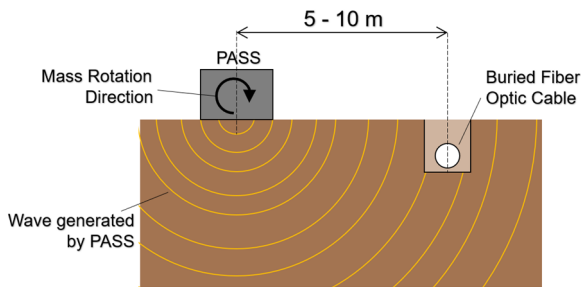


Figure 6. DAS-PASS Installation Setup

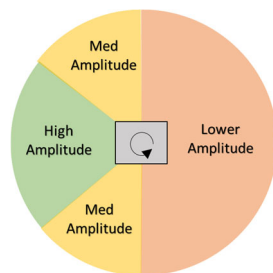


Figure 7. Strength of Amplitude Signal Produced by a single mass PASS

3.2 DAS Acquisition Parameter

The performance and sensitivity of a DAS-based seismic monitoring system are strongly influenced by its acquisition parameters, which must be carefully optimised to meet the specific requirements of the target application. Key acquisition parameters include gauge length, channel spacing, sampling rate, and the number of shot repetitions, all of which determine the spatial and temporal resolution of the dataset.

The gauge length refers to the effective length along the fibre over which strain (or strain rate) is measured and averaged

by the DAS interrogator. It typically ranges from 1 to 20 meters, depending on the interrogator design and application. A shorter gauge length improves spatial resolution and sensitivity to localised strain, which is crucial for detecting small-scale features or subtle velocity changes in near-surface layers. However, shorter gauge lengths may reduce signal amplitude and increase noise sensitivity, requiring a trade-off based on site conditions.

Spatial sampling, often set equal to or smaller than the gauge length, defines the interval between adjacent virtual sensing points along the fiber. A small channel spacing enables dense spatial sampling, which is critical for resolving short-wavelength seismic signals and constructing high-resolution data of the subsurface. This dense sampling also supports more accurate waveform stacking and noise suppression across the array.

The sampling rate, typically ranging from 500 Hz to several kHz, determines the temporal resolution of the recorded DAS data and sets the upper limit of the frequency content that can be accurately captured, in accordance with the Nyquist criterion. An adequate sampling rate is essential to preserve the waveform fidelity, especially when using broadband chirp signals or when aiming to detect subtle changes in signal arrival times or spectral characteristics over time. According to the Nyquist-Shannon sampling theorem, a minimum sampling rate of twice the highest frequency component (Equation 1) is required to avoid temporal aliasing (Shannon, 1949).

$$f_{sampling} \geq 2 \times f_{max} \quad (1)$$

where $f_{sampling}$ is the sampling rate in Hz and f_{max} is the highest frequency component in the signal in Hz.

However, in seismic acquisition, it is common to use 2.5 to 5 times oversampling to improve waveform resolution and ensure the integrity of frequency sweeps, particularly for controlled-source applications (Parker et al., 2014).

3.3 Seismic Shot Repetition

Environmental noise, instrument noise, and variability in source-ground coupling can degrade the quality of individual records. To mitigate these effects, the seismic source is triggered multiple times at each shot location (depending on the monitoring period and available power consumption of PASS), and the resulting waveforms are stacked using a weighted stacking technique (Schimmel & Paulssen, 1997). These stacking techniques enhance the coherency of repeatable seismic energy while suppressing random, uncorrelated noise, thereby improving both the SNR and the stability of the dataset. A detailed explanation related to this stacking technique is included in Section 4.5.

The implementation of staggered shot sequences can significantly enhance the temporal resolution and continuity of seismic monitoring. By intentionally offsetting the activation times of repeated seismic sources at various locations, staggered shooting allows for denser temporal sampling without overlapping energy interference. In these contexts, repeatability is important. High repeatability ensures that any observed seismic amplitude or travel-time changes are due to genuine subsurface processes rather than inconsistencies in source characteristics or coupling effects (Henninges et al., 2017).

3.4 Spatial Resolution

High spatial resolution is essential for resolving small-scale features and local anomalies, particularly in heterogeneous or engineered geotechnical environments. Fine spatial sampling improves the accuracy of waveform-based analyses (Ajo-

Franklin et al., 2019). When integrated with repeated PASS activations, this dense sampling facilitates a high-resolution and is capable of capturing both spatially and temporally localised changes in groundwater level.

4 SIGNAL PROCESSING WORKFLOW

Processing DAS data for groundwater monitoring presents unique challenges that require a specialized workflow, primarily due to the nature of DAS measurements and the extremely high spatial sampling density along the fibre optic cable. The raw data quality can be highly variable and is often influenced by both coherent and incoherent noise sources, depending on the environmental and geological conditions of the site.

The shot gathers along the cable typically exhibit a complex wavefield, with strong refracted arrivals that dominate the early portion of the records. These are often followed by low velocity shallow reflections, which can interfere constructively or destructively depending on the local stratigraphy and source-receiver geometry. The interference of coherent and incoherent waveforms, especially in heterogeneous or saturated subsurface environments, further complicates arrival picking and subsequent velocity analysis.

To address these issues, a signal processing workflow is essential. This includes trace preconditioning, noise suppression techniques, and stacking strategies to enhance signal coherency and suppress random noise. Each of these steps plays a vital role in preparing the DAS dataset for meaningful interpretation in the context of groundwater level changes.

4.1 Preprocessing

Raw Initial preprocessing focuses on the alignment and amplitude correction of raw DAS traces. Due to lateral heterogeneity and the presence of near-surface low-velocity layers, static corrections are necessary to align first arrivals across the shot gather. This can be achieved by constructing a laterally interpolated velocity function that allows the application of static time shifts. This method proves effective in environments with a relatively uniform, thin weathered layer. While first-break picking followed by time-shift static correction can address large-scale misalignments, residual timing errors often persist in far-offset traces. These are typically caused by high-frequency noise that obscures early arrivals. To compensate for this, residual static corrections are applied in a later stage to fine-tune arrival alignment.

To preserve true amplitude characteristics essential for quantitative interpretation, the dataset is analytically scaled using a parametric gain function. This function is derived from the average amplitude decay trend observed across multiple shot gathers. Equation (2) shows the amplitude decay curve $A(x)$ as a function of offset distance x can be empirically estimated from the data using the root-mean-square (RMS) amplitude of the signal in a time window around the first arrival.

$$A(x) = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} x^2(x, t) dt} \quad (2)$$

where $x(x, t)$ is the recorded strain rate signal at the time (t) and offset x , T is the duration of the analysis time window, and t_0 is the start time of the window. Once the average amplitude decay $A(x)$ is computed, a gain function $G(x)$ as shown in Equation (3) is defined as the inverse of the decay trend.

$$G(x) = \frac{1}{A(x) + \epsilon} \quad (3)$$

where ϵ is a small stabilization constant to prevent division by zero (typically chosen as a small fraction, 10^{-6} of the maximum recorded amplitude). The raw trace $x(x, t)$ is then scaled to obtain the amplitude-compensated trace \tilde{x} as shown in Equation (4).

$$\tilde{x}(x, t) = G(x) \cdot x(x, t) \quad (4)$$

This gain correction ensures more uniform amplitudes across traces, enhancing signal visibility and improving the reliability of subsequent processing steps.

4.2 Frequency Filtering

Selected shot gathers from the data were filtered with narrow band-pass filters, 10 to 50 Hz, and displayed in a panel form to study the characteristic frequency of signal and noise in the data set. This is important to observe that the frequency collected in this range is not mixed with the frequency produced by other sources.

4.3 f - k filtering

Traditional time-domain frequency filtering was insufficient in attenuating coherent noise without compromising the integrity of useful seismic arrivals. To address this, employed frequency-wavenumber ($f-k$) filtering, which transforms the seismic wavefield $x(x, t)$ into the $f-k$ domain using a two-dimensional Fourier transform. In this domain, coherent noise components manifest as energy concentrated along specific wavenumber-frequency trajectories associated with their apparent velocities. By applying a velocity-based mask to suppress energy below a threshold (choose a value just above the velocity of coherent noise), noise with low apparent velocity was effectively attenuated while preserving the higher-velocity signal energy. The filtered spectrum was then transformed back to the time-space domain via inverse FFT. This method proved particularly effective for DAS data with high spatial sampling density, where conventional filtering techniques failed to distinguish overlapping spectral content. (Dobrin & Savit, 1988)

4.4 Deconvolution

Deconvolutions need to be performed to improve the temporal resolution by suppressing the multiples and collapsing the wavelet to as many spikes as possible. Spiking deconvolution assumes that the source wavelet is minimum-phase and aims to compress it to a spike, thereby increasing temporal resolution. This is achieved by designing a whitening filter $h(t)$ as shown in Equation (5).

$$h(t) \times w(t) \approx \delta(t) \quad (5)$$

where $w(t)$ is the source wavelet and $\delta(t)$ is the Dirac delta function. When applied to the seismic trace, this filter yields as shown in Equation (6).

$$h(t) \times x(t) = r(t) + h(t) \times n(t) \quad (6)$$

where $n(t)$ is the additive noise. The whitening filter is typically computed by minimizing the prediction error over a given lag. The prediction lag is often set equal to the sampling interval, Δt , which enables the filter to anticipate the next sample based on prior values. This approach assumes the signal is predictable, whereas noise and multiples are not.

In addition, post-stack predictive deconvolution is applied to attenuate periodic multiples, particularly water-bottom reverberations or surface-related multiples that remain after

stacking. The filter in this method is designed to predict and subtract coherent, repeating energy from the stacked section by exploiting the periodic nature of multiples.

4.5 Weighted Stacking (WS)

To enhance signal coherency across repeated shots, a WS technique is applied. Unlike simple linear stacking, where all traces are summed equally, WS assigns weights based on signal attributes such as SNR, amplitude envelope, or cross-correlation metrics. A general form of the weighted stack is shown in Equation (7).

$$S(t) = \frac{\sum_{i=1}^N w_i(t)x_i(t)}{\sum_{i=1}^N w_i(t)} \quad (7)$$

where $x_i(t)$ is the i -th trace, $w_i(t)$ is corresponding weight at time (t), and $S(t)$ is the resulting stacked signal. The weights are computed based on local signal coherence and amplitude stabilization to reduce random noise and improve clarity of direct and reflected arrivals. WS is particularly effective for DAS-PASS datasets due to the consistent source characteristics and strong direct arrivals.

4.6 Velocity Analysis

Following weighted stacking to improve the SNR, velocity analysis needs to be conducted to estimate seismic wave propagation velocities within the subsurface. This can be achieved using semblance analysis, where trial normal moveout (NMO) velocities are applied to common-midpoint (CMP) gathers, and the velocity that best flattens reflection events is identified. High semblance values indicate that the velocity correctly aligns the seismic arrivals, making it a reliable estimate of subsurface velocity at that time-depth location.

To monitor temporal variations in seismic velocity, relative velocity variations (dv/v) must be computed using the stretching method. This technique involves comparing a reference waveform with a daily waveform by stretching the time axis of one to maximize their cross-correlation. The daily (dv/v) estimates are then aggregated using a cumulative median filter to minimize the influence of outliers and short-term fluctuations. This cumulative trend is used to compare directly with environmental data, such as precipitation. The method offers a sensitive tool for detecting small-scale changes in the near surface related to hydrogeological processes.

5 ADVANTAGES OF THE DAS-PASS FRAMEWORK

The integration of DAS with a PASS offers a powerful framework for high-resolution, repeatable, and non-invasive subsurface monitoring. This combined system provides several distinct advantages over conventional geophysical methods.

Firstly, DAS transforms existing or dedicated fibre optic cables into dense linear sensor arrays, capable of capturing full-wavefield seismic data with high spatial resolution. This enables fine-scale imaging of shallow subsurface features, including water table fluctuations. When coupled with PASS, the energy input becomes precisely controlled and highly repeatable, addressing a common limitation of passive DAS monitoring, where signal variability and external noise can hinder temporal comparisons and quantitative interpretation.

The PASS unit itself is designed for operational flexibility in diverse field conditions. Its compact, portable form factor allows deployment in remote or difficult-to-access environments without the logistical constraints of larger seismic sources. The system can be operated manually or automated via timers or wireless triggering, making it suitable for time-lapse or continuous monitoring applications. When

multiple PASS units are deployed along extended fibre networks, the system becomes spatially scalable. With integrated solar power options, this setup supports autonomous, wide-area monitoring campaigns without the need for constant human presence or external infrastructure.

Another key advantage lies in the permanence and non-invasiveness of the fibre optic sensor network. Once installed, the fibre can be reused repeatedly without disturbing the site, enabling long-term environmental monitoring. This is particularly valuable for applications such as groundwater level tracking, seepage detection in dams and levees, or hydrogeological studies in agricultural or urban settings. Repeat surveys can be performed with minimal marginal cost and zero environmental footprint, enhancing the practicality of time-lapse seismic studies.

6 CONCLUSION

This study presents a data acquisition strategy and signal processing workflow using the integration of high spatial resolution DAS measurements with repeatable seismic energy generated by PASS, enabling dynamic groundwater level monitoring with minimal site disturbance.

The processing workflow addresses key challenges associated with DAS data, including high channel density, directional sensitivity, and various forms of coherent and incoherent noise. Techniques such as preprocessing, deconvolution, frequency-wavenumber ($f-k$) filtering, weighted stacking, and velocity analysis were applied to enhance signal clarity, temporal resolution, and interpretability. Weighted stacking was particularly effective in improving SNR by emphasizing coherent waveforms while suppressing random noise. Furthermore, velocity analysis following stacking enabled the derivation of velocity variations that are essential for identifying hydrologically active zones.

To support long-term hydrological monitoring, relative seismic velocity changes were calculated through waveform cross-correlation, and a cumulative median of daily dv/v was used to track temporal variations. This provided a direct means of comparison between seismic observations and hydrological data.

This work demonstrates that DAS paired with a PASS holds strong potential as a transformative tool in near-surface geophysics and hydrological monitoring. Future efforts will focus on applying this approach across different hydrogeological settings and integrating it with other geophysical and hydrological datasets for more comprehensive subsurface characterization.

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