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# Seismic Crosswell Surveys using Distributed Acoustic Sensing (DAS) for Enhanced Geotechnical Monitoring and Subsurface Imaging: Insights from the Svelvik CO2 Field Lab

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ABSTRACT: Seismic tomography is a key technique in geophysical engineering for imaging subsurface properties relevant to infrastructure development, hazard mitigation, and environmental monitoring. While P-wave tomography is widely used for its simplicity and sensitivity to compressibility and fluid content, it provides limited information on mechanical behavior. S-wave tomography, directly related to the small-strain shear modulus ($G_0$), offers a more reliable measure of subsurface stiffness but remains time- and cost-intensive. Emerging technologies such as Distributed Acoustic Sensing (DAS) can address these limitations. Integrating DAS with a borehole SV-wave source (BIS-SV) may substantially improve the efficiency and resolution of S-wave seismic site characterization for geotechnical and environmental applications. This study demonstrates the effectiveness of combining a vertically polarized SV-wave source with Distributed Acoustic Sensing (DAS) for shear-wave tomography at the ECCSEL Svelvik $CO_2$ Field Lab, Norway. The SV-wave source generates vertically polarized shear waves that align with the axial sensitivity of DAS fibers, enabling efficient, high-resolution acquisition without conventional receivers. This configuration provides dense, borehole-length seismic coverage with acquisition times comparable to standard P-wave surveys. The resulting SV-wave tomograms reveal distinct lateral and vertical heterogeneities, offering improved imaging of shear stiffness—an essential parameter for assessing ground stability and seismic risk. The approach simplifies field operations, removes the need for water-filled boreholes, and reduces costs by 30–50% relative to traditional methods. These results highlight the potential of DAS–SV-wave integration for advanced geotechnical and environmental site characterization.

KEYWORDS: Distributed Acoustic Sensing, SV-wave Tomography, Geotechnical Monitoring, Shear Stiffness, Crosswell Seismic Imaging, Fiber-optic Sensors, Svelvik CO2 Field Lab

## 1 INTRODUCTION

Seismic tomography has long served as a foundational technique in both geophysical and geotechnical engineering, facilitating the detailed characterization of subsurface structures and material properties that are critical for infrastructure design, hazard mitigation, and environmental assessment. Among tomographic approaches, P-wave tomography has traditionally been the method of choice due to its relative ease of implementation, high signal-to-noise ratio, and well-established interpretative frameworks (Paasche et al., 2011). Nevertheless, P-wave measurements are predominantly sensitive to variations in bulk modulus and density, providing limited information regarding subsurface shear stiffness, an essential parameter for evaluating small-strain shear modulus ($G_0$) and the deformation behavior of geomaterials under static and dynamic loading conditions (e.g., Stewart, 1991; Fichtner et al., 2024).

In contrast, shear-wave (S-wave) tomography offers a fundamentally different sensitivity profile, as S-wave velocities are directly linked to the small-strain shear modulus ($G_0$). Consequently, S-wave tomography constitutes a more representative proxy for assessing the dynamic mechanical properties of soils and rocks (Ketelhodt et al., 2017). Owing to these advantages, S-wave tomography should be adopted more extensively in seismic investigations, particularly in studies requiring high-resolution imaging of lithological heterogeneities, fault zones, and geomechanical features. Its enhanced sensitivity to shear stiffness and structural integrity renders it an invaluable tool in applications such as earthquake hazard assessment, construction site characterization, and subsurface monitoring for geothermal energy and carbon sequestration projects (e.g., Hussien & Karray, 2015).

Substantial progress has been achieved in the development of advanced instrumentation to facilitate the efficient acquisition of S-wave borehole tomographic data. Historically, the implementation of S-wave tomography has been more time-intensive than its P-wave counterpart, primarily due to challenges associated with generating reliable S-wave sources and the requirement for multi-channel receiver systems capable of effectively recording shear-wave signals. Unlike P-waves, which are relatively straightforward to produce and detect, S-waves necessitate specialized source mechanisms that induce controlled shear motion in the subsurface, thereby ensuring accurate and repeatable wave propagation. Figure 1 summarizes the principal advantages and limitations of S-wave tomography in comparison to conventional P-wave tomography.

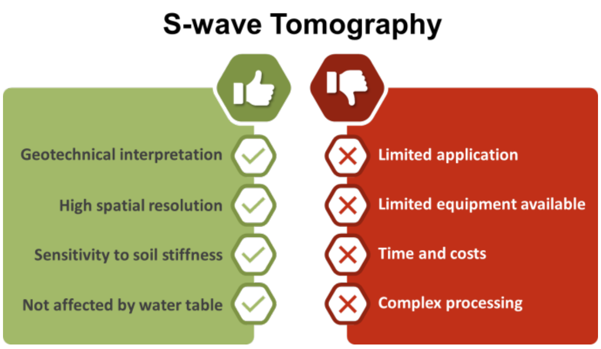


Figure 1. Advantages and disadvantages of S-wave tomography compared to traditional P-wave tomography.

Over the past decade, the emergence of Distributed Acoustic Sensing (DAS) has demonstrated substantial advantages over conventional seismic sensors, offering sub-meter spatial resolution across tens of kilometers, exceptional repeatability, and significant time efficiency in borehole active seismic surveys (e.g., Isaenkov et al., 2021). The integration of fiber-optic sensing through DAS with S-wave tomography presents transformative opportunities for geotechnical engineering applications.

The benefits of this integration are manifold. DAS enables the deployment of hundreds of virtual receivers per borehole without the need for mechanical coupling or water-filled casings, thereby reducing logistical complexity and operational costs. Moreover, DAS fibers exhibit high sensitivity to the vertical particle motion of S-waves, yielding enhanced signal-to-noise ratios and reliable travel-time measurements for tomographic inversion (e.g., Koedel et al., 2024). These capabilities facilitate S-wave tomograms with improved spatial resolution and sensitivity to subsurface heterogeneity, allowing direct imaging of shear stiffness between boreholes.

Despite its promise, several limitations persist. DAS systems record only a single component and are thus sensitive to specific wave polarizations and incidence angles. SH-waves, with particle motion perpendicular to the fiber orientation, are poorly captured, and inconsistent fiber coupling or poor installation can introduce high noise levels or artifacts. Nonetheless, when optimized for SV-wave acquisition, DAS provides a highly efficient, repeatable, and spatially dense dataset—making it particularly attractive for geotechnical site characterization.

In this study, we present the first SV-wave crosswell survey employing DAS technology, highlighting the considerable time and cost savings achieved in S-wave tomography. The approach demonstrates that DAS-based S-wave tomography can achieve parity with conventional P-wave methods in acquisition efficiency while providing direct insights into soil stiffness and dynamic parameters essential for geotechnical analysis. This work was conducted within the framework of the EU-funded GeoInquire program, which aims to facilitate industry access to and utilization of existing geotechnical test sites.

## 2 METHOLOGY

### *2.1 THE SVELVIK TEST SITE AND MEASUREMENT SETUP*

The field experiments presented in this study were conducted in 2021 and 2024 at the ECCSEL Svelvik $CO_2$ Field Lab, a small-scale research facility located at the Drammensfjord outlet in Norway (Eliasson et al., 2018; SINTEF, 2025) (Figure 2). Operated by SINTEF, the site is designed to enable rapid and cost-effective testing of geophysical monitoring technologies for $CO_2$ storage applications.

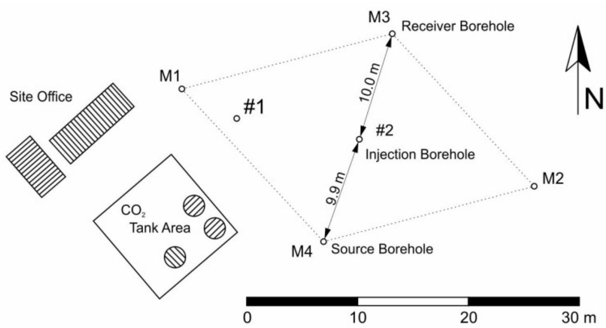


Figure 2. Sketch of the Svelvik test-site.

The facility comprises one main injection well (B2) and four surrounding monitoring wells (M1–M4), each approximately 100 m deep. The wells are arranged to allow crosswell seismic imaging along multiple azimuths and offsets. All boreholes are PVC-cased, with annular spaces filled with cement except at selected instrumented intervals, where gravel backfill enhances sensor coupling.

The 2021 field campaign primarily employed a P-wave sparker source (SBS42) for crosswell P-wave tomography aimed at monitoring $CO_2$ migration. In addition, SH-wave (BIS-SH) and SV-wave (BIS-SV) sources were deployed, together with hydrophone chains (BHC5) and a tri-axial Multi-station Borehole Acquisition System (MBAS) (Figure 3).

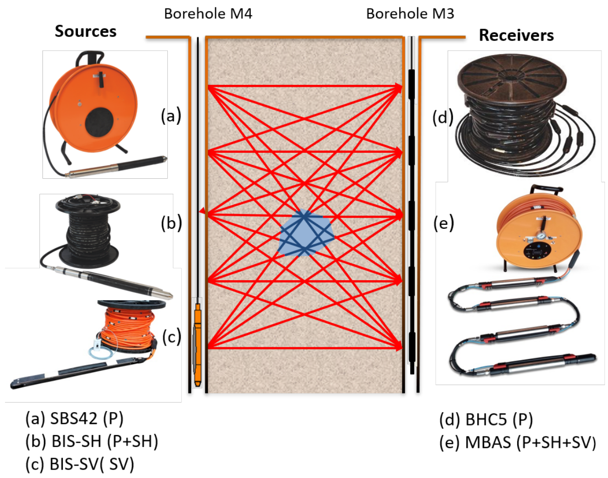


Figure 3. Conventional sources and receivers used in the experiment in 2021 (a) P-wave source (SBS42), (b) SH-wave source (BIS-SH), (c) SV-wave source (BIS-SV), (d) Hydrophone chain (BHC5), (e) tri-axial Multi-station Borehole Acquisition System (MBAS).

For Distributed Acoustic Sensing (DAS) measurements, each monitoring well was equipped with both linear and helically wound optical fibers affixed to the external casing. The fibers were permanently installed and spliced into a closed loop to enable simultaneous interrogation using a Silixa iDAS v2 and an OptoDAS unit. This configuration allowed a direct comparison of linear and helical fiber responses under identical acquisition conditions and ensured full-depth data coverage across all boreholes.

The 2024 campaign utilized a dedicated SV-wave source and DAS acquisition (Figure 4). Data were recorded with a 3 m gauge length and 0.5 m spatial sampling, optimizing the system's frequency response within the expected seismic bandwidth. Each shot was repeated and stacked to enhance the signal-to-noise ratio, resulting in an average acquisition time of approximately 3–4 minutes per source depth, including clamping, excitation, and release.

### *2.2 DATA PROCESSING*

Both the DAS and conventional geophone datasets underwent comprehensive processing and inversion to produce high-resolution tomograms of subsurface shear-wave velocity. The primary objective was to extract SV-wave travel times generated by the BIS-SV source and recorded by DAS fibers and geophones across the instrumented boreholes. Owing to the high spatial density of the DAS recordings (~95 traces per shot), customized workflows were implemented to accommodate the strain-based measurement nature of the data (Figure 4).

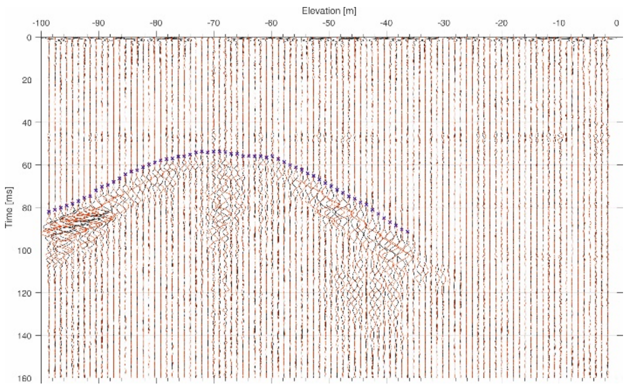


Figure 4. Example of a DAS seismic crosswell record with opposite polarization direction. Traveltime picks are displayed as blue crosses.

Initial preprocessing involved selecting the fiber segments corresponding to the monitored depth intervals and defining the geometric relationships between source and receiver positions. The DAS data were bandpass filtered using a second-order Butterworth filter (150–2000 Hz) to isolate the dominant SV-wave energy and suppress low-frequency noise and high-frequency artifacts. SV-wave arrivals were identified based on the polarization reversals induced by the bidirectional strikes of the SV source. Manual travel-time picking was conducted by overlaying "up" and "down" waveforms, enhancing the detection of first arrivals through polarity comparison.

Conventional geophone data, acquired in parallel within a single borehole, were processed similarly. Manual picking was performed on the vertical component of the triaxial recordings, emphasizing opposite-polarized SV-wave onsets. Accurate depth alignment between source and receiver positions was maintained, with borehole deviation data used to correct lateral offsets, ensuring precise raypath geometry for inversion.

To validate the DAS-derived travel times, nearly horizontal raypaths were directly compared with those obtained from the borehole geophone data. The two datasets exhibited strong agreement, with minor delays in the DAS arrivals attributed to the 3 m gauge-length averaging effect. Despite this, the high spatial density and consistent signal quality of the DAS data enabled robust inversion and detailed velocity imaging.

Tomographic inversion was performed using GeotomCG, which applies a curved-ray Simultaneous Iterative Reconstruction Technique (SIRT). The initial velocity model, representing a horizontally layered structure consistent with the Svelvik site's sedimentary setting, was constructed using near-horizontal raypaths (incidence angles ≤5°). To avoid out-of-plane effects, raypaths exceeding 35° were excluded. Ten SIRT iterations were executed to iteratively minimize travel-time residuals and refine the shear-wave velocity distribution.

This workflow yielded tomograms that accurately represent spatial variations in subsurface shear stiffness, providing a robust foundation for high-fidelity geotechnical interpretation and site characterization.

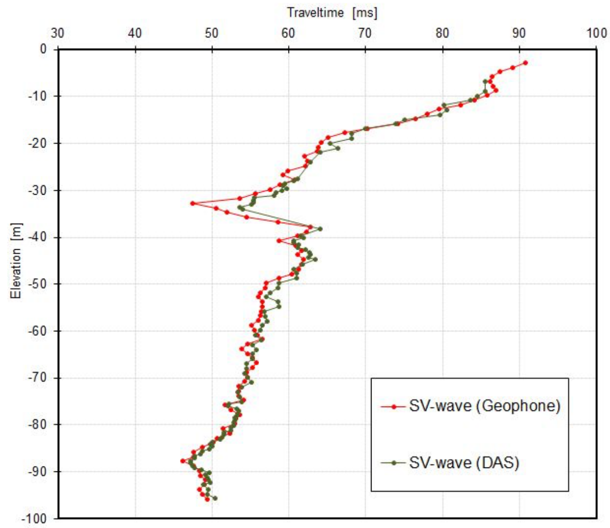


Figure 5. Comparison of S-wave travel times obtained with traditional geophones and arrival times from DAS for horizontal rays.

## 3 RESULTS

### *3.1 P- WAVE TOMOGRAM*

The structural and mechanical characteristics of the subsurface are revealed by the tomographic inversion results for both P- and SV-wave datasets acquired at the Svelvik $CO_2$ Field Lab. The P-wave tomogram was generated using conventional hydrophone data from the 2021 $CO_2$ injection experiment (Figure 6).

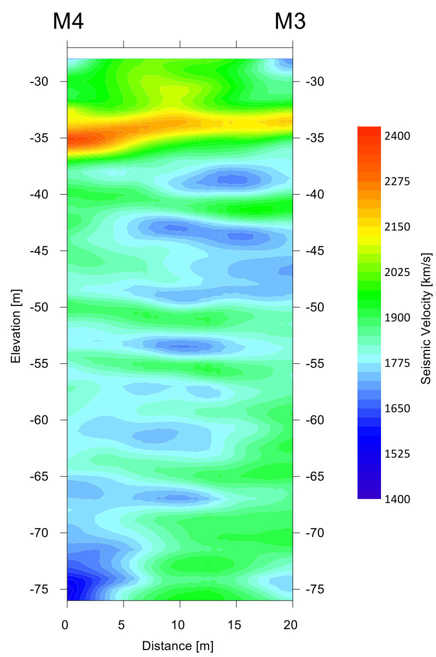


Figure 6. P-wave tomogram

The P-wave tomogram, which covers depths from approximately 30 to 77 meters, shows a horizontally layered structure with alternating zones of high and low seismic velocities (see Figure 2). This stratification is consistent with typical sedimentary layering and reflects changes in lithology and pore fluid distribution. P-wave velocities range from approximately 1,500 to 2,500 meters per second, with higher velocities in deeper layers. The tomogram clearly delineates the clay-rich sealing layer at a depth of approximately 35 meters, which was previously confirmed through borehole logging and $CO_2$ plume migration studies. However, due to its primary sensitivity to bulk modulus and compressibility, the P-wave image is less effective in capturing variations related to mechanical stiffness or shear resistance.

### *3.2 SV- WAVE TOMOGRAM*

The SV-wave tomogram is displayed in Figure 3. In contrast to the P-wave tomogram the SV-wave tomogram obtained from DAS measurements reveals a different image of the subsurface.

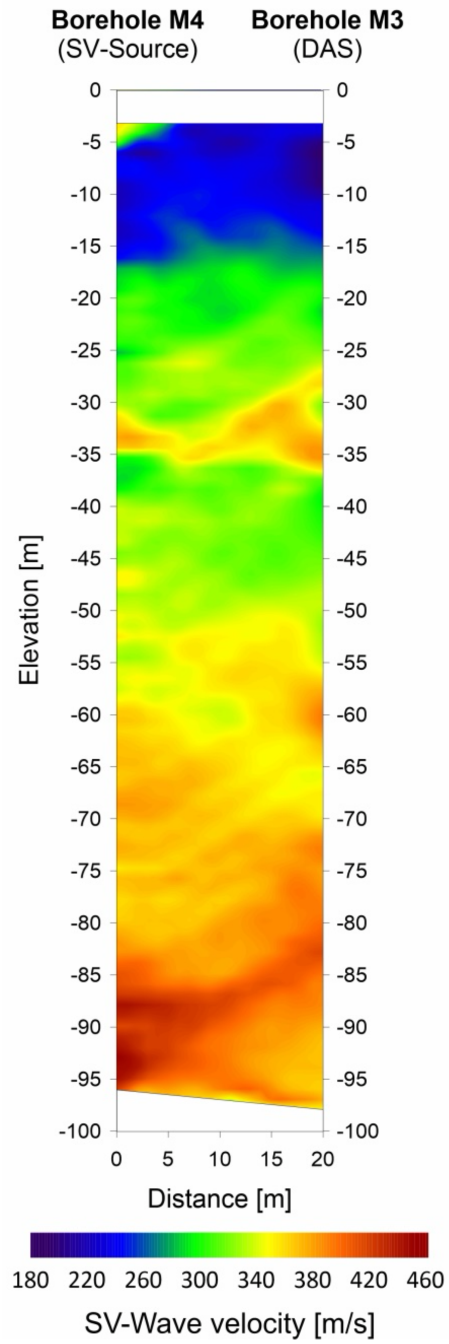

Figure 7. SV-wave tomogram.

The SV-wave image, which covers the full depth range from about 0 to 100 meters, shows significant lateral and vertical heterogeneities, particularly between 30 and 60 meters. Shear wave velocities range from 150 to 500 meters per second (m/s), and a high-velocity zone is identified between 30 and 35 meters. This feature correlates spatially with the high-velocity zone in the P-wave tomogram, yet it appears more localized and sharply defined in the SV-wave image. Below 60 meters, SV-wave velocities increase more gradually, indicating a transition to stiffer, more consolidated sediments.

### *3.3 COMPARISON OF P- AND SV- WAVE TOMOGRAMS*

A quantitative analysis of conventional crosswell data corroborates the qualitative observations of distinct wave sensitivities. The coefficient of determination between P- and S-wave travel times is low ($R^2 = 0.196$; Figure 8), highlighting the complementary nature of the two wave modes: P-waves predominantly reflect variations in density and compressibility, whereas S-waves are more sensitive to shear stiffness and structural rigidity. Furthermore, SV-wave travel times exhibit substantially greater variability (~50%) compared to P-wave travel times (~13%), emphasizing the enhanced sensitivity of S-waves to small-scale heterogeneities and mechanical contrasts.

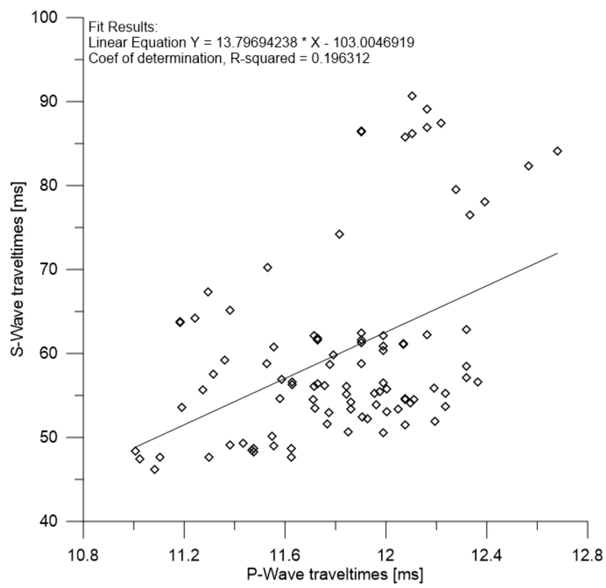

Figure 8. Correlation between P- and S-wave traveltimes.

These findings underscore the value of incorporating SV-wave tomography into geotechnical investigations. While P-wave imaging establishes a robust structural framework, SV-wave data provide direct insight into geomechanical properties, enabling more accurate assessments of ground stiffness, stability, and potential failure zones. Integrating both datasets allows for a more comprehensive, multi-parameter characterization of the subsurface, thereby supporting improved infrastructure design and subsurface monitoring.

To obtain a distribution of soil stiffness, i.e. the small-strain shear modulus ($G_0$) is calculated using the S-wave velocity ($V_s$) and the soil density ($\rho$) by using the equation: $G_0 = \rho V_s^2$ (e.g. Guadalupe et al., 2013). Essentially, the square of the S-wave velocity, multiplied by the density, represents the material's resistance to shear deformation at small strain levels. Assuming a density value of 2000 kg/m$^3$ a dynamic shear stiffness map can be calculated and is shown in Figure 9.

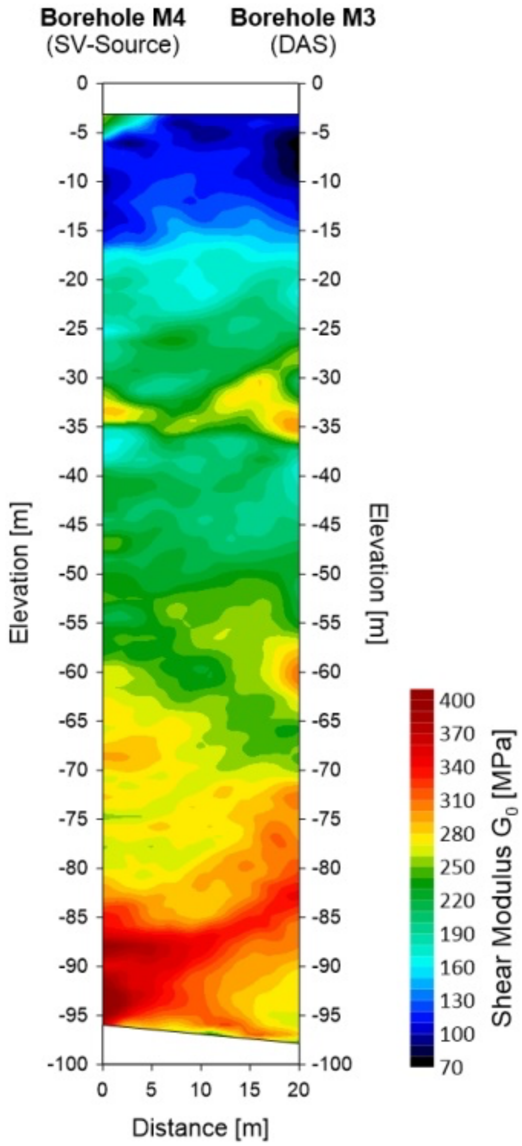


Figure 9. Shear modulus tomogram.

## 4 CONCLUSION

The Svelvik $CO_2$ Field Lab provided a controlled environment with advanced instrumentation to evaluate the feasibility and effectiveness of Distributed Acoustic Sensing (DAS) crosswell seismic tomography. The experimental campaign enabled a direct comparison between DAS and conventional geophone measurements, as well as a systematic assessment of optical fiber configurations and wave types. The resulting dataset demonstrates the viability of DAS for high-resolution subsurface imaging and establishes a benchmark for its broader application in geotechnical and environmental monitoring.

A principal outcome of this study is the demonstrated utility of incorporating SV-wave tomography into geotechnical investigations. While P-waves are primarily sensitive to bulk modulus and fluid content, SV-waves provide direct insight into shear stiffness, a critical parameter governing soil mechanical behavior under both static and dynamic loading. The SV-wave tomograms obtained via DAS reveal pronounced heterogeneity and sharper velocity contrasts, enabling precise delineation of zones with varying stiffness and stability. Such information is particularly relevant for earthquake hazard assessment, foundation design, and slope stability analyses.

The use of DAS for SV-wave tomography confers several operational and technical advantages. The system achieves high spatial resolution, recording up to 95 traces per shot, substantially exceeding the density of conventional geophone arrays. The fiber-optic setup obviates the need for water-filled boreholes, simplifying field operations and reducing logistical complexity. Moreover, cost reductions of 30–50% are achievable relative to traditional crosswell surveys, particularly for repeat or long-term monitoring campaigns. The enhanced sensitivity of SV-waves to shear stiffness further improves the accuracy of mechanical property characterization, critical in seismically active or structurally complex settings.

From an operational perspective, acquisition times for DAS-based SV-wave tomography were comparable to conventional P-wave surveys, averaging three to four minutes per shot depth. This efficiency, combined with continuous depth coverage without sensor repositioning, establishes DAS as a scalable and practical solution for a wide range of geophysical applications.

Several limitations were observed. Signal-to-noise ratios varied among DAS channels, primarily due to inconsistencies in cable coupling, highlighting the importance of optimized installation procedures, including uniform clamping and careful cementation. Nonetheless, overall data quality and inversion reliability remained high, validating the robustness of the DAS approach even under suboptimal coupling conditions.

The integration of a borehole-coupled BIS-SV source with DAS offers distinct technical advantages. The source generates vertically polarized shear waves, aligning optimally with linear DAS fibers, which are directionally sensitive along their longitudinal axis. This source-sensor compatibility enhances waveform clarity and improves first-arrival picking, critical for accurate tomographic inversion. Additionally, the BIS-SV source produces bidirectional impacts ("up" and "down" strikes), which, combined with conventional P-wave sources, maximizes imaging capability while reducing field complexity.

In summary, the combination of DAS, SV-wave sources, and conventional seismic methods provides a cost-effective, high-resolution approach for advanced subsurface imaging. The complementary insights from P- and SV-wave tomography enable a multi-parameter characterization of the subsurface, supporting improved infrastructure design, refined geotechnical risk assessments, and enhanced monitoring of subsurface storage operations. The Svelvik campaign demonstrates the potential of DAS-enabled seismic technologies and provides a foundation for their broader implementation in geotechnical and environmental geophysics.

## 5 ACKNOWLEDGEMENTS

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